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LTE in high capacity locations:

A case study of Lerkendal Stadium

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Title: LTE in high capacity locations:
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Problem description:

For large happenings like football matches and concerts Telenor Norge is normally adding extra capacity in the mobile network to secure a good customer experience. The demand for mobile data is expected to keep on growing, so how should Telenor build and invest in the mobile network to handle these high capacity events in the future?

This thesis focus on the LTE network and the network installations by Telenor Norge at high capacity locations. The student will conduct research based on data provided by Telenor Norge in order to identify success factors in LTE network installations. With the LTE network installation at Lerkendal Stadium as a starting point, measurements and traffic data will be analyzed and compared towards the similar installation at Ullevål Stadium. By using historic data and forecasts for future traffic growth this thesis aim to provide feedback on how to build the LTE installations of tomorrow.

Background information and history will be presented to gain a better understanding of the behaviour of the technology. Methods for measuring signal strength and noise as well traffic data analysis tools will be elaborated.

Finally, a set of criteria will be established for evaluating the performance of a base station, in order to design the most efficient LTE network installation. Furthermore, determine the profitability of investing in multiple base stations versus using a single base station at a location.

Responsible professor: Yuming Jiang, ITEM
Supervisor: Bjarte Kvarme, Telenor Norge

Abstract

As the demand for mobile data is expected to keep on growing, the mobile network needs constant development. So, how should Telenor Norway build and invest in the mobile network in order to handle high capacity events in the future? As the frequency spectrum available for mobile data traffic is limited, we need to find the most efficient way of using it.

By using new frequency efficient technologies and innovative solutions for the radio interface, the mobile network capacity can be increased. For high capacity locations as concert arenas, stadiums and such, the challenge is providing tightly gathered devices with sufficient capacity without causing interference.

The LTE network installation at Lerkendal Stadium, Norway, is the starting point for this thesis. By comparing this to other high capacity locations with a LTE installation by Telenor Norway, this thesis identifies success factors in the LTE installations.

Furthermore, by considering historic data and forecasts for future traffic growth provided by Telenor Norway, this thesis aims to provide feedback on how to build the LTE installations of tomorrow.

Sammendrag

Ettersom etterspørsel og krav til hastighet på mobildata stadig øker, må mobilnettverket utvikles raskt for å imøtekomme dette. Så, hvordan skal Telenor Norge bygge og investere i mobilnettverket for å takle fremtidens krav til kapasitet? Ettersom de tilgjengelige frekvensene for mobilnettverk er begrenset, må man finne den beste måten å utnytte dem på.

Ved å benytte frekvenseffektiv teknologi i kombinasjon med innovative løsninger i radiogrensesnittet kan man øke kapasiteten i mobilnettverket. På steder med krav om høy kapasitet, slik som konsertarenaer og stadioner, er det viktigste å dele inn brukerne i sektorer uten å skape høy interferens.

LTE-nettverksinstallasjonen på Lerkendal stadion, i Trondheim, brukes som utgangspunkt for denne oppgaven. Ved å sammenlikne denne med andre LTE-installasjoner av Telenor Norge på steder med høyt kapasitetsbehov, vil man i dette prosjektet finne suksessfaktorene som får et mobildatanettverkt til å operere effektivt.

Videre, ved å ta i betraktning historisk trafikkdata og antatt vekst for framtiden, samlet fra installasjonene som inngår i denne oppgaven, kommer man frem til forslag til hvordan morgendagens mobilnettverk kan bygges.

Preface

This paper is the final product of the research conducted during the work on my Master's Thesis in the subject TTM4905, carried out during the autumn of 2017. The Master's Thesis is the final assignment of my five year degree to become a Master of Science in Communication Technology with specialization in Information Security.

The project is the continuation of preparatory work carried out in the spring of 2017 and involves a case study of Lerkendal Stadium. The work has been conducted in collaboration with Telenor Norway and the Norwegian University of Science and Technology (NTNU).

As an employee of Telenor since 2015 I would like to thank the Company for all opportunities and trust on my way to completing my master's degree.

Many people have been involved in revising the different chapters and have given invaluable suggestions on content, style and grammar. I would especially like to thank Bjarte Kvarme, supervisor at Telenor, Yuming Jiang responsible professor at NTNU and Muhammad Hussain network planner at Telenor.

Einar Flobak

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List of Acronyms

NTNU Norwegian University of Science and Technology

3GPP Third Generation Partnership Project

NMT Nordic Mobile Technology

GSM Global System for Mobile Communication

GPRS General Packet Radio Service

EDGE Enhanced Data rates for GSM Evolution

UMTS Universal Mobile Telecommunications System

LTE Long Term Evolution

RBK Rosenborg Ballklub

EPC Evolved Packet Core

EPS Evolved Packet System

E-UTRAN Evolved Universal Terrestrial Radio Access Network

MS Mobile Station

UE User Equipment

eNB Evolved Node B

MME Mobility Management Entity

S-GW Serving Gateway

PDN-GW Packet Data Network Gateway

RRC Radio Resource Control

RMM Radio Mobility Management

HSS Home Subscriber Server

CQI Channel Quality Indicator

FDMA Frequency Division Multiple Access

TDMA Time Division Multiple Access

CDMA Code Division Multiple Access

OFDMA Orthogonal Frequency Division Multiple Access

OFDM Orthogonal Frequency Division Multiplexing

WBCDMA Wide Band Code Division Multiple Access

PRB Physical Resource Blocks

QoS Quality of Service

HLR Home Location Register

AuC Authentication Centre

PDN Packet Data Network

MIMO Multi-Input Multi-Output

QPSK Quadrature Phase Shift Keying

QAM Quadrature Amplitude Modulation

TDD Time Division Duplex

FDD Frequency Division Duplex

NMS Network Management System

RRU Radio Remote Unit

BBU Base Band Unit

DSP Digital Signal Processor

Tx Transmit

Rx Receive

RF Radio Frequency

RFU Radio Frequency Unit

BTS Base Transceiver Station

CPRI Common Public Radio Interface

PHY Physical Layer

TTI Time Transmission Interval

PS Packet Scheduler

PDCCH Physical Downlink Control Chanel

SNR Signal to Noise Ratio

SWR Standing Wave Ratio

PIM Passive Intermodulation

AAS Active Antenna System

Chapter 1 Introduction

The topic area of this thesis is how high capacity events as concerts, soccer matches etc. are handled in the mobile network. By looking at the architecture of the mobile network installation at Lerkendal Stadium, located in Trondheim (Norway), this thesis aims to identify success factors in the installation. Furthermore, focusing at the Long Term Evolution (LTE) network the findings will be used to derive suggestions on how to build and invest in future network installations.

The following chapters will introduce the case and Telenor. Furthermore, provide an in depth description of the LTE network as background for the following chapters.

1.1 Introduction to Telenor

Telenor saw the first light of the day as early as 1855 as the first Norwegian telegraph line opened between Christiania (Oslo) and the city of Drammen. The Norwegian Telegraph Administration (Telegrafverket), as it was named at the time, later moved on to become Norwegian Telecommunications (Televerket) in 1969. One major milestone in Norwegian telecommunication history was the opening of the Nordic Mobile Technology (NMT) network in 1981.

Figure 1.1: Old Telenor logo

During the liberalization of the telecommunication monopoly during the 1990s the company went through some changes. Among the changes were the introduction of the Global System for Mobile Communication (GSM) network in 1993 and the name change to Telenor in 1995. The next major technologically leap forward was the introduction of the Universal Mobile Telecommunications System (UMTS) in 2004, followed by the LTE network in 2012 [ASA].

Figure 1.2: Current Telenor logo

Today Telenor is one of the largest mobile telecommunication companies in the world with over 200 million subscribers world wide. More than 3 million (Q2 2017) of the subscribers are connected to the Norwegian branch, Telenor Norway, making it Norway's leading supplier of tele- and data services.

1.2 History of Lerkendal Stadium

Lerkendal Stadium is one of the largest soccer stadiums in Norway, and is home to the Norwegian top league team Rosenborg Ballklub (RBK). Construction of the stadium started in the 1930s, but wasn't officially completed until 1947. Over the years the stadium has been upgraded several times. The first major upgrade was the addition of a terrace (standing-only) and a roofed grandstand in 1962.

Figure 1.3: Aerial view of Lerkendal Stadium

Some thirty years passed before the next major upgrade in 1996, as the terrace was replaced by a roofed grandstand seating 7457 spectators. In a major upgrade at the beginning at the millennium the the roofed grandstand from 1962 was replaced, in addition grandstands at both short ends were built. The stadium was reopened September of 2002, seating a total of over 21000 spectators.

1.3 Scope

The scope of this thesis is the LTE network, but will also include legacy networks providing background for the technological decisions made in LTE. The heritage from previous network generation is an important part of 4G, which also is reflected in the technical name Long Term Evolution. As the 5G network as of now (October 2017) still is in the early stages, it will not be included in this thesis, but may be subject of further work.

1.4 Ambitions and Goals

The goal for this thesis is, as mentioned initially, deriving suggestions on how to build and invest in the LTE network in the future. In order to achieve this goal, the following research questions are formulated:

- What are the key success factors in the LTE installation at Lerkendal Stadium?
- What measures should be taken to future proof installations today?
- Where is the threshold for adding a base station?

Furthermore, the ambition is that the suggestions derived in this thesis will be used in the planning of LTE installations of the future.

1.5 Related Work

The topic area of this thesis, the mobile network, is subject to continuous research and development. Hence, there are several papers concerning the LTE network. The following section introduces some of the papers related to this.

1.5.1 QoS performance of LTE networks with network coding

This Master's Thesis written by Tewelde Degefa Assefa in 2015 provides an analysis of the Quality of Service (QoS) in the LTE network. The main performance parameters considered are the throughput, packet delay, spectral efficiency, capacity and coverage. [Ass15]

Chapter 2
Theory

This chapter will provide the necessary background for the case study performed for this thesis. Furthermore, describe the most important parts of the LTE architecture, the LTE access network and the use and distribution of frequencies for mobile communication. In addition, theories of signal and noise will be elaborated, and further described how theory is put into practice when planning LTE network installations.

2.1 LTE Architecture

In this section the architecture of the LTE network will be described. In addition the architecture of some legacy networks will be mentioned, which forms the basis for - and is key to understanding the design decisions made for 4G.

2.1.1 The Evolution Towards 4G

Starting of with the GSM network in the early-1990s the mobile network was primarily designed for voice only communication. This was done by establishing a dedicated persistent connection between the two calling parties, hence a circuit switched network. However, together with the 1990s came the popularity of the Internet and the ever increasing demand for additional capacity. The Third Generation Partnership Project (3GPP) responded by introducing the General Packet Radio Service (GPRS), an addition to the circuit switched GSM, that enabled packet switching.

The concept of packet switched networks meant that data could be transported without the establishment of dedicated circuits. However, the system was still dependent on the circuit switched core for paging. In the following years the GPRS was further developed to the Enhanced Data rates for GSM Evolution (EDGE) and in 3GPP Release 99 UMTS was introduced - now know as 3G [Sau10].

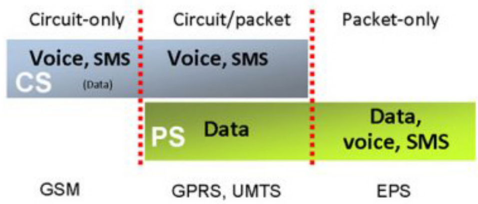

Figure 2.1: Technologies and domains

In an effort to ensure that the mobile network also in the future would remain competitive, 3GPP began a project in 2004 to define the long term evolution of UMTS. The result of this project is first revealed in 3GPP Release 8, and is now what we know as the LTE network.

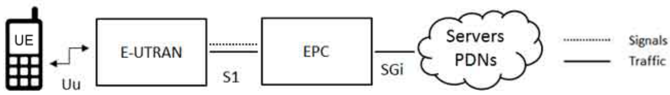

Figure 2.2: LTE High Level Architecture

The new LTE architecture, called the Evolved Packet System (EPS), consists of two new sub-systems. One part is the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and the other is the Evolved Packet Core (EPC). The two most important differences between the LTE- and UMTS architecture is: fewer node types in the EPS and the removal of the circuit switched domain. [Wid08]

2.1.2 Components in the Evolved Packet System

When looking at the EPC there are four key nodes that should be considered. The Mobility Management Entity (MME), the Serving Gateway (S-GW), the Packet Data Network Gateway (PDN-GW) and the Home Subscriber Server (HSS). Looking at the E-UTRAN, the other part of the EPS, the key nodes that should be considered are the User Equipment (UE) and the Evolved Node B (eNB).

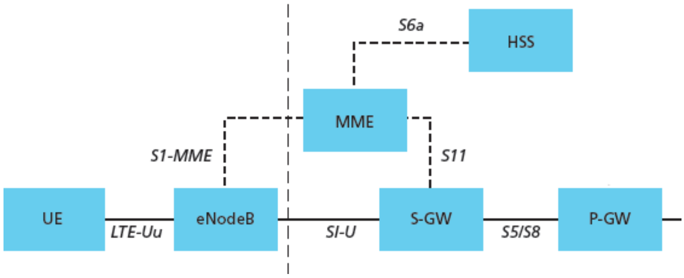

Figure 2.3: The Evolved Packet System

User Equipment

The UE is the device used connecting to the network by the end user. In earlier 3GPP releases this node was know as Mobile Station (MS). The UE can be a hand-held phone, a laptop, or any other device. All UE is categorized into a rank describing its capabilities allowing more effective communication with the eNB [MK12]. The radio interface between the UE and eNB is called LTE-Uu.

Evolved Node B

The eNB is the main component in the radio interface, and can be seen as the base station. The eNB, from a functional perspective, is responsible for the modulation and de-modulation as well as channel coding and de-coding for transmission and reception over the radio interface. Furthermore, the eNB is also responsible for Radio Resource Control (RRC) and Radio Mobility Management (RMM), i.e. respectively allocation, modification and release of radio resources - and measurement processing and handover decisions.

Mobility Management Entity (MME)

The MMEs main responsibilities are functions related to subscriber and session management.

- Security procedures - related to end-user authenticating and negotiation of ciphering and integrity protection algorithms.
- Terminal to network session handling - signaling for setting up data network sessions and negotiation of associated parameters.
- Idle terminal location management - relates to the tracking area process.

The MME is linked to the HSS over the S6 interface.

Home Subscriber Server (HSS)

In the LTE network architecture the HSS is a merge of the Home Location Register (HLR) and Authentication Centre (AuC). The HSS is responsible for the following tasks:

- User identification and addressing, also storing user profile information and identifiers.
- Generating security keys from the stored user identity information.
- Mutual network-terminal authentication and radio path encryption based on the generated keys.

Serving Gateway

The S-GW is the termination point of the E-UTRAN towards the EPC. The main responsibilities of the S-GW are session handling on instruction from the MME, and signalling between the PDN-GW and the MME.

Packet Data Network Gateway

The PDN-GW is the termination point of the EPC towards the external Packet Data Network (PDN). Furthermore, the PDN-GW acts as a router between the external PDN and EPS and is also responsible for allocation of IP addresses.

2.2 LTE Access Network

The following sections introduces the principles on which the multiple access techniques of LTE is built upon. Furthermore, the physical layer of LTE architecture and its role in increasing capacity by providing better spectral efficiency than legacy networks.

2.2.1 Evolved Node B

The main component of the LTE access network, E-UTRAN, is the eNB. As described in the previous section the eNB can be seen as a base station responsible for, among other, modulation and de-modulation as well as channel coding and de-coding for transmission.

In practice the eNB consists of multiple sub-components. The components can be divided into the Base Transceiver Station (BTS) and antenna. Furthermore, the BTS consists of a Base Band Unit (BBU) and at least one Radio Frequency Unit (RFU) or Radio Remote Unit (RRU).

Base Band Unit

Base Band refers to the original signal, i.e. signals not frequency shifted by means of modulation. The BBU has a Digital Signal Processor (DSP) responsible for the conversion between analog and digital signals for both Transmit (Tx) and Receive (Rx). The BBU is also responsible for communication with the EPC using the S1 interface, other eNBs using the X2 interface and the RFU using the Common Public Radio Interface (CPRI).

Radio Frequency Unit

One or more RFUs constitute the radio part of the eNB. In the case of a remotely mounted RFU the module is named RRU. The RFUs main tasks are modulate and demodulate Base Band signals and Radio Frequency (RF) signals, process data, amplify power and detect standing waves.

2.2.2 Channel Capacity

The main challenge network operators today is facing - is the efficient utilization and sharing of resources, i.e. frequency spectrum. However, there is an upper bound of capacity over a channel of a given bandwidth. We can find this upper bound by using the Shannon-Hartley theorem.

$$\text{Capacity} = \text{Bandwidth} \cdot \log\left(1 + \frac{\text{Signal}}{\text{Noise}}\right) \tag{2.1}$$

From the equation above it is clear that noise makes a major impact on the maximum information rate. Thus making the separation of cells and having the least amount of overlap some of the most important aspects of radio network design and planning.

2.2.3 Orthogonal Frequency Division Multiple Access

Connecting multiple devices to a single access point requires multiple access schemes. The most basic multiple access schemes are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA).

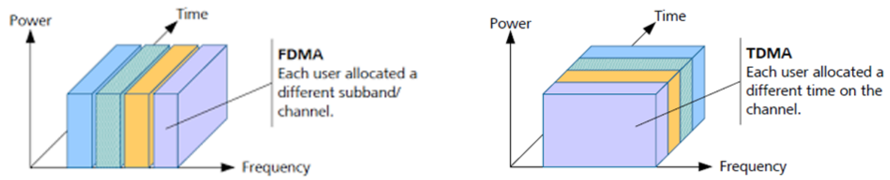

Figure 2.4: Multiple Access methods [Siv]

However, the mobile network also consists of a number of base stations (eNBs in the case of LTE). In order to reduce interference between the base stations a number of different techniques can be applied. In GSM the problem was solved by using different frequencies on adjacent cells for transmission. Hence, the frequency band was used inefficiently. Together with UMTS the concept of a frequency reuse factor of 1 was applied, i.e. all base stations transmit using the same frequency band. This was made possible by using Wide Band Code Division Multiple Access (WBCDMA) - an extension of CDMA. However, whilst improving the spectral efficiency it also increased the interference in the system.

Starting with the LTE network, Orthogonal Frequency Division Multiple Access (OFDMA) was introduced. It can be seen as that the bandwidth is broken down into multiple smaller units known as sub-carriers. These can be grouped together and dynamically allocated. This technique is known as *fractional frequency re-use*, decreasing interference in the system, thus providing better spectral efficiency.

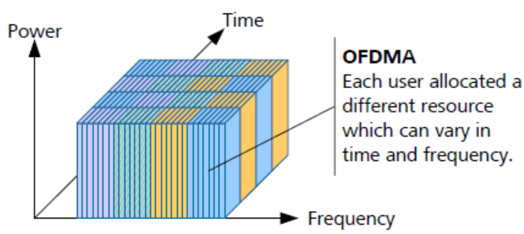

Figure 2.5: Orthogonal Frequency Division Multiple Access [Siv]

Furthermore, by communicating over the X2 interface the eNBs in the LTE network exchanges information on how they are using the frequency band. This improves the flexibility of the system, enabling the network to keep interference at a minimum.

2.2.4 LTE Physical Layer

The Physical Layer (PHY) of LTE is by default, in the time domain, divided in Time Transmission Interval (TTI) of 1 ms where each TTI contains 14 Orthogonal Frequency Division Multiplexing (OFDM) symbols. Following, by default the frequency domain is divided in equal size Physical Resource Blocks (PRB) of 12 sub-carriers, corresponding to a bandwidth of 180kHz and a sub-carrier spacing of 15 kHz. [PEM09]

Chanel Bandwidth (MHz)	1,4	3	5	10	15	20
Resource Blocks	6	15	25	50	75	100
Sub-carriers	72	180	300	600	900	1200

Table 2.1: Transmission bandwidth configuration [Wid08]

The Dynamic Packet Scheduler (PS) is the controlling entity of the allocation of resources, i.e. PRBs. The PS performs packet scheduling decisions, as well as assigning modulation and coding schemes, in order to maximize the spectral efficiency. By using the Physical Downlink Control Chanel (PDCCH) the allocated PRBs, selected modulation and coding scheme are signalled to the user. [PEM09]

2.2.5 Antenna

The most important component of the LTE air interface is the antenna. This section introduces some of the properties of antennas used for LTE.

Directivity

A directional antenna, in contrast to an omnidirectional antenna who radiates equally in all directions, radiates greater power in one direction. These antennas are suitable for use in the mobile network as the antenna beam can be focused and geographically limiting the size of a sector and reducing the interference to other sectors.

Cross Polarity

In order to fully utilize the air medium cross polar antennas are used. In practice cross polar antennas are two antennas mounted in the same housing perpendicular to each other. This is in order to receive uncorrelated signals and provide separation between the antennas.

Antenna Types

There are several ways of designing an antenna, giving it distinct properties. Some of the most common antenna designs used for mobile networks are *panel antennas* and *log-periodic antennas*. Panel antennas consists of dipoles mounted in front of a reflector [Del13]. Log-Periodic antennas differs from panels antennas physically as dipole rod elements are mounted in a line along a support beam, and functionally as they generally supports a wider frequency range.

2.2.6 Multi-Antenna Techniques

The LTE network specification supports the use of multiple antennas at both transmitter and receiver. This is in order to improve system performance by increasing capacity and extending coverage. In short there are three multi-antenna techniques:

- Directivity - Transmit the signal in the best direction.
- Diversity - Transmit the signal in all directions.
- Spatial Multiplexing - Transmit several signals in different directions.

Furthermore, in the case of simultaneous availability of multiple antennas at the transmitter and receiver spatial multiplexing can be applied. This can be seen as multiple parallel communication channels which can provide very high bandwidth utilization without a corresponding reduction in power efficiency. This technique is also referred to as Multi-Input Multi-Output (MIMO) [Cox12].

2.2.7 Carrier Aggregation

The theoretical achievable data rate in the LTE specification of 3GPP Release 8 is 300 Mbps in the down-link and 75 Mbps int the up-link. However, together with 3GPP Release 10 carrier aggregation was included in the specification for both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) implementations. This enables the UEs to use multiple carriers simultaneously increasing the maximum data rate. As of 3GPP Release 10 a maximum of 5 carriers of 20 MHz can be aggregated, combining into a total of 100 MHz aggregated carrier, improving the theoretical achievable data rate considerably.

2.2.8 Modulation Techniques

The LTE network specification supports the use of a set of modulation techniques, Quadrature Phase Shift Keying (QPSK) and Quadrature Amplitude Modulation (QAM) (16 and 64) for down-link and QPSK, 16QAM for up-link. QPSK carries 2 bit/symbol, 16QAM carries 4 bit/symbol and 64QAM carries 6 bit/symbol.

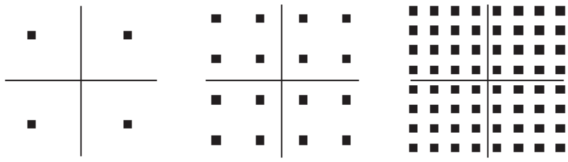

Figure 2.6: QPSK, 16QAM and 64QAM

By using QPSK a reliable transmission in provided in high boise environments, however the bandwidth utilization is poor. Using 64QAM provides improved bandwidth utilization, while the transmission is more prone to errors caused by noise.

2.3 LTE Quality of Service

This section introduces how the LTE network dynamically adapts to the surrounding conditions and handles operating in environments with low signal to noise ratio.

2.3.1 Channel Quality Indicator

The Channel Quality Indicator (CQI) is a parameter for indicating the quality of the down link channel, and identifies the optimal modulation and coding scheme for the eNB to use under the given condition. In short the UE report the current communication channel quality to the network, which decides what CQI value it corresponds to. There are 15 different CQI values ranging from 1 to 15 (4 bits), as seen in table 2.2.

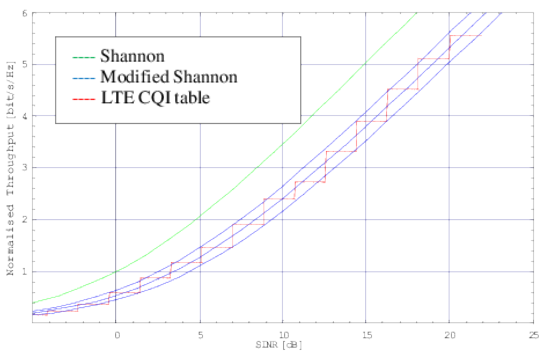

Figure 2.7: Shannon theoretical channel capacity vs. LTE [Øs11]

Each CQI value corresponds to a modulation code and the amount of redundancy used for error correction. An high-noise environment will give a low CQI value corresponding to a robust modulation.

By using the theorem in section 2.2.2 we can calculate the theoretical capacity of a communication channel. When graphing the theoretical channel capacity found using Shannon-Hartley and comparing it to the bit rates given by the LTE network under the same conditions, we find the spectral efficiency of LTE as seen in figure 2.7.

CQI Index	**Modulation**	**Code Rate x 1024**	**Efficiency**
0	n/a	n/a	n/a
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.0616
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

Table 2.2: CQI table[Co.10]

2.3.2 Distribution and Use of Frequency Bands

The Norwegian National Communication Authority (Nkom) is responsible for the distribution and management of frequency licenses in the Norwegian domestic market. According Norwegian legislation frequencies in the electromagnetic spectrum may not be used without the approval of Nkom or the Norwegian Ministry of Transport and Communications. In order to obtain a frequency license the following should be considered, the frequency should be used efficient in order to gain the society and promote sustainable competition, free selection of services and harmonize with other use of frequencies [Nko15].

Frequency licenses permits the use of a frequency in a restricted geographic area and is obtained by sending an application to Nkom - and paying an annual fee calculated according to government regulations. The mobile network frequency licenses held by Telenor and their current usage are described in table 2.3.

Band identifier	**Frequency Range**	**Bandwidth**	**Technology**
L08	800 MHz	10 MHz	LTE
G09	900 MHz	10 MHz	GSM
U09	900 MHz	5 MHz	UMTS
L18-1	1800 MHz	20 MHz	LTE
L18-2	1800 MHz	10 MHz	LTE
U21	2100 MHz	20 MHz	UMTS
L26-1	2600 MHz	20 MHz	LTE
L26-2	2600 MHz	20 MHz	LTE

Table 2.3: Telenors mobile network frequencies

However, LTE is also able to operate in *unlicensed band*, i.e. Industrial, Scientific and Medical (ISM) band (as of 3GPP Release 13). This allows LTE and Wi-Fi-based technologies to coexist and operate together in the 5 GHz spectrum band [3GP15b].

In general low frequencies are more desirable in terms of long range radio transmission. For instance, the 900 MHz band is well suited for long range coverage, while the properties of the 5 GHz band makes the range significantly reduced for a signal transmitted using the same power. Thus making the 5 GHz band well suited for short distance, hence the popular usage in local area networks as Wi-Fis.

2.4 Radio Planning

The following section provides the theoretical background on the properties of the air as transmission medium. In addition some of the main attributes of RF equipment are described. Furthermore, the main considerations made when setting up the link budget of a radio interface are introduced and elaborated.

2.4.1 Antenna Selection

As mentioned the section about antennas (2.2.5), the antenna is the most important component in the LTE air interface. Thus making the antenna design vital for the LTE network performance. Furthermore, deciding on an active or passive system has some implications for the necessary RF equipment.

Passive Solution

When designing a passive antenna system the RF equipment consists of a RFU and antenna - as described in the section about eNBs (2.2.1). In a passive antenna system the RF components are connected using coaxial cables matching the impedance of the other components and antenna. All high capacity location considered in the research for this thesis have passive antenna systems.

Active Solution

Another approach is designing an Active Antenna System (AAS), introduced in 3GPP release 12. One main difference from a passive antenna system is the use of fiber cables, replacing the coaxial cables. Furthermore, the components along the transmission line in an AAS differs from the components in an passive antenna system, replacing the combiners with repeaters. The benefits of having an AAS includes reduced power loss along the transmission size, improvements in coverage, capacity, network utilization, and peak data rates [3GP15a].

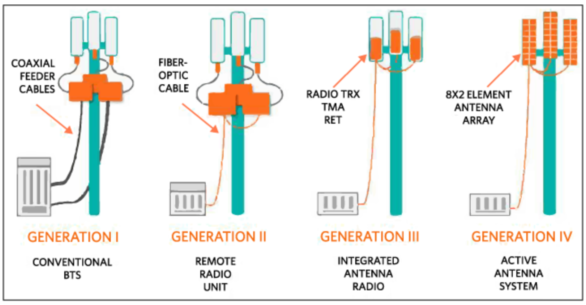

Figure 2.8: Iterations of Active Antenna Systems [Øs11]

2.4.2 Antenna Placement

When placing antennas several factors need considering. Assuming we know the properties of the antenna the main goal is achieving *dominance* for the UE. Dominance is achieved when the UE receives a signal with higher Signal to Noise Ratio (SNR) than the neighboring cells. This prevents the UE from re-selecting cells and possible service drops.

2.4.3 Total Capacity

When planning a mobile network installation the total capacity demand needs to be calculated. In order to find the demand - some assumptions must be made:

- Number of subscribers
- What type of data is expected
- Expected growth in data demand

By combining these the assumptions we can calculate the total demand for capacity in the network and dimension the network accordingly. This is in order to scale the network properly avoiding under dimensioning causing poor network performance, or over dimensioning leading to unnecessary costs. At high capacity locations we usually know where spectators will be seated or gathered, which makes it easier finding what areas will need the most capacity. Dividing users into sectors is important in order to provide sufficient service quality and avoiding congestion at the air interface.

2.4.4 Link Budget

As the name suggests, a link budget is the accounting of all of the gains and losses along the transmission line from the transmitter, through the medium to the receiver. The main factors contributing to gains and losses are described in the following sections.

Standing Wave Ratio

Impedance mismatches on the radio equipment (RF-cables, antennas and RFUs) result in standing waves along the transmission line which in turn cause power-loss and reflection of energy. The Standing Wave Ratio (SWR) is defined as the ratio of the partial standing wave's amplitude at an antinode (maximum) to the amplitude at a node (minimum) along the transmission line.

Passive Intermodulation Distortion

Passive Intermodulation (PIM) is the generation of interfering signals caused by non-linearities in mechanical components. Two signals mix together (amplitude modulation) to produce sum and difference signals and products within the same band, causing interference. PIM occurs along the transmission line in antenna elements, coax connectors, coax cable, and grounds. It is caused by rust, corrosion, loose connections, dirt, oxidation, and any contamination of these factors.

Path Loss

Path loss, or free-space path loss, is the attenuation of energy between two antennas. By using Friis Transmission Formula the free-space path loss and antenna gain is found. Knowing the frequency used for transmission and distance between the transmitting and receiving antenna the relation between received power and the power of the transmitting antenna is found using the free-space path loss formula.

2.4.5 Interference and Overlap

Overlap between cells causes interference, however is a necessity as it is enables handover. However, the amount of overlap must be carefully calculated in order to maximize the network efficiency. Furthermore, the area covered by the antenna beams side lobes should be minimized in order to achieve cause the least amount of interference.

2.4.6 Outer Interference

High capacity locations located in densely populated areas are often subject to interference caused by the surrounding LTE network. Depending on the stadium design this may impact the network performance to some degree.

Chapter 3 Method

This chapter discusses the methodology used when conducting the research leading to this thesis. Furthermore, background for the selection of the high capacity locations considered and uncertainties related to the research. In addition, uncertainties will be further elaborated and addressed in the following chapters.

3.1 Methodology

Throughout this thesis research was conducted according to qualitative research method. Initially data and documentation on a number of LTE installations by Telenor was collected. This was in order to identify characteristics, advantages and limitations of LTE installations, finding ideal locations for comparison and further research. In a similar way data was collected for the LTE technology, from the LTE standard specification, internal documentation provided by Telenor and equipment manufacturers. Hence, research is based on collecting the relevant data which is used to obtain the necessary information and make conclusions.

3.2 Traffic Data Gathering and Analysis

Traffic data gathering for the high capacity locations considered in this thesis was conducted using Telenor's Network Management System (NMS). The software used for exporting data, PrOptima, is described in the following section. In addition, the data was further analyzed and graphically presented using Microsoft Excel.

PrOptima

PrOptima is a Network Performance Management solution for Mobile/IP/Virtualized/Fixed technologies. Furthermore, a data storage and analysis tool. By using big data technologies data is presented and sorted by relevant metrics. Detailed data can be displayed for selected time intervals and geographic locations.

3.3 Selection of High Capacity Locations

Lerkendal Stadium was selected as the main focus of this case study due to the characteristics of the LTE network installation. The relative high network performance in combination with innovative radio interface and network design, makes this location ideal for comparison. A number of the design decisions made for the installation at Lerkendal Stadium has been used when planning later installations, and has become the norm of how new LTE installations are made.

A somewhat similar LTE installation can be found at Ullevål Stadium, however the network performance at this location differs significantly from Lerkendal Stadium. In addition, the new stadium at Vålerenga, also having a similar LTE network design, is included. For comparison traffic data gathered from both Brann Stadium and Oslo Spectrum (concert arena) is included.

3.4 Uncertainties

The data collected from the NMS is the average of measurements made continuously, and is presented in 15 minute intervals. This implies that spikes in the data will be evened out - leading to inaccuracies in the graphical representations made for this thesis. As a result data collected during half-time breaks will be presented as one data point.

Costs related to the purchase and installation of equipment are based on operator specific agreements and will not be elaborated in this thesis. This implies that the suggestions made for future installation are based on approximations of equipment and installations costs - as the exact prices are left out of this thesis.

As some of the LTE network installations considered for this thesis are of relative high age, changes may have been made to the installations which may not be apparent from the design documentation.

Furthermore, the effects of carrier aggregation affects the data throughput, however carrier aggregation is restricted at the locations considered. Hence, additional throughput resulting from carrier aggregation is not considered in this thesis.

Other factors affecting the data usage are: smart phone penetration changing dependent on the audience demographic, weather affecting the user habits - cold weather makes using the phone less desirable etc.

Chapter 4
High Capacity Locations

The following chapter provides an overview of the high capacity locations considered in the research for this thesis. The characteristics, and relevant statistics, of each location are reviewed and technical details of the LTE installations are elaborated.

4.1 Overview

The following selection of high capacity locations consists of soccer stadiums with a LTE installation by Telenor Norway. In addition, traffic data and statistics are also collected from Oslo Spectrum - an indoor concert arena.

Stadium Name	**Location**	**Capacity**
Lerkendal	Trondheim	21850
Brann	Bergen	17686
Vålerenga	Oslo	17834
Ullevål	Oslo	28000

Table 4.1: Overview of stadiums

4.1.1 LTE Installations

The following section provides an overview of the LTE installation characteristics of the high capacity locations considered in this thesis.

Location Name	**Antenna count**	**Sector count**	**Node count**	**LTE Bands**
Lerkendal	14	6	4	L18-1,L18-2,L26-1,L26-2
Brann	1	1	14	L18-1,L18-2,L26-1,L26-2
Vålerenga	14	6	4	L18-1,L18-2,L26-1,L26-2
Ullevål	8	8	2	L18-1,L18-2,L26-1,L26-2
Oslo Spektrum	1	1	1	L18-1,L18-2

Table 4.2: Overview of LTE installations

4.1.2 Antennas

The following section provides an overview of the antennas installed at the high capacity locations considered in this thesis. Detailed documentation on the antennas is attached, and is found in the appendix section.

Stadium Name	**Antenna count**	**Manufacturer**	**Model**	**RU-Type**
Lerkendal	14	Commscope	CNLPX3055F	RFU
Brann	1	Kathrein	80010621	RFU
Vålerenga	14	Commscope	CNLPX3055F	RFU
Ullevål	8	Kathrein	80010681/80010621	RRU
Oslo Spektrum	1	Kathrein	80010248	RFU

Table 4.3: Overview of Antennas

4.1.3 Frequency Spectrum

The frequencies used by Telenor Norway for the LTE network are in the 1800 MHz and 2600 MHz range, also referred to as L18 and L26. In addition frequencies currently used for legacy networks will be made available for LTE traffic in the future as both the GSM network and UMTS network is phased out [Maj15].

Band identifier	Bandwidth	Technology
L18-1	20 MHz	LTE
L18-2	10 MHz	LTE
L21/U21	20 MHz	UMTS/LTE
L26-1	20 MHz	LTE
L26-2	20 MHz	LTE

Table 4.4: Overview of available LTE frequencies

Several of the locations considered have a Wi-Fi network installation along side the mobile data network. As mentioned in chapter 2.3.2 - LTE is able to operate in the unlicensed 5 GHz band (as of 3GPP Release 13). By making use of this technology the network capacity can be further expanded without acquiring additional frequency licenses.

4.2 Lerkendal Stadium

This historic football stadium serves as the main focus of this thesis. Having four two tier roofed grandstands surrounding the football field in the middle, this stadium fits 21850 spectators fully seated. In regards to reflection, this stadium design makes for a challenging environment as signals reflects off both walls behind the grandstands and the player field.

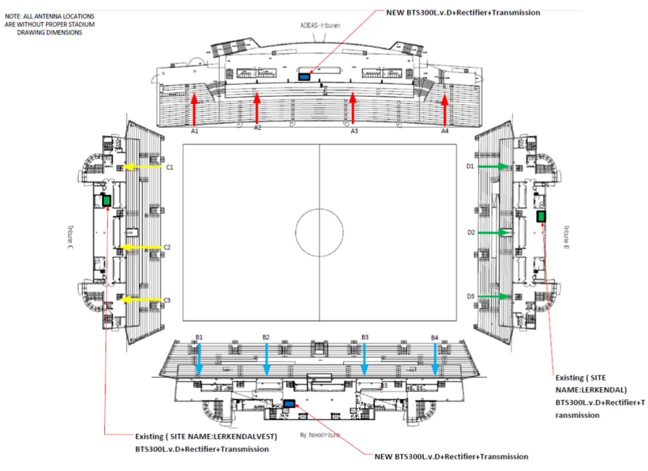

Figure 4.1: Antenna placement at Lerkendal Stadium [Moh15]

The LTE network installation consists of 14 (Commscope CNLPX3055F) directional antennas mounted in the ceiling above the grandstands. 3 antennas per short side (west and east) and 4 antennas per long side (north and south), proving the grandstands with full coverage. The antennas are mounted at a 46 degree angle, facing the beam of the antenna inwards. While providing both heights (tiers) of grandstands with line of sight coverage, there is no line off sight coverage of the player field. However, there will be coverage due to reflection of the grand stands - as well as antenna side lobes and back lobes. This will provide little dominance, high noise and low throughput to devices at the player field.

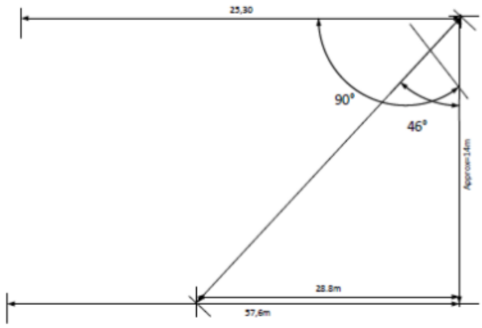

Figure 4.2: Antenna mounting angle at Lerkendal Stadium [Moh15]

Furthermore, in the current setup all 3 antennas at the west side (C1, C2 and C3) are combined trough a pair of Spinner Hybrid Combiner 4:4 (BN570538) forming only one sector. An identical setup is used at the east side (D1, D2 and D3) forming one sector. Both L18 (1800 MHz) and L26 (2600 MHz) LTE RFUs are combined trough a pair of Kathrein Quad-Band Combiners (78210643).

At the north side antennas A1 and A2 are combined, and A3 and A4 combined, forming 2 sectors. Also antennas B1 and B2 are combined, and B3 and B4 are combined, at the south side. Each antenna pair is combined and connected to the RFU using similar equipment to the west and east side.

This forms coverage areas as illustrated in figure 4.3 where the coverage area for each sector is sketched. The areas marked in red shows approximately the area where the signal from each sector is dominant, and intersecting areas where the handover zones are.

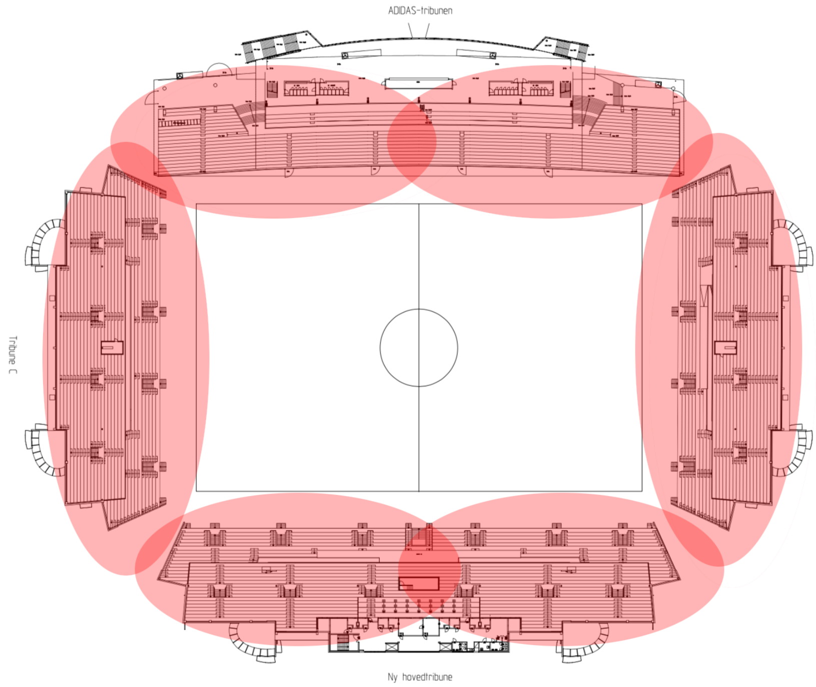

Figure 4.3: Coverage area of antennas at Lerkendal Stadium

4.3 Ullevål Stadium

Ullevål Stadium is the largest football stadium in Norway, seating 28000 spectators. Localized north in the capital, Oslo, the stadium consists of a continuous two-tier grandstand surrounding the player field.

The LTE installation at Ullevål Stadium, designed by Huawei, consists of 8 antennas mounted in the ceiling surrounding the grandstands. Antennas S1, S2, S3 and S4 are placed on the south side of the stadium, two on the long side and one antenna at the north side of both short sides.

Antennas S5, S6, S7 and S8 are placed on the north side forming 4 addition sectors, in a similar manner as the south side, making a total of 8 sectors. The antenna RF equipment is remotely mounted (RRUs), and BBUs are divided on two technical rooms. Signals from both LTE BBU and UMTS BBU are run through a combiner and shares the antenna infrastructure.

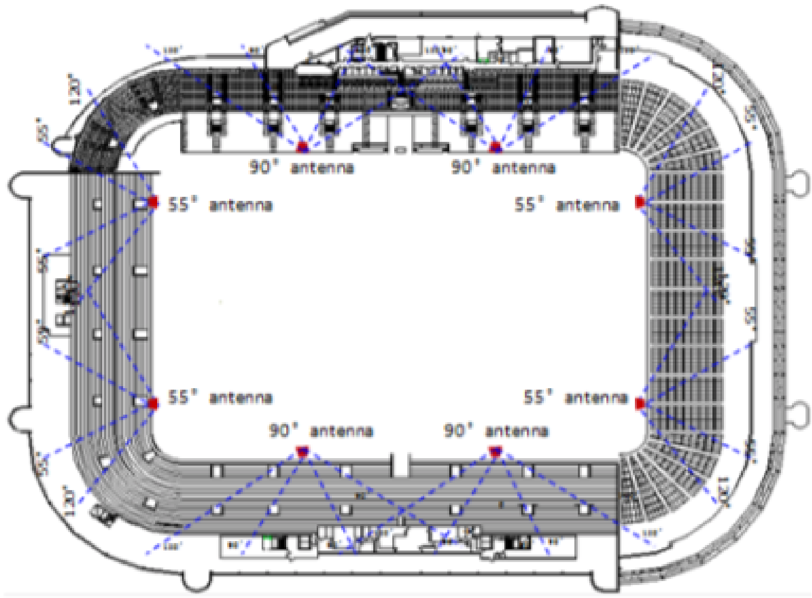

Figure 4.4: Antenna placement at Ullevål Stadium [Moh12]

4.4 Vålerenga Stadium

Vålerenga Stadium was first opened to the public September 2017, making both the stadium and LTE installation the newest considered in this thesis. The Stadium consists of four single tier roofed grandstands seating 17834 spectators.

The LTE installation at Vålerenga Stadium is similar to the installation at Lerkendal Stadium. 14 Commoscope CNLPX3055F antennas are mounted in the ceiling of the grandstand at a 46 degree angle. Antennas S1, S2 and S3 is located at the short south side are combined through a pair of Spinner Hybrid Combiner 4:4 (BN570538) and connected to the LTE RFU trough a pair of Kathrein Quad-Band Combiners (78210643). The same setup is used for antennas N1, N2 and N3 at the short north side.

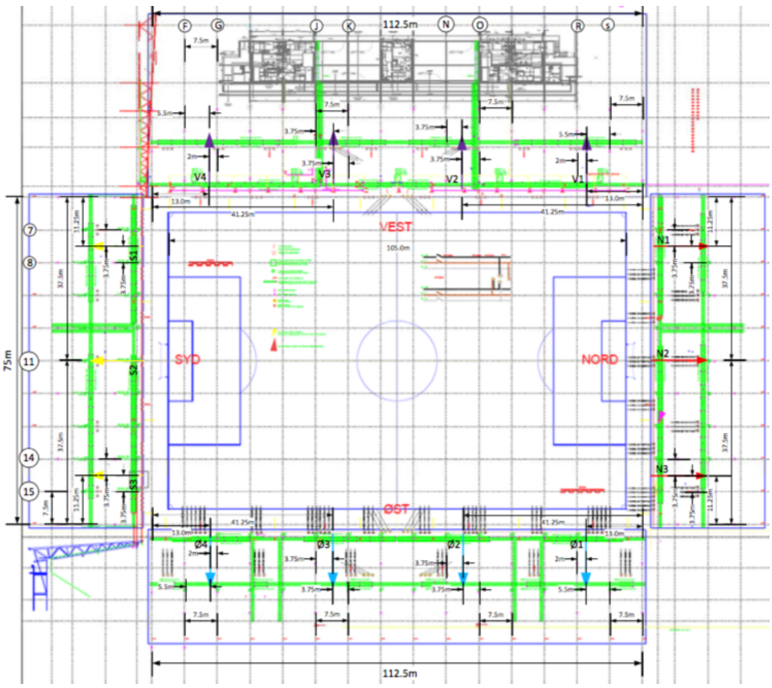

Figure 4.5: Antenna placement at Vålerenga Stadium [Moh17]

At the west side antennas V1 and V2 are combined, and V3 and V4 combined,forming 2 sectors. Also antennas Ø1 and Ø2 are combined, and Ø3 and Ø4 are combined, at the east side. Each antenna pair is combined and connected to the LTE RFU using similar equipment to the north and south side. However, these antennas are shared with the network operator Telia as the signal from both Hybrid Combiners is passed to their separate LTE RFU.

4.5 Brann Stadium

Brann Stadium, with a capacity of 17686 spectators, is a football stadium located in Bergen. The player field is surrounded by four single tier grandstands, which of two are connected through the corner.

The LTE installation at stadium consists of a single Kathrein 80010621 antenna, covering all grandstands. The single antenna is providing both LTE in the 1800 MHz band and the 2600 MHz band.

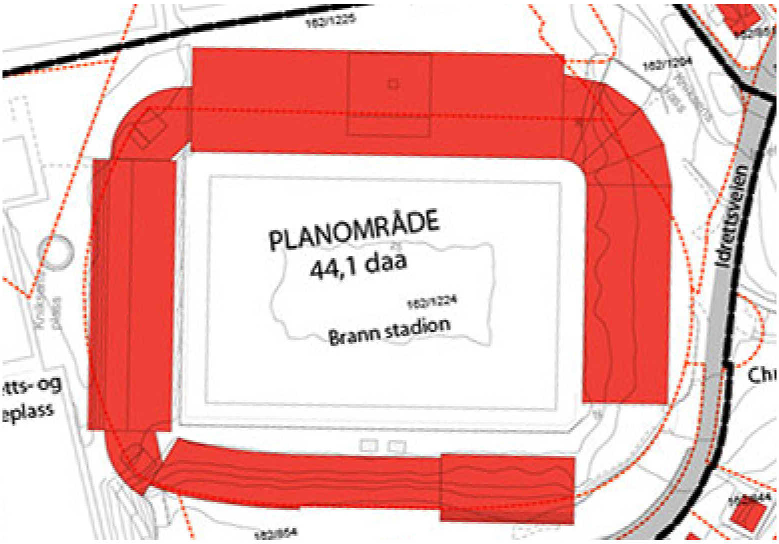

Figure 4.6: Brann Stadium design [AS16]

4.6 Oslo Spektrum

Oslo Spektrum is the only indoor high capacity location considered in this thesis. The location is mainly used for big events as concerts, sporting events and exhibitions - however not for soccer, as size limitations of the player field.

The RF equipment used for the LTE installation consists of a single Kathrein 80010248 antenna mounted to the ceiling and a RFU, providing LTE at the 1800 MHz band.

Chapter 5
Measurements

The following chapter provides measurements and traffic data collected at the high capacity locations introduced in the previous chapter. The measurements in this chapter will be described briefly and further analyzed and discussed in the following chapter.

5.1 Lerkendal Stadium 01.10.17

The following traffic data and measurements were collected during the football match between Sarpsborg and Rosenborg.

Loaction	Date	Time	Spectators
Lerkendal	01-10-2017	20:00 - 21:45	15 801

Table 5.1: Match information

The following data is collected during the game in 15 minute intervals. There are 6 sectors, each having 4 frequency bands - here represented as a line in the charts below.

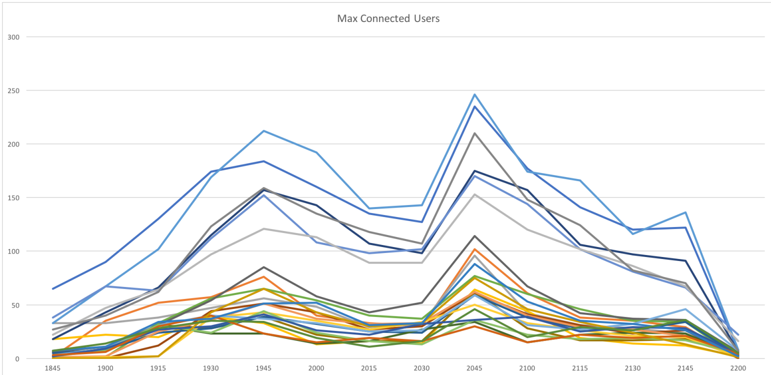

Figure 5.1: Max connected users per sector

The graph below (5.2) shows the utilization of PRBs. Note that the half-time break occurs at 20:45 - 21:00.

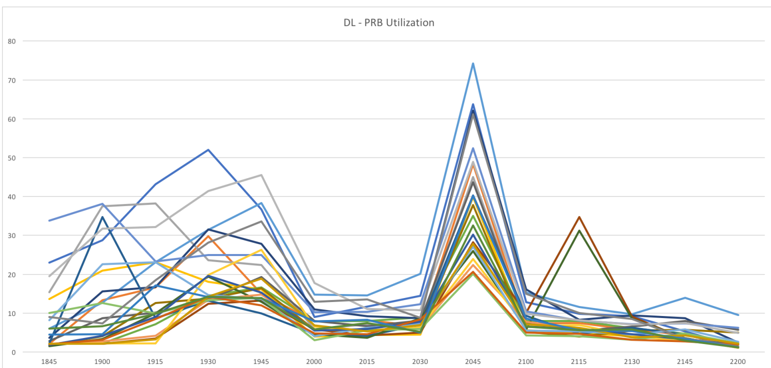

Figure 5.2: Down Link - PRB Usage

Graph 5.3 shows the average CQI measured for 15 minute intervals. Each line represents a frequency band at each antenna.

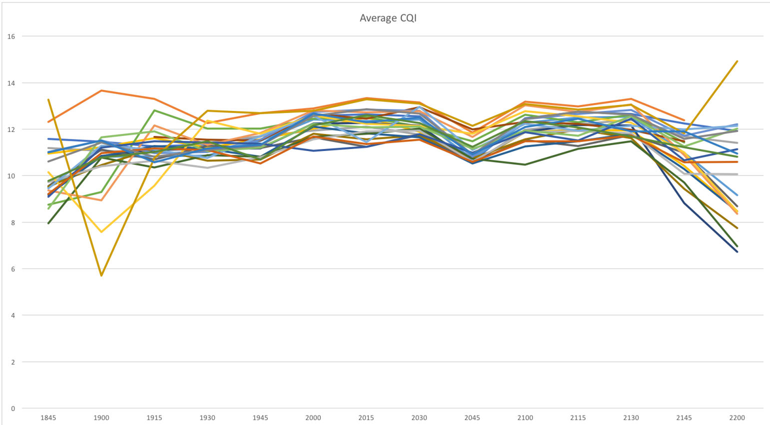

Figure 5.3: Average CQI

Graph 5.4 shows the total down-link throughput for each frequency band at all antennas. The throughput is measured using Mbps.

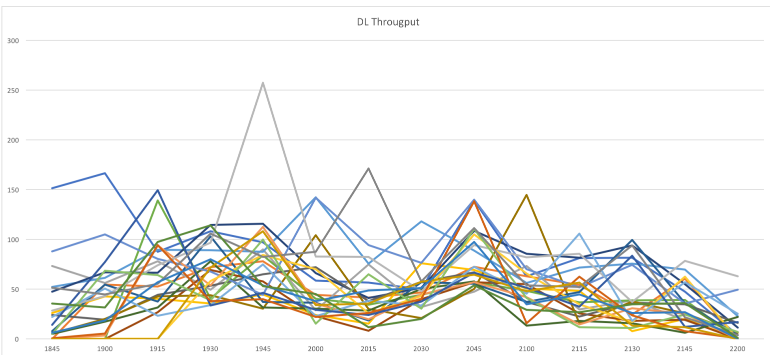

Figure 5.4: Down Link - Throughput

Graph 5.5 shows the down-link user perceived rate, giving a good indication on the throughput per user. The throughput is measured using Mbps.

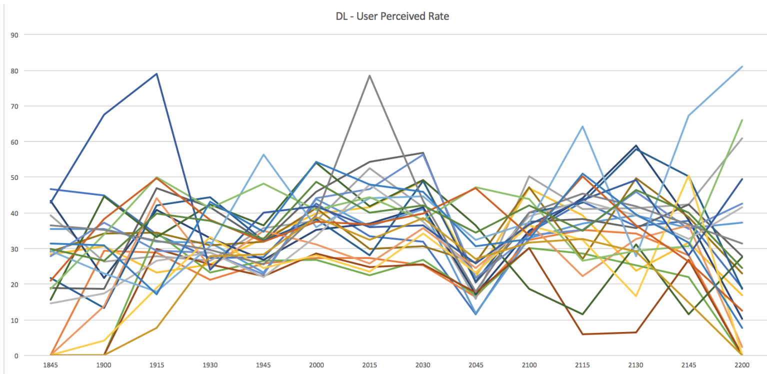

Figure 5.5: Down Link - User Perceived Rate

Graph 5.6 shows how the down-link user perceived rate changes depending on the number of connected users. The throughput is measured using Mbps.

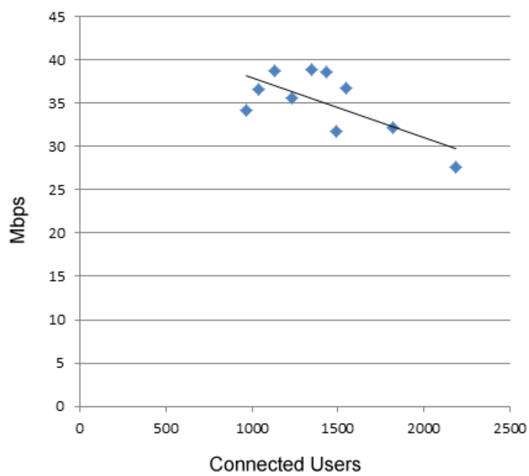

Figure 5.6: Down Link - User Perceived Rate and Connected Users

5.2 Brann Stadium 29.09.17

The following traffic data and measurements were collected during the football match between Brann and Kristiansund.

Loaction	Date	Time	Spectators
Brann Stadium	29-09-2017	19:00 - 20:45	10 025

Table 5.2: Match information

The following data is collected during the match in 15 minute intervals. There is 1 sector having 4 frequency bands - here represented as lines in the charts below.

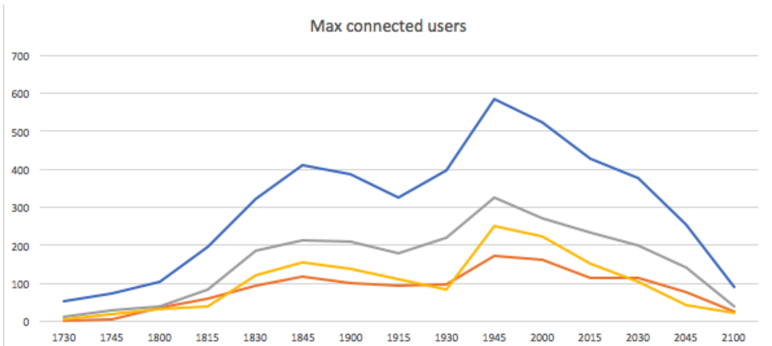

Figure 5.7: Max connected users per sector

The graph below (5.8) shows the utilization of PRBs. Note the half-time break at 19:45 - 20:00.

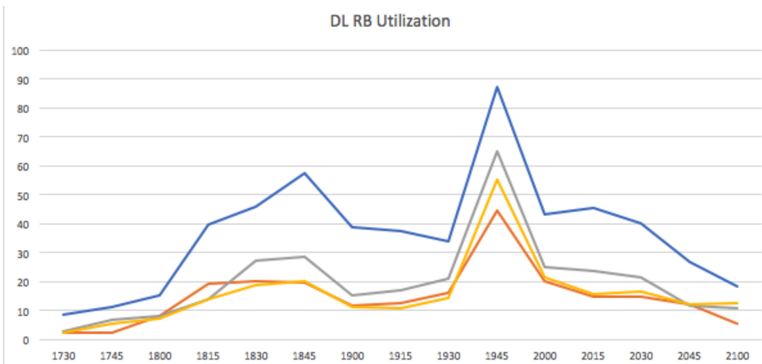

Figure 5.8: Down Link - PRB Usage

Graph 5.9 shows the average CQI measured for 15 minute intervals. Each line represents a frequency band at the antenna.

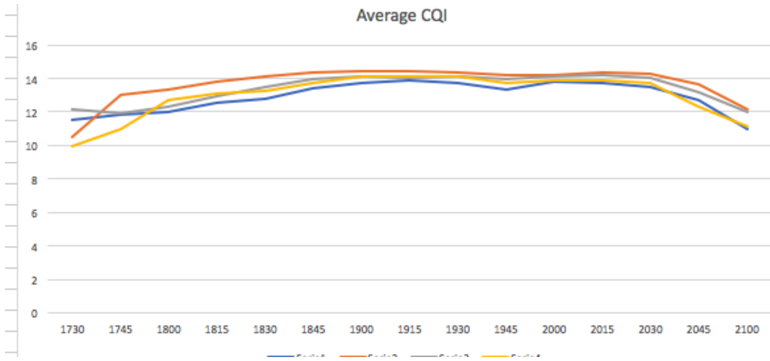

Figure 5.9: Average CQI

Graph 5.10 shows the total down-link throughput for each frequency band at the antenna. The throughput is measured using Mbps.

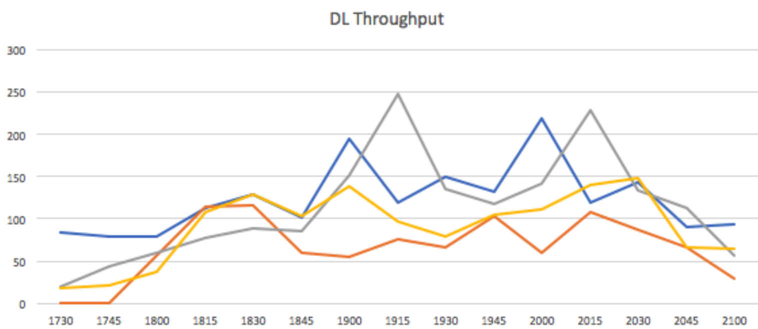

Figure 5.10: Down Link - Throughput

Graph 5.11 shows the down-link user perceived rate, giving a good indication on the throughput per user. The throughput is measured using Mbps.

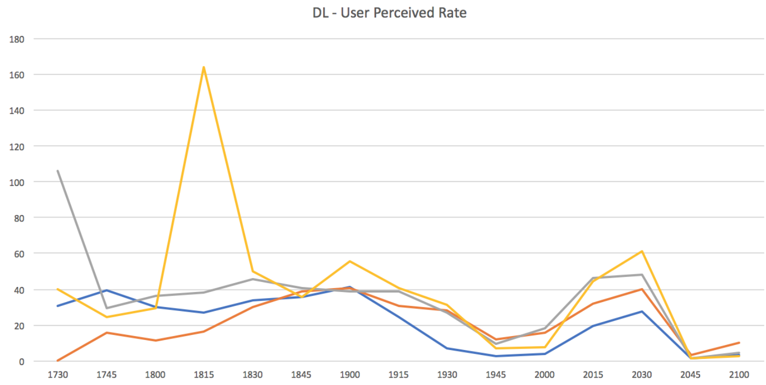

Figure 5.11: Down Link - User Perceived Rate

5.3 Vålerenga Stadium 24.09.17

The following traffic data and measurements were collected during the football match between Vålerenga and Brann.

Loaction	Date	Time	Spectators
Vålerenga Stadium	24-09-2017	20:00 - 21:45	10 051

Table 5.3: Match information

The following data is collected during the game in 15 minute intervals. There are 6 sectors, each having 4 frequency bands - here represented as a line in the charts below.

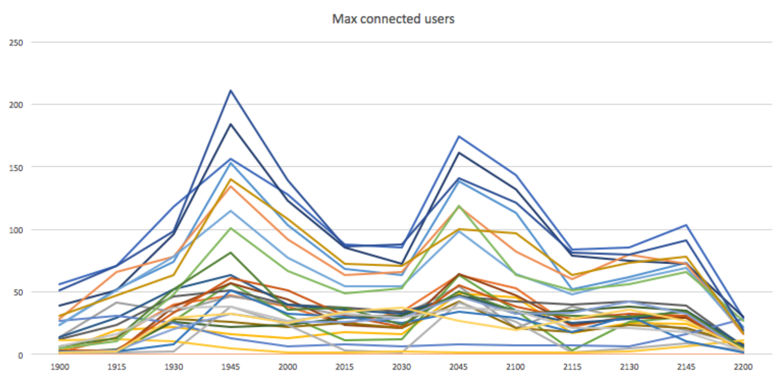

Figure 5.12: Max connected users per sector

The graph below (5.13) shows the utilization of PRBs. Note the half-time break at 20:45 - 21:00.

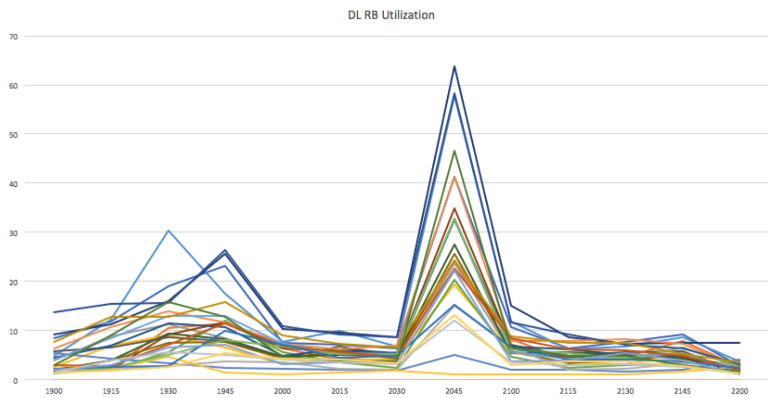

Figure 5.13: Down Link - PRB Usage

Graph 5.14 shows the average CQI measured for 15 minute intervals. Each line represents a frequency band at each antenna.

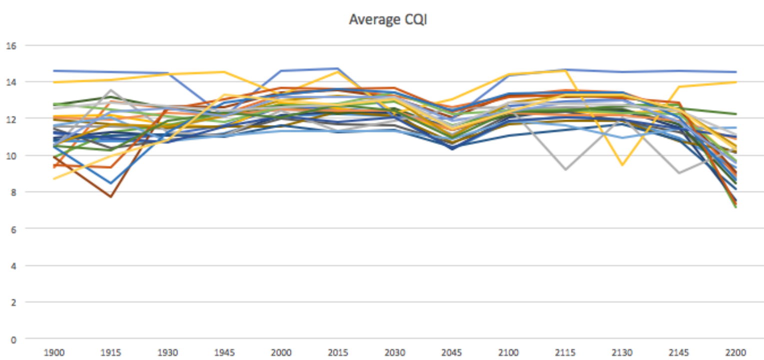

Figure 5.14: Average CQI

Graph 5.15 shows the total down-link throughput for each frequency band at all antennas. The throughput is measured using Mbps.

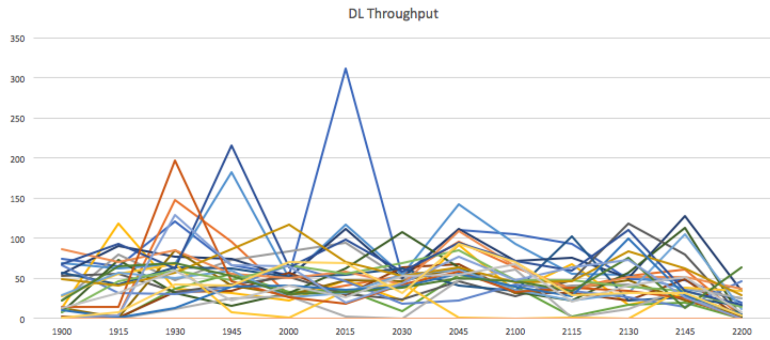

Figure 5.15: Down Link - Throughput

Graph 5.16 shows the down-link user perceived rate, giving a good indication on the throughput per user. The throughput is measured using Mbps.

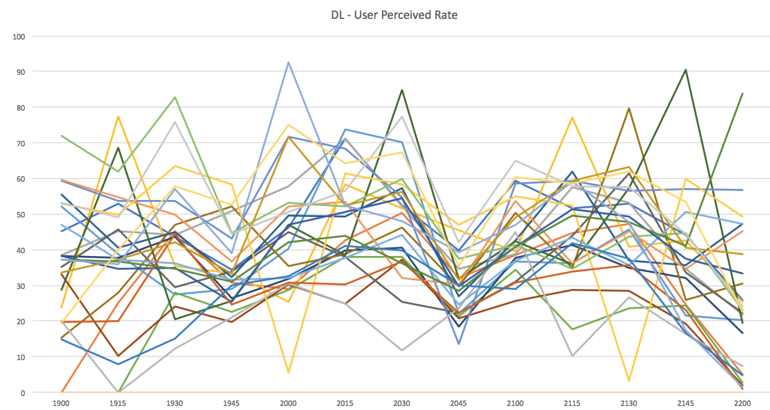

Figure 5.16: Down Link - User Perceived Rate

5.4 Ullevål Stadium 03.12.17

The following traffic data and measurements were collected during the football match between Lillestrøm and Sarpsborg.

Loaction	Date	Time	Spectators
Ullevål Stadium	03-12-2017	13:15 - 15:00	25 091

Table 5.4: Match information

The following data is collected during the game in 15 minute intervals. There are 8 sectors, each having 4 frequency bands - here represented as a line in the charts below.

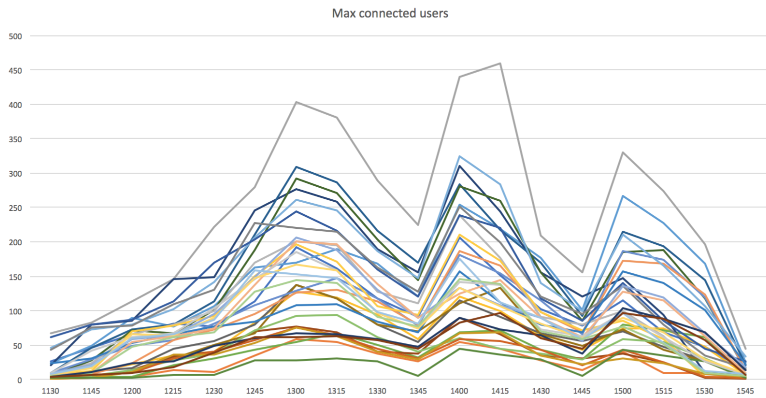

Figure 5.17: Max connected users per sector

The graph below (5.18) shows the utilization of PRBs. Note the half-time break at 14:00 - 14:15.

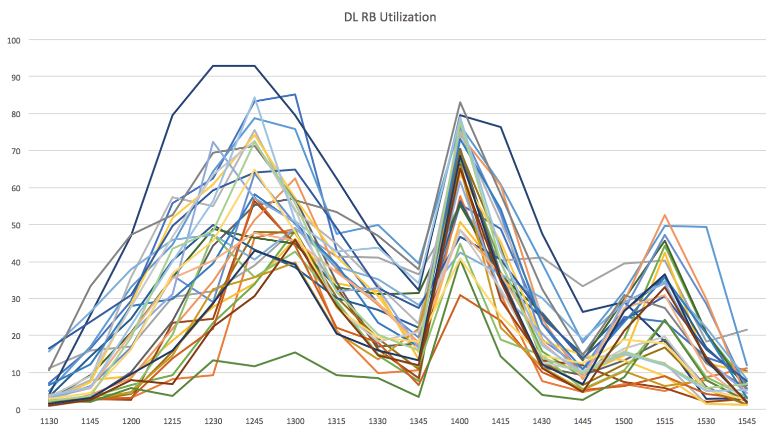

Figure 5.18: Down Link - PRB Usage

Graph 5.19 shows the average CQI measured for 15 minute intervals. Each line represents a frequency band at each antenna.

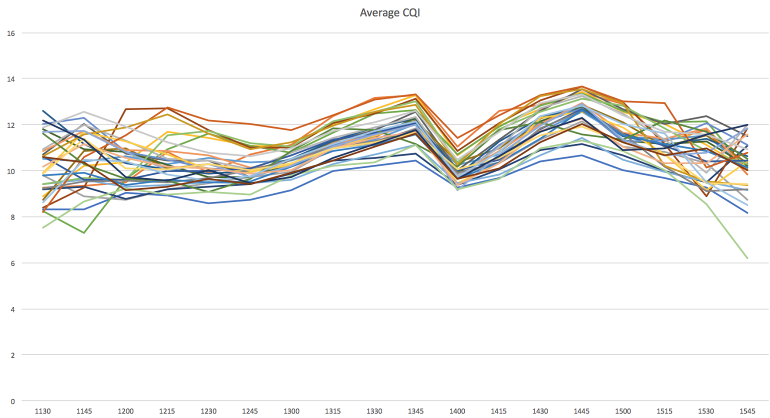

Figure 5.19: Average CQI

Graph 5.20 shows the total down-link throughput for each frequency band at all antennas. The throughput is measured using Mbps.

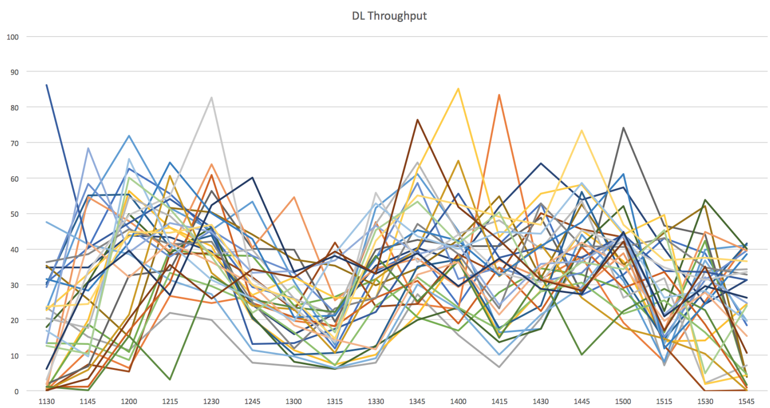

Figure 5.20: Down Link - Throughput

Graph 5.21 shows the down-link user perceived rate, giving a good indication on the throughput per user. The throughput is measured using Mbps.

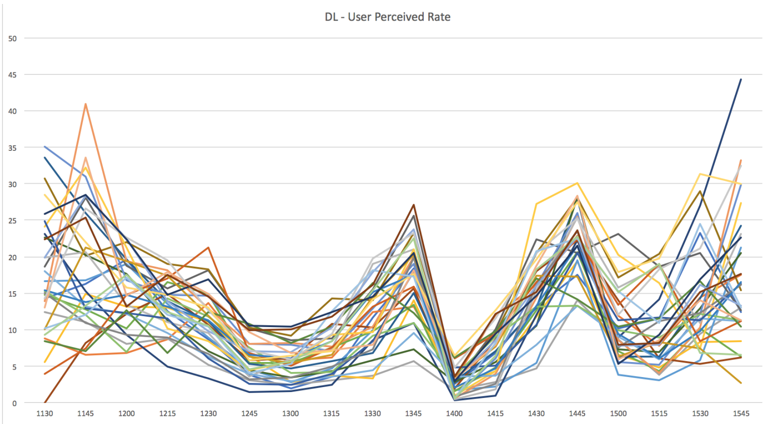

Figure 5.21: Down Link - User Perceived Rate

Graph 5.22 shows how the down-link user perceived rate changes depending on the number of connected users. The throughput is measured using Mbps.

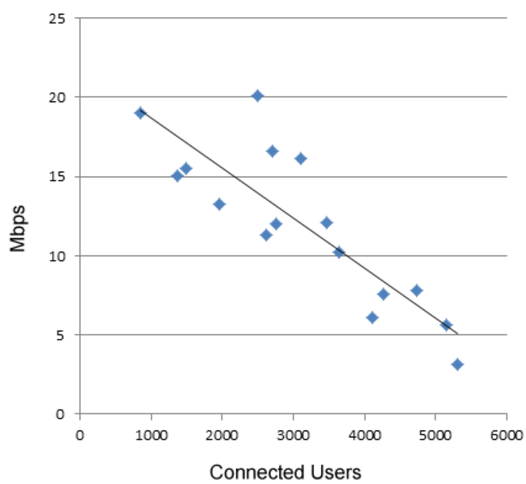

Figure 5.22: Down Link - User Perceived Rate and Connected Users

5.5 Oslo Spektrum 04.10.17

The following traffic data and measurements were collected during an stand-up show at Oslo Spektrum October 4th 2017. Note that the show started at 19:30.

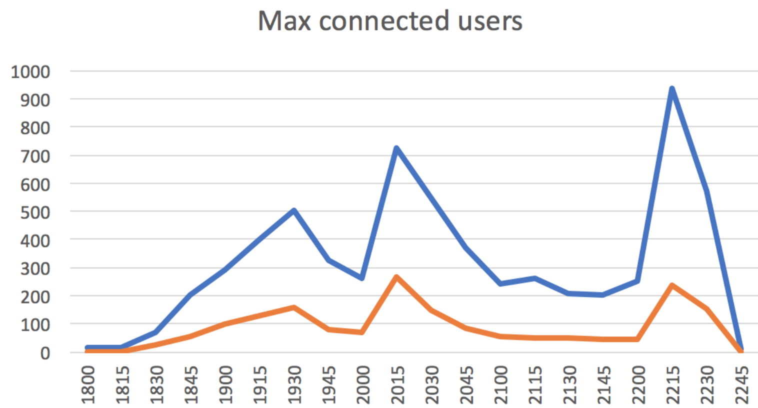

Figure 5.23: Max connected users per sector

The graph below, 5.24, shows the utilization of PRBs.

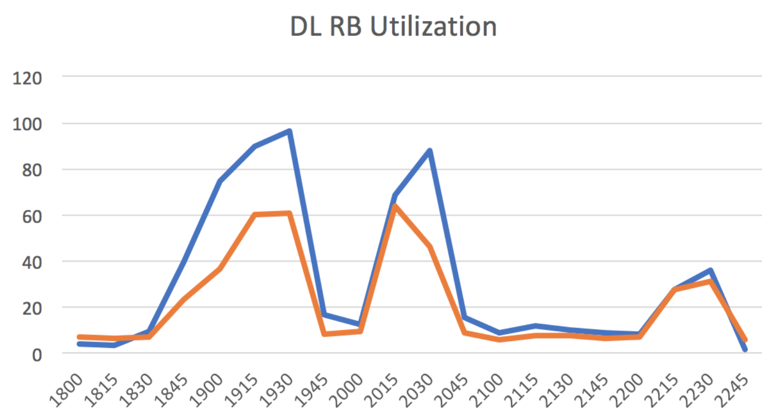

Figure 5.24: Down Link - PRB Usage

Graph 5.25 shows the average CQI measured for 15 minute intervals. Both lines represents a frequency band at the antenna.

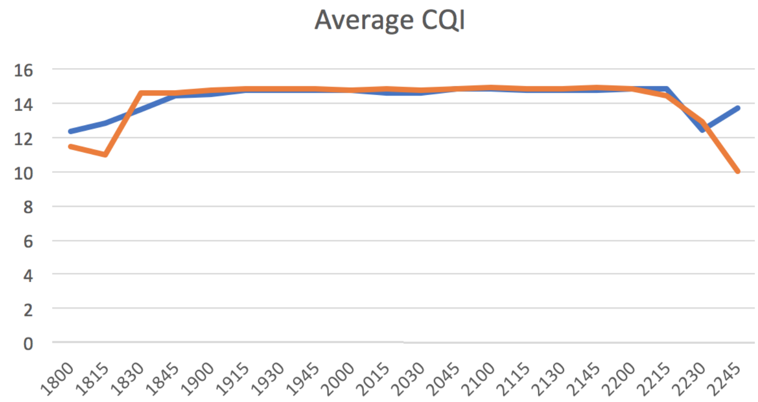

Figure 5.25: Average CQI

Graph 5.26 shows the total down-link throughput for both frequency bands at the antenna. The throughput is measured using Mbps.

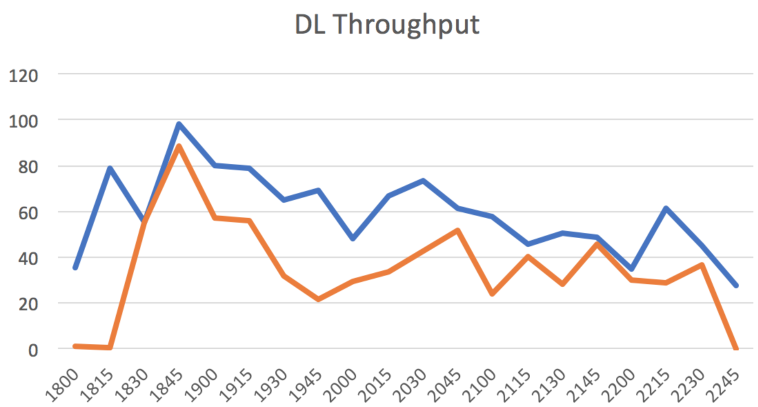

Figure 5.26: Down Link - Throughput

Graph 5.27 shows the down-link user perceived rate, giving a good indication on the throughput per user. The throughput is measured using Mbps.

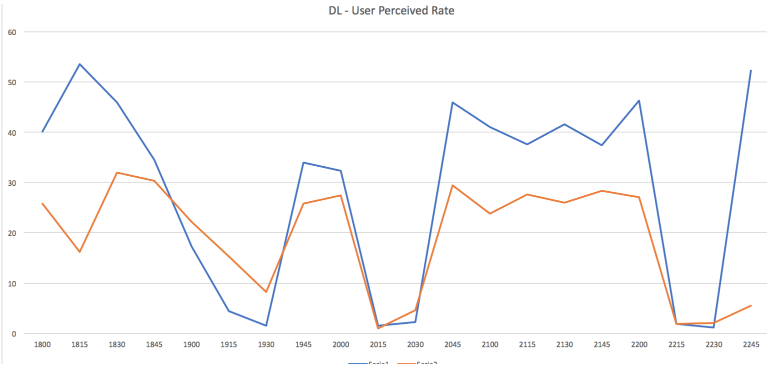

Figure 5.27: Down Link - User Perceived Rate

Chapter 6
Findings

This chapter discusses the measurements from the previous chapter, and evaluates the performance of the LTE installations considered in this thesis. The second part of this chapter looks towards the installations of tomorrow, discussing options on how to build and invest in the future.

6.1 Current Installations

In order to achieve the most efficient operation of a LTE network we want to maximize the throughput with our available resources. However, the bottle-neck in most cases is the radio interface. What are the main factors affecting the performance of the LTE network installations?

- Noise
- Load balancing
- Frequency spectrum

These factors will be considered in the following sections, and how these factors are affecting the high capacity installations considered for this thesis will be discussed.

6.1.1 Lerkendal Stadium and Ullevål Stadium

This section compares Ullevål Stadium and Lerkendal Stadium, both the stadium design and the LTE network installation are considered - and main differences are discussed.

Stadium design

There are several differences between the two locations. Firstly, the continuous grandstand stadium design at Ullevål seating spectators in the corners introduces new challenges in regards to interference. Of the locations considered, this design is unique to Ullevål Stadium, however similar challenges are also found at Brann Stadium where two of the grandstands are connected. Both Ullevål Stadium and Lerkendal Stadium are built according to stadium design norms, thus the proportions of the two-tier grandstands at Ullevål are close to those of Lerkendal Stadium.

LTE Installation Design

The main difference regarding the LTE installations at the two locations is the antenna types used in the radio interface. Hence, much of the performance difference can be explained when considering the properties of the antenna types. The antennas used in the LTE installation at Lerkendal Stadium are, as described in chapter 4.2, stadium antennas made by Commscope. These panel antennas are designed specifically for stadium use, producing an almost square beam pattern as seen in figure 6.1.

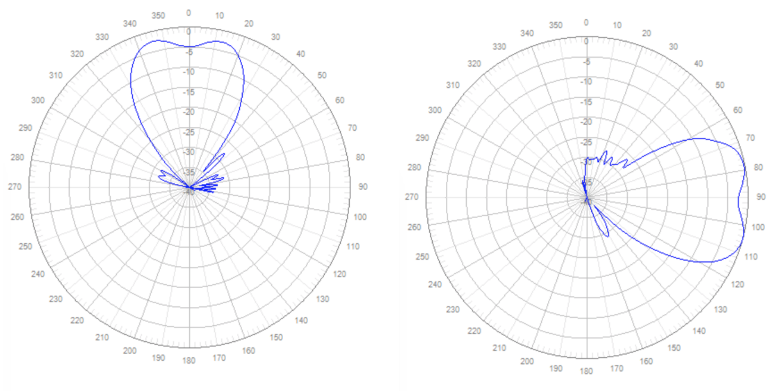

Figure 6.1: Horizontal and Vertical beam pattern at 2600 MHz [Com]

The beam pattern suggests that the side lobes of the stadium antenna are very weak, causing little interference to the neighboring sectors. Furthermore, antennas used at Ullevål Stadium are panel antennas designed for use in the macro network. The properties of these antennas differ from the stadium antennas in several ways.

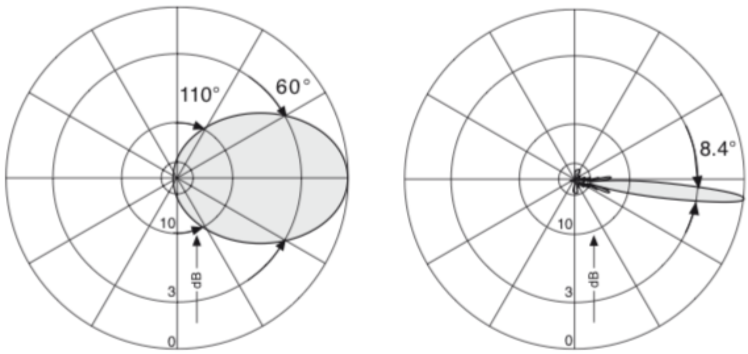

Figure 6.2: Horizontal and Vertical beam pattern at 2600 MHz [KI]

From the beam pattern in figure 6.2 we see that the antenna beam is wider when using this particular Kathrein antenna when compared to the Commscope antenna in figure 6.1. One of the negative side effects of the wide antenna beam is a larger intersecting area between two neighboring sectors causing additional interference. By also considering the stadium design of Ullevål, as seen in figure 4.4, we see that the corner areas will have no dominant signal, hence poor radio conditions.

By looking at figures 5.6 and 5.22 we see how both networks perform when subjected to different loads. Using the user perceived data rate gives an indication on what bit rate the end user experiences.

6.1.2 CQI Measurements

When considering figures 5.19, 5.3 and 5.14, graphing the average CQI values through a soccer match, there are several patterns appearing. Firstly, the CQI average is significantly lower in the time before the match begins and after it ends. This can be due to a number of reasons, e.g. devices outside the stadium connecting to the network before physically entering the stadium - leading to poor signal strength, devices attaching to a sector while moving inside the stadium - exiting the coverage when entering a neighboring sector etc.

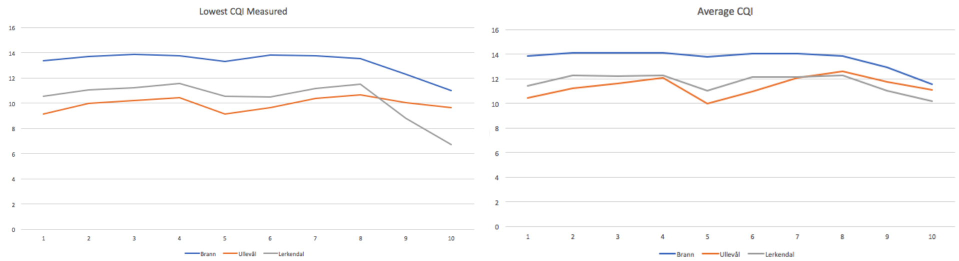

Figure 6.3: Minimum and average CQI during matches at Brann, Lerkendal and Ullevål Stadium

Furthermore, there is a drop in the CQI average occurring during the half-time break. When also considering figures 5.18, 5.2 and 5.13, showing the down-link resource block utilization, we see that the network load is at its peak during the half-time break. The low CQI average is likely due to a combination of the following:

- High levels of noise
- Moving devices

For comparison figure 5.25 can be considered, graphing the average CQI value during an event at Oslo Spektrum. As the LTE network installation at this location is placed indoor outer interference is negligible, making this network perform close to optimal. This installation may be used as a reference for the upper bound of LTE network performance.

6.1.3 Load Balancing

One of the most important aspects when designing any network is the distribution of load over the network. As seen from the down-link PRB measurements at Ullevål 5.18 the load distribution among antennas is correlated, there is however a significant difference from the least loaded channel to the heaviest loaded channel. During the half-time break we see that the least loaded channel has a PRB utilization of 30 %, while the heaviest loaded has a PRB utilization of 83 %.

The lines in figure 6.4 represents the PRB utilization pr. sector at Lerkendal Stadium (left) and Ullevål Stadium (right).

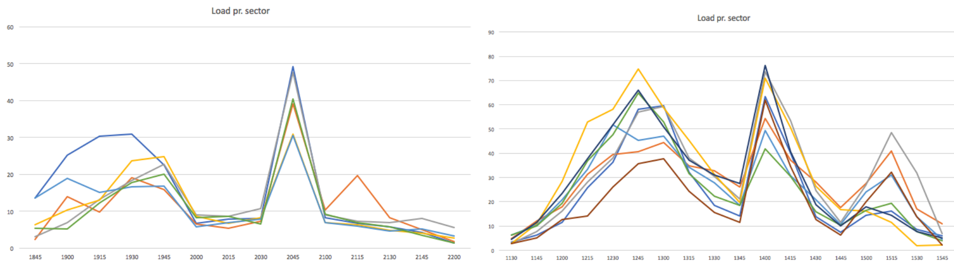

Figure 6.4: Load distribution for sectors at Lerkendal (left) and Ullevål (right)

From the chart we see that the load is more evenly distributed at Lerkendal Stadium when compared to Ullevål Stadium. Some contributing factors may be the distribution of spectators, as neither of the stadiums were fully seated during the data capturing period.

The lines in figure 6.5 represents the PRB utilization pr. channel at Lerkendal Stadium (left) and Ullevål Stadium (right).

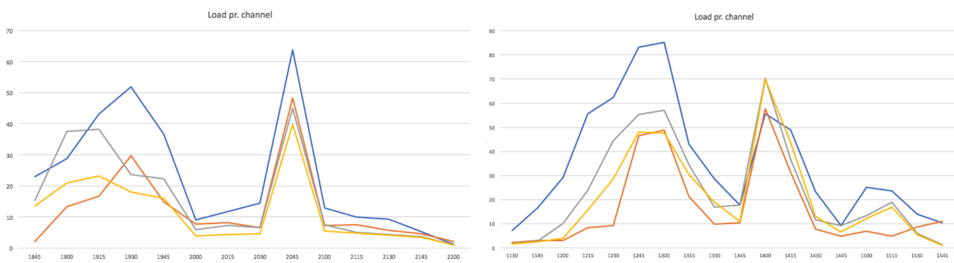

Figure 6.5: Load distribution for channels at Lerkendal (left) and Ullevål (right)

Furthermore, when considering 6.5 we see that the load distribution among channels within a sector is more balanced. This is however controlled by the network itself in accordance to a set network configuration.

6.1.4 Evaluation of Base Stations

When evaluating base station performance we make some assumptions of the operating environment, the network capable device (e.g. smartphone) penetration is the same for all locations and data usage is evenly distributed among the connected devices.

The main goal is maximizing the throughput per user, however in order to achieve the highest throughput per user a high CQI value is required. For the network to use a high CQI value, a good SNR is required - which in turn is achieved by having a dominating signal (e.g. 10 dBm signal strength difference).

When comparing figure 5.20 and 5.26 graphing the down link throughput of Ullevål Stadium and Oslo Spektrum, there is a significant difference in peak network throughput. The main contributing factor is the high CQI average measured at Oslo Spektrum (figure 5.25). In general a well performing base station is characterized by the following:

- Dominance
- Dimensioning

This establishes the criteria for evaluating the performance of a base station. When considering the graph in figure 2.7, based on the Shannon-Hartley theorem (2.2.2), we see that the capacity of the channel is strictly dependent on the signal strength to noise relation. Hence, having a dominant signal is crucial for the network performance

Furthermore, for the case of network dimensioning, we consider figures 5.24 showing the PRB utilization, 5.25 showing the CQI average and 5.27 showing the user perceived down-link data rate at Oslo Spektrum. From the figures we see that peak network utilization is close to the upper bound, while operating under close to perfect SNR conditions, the network provides poor data rate per user (approximately 1 Mbps). Thus making adequate network dimensioning crucial, even for a network operating under ideal radio conditions.

6.2 Future Installations

How much throughput is needed in order to satisfy the end user's needs? The data demand varies greatly based on user demographic, however by assuming that applications and services functions within a set of constraints we can generalize user demands.

6.2.1 Today

As a generalization we divide the user experience into three levels: *excellent*, *acceptable* and *poor*. An excellent user experience implies that applications and services will function optimally. An acceptable user implies that application and service performance will be sufficient, but the user may experience delays. A poor user experience implies unsatisfactory performance of applications and services, and may include service drops and high latency.

User experience	Throughput
Excellent	> 5 Mb/s
Acceptable	< 5 Mb/s, > 2 Mb/s
Poor	< 2 Mb/s

Table 6.1: User experience and throughput

There are major differences in the required bandwidth for using some of the most popular apps and services on mobile. The required bandwidth for streaming music using Spotify is 96 kbps, however streaming high definition music requires 320 kpbs. Streaming video requires considerably more bandwidth, the minimum requirement for Netflix is 0,5 Mbps, while for high definition video 5 Mbps is recommended and for 4K video 25 Mbps is recommended [Net].

6.2.2 Forecasting Future Demand

Forecasting the development in demand of mobile data is a challenging task which involves great uncertainty. However, basing forecasts on historic data gives indications on tendencies and growth in the data demand development.

According to technical reports made by Ericsson [Eri16] and Qualcomm [Inc13] predictions for mobile data growth by year 2020 is 1000 times that of the 2010 base line.

A recent report (November 2017) also made by Ericsson predicts a 42 % annual growth world wide of mobile data consumption in the years towards the end of 2023. For Western Europe the monthly average data consumption is expected to grow from 4.1 GB to 28 GB by the end of 2023 as seen in figure 6.6 [PJ17].

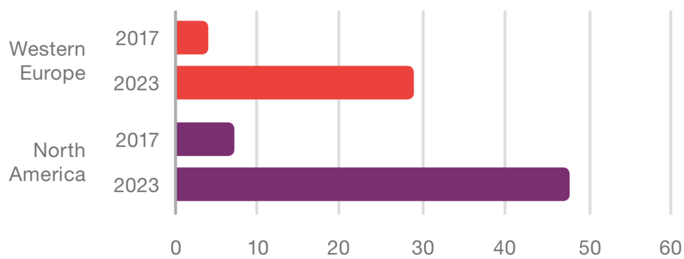

Figure 6.6: Data traffic pr. active smartphone (GB pr. month) [PJ17]

The same report also covers data usage related to application categories during sporting events. Figure 6.7 shows the data usage distribution based on data collected during the Hungary world championships for aquatic sports in 2017.

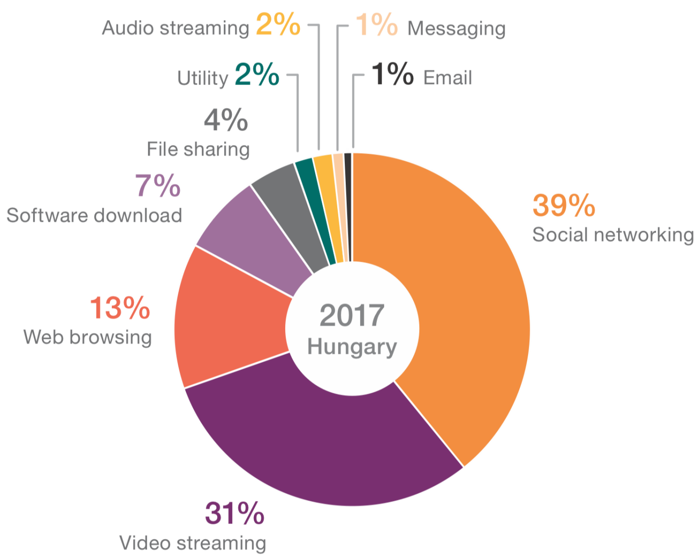

Figure 6.7: App category share of traffic [PJ17]

Furthermore, when considering historic data the trend is an increase in downstream data demand, hence the *consumed* data increases. While the downstream data demand has been increasing, the demand for upstream capacity has however, not increased in a proportionate manner - leading to asynchronous upstream and downstream capacities.

Later years development in mobile data usage shows an increasing upstream data usage. This may be due to the increased usage of social media applications for sharing photos and video. As seen from figure 6.7 social media applications account for 39 % of the mobile data traffic.

6.2.3 Future LTE Installations

When planning future LTE installations several factors affects the network design. However, the total cost of the installation plays a significant role, making cost effectiveness one of the main goals. Assuming frequency licenses is not taken into account, establishing a LTE installation at a new site has a relative high base cost.

The base cost is associated to the establishment of a technical room, the connection to power and backbone network, BTS and RF equipment, and the cables. The cost associated with BTS and RF equipment is expected to grow step wise as sketched in figure 6.8.

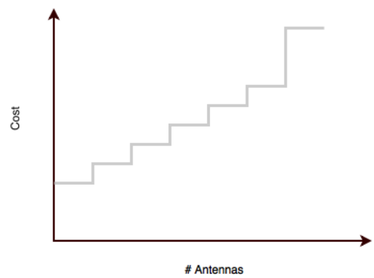

Figure 6.8: Development of expenses

As seen from the sketch of expense development there is a leap as the amount of antennas exceeds a certain number. This is due to BBUs supporting only a limited number of antennas, thus adding more antennas requires an additional BBU - significantly increasing costs. In addition, a similar leap in costs occurs when exceeding a certain number of BBUs, requiring additional cabinets and power infrastructure.

However, by building an expandable network installation future investment costs will be considerably reduced. A solution is building the antenna infrastructure, combining antennas pair-vise - as is done at Lerkendal Staduim, reducing the future equipment cost and future installation costs. In addition, by installing all antennas simultaneously only one iteration of radio planning will be needed, leading to both reduced costs and possibly an overall better design.

Antennas	Equipment	Requirements
1	1 RFU 1 BBU	1 Technical room
6/14	6 RRU 2 BBU	1 Technical room
6/14	6 RFU 4 BBU	4 Technical room
14	14 RRU 4 BBU	1 Technical room
14	14 RFU 14 BBU	4 Technical room

Table 6.2: Suggested LTE Installation Solutions

By installing the LTE network infrastructure in multiple stages the total investment costs may be reduced. Table 6.2 lists some possible combinations for soccer stadium installations, providing the general details of each, some of which are currently used at the locations considered in this thesis.

As discussed in section 6.2.2 the annual growth in data consumption is forecasted at 42 %, although the growth in data consumption is not necessarily the same as the growth in bandwidth demand, it fits well with Nielsen's Law of Internet Bandwidth:

A high-end user's connection speed grows by 50 % per year. [Nie98].

By combining estimations of annual traffic growth, bandwidth demand of and historic traffic data - the estimated capacity over time is estimated in table 6.3. Each row represents the suggestions made in table 6.2. The capacity is the stadium spectator capacity, assuming that Telenor's market share (i.e. percentage of subscribers) remains the same.

Installation	2018	2019	2020	2021
1 Sector	22 000	15 488	10 904	7676
6 Sectors	30 000	21 120	14 868	10 467
14 Sectors	40 000	28 160	19 825	13 957

Table 6.3: Estimated capacity over time

The capacity gain going from a 6 sector solution, as Lerkendal, to a 14 sector solution is considerable. However, some of the capacity gain is lost as more handover zones are needed between sectors as seen in figure 6.9. As none of the high capacity locations considered currently has this 14 sector network set-up the addition capacity gained is estimated and represented as the *14 Sectors* row in table 6.3.

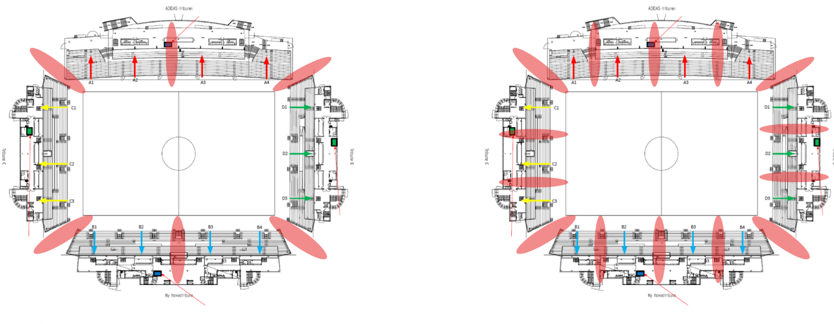

Figure 6.9: Handover zones at Lerkendal 6 sectors & 14 sectors

6.2.4 UMTS to LTE

Currently Telenor is using a total of 25 MHz for the UMTS network distributed over the 900 MHz and 2100 MHz frequency bands. One option for expanding the capacity in the LTE network is using these frequencies, that are now dedicated to the UMTS. As LTE provides higher throughput per frequency when compared UMTS the overall spectral efficiency will increase. Another option is using some 5 MHz from the GSM network, also located at the 900 MHz band.

However, by dedicating all UMTS frequencies to LTE old user equipment, mobile stations in 3G terminology, will be unable to access the network. This might lead to subscribers churning, in favour of network operators providing UMTS. However, according to a statement made by Telenor Norway's CTO, Magnus Zetterberg, the UMTS network will not be closed until 2020 [Maj15].

Chapter 7 Conclusion

This thesis provided an introduction to Telenor, Lerkendal Stadium and the main features of some legacy networks. Furthermore, a theoretical background study on the LTE network architecture, LTE Access Network and LTE Quality of Service. The EPS and key nodes are elaborated, in addition, radio planning and main factors taken into account when calculating the link budget are described. High capacity locations are introduced and the findings from the data analysis are presented.

The QoS performance of the LTE network installations at the high capacity locations considered is measured and evaluated in terms of system throughput, resource utilization and user perceived data rate. The measurements showed valuable results for performance assessment and analysis which is used to predict the performance of the network in the years to come.

7.1 Success Factors

Factors contributing to the high performance of the LTE installation at Lerkendal Stadium can be divided into two categories: the radio interface *equipment* and the radio interface *planning*.

Firstly, the radio interface equipment contributes greatly to the good performance of the network. The antennas used, Commscope CNLPX3055F, are specifically designed for stadium use and produce a beam with very small side lobes - as seen in figure 6.1. The antenna beam properties leads to little interference in the neighboring cells while proving dominance in the area covered by the beam.

Secondly, considering the radio interface planning, the decision of combining antennas pair-wise at the long sides, and combining all antennas at the short sides leads to reduced equipment costs. In addition, the area used for handover zone, having high noise, is reduced. As seen in figure 7.1, the zones for handover - marked in red - are mostly outside the seating areas, leading overall good radio condition on the grandstands.

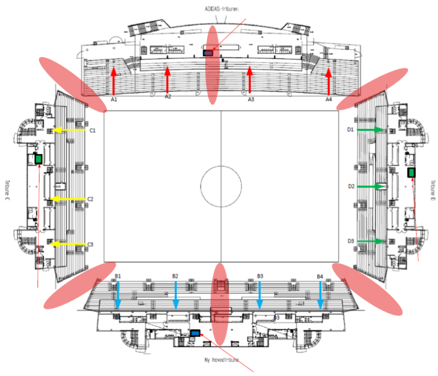

Figure 7.1: Map of handover zones at Lerkendal Stadium

Furthermore, the costs associated with future expansions are significantly reduced. Thus, the majority of costs associated with the installation of equipment is realized, the remaining costs will be mostly related to expanding the BTS equipment.

7.2 Recommendations

The recommendation in this section are based on the measurements from chapter 5 and the findings in chapter 6. Assumptions that are made in the previous chapters applies to these recommendations.

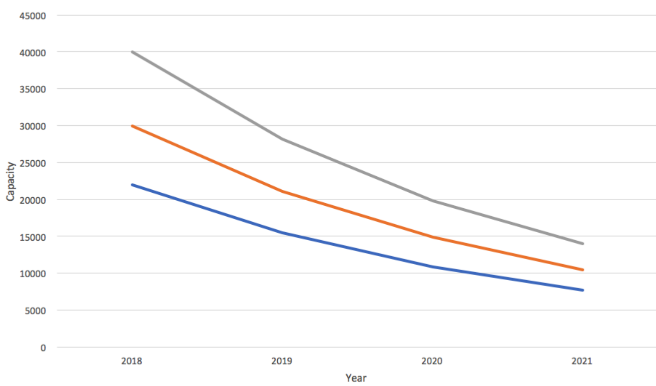

Figure 7.2: Estimated capacity over time

Using table 6.3 the suggested solutions from chapter 6 are graphed in figure 7.2. By knowing the spectator capacity of the stadium and the time perspective of the installation, the graph suggests what solution will be the most cost effective.

In the case of future proofing current installations, we conclude that the goal is to achieve the best possible radio conditions, allowing for high throughput. Meaning that for locations currently providing poor channel quality a solution may be merging sectors, reducing the amount of overlap between sectors as less handover zones in the seating area is required. Another option is planning a radio interface with less overlap between sectors and replacing the current radio interface.

In addition, by using purpose built stadium antennas, the network performance may be improved as interference between sectors is reduced due to the square beam pattern as seen in figure 6.1.

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Appendix A
Kathrein 80010621 V01

Multi-band Panel
Dual Polarization
Half-power Beam Width
Adjust. Electrical Downtilt
Enhanced Sidelobe Suppression

Multi-band Panel	1710–2690
Dual Polarization	X
Half-power Beam Width	65°
Adjust. Electrical Downtilt	0°–12°
Enhanced Sidelobe Suppression	18dB

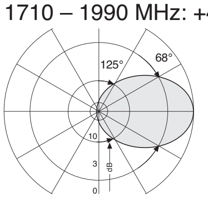
KATHREIN
Antennen · Electronic

Downtilt set by hand or by optional RCU (Remote Control Unit)

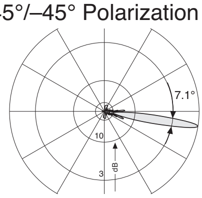
XPol Panel 1710–2690 65° 18dBi 0°–12°T ESLS

Type No.	80010621V01			
	1710–2690			
Frequency range	1710 – 1990 MHz	1920 – 2200 MHz	2200 – 2490 MHz	2490 – 2690 MHz
Polarization	+45°, –45°	+45°, –45°	+45°, –45°	+45°, –45°
Gain (dBi) Tilt	17.4 ... 17.4 ... 17.3 0° ... 6° ... 12°	18.2 ... 18.0 ... 17.9 0° ... 6° ... 12°	18.2 ... 18.1 ... 17.7 0° ... 6° ... 12°	18.3 ... 18.0 ... 17.6 0° ... 6° ... 12°
Horizontal Pattern:				
Half-power beam width	68°	64°	61°	60°
Front-to-back ratio (180°±30°)	> 25 dB	> 25 dB	> 25 dB	> 25 dB
Cross polar ratio 0° Sector ±60°	Typically: 25 dB > 10 dB	Typically: 25 dB > 10 dB	Typically: 25 dB > 10 dB	Typically: 25 dB > 10 dB
Tracking, Avg.	1.0 dB			
Vertical Pattern:				
Half-power beam width	7.1°	6.5°	5.9°	5.7°
Electrical tilt	0°–12°, continuously adjustable			
Sidelobe suppression – for first sidelobe above main beam – within 0°–20° sector above horizon	0° ... 6° ... 12° T ≥ 18 ... 18 ... 18 dB ≥ 17 ... 17 ... 16 dB	0° ... 6° ... 12° T ≥ 18 ... 18 ... 18 dB ≥ 17 ... 17 ... 16 dB	0° ... 6° ... 12° T ≥ 18 ... 18 ... 18 dB ≥ 16 ... 18 ... 17 dB	0° ... 6° ... 12° T ≥ 18 ... 18 ... 18 dB ≥ 17 ... 17 ... 17 dB
Impedance	50 Ω			
VSWR	< 1.5			
Isolation, between ports	> 30 dB			
Intermodulation IM3	< –150 dBc (2 x 43 dBm carrier)			
Max. power per input	400 W (at 50 °C ambient temperature)			

1710 – 1990 MHz: +45°/–45° Polarization

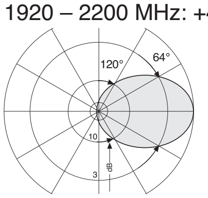


Horizontal Pattern

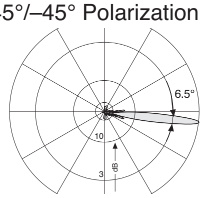


Vertical Pattern
0°–12° electrical downtilt

1920 – 2200 MHz: +45°/–45° Polarization

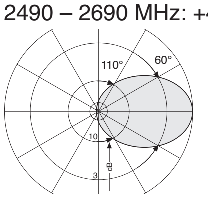


Horizontal Pattern

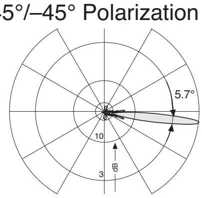


Vertical Pattern
0°–12° electrical downtilt

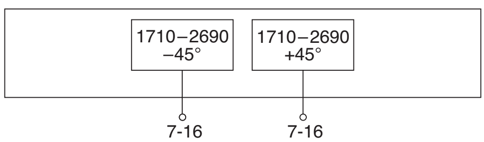
2490 – 2690 MHz: +45°/–45° Polarization



Horizontal Pattern



Vertical Pattern
0°–12° electrical downtilt



Mechanical specifications	
Input	2 x 7-16 female
Connector position	Bottom
Adjustment mechanism	1x, Position bottom continuously adjustable
Wind load	Frontal: 370 N (at 150 km/h) Lateral: 135 N (at 150 km/h) Rearside: 420 N (at 150 km/h)
Max. wind velocity	200 km/h
Height/width/depth	1410 / 154 / 70 mm
Category of mounting hardware	M (Medium)
Weight	6.5 kg / 8.5 kg (clamps incl.)
Packing size	1685 x 172 x 92 mm
Scope of supply	Panel and 2 units of clamps for 42 – 115 mm diameter

936.4336/a Subject to alteration.

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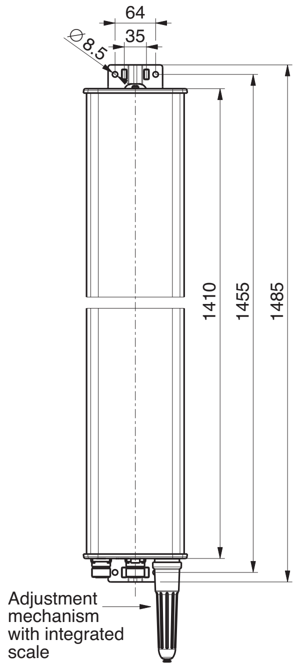
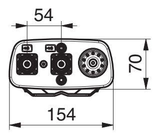
KATHREIN
Antennen · Electronic

Accessories

Type No.	Description	Remarks	Weight approx.	Units per antenna
738546	**1 clamp**	**Mast: 42 – 115 mm diameter**	**1.1 kg**	**2 (included in the scope of supply)**
731651	1 clamp	Mast: 28 – 60 mm diameter	0.8 kg	2 (order separately if required)
85010002	1 clamp	Mast: 110 – 220 mm diameter	2.7 kg	2 (order separately if required)
85010003	1 clamp	Mast: 210 – 380 mm diameter	4.8 kg	2 (order separately if required)
737978	1 downtilt kit	Downtilt angle: 0° – 16°	2.3 kg	1 (order separately if required)

For downtilt mounting use the clamps for an appropriate mast diameter together with the downtilt kit.
Wall mounting: No additional mounting kit needed.





Bottom view

Material: **Reflector screen:** Aluminum. **Radiator:** Tin-plated zinc.
Flat fiberglass radome: The max. radome depth is only 70 mm. Fiberglass material guarantees optimum performance with regards to stability, stiffness, UV resistance and painting. The color of the radome is grey.
All screws and nuts: Stainless steel.

Grounding: The metal parts of the antenna including the mounting kit and the inner conductors are DC grounded.

Environmental conditions: Kathrein cellular antennas are designed to operate under the environmental conditions as described in ETS 300 019-1-4 class 4.1 E.
The antennas exceed this standard with regard to the following items:
– Low temperature: –55 °C
– High temperature (dry): +60 °C

Ice protection: Due to the very sturdy antenna construction and the protection of the radiating system by the radome, the antenna remains operational even under icy conditions.

Environmental tests: Kathrein antennas have passed environmental tests as recommended in ETS 300 019-2-4. The homogenous design of Kathrein's antenna families use identical modules and materials. Extensive tests have been performed on typical samples and modules.

Please note: **As a result of more stringent legal regulations and judgements regarding product liability, we are obliged to point out certain risks that may arise when products are used under extraordinary operating conditions.**

The mechanical design is based on the environmental conditions as stipulated in ETS 300 019-1-4 and thereby respects the static mechanical load imposed on an antenna by wind at maximum velocity. Wind loads are calculated according to DIN 1055-4. Extraordinary operating conditions, such as heavy icing or exceptional dynamic stress (e.g. strain caused by oscillating support structures), may result in the breakage of an antenna or even cause it to fall to the ground. These facts must be considered during the site planning process.

The installation team must be properly qualified and also be familiar with the relevant national safety regulations.
The details given in our data sheets have to be followed carefully when installing the antennas and accessories.
The limits for the coupling torque of RF-connectors, recommended by the connector manufacturers must be obeyed.

Any previous datasheet issues have now become invalid.

936.4336/a Subject to alteration.

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Appendix B
Kathrein 80010681

Multi-band Panel Dual Polarization Half-power Beam Width Adjust. Electrical Downtilt

Multi-band Panel	1710–2690
Dual Polarization	X
Half-power Beam Width	65°
Adjust. Electrical Downtilt	0°–12°

set by hand or by optional RCU (Remote Control Unit)

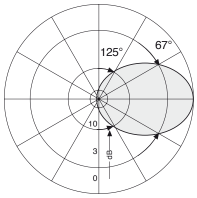
KATHREIN
Antennen · Electronic

XPol Panel 1710–2690 65° 16.5dBi 0°–12°T

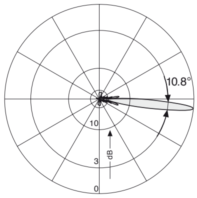
Type No.	80010681			
Frequency range	1710–2690			
	1710 – 1990 MHz	1920 – 2200 MHz	2200 – 2490 MHz	2490 – 2690 MHz
Polarization	+45°, –45°	+45°, –45°	+45°, –45°	+45°, –45°
Gain at 0° tilt	2 x 15.5 dBi	2 x 16.3 dBi	2 x 16.7 dBi	2 x 16.7 dBi
Horizontal Pattern:				
Half-power beam width	67°	64°	60°	60°
Front-to-back ratio (180° ±30°)	> 25 dB	> 25 dB	> 23 dB	> 23 dB
Cross polar ratio 0° Sector ±60°	Typically: 25 dB > 9 dB	Typically: 28 dB > 8 dB	Typically: 28 dB > 8 dB	Typically: 28 dB > 11 dB
Vertical Pattern:				
Half-power beam width	10.8°	9.9°	8.8°	8.4°
Electrical tilt	0°–12°, continuously adjustable			
Sidelobe suppression – for first sidelobe above main beam	0° ... 6° ... 12° T ≥ 12 ... 13 ... 15 dB	0° ... 6° ... 12° T ≥ 13 ... 14 ... 15 dB	0° ... 6° ... 12° T ≥ 13 ... 14 ... 16 dB	0° ... 6° ... 12° T ≥ 15 ... 15 ... 17 dB

Impedance	50 Ω
VSWR	< 1.5
Isolation, between ports	> 30 dB
Intermodulation IM3	< –150 dBc (2 x 43 dBm carrier)
Max. power per input	250 W (at 50 °C ambient temperature)

1710 – 1990 MHz: +45°/–45° Polarization

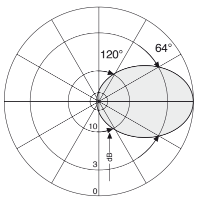


Horizontal Pattern

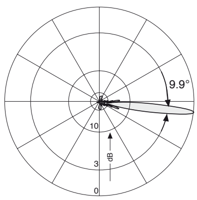


Vertical Pattern
0°–12° electrical downtilt

1920 – 2200 MHz: +45°/–45° Polarization

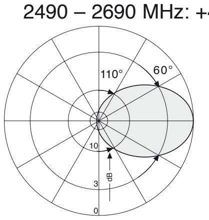


Horizontal Pattern

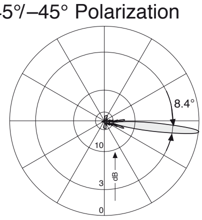


Vertical Pattern
0°–12° electrical downtilt

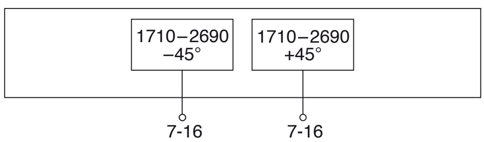
2490 – 2690 MHz: +45°/–45° Polarization



Horizontal Pattern



Vertical Pattern
0°–12° electrical downtilt



Mechanical specifications	
Input	2x 7-16 female
Connector position	Bottom
Adjustment mechanism	1x, Position bottom continuously adjustable
Wind load	Frontal: 210 N (at 150 km/h) Lateral: 60 N (at 150 km/h) Rearside: 220 N (at 150 km/h)
Max. wind velocity	200 km/h
Height/width/depth	851 / 155 / 70 mm
Category of mounting hardware	L (Light)
Weight	5 kg / 5.2 kg (tension bands incl.)
Packing size	1146 x 172 x 92 mm
Scope of supply	Panel and 1 unit of tension bands for 45 – 125 mm diameter

936.4019/a Subject to alteration.

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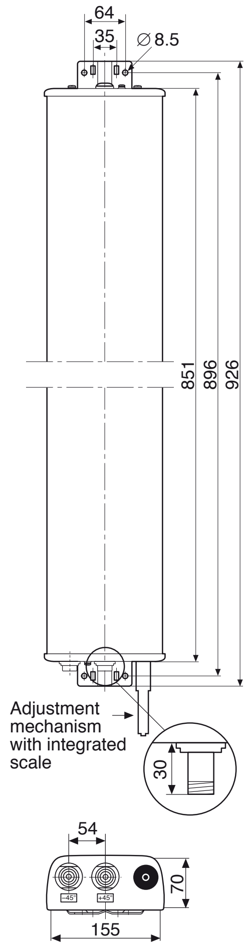
Accessories

Type No.	Description	Remarks	Weight approx.	Units per antenna
734365	**2 tension bands**	**Mast: 45 – 125 mm diameter**	**0.08 kg**	**1 (included in the scope of supply)**
734360	2 tension bands	Mast: 34 – 60 mm diameter	0.06 kg	1 (order separately if required)
734361	2 tension bands	Mast: 60 – 80 mm diameter	0.07 kg	1 (order separately if required)
734362	2 tension bands	Mast: 80 – 100 mm diameter	0.08 kg	1 (order separately if required)
734363	2 tension bands	Mast: 100 – 120 mm diameter	0.09 kg	1 (order separately if required)
734364	2 tension bands	Mast: 120 – 140 mm diameter	0.11 kg	1 (order separately if required)
731651	1 clamp	Mast: 28 – 60 mm diameter	0.8 kg	2 (order separately if required)
738546	1 clamp	Mast: 50 – 115 mm diameter	1.0 kg	2 (order separately if required)
85010002	1 clamp	Mast: 110 – 220 mm diameter	2.7 kg	2 (order separately if required)
85010003	1 clamp	Mast: 210 – 380 mm diameter	4.8 kg	2 (order separately if required)
732327	1 downtilt kit	Downtilt angle: 0° – 15°	1.0 kg	1 (order separately if required)

For downtilt mounting use the clamps for an appropriate mast diameter together with the downtilt kit.
Wall mounting: No additional mounting kit needed.



Bottom view

Please note: **Using a downtilt kit is only possible in combination with clamps 731651, 738546, 85010002 or 85010003.**

Material:
Reflector screen: Aluminum / tin-plated copper.
Radiator: Tin-plated zinc.
Flat fiberglass radome: The max. radome depth is only 70 mm. Fiberglass material guarantees optimum performance with regards to stability, stiffness, UV resistance and painting. The colour of the radome is grey.
All screws and nuts: Stainless steel.

Grounding: The metal parts of the antenna including the mounting kit and the inner conductors are DC grounded.

Environmental conditions: Kathrein cellular antennas are designed to operate under the environmental conditions as described in ETS 300 019-1-4 class 4.1 E.
The antennas exceed this standard with regard to the following items:
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Environmental tests: Kathrein antennas have passed environmental tests as recommended in ETS 300 019-2-4. The homogenous design of Kathrein's antenna families use identical modules and materials. Extensive tests have been performed on typical samples and modules.

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Appendix C
Commscope CNLPX3055F

Product Specifications

COMMSCOPE®

CNLPX3055F

2-port stadium sector antenna, 2x (790–960, 1710–2170, & 2300–2690 MHz), 50° HPBW. This triband antenna produces rectangular patterns with sharp cutoff for illuminating a section of the crowd. The three bands are internally triplexed, allowing a dual connector interface to be used.

- The antenna includes an internal triplexer for a set of ±45° RF input ports for 2x2 MIMO capabilities

Electrical Specifications

Frequency Band, MHz	**790–960**	**1710–2170**	**2300–2690**
Gain, dBi	11.2	11.4	11.7
Beamwidth, Horizontal, degrees	55	49	47
Beamwidth, Horizontal at 20 dB, degrees	90	81	79
Beamwidth, Vertical, degrees	55.0	48.5	47.4
Beam Tilt, degrees	0	0	0
USLS (First Lobe), dB	25	20	22
Front-to-Back Ratio at 180°, dB	39	40	38
CPR at Boresight, dB	20	23	18
CPR at 3 dB Horizontal Beamwidth, dB	18	15	18
Isolation, dB	30	30	30
Isolation, Intersystem, dB	30	30	30
VSWR | Return Loss, dB	1.5 | 14.0	1.5 | 14.0	1.5 | 14.0
PIM, 3rd Order, 2 x 20 W, dBc	-150	-150	-150
Input Power per Port, maximum, watts	100	100	100
Polarization	±45°	±45°	±45°
Impedance	50 ohm	50 ohm	50 ohm

Electrical Specifications, BASTA*

Frequency Band, MHz	**790–960**	**1710–2170**	**2300–2690**
Gain by all Beam Tilts, average, dBi	10.9	11.4	11.4
Gain by all Beam Tilts Tolerance, dB	±0.7	±0.9	±0.9
Beamwidth, Horizontal Tolerance, degrees	±4	±5	±4.3
Beamwidth, Vertical Tolerance, degrees	±4.3	±5.3	±4.2
USLS, beampeak to 20° above beampeak, dB	25	15	16
Front-to-Back Total Power at 180° ± 30°, dB	32	34	34
CPR at Boresight, dB	20	19	20

* CommScope® supports NGMN recommendations on Base Station Antenna Standards (BASTA). To learn more about the benefits of BASTA, download the whitepaper Time to Raise the Bar on BSAs.

General Specifications

Operating Frequency Band	1710 – 2170 MHz | 2300 – 2690 MHz | 790 – 960 MHz
Antenna Type	Sector
Band	Multiband
Performance Note	Outdoor usage

Mechanical Specifications

RF Connector Quantity, total	2
RF Connector Interface	7-16 DIN Female
Grounding Type	RF connector inner conductor and body grounded to reflector and mounting bracket

Product Specifications

Radiator Material	Brass | Low loss circuit board
Radome Material	Fiberglass, UV resistant
Reflector Material	Aluminum
RF Connector Location	Rear | Side
RF Connector Quantity, diplexed low and high bands	2
Wind Loading, lateral	1452.0 N @ 150 km/h 326.4 lbf @ 150 km/h
Wind Speed, maximum	160 km/h | 99 mph

Dimensions

Length	1354.0 mm | 53.3 in
Width	853.0 mm | 33.6 in
Depth	210.0 mm | 8.3 in
Net Weight, without mounting kit	37.0 kg | 81.6 lb

Packed Dimensions

Length	1464.0 mm | 57.6 in
Width	990.0 mm | 39.0 in
Depth	411.0 mm | 16.2 in
Shipping Weight	55.0 kg | 121.3 lb

Regulatory Compliance/Certifications

Agency	**Classification**
RoHS 2011/65/EU	Compliant by Exemption
China RoHS SJ/T 11364-2006	Above Maximum Concentration Value (MCV)
ISO 9001:2008	Designed, manufactured and/or distributed under this quality management system

Included Products

F-122-GL — Fixed Tilt Pipe Mounting Kit for 2.9"-4.5" (75-115mm) OD round members for panel antennas. Includes 2 clamp sets.

* Footnotes

Performance Note	Severe environmental conditions may degrade optimum performance