ASSESSMENT OF DYNAMIC SPECTRUM ALLOCATION IN REALISTIC MOBILE NETWORKS

MASTER OF SCIENCE THESIS

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ABSTRACT

Since the advent of radio communications, radio spectrum has been increasingly getting crowded with different kinds of applications. Different radio communications systems have been developed for various purposes and multiple actors became interested in using these systems at the same time and space. Such situation inevitably led to the point when practically entire usable radio spectrum became occupied by different actors. To alleviate this problem, Dynamic Spectrum (Re)Allocation (DSA) has been proposed, which is a branch of frequency spectrum management that aims to improve spectrum usage efficiency and end-user experience by introducing more flexibility to spectrum usage.

This thesis aims to provide additional insight into DSA applicability and effectiveness in a typical realistic cellular network, in intra-operator scenario, taking into account 2G and 4G radio technologies, with the aim of improving 4G performance without adverse impact to 2G. We use realistic dynamic system level simulations to assess DSA performance in the selected cellular network areas that can be classified as urban, suburban and rural.

Our simulation results show that DSA is capable of improving 4G throughput without adverse impact to 2G performance in all simulated areas. Among the simulated areas, urban area benefits from DSA most, as significant throughput gains for 4G are achieved without adverse impact to 2G performance, while simulations show that spectrum refarming is clearly not an option for this type of area. However, throughput gains for 4G in urban area are limited during the busy-hours. Suburban and rural areas indicate benefits from DSA too, however the difference between DSA and spectrum refarming in these areas is diminishing. Hence, with reasonable half-rate timeslot tolerance for 2G voice calls, spectrum refarming could be an option in the simulated suburban and rural areas.

ACKNOWLEDGMENTS

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ACRONYMS

3GPP 3rd Generation Partnership Project

AMPS Advanced Mobile Phone System

AMR Adaptive Multi-Rate

BCCH Broadcast Control Channel

BLAST Bell Laboratories Layered Space-Time

BPL Building Penetration Loss

BS Base Station

CAGR Compound Annual Growth Rate

CDR Call Detail Record

CS Circuit Switched

DFCA Dynamic Frequency and Channel Allocation

DTMC Discrete Time Markov Chain

DTX Discontinuous Transmission

DSA Dynamic Spectrum (Re)Allocation

DVB-T Digital Video Broadcasting-Terrestrial

EDGE Enhanced Datarates for GSM Evolution

EGPRS Enhanced-GPRS

E-UTRA	Evolved-UTRA
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FDPS	Frequency Domain Packet Scheduling
FH	Frequency Hopping
FSA	Fixed Spectrum Allocation
GoS	Grade of Service
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GSM-R	GSM-Rail
GMSK	Gaussian Minimum-Shift Keying
HSCSD	High Speed Circuit Switched Data
HSN	Hopping Sequence Number
ICIC	Inter-Cell Interference Coordination
IST	Information Society Technologies
ILP	Integer Linear Programming
ITU-R	International Telecommunications Union-Radio communications sector
ISM	Industrial, Scientific and Medical
LTE	Long Term Evolution
LTE-A	LTE-Advanced
M2M	Machine-to-Machine
MA	Mobile Allocation
MAE	Mean Absolute Error
MAIO	Mobile Allocation Index Offset
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MMS	Multimedia Messaging Service
MS	Mobile Station

NGMN	Next Generation Mobile Networks
OFDMA	Orthogonal Frequency Division Multiple Access
POTS	Plain Old Telephone Service
PSK	Phase Shift Keying
PS	Packet Switched
PSTN	Public Switched Telephone Network
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Acccess Network
RAT	Radio Access Technology
RSB	Regional Spectrum Broker
SB	Spectrum Broker
SC-FDMA	Single Carrier Frequency Division Multiple Access
SIMO	Single Input Multiple Output
SINR	Signal-to-Interference-plus-Noise Ratio
SDR	Software Defined Radio
TCH	Traffic Channel
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TBS	Transport Block Size
TTI	Transmission Time Interval
UMTS	Universal Mobile Telecommunications System
UWB	Ultra Wide Band
VHF	Very High Frequency
WAP	Wireless Application Protocol
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network

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INTRODUCTION

A little over 100 years have passed since the first long distance radio signal transmission was made in the end of XIX century by Guglielmo Marconi. While during the early days of radio transmission people were astounded by the novelty of wireless telegraphy and audio, in the modern era personal wireless high definition video streaming, Internet browsing, voice calling and messaging are accepted as a standard. All these services are enabled to us by complex telecommunications and computing technology, developed largely after the invention of the transistor.

Despite the continually increasing computational power and efficiency of radio transmission schemes, the radio transmission medium (frequency spectrum[1]) is constant in its size and limited by physics. As pointed out by Akyildiz et al. [11], this limitation and achievements in computational power have led to the point when cellular radio technologies like Long Term Evolution (LTE) have been developed, which are capable of achieving data rates close to the *Shannon-Hartley* maximum channel capacity limit for a given bandwidth and Signal-to-Interference-plus-Noise Ratio (SINR). The attainment of such spectral efficiencies meant that further efforts to increase wireless transmission performance for an end user must concentrate on improving SINR, or by providing more bandwidth. While with confidence it can be stated that improvement of SINR receives a lot of attention during design phase of any radio transmission system within given physical and budget constraints, underutilized licensed spectrum, as a source for further capacity improvement, started to attract significant interest since around a decade ago [1]. The only action that is taken in reality (besides minor initiatives discussed later in this thesis) to alleviate inefficient spectrum usage, is spectrum refarming.

Since approximately the year 2000, an increasing number of research activities emerged that started investigating potential ways and schemes to benefit from dynamic spectrum access. Different approaches emerged which are now known as spectrum overlay or underlay access, centralized spectrum broker, spectrum secondary markets, and others, that will be discussed later in the thesis. The motivation for this thesis work stems from unanswered questions regarding DSA effectiveness, which is one of the proposed dynamic spectrum access methods, as will be discussed further. Motivation will now be

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[1] In this thesis we refer to *spectrum* as the bandwidth of electromagnetic spectrum that is used for radio communication. Generally the range between 3 kHz and 3000 GHz is split into bands for the communications purposes.

presented in the next section, followed by the formulated research questions.

1.1 RESEARCH MOTIVATION

It is a well-known issue that wireless spectrum for communications is a highly demanded, limited and expensive resource. The best example of this must be a European Universal Mobile Telecommunications System (UMTS) spectrum auctioning during the year 2000–2001, which raised roughly 90 billion euros [40]. This auctioning proved to be crushing for some operators as they were faced with a bankruptcy threat [21].

In a shadow of skyrocketing mobile data demand, such situation becomes a headache. Recent predictions by Cisco [8] show that mobile connections in North America and Europe are expected to grow approximately at 14 % Compound Annual Growth Rate (CAGR) during the period 2014-2019 (approximately twofold increase). Fulfilling a demand in traditional ways, i.e. network expansion or spectrum acquisition, involves big expenses that must reflect on bills that users are charged, or degradation of communications provider service quality. Under such circumstances, novel spectrum management approaches, such as DSA, are expected to improve the efficiency of resource usage, consequently increasing network capacity and improving user experience without major investments.

As a follow up of ongoing research and discussions on dynamic spectrum management, the 3rd Generation Partnership Project (3GPP) has recently initiated a new technical report 37.870 as part of the standard release 13 to identify general scenarios and requirements for multiple Radio Access Technology (RAT) coordination and to study candidate solutions [39]. The specification bases the need for RAT coordination system on real network observations during the year 2013. Observations show that traffic load distribution over the network cells greatly varies during the day for each RAT independently and during some periods legacy systems don't make sufficient use of the allocated spectrum, while a more advanced RAT could potentially make use of an additional capacity. Hence, it is stated in the specification, that traditional spectrum refarming cannot keep up with the reduction in spectrum requirements of legacy RAT. It is also believed that the extent of traffic load variations depends on whether a cell is in an urban or suburban area. Therefore, it is expected that these variations can be exploited for the benefit of a network operator and an end-user by making a more efficient use of available spectrum.

The 3GPP work item discusses the possibility of two different techniques, to exploit traffic load variations and herewith improve user Quality of Experience (QoE), efficiency of resource usage and network capacity. They are, namely traffic steering and spectrum (re)allocation, and are considered for cellular radio technologies, as well as Wireless Local Area Network (WLAN) [61]. These two approaches, however, require validation to prove the likelihood of anticipated benefits.

This master thesis project aims to validate one of the proposed techniques as mentioned – DSA in temporal (minutes, hours) and spatial (cell-to-cell) dimensions, as spectrum (re)allocation opportunities depend on time of a day and can differ in each cell at any particular moment. The thesis research is limited to 2G and 4G radio technologies, and conducted based on the cellular network data provided by Royal KPN N.V. (hereafter KPN) which is interested in the outcome due to the potential benefits of such coordination system to mobile network operators. WLAN incorporation together with traffic steering are considered to be ample enough topics on their own, that are investigated in other projects.

1.2 RESEARCH QUESTIONS

The main research question to be answered by this thesis project, is whether a network and an end-user performance can be improved by implementing intra-operator DSA mechanism. To answer this question, an algorithm for spectrum reallocation must be devised and investigated in different network scenarios: taking network areas that are in urban, suburban and rural environments, testing different period durations for which reallocation decisions are made. The key research questions can be summarized as the following:

1. Is 3GPP assumption, stating that spectrum reallocation may increase system throughput without adverse impact on legacy systems performance, valid?
2. By how much can cell and end-user throughput be improved by implementing DSA in typical realistic network setting?
3. Are there any differences in the number of potential spectrum reallocation opportunities and operating performance among environments that can be classified as urban, suburban and rural?

The validation of the 3GPP assumptions is done by running realistic computer simulation scenarios and analyzing the outcome data. Simulations are developed by using realistic network traffic data, propagation models and other relevant parameters provided by KPN, as will be further discussed in this thesis. The thesis will not discuss the technological requirements or obstacles that have to be taken into account at the level of base station subsystem or core network, to make DSA approach possible.

2

OVERVIEW OF CELLULAR NETWORKS

The purpose of this chapter is to briefly introduce the radio interfaces of cellular communications technologies covered in this thesis, as well as radiowave propagation modeling. Throughout the evolution of mobile telecommunications, different generations of mobile technology have been established, each having their own specific traits. Since this work takes European telecommunications operator as an example case, 2G and 4G technologies will be covered that are used in Europe and specifically by KPN. A general understanding of how both technologies work is necessary before moving on to the details of the thesis problem assessment.

2.1 GSM, GPRS AND EGPRS (EDGE)

The second generation (2G) cellular telecommunications systems have replaced the first generation (1G) analog systems with a primary goal to provide cellular voice services comparable to Public Switched Telephone Network (PSTN) and to allow roaming throughout different countries. The enabler of such 2G services in Europe became Global System for Mobile Communications (GSM)[1] which is the first fully digital Circuit Switched (CS) cellular system. GSM standardization was established in the 1980s within 'Conférence Européenne des Postes et Télécommunications' (CEPT). Development work was later transferred to 3GPP and combined with the third generation (3G) systems. Although declining in its global share, GSM has long been and still is the most popular mobile subscriber technology [9]. In further subsections, more details are provided about 2G characteristics based on Halonen et al. [26] and Saily et al. [57].

2.1.1 *GSM*

GSM is a multi-carrier, Frequency Division Duplex (FDD), Time Division Multiple Access (TDMA) cellular communications system. Initially in Europe GSM has been deployed using 890–915 MHz band for uplink and 935–960 MHz for downlink, and is called GSM900. Later GSM1800 was introduced using 1710–1785 MHz for uplink and 1805–1880 MHz for downlink. Carriers in radio system are spaced every 200 kHz with 100 kHz wide guard bands at both ends of the frequency range, leaving 124 and 374 physical channels for GSM900 and

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[1] The original GSM title was 'Groupe Spécial Mobile'.

GSM1800 respectively. Duplex spacing used is 45 MHz in GSM900 ($f_d = f_u + 45\,\text{MHz}$) and 95 MHz in GSM1800 ($f_d = f_u + 95\,\text{MHz}$).

Further, each frequency channel is subdivided in the time domain by frames of 4.615 ms length. Each frame consists of 8 timeslots (577 µs per slot) as shown in Figure 1. A timeslot represents a single time multiplexed frequency channel and data carried by one time slot is called a burst. Logically physical channels are divided into traffic (TCH) and control (CCH) channels. Traffic channels can be full- and half-rate, with half-rate providing double cell capacity at the cost of a reduced connection performance. Twelve slots of user data are followed by a signaling slot. After another 12 data slots, an unused slot follows. This pattern of 26 slots occurs periodically and is called a multi-frame. This results in 24 out of 26 physical slots being used for traffic effectively. Multiframes are further combined into superframes and hyperframes, and traffic and data channels have further subdivisions.

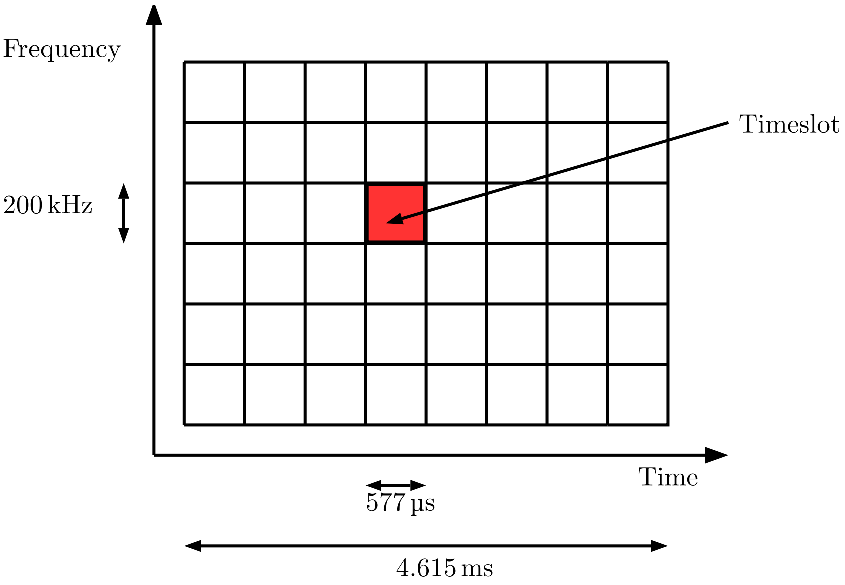

Figure 1: GSM radio channel subdivision

GSM modulates frequency using Gaussian Minimum-Shift Keying (GMSK). Since GSM Rel'98, speech traffic channels employ narrowband Adaptive Multi-Rate (AMR) codec which can provide bit rates of 4.75–12.2 kbps that depend on channel conditions and network load. Later introduced wideband AMR uses wider speech coding bandwidth and higher bitrates (6.60–23.85 kbps) to provide voice quality that exceeds Plain Old Telephone Service (POTS). However, few GSM mobile stations support it.

Data traffic transmissions in early GSM specifications were limited to 9.6 kbps on a single timeslot. Later, High Speed Circuit Switched Data (HSCSD) service enabled time slot bundling that can be asymmetrical in terms of uplink and downlink communications. Number of slots that can be used in downlink, in uplink and in both directions simultaneously (if capable), depends on 2G release version and Mobile Station (MS) hardware. However, the downside is that signaling overhead is increased by the number of channels bundled.

In order to elude frequency selective fading, average interference levels and therefore allow frequency reuse factor of one in Traffic Channel (TCH) space, GSM uses the so-called slow Frequency Hopping (FH) mechanism (not available in early GSM deployments) which works on a frame-to-frame basis (approximately $1/(4.615 \times 0.001) = 217$ times per second) and is mostly helpful for quasi-stationary MSs, which are most vulnerable to static fading situations. The frequency used for a frame is determined by Mobile Allocation Index Offset (MAIO) and Hopping Sequence Number (HSN). MAIO can take any value as there are frequencies in the hopping list (Mobile Allocation (MA) list). HSN has 64 different values, where a value of zero enables cyclic hopping and others enable pseudo-random sequences. Sequences with the same frame number and HSN, but different MAIO, will never overlap (they are orthogonal). To achieve this between the cells of a site, frame numbers need to be synchronized. The number of frequencies in MA list can vary, but it must be higher than the number of transceivers within the site, in order to keep sequences orthogonal. Interference averaging between the sites is achieved, because channels that use the same timeslot number, MA list and different HSN will interfere only in 1/N bursts, where N is the length of MA list. Hopping sequences are commanded to mobile stations by base stations and they are fixed for a longer period of a time. Power control and Discontinuous Transmission (DTX) mechanisms are also used to reduce interference among other methods.

As any other mobile network, GSM uses spatial division multiplexing to reach higher capacity and better coverage. However, compared to 3G and 4G technologies, the frequency reuse factor was not equal to one before frequency hopping hardware became available. Nowadays, traffic channel carriers are typically deployed on hopping frequencies with reuse factor of one, while control channel carriers are deployed on non-hopping frequencies after a deliberate planning is done. Frequency planning deploys carriers in clusters (N = 3, 4, 7, 9, 12) and within a cluster each frequency can be used only once. Such strategy ensures that adjacent cells never use the same frequency, therefore reducing interference effects.

When frequency hopping is used together with a MAIO function and the number of hopping frequencies is higher than the average number of transceivers on the site, the effective frequency reuse factor becomes higher than one. It is expressed as $R_{eff} = \frac{N_{freqsTOT}}{N_{TRX}}$, where $N_{freqsTOT}$ denotes a total number of hopping frequencies and N_{TRX} denotes the average number of transceivers within the site. Co-channel interference between the site sectors is avoided when $R_{eff} \geq 3$ and adjacent channel interference between the site sectors is avoided when $R_{eff} \geq 6$.

Besides civilian GSM, a railroad version GSM-Rail (GSM-R) with additional features and services has been introduced, which operates on separate frequencies.

2.1.2 *GPRS*

General Packet Radio Service (GPRS) is an improvement over data services provided by GSM and HSCSD. GPRS enables Packet Switched (PS) data transfer that is a much more efficient way for application generated information to be transferred due to its bursty nature. GPRS made services like Multimedia Messaging Service (MMS) and Wireless Application Protocol (WAP) among others possible, and can be operated in parallel with GSM services. Packet-switched traffic channels are referred to as packet data traffic channels (PDTCH).

For GPRS to be enabled, GSM system allocates for this service from 1 to 8 slots within a frame. Allocations are not predetermined or fixed, but based on demand, operator preferences and load. Hence, the number of time slots allocated can vary during a data flow. Depending on an operator, it can be that higher GSM voice demand forces more time slots to be allocated to GSM voice services. Users can share all time slots independently for uplink and downlink.

Modulation wise, GPRS also uses GMSK as does GSM. Achievable user bitrates depend on time slot allocations by operator, channel coding schemes that depend on a link quality, and mobile station capabilities. Available coding schemes with corresponding bitrates are shown in Table 1. There are 45 mobile station multi-slot classes, with first class supporting one slot per downlink and one per uplink, and class 29 supporting transmission and reception using all 8 slots. Classes also differ by their duplexing capabilities. A typical MS supports up to four timeslots in downlink and one slot in uplink.

Table 1: GPRS coding schemes

Coding scheme	**Bitrate (kbps/slot)**	**Modulation**
CS-1	9.05	GMSK
CS-2	13.4	GMSK
CS-3	15.6	GMSK
CS-4	21.4	GMSK

2.1.3 *EGPRS (EDGE)*

Enhanced-GPRS (EGPRS), also known as Enhanced Datarates for GSM Evolution (EDGE), is yet another improvement to GSM system based data communications services and in Europe is seen as a bridge to 3G technology. It is also sometimes called a 2.5G technology. Through the improvements in channel coding, EGPRS delivers roughly 3 times the performance compared to GPRS connections. This is achieved by an introduction of 8-Phase Shift Keying (PSK) modulation which can carry 3 bits per symbol while GMSK carries only 1. Also, different error coding schemes were introduced that vary depending on the channel quality. Hence, higher bitrates are possible, with modulation and coding schemes listed in Table 2. However, 8-PSK is more sensitive to phase noise and peak data rates require a better radio link. As in GPRS, achievable performance also depends on operator scheduler allocations and mobile station capabilities.

Table 2: EGPRS (EDGE) coding schemes

Coding scheme	**Bitrate (kbps/slot)**	**Modulation**
MCS-1	8.8	GMSK
MCS-2	11.2	GMSK
MCS-3	14.8	GMSK
MCS-4	17.6	GMSK
MCS-5	22.4	8-PSK
MCS-6	29.6	8-PSK
MCS-7	44.8	8-PSK
MCS-8	54.4	8-PSK
MCS-9	59.2	8-PSK

With regard to mobile station capabilities, same multi-slot classes apply as described in the previous subsection.

2.1.4 *Channel allocation*

In order to manage channel allocations among PS and CS network traffic, a timeslot allocating algorithm is necessary. CS traffic needs stable timeslot allocation for a continuous traffic flow, while PS traffic is of bursty nature and shorter duration. To accommodate both, generally two different approaches are used: resource division into two resource pools and common pool of resources.

When resources are separated into two pools, PS timeslots are always consecutive to each other and it is easier to allocate multiple slots when supported by the MS. Moreover, CS services experience a more stable timeslot allocation for continuous traffic. If needed, timeslots can be converted from one type of traffic to another, to support load variations.

A common pool of resources gives more freedom when allocating timeslots to data flows. However, optimization for different services is not possible and resources can get fragmented, therefore multi-slot allocations can get limited.

2.2 LTE

LTE can be considered[2] as the latest generation of cellular communications systems. It has higher spectral efficiency and performance than previous generations cellular technologies, and is packet-switched only. However, according to 3GPP 4G standard requirements, LTE does not fully qualify[3] to be called as 4th generation technology, mainly because its peak data rates are too low. In this work though, we will call it 4G for the sake of convenience. The newer and more advanced version - LTE-Advanced (LTE-A), can however be called a "true 4G", because it meets the standard requirements. However, LTE-A is not included in our evaluation work.

The LTE air interface can employ either FDD or Time Division Duplex (TDD) duplexing schemes. In Europe, LTE-FDD has been deployed as LTE1800 with 1710–1785 MHz for uplink and 1805–1880 MHz for downlink, LTE800 deployed with 832–862 MHz for uplink and 791–821 MHz for downlink, and LTE-TDD deployed as LTE2600 within the range of 2570–2620 MHz. Duplex spacings for LTE1800 and LTE800 FDD versions are 95 MHz and -41 MHz respectively, where in the latter case the downlink uses lower frequencies than the uplink. LTE has rather flexible channel bandwidths: 1.4, 3, 5, 10, 15 and 20 MHz, that are convenient for spectrum reallocation purposes. Further we will discuss the FDD version only, as TDD is not included in our evaluation work.

In the downlink LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) multiplexing which allocates resources to users in time and frequency domains, and employs narrow subcarriers instead of using a single wide band. Subcarriers are spaced every 15 kHz and 12 subcarriers make up a resource block (180 kHz), multiples of which are assigned to users. In the time domain carriers are divided by 10 ms long frames (shown in Figure 2) which are divided into 10 subframes. Each subframe is further subdivided into two slots, 0.5 ms duration each, and each slot into 7 symbols. A resource block in LTE is of single slot length. The LTE scheduler works on subframe basis and assigns users resources that are 180 kHz wide and 1 ms long (known as Transmission Time Interval (TTI) or a scheduling block).

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[2] In December 2010 International Telecommunications Union-Radio communications sector (ITU-R) recognized that 4G title can be applied to technologies "providing a substantial level of improvement in performance and capabilities with respect to the initial third generation systems now deployed".[4]

[3] The main requirement was set in March 2008 by ITU-R that 4G systems should reach peak rates of 100 Mbps for highly mobile communications and up to 1 Gbps for stationary communications.

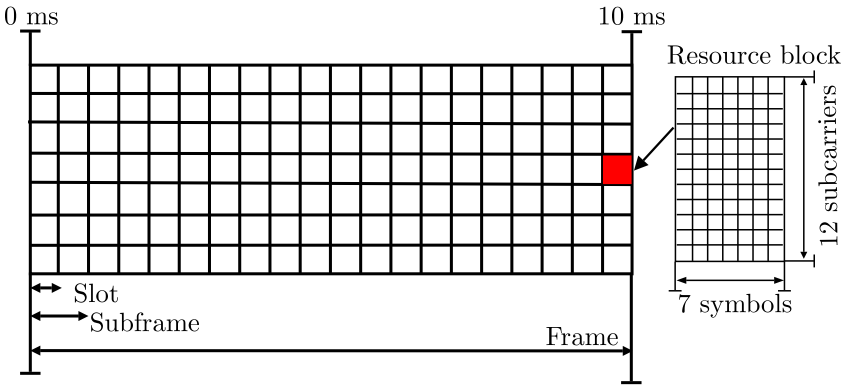

Figure 2: LTE frame structure

In the uplink LTE uses Single Carrier Frequency Division Multiple Access (SC-FDMA) multiplexing scheme. This scheme was chosen for uplink due to its low signal peak to average power ratio which is essential for MS battery life. Low ratio is achieved by better spreading of information over sub-carriers, thus reducing power differences between them.

Modulations used are QPSK, 16QAM and 64QAM which are chosen by resource scheduler based on carrier quality feedback from MS. LTE makes use of Multiple Input Multiple Output (MIMO) and Inter-Cell Interference Coordination (ICIC) besides other numerous functions to improve capacity and reduce interference as frequency reuse factor in LTE networks is equal to one. Achievable user data rates, as typically, depend on user equipment and operator network capabilities, and theoretically can go up to 300 Mbps in downlink (8x8 MIMO) and 75 Mbps in uplink (4x4 MIMO) with Rel.8 LTE. Physical layer bandwidth in LTE is divided into steps of resource blocks with additional guard space on the edges as shown in Table 3.

For more information on LTE technology, reader is referred to Sauter [60].

Table 3: LTE channel bandwidths

Channel BW [MHz]	**Signal BW [MHz]**	**Number of RBs**
1.4	1.08	6
3	2.7	15
5	4.5	25
10	9	50
15	13.5	75
20	18	100

2.3 RADIOWAVE PROPAGATION MODELING

This subsection will briefly describe outdoor radiowave propagation modeling used to plan cellular networks, based on Barclay [14] and Goldsmith [24]. Radio link planning is necessary when designing mobile networks to ensure spatial coverage by a radio signal.

The wireless communications channel is affected by additive (thermal noise, co-channel interference) and multiplicative (propagation losses) effects. A radio signal that arrives at a receiver is always affected by free-space loss (outward spherical spreading) and possibly by one or more additional physical processes that take place during the propagation through a medium: reflection, absorption, scattering, diffraction and refraction. Multiplicative processes are typically grouped into free-space loss, slow fading (shadowing) and fast fading (multipath). The effect of all these processes on a particular channel, changes together with relative receiver position to a transmitter.

Mobile communications operate using Very High Frequency (VHF) which correspond to wavelengths that are shorter than most obstructions in a radio link path (1–10 m). Thus, propagation modeling uses high frequency approximations. The level of detail (resolution) used to model radiowave propagation can be high, however it is a computationally costly procedure, hence a compromise between area size, modeling complexity and accuracy is typically chosen.

Path loss predictions can be done using empirical or deterministic models, or a combination of both. Empirical models take into account all complex propagation loss mechanisms by making extensive path loss measurements and fitting an appropriate function to them with a set of parameters for a particular environment.

Okumura-Hata model is arguably the most widely used empirical model which was created by making a series of path loss measurements in Tokyo, Japan and using them to develop a prediction model. This model has been enhanced by creating approximations of measured data to capture the effects of terrain irregularities and different antenna heights. Okumura-Hata model covers frequency range of 150–1500 MHz and distances of 1–20 km. COST 231-Hata model (also known as the Extended Hata model) is another empirical model, created in Europe to provide a good design tool for 3G cellular systems. It has extended Okumura-Hata model by covering frequency range of 1500–2000 MHz and is suitable for smaller distances of 1–10 km.

While empirical models seem like a convenient solution to propagation modeling, they suffer from a few shortcomings: they are limited to parameters of original measurement setup, subjective environment classification and little insight into physical mechanisms of propagation.

Deterministic models, on the other hand, use physical laws to model radiowave propagation and are considered to be more accurate than empirical models. However, they are more complex and expensive to produce, as detailed calculations, taking into account various objects in the path, need to be done. The example objects that typically get included, are buildings, roofs, trees and walls. Acquiring information about these objects is costly. Among various deterministic models, Longley-Rice model is used for irregular terrains, Ikegami model is used for cases of urban environment and mobile terminals, Walfish-Bertoni is used for very dense urban environments like old towns and downtowns. The models differ from each other due to the physical phenomenas (reflection, diffraction, etc.) that a radiowave is expected to undergo (and how many times) in the particular environment, hence different mathematical approximations are used.

Another common deterministic approach to model radiowave propagation is Ray Tracing. This method takes geometric approach and models radiowaves as light rays traveling from the transmitter to the receiver, and possibly reflecting from various surfaces. Ideally all rays that can transfer energy from the transmitter to the receiver are determined and attenuations for resulting paths are computed, eventually providing all multipath components. This model also needs a detailed information about the area, thus generated predictions are site-specific and are not suitable for other locations.

Hence, for radio planning typically a combination of different models and techniques is used to develop a thorough assessment of an area. While empirical models are good for long distance path loss estimations, shorter distances in urban environments are more often evaluated using deterministic calculations to get an accurate picture.

3

REVIEW OF RELATED LITERATURE

In this chapter the outline of spectrum management and sharing is provided. The chapter starts with a short historical perspective of spectrum management, from the early to modern days of radio communications. Next, spectrum sharing concepts and dynamic spectrum access is presented in more detail. Different approaches and scenarios are reviewed together with notable research work. Finally, the chapter is ended by specifying how this thesis work contributes to the available knowledge.

3.1 THE ROAD TO SPECTRUM MANAGEMENT

The magnificence of radio communications led to rapid application of this new method of information transfer. However, with increasing usage of radio, very quickly the problem of interference emerged. The first radio systems used spark-gap transmitters that occupied huge amount of spectrum and are now illegal[1]. The first modulation technique - amplitude modulation (AM), invented and first used by Reginald Fessenden in 1906, was the first enabler for more than one transmitter at a time to send signals. Still and all, number of radios around the world kept increasing and other modulation techniques, like frequency modulation (FM) and phase modulation (PM), were invented, but they all were not specifically targeted and suitable to reduce interference.

To mitigate interference, multiple access techniques in different domains were established which we now know as TDMA (Time Division Multiple Access), FDMA (Frequency), SDMA (Space), CDMA (Code) and PDMA (Polarization), as well as random access methods: CSMA/CA, CSMA/CD, ALOHA and others. All these techniques nowadays are employed and working, but they wouldn't without spectrum management which partitions spectrum into bands, distributes them to actors (owners) who can then apply suitable modulation and multiplexing techniques for their purposes.

As Cave et al. [19] defines, "Spectrum manager provides each user with the right to transmit on a particular frequency over a particular area, typically in the form of a license". The role of spectrum manager since the very beginning of communications, was taken by state governed agencies that are responsible for all kinds of communica-

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[1] An extreme example of how inefficient spark gap transmitters were by creating huge interference, is a tragic story of Titanic ship which due to interference was unable to contact nearby ships for help [5].

tions regulations. Arguably the first ever commercial broadcasting license, which allowed radio transmission between two cities, was issued in 1919 to the privately held radio station PCGG[2] in The Hague, The Netherlands [66]. However, licenses at that time were dispensed without any framework and even with abundance of spectrum, interference problems quickly arose. This was until year 1927, when the Radio Act was established in the USA [27], which stipulated further spectrum management developments. Since then licenses started to be more strictly limited by geographical boundaries, transmission power, time, etc. Regulations were getting stricter and more granular, and led to the point that exists now.

Nowadays the world is filled with billions of pocket-sized devices that are all connected to related networks and can interconnect practically anytime. Spectrum is distributed to commercial actors to provide cellular and broadcasting services, and to government for public safety functions, aviation and other services. Under such conditions and increasing usage, as more and more services started relying on radios, spectrum managers had to impose stricter and finer regulations to keep all spectrum owners and users happy. Spectrum started being divided into narrower and narrower bands, constraints tightened on spectral leakage and also requirements were imposed on minimum spectral efficiency.

Due to spectrum scarcity and increasing demand for it, commercial spectrum auctions have been introduced which not only generate hefty amounts of money for governments, but also condition that spectrum is used as efficiently as possible. An extraordinary competition is for frequencies in the so-called "sweet spot" region which is roughly in the range between 0.3–3 GHz. Frequencies in this range are highly valued by mobile network operators because they have favorable propagation and penetration characteristics for civil purposes, and are efficient with small antennas. Such features led to distinctly high license prices for bands in this particular frequency range, as shows the given example of European spectrum auctioning experience in Chapter 1.

In turn, companies are highly motivated to improve usage efficiency of their acquired bands which can be done by choosing technology that they think suits best. The progress can be well illustrated by the fact that a link spectral efficiency of LTE-advanced (8x8 MIMO) is up to 30 b/s/Hz [11] while Advanced Mobile Phone System (AMPS) (obsolete 1G cellular system) used to achieve only 0.01 b/s/Hz [16] .

There were other approaches to spectrum distribution before auctioning, like lottery approach in USA [37]. However, this approach was quickly abandoned due to too many entrants trying to enlist for lottery participation. Various companies even without credible telecommunications business tried to persuade Federal Communica-

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[2] 'PCGG' was a call sign of the station.

tions Commission (FCC) to allow them to participate, hoping to win and then speculate the obtained spectrum. The "beauty contest" [17] is yet another approach, which chooses the winner based on the guarantees of lowest costs to consumers, highest investments in infrastructure, etc. However this approach is also considered flawed, as it is arguably impossible to properly quantify the benefits and usefulness of the mentioned guarantees, especially for the longer term.

The short history[3], described in this introduction, presented the spectrum management type called Fixed Spectrum Allocation (FSA). Its efficiency was not widely questioned until roughly year 2002. The FCC then published the tech-report [1] which revealed that FSA leads to inefficient spectrum usage as designated band owners don't fully utilize their owned spectrum blocks all the time. These findings later were confirmed by a number of investigations [49, 64]. To some surprise at that time, FCC encouraged an idea that spectrum management should become more dynamic in order to get rid of the observed inefficiencies and alleviate the spectrum shortage. This discovery fueled a number of research activities and projects which fall under the branch of spectrum management called dynamic spectrum access. The basic idea behind this new approach is that spectrum has to be shared among multiple users or operators, and this should lead to a higher efficiency and better end-user experience.

Dynamic spectrum access will now be presented in the following subsections.

3.2 SPECTRUM SHARING

The approaches taken during the last decade to dynamic spectrum access were diverse. To have a better perception, in the following subsections the taxonomy of spectrum access methods is presented which is based on the selected state-of-the-art dynamic spectrum access survey papers [68, 58, 18, 15]. The visualization of taxonomy is shown in the Figure 3 . Different spectrum access methods have distinguishable characteristics which are additionally discussed in [32, 35, 23].

These characteristics can be generalized as:

A. Orthogonality:
   a) orthogonal sharing - corresponds to spectrum being exclusively dedicated to one operator;
   b) non-orthogonal - multiple operators concurrently use the same frequency bands in the same geographical area;

B. Access rights:

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[3] For an extensive history of spectrum allocation policy, reader is encouraged to take a look at Hazlett [27]

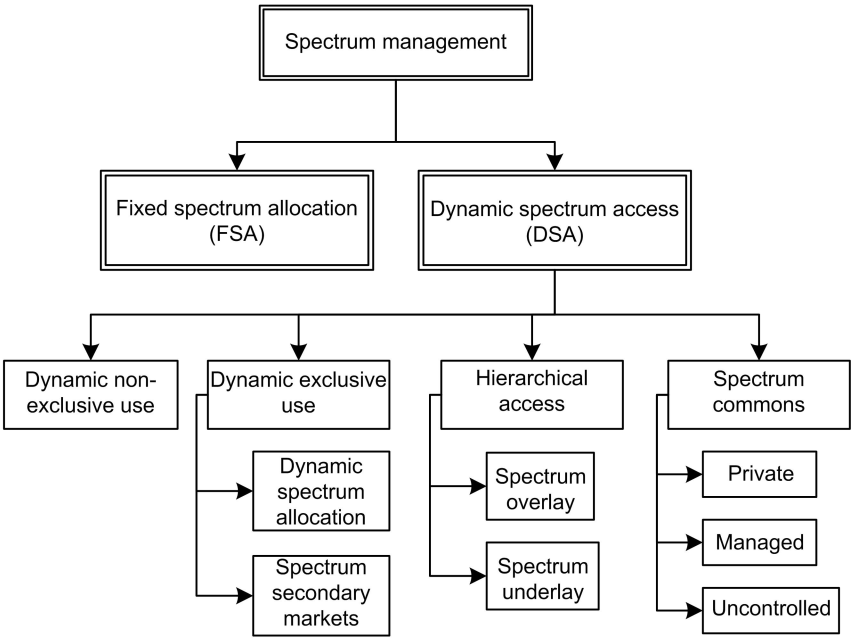

Figure 3: Spectrum management taxonomy

a) horizontal - occurs when all systems have equal rights to access a particular spectrum band;

b) vertical - as opposed to horizontal, defines radio access when one or more systems have priority over others;

c. Spectrum coordination:

a) distributed - spectrum is accessed via a terminal-centric approach; terminals independently assess the environment conditions and choose spectrum band to operate on;

b) centralized - a centralized entity coordinates spectrum usage between multiple systems.

The relation of these characteristics to the taxonomy of spectrum access methods, will be described in the further subsections.

3.2.1 *Fixed spectrum allocation*

This is a standard spectrum assignment approach which until recent years was the only used spectrum allocation method, coordinated by regulating authorities. It is also called the *command and control* method. Spectrum is assigned by laying down technology and service specific details which cannot be changed during the license lifetime. Licenses are typically assigned via a market mechanism (e.g. auction) when there is a competition to acquire them. Otherwise spectrum simply gets dedicated to a certain entity based on the reasoning and need. The latter case usually applies to military, government bodies, etc.

While this spectrum allocation method is convenient for regulatory bodies due to straightforward management and service quality assurance, it poses two major problems as discussed by Pereirasamy et al. [54]:

A. Scarcity

   Usable spectrum is a limited resource. Provisioning of a dedicated block of spectrum to each service and technology leads to a point when there is no more free spectrum available.

B. Scalability

   Comprehensive frequency and system planning has to be done in each country to ensure smooth operation of various services. The increasing number of services and technologies each with their dedicated spectrum block results in spectrum management and coordination that is inconveniently cumbersome and time consuming.

By looking at both problems, it becomes clear that it is the static essence of fixed spectrum allocation method, that makes it no longer suitable for recent trends in wireless communications. Dynamic approaches should be used to exploit temporal and spatial spectrum utilization variations, and thereby enhance the efficiency of spectrum usage. Such dynamic approaches are discussed in the next subsection.

3.2.2 *Dynamic spectrum access*

Dynamic spectrum access is a relatively new concept in spectrum management that aims to introduce more flexibility to frequency usage. There are few main goals that this new approach tries to achieve: technology and service neutrality, spatial and temporal scope reduction (more frequent spectrum refarming/(re)allocation for any area independently) and secondary usage. Many of these ideas became possible with increasing computational power of available hardware. Since there are so many goals to be achieved in various network setups, naturally many different approaches to dynamic spectrum access were taken by experts of the field in their proposed models. They are presented below.

A. Dynamic exclusive use

   Under this model, only one entity has rights to use designated spectrum, however the type of usage (technology, service) and owners can change. Dynamic exclusive use can be considered as the most humble step towards dynamic spectrum access, as spectrum sharing in this model is still coordinated centrally, i.e. by an operator and is orthogonal.

a) Dynamic spectrum allocation

This approach exploits temporal and spatial load variations of different radio technologies. Although spectrum re-farming is already used to move chunks of spectrum away from technologies that are declining in usage [25, 56], dynamic allocation aims for a much finer temporal scale (hours, minutes) and smaller area (cell-to-cell). As in fixed spectrum allocation, using this method, at any given time and space, spectrum block is exclusively dedicated to a particular owner and technology. The so-called technology-agnostic spectrum is already approved by regulators in a number of European countries, USA, Australia and China [39]. The most straightforward application of this approach is intra operator dynamic spectrum allocation to different RATs or dynamic underutilized carrier shutting down to save energy [28, 52, 47, 65]. This particular idea of intra-operator dynamic spectrum allocation is the pivot of this thesis project. Inter-operator exclusive spectrum sharing has also been investigated by other analyses [35, 12, 54, 53].

b) Spectrum secondary markets

Spectrum secondary markets enable owners who possess underutilized spectrum to sell or lease it to other parties, as well as choose any technology. Thus, markets and economy are more engaged into making most profitable and efficient use of spectrum. This approach has already found its way in spectrum distribution ecosystem. Shortly after the release of the tech-report showing inefficient spectrum usage, FCC has put an effort in rule making to enable secondary markets [2]. As it was later found out, the changes in ruling were successful, as "significant spectrum resources have flowed not only to all four nationwide carriers, but also to non-nationwide carriers, and to small and very small businesses" [6].

B. Dynamic non-exclusive use covers the non-orthogonal spectrum sharing between the systems. Shared bands are used by more than one system at any time while each system also has the protected bands for Quality of Service (QoS) guarantees. Inter-system interference on the physical layer is created, but by using e.g. transceiver beamforming, spectral efficiency gains are possible [36].

C. Hierarchical access

This model is based on hierarchical spectrum access structure when systems do not have equal rights for spectrum usage. Licensed to primary users, spectrum is proposed to secondary users who can use it given that interference to primary users is absent or limited. An enabling technology for this method is cognitive radio[4] which is based on a Software Defined Radio (SDR)[5]. As discussed by Akyildiz et al. [10], DARPA NeXt Generation (xG) program has actively explored this technology to develop policy-based intelligent radios that would form so-called next-generation dynamic access networks. The model has also been investigated in other research works [62, 45, 30, 38]. This model can be considered as the closest to dynamic spectrum access idea, as each terminal makes its own decisions based on given circumstances in the most effective way possible and there is no central coordination. There are two approaches to hierarchical access:

a) Spectrum overlay

   Also called *opportunistic spectrum access*, spectrum overlay aims to exploit spatial and temporal "white-spaces" that could be used by secondary users in a non intrusive manner. Secondary users form a flat network and perform three steps: spectrum sensing - radios monitor presence of white-spaces, coordination with peers and data transmission - multiple nodes have to contend and coordinate transmissions, relinquish the spectrum - "return" spectrum if primary user transmission is sensed.

b) Spectrum underlay

   The underlay approach can employ Ultra Wide Band (UWB) technology to transmit information with low power in short range and with high data-rates. In other words, spectrum sharing is done in the power domain. This way secondary users can operate without interfering to primary users as transmission power is very low (below noise floor of primary users). Transmission opportunities in this context are called "grey-spaces". However, types of network configurations are limited (e.g. by communications distance) due to the low power nature of radio access. Spread spectrum technologies, e.g. CDMA, can also be used for spectrum underlay with explicit interference protection for primary users and QoS constraints for secondary users.

D. Spectrum commons

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[4] CR - "A really smart radio that would be self-aware, RF-aware, user-aware, and that would include language technology and machine vision along with a lot of high-fidelity knowledge of the radio environment." [67]

[5] SDR - "A mostly digital radio that could be reconfigured in fundamental ways just by changing the software code running on it." [67]

Also called open sharing, this model facilitates a license-free, shared spectrum usage by secondary users. Three variants of spectrum commons are distinguished below.

a) Private

   This concept allows the use of frequency agile radios that are able to sense spectrum or listen to coordination channels, to access the licensed spectrum block at the discretion of license holder. The ultimate ownership of spectrum is centralized at license holder who is responsible to set the rules of access. This approach was first mentioned in FCC report on barrier elimination for secondary markets [3].

b) Managed

   Managed commons are owned by a group of entities who control the spectrum. The group establishes and enforces restrictions on who, how and when is allowed to use the spectrum. In such way a limited form of order is imposed to avoid chaos. This concept provides license-free, shared use of spectrum using multiple technologies. As an example, in 2004 FCC has created a 50 MHz spectrum block with government controlled commons [3] to help rural wireless service providers introduce advanced services. However, this initiative was not welcomed with great enthusiasm due to various restrictions imposed on technology. Intuitively, private and managed commons approaches are classified as centrally coordinated.

c) Uncontrolled

   This is the simplest commons approach of all and also referred to as "open spectrum access". In this case anyone can use the spectrum with any number of devices. However, there are constraints, such as transmit power, application of particular band, spectrum must be spread and confined within a band. The best example of this type of commons is Industrial, Scientific and Medical (ISM) spectrum bands with Wireless Fidelity (WiFi) being the most widespread technology that uses it. Absence of controls (specifically no interference control) resulted in mass produced devices that use technology relying on ISM bands: Bluetooth, WiFi, ZigBee, etc. Uncontrolled commons approach is considered to have no coordination at all, neither centralized, nor distributed.

Further in our discussion we will concentrate on DSA approach that falls under dynamic exclusive spectrum use model, which is the core topic of this thesis.

3.3 DYNAMIC SPECTRUM (RE)ALLOCATION

3.3.1 *The 3GPP work item: TR* 37.870 *(Rel'*13*)*

The study on multi-RAT joint coordination is a work item established by 3GPP as part of standard release 13. In the work item version v0.4.0 [39] which inspired the thesis work, it is argued that coexistence of multiple RATs introduces operational coordination problems for network operators. The need for coordination cannot be avoided, as coexistence of various RATs is a reality and will be relevant in the future. Under such circumstances, multi-RAT coordination is expected to improve user QoE, resource usage efficiency and network capacity.

The main objectives of the work item are:

- Identify the potential scenarios and use cases where multi-RAT coordination would be useful, including LTE, UMTS, GSM and WLAN: benefits, functionalities, traffic steering (e.g. to WLAN), taking into account QoE, constraints, etc;
- Develop and/or assess efficient multi-RAT joint radio resource coordination schemes to improve load balancing and for an operator to enable, e.g. spectrum re-farming. An emphasis is put on LTE and GSM, to provide an operator a smooth transition from GSM to LTE, while still keeping basic GSM coverage for e.g. voice or GSM Machine-to-Machine (M2M) services. Similar migration and spectrum sharing scenarios may also exist for UMTS and LTE.

Further, we will concentrate on multi-RAT joint radio resource coordination in terms of spectrum (re)allocation in an intra-operator inter-RAT (2G and 4G) scenario, which is the chosen core topic of the thesis. In this project we refer to *spectrum (re)allocation* as "assignment of spectrum from one RAT to another, in a reversible manner, for a period of time (temporal) or in an area (spatial)" [39]. This function can also be defined as "bringing resources to the traffic" and by looking at the spectrum sharing taxonomy presented in the previous section, it belongs to the dynamic exclusive use model. Traffic steering between different RATs (also known as "bringing traffic to the resources") is out of scope for our investigation.

According to 3GPP, spectrum reallocation can be categorized into temporal and spatial types. Spatial reallocation is regarded as spectrum reallocation in a particular area that is smaller than the whole network, and temporal is reallocation is categorized into:

- Dynamic - on a timescale of seconds or minutes;
- Semi-static - on a timescale of hours or days;
- Static - on a timescale of months or years (also known as spectrum refarming).

As old radio technology generations slowly decline in popularity, freed-up parts of spectrum are dedicated to other applications. Static spectrum reallocation, also know as spectrum refarming, is effectively used in practice. KPN is no exception, as e.g. GSM1800 band has recently been refarmed to LTE in the entire network. However, semi-static and dynamic reallocation approaches have not been thoroughly assessed to the date when this thesis research has been started. In that regard, this thesis project aims to provide additional insight about the dynamic/semi-static (re)allocation approach potential of an operator in terms of end-user benefits.

3.3.2 *Research publications*

The European Information Society Technologies (IST) project DRiVE [47] has investigated the co-existence of UMTS and DVB-T dynamic Radio Acccess Network (RAN) which were assumed to have uncorrelated time-varying traffic patterns. Two methods: temporal and spatial (on an area of region scale) DSA, have been investigated in vehicular environments. While the temporal DSA algorithm attempted to adapt spectrum allocations to time-varying loads, spatial DSA adapted to load variations across different regions. DRiVE project used a contiguous DSA scheme, where contiguous blocks of spectrum were allocated to networks separated by a guard band. These blocks were allowed to vary in size at the expense of each other with predetermined priority, depending on the observed load. The operation of this approach relies on differences of load that individual RANs experience at a given point in time. In case of contention between the two RANs for an additional spectrum, a set of algorithms was investigated, that use combinations of parameters with different priorities, such as the number of carriers requested by the RANs, the number of currently allocated carriers, and random selections, to elect which RAN gets additional spectrum. The allocation algorithm consists of three main functions: load measurements, load history and time-series prediction. During temporal DSA investigations, three main aspects have been alternated: time interval between spectrum reallocations, load prediction scheme and carrier allocation scheme. The results show that the best prediction scheme among those tested, utilizes load history combined with short-term prediction and that DSA with imperfect load prediction should be run with interval length of less than one hour. Spatial DSA tried to adapt to regional variations of load per each RAN. The mathematical optimization problem was solved with the aim that spectrum allocations of adjacent regions should not overlap and a primary objective was to maximize the Grade of Service (GoS) in each area and RAN. The temporal and spatial DSA indicated that around 30% spectrum efficiency improvement can be gained from DSA and it is believed to depend on the traffic patterns.

The IST project OverDRiVE [65] has extended the DRiVE project results by applying the fragmented DSA scheme. Using the fragmented DSA scheme, spectrum is treated as a single shared block and any RAN can be assigned a piece of spectrum anywhere in this block. Fragmented DSA scheme has advantages when more than two RANs share the spectrum, but it is more difficult to control in terms of interference. In addition, regional coexistence of different cell-layer access systems in a single shared frequency band has been investigated. The aim of these investigation was to develop algorithms for the definition of DSA areas and cell planning, whereby regional traffic demands are used as limiting parameters. The original results of this project, however, could not be identified.

In the paper by Kovacs et al. [41] DSA is again investigated in spatio-temporal domain, complementing ideas provided by DRiVE and OverDRiVE projects. In this case spectrum is allocated by Regional Spectrum Broker (RSB) that also coordinate spectrum access between regions. A Spectrum Broker (SB) is typically needed when there is contention for spectrum between individual bodies (e.g. providers). Interference between different regions and providers is handled by a flexible description using radio technology and geographical coupling parameters that show how the radios operating at the same frequency simultaneously in both regions disturb each other. Optimal allocation is found by solving an Integer Linear Programming (ILP) problem. The proposed model is reported to achieve higher gains during busy hours when compared to OverDRiVE proposal (26.15% in contrast to 17.65%).

The SB approach is also taken in [31]. Here interference constrained DSA problem is addressed by proposing interference management scheme that collaboratively works with spectrum allocation algorithm. Interference is managed between the base stations in the region to provision QoS over the allocated channels. In this DSA scenario, SB periodically leases spectrum to base stations in the region, seeking to maximize the spectrum utilization or revenue from spectrum leasing. Provided results argue that the proposed scheme overcomes the limitations of the previous work by Subramanian et al. [63] in reaching the target SINR values without over-allocating or under-allocating Base Station (BS)s with spectrum.

A Discrete Time Markov Chain (DTMC) has been developed by Chung and Tsai [20] to model the DSA process in an environment where spectrum is shared between a Wireless Metropolitan Area Network (WMAN) and a cellular network. Spectrum-level and call-level models have been proposed, and validated by simulations. The results show a reduction in call blocking probabilities when using DSA. Under fixed targeted QoS, spectrum utilization is improved.

The project SEMAFOUR (Self-Management for Unified Heterogeneous Radio Access) has also recently investigated DSA function in one of their work-items [44] which was published during the project work of this thesis. The initial DSA use case investigated in the SEMAFOUR project considered an intra-LTE scenario with micro- and macro-cells, and several frequency layers. The acquired results of their algorithm based on averaged cell load as an input and with fixed set of cell load thresholds, under time-varying traffic conditions showed a very low DSA gain of 1% in terms of network capacity. The second use case had investigated realistic inter-RAT scenario where DSA algorithm is applied for LTE and GSM technology coexistence. The test setup is comprised of a GSM-only Broadcast Control Channel (BCCH) band and a GSM TCH band that overlaps with LTE band. The overlapping LTE band and GSM carriers are turned off and on by DSA algorithm in a selected cell every hour, depending on the load, to increase LTE capacity and limit interference to GSM. The overlapping band's position in the whole band range is also altered by the algorithm which tries to find the optimal (least interfering) setup. The results of this work show a high potential to increase LTE cell capacity by more than 100%.

Another ongoing DSA project is administered by Next Generation Mobile Networks (NGMN) Alliance [48]. The project presents the motives and benefits of Multi-RAT Joint Radio Operation (MRJRO), as well as specifies hardware, reliability, adaptation and implementation requirements for two differentiated modes: semi-dynamic and fully dynamic. In semi-dynamic solution only one RAT can be active on any frequency at any time. Fully dynamic solution enables the ability of radio frequency resources to be assigned to users on a frame/subframe basis. The two major constraints: inter-cell interference and control signaling, are also studied. The project contributes to the same 3GPP study as this thesis and will be continued in NGMN's 5G project [22].

3.3.3 *A working example: Dynamic Frequency and Channel Allocation*

A relevant technology in frame of this thesis topic, is an optional Dynamic Frequency and Channel Allocation (DFCA) function that can be used within 2G networks. It is a good example, showing that dynamic radio resource optimization problem has been approached not just during the last decade.

A good explanation of this function is provided by Salmenkaita [59]. In an article, DFCA is used to describe radio resource optimization process that is categorized into traffic adaptive and interference adaptive. Traffic adaptive algorithm allows dynamic usage of a common channel pool and avoids inter-cell interference by exchanging information about the used channels. Interference adaptive algorithm in addition uses real-time interference measurements to estimate SINR on possible channels and to avoid interference. It can be noted, that this function extensively uses forced half-rate mode channel allocations, without degrading channel quality, to reduce interference effects. The live network results presented by Lasek et al. [43] show around 50% connection error reduction and significant increase in service quality when using DFCA.

3.4 THESIS CONTRIBUTION

Having reviewed the latest developments of spectrum management, we see that there are multiple approaches to dynamic spectrum access. All of them seem to attract a respective share of interest from academia, and all of them are promising improvements and benefits to the performance of wireless networks. However, although signal processing capabilities and cognitive radio technology went through grand improvements during last decades, one could argue whether all of the proposed approaches are yet equally viable in real life, especially by looking from a perspective of mobile network operator. Dynamic spectrum (re)allocation, which is considered to be the most humble step towards dynamic spectrum access, in our opinion appears to be the most feasible option to alleviate increasing spectrum demand.

This thesis aims to further investigate intra-operator inter-RAT DSA approach, taking 2G and 4G technologies as an example case, as it is considered to be the most relevant case, as discussed by 3GPP [39]. At the time this thesis research started, no research works have been identified that would provide realistic performance results of cellular network operating in such scenarios. Previous research publications do report investigations only on spectrum sharing between cellular RAT and Digital Video Broadcasting-Terrestrial (DVB-T) or WMAN setups in a large spatial domain. Moreover, reported results are based on non-realistic network setups. This thesis project aims to use realistic (real) input data in terms of network layout, traffic distribution and propagation modeling, provided by mobile network operator KPN, to assess a DSA algorithm via system-level simulations in different scenarios, which are expected to produce realistic performance results. Based on the results, we will present a comparison of network performance between DSA and FSA network operating modes, highlighting the observable performance trade-offs and the achievable gains.

4

DSA ASSESSMENT

To examine the effect of DSA on cellular network performance, it was determined in the thesis project to build a system level simulator and to run simulations of different network setup scenarios for the downlink communications. Such approach was chosen, because due to a large number of variables in cellular network operation, an analytical study is deemed not feasible. This especially holds in the context of DSA, which perpetually alters individual RAT capacity potential, based on the observed traffic load which is time dependent.

The objective to make the simulations as realistic as possible was kept while designing them within the project time constraints. Simply put, realistic model output requires realistic input. Therefore, the cooperation with KPN was particularly valuable for the project, as information provided by KPN, formed the essential base for establishing realistic simulation conditions. While most of the simulation models that are reported by research publications, are built on generalized network layouts, radio propagation, traffic load and service models, our simulation uses data that is extracted from real cellular network areas. In other words, the simulations that were run during the thesis project, tried to mimic the behavior of the real network areas, with and without DSA algorithm being enabled. The approach and decisions that were taken when building simulations, are described in the next sections.

4.1 DSA MODEL

To make the context more clear, before describing the details of how the simulator was built, the approach to DSA that was taken in this thesis is introduced.

While reported investigations of DSA, that were discussed in the previous chapter, have taken different approaches to the problem, this project aims to investigate the most simplistic and arguably the most realistic approach. In the DSA model used in this thesis, a certain spectrum block at any given time and location is exclusively dedicated to only one cellular radio technology. However, from the perspective of a cellular RAT, the number of spectrum blocks that are allocated to it, their size (bandwidth) and location in the radio frequency spectrum, can change with time. Such dynamics of spectrum allocations, depend on the observed traffic load on a particular RAT and spectrum blocks that are at hand of an operator.

In a realistic typical case, a network operator is licensed to use one or more spectrum blocks that are spread in the radio spectrum. Each spectrum block, depending on its size, operator preferences and state rules[1], can be divided among one or more radio technologies. DSA model that is considered in this thesis, aims to exploit temporally and spatially varying individual RAT traffic load, and frequency domain division flexibility that is supported by a certain RAT. In the particular case of this thesis, DSA is aimed to be applied to 2G and 4G radio technologies which respectively have minimum frequency domain granularities of 200 kHz and 1.4 MHz. These features allow to identify potential spectrum (re)allocation possibilities in a particular operator case.

Once spectrum (re)allocation possibilities are identified, another key factor in making DSA possible, is traffic load prediction algorithm which will estimate/predict the load that will be experienced during a next spectrum allocation period. The prediction algorithm must be as precise as possible, because incorrect prediction can cause under-allocation of a particular RAT, and its users would then experience lower than target QoS in terms of call blocking, dropping and throughput. Traffic load prediction algorithm used in this thesis will be described in Subsection 4.3.4.

The spectrum allocation period and prediction algorithm in DSA simulations are configurable parameters. Allocation period duration can be e.g. as short as one minute and as long as few hours. The shorter the duration, the more dynamic an algorithm is considered, as presented in 3GPP classification in Section 3.3.1. Prediction algorithm can be configured and tuned by applying different time series forecasting methods. In addition, algorithm's "aggressiveness" can be configured by adjusting the traffic load margin under which a spectrum reallocation decisions are made. It should be emphasized, that in our simulations, the spectrum allocation decision that is made for a certain period, is fixed and irreversible until the period duration ends.

The DSA setup that is assessed in this thesis, considers 2G technology as spectrum donor and if opportunity allows (based on traffic load of 2G) reallocates part of its spectrum to 4G for a set period of a time. Reallocation decisions are purely based on a predicted 2G traffic load and are done with no respect to current or future traffic load conditions of 4G. In that sense, an extra spectrum allocation to 4G can possibly give it a capacity boost for a period of a time, which would be more or less efficiently utilized depending on the traffic load.

In the spatial domain, DSA model works on a cell level granularity. Meaning that spectrum allocation state in each individual cell can be different and inter-RAT interference situations can occur. Spectrum in

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[1] As stated in [39], recent rule changes made spectrum technology-agnostic in many countries.

this thesis model is reallocated from one technology to another only if their respective transceivers belong to the same sector. Effectively, in a realistic scenario which is considered in this thesis, 2G and 4G have the same sectorization, hence DSA decisions are made for 2G-4G sector-pairs. This holds true for all sites in all scenarios considered in this thesis. Moreover, it is considered in our model that a 4G terminal can only aggregate the dedicated and additional (re)allocated spectrum to reach higher throughputs, if both channels are served by the same sector.

More details on the particular spectrum blocks and their division used in this project, traffic load prediction algorithm, allocation periods and etc. will follow in the next sections.

4.2 SIMULATION MODELS

4.2.1 *Introduction*

As described by Banks [13], "a simulation is the imitation of the operation of a real-world process or system over time. Simulation involves the generation of an artificial history of a system and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system." In case of this thesis, the simulation has to imitate cellular network operation.

According to Halonen et al. [26], typical cellular system level simulation has the following methodology: MS creation in random places in the network, selecting serving BS, transmission power adjustment, radio resource management and statistics collection. The steps are repeated until sufficient statistical confidence is achieved. Each of the steps can contain more detailed iterative processes as desired. Simulation can be event-driven or time-driven. In case of time-driven simulations, a fixed time-step is used as a period for all simulator function execution. In the event-driven simulations, an event such as a call arrival or MS movement can be a trigger for system state reevaluation. An important practical property is that the simulator should be able to reproduce the results, provided that the input is the same.

Cellular system-level simulations have a list of elements on which they are built, and which determine the overall network performance, as they are related to the mentioned simulation methodology. These elements are: traffic service type (voice call, data session), service characteristics (session size or duration distributions), radio wave propagation models, MS geographical placement models, RAT specific parameters and network layout. The modeling of these elements will be described further.

4.2.2 *Network layout*

To build a system level simulation, we have collected the former data for the selected three KPN cellular network areas in the Netherlands, that based on report by Janssen and Mantel [34] can roughly be considered as representing urban, suburban and rural environments. The selected areas, accordingly, are in Amsterdam city center, Purmerend and Friesland, and are illustrated in Figure 4. Using the collected network data, the aim is to simulate the operating performance behavior of these areas, with DSA enabled or not. Detailed network composition[2] is presented in Table 4. The number of cells is chosen such that a reasonably great area is considered, while keeping the computational time within reasonable bounds.

In order to eliminate the boundary/edge effects (absence of interference from outside the simulated area) in our simulations, the choice was made to add artificial interference, as each simulated pixel in a simulated area has path loss values associated to nine strongest interferers (simulated or not). Using warm-up simulation runs, an average load over all cells in a particular area was determined and applied for further simulations as a probability of interference coming from outside the simulated area. The average load values were set separately per each simulated area and traffic load scenario, but they were kept constant during simulations of the same setup, when DSA was applied and not, to have a more accurate DSA performance evaluation.

Table 4: Composition of simulated cellular network areas

Area [km^2]	**Type**	**Number of BS**	**Number of cells**		
			2G	4G	**Total**
Amsterdam [6]	Urban	8	24	24	48
Purmerend [24]	Suburban	8	24	24	48
Friesland [484]	Rural	11	33	33	66

4.2.3 *Radiowave propagation characteristics*

One of the essential building blocks of simulation is radiowave propagation modeling which was briefly described in Section 2.3. Due to a critical influence of SINR on the communications link performance, realistic propagation modeling is essential when simulating cellular networks. After interference effects are taken into account, SINR values translate into user experienced bitrate values with the help of

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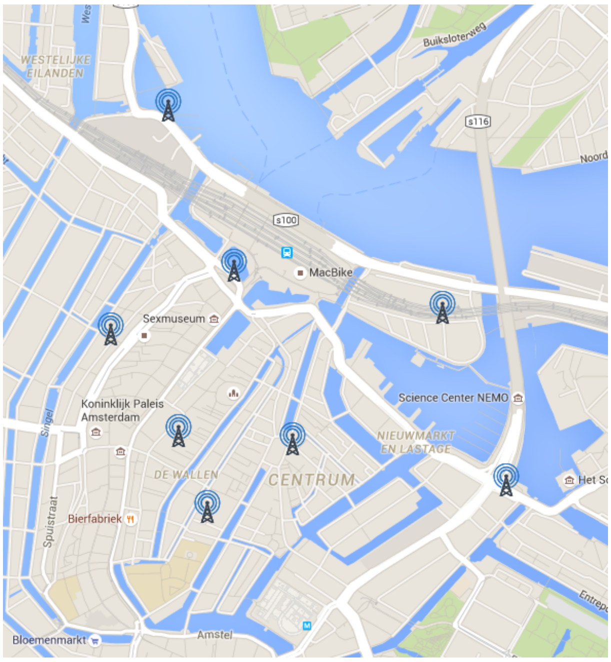
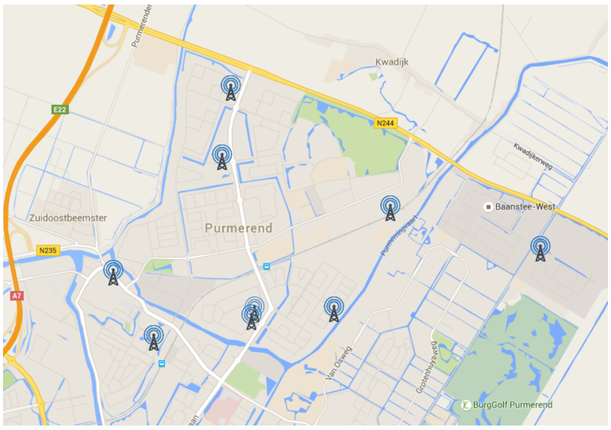
[2] Note that cell is represented by a single RAT carrier in case of 3G or 4G technologies. For example, a 10 MHz bandwidth LTE carrier covering a certain area represents an individual cell. In case of 2G, a multiple of 200 kHz carriers form a cell.



(a) Urban area: Amsterdam city center



(b) Suburban area: Purmerend

(c) Rural area: Friesland

Figure 4: Simulated cellular network areas

link-to-system level interfaces (mapping of SINR to bitrate values) that will be described in Section 4.3.

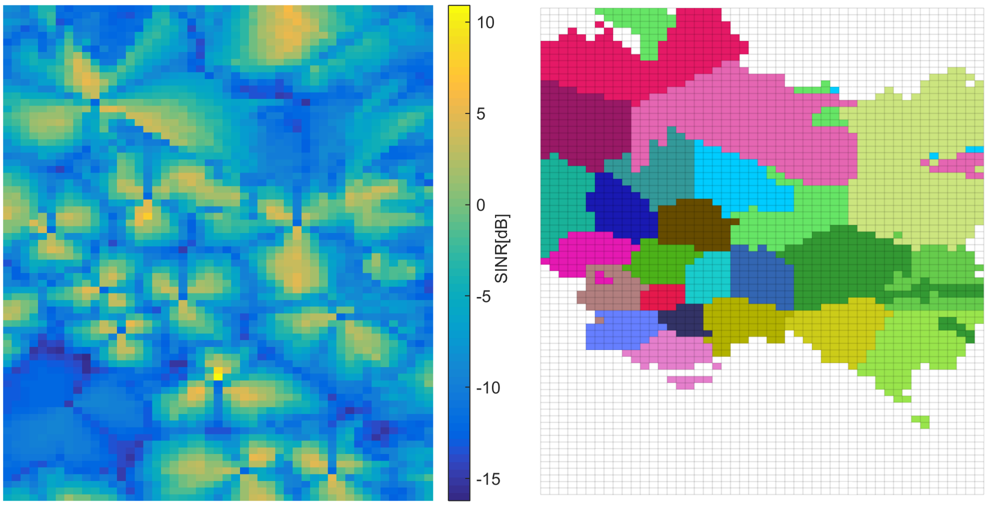
The simulations did not need to perform path-loss calculations, as propagation maps validated and provided by KPN per each frequency band, were used instead. That is a big advantage for a computer simulation because of the two reasons. Firstly, propagation maps provided by a telecommunications operators are compiled by professional modeling tools which are used in cellular network planning. Secondly, propagation characterization is a computationally intense procedure, which in our case can be omitted, saving valuable computation time. As an example, visualizations of achievable SINR values in hypothetic maximum interference case and best server maps for LTE800 band, are presented in Figure 5.

Propagation maps are in the form of pixel matrices, where each pixel represents a 40 m by 40 m geographical area. Maps with better pixel resolution (smaller pixel size) were possible to get acquired too, however KPN experience shows that higher resolution than the one we have chosen does not provide a significant difference in terms of modeling precision. Each pixel has a propagation loss value associated to it, that corresponds to a radio link to the best serving BS sector transceiver. Propagation losses of nine strongest interferers (neighboring co-channel cell transceivers) for the particular pixel are included too. Propagation loss values involve path loss, slow fading and averaged fast fading effects, transmitting antenna characteristics (tilt, azimuth, etc.), losses in an antenna feeding line and combiner (diplexer).

In the simulations of this project it is assumed that all sessions originate from indoor locations, hence Building Penetration Loss (BPL) is taken into account when estimating SINRs. The characteristic area mean BPL values are based on KPN radiowave propagation models and are presented in Table 5. The BPL value is applied to every radio signal that reaches a given MS when estimating SINR, i.e. both the desired and an interfering signals. Random shadowing loss is not applied in order to make sure that a call arrival ends up being served by a certain cell. In other words, each cell in the simulated area has it's specific load at any given point in time, which we want to retain, as will be described further.

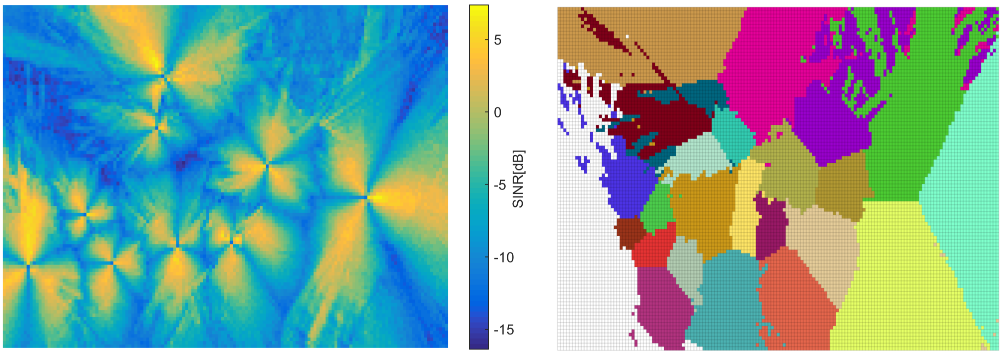
Table 5: BPL values for the 800/900 bands

Area type	**Building penetration loss [dB]**
Urban	19
Suburban/Rural	11



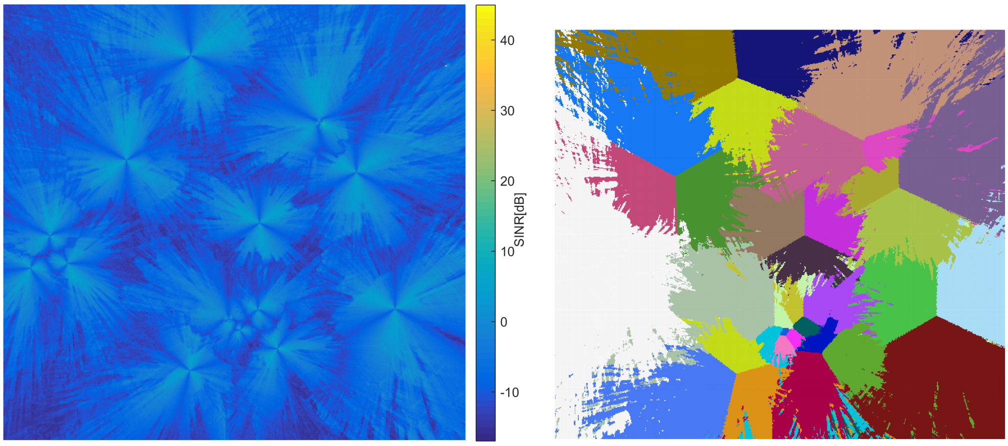
(a) Amsterdam SINR map

(b) Amsterdam best server map



(c) Purmerend SINR map

(d) Purmerend best server map



(e) Friesland SINR map

(f) Friesland best server map

Figure 5: Coverage maps of selected simulation areas for LTE800 band. Note: white pixels in best server maps do not belong to simulated cells; SINR maps were produced assuming maximum interference from nine strongest interferers

4.2.4 *Frequency allocations*

Carrier frequency allocations indicate how much bandwidth is available at certain frequencies for the particular network operator and how an operator chooses to distribute it among different RATs. The summary of frequency bands that are used in simulations of our selected network areas, is presented in Table 6.

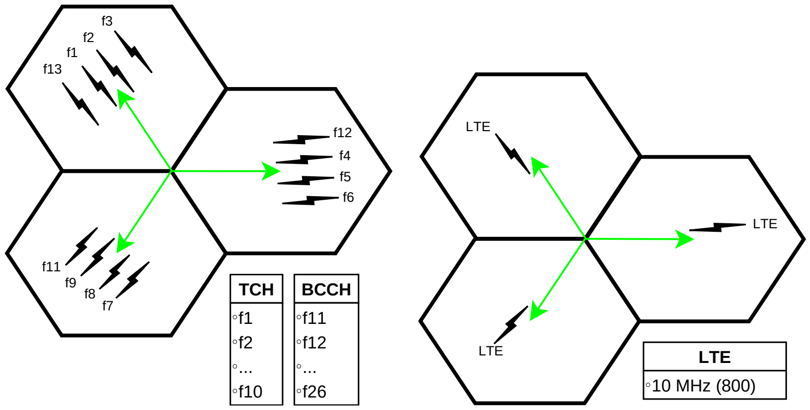
As can be seen, in this thesis model scenario it was chosen to simulate GSM900 and LTE800 bands. Having the information about carrier frequency allocations enables us to realistically model possible radio spectrum reallocation scenarios, bandwidth assignments to MS and, consequently, achievable data rates.

Table 6: Frequency allocations in downlink [MHz]

Frequency band	Bandwidth	BCCH	TCH	Downlink	
				Begin	End
LTE800	10	-	-	811	821
GSM900	5.2	3.2	2	935	940.2

As has already been discussed, this thesis aims to model spectrum reallocation from legacy radio access technologies to modern technologies. That is, spectrum in our work can spatially and temporally be reallocated from 2G to 4G radio interface. The minimum bandwidth that can be reallocated is determined either by RAT that is receiving additional spectrum or by a donor. In GSM-LTE case, LTE has a minimum operating bandwidth of 1.4 MHz while GSM uses fixed 200 kHz carriers. Hence, since GSM has only 2 MHz of spectrum dedicated to TCH channels and we cannot tamper with BCCH-carrying frequency channels as they are critical for cell operation, it is obvious that 1.4 MHz spectrum block is a minimum and altogether a maximum bandwidth that can be reallocated from 2G to 4G in such scenario.

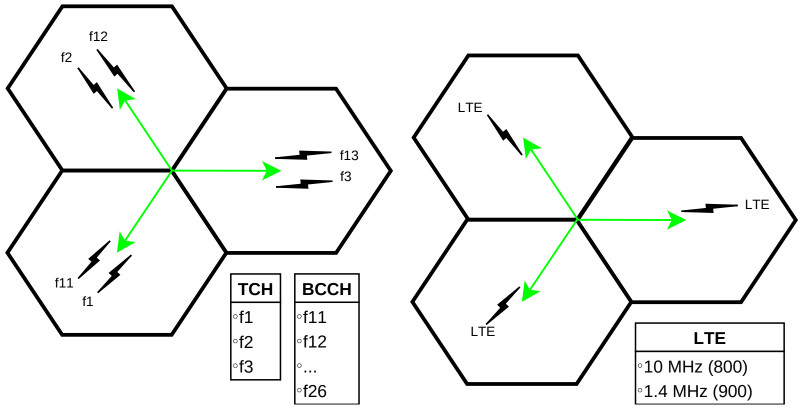
Under normal operating conditions, 2G has ten dedicated TCH carriers ($10 \times 200\,\text{kHz} = 2\,\text{MHz}$) besides the 16 BCCH carriers (3.2 MHz) that are allocated according to a fixed frequency plan. Synthesized frequency hopping is implemented only over TCH carrier space, with MAIO function enabled on each site. This means that the frequency reuse factor for TCH carriers is equal to one and MAIO function makes sure that sectors that make up a single site, don't interfere with each other. I.e., co-channel interference effects within the site are removed by clever timeslot scheduling. This means that each sector at any given moment can use a maximum of three TCH carriers, but frequency hopping is done over all ten carriers (each transceiver goes through each frequency in a hopping list). This is necessary to make sure that no timeslot overlaps within any single site, as each site comprises three sectors ($\lfloor \frac{10}{3} \rfloor = 3$ carriers/sector). A simplistic visualization of such scenario is presented in Figure 6. In the visualization, 2G and 4G spectrum conditions are uniform through all the sectors that comprise a site, but in our model it can also be that each sector has different conditions.



(a) 2G (b) 4G

Figure 6: Default spectrum allocation setup

When part of a spectrum is reallocated (1.4 MHz in our scenario) to LTE, 2G has only three TCH frequency carriers left. Hence, only single TCH carrier is then allowed per sector (besides BCCH), as it ensures that if all three sectors within any single site have spectrum reallocated, still no timeslot overlap would occur. Such situation is visualized in Figure 7. This logic holds despite the possibility of different spectrum reallocation scenarios among sectors within a site. In other words, if spectrum is reallocated within the sector, then 2G transceiver of that sector has only single TCH carrier left which hops over three frequencies, and one fixed BCCH carrier with seven additional timeslots for traffic. The scenarios are summed up in Table 7.



(a) 2G (b) 4G

Figure 7: Reallocated spectrum conditions

Table 7: DSA scenarios per sector

Spectrum state	**2G channels**		**4G spectrum**	
	Sector/Total TCH	**BCCH**	**Dedicated**	**Additional**
Default	3/10	1	10 MHz	-
Reallocated	1/3	1	10 MHz	1.4 MHz

4.2.5 *Session arrival time modeling*

To simulate realistic traffic load, voice call and data session arrival rates from live network were collected for each individual simulated sector and technology for multiple days. From the collected logs, a single working day was randomly chosen and its corresponding logs of each sector and technology were used as described below, to generate call arrival traces for all simulations. This provides us with temporal call distribution over an entire working day over all and every simulated area.

Voice call and data session arrival rates were collected as separate aggregate counters over 15 minute periods for each cell and for 2G and 4G technologies individually. 15 minute logging periodicity was the minimum possible time granularity to collect network traffic logs. Higher granularity is possible only with debugging mode enabled on a BS, however it severely affects the processing unit load and can cause service quality degradation, and hence was not done.

Therefore, when using 15 minute periods, log trace for a full simulation day consists of 96 periods in total. In order to make any use of these values in our simulation, we use a stochastic point process, the Poisson process, to sample individual call arrival instants based on these 15 minute averages over the whole period. In our case it is used for human generated voice and data session inter-arrival time sampling. In general, as Iversen [33] observes, the more complex a process is, the better it is described by the Poisson process.

The inter-arrival times in Poisson process are distributed according to (negative) exponential distribution. This distribution is particularly suitable for communications traffic modeling because of its fundamental characteristic, Markov property, which means a lack of memory (no dependence on the past). The time in seconds between two successive arrivals (inter-arrival time) is expressed as:

$$X_i = T_i - T_{i-1}, \quad i = 1, 2, \dots \tag{1}$$

In case of exponential inter-arrival time distribution, the inter-arrival time is sampled by the following formula:

$$X_i = \frac{ln(1 - F(X_i))}{-\lambda} \quad [\mathrm{s}], \quad i = 1, 2, \dots, \tag{2}$$

where $F(X_i)$ is the probability of observing inter-arrival time lower or equal to X_i at interval $i = 1, 2, \ldots$ given the arrival intensity λ. Arrival intensity λ is expressed as a number of session arrivals per 1 s. Averaged over an area session arrival intensities are presented in the figure below. Therefore, in our simulation we generate inter-arrival times by using the acquired aggregate (over the 15 minute period) session arrival counters to obtain λ parameters and Mersenne Twister pseudorandom number generator to sample $F(X_i)$. By using this mechanism, arrival times for each 15 minute period for voice calls and data sessions were generated for all simulated cellular technologies per each cell and then joined into one continuous session arrival trace over the whole 24 hour period, which represents a selected simulation day.

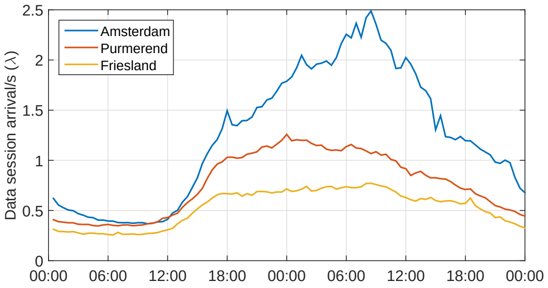


Figure 8: Average 4G data session arrival rate

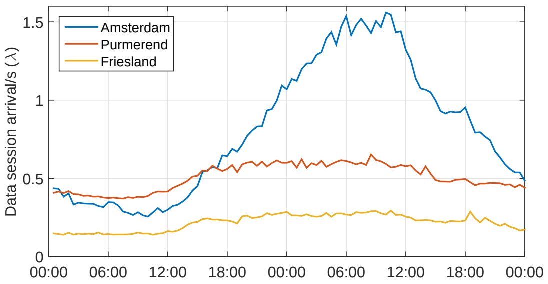


Figure 9: Average 2G data session arrival rate

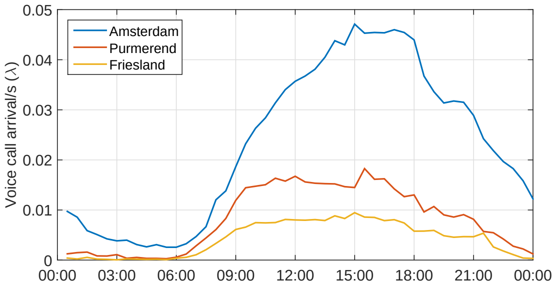


Figure 10: Average voice call arrival rate

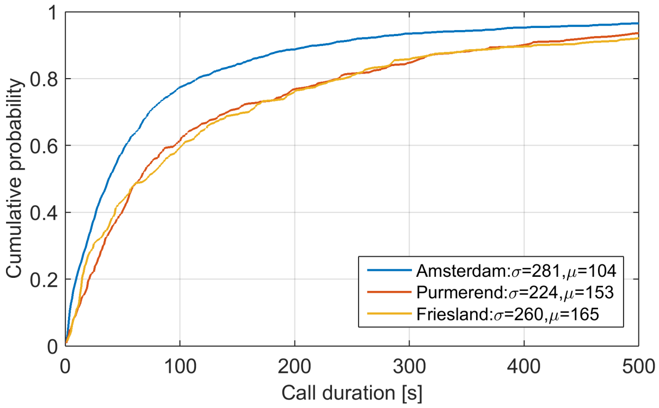
4.2.6 *Service modeling*

Besides voice call and data session arrival rates per technology, service characteristics are necessary in order to have fully specified traffic load models. Service characteristics for voice and data sessions are modeled in terms of voice call duration (holding time in seconds) and session size (in megabits) distributions. These distributions were compiled from real service usage data that was again extracted from logging systems for all three selected areas individually for multiple days. Service models were compiled per each area separately, as service usage behavior differences between Amsterdam city center, Purmerend and Friesland were anticipated. This was later confirmed by processed session size and voice call duration empirical distributions, which are presented in the Figure 11. Data session volume distributions were generated based on measured 15 minute averages. Voice call duration distributions were generated using exact individual call durations acquired from Call Detail Record (CDR) data that was collected at the selected areas.

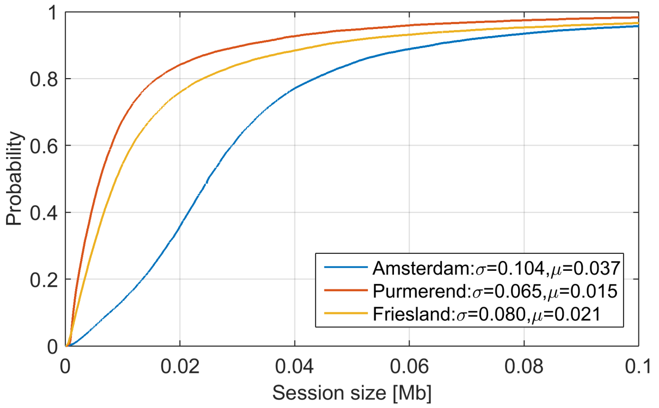
Using these corresponding distributions, each data session or voice call that is generated by the Poisson arrival process, is sampled and gets a random session size (or duration) assigned to it. This way, a trace of session arrivals for an entire day is compiled, including corresponding sizes and durations.

4.2.7 *MS placement and mobility*

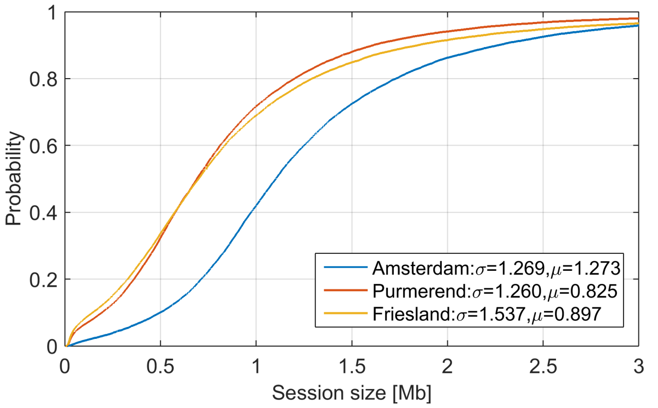
As has already been mentioned, MS geographical placement and mobility within the network area are influential factors when determining end user performance. Typically user concentrations are determined by office building, public venue or large residential building presence. This means that a large portion of users, served by a certain carrier, experience similar signal attenuation characteristics and therefore likely similar communications performance. Moreover, network operators typically design their networks to provide better signal coverage at such hot-spot areas. However, information about MS distribution and mobility at the time when the thesis project was exercised, was not available. The information that we have collected, provided us only with traffic intensities on a cell level. Therefore, simulations use a uniform MS distribution in each simulated cell with their respective time dependent load, and consider no mobility. All MS are considered to be indoors, therefore they experience characteristic indoor signal attenuation, as described in Subsection 4.2.3.



(a) 2G voice call duration distributions for different areas (X-axis limited at 500 s for visual purposes)



(b) 2G data session size distributions (X-axis limited at 0.1 Mb for visual purposes)



(c) 4G data session size distributions (X-axis limited at 3 Mb for visual purposes)

Figure 11: Voice call duration and session size CDFs

4.3 SIMULATION METHODOLOGY

A suitable system level simulator platform was necessary to run the thesis simulation scenarios. After some research, a conclusion was made that there is no accessible simulator available which would have all the necessary simulation capabilities, reasonably low complexity for simulation speed and would accept our input data. Hence, own simulator implementation was inevitable. The simulator for the thesis research purposes was built using MATLAB computing environment. MATLAB was chosen because it provides a vast computational function library, high speed of development and convenient debugging features. Moreover, parts of the script can be converted to compiled C/C++ code for computation time improvement.

Since we had session arrival time and service holding time models based on real data in place, the decision was made to implement an event-based simulation flow. Using the previously described session arrival time and service hold time models, a trace of events for a full 24 hour day was generated for each simulated area independently. A generated trace contains both voice call and data session arrivals for each radio technology. Going through a list, event by event, makes up a simulation time flow.

Each event (session) in a list is associated to a certain cell and to a certain radio technology. Once a time of the session arrival comes, session gets associated with a random propagation map pixel in a cell coverage area which in effect assigns a certain propagation loss value to it. This propagation loss value, as well as propagation loss values for nine strongest interferers, will be used for an entirety of session duration until it departures.

An arrival or departure of any kind of session triggers a system interference state recalculation for all parties that use the same frequency band. Interference and SINR levels change, as well as resource sharing. Such alterations stipulate changes in user achievable bitrates, therefore projected data session departure times must be re-evaluated, session dropping criteria checked, statistical measures logged, etc. During the time when no sessions arrive or depart, system state stays frozen and user achievable bitrates do not change.

4.3.1 *SINR calculation*

Downlink SINR calculation for all radio technologies follows a standard approach. The received power of a signal of interest for a MS is calculated by taking serving transceiver transmit power and applying propagation loss and BPL values. Propagation loss value is taken from the radio wave propagation map and includes all propagation loss effects and BS hardware parameters as discussed previously. BPL is set according to Table 5. The interference power is calculated by taking nine strongest interferers, applying to them the same procedure as to the serving signal and adding them up together. Thermal noise power N is evaluated at the temperature of 290 K.

Hence, SINR for the given MS is calculated according to the following formula:

$$SINR\,[\text{dB}] = 10 \times log_{10}\left(\frac{P_{Tx} \times L_{Tx} \times BPL}{\sum_{i=1}^{9}(\, I_i \times L_i \times BPL) + N \times NF}\right) \qquad (3)$$

Where, in linear units,

- P_{Tx} - transmit power of the MS serving transceiver;
- $\mathrm{L_{Tx}}$ - mean outdoor path loss between the MS and serving transceiver;
- L_i - mean outdoor path loss between the MS and interfering co-channel transceiver i;
- BPL - characteristic building penetration loss (Table 5);
- I_i - co-channel transceiver transmit power for interferer i;
- N - thermal noise;
- NF - user terminal noise factor.

Interference power evaluation methodology for each radio technology will be discussed in Subsection 4.3.2.2.

4.3.2 *2G simulation*

As has previously been introduced, 2G radio cells consist of a number of TCH carriers and a single BCCH carrier. TCH carriers are entirely dedicated to a network traffic (eight time-slots per frame)[3], while the BCCH carrier uses one timeslot for control signaling and has the remaining seven slots available for network traffic. TCH carriers are deployed with frequency reuse factor equal to one, while BCCH carriers have an extensive reuse plan implemented to ensure high quality signal for control signaling.

Traffic that is served using TCH timeslots, has SINR values calculated using the acquired radiowave propagation maps. However, for this thesis project the BCCH frequency reuse plans with propagation characteristics were not acquired. Hence, there is no possibility to evaluate SINR values for traffic that gets timeslots on the BCCH carrier. In such situation, a compromise had to be taken and a decision was made to reserve BCCH timeslots for voice calls only and assume that

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[3] In reality, as presented in Subsection 2.1.1, signaling and empty slots periodically appear on TCH carriers. However, in our simulations they are ignored.

all calls that are served on BCCH carriers, experience sufficient signal quality for an entirety of call duration. This is a safe assumption considering high SINR requirement for BCCH carriers. Voice calls that do not fit onto the BCCH carrier and all data sessions get resources allocated in TCH carrier space. The timeslots that are not occupied on BCCH carrier with voice calls, are left unused and filled with dummy bursts as described in GSM specification. This might cause worse 2G data session QoS during DSA operation than if all BCCH timeslot capacity would be used.

In the simulations of 2G voice service, an implementation of DTX function is assumed. Therefore, whether a voice call dedicated timeslot is occupied by a burst or not, has a probability of 0.5 (listen/talk ratio). This probability is taken into account when calculating interfering powers as will be described in Subsection 4.3.2.2. Co-channel interference is assumed to be non-present between the sectors that belong to the same site due to the MAIO function.

4.3.2.1 *Resource scheduling*

Having two capacity spaces for traffic (TCH and BCCH) with different characteristics, requires a resource scheduling strategy. All simulations that were run during this thesis project, have used the timeslot allocation procedure as presented below.

The resource scheduling algorithm for 2G network traffic has been implemented with a goal to prioritize voice calls, but also have a fraction of capacity reserved for data sessions. Data sessions always get capacity allocated at TCH timeslot space with preemptive priority for voice calls, but with a conditional exception for one carrier as discussed further. Voice calls, as discussed in the beginning of this section, can get timeslot allocations both in BCCH and TCH space. Firstly, depending on the DSA reallocation state, the maximum number of full-rate and half-rate timeslots, available for voice calls in TCH and BCCH spaces, is set as shown in the Algorithm 1 below.

Algorithm 1 Maximum number of TCH slots for voice calls

```
if $SpectrumState = Reallocated$ then
    $MAXvoiceTCHfr \leftarrow 0$
    $MAXvoiceTCHhr \leftarrow 16$
    $MAXvoiceBCCHfr \leftarrow 7$
    $MAXvoiceBCCHhr \leftarrow 14$
else if $SpectrumState = Default$ then
    $MAXvoiceTCHfr \leftarrow 16$
    $MAXvoiceTCHhr \leftarrow 48$
    $MAXvoiceBCCHfr \leftarrow 7$
    $MAXvoiceBCCHhr \leftarrow 14$
end if
```

As can be seen, when spectrum is reallocated, voice calls are not allowed to get full-rate timeslots in TCH space, but only in half-rate mode. This is in order to keep sufficient amount of capacity left for data traffic when spectrum is reallocated and to minimize interference. The similar approach is taken under default spectrum allocation conditions. Voice calls can occupy only 16 full-rate slots (two TCH frequency carriers) in TCH space and one carrier is conditionally reserved for data sessions, and can be occupied by voice calls in half-rate mode only if system would be running out of capacity.

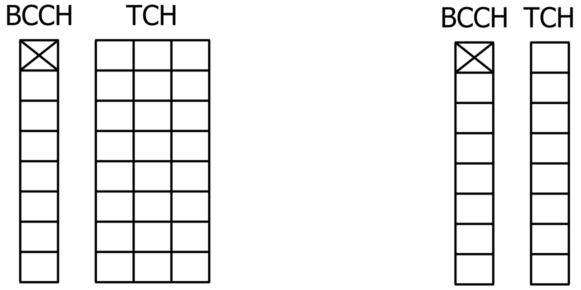
After the maximum timeslot numbers that can be dedicated to voice calls are set, the resource scheduler checks timeslot occupancy in BCCH and TCH spaces, and makes an allocation decision based on the logic shown in Algorithm 2 below. As can be seen, data sessions are always assigned to TCH space and there is no distinction in the type of timeslots allocated. In the simulations it is considered that any data session can use up to 4 timeslots for aggregate downlink channel assignment. The resource scheduler is assumed to operate in Round-Robin manner. Hence, after allocations for voice calls are done, a number of left free TCH timeslots is simply divided by the number of active data sessions and the result (N) is used as an average number of timeslots per data session. As has been stated, this number is limited to 4 timeslots maximum.

Algorithm 2 Timeslot allocation procedure

```
if $ServiceType = Voice$ then
    if $NumVoiceBCCH < MAXvoiceBCCHfr$ then
        $TimeSlot \leftarrow BCCHfr$
    else if $NumVoiceTCH < MAXvoiceTCHfr$ then
        $TimeSlot \leftarrow TCHfr$
    else if $NumVoiceBCCH < MAXvoiceBCCHhr$ then
        $TimeSlot \leftarrow BCCHhr$
    else if $NumVoiceTCH < MAXvoiceTCHhr$ then
        $TimeSlot \leftarrow TCHhr$
    else
        $Blocked$
    end if
else if $ServiceType = Data$ then
    $TimeSlot \leftarrow TCHfr * N$
end if
```

In case of voice calls, the algorithm firstly tries to use full-rate timeslots in BCCH space and then in TCH space. If both run out of full-rate capacity as set by Algorithm 1, timeslots in BCCH space are converted to half-rate mode up to the maximum capacity of 14 and then the same is done in TCH space with up to 48 half-rate timeslots. Such conversions from full-rate to half-rate mode and vice versa are also known as compression/decompression handovers and are done to reduce interference and increase system capacity, as discussed by Müllner et al. [51]. Hence, as implied by the Algorithm 2, timeslots can be occupied in full-rate or half-rate modes[4], and different modes can be used by different sessions at the same time, which depends on how heavily the system is loaded. The full-rate timeslot availability under different spectrum allocation conditions is illustrated in Figure 12.

In case all time-slots are filled with voice calls (62 half-rate timeslots), new voice calls do get blocked. Data sessions, on the other hand, are admitted to the queue, but they do get dropped if they don't achieve a minimum throughput of 3 kbps over a 5 s period.



(a) Default spectrum allocation: 31 FR timeslots

(b) DSA reallocation: 15 FR timeslots

Figure 12: Timeslot availability for 2G traffic

4.3.2.2 *Interference*

The calculation of interference power for the TCH carrier space depends on a particular scenario. Below the expressions, that are used in this thesis simulations, are provided for total interference power on the transmitter side. In further descriptions we will refer to the *serving cell* as to the cell that is affected by interference from neighboring interfering cells, and to an *interfering cell* (interferer) as a cell whose transmission causes interference to the serving cell. The generalized situation, as described, is depicted in Figure 13.

When spectrum in the serving cell is not reallocated, the following calculations are applied:

1. If the interferer is on the same site and does not have spectrum reallocated:

$$I_i\,[mW] = 0$$

Interfering power is equal to zero, because the MAIO function is enabled.

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[4] The necessary timeslot conversions from full-rate to half-rate mode, or vice versa, are handled by the scheduler on every session arrival or departure event during 2G service simulations.

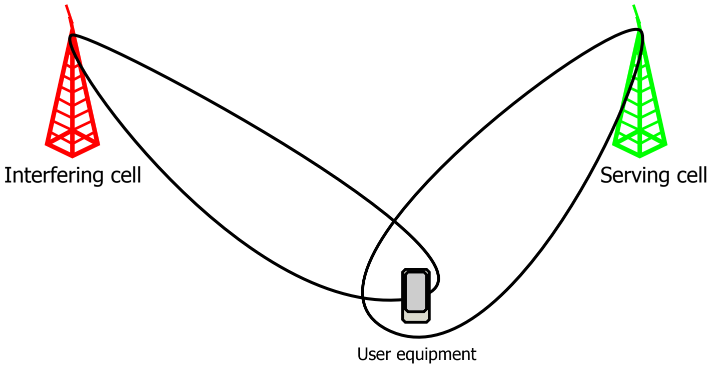


Figure 13: Inter-cell interference in the downlink scenario

2. If the interfering cell is not on the same site and does not have spectrum reallocated:

$$I_i\,[\text{dBm}] = 10 \times log_{10}\left(P_{Tx}^{2G} \times \frac{N_{used2G}}{N_{total}}\right) \tag{4}$$

   where P_{Tx}^{2G}=20 000 mW, N_{used2G} denotes the number of time slots carrying traffic and can be fractional in case half-rate voice call slots are used. N_{total} denotes the total number of slots in a cell designated for 2G traffic transmission (including all frequency carriers in the hopping list). A downlink interference caused by a 2G interferer to a 2G serving cell, is expressed as a ratio of N_{used} over N_{total}. This expression is valid due to the frequency hopping function used in 2G networks, which effectively randomizes timeslot allocations between the sites. Hence, only by chance it can happen that the same timeslot on the same frequency carrier, at the same time is used.

3. If interfering cell has spectrum reallocated and both parts (the remaining TCH part and the one dedicated to LTE) are used:

$$I_i\,[\text{dBm}] = 10 \times log_{10}\left(P_{Tx}^{2G} \times \frac{N_{used2G}}{80} + \frac{P_{Tx}^{LTE1.4}}{7} \times \frac{N_{usedLTE1.4}}{80}\right)$$

   where N_{used2G} denotes the number of TCH timeslots used by 2G when spectrum is reallocated, which can be equal to up to eight timeslots. The fraction on the right side represents interference power caused by reallocated spectrum that is used by LTE. The reallocated spectrum is equal to 1.4 MHz or seven 2G carriers ($N_{usedLTE1.4}$=56 timeslots). Since LTE uses entire bandwidth whenever transmitting any data, it is assumed that interference equals to as if all 56 timeslots are occupied. LTE power is additionally divided by seven, because spectral power density of LTE on 1.4 MHz band is seven times lower than 2G, or expressed in terms of power spectral density: $PSD^{LTE1.4} = \frac{PSD^{2G}}{7}$. This is because 2G uses 43 dBm transmit power per 200 kHz carrier and LTE uses the same power for 1.4 MHz carrier. N_{used2G} and $N_{usedLTE1.4}$ are determined based on user activity and can be expressed as:

$$N_{used2G} = \begin{cases} N_{used2G} & N_{usersActive2G} > 0 \\ 0 & N_{usersActive2G} = 0 \end{cases}$$

$$N_{usedLTE1.4} = \begin{cases} 56 & N_{usersActiveLTE1.4} > 0 \\ 0 & N_{usersActiveLTE1.4} = 0 \end{cases}$$

where $N_{usersActiveLTE1.4}$ and $N_{usersActive2G}$ denote the number of active users in the reallocated 1.4 MHz band and in 2G respectively. N_{used2G} is determined by summing up the used timeslots by the active users after resource scheduler makes allocations to voice calls and data sessions, and DTX function is applied.

4. If interfering cell is not within the boundaries of simulated area, it is assumed that it is a cell that operates under ordinary conditions (spectrum not reallocated) and its power is expressed as:

$$I_i\,[\text{dBm}] = 10 \times log_{10}\left(P_{Tx}^{2G} \times \alpha\right) \tag{5}$$

where α denotes a (fixed) fraction of timeslots used in a simulated cell on average (throughout the entire simulated day) and is determined by running 'warm-up' simulations.

When spectrum in the serving cell is reallocated to LTE, the following calculations are applied:

1. If interfering cell is on the same site and also has spectrum reallocated:

$$I_i\,[mW] = 0 \tag{6}$$

2. If interfering cell does not have spectrum reallocated, then formula (4) is used with N_{total} equal to 80, because interferer performs frequency hopping over 10 carriers, and $0 \leq N_{used2G} \leq 24$.-

3. If interfering cell is not on the same site and has spectrum reallocated, then formula (4) is used with $N_{total} = 24$ and $0 \leq N_{used2G} \leq 8$.

4. If interfering cell is not within the boundaries of simulated area, the formula (5) is applied.

These calculations are applied to the nine strongest interferers, and after propagation losses are added and powers are summed up in linear scale, total resulting interference power at a MS is obtained. For visualization purposes, to better grasp the presented expressions, a hypothetical interference situation under reallocated spectrum conditions is depicted in the Figure 14. In the figure, the grid represents time and frequency domain divisions by timeslots as used in 2G technologies. The green part denotes 4G spectrum occupancy in time and frequency domains, the yellow grid denotes the same for 2G, and the red grid denotes the part that is used by both technologies and where interference occurs. This is a particular situation when spectrum in one cell is reallocated and used by both technologies (2G and 4G), while in other cell it is is not and entire frequency band is used for frequency hopping by 2G.

As has been explained, SINR calculations in the simulations of this thesis are not done for BCCH carriers, therefore interference power for them does not need to be calculated.

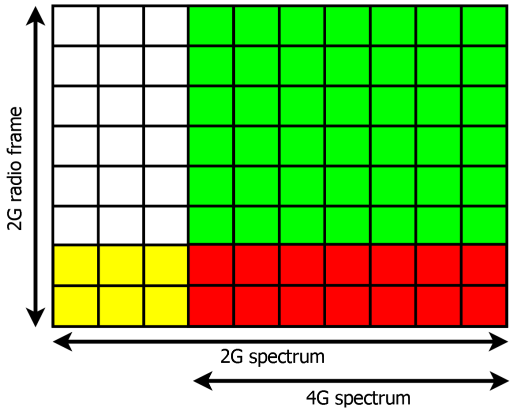


Figure 14: Hypothetical 2G-4G interference scenario under reallocated spectrum conditions

4.3.2.3 *Bitrate estimation*

Data sessions during 2G simulation are handled by GPRS and EGPRS radio access technologies. The amount of traffic handled by each technology is not even. Based on the collected network traffic data, the ratios were found and are presented in Table 8. These ratios are preserved during simulations by randomly, with a set probability, assigning session arrivals to an according technology.

Table 8: GPRS and EGPRS traffic load ratios [%] for different areas

Area	**GPRS**	**EGPRS**
Amsterdam	2	98
Purmerend	12	88
Friesland	3	97

In order to estimate a user achievable bitrates for data sessions, a link-to-system level interfaces are necessary. SINR to throughput mapping curves, as presented in Figure 15, will be used for this purpose. Throughput mapping represents achievable throughput per single timeslot, hence in case of multiple slots being used, mapped value must be multiplied by the number of used timeslots. The curves are replicated from Subsection 7.1.4.3 by Halonen et al. [26] and represent frequency hopping conditions with ideal link adaptation.

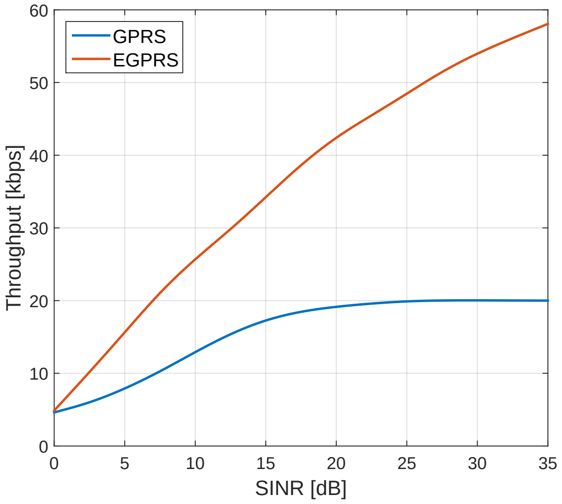


Figure 15: Frequency hopping GPRS and EGPRS throughput vs. SINR mapping with incremental redundancy

4.3.2.4 *2G summary*

Environment	Urban, suburban & rural
Type of users	Indoor
Traffic type	CS voice & PS data
Multi-slot capability	4 receive slots
User distribution	Uniform
Traffic load	Time varying, based on collected logs
Session size or duration	Empirical distribution based
Time-scale	Event-based
Mobility	No
Multipath fading	Averaged
Propagation modeling	KPN proprietary
Scheduler	Round-Robin
$\mathbf{P}_{Tx}^{2G}$ **/200 kHz**	43 dBm
$\mathbf{P}_{Tx}^{LTE1.4}$ **/1.4 Mhz (200 khz)**	43 dBm (34.5 dBm)
$\mathbf{N}_{\mathbf{TRX}}$**/Sector**	3
FH list length	10
Cell layout, antennas, etc.	Real network based
DTX	Yes (factor of 0.5)
MAIO	No intra-site co-channel interference
Cell selection	Propagation loss based
Carrier frequency	900 MHz
MS Noise figure	9 dB
Data session dropping criteria	<3kbit/5s

4.3.3 *4G simulation*

Simulation of LTE requires only data sessions to be simulated and is much more simplistic than 2G. Resource sharing is assumed to be done in Frequency Domain Packet Scheduling (FDPS) manner. Simplified FDPS modeling is implemented by adding a 2.1 dB gain to session SINR in order to model multi-user diversity gains from channel-adaptive scheduling, which roughly corresponds to 40% throughput gains reported by Holma and Toskala [29] when using FDPS in LTE under low MS velocities. A simplistic 2x2 MIMO antenna modeling is used which is described further. The simulated LTE sessions (users) can use both, the default 10 MHz and the reallocated 1.4 MHz, bands to benefit from an aggregate throughput. However, one or none of them can be used too, which depends on the experienced SINR values on the particular band. Resource sharing is done per each band separately.

The buffer for sessions is assumed to be infinite, hence LTE sessions cannot get blocked. However, a session dropping function is implemented which drops sessions that achieve less than 300 kbit/s throughput over a 5 s period.

4.3.3.1 *Interference*

SINR and interference power calculations are done in a similar manner, as in 2G. Interference power on the transmitter side, caused by an interferer to users in a serving cell, is expressed as the following, considering first the 10 MHz carrier:

1. If interfering cell is simulated:

   $$I_i\,[\mathrm{dBm}] = 10 \times log_{10}\left(P_{Tx}^{LTE10}\right)$$

   where

   $$P_{Tx}^{LTE10}\,[\mathrm{mW}] = \begin{cases} 40000 & N_{usersActiveLTE10} > 0 \\ 0 & N_{usersActiveLTE10} = 0 \end{cases}$$

   and $N_{usersActiveLTE10}$ denotes the number of active users on the LTE 10 MHz carrier.

2. If interfering cell is not within the boundaries of simulated area, it is assumed that it is a cell that operates under ordinary conditions (spectrum not reallocated) and its power is expressed as:

   $$I_i\,[\mathrm{dBm}] = 10 \times log_{10}\,(40000 \times \alpha)$$

   where α denotes a fraction of time, on average throughout the entire simulated day, that a transmitter is active and is determined by running 'warm-up' simulations.

If a serving LTE cell has additional spectrum allocated, then the interference power is estimated as follows:

1. If interference comes from a 2G cell that has no spectrum reallocated, then interfering power is calculated as:

   $$I_i\,[\mathrm{dBm}] = 10 \times log_{10}\left(7 \times P_{Tx}^{2G} \times \frac{N_{used2G}}{N_{total}}\right)$$

   where P_{Tx}^{2G}=20 000 mW, N_{used2G} denotes the number of time slots carrying 2G traffic and can be fractional in case half-rate voice call slots are used. N_{total} denotes the total number of slots in a cell designated for 2G traffic transmission (including all frequency carriers in the hopping list). Power in linear scale is multiplied by seven, due to higher spectral power density of 2G.

2. If interference comes from LTE operation on reallocated band:

$$I_i\,[\text{dBm}] = 10 \times log_{10}\left(P_{Tx}^{LTE1.4}\right)$$

where

$$P_{Tx}^{LTE1.4}\,[\text{mW}] = \begin{cases} 20000 & N_{usersActiveLTE1.4} > 0 \\ 0 & N_{usersActiveLTE1.4} = 0 \end{cases}$$

and $N_{usersActiveLTE1.4}$ denotes the number of active users in LTE 1.4 MHz band.

3. If interfering cell is not simulated, but is among nine strongest interferers for a particular cell, then an ordinary 2G cell is assumed and its interference power is set as:

$$I_i\,[\text{dBm}] = 10 \times log_{10}\left(7 \times P_{Tx}^{2G} \times \alpha\right)$$

where α denotes a (fixed) fraction of timeslots used in a simulated cell on average (throughout the entire simulated day) and is determined by running 'warm-up' simulations, $P_{Tx}^{2G} = 20000\,[\text{mW}]$. Power in linear scale is multiplied by seven, due to higher spectral power density of 2G.

4.3.3.2 *Bitrate estimation*

A link-to-system interface for LTE bitrate estimations is used, that is a combination of baseline Evolved-UTRA (E-UTRA) model described in Annex A.1 of [42] and Bell Laboratories Layered Space-Time (BLAST) 2x2 MIMO antenna scheme described by Mogensen et al. [50]. The resulting formulas, used to approximate the throughput over a channel with a given SINR, when using link adaptation, are the following:

$$R\,[bps] = \begin{cases} 0 & SINR < SINR_{min} \\ B \times \alpha \times log_2\,(1 + SINR) & SINR_{min} < SINR < 10.5 \\ 2 \times B \times \beta \times log_2\,(1 + SINR - \gamma) & 10.5 < SINR < SINR_{max} \\ B \times Thr_{max} & SINR > SINR_{max} \end{cases} \tag{7}$$

where:

- R – bitrate [bps];
- B – bandwidth [Hz];

Table 9: Parameters describing 2x2 MIMO LTE link level performance

Parameter	Downlink	Comment
α	0.6	System BW efficiency [42]
β	0.56	System BW efficiency [50]
γ [dB]	6.02	SINR efficiency [50]
$SINR_{min}$ [dB]	-7.5	Based on section 7.1.7.2 of [7]
$SINR_{max}$ [dB]	25.5	Based on section 7.1.7.2 of [7]
Thr_{max} [b/s/Hz]	7.3	Based on $SINR_{max}$

- α – attenuation factor, representing implementation losses: bandwidth efficiency, cyclic prefix, pilot overhead, dedicated and common control channels;
- β – attenuation factor used with MIMO;
- γ– SINR efficiency [dB];
- $SINR_{min}$ – minimum SINR of the codeset [dB];
- Thr_{max} – maximum spectrum efficiency of the codeset [b/s/Hz];
- $SINR_{max}$ – SINR at which maximum throughput is achieved [dB].

Chosen parameter values are listed in Table 9. $SINR_{min}$ and $SINR_{max}$ values are determined using section 7.1.7.2 of 3GPP technical specification 36.213 [7]. $SINR_{min}$ value is determined by assuming Modulation and Coding Scheme (MCS) 0 and looking up Transport Block Size (TBS) table for single spatial layer channel, as the Shannon curve used in our LTE simulations uses the Single Input Multiple Output (SIMO) model in lower SINR range. $SINR_{max}$ value is determined by assuming MCS 28 and looking up TBS table for two spatial layer multiplexing channel. Resulting spectrum efficiency, depending on an SINR, is presented in Figure 16. Bitrate is calculated for 1.4 MHz and 10 MHz carriers individually, depending on DSA state.

4.3.3.3 *4G Summary*

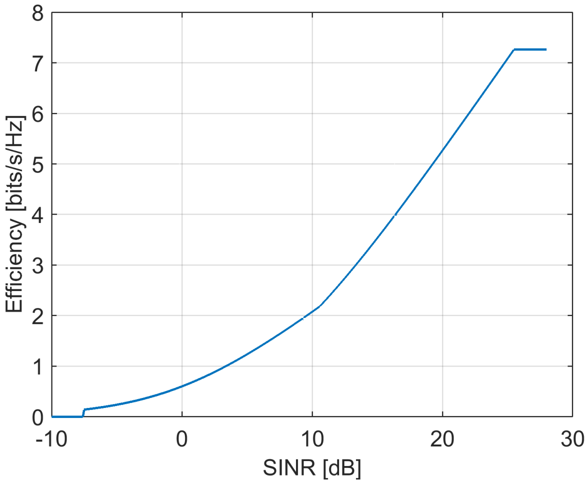


Figure 16: LTE 2x2 MIMO spectral efficiency

Environment	Urban, suburban & rural
Type of users	Indoor
User distribution	Uniform
Traffic load	Time varying, based on collected logs
Session size or duration	Empirical distribution based
Time-scale	Event-based
Mobility	No
Multipath fading	Averaged
Propagation modeling	KPN proprietary
$\mathbf{P}_{Tx}^{LTE10}$	46 dBm
$\mathbf{P}_{Tx}^{LTE1.4}$	43 dBm
Bandwidth	10 MHz
Additional bandwidth (DSA)	1.4 MHz
Cell layout, antennas, etc.	Real network based
Scheduler	FDPS
Cell selection	Propagation loss based
Carrier frequency	800 MHz
MS Noise figure	9 dB
Dropping criteria	<300kbit/5s

4.3.4 *Load prediction*

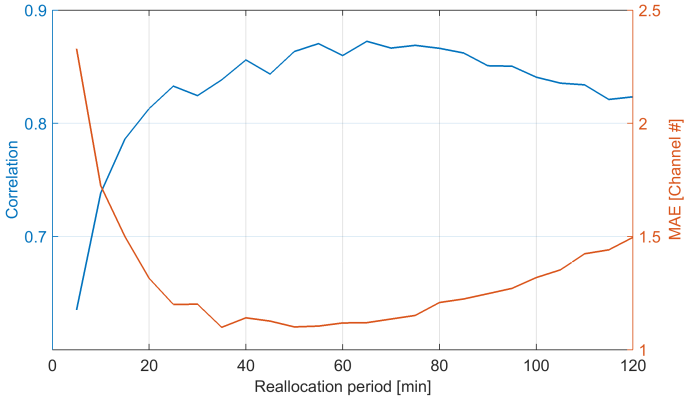
As has been mentioned, in order for DSA algorithm to work, a load prediction algorithm is necessary. In report by Leaves and Huschke

[46], linear and exponential regression approaches are chosen in combination with historical load, to predict traffic load during an upcoming DSA period. In the simulations of this thesis, however, the decision was made to use a naive approach for predictions - a moving average of order 1. I.e., traffic load during the next period is assumed to be the same as during the previous one. It was done so, because time series prediction problem is considered to be an ample topic, which for the case of network traffic load could be investigated in a separate project.

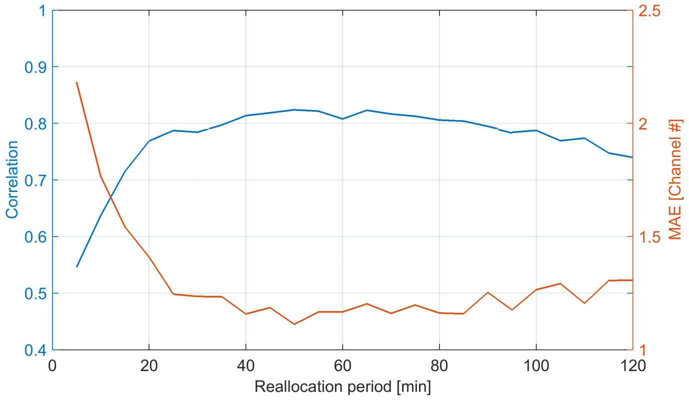
Since spectrum in DSA model of this thesis is temporally and spatially reallocated from 2G to 4G, load predictions have to be done for 2G traffic only. Reallocation decisions were chosen to be done based on voice call traffic only, and leaving data traffic as a best effort service. The number of voice calls observed during the last period, together with historical voice call duration average, are used as an input to Erlang B formula to find the number of full-rate channels necessary to handle the predicted traffic during the next period. An algorithm used to evaluate the number of channels needed to serve the predicted traffic load is taken from work by Qiao and Qiao [55]. The maximum allowed blocking probability, used in the calculations, is equal to 0.005 and is based on KPN network setup.

As was introduced in subsection 4.3.2.1 on page 44, after spectrum is reallocated from 2G to 4G in this thesis model scenario, 2G is left with one BCCH and one TCH carrier. The decision to reallocate spectrum is done when predicted voice call traffic during the next period requires seven or fewer full-rate channels. I.e., all voice call traffic must be able to be served using full-rate mode on BCCH carrier, and TCH carrier is left for data. Validation of our prediction model, using averaged Mean Absolute Error (MAE) and correlation estimations over all cells in selected areas, shows promising accuracy, as presented in Figure 17.

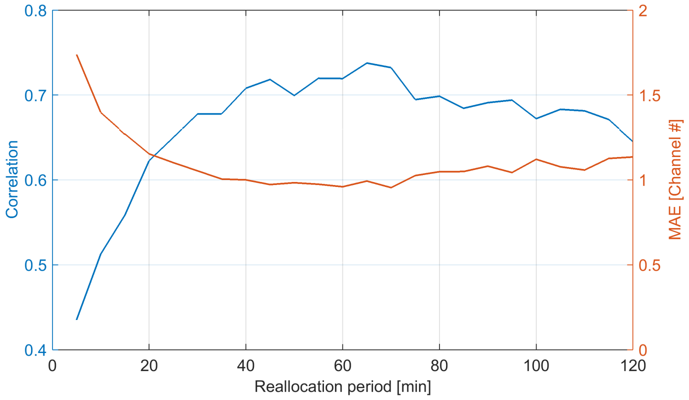
The prediction algorithm appears to perform best when the reallocation period duration is around 1 hour, which shows average MAE of around 1–1.5 channels through different areas. This error can be negative or positive, i.e. prediction can underestimate or overestimate the required number of channels. Overestimation has a negative effect of spectrum being potentially not reallocated. Underestimation would have a more severe effect, since traffic can potentially experience worse GoS. Moreover, observing more active calls than predicted, can be a consequence of ongoing calls that started in the previous period too. However, in such situation the underestimation consequences can be avoided by allocating voice call with a half-rate timeslot. This means that the prediction algorithm can effectively have an error margin of seven channels (BCCH has seven timeslots) with the only consequence being that voice calls would possibly experience lower voice quality. However, such a huge error is not likely on average, as our validation shows a maximum averaged error of less than roughly 2.3 channels in extreme cases. In case of extreme underestimation, simulator allows voice calls to get channels allocated in TCH space too.



(a) Amsterdam



(b) Purmerend



(c) Friesland

Figure 17: Voice call load prediction accuracy

4.3.5 *Key performance indicators*

Performance evaluation for data calls is done by measuring average throughput and 10th user throughput (cell-edge) percentile. Data calls can get dropped if the average throughput that they experience is too low, hence dropping counters are used too. Blocking counters for data calls are not used, as infinite session buffer is assumed. Voice call performance is evaluated by measuring the total time that they spend with SINR below 9 dB. A threshold of 9 dB has been set based on Halonen et al. [26], where it is stated that this threshold is normally chosen because below it a poor speech quality would be obtained. The percentage of total voice call time spent in half-rate mode is measured too, as it can indicate poor speech quality under low SINR conditions. Due to a limited number of timeslots in 2G system, voice calls can get blocked, hence blocking counters are used.

5

RESULTS

To answer the research questions and gain insight into DSA performance, it was determined to run multiple simulation runs per each area, with DSA period length kept as a variable. Two different period durations have been simulated: 5 and 30 minute length, as well as a refarmed spectrum version. Moreover, two different traffic loads have been used: base load (as acquired from the network traffic logs) and base LTE load increased by a factor of four in case of rural and suburban areas, and by a factor of two in case of urban area. Load has been increased by multiplying both the number of sessions and their size distributions by a square root of the increase factor, as an increase in the number of sessions and their size is anticipated. 2G load was kept unchanged. Such scenario was chosen to imitate traffic growth of 4G in the future, with 2G remaining a relevant technology. The load increase factors were chosen based on anticipated capacity limits of the cells and to keep simulation time within reasonable bounds. The number of call arrivals (events) simulated in each area, is summarized in Table 10.

Table 10: Number of calls simulated in different areas

Load	Urban		Suburban		Rural	
RAT	Base	2x	Base	4x	Base	4x
4G data	2.7M	3.8M	1.7M	3.4M	1.6M	3.2M
2G data	1.7M	1.7M	1.1M	1.1M	0.7M	0.7M
2G voice	50k	50k	17k	17k	12k	12k

5.1 SERVICE USAGE BEHAVIOR

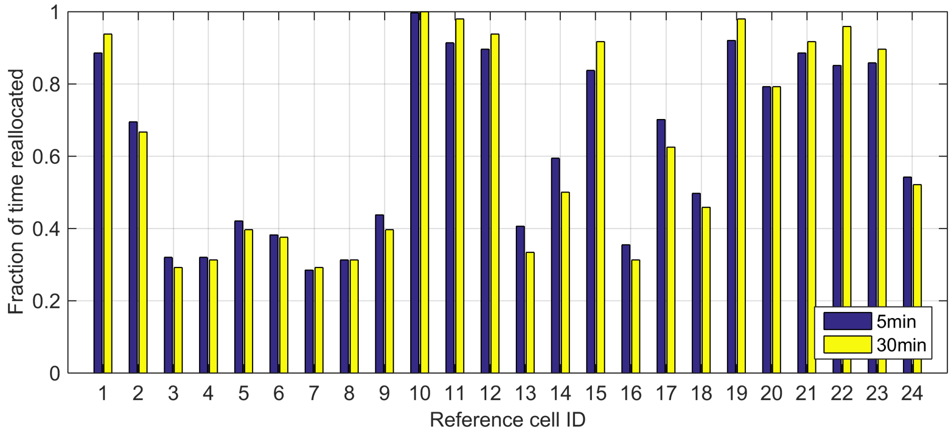
By looking at the compiled service usage distributions presented in Section 4.2.6 that are used for simulations, some significant differences between service usage behavior in different areas are visible. However, we can only speculate from where do these differences stem. If we look at the call duration distributions, it can be seen that average call duration in Amsterdam is roughly one minute shorter than in Friesland or Purmerend. This might be due to the fact that in the city center of Amsterdam the larger portion of users is youth, who nowadays heavily use packet data based messaging applications for all sorts of conversations, and voice calls are made only on spontaneous, important events, and therefore are shorter. Another reason can be related to the fact that the simulated area is crowded with tourists, who also often need to make a call, but their conversations might be much shorter due to their own efforts to keep it short and save money on more expensive roaming call. And tourists are on vacation, hence less business to talk about. When comparing data session size distributions, the tendency is opposite - Amsterdam users are roughly twice as heavy users of 2G and 4G data services. This is again likely related to the average user age differences between the areas, with younger people being more heavy users of mobile applications, video streaming, photo browsing, etc.

5.2 SPECTRUM REALLOCATION OPPORTUNITIES

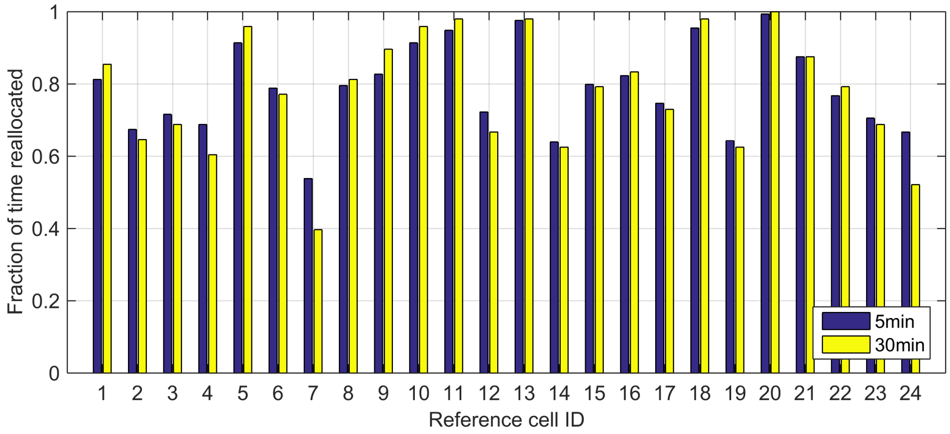
In order to answer the question whether there are any differences in the number of spectrum reallocation opportunities among the selected areas, the fraction of time that each cell spends with spectrum being reallocated based on our algorithm, was calculated over a full simulation day (24 h). The results are presented in the Figure 18.

The first observation is that there are no evident differences in reallocation opportunities between the two DSA period durations tested. The fraction of time that spectrum is reallocated with different period durations varies from cell to cell. Secondly, the number of opportunities over all cells significantly varies between the selected areas, with urban environment (Amsterdam) having least and rural environment (Friesland) having most opportunities for spectrum reallocation, and suburban (Purmerend) in between. This observation is better illustrated by the overall reallocation time fractions presented in the Figure 19. Such outcome is purely due to a larger number of voice calls (Table 10) made in urban area than in suburban or rural areas, as our reallocation decision algorithm takes into account predicted number of voice calls only. As third observation, it can be noted that big differences in fraction of time that spectrum can be reallocated exist even within the areas. This means that big differences in load exist from cell to cell, and each cell can have a unique situation.

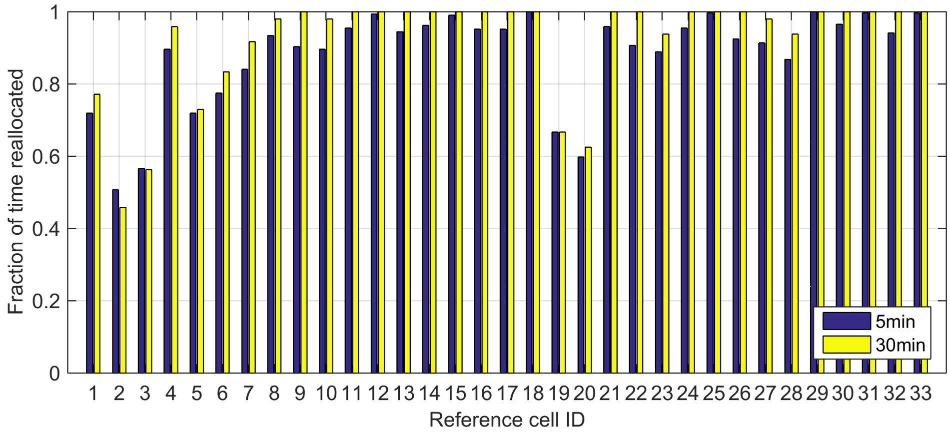
Hence, the acquired results create a strong case for temporal and spatial spectrum reallocation and confirm the claims of 3GPP as presented in the introduction.



(a) Amsterdam



(b) Purmerend



(c) Friesland

Figure 18: Spectrum reallocation opportunities in different areas

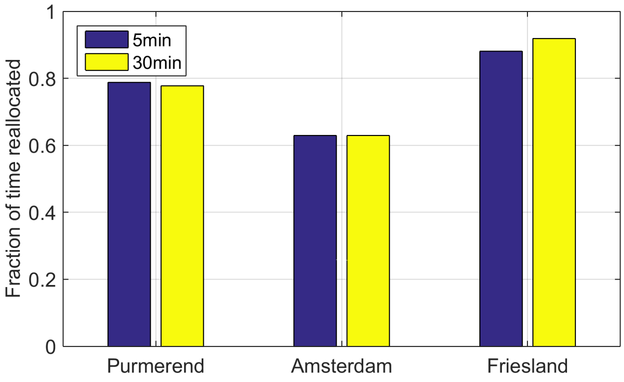


Figure 19: Overall reallocation time fractions for different areas.

5.3 PERFORMANCE EVALUATION

Performance evaluation results for simulated technologies are presented next. The 10th user throughput percentile and average throughput for different setups are plotted for the period of full simulation day. The metrics are presented as averages over a whole simulation area. In addition, the worst performing cell in each area during the selected busy hour (16:30-17:30) is presented in separate figures, to showcase the effects on performance in worst case busy-hour conditions. Session dropping (if evident) and voice call quality indicators over the whole areas are included too.

5.3.1 *Urban area (Amsterdam)*

The simulation results presented in Figures 20 and 21 show evident LTE gains in average throughput and 10th user throughput percentile, when using DSA or having spectrum refarmed under both traffic load scenarios. However, LTE gains from DSA, when compared to spectrum refarming, are limited during busy hours of the day, as increasing number of voice calls limits the number of spectrum reallocation opportunities.

The performance of 2G data sessions shows a clear advantage of DSA over the spectrum refarming during the daytime. While both performance indicators follow the same trend over an entire day under default spectrum allocation conditions and when using DSA, spectrum refarming shows significant detrimental influence on the same metrics and especially during working hours. The 10th user throughput percentile declines by over 25% and 70% on average over the full day and during busy hour accordingly. The average throughput, accordingly, declines by 10% and 40%. The negative effect of spectrum refarming on 2G user throughput is also indicated by appearing session droppings and extensive half-rate timeslot usage for voice calls.

SINR levels appear to be slightly improved by spectrum refarming, but this is due to a more extensive BCCH carrier usage, as more calls are compressed into BCCH timeslots as a consequence of inaccurate voice call traffic predictions.

Average throughput and 10th user throughput percentile over the full day and area for LTE are respectively improved by around 5% and 8% under base load conditions and by around 8% for both metrics under increased load conditions.

The selected 2G-4G sector pair under base load conditions shows that gains from DSA during the busy-hour are negligible, with only 30 min DSA period showing a roughly 2% gains in average throughput and 10th user throughput percentile. Almost no effect on the throughput performance is observed for 2G data sessions too. These observations mean that the number of voice calls during busy hour is high and therefore there are no opportunities for spectrum reallocation. Hence, neither LTE gets any benefit, nor 2G experiences any detrimental effects. Spectrum refarming, as expected, provides highest gains for LTE and highest detrimental effects on 2G data sessions, as well as voice calls, as indicated by extensive half-rate timeslot usage.

Similar effects are visible under increased load conditions as presented in Figure 21. The only difference in this scenario, is that increased LTE load introduces session dropping. The full-day/area-wide session dropping statistics show that session dropping is effectively reduced by about half when using DSA and it completely disappears when spectrum is refarmed. During the busy hour in the selected cell, both DSA and spectrum refarming are able to avoid session droppings. Hence, while DSA has little effect on throughput performance, it is still capable of notably improving the GoS.

With respect to DSA period length, no evident differences in the overall performance can be seen from the 5 minute and 30 minute DSA simulation runs. In urban area's case, it is evident that spectrum refarming is not an option due to high detrimental effects on 2G data session throughputs and voice call quality. DSA on the other hand, shows clear advantage, as detrimental effects on 2G data session throughputs are only up to few percent and no effect on voice call quality is evident.

5.3.2 *Suburban area (Purmerend)*

Performance results for suburban area are presented in Figures 22 and 23. It is evident that under both load scenarios spectrum refarming and DSA are able to improve LTE performance both on average over the full day and during the busy hour. The average LTE throughput increase over the full day and area when using DSA and spectrum refarming is respectively 7% and 13% under base load, and 10% and 20% under increased load conditions.

The influence on the performance of 2G data sessions is negligible, as a degradation of only up to around 1.5% under base load scenario and up to around 2% under increased load is evident, which holds even when spectrum refarming is used. However, spectrum refarming increases half-rate timeslot usage, with the voice call time fraction of around 2% over the full day and area, and around 27% during the busy hour in a selected worst performing cell under both traffic load conditions. No voice call time below the 9 dB margin have been logged under any scenario. Spectrum refarming under base load conditions during busy hour appears to cause less detrimental effect on 2G 10th user throughput percentile than DSA. The same is visible under increased load for 2G average user throughput. However, these counterintuitive results can be attributed to limited simulation accuracy, as the absolute result difference is in the order of a fraction of a percent.

Under base load conditions, no significant differences are evident between the 5 minute and 30 minute DSA period performance. Under increased load conditions, 5 minute period duration tends to bring higher LTE throughput gains and altogether higher detrimental effects on 2G performance. However, in all scenarios spectrum refarming brings about twice the improvement of DSA, with around the same detrimental effect on 2G data session performance.

In suburban area's case it is evident that due to a low 2G data traffic load, almost no detrimental effect on 2G session throughput is evident both when using DSA or having spectrum refarmed. Voice call quality when spectrum refarming is done, experiences degradation, as half-rate timeslot usage appears which is more extensive during the busy-hour. Hence, with additional consideration regarding half-rate timeslot usage impact on voice call quality, an operator could choose spectrum refarming to improve spectrum usage efficiency.

5.3.3 *Rural area (Friesland)*

Performance results for rural area are presented in Figures 24 and 25. Average throughput and 10th user throughput percentile performance behavior over a full simulated day under both traffic load conditions is similar to the suburban area. The average LTE throughput increase over the full day and area when using DSA and spectrum refarming is respectively 8% and 13% under base load, and 18% and 25% under increased load conditions.

The influence on the performance of 2G data sessions is low, as a degradation of only up to around 5% under both load scenarios is evident, which holds even when spectrum refarming is used. Spectrum refarming causes a more noticeable half-rate timeslot usage when measured over a full day and area. No voice call time below the 9 dB margin is logged under any scenario. Spectrum refarming under base load conditions during busy hour appears to cause less detrimental effect on 2G data session throughputs than DSA. The same is visible under increased load for 2G average busy hour user throughput. For the same metric, a counterintuitive result of DSA with 30 minute period is observed, where 2G throughput is improved. However, these counterintuitive results can be attributed to limited simulation accuracy, as the absolute result difference is in the order of a fraction of a percent. Moreover, this can be explained by the likely interference reduction in 2G TCH space once spectrum is reallocated, as voice calls dominate resource usage and more voice calls are packed into BCCH space, leaving TCH space less occupied and creating less interference. Also, LTE operation using the reallocated 2G spectrum creates less interference to neighboring 2G cells, as spectral power density of LTE using 1.4 MHz bandwidth is seven times lower than of 2G.

With respect to DSA period length, no evident differences in the overall performance can be seen from the 5 minute and 30 minute DSA simulation runs under both load conditions. As in suburban area, due to low 2G data traffic, little detrimental effect on 2G throughput is evident both when using DSA or having spectrum refarmed. Voice call quality, when spectrum refarming is done, experiences slight degradation, as half-rate timeslot usage is more visible over the full day and area. Hence, with additional consideration regarding half-rate timeslot usage impact on voice call quality, an operator could choose spectrum refarming to improve spectrum usage efficiency, as in the case of suburban environment.

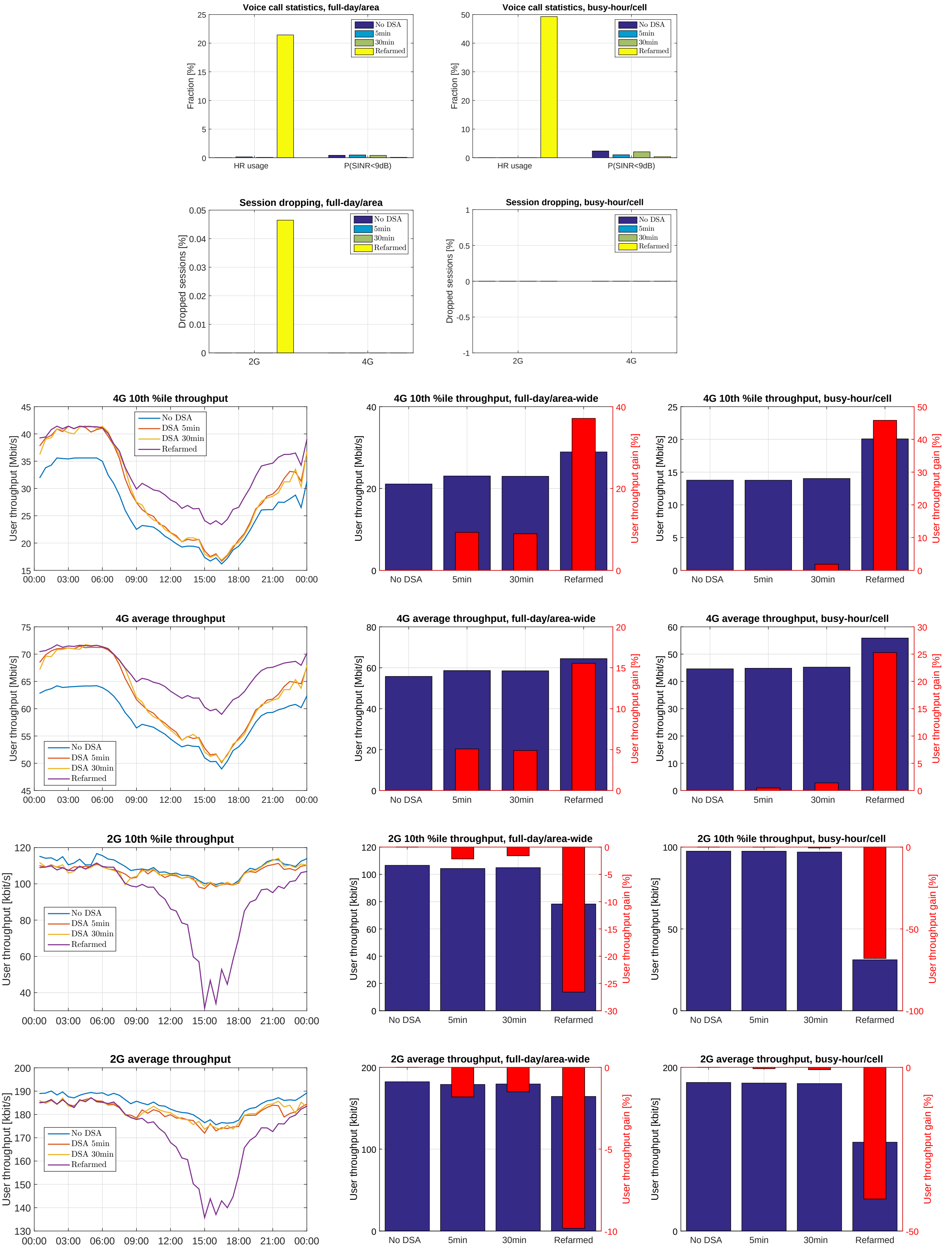


Figure 20: Amsterdam: base load

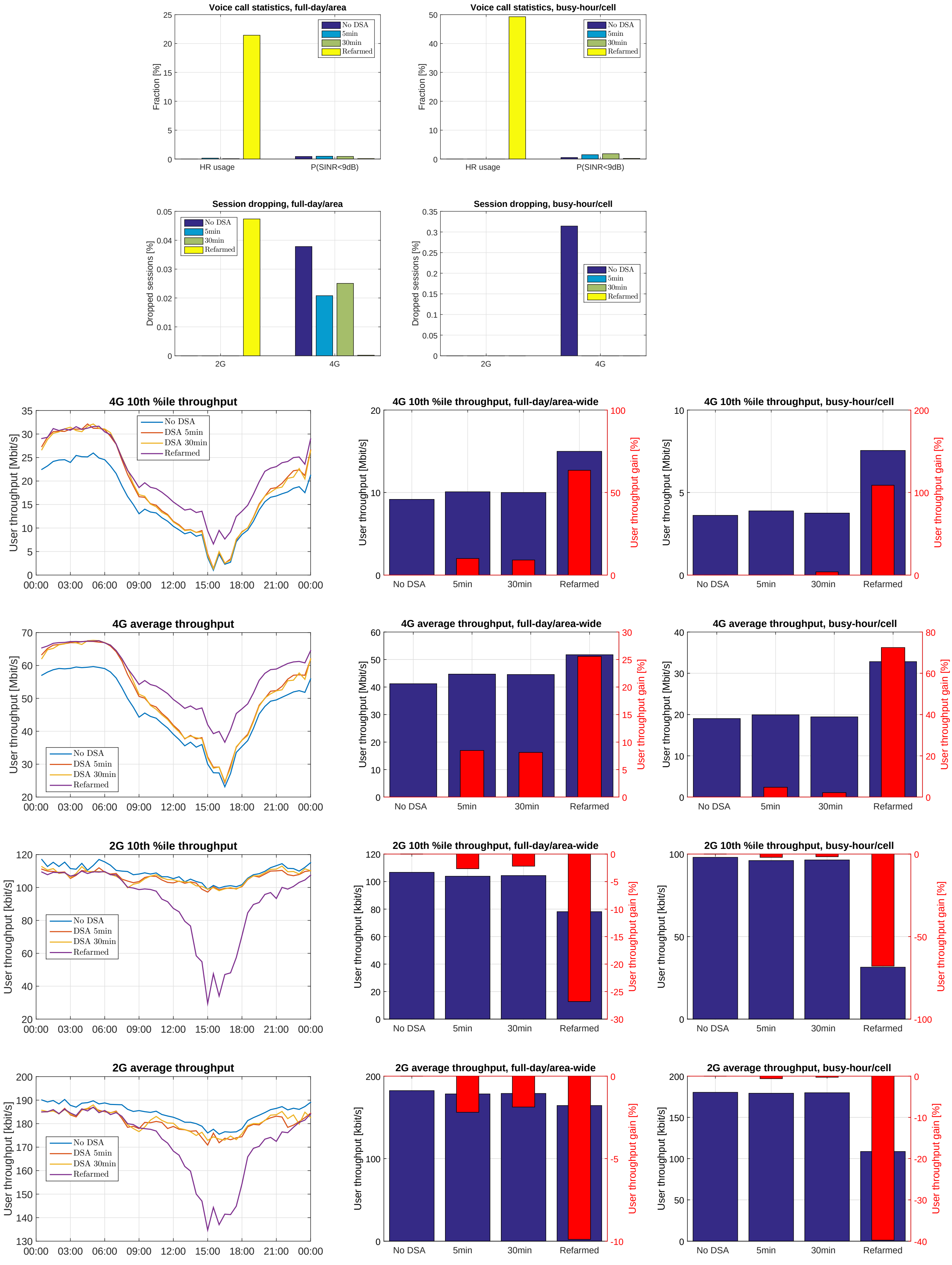


Figure 21: Amsterdam: increased load

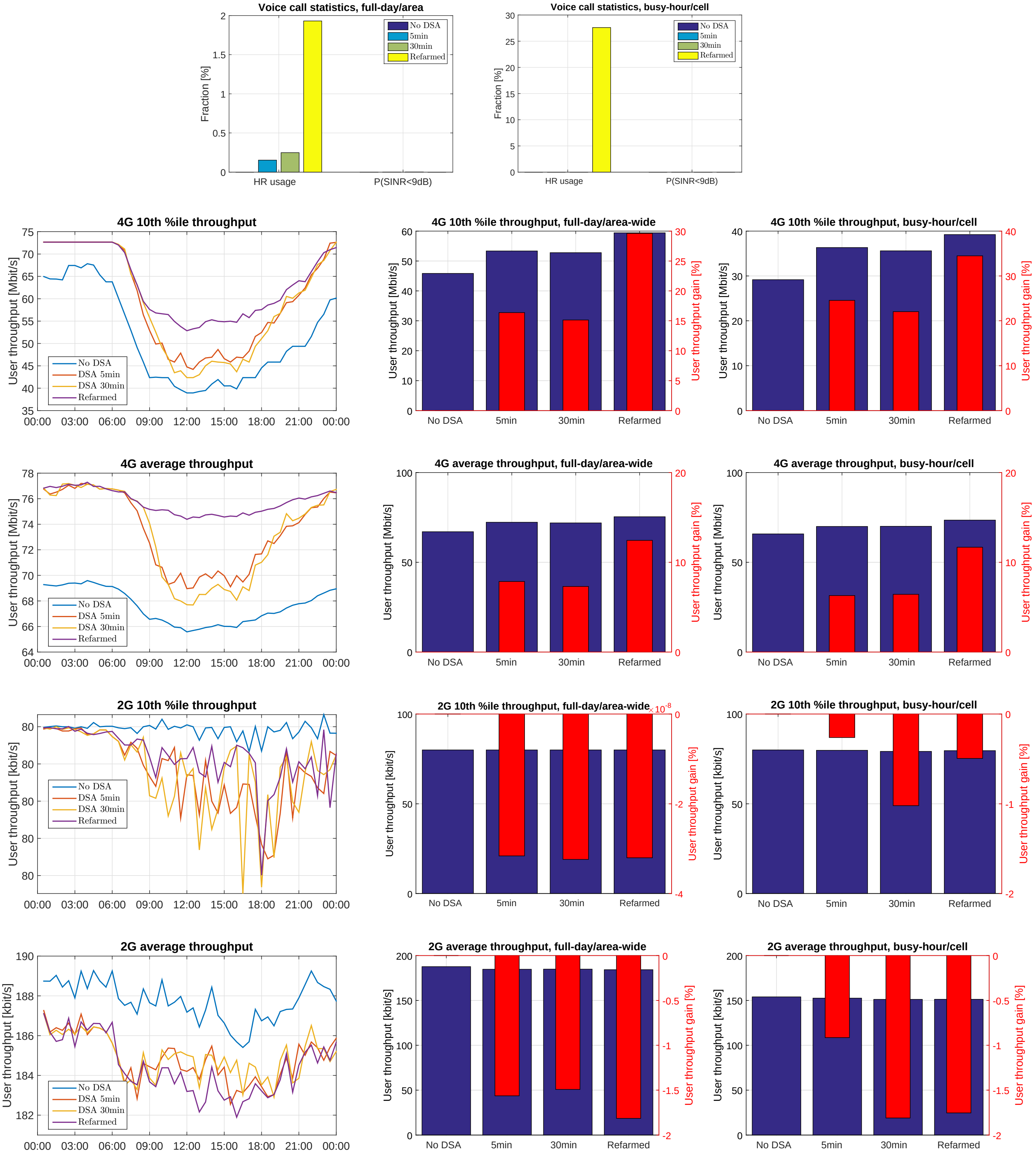


Figure 22: Purmerend: base load

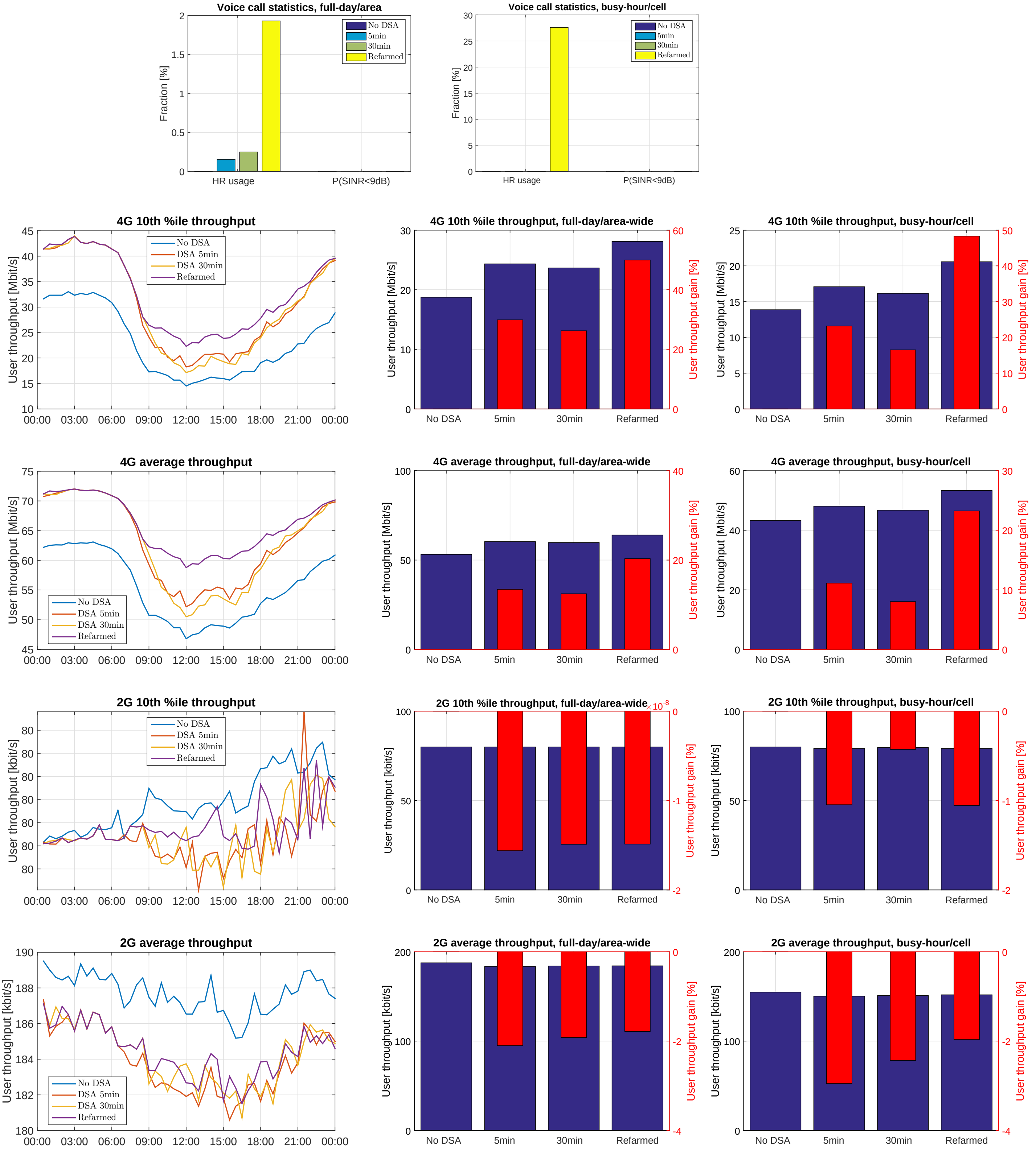


Figure 23: Purmerend: increased load

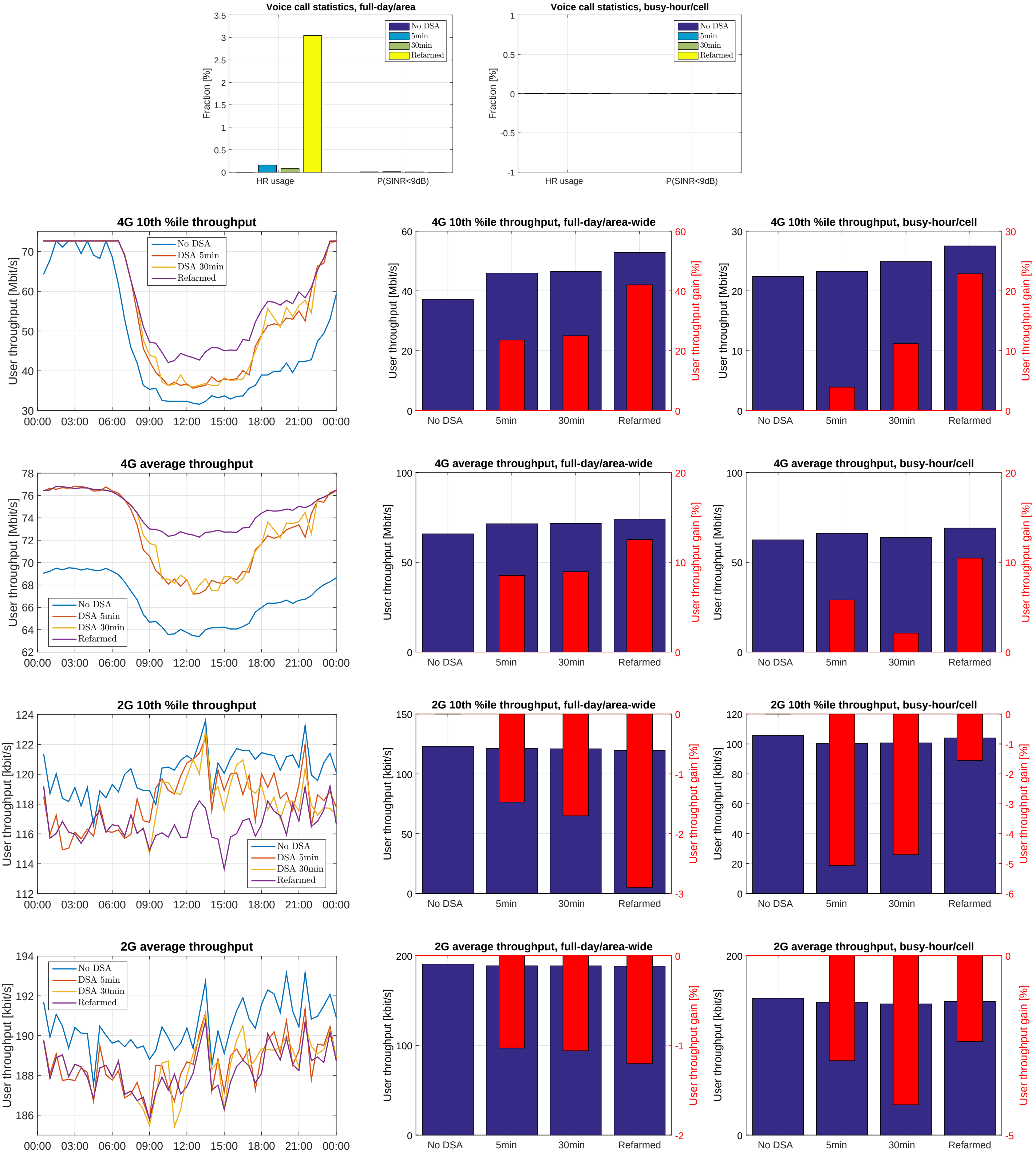


Figure 24: Friesland: base load

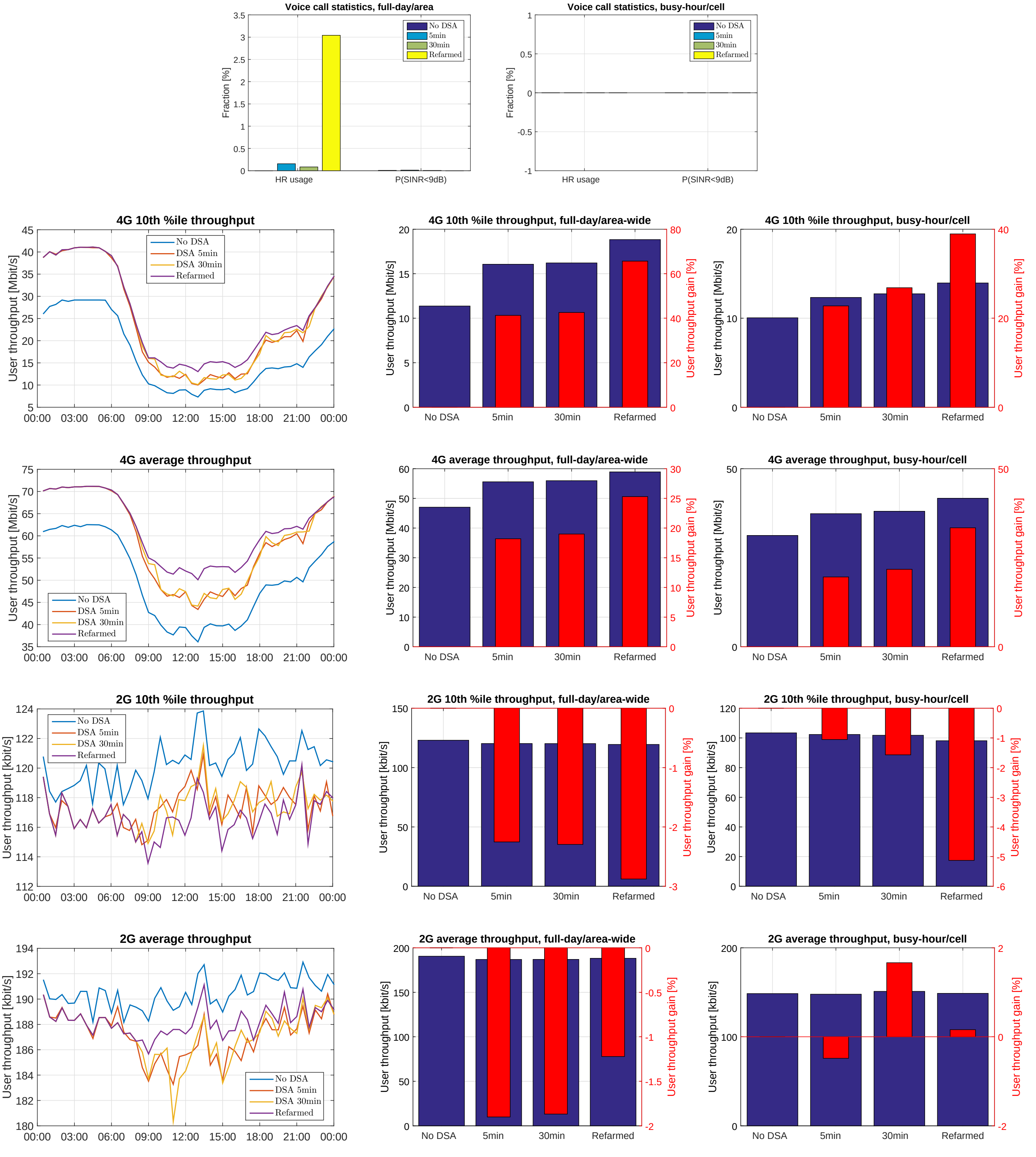


Figure 25: Friesland: increased load

6

CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

In this thesis, the goal has been set to assess DSA performance in a realistic mobile network conditions. The key research questions have been raised: whether spectrum reallocation may increase system throughput without adverse impact on legacy systems performance? By how much can end-user throughput be improved by implementing DSA? Are there any differences in the number of spectrum reallocation opportunities and performance among different types of network areas? These questions were set to be answered by performing realistic system level simulations of different cellular network areas. Three different cellular network areas have been selected in KPN network to test DSA, that are considered to represent urban, suburban and rural conditions. To perform the simulations, data that fully describes the network traffic load conditions and the network itself in the selected areas, has been collected. Using the data, multiple simulations scenarios have been developed and run using the purpose built simulator.

The acquired simulation results show that DSA in an intra-operator inter-RAT scenario is able to improve 4G end-user performance in terms of average throughput and 10th user throughput percentile in all considered scenarios. The gains are limited only in the urban area in the busy-hour scenario, where due to high voice call activity, no spectrum reallocation opportunities exist, hence no 4G gains or detrimental effects to 2G are visible.

An observable impact by DSA on legacy systems is considered to be low, as average 2G throughput loss over the full simulated day and area is up to around 3% for urban area and 2% for suburban and rural areas. Similarly low losses are logged for 10th user throughput percentiles over the full simulated area and day.

DSA effect on voice call quality is low. Only spectrum refarming shows significant impact on voice calls, as in urban area scenario under both load conditions around 22% of total call time is spent in the half-rate mode over the full day and area, and around 50% during the busy hour in a selected cell. Half-rate usage with spectrum refarming is also significant in suburban environment, with 2% and 27% fractions over the the full-day/area and during busy-hour/cell respectively.

The number of spectrum reallocation opportunities throughout a whole area indicates that rural area has most spectrum reallocation opportunities, followed by suburban and urban areas. This is purely due to a lower number of voice calls made in rural area, than in suburban or urban areas, as spectrum reallocation algorithm in this thesis takes into account voice call load only.

Generally, the results indicate that intra-operator inter-RAT DSA has potential to improve 4G performance without adverse impact to 2G. Among the simulated scenarios, urban area (Amsterdam) could potentially benefit from DSA most, as no significant service quality degradation for 2G services is evident with significant throughput gains for 4G on average over the full simulated day and area are logged, and simulation results show that spectrum refarming is clearly not an option in the urban area. While suburban (Purmerend) and rural (Friesland) areas can clearly benefit from DSA too, due to a relatively low 2G data traffic, with additional operator consideration of half-rate time slot usage impact on voice call quality, spectrum refarming could be an option to improve 4G performance in these areas.

6.2 FUTURE WORK

The conducted investigation of DSA helped to gain additional insight into a more efficient ways of frequency spectrum usage. However, some unanswered questions are left. As an extension of this project, a more extensive study of different DSA period durations could be done, traffic load prediction algorithm could be tested using different degrees of reallocation 'aggressiveness' and generally different algorithms could be applied to find the most accurate one. A better assessment of DSA impact on the perceived 2G voice call quality should be conducted to evaluate the influence of half-rate timeslot usage. Modeling could be made more realistic by including variability in propagation loss due to shadowing and variability of BPL. Moreover, more realistic modeling could be made by implementing propagation modeling for BCCH frequency carriers. Looking broader, DSA concept could be applied in intra-RAT scenario to investigate whether spectrum could be reallocated when frequency duplexing is used, as sufficient traffic load asymmetries between uplink and downlink might exist.

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COLOPHON

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