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RADIO NETWORK PLANNING AND OPTIMISATION FOR WCDMA

Thesis for the degree of Doctor of Science in Technology

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission for public examination and debate in Auditorium S4 at Helsinki University of Technology (Espoo, Finland) on the 1st of July 2002 at 12 o'clock noon.

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PREFACE

This thesis is based on work carried out in Network Research and Standardisation, Nokia and Operations Support Systems, Nokia during 1997-2001.

I wish to express my gratitude to Ms. Anneli Korteniemi and Mr. Peter Muszynski for providing me a very challenging and motivating working environment. Moreover, they have given me the freedom to research issues I have found relevant and thus I have had the possibility to finalize my thesis. I also want to thank all my colleagues in Nokia and elsewhere for fruitful teamwork, good debates and comments through these years. I have a feeling that for us work is a passion and the possibility to learn more is the greatest motivator. Especially I wish to thank Achim Wacker, Pauli Aikio, Kari Sipilä, Albert Höglund and Mikko Kylväjä from Nokia and Kimmo Raivio, Pasi Lehtimäki and Professor Olli Simula from Helsinki University of Technology, with whom my publications are mostly generated. Kirsi Heikkonen corrected my "engineer's English with Finnish flavour", and surely that improved the readability of the thesis.

I am also very grateful to Professor Pertti Vainikainen. With his discrete way he has forced me to collect the pieces of my research and compile this thesis.

I also want to thank the personnel of Nokia Information Services. With patience they searched and provided me with publications, which in this fast developing and changing business area were already considered as ancient.

Last but certainly not least, I warmly, with thousands of hugs and kisses, thank my *home team*: Tuupi, Sonja and Wolfgang for encouragement and patience. I understand that absent minded mother or spouse is not that easy to live with!

Jaana Laiho

ABSTRACT

The present thesis introduces the radio network planning process and optimisation for WCDMA (FDD mode), as defined by 3GPP. This thesis consists of three parts: modelling and tools for radio network planning, process for pre-operational network control and optimisation for the operational network. General challenges to face in 3G network control are based on the fact that many issues are interconnected and should be simultaneously considered, such as

- Planning means not only to meet current status and demands, but the solution should also comply with the future requirements by providing an acceptable development path.
- Traffic modelling is not only the question about the total amount of traffic growth, but also the question about the future service distribution and performance demands.
- All CDMA systems have a relation between capacity and coverage. Consequently, the network planning itself is not only based on propagation estimation but also on the interference situation in the network. Ideally, site selection consideration will be done based on the network analysis with planned load and traffic/service portfolio, taking possible co-siting constraints into account.
- Provision of multiple services and seamless management of at least two multiple access systems require rapid evolution of the management tools and processes. The network performance in terms of capacity, quality, and implementation and operational costs forms a multidimensional space. Operators' task will be to convert the business strategy to an operating point in the performance space in a cost efficient manner.

The contribution of this thesis in terms of modelling and tools is as follows:

- Improvement of the accuracy of radio link budget by introducing power control *headroom* (also called fast fading margin)
- Improvement of loading equation by introducing a *transmit power increase* term.
- Development of theory and modelling for a planning tool capable of multi-service and multi-carrier interference, capacity and coverage analysis
- Development and implementation an interface taking into account the true traffic distribution (not uniform) and terminal speed.

In the area of pre-operational planning process the contribution of this thesis is as follows:

- Development of dimensioning methodology for multi-service network site density estimation, utilising the modelling of power control headroom, transmit power increase, soft handover and E_b/N_0.
- Development of radio network planning process for multi-service environment including capacity and coverage evaluation for a given traffic mixture, quality and area requirements.
- Analysis of means to improve radio network performance with Mast Head Amplifier (MHA), diversity reception, sectorisation and proper antenna selection.

In the area of optimisation of the operational network the contribution of this thesis is as follows:

- Definition for optimisation target in the case of 3G. The optimisation will be capacity–quality trade-off management instead of plain quality improvement process.
- Introduction of Self Organizing Map (SOM) in the analysis of cellular networks.
- Analysis of the applicability of SOM in WCDMA cellular network optimisation.
- Introduction of SOM based applications to support network capacity–quality trade-off management.

It is worth noting that process and methods described in this work are not limited to 3G systems with WCDMA radio access technology, but they are applicable to other CDMA standards as well.

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[P1] K. Sipilä, J. Laiho-Steffens, M. Jäsberg, A. Wacker, "Modelling the impact of the fast power control on the WCDMA uplink," *IEEE VTS Proceedings of Vehicular Technology Conference 1999 spring*, Houston, Texas, May 1999, pp. 1266-1270.

[P2] A. Wacker, J. Laiho-Steffens, K. Sipilä, M. Jäsberg, "Static simulator for studying WCDMA radio network planning issues," *IEEE VTS Proceedings of Vehicular Technology Conference 1999 spring,* Houston, Texas, May 1999, pp. 2436 -2440.

[P3] J. Laiho, A. Wacker, "Radio network planning process and methods for WCDMA," *Annals of Telecommunications*, Vol. 56, No. 5-6, Mai/Juin 2001, pp. 317-331.

[P4] H. Holma, Z. Honkasalo, S. Hämäläinen, J. Laiho, K. Sipilä, A. Wacker, "Radio network planning," Chapter 8 in H. Holma and A. Toskala (ed.), *WCDMA for UMTS*, John Wiley & Sons, 2001, Revised Edition.

[P5] J. Laiho-Steffens, A. Wacker, P. Aikio, "The impact of the radio network planning and site configuration on the WCDMA network capacity and Quality of Service," *IEEE VTS Proceedings of Vehicular Technology Conference 2000 spring*, Tokyo, Japan, May 2000, pp. 1006-1010.

[P6] J. Lempiäinen, J. Laiho-Steffens, "The performance of polarisation diversity schemes at a base station in small/microcells at 1800 MHz," *IEEE Transactions on Vehicular Technology,* Vol. 47, No. 3, August 1998, pp 1087-1092.

[P7] K. Raivio, O. Simula, J. Laiho, "Analysis of mobile radio access network using the self-organizing map, " *Proceedings of IEEE International Conference on Data Mining*, San Jose, California, November-December 2001, pp. 457-464.

[P8] J. Laiho, K. Raivio, P. Lehtimäki, K. Hätönen, O. Simula, "Advanced Analysis Methods for 3G Cellular Networks", *Report A65, Publications in Computer and Information Science*, Helsinki University of Technology, 2002. Slightly modified version (split to Part I Methods and Part II Applicability of Methods) resubmitted to IEEE Transactions on Wireless Communications end 4/2002.

[P9] J. Laiho, M. Kylväjä, A. Höglund, "Utilization of Advanced Analysis Methods in 3G Networks," *IEEE VTS Proceedings of Vehicular Technology Conference 2002 spring,* Birmingham, Alabama, pp. 726-730.

In [P1] the initial link level simulations to study the phenomenon were done by the author of this thesis. The final link level simulations and result analysis was done by the first author. Main contributors to the paper were the first author and the author of this thesis; the overall responsibility of the paper generation was on the first author. [P1] is in close connection with [P2].

Work for publication [P2] was split as follows: the development of the tool and main contribution to the publication was done by the first and the author of this thesis, the responsibility of the third author was to implement link level performance modelling to the simulator.

In the case of [P3] the process description, the dimensioning modelling, the comparison of dimensioning with the static tool and comparison of the static tool with the dynamic tool was the responsibility of the author of this thesis. The second author provided the static simulator description. The overall composing of the paper was a shared responsibility.

In [P4] the authors are in alphabetical order due to editorial reasons. The responsibility of the author of this thesis in relation to [P4] was as follows: development of the dimensioning process for WCDMA as defined in section 8.1, development of the modelling for the radio link budget, in the case of the downlink modelling the

contribution from second and fifth author was also significant. The author of this thesis also contributed to the identification of the WCDMA specific issues in the link budget. Sections 8.3.2 to 8.3.3 were solely the responsibility of the author of this thesis. The author of this thesis performed the simulations and the simulation post processing, drew the conclusions and generated the text. The first author was responsible of the soft capacity and GSM co-planning issues and the final editorial work. The second author was also responsible for the text generation for the dimensioning part; the third author was responsible for the multi-operator interference modelling issues. The sixth author supported the first author in the editorial tasks.

The simulations and the post processing for work in [P5] were performed by all the authors. The modifications to the simulator required for the study were done by the author of this thesis and the second author. The main responsibility for the paper generation was on the author of this thesis

The measurements, measurement analysis and reporting of the results were conducted by both of the authors in the case of [P6]. The author of this thesis was responsible for generating the analysis tools.

The work done in connection with [P7] was split as follows: the first and second authors' expertise lie in the area of neural networks. Therefore especially the first author was responsible for the neural analysis. The author of this thesis was responsible for the "radio aspects": planning the radio network used in the study, generating the optimisation concept and drawing conclusions of the clustering. The main responsibility of the report generation was on the first and the author of this thesis.

The work done in connection of [P8] was split as follows: The optimisation concept (Introduction), the analytical formulation, traditional analysis results, SOM applicability analysis and conclusions were solely the author of this thesis's responsibility. The third author performed the SOM analysis and his contribution in explaining the SOM results was significant. In the combination of the traditional analysis results and SOM results the role of the author of this thesis was significant. The fourth author is responsible for the pre-processing part, and the fifth author has provided the text for SOM introduction. The main responsibility of the paper generation was on the author of this thesis; the main effort for the compilation of this paper was from the first three authors.

The author of this thesis had the main responsibility of [P9]. The author of this thesis has generated most of the SOM use cases described in the paper. The contribution of the second author was important in the case of RGB visualization. The third author is an expert in the area of SOM and anomaly detection, thus he had an important role in the anomaly detection part.

The selection of these papers for this thesis is as follows: From technical point of view the papers cover areas of the planning and optimisation related modelling and tasks. Paper [P1] contains the fundamental findings in the power control related modelling introduced in this work. The modelling is enhanced to multi-cell case in [44]. Paper [P2] was chosen because it is the paper introducing the modelling in the WCDMA planning tool for the first time. It is a strong basis for the further work done for this thesis. Paper [P3] covers a large entity of radio network planning modelling issues, and thus from WCDMA planning modelling point of view it is the main contribution to this thesis. Papers [P4] and [P5] are then based on the theory presented in [P3]. In [P4] and [P5] practical examples of the impact of the modelling introduced in [P3] are introduced. In those papers it is demonstrated that by accurate modelling the WCDMA phenomena can be taken into account already in the pre-operational phase. In the future the data services will dominate the cellular world. Thus all means applicable to the improvement of the capacity and quality performance of the networks are essential. In [P5] the impact of

sectorisation, mast head amplifier, antenna tilt and antenna selection on the network performance is shown. In [P6] the diversity gains with different antenna selections (space diversity and polarization diversity with horizontal- vertical (HV) or slanted ±45° configuration) are presented, those are also applicable to WCDMA and thus this paper was selected to be part of the thesis.

SOM based application in the analysis of cellular networks is not widely spread and thus the verification and understanding of the method and results is important. Papers [P7] to [P9] demonstrate the capabilities of SOM usage in cellular application. [P7] is written from the SOM point of view; the paper is the first demonstration of SOM in the analysis of WCDMA networks. [P8] provides analysis results for a WCDMA cellular network acquired in traditional and advanced means. The SOM results are explained by combining cost function approach using traditional analysis results as input and expert knowledge. The advanced SOM based analysis and traditional analysis (added with expert knowledge) show good agreement and thus SOM based analysis is recommended for future cellular networks to aid effective network management. [P9] shows examples of how SOM based tools could be utilised in real network management systems.

LIST OF ACRONYMS

0-9	
2D	Two dimensional
2G	2nd Generation
3D	Three dimensional
3G	3rd Generation
3GPP	3G Partnership Project
A	
AMPS	Advanced Mobile Phone System
B	
BCCH	Broadcast Control CHannel
BER	Bit Error Rate
BS	Base Station
BSC	Base Station Controller
BSS	Basestation SubSystem
C	
CAPEX	CAPital EXpenditure
CDMA	Code Division Multiple Access
CF	Cost Function
CM	Configuration Management
COST	European COoperation in the field of Scientific and Technical research
CRMS	Common Resource Management Server
D	
D-AMPS	Digital AMPS
DL	DownLink
E	
EDGE	Enhanced Data Rate for GSM Evolution
F	
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
G	
GPRS	General Packet Radio Service
GSM	Global System for Mobile communication
H	
HO	HandOver
HV	Horizontal-Vertical
I	
ID	IDentification
IP	Internet Protocol
IPBTS	IP Base Transceiver Station
ITRM	IP Transport Resource Manager
ITU	International Telecommunication Union
J	
JTACS	Japan TACS
K	
KPI	Key Performance Indicator
M	
MHA	Mast Head Amplifier

MS	Mobile Station
N	
NE	Network Element
NMS	Network Management System
NMT	Nordic Mobile Telephone
NRT	Non Real Time
NTT	Nippon Telegraph and Telephone
NW	NetWork
O	
OPEX	OPerating EXpenditure
P	
P-CPICH	Primary Common PIlot CHannel
PCS	Personal Communications System
PDC	Pacific Digital Cellular
PI	Performance Indicator
PS	Performance Spectrum
Q	
QoS	Quality of Service
R	
RAN	Radio Access Network
RLB	Radio Link Budget
RNC	Radio Network Controller
RRM	Radio Resource Management
RT	Real Time
S	
SDCCH	Standalone Dedicated Control CHannel
SHO	Soft HandOver
SIR	Signal to Interference Ratio
SOM	Self Organising Map
T	
TACS	Total Access Communication System
TCH	Traffic CHannel
TDMA	Time Division Multiple Access
TPC	Transmit Power Control
Tx	Transmit
U	
UL	UpLink
UMTS	Universal Mobile Telecommunications System
W	
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network

1 Introduction

1.1 Introduction to radio network planning and optimisation for WCDMA

The mobile communication industry is currently shifting its focus from second (2G) generation towards the third. The shift is not only related to the evolution of the (radio) access technology, but also to the vision of the development of service provisioning and service demands, customer expectations and customer differentiation. Furthermore, the operators' role is also changing: one can distinguish between service provider (virtual operator) and network operator, carrying the responsibility of the infrastructure and leasing airtime for service providers.

While current 2G wireless networks will still evolve and, for example, bring new internet packet data services into the markets, an increasingly larger number of operators and other wireless communication professionals are becoming familiar with the WCDMA technology and preparing themselves for 3G networks. There will be a number of new challenges when transitioning from the 2G to the new 3G networks, many of them related to the design and the planning of true multi-service radio networks, and some of them to particular aspects of the underlying WCDMA radio access technology.

Before looking into more detail what actually will be new (and different) in WCDMA radio network planning and optimisation, it is useful to summarise some of the defining characteristics of 3G multi-service radio networks. One can characterise 3G radio access with the following attributes:

- Highly advanced radio interface, aiming at great flexibility in carrying and multiplexing a large set of voice and in particular data services. Furthermore the throughput ranging from low to very high data rates, ultimately up to 2 Mbit/s.
- Cell coverage and service design for multiple services with largely different QoS requirements. Due to the large differences in the resulting radio link budgets, uniform coverage and capacity designs as practised in today's voice-only radio networks, can no longer be obtained. Traffic requirements and QoS targets will have to be distinguished among the different services.
- A large set of sophisticated features and well-designed radio link layer. Examples of this are: various radio link coding / throughput adaptation schemes; support for advanced performance enhancing antenna concepts, such as BS transmission diversity, or the enabling of interference cancellation schemes.
- Efficient mechanisms for interference averaging and robustness to operate in a strongly interference limited environment. High spectral efficiency operation will require good *dominance* of cells by proper choices for site locations, antenna beamwidths, tilts, orientation, etc.
- Extensive use of "best effort" provision of packet data capacity, i.e. temporarily unused radio resource capacity shall be made available to the packet data connections in a flexible and fair manner.
- The importance of the radio network optimisation phase will increase compared to today's 2G networks, where the primary burden is on initial frequency planning. Reason for this is the capacity limited nature of the networks.
- In order to be able to provide ultimately high radio capacity, 3G networks must offer efficient means for multi-layered network operation. Furthermore, seamless interoperation of 2G and 3G is required.

- Another very important aspect is the possibility of co-siting of 3G cells with the existing 2G sites, reducing costs and overheads during site acquisition and maintenance. However, 2G-3G co-siting raises a number of issues, which the radio network (and transmission) planner has to consider.

In this introduction WCDMA was considered briefly. Summarising the listed issues, one can see that there will be some new items and certainly much new detail for the network provider to consider and deal with when planning and optimising WCDMA networks. And, yet, there is in some sense very little new about planning WCDMA: it merely requires good planning practices of today's wireless systems to be recognised and implemented in a consequent and disciplined fashion.

General challenges to face in 3G network planning are based on the fact that a lot of issues are interconnected and should be considered simultaneously:

- Planning means not only to meet current status and demands, but the selected solution shall also comply with the future requirements in the sense of acceptable development path. Furthermore, the network control mechanisms must support the operators processes and indicate not only areas where coverage/capacity is a bottleneck, but identify areas where new services could be introduced within the existing infrastructure.
- Uncertain estimation of the traffic growth. There is not only the question about the total amount of traffic growth, but also the question about the future service distribution and demands. Trend analysis can be utilized with the existing services, but introduction of a new service can result in a completely new service demand mix.
- Furthermore, there are real constraints network planning has to face. If the operator has already a network, then either due to economical or technical reasons site co-location will be used. In the case of greenfield operator, there are more and more practical limitations set by site acquisition process.
- All CDMA systems have an interconnection between capacity and coverage, and thus also quality. Consequently, the network planning itself is not only based on propagation estimation but also on the interference situation in the network. Ideally, site selection consideration will be done based on the network analysis with planned load and traffic/service portfolio.

1.2 A brief look at cellular history

The history of mobile communications started with the experiments of the first pioneers in the area. The studies of Hertz in late 1800 century inspired Marconi to search market for the new commodity (to be). The communication needs in the first and second world wars was also aiding the start of cellular radio, especially in terms of utilisation of ever higher frequencies. The first commercial systems were simplex, and the operator was required to place the call. In the case of a mobile originated call the customer had to search for an idle channel manually [1]. Bell Laboratories first introduced the cellular concept as known today. In December 1971 they demonstrated how the cellular system could be designed [2].

The first operational cellular system in the world was in Tokyo, Japan in 1979. The network was operated by NTT, known also as strong driver for WCDMA based cellular systems. The system utilised 600 duplex channels in the 800 MHz band, with channel separation of 25 kHz. Another analogue system in Japan was JTACS. In Japan it was realised that from the user point of view a single air interface was required to provide roaming capabilities. A development study was initiated 1989 by the Government and a new digital system was developed in 1991: Pacific Digital Cellular (PDC) was introduced.

1981, two years later than in Japan, the cellular era reached Europe. Nordic Mobile Telephone at 450 MHz band (NMT-450 system) started operation in Scandinavia. Total Access Communication System (TACS) launched in United Kingdom 1982 and Extended TACS was deployed 1985. Subsequently in Germany the C-450 cellular system was introduced in September 1985. Thus, at the end of 1980's Europe was equipped with several different cellular systems, which were not able to interoperate. By the late 1980's it was clear that the first generation cellular systems were becoming obsolete. The integrated circuit technology had made digital communications not only practical but also more economical than analogue technology. In early 1990's second generation (digital) cellular systems began to be deployed throughout the world. Europe led the way by introducing GSM (Global System for Mobile communications). The purpose of GSM was to provide a single unified standard in Europe. This would enable seamless speech services throughout Europe in terms of international roaming.

The situation in the United States was a bit different than in Europe. The analogue first-generation systems were supported with Advanced Mobile Phone System (AMPS) standard, available for public since 1983. During the cellular evolution in the United States the digital world was divided into three. The first digital system introduced 1991 was the IS-54 (North American TDMA Digital Cellular) and a new version supporting additional services (IS-136) was introduced 1996. The IS-95 (cdmaOne) was introduced 1993. Both of these standards operate in the same band as AMPS. At the same time FCC auctioned a new block of spectrum at the 1900 MHz band. This opened the GSM1900 (PCS) entry to the US market. Interesting overview of the GSM and evolution towards 3G can be found in [3].

Over the last decade the world of telecommunications has been changing drastically for various technical and political reasons. The wide spread use of digital technology in telecommunications has brought about radical changes in services and networks. Furthermore, as time has been passing by, the world has got smaller: roaming in Japan, roaming in Europe or roaming in the United States alone is not anymore enough. Globalisation is having its impact also in the cellular world. In addition to this current strong drive towards wireless Internet access through mobile terminals generated needs for universal standard, Universal Mobile Telecommunication Standard, 3G [4], [5], [6].

The third generation networks are being developed by integrating the features of telecommunications and Internet Protocol (IP) based networks. Networks based on IP, initially designed to support data communications, have begun to carry streaming signals such as voice/sound traffic, although with limited voice quality and delays, which were hard to control. Commentaries and predictions regarding wireless broadband communications and wireless internet services are cultivating visions of unlimited services and applications that will be available to the consumer "anywhere and anytime". Consumers expect to surf the Web, check the email, download files, have real time videoconference calls and perform variety of other tasks through wireless communication link. The consumer expects a uniform user interface that will provide access to wireless link whether shopping at the mall, waiting at the airport, walking around the town, working in the office or driving on the highway.

The new generation is not revolutionary only radio access technology wise, and one can state that the drive for new technical solution is not the only motivation for 3G. The requirements come also from the expanded customer demands, new business visions, and new priorities in life.

1.3 Evolution of radio network planning

There is very little published on the radio network planning process itself. An integrated planning approach is proposed in [7], but this is more related to the functionalities of a planning tool, than the overall planning process. This paper criticised the planning practises. Planning was based on hexagonal approach and weaknesses of it were listed:

- Traffic density cannot be assumed to be uniform
- Radio propagation cannot be assumed to be uniform
- Base station locations cannot be chosen arbitrary
- Traffic region usually has a boundary, which should be considered.

An integrated tool, which handles the base station planning (antenna issues, location), propagation prediction and frequency allocation is proposed also in [7]. Furthermore, traffic density issues are discussed. All these items are taken as granted today.

The discussion of planning practises is continued in [8]. It also introduces the impacts of quality requirements in the radio network planning. This paper starts to have a process approach and capacity enhancement with sectorisation to support network evolution is discussed. The challenges of non-uniform traffic conditions are identified and cell splitting as a solution is proposed.

It can be noted that radio network planning and its development through time can be easily mapped to the development of the access technologies and requirements set by those. The first analog networks were planned based on low capacity requirements. The radio network planning was based purely on coverage. Sites were high to keep the site density low, omni-directional antennas were used. The Okumura-Hata propagation model was and still is widely used for coverage calculation in macrocellular network planning. Based on measurements made by Y. Okumura [9] in Tokyo at frequencies up to 1920 MHz these measurements have been fitted to a mathematical model by M. Hata [10]. In the original model the path loss was computed by calculating the empirical attenuation correction factor for urban areas as a function of the distance between the base station and mobile station and the frequency. This factor was added to the free space loss. The result was corrected by the factors for base station antenna and the mobile station antenna heights. Further correction factors were provided for street orientation, suburban, open areas, and over irregular terrain. Hata's formulas are valid when the carrier frequency is between 150 to 1000 MHz, the base station height is between 30 to 200 m, the mobile station height is between 1 to 10 m and the distance is between 1 to 20 km. The base station antenna height must be above the rooftop level of the buildings adjacent to the base station. Thus, the model is proposed to be used in propagation studies of macrocells. The original data on which the model was developed was averaged over a 20 m interval being some kind of minimum spatial resolution of the model. Due to frequency band limitation the original model was tailored by COST-231 resulting in a COST-231-Hata model having the range of 1.5-2.0 GHz, which is applicable also to third generation radio networks [11]. The latest COST developments of this area can be found in [12].

Of the available propagation models the Okumura-Hata model is most frequently referred to. It therefore became a reference to which other models are compared. The range of usability with different land use and terrain types and for different network parameters has made the Okumura-Hata model very useful in many different propagation studies.

During the course of time, together with the evolution of the 2G systems site density was getting higher due to increasing capacity requirements. Furthermore, the initial assumption that cellular customers would mostly be vehicular turned out to be incorrect. Thus the maximum Tx power levels of the user equipment were reduced by at least 10

dB, causing need to rebalance the radio link budgets. All this forced the cellular networks to omit the omni directional site structure and lead to the introduction of cell splitting, i.e. one site consisted of three sectors instead of just one [8], [13]. Owing to the increased spectral efficiency requirements the interference control mechanism became more important. In addition to the sectorisation also antenna tilting was introduced as a mechanism for co-channel interference reduction [14]. Furthermore, the macrocellular propagation model was not anymore accurate enough; new models were needed to support microcellular planning.

Walfisch-Ikegami is another model often referred to. This model is based on the assumption that the transmitted wave propagates over the rooftops by a process of multiple diffraction. The buildings in the line between the transmitter and the receiver are characterised as diffracting half screens with equal height and range separation [15], [16]. Although the Walfisch-Ikegami model is considered to be a microcell model, it should be used very carefully when the antenna of the transmitter is below the rooftops of the surrounding buildings.

The above mentioned propagation models' applicability for 3G has been studied, and conclusions for the studies can be found in [17] and [18].

The propagation modelling has been an important issue for the frequency plan performance. The frequency allocation, independent of the actual allocation method, is based on predicted propagation data, and therefore a need for more and more accurate propagation modelling has arisen. Examples of more accurate models are the ones based on ray-tracing . Some ray-tracing models can be found, for example, in [19] to [23]. With ray-tracing 2D and 3D modelling has been applied, and furthermore, propagation modelling indoors is an item that has been studied a lot. In [19] the utilisation of ray-tracing in propagation prediction is introduced in a rather general level. The practical limitations (like geometrical model accuracy) are discussed. [20] contains a novel 2D ray-tracing model. The diffraction modelling has been enhanced to provide more accurate predictions in the case of non-uniform building heights and separations, and flat terrain. [21] introduces an adaptive 3D model. The main motivation in this paper is to avoid computational complexity, but still provide accurate predictions for microcellular environment. 3D model is used only there where required and triggers to change the 3D model to simpler 2D model during the field strength estimation are studied with help of real measurements. [22] and [23] provide methods for propagation estimation indoors. The approach in these two papers is very different. [22] introduces very accurate modelling of the walls (patched wall model) and combination of 2D and 3D ray-tracing. In [23] the approach is rather simple: the field strength outside the building is estimated using 3D outdoor-model. The field strength indoors is calculated using a wall loss ([dB]) and indoor loss ([dB/m]). No additional information of the internal structures of the buildings is needed. The modelling has been compared to measured data and the performance is fairly accurate.

Recently, methods for GSM frequency planning based on mobile station measurements reports have been introduced and implemented, see [24] and [25]. The possibilities offered by the mobile reports in GSM and WCDMA should be more utilised in the network control process (planning, optimisation and integration of those two).

In addition to the propagation model development it was noticed that the increasing capacity demands could be met only with more accurate frequency planning. The frequency assignment together with neighbour cell list (for handover purposes) planning and optimisation were the main issues when planning GSM networks. In the case of GSM, frequency hopping was introduced to further improve the spectrum efficiency. Advanced frequency allocation methods can be found in literature, one example based on simulated annealing is in [26]. In [27] a method for automatic frequency planning for D-

AMPS is studied. In [28] advanced features for FDMA/TDMA systems are introduced. These features include improving frequency reuse with

- Frequency hopping
- Adaptive antennas
- Fractional loading
- Hierarchical cell structures.

It can be concluded based on several papers (for example [29], [30], [32],) that the prediction of propagation is of limited accuracy due to the fact that propagation environment is very difficult to model and thus generating a generic model, which is applicable in multiple cells is by nature accuracy limited. This is especially applicable when the fading characteristics (both fast and slow) need to be considered. The latest radio network control activities concentrate on the closed loop optimisation of the plan. The initial planned configuration is (semi)automatically tuned based on statistics collected form the live network. Proposals for handover performance improvement in terms of correct neighbouring cell lists can be found in [29], [30]. The important aspect with this method is that the neighbour relations that are initially based on propagation prediction are autotuned based on real measurements. Thus the inaccuracies can be compensated in the optimisation phase. Similar measurement based concept can be utilized also for WCDMA intra- and intersystem neighbour relations [31].

A new trend in the radio network planning research is plan synthesis, meaning automatic generation of base station site locations depending on a cost function output. In [33] the target is to utilise a cost function to minimise implementation costs, maximise the coverage, maximise the offered traffic and maximise the SIR in the network. Additional challenge for this type of approach is to take antenna directions, number of sectors and tilting into account. Similar idea using neural networks can be found in [35]. Radio network planning synthesis using genetic approach is introduced in [36]. Limitations for this type of approaches arise from the fact that site locations in practise are limited and site reuse and site sharing between operators are more and more common. Thus, the “site pool” from which the algorithm can choose the optimum locations is rather small. As an academic exercise, when there are no practical limitations, this approach is interesting. Results of the plan synthesis can be utilised to bring more accuracy to the dimensioning phase (or tendering), but during the planning the real world limitations must be considered.

In cellular networks the network utilisation control requires such functionality that can utilise the measured feedback information and react correctly based on that. Therefore, it is crucial that the planning phase is tightly integrated to other network control functions and network management system. This is especially important in the case of WCDMA, owing to the fact that there will be a multitude of services, that is, customer differentiation setting a multidimensional matrix of QoS requirements. Planning such a network very accurately is not feasible due to limited accuracy of the input data (propagation, traffic amount, traffic distribution etc.). An example of the integration of a network management system and planning for 2G systems can be found in [33].

1.4 Main contributions of this thesis

This thesis consists of three parts: modelling and tools for radio network planning, process for pre-operational network control and optimisation method for the operational network.

Major difference of the work presented here and earlier published results relate to fast power control. 3GPP has specified the TPC rate of 1600 kHz, in cdmaOne it is half of that. Furthermore in the beginning of the 1990’s the cellular environment was still very

vehicular. These differences in the assumptions explains the fact that the WCDMA radio network planning specific issues, namely transmit power increase and TPC headroom, introduced in [P1] and [P3] are not reported elsewhere in CDMA related literature. Verification of the impact of the headroom and transmit power increase on the QoS during radio network planning is among other things further studied in [P4]. The tool used in the study and into which the average value interfaces are implemented is introduced in [P2] and [P3]. The modelling in the tool is novel, and not found elsewhere in available literature.

During the course of the work collected to this thesis a radio network planning process was generated for multi-service WCDMA networks, see [P3]. Issues presented for example in [45] and [63] are for CDMAOne systems. Furthermore those references describe single service case only. The impact of data services neither on the network performance nor to the planning process has been discussed.

In this thesis the coverage and capacity interdependency of CDMA systems are further studied and clarified. In [45], page 227, it is stated that cdmaOne system is typically uplink limited. This fact simplifies the planning process; it is enough to consider uplink performance only. The case is different with WCDMA owing to the fact the multipath propagation in macrocellular environment will "degrade" the orthogonality and thus the system will be downlink limited. Also strong asymmetry in the services is anticipated and this also shall lead to downlink limitations. The downlink dimensioning issues introduced in [P3] (and in [41]) are thus new in literature. In [61] also downlink related issues are discussed. It has significant differences compared to work presented in this thesis: multi-service environment is largely simplified, the SIR target is constant per traffic type, no speed impacts, nor TPC effects are included. Furthermore, orthogonality is not at all addressed, even though the simulation environment is macrocellular, and thus the probability for multipath propagation is very high.

Due to the fact that the WCDMA shall be capacity limited optimisation in terms of interference control already in the planning phase is essential. Also means to support fast roll out of the network are important. The study of [P5] demonstrates the usability of MHA. Furthermore, the effect of antenna selection, tilting and sectorisation on the interference situation and thus the capacity is verified.

In addition to the TPC modelling, the impact of number of sectors and antenna selection has been implemented to the CDMA loading equation. The enhancement has significant impact on the capacity evaluation as demonstrated in Conclusions and Discussions section. The new loading estimation has also an impact on the coverage estimation, owing to the fact that the interference margin is directly proportional to the loading figure. Furthermore, correct values (depending on service and site configuration) for variables in the equation are provided. This fact makes the work here also an important engineering reference for cellular operators.

[P7], [P8] and [P9] introduce a new concept for cellular optimisation work. The method is especially applicable for 3G multi-service networks. The need for advanced analysis methods arise from the fact that practical implementation of a CDMA network brings limitations, which are not supported with earlier published CDMA theory. The enhanced theory and planning process utilisation presented in this thesis provides the first estimation of the network behaviour and performance. After provisioning of the configuration parameters controlling the network elements it is a must to collect counter (measurement) information from the network elements in order to tune the network performance. The number of individual counters already today is thousands. When the 3G multi-service environment is monitored, the number of measurements will increase and thus effective statistical methods are required. The work of [P7] to [P9] as a cellular application is novel, not earlier reported in literature. [P7] is written from the SOM point

of view; the paper is the first demonstration of SOM in the analysis of WCDMA networks. [P8] provides analysis results for a WCDMA cellular network acquired in traditional and advanced means. The SOM results are explained by combining cost function approach using traditional analysis results as input and expert knowledge. The advanced SOM based analysis and traditional analysis (added with expert knowledge) show good agreement and thus SOM based analysis is recommended for future cellular networks to aid effective network management. [P9] shows examples how SOM based tools could be utilised in real network management systems.

The scope for this thesis has been chosen to cover the radio network planning and the optimisation. Furthermore it has been demonstrated that the network performance (both pre-operational and operational) is strongly dependent on the conditions in the cell (propagation environment, speed distribution of the users, services) and actual implementation, i.e. algorithms controlling the network elements, equipment and antennas at the base station site. The actual implementation and its effects and limitations must be taken into account in all the network development phases.

2 WCDMA radio network planning and optimisation

As the launch of third generation technology approaches, operators are forming strategies for the deployment of their networks. These strategies must be supported by realistic business plans both in terms of future service demand estimates and the requirement for investment in network infrastructure. The requirement for network infrastructure can be achieved using system dimensioning tools capable of assessing both the radio access and the core network components. Having found an attractive business case, system deployment must be preceded by careful network planning. Technical aspects related to the process and tools can be found in [P3]. The network planning tool must be capable of accurately modelling the system behaviour when loaded with the expected traffic profile. In the operation phase effective measurement based feedback loops are the core of the effective operation of the network. More about modelling in the tools can be found in [P1] and [P2], advance analysis methods to support optimisation are presented in [P9]. Applicability of these methods is analysed in [P7] and [P8].

The 3G traffic classes and user priorities, as well as the radio access technology itself form the two most significant challenges when deploying a WCDMA based third generation system. In the case of 3G networks the operators' task is to find cost wise feasible capacity and coverage trade-off, and still provide competitive services. Furthermore, network management system should not only identify a lack of capacity in the current network but also identify where there is potential to introduce data services where they currently do not exist.

In [18] some of the issues relevant for 3G planning are listed:

- Introduction of multiple services
- QoS requirements
- Modelling of traffic distributions (for example traffic hot spots)
- Mobility impact on planning
- Hierarchical cell structures, and other special cell types
- Site synthesis
- Increasingly important role of network management system.

This chapter is organized as follows:

First the radio network control loops are introduced. In pre-operational phase the performance of the network is estimated. Papers [P4], [P3], [P5] and [P6] are related to this part of the control loop. The better the modelling the more accurate initial estimate of the network performance will be. The modelling issues are addressed in [P1], [P4] and [P3]. Papers [P7] to [P9] propose novel analysis to aid decisions during statistical non real time optimisation.

In Section 2.2 the planning process according to [P3] is described. First the dimensioning is discussed and the WCDMA modelling issues are introduced in more detail ([P1], [P3]). Secondly WCDMA specific detailed planning is introduced and the modelling in the planning tool is described ([P1], [P2], [P3]).

After presenting the process and modelling in different process phases, the impact of the modelling is analysed and means to improve the performance of the radio network plan are investigated ([P4], [P5] and [P6]).

Section 2.3 investigate WCDMA optimisation issues. The trend towards capacity-quality trade-off management with 3G networks is presented and novel analysis methods to aid statistical non real time optimisation are examined ([P7], [P8] and [P9]).

2.1 Radio network control loops

When provisioning 3G services the control for the access part can be divided into three levels. These control levels are depicted in Figure 2.1. Additionally a layer for the pre-operational mode can be modelled. This loop can be placed on the same level with the statistical network level optimisation loop. Pre-operational mode includes the actions performed with an off-line planning tool/simulator. Major enhancements or new service roll-outs are planned by utilizing the measured long term performance data from existing network. The pre-operational mode planning is providing the first values for the performance iteration done with the statistical optimisation loop. The highest control layer in Figure 2.1 is for Statistical non real time optimisation and radio network performance tuning based on statistical data. This is done inside network management system, close to configuration management and performance management (i.e. measurements from the network). This loop statistically controls the behaviour of the other control loops closer to network elements (NEs). The loop enables also automated trouble shooting process when performance faults can be corrected fast by delivering the information of alarms or reports to optimisation engine and configuration management between NMS modules. The planning (pre-operational mode) and statistical optimisation process cannot be isolated to one tool but the seamless co-operation between several applications is involved. Faults and monitored performance data can be easily passed to "Optimizer" for further analysis, verification and problem solving. Configuration data is available from "Configurator" who also provides means for change implementation and provisioning, see Figure 2.12. By adding centralised task management the whole process can be automated. However, the user keeps the control, defines the targets, approves results and schedules the implementation.

The pre-operational mode can be further divided into two phases: initial planning (dimensioning) and detailed radio network planning. More about this is in Section 2.2. The Statistical non real time optimisation loop is based on a collection of longer-term measurements from the network. Measurements are combined with a cost function, and furthermore the output of the cost function is optimized. The optimisation is realized by tuning the configuration parameter settings. Automated support is needed for the cost function optimisation process, see Section 2.3.

The two lower layers in Figure 2.1 consist of the real-time feedback loops in base station, Radio Network Controller (RNC), Base Station Controller (BSC) or Common Resource Management Server (CRMS). The main differentiator in these two real time loops is the time needed for the decision making.

- The slow real time optimisation loop handles dynamic control of systems' interworking, self regulation of radio network parameters (like load thresholds), etc. Depending on the functional split of the network controlling functions this loop can be placed into the actual network elements or it can be positioned in the network management system. Main benefit of the utilization of the NMS is the possibility to utilize statistical data covering the whole network area.
- Fast real time control loops are related to fast power control, fast congestion control, link adaptation and channel allocation. It is important to notice that this loop has impact on the radio network planning process in terms of modelling power control and handover behaviour, etc.

The real time loops are also called as Radio Resource Management (RRM) algorithms. RRM consists of set of algorithms of admission control, power control, handover control etc and it is responsible for providing reasonable operation of the network. This is achieved by providing default parameter sets to control the network operating point in terms of capacity-coverage cost -(CAPEX, OPEX) trade-off. In short,

this means that the operator needs to make business decisions related to the Quality of Service, QoS, such as, does one offer high quality with reduced capacity, or does one aim for expensive infrastructure but high coverage also for high bit rate users, etc. Fast feedback loops in radio access network elements can be considered as adaptive RRM.

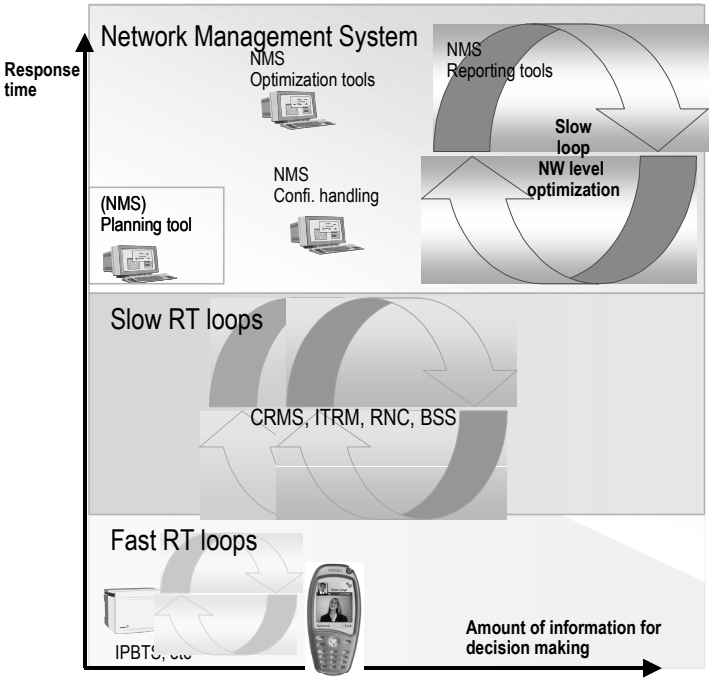

Figure 2.1. Hierarchy in the optimisation loops in a cellular network. NOTE: As much of the automation/optimisation as possible should happen already at the low hierarchy layers. In this figure the pre-operational loop is combined with the NMS statistical optimisation loop.

The statistical optimisation loop is needed to change the limits controlling RRM so that the network operating point is in optimum in terms of capacity and quality. The capacity – quality trade off and interaction of optimisation and RRM is illustrated in Figure 2.2.

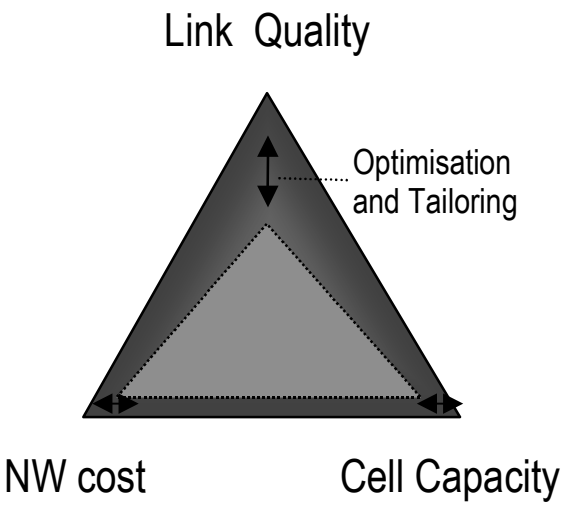

Figure 2.2. Capacity-quality trade-off management. Task of the operator is to support the business strategy with correct weighting of the performance space. RRM provides the upper bounds for the outer triangle; optimisation changes the shape of the inner triangle to support the operators' strategy.

2.2 Radio network planning process

The planning references for cdmaOne, for example [45] and [63], focus on single service case only, the capacity-coverage trade-off is not clearly presented. The planning process for multi-service CDMA networks as in [P3] is not found elsewhere in literature as a complete process description combining the capacity, quality and coverage aspects. In [P3] the process defining the translation of traffic, QoS and area requirements to site density is provided. Furthermore, the impact of the fast power control (in the case of slow mobile stations) to the dimensioning and planning is analysed.

The process in the radio network planning phase is depicted in Figure 2.3. The process itself is from top to down. Inputs and outputs for each of the phases can be found on the left and right hand side of the figure. The triggers for the process to iterate can be

- Performance below set targets
- Change in the business strategy
- New services
- Change in service priorities
- Change in customer priorities etc.

The business strategy related changes reflect the input parameter settings. In the case of performance problems the situation is to be changed with RRM parameter changes, hardware changes etc. The external interference analysis refers to activities required to determine the actual noise floor at the receiver (including environmental noise). This is out of the scope of this work, even though it is considered an important part of the process and performance evaluation. More about this issue can be found in [37].

Initial planning (i.e. system dimensioning) provides the first and most rapid evaluation of the network size as well as the associated capacity of elements involved. This includes both the radio access network as well as the core network. Dimensioning in more detail can be found in Section 2.2.1.

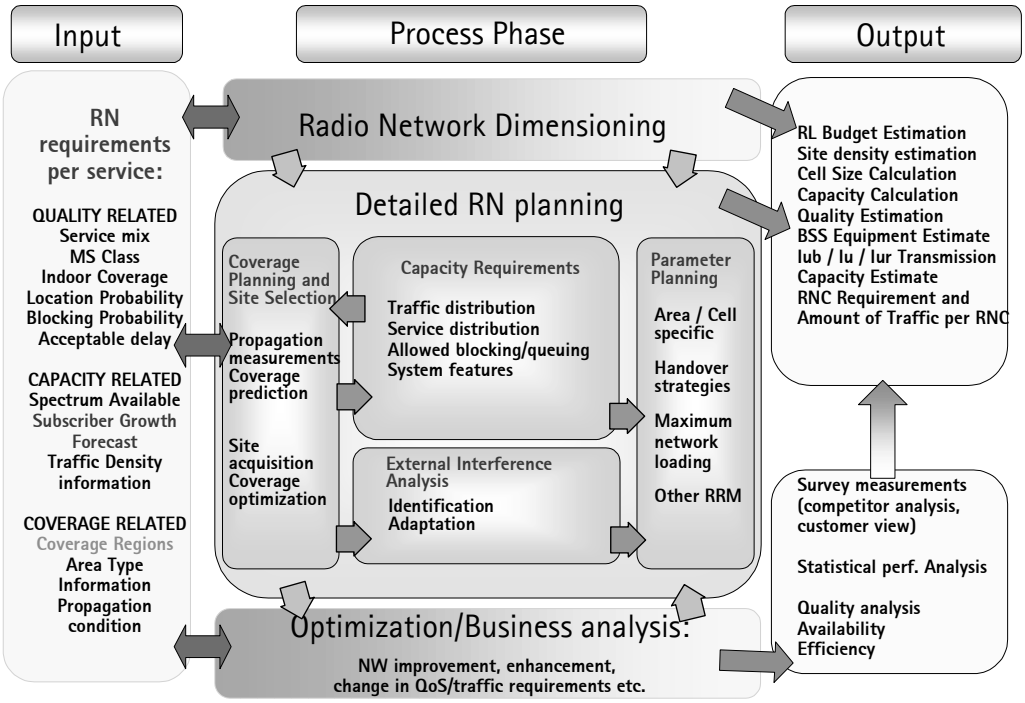

Figure 2.3. Radio network planning and optimisation process, adapted from [P4]. In the output side the measurements from live network can replace the estimations used in the planning/dimensioning phase. Good examples of this are propagation model tuning or automatic adjacency generation.

In the detailed planning phase the dimensioned site density is transferred on a digital map taking the physical limitations coming, for example, from site acquisition, into account. The WCDMA analysis itself is an iterative process, the capacity requirements are taken into account as discrete MSs in the WCDMA simulation. In the detailed planning phase multiple analysis is performed to verify if the set requirements are actually met. In the planning phase the optimisation means can be performed by interference control in terms of proper antenna and site configuration and location selection, or antenna tilting. Furthermore, network performance can be brought closer to the required targets with utilisation of, for example, mast head amplifier (MHA) or diversity schemes.

In case the operator's business strategy changes, dimensioning and detailed planning can provide valuable information related to the network expansion. The measured traffic information can be imported to the planning tool and this information can be further used when verifying the capacity and coverage capabilities of the planned network

The modelling and methodology inside the planning tool (not visible to the user) is described in Section 2.2.2. In Section 2.2.3 the impact of the RRM modelling on the planning result is introduced. Furthermore Section 2.2.4 provides practical examples related to the plan optimisation for example in terms of proper antenna selection.

In the following sections the radio network planning process is discussed in more detail. A detailed process description can also be found in [P4].

2.2.1 Dimensioning

Dimensioning process and multi-service impacts on the WCDMA dimensioning, in addition to the modelling of TPC issues in dimensioning are mainly contributed by the author of this thesis.

The target of the dimensioning phase is to estimate the required site density and site configurations for the area of interest. Initial RAN planning activities include radio link budget (RLB) and coverage analysis, capacity estimation, and finally, estimation for the amount of base station hardware and sites, radio network controllers (RNC), equipment at different interfaces, and core network elements.

System dimensioning provides the first, rapid evaluation of the possible network configuration. This includes both the radio access network as well as the core network. The dimensioning is based on a set of input parameters and the provided result is relevant for that set of input parameters only. These parameters include area, traffic and QoS related information. The quality is taken into account in terms of blocking and coverage probability.

RLB calculation is done for each service, and the tightest requirement determines the maximum allowed isotropic path loss. This section focuses on the radio access part only.

2.2.1.1 WCDMA specific issues in dimensioning

This section merely concentrates on the WCDMA specific issues, for the complete WCDMA dimensioning process see [P4], [P3].

<u>Issues in Uplink Radio Link Budget</u>

The theoretical spectral efficiency of a WCDMA is derived from the load equation whose derivation is starting with Equation (2.1), consisting of the sum of the loadings of each user. The uplink load factor, η_{UL}, can be calculated as a sum of load factors L_k of all K_N uplink connections in a cell:

$$\eta_{UL} = \sum_{k=1}^{K_N} L_k \tag{2.1}$$

The *interference margin* is a function of the total cell loading, see Equation (2.2). The more loading is allowed in the system, the larger interference margin is needed in uplink, and the smaller is the coverage area. The total loading value has direct impact to the cell coverage and thus indirectly to the quality of the offered services. Degradation of the link budget due to the total loading is:

$$L = 10 \cdot \log_{10}(1 - \eta_{UL}) \tag{2.2}$$

Depending on the maximum allowed loading in a cell, the number of users can be calculated using the load equation, provided that the loading of each individual user can be estimated. The uplink loading for each connection can be derived as follows. For the sake of simplicity the derivation is performed with service activity $v = 1$.

To find out the required uplink transmitted and received signal power for a mobile station MS_k connected to a particular base station BS_n, the basic CDMA equation (2.3) is used. The usual, slightly idealistic, assumption in there is that I_{oth}, the power received from the MSs connected to the other cells is directly proportional (proportionality constant i) to I_{own}, the power received from the MSs connected to the same BS_n as the desired MS. Assume that the MS_k uses bit rate R_k, its E_b/N_0 requirement is ρ_k and the WCDMA chip rate is W (3.84 Mchip/s). Then the received power of the k-th mobile, p_k, at the base station it is connected to, must be at least such that

$$\frac{W}{R_k} \cdot \left(\frac{p_k}{I_{own} - p_k + I_{oth} + N} \right) = \frac{W}{R_k} \cdot \left(\frac{p_k}{I_{own} - p_k + i \cdot I_{own} + N} \right) \geq \rho_k, \quad k = 1, \ldots, K_N \tag{2.3}$$

where K_N is the number of MSs connected to BS_n, and

$$N = N_0 \cdot W = N_f \cdot \kappa \cdot T_0 \cdot W \tag{2.4}$$

is the noise power in the case of an empty cell, N_f is the receiver's noise figure, κ is the Boltzmann constant ($1.381 \cdot 10^{-23}$ Ws/K) and T_0 is the absolute temperature. For $T_0 = 293$ K (20 °C) this results in $N_0 = -174.0$ dBm/Hz and $N = -108.1$ dBm. Note that in Equation (2.3) the impact of the wanted signal is subtracted in the term $\boldsymbol{I_{own} - p_k} + i \cdot I_{own}$.

The inequalities in Equation (2.3) are slightly optimistic because it is assumed that there is no interference from the own signal, which is not exactly true in real multipath propagation conditions.

Solving the inequalities as equalities means solving for the minimum required received power (sensitivity), p_k:

$$p_k \cdot \left(1 + \frac{\rho_k \cdot R_k}{W} \right) = \frac{\rho_k \cdot R_k}{W} \cdot (1+i) \cdot I_{own} + \frac{\rho_k \cdot R_k}{W} \cdot N \quad \Rightarrow$$

$$p_k = \frac{1}{1 + \frac{W}{\rho_k \cdot R_k}} \cdot (1+i) \cdot I_{own} + \frac{1}{1 + \frac{W}{\rho_k \cdot R_k}} \cdot N, \quad k = 1, \ldots K_N \tag{2.5}$$

Since $p_k = L_k \cdot [(1+i) I_{own} + N]$, we obtain the load factor of one connection:

$$L_k = \frac{1}{1 + \frac{W}{\rho_k \cdot R_k}} \tag{2.6}$$

If the Equations in (2.5) are summed over the mobile stations connected to BS_n in order to derive the total power received at the base station, i.e. the total loading, then

$$\sum_{k=1}^{K_N} p_k = \left[\sum_{k=1}^{K_N} \frac{1}{1+\frac{W}{\rho_k \cdot R_k}} \cdot (1+i)\right] \cdot \sum_{k=1}^{K_N} p_k + \left[\sum_{k=1}^{K_N} \frac{1}{1+\frac{W}{\rho_k \cdot R_k}}\right] \cdot N \Rightarrow$$

$$\sum_{k=1}^{K_N} p_k \cdot (1+i) = \frac{N \cdot \left[\sum_{k=1}^{K_N} \frac{1}{1+\frac{W}{\rho_k \cdot R_k}} \cdot (1+i)\right]}{1-\left[\sum_{k=1}^{K_N} \frac{1}{1+\frac{W}{\rho_k \cdot R_k}} \cdot (1+i)\right]} = \frac{N \cdot \eta_{UL}}{1-\eta_{UL}} \tag{2.7}$$

since $I_{own} = \sum_{k=1}^{K_N} p_k$ and the definition of the total uplink loading is the sum of individual loadings (see (2.6)) multiplied with the effect of the multicell environment, i.e. with the term (1+*i*).

$$\eta_{UL} = \sum_{k=1}^{K_N} \frac{1}{1+\frac{W}{\rho_k \cdot R_k}} \cdot (1+i) \tag{2.8}$$

The loading defines how much power the base station is receiving in a cell in addition to the basic noise floor. Continuing the derivation of Equation (2.7) the total loading gets the form:

$$\eta_{UL} = \frac{I_{own} + I_{oth}}{N + I_{own} + I_{oth}} = \frac{I_{total}}{N + I_{total}} \tag{2.9}$$

In other words, total loading indicates how much the sensitivity of a base station has degraded due to the fact that all users in a carrier are operating with the same frequency. This additional power consists of signals transmitted by the MSs in the own cell and in the other cells.

The relevance of the estimation of the loading of an individual user (i.e. Equation (2.6)) is visible for example during the call admission process. The system needs to know the current total loading, allowed total loading and the loading increase caused by the new possibly admitted user in order to make a decision whether to admit the new call or not.

In a similar manner during dimensioning a cell can be filled with users as long as the total loading (according to Equation (2.8)) stays below set total target threshold. During dimensioning loading equation in the form of (2.8) is used instead of (2.9) because it is essential, from the capacity point of view, to know the exact amount of traffic (users with different kind of service requests) rather than just the total amount of interference. The latter would be adequate in coverage limited cases.

The loading definition of Equation (2.11) can be modified to include the effect of sectorisation (sectorisation gain ζ, number of sectors, N_S) and service activity, ν. Values for the sectorisation gains can be found in [39] and [40]. This expression is different from the one reported in [P3], because the way, the sectorisation gain values are reported in [39] and [40], does not support the notation of [P3]. The main issue with the sectorisation gain is that sectorisation does increase the capacity one site can offer. But, due to the fact that the sectorisation is not ideal the gain is not linear function of the number of sectors. The capacity gain depends on the antenna selection and sector overlapping, which cannot be avoided. This overlapping is increasing the other to own cell interference ratio (*i*). The reported gains in [39] and [40] are not normalized with the number of sectors, and the equation in [P3] has thus an error. Furthermore, the inverse in the equation in [P3] is missing. See also Errata.

Sectorisation gain is discussed also in [45], page 228. The main addition of this thesis compared to the theory in [45] is the fact that sectorisation has also an impact to the i value. [45] only discusses the capacity increase effects of sectorisation, but does not point out the importance of antenna selection. This information is very important to the engineering society implementing the WCDMA networks.

When comparing Equation (2.10) to Equation (8.9) in [P4] the definition of i is different. In [P4] the i already includes the effects of sectorisation.

$$\eta_{UL} = \sum_{k=1}^{K_N} \frac{1}{1+\frac{W}{\rho_k \cdot R_k}} \cdot v_k \cdot \left(1 + i \cdot \frac{N_S}{\zeta}\right) \tag{2.10}$$

In [42] the uplink loading is estimated using Equation (2.11)

$$\eta_{UL} = \frac{1}{W} \cdot \sum_{j=1}^{m} R_j \cdot v_j \cdot \rho_j \cdot (1+i) \tag{2.11}$$

where m is the number of services used and each single user is counted as a separate service. The differences between Equations (2.10) and (2.11) are due to the fact that Equation (2.11) does not include sectorisation gain and that in the derivation starting from Equation (2.3) the denominator is $I_{own} - p_k + i \cdot I_{own} + N$ (i.e. wanted signal not included) rather than $I_{own} + i \cdot I_{own} + N$, which is the case when $p_k << I_{own}$ and $<< N$.

Issues in Downlink Radio Link Budget

In cdmaOne work (for example the main references in the area i.e. [45] and [63]) the downlink has been treated rather lightly for dimensioning and radio network planning point of view, owing to the fact that cdmaOne is claimed to be uplink limited. Thus the issues reported in this thesis ([P2]) are new in literature.

The downlink dimensioning follows the same logic as the uplink. For a selected cell range the total base station transmit power ought to be estimated. The total transmit power is a sum of the individual link (user) transmit powers in a cell. In this estimation the soft handover connections must be included. If the power is exceeded either the cell range ought to be limited, or number of users in a cell has to be reduced. In the downlink direction the orthogonality of the codes needs to be considered. This is done by introducing an orthogonality factor α. Values for α range from 0 to 1 depending on multipath conditions ($\alpha = 1$: fully orthogonal, $\alpha = 1/2$: two equally strong taps). More about orthogonality can be found in [43]. For downlink the loading (η_{DL}) is estimated in [41] as

$$\eta_{DL} = \sum_{i=1}^{I} \left[\frac{\rho_i \cdot R_i \cdot v_i}{W} \left((1-\alpha_i) + \sum_{n=1, n \neq m}^{N_{BS}} \frac{Lp_{mi}}{Lp_{ni}} \right) \right] \tag{2.12}$$

where Lp_{mi} is the link loss from the serving BS_m to MS_i, Lp_{ni} is the link loss from another BS_n, to MS_i, ρ_i is the *transmit* E_b/N_0 requirement for the MS_i, including the SHO combining gain and the average power rise caused by fast power control, N_{BS} is the number of base stations, I is the number of connections (including the soft handover connections, I in general is larger than K_N) in a sector and α_i is the orthogonality factor.

The term $i_{DL} = \sum_{n=1, n \neq m}^{N_{BS}} \frac{Lp_{mi}}{Lp_{ni}}$ defines the other-to-own-cell interference in DL. Thus (2.12) gets form:

$$\eta_{DL} = \sum_{i=1}^{I} \left[\frac{\rho_i \cdot R_i \cdot v_i}{W} \left((1-\alpha_i) + i_{DL} \right) \right] \tag{2.13}$$

Direct output of the downlink RLB is the single link power required by a user at the cell edge. The total base station Tx power estimation must take into account multiple communication links with average ($\overline{Lp_{mi}}$) distance from the serving base station. Furthermore, the multicell environment with orthogonalities α_i should be included in the modelling. More on the downlink loading and transmit power estimations can be found in [41].

In the RLB calculation in uplink direction the limiting factor is the mobile station transmit power, in downlink direction the limit is the total base station transmit power. When balancing the uplink and downlink service areas both links must be considered.

The *interference margin* ([P2]) to be taken into account in the link budget due to a certain loading η (either in uplink or downlink) is according to Equation (2.2).

Power control headroom is another WCDMA specific item in the RLB not reported earlier in literature. Some margin is needed in the mobile station transmission power for maintaining adequate closed loop fast power control in unfavourable propagation conditions like in the cell edge. This is applicable especially for pedestrian users where the E_b/N_0 to be maintained is more sensitive to the closed loop power control. The power control headroom has been studied in more detail in [P1] and [44].

Another impact of the fast power control is the increase in the average needed transmit power *(transmit power rise).* This is another finding in [P1] and [P2] not reported elsewhere in literature. In the case of a slowly moving mobile station the power control is able to follow the fading channel and the average transmitted power increases. In own cell this is needed to provide adequate quality for the connection and does not cause any harm, since increased transmit power is compensated by the fading channel. For neighbouring cells however this means additional interference because the fast fading in the channels is uncorrelated. The transmit power increase *(TxPowerInc)* is used to reduce the reuse efficiency according to Equation (2.14). When comparing to other work in the field (for example [42], [46]) the new issue is the multiplication with the term *TxPowerInc* in the frequency reuse efficiency equation. This equation presented in [P2] is not reported elsewhere in literature, it is one of the important outcomes of the work in this thesis.

$$F_r = \frac{1}{1 + TxPowerInc \cdot i} \tag{2.14}$$

Also in Equation (2.8) i should be replaced with term $TxPowerInc \cdot i$ in case the mobile station transmit power increase is significant, i.e. in the case of slowly moving mobile station.

Soft handover gain is discussed already in [45]. Handovers – soft or hard – provide gain against shadow fading by reducing the required fading margin. Due to the fact that the slow fading is partly uncorrelated between cells, and by making handovers, the mobile can select a better communication link. Furthermore, soft handover (macro diversity) gives an additional gain against fast fading by reducing the required E_b/N_0 relative to a single radio link. The amount of gain is a function of mobile speed, diversity combining algorithm used in the receiver and channel delay profile. More about the SHO gain can be found in [44].

The dimensioning methodology has been compared with static simulations (see the following section) in [P3]. The results indicate that the accuracy of the dimensioning is adequate for the initial estimation of the required network configuration.

Earlier works related to the CDMA capacity estimation are the “classical” CDMA references: [45]- [49], [63]. None of these references discusses the dimensioning for multi-service environment. The classical loading equation is presented, but the impact of

power control to the loading definition, or the impact of the power control to the radio link budget is not adequately discussed. The process as in [P2] describing how to utilize analytical methods to determine the initial site density fulfilling given capacity and quality requirements are not addressed.

2.2.2 Detailed planning

The planning methodology presented here supports multi-service environment, and as such it has not been reported in literature earlier. The author of this thesis has done a major contribution in developing the methodology. Furthermore, the modelling of the impact of TPC and also the mobile station speed on the network performance and capacity is new, and thus not presented earlier in literature.

Link budgets and load equations are effective in demonstrating the fundamental trends and principles prior to commencing detailed planning. Link budgets are associated with studying service coverage. Capacity analysis requires a combination of link budgets and load equations. Sophisticated WCDMA radio network planning tools are based upon the same type of link budgets and load equations as those used in the earlier section. Radio network control tool(s) should assist the network planner in the whole planning process covering dimensioning, detailed planning and finally network optimisation when network is being maintained after implementation.

The planning methodology described here is considered as static. Static meaning that the traffic is generated in terms of discrete mobile stations and during the simulations the mobile stations are stationary and the mobility is only seen in the average E_b/N_0 values allocated for the modelled mobile stations, i.e. depending on the mobile station speed the E_b/N_0 for the same service is different. The derivation of the E_b/N_0 values is based on link level simulations, see [P1], [P4], [P3] and [44].

In the case of WCDMA networks the detailed planning is itself an optimisation process. In the case of the 2G the detailed planning concentrated strongly on the coverage optimisation. The 3G planning is more interference and capacity analysis than just a coverage area estimation. During the course of the radio network planning base station configurations need to be optimised, antenna selections and antenna directions and even site locations need to be tuned as much as possible in order to meet the QoS and the capacity and service requirements with minimum cost. To achieve an optimum result the tool must have knowledge of radio resource algorithms in order to perform operations and make decisions like the real network. Uplink and downlink coverage probability analysis ought to be performed for different services and for common channels to guarantee proper network performance. A detailed description of a planning tool can be found in [P2], [P3] and [38].

When comparing the radio network planning of capacity limited GSM networks and WCDMA networks the actual process does not differ very much. Sites and sectors are placed in the tool and the traffic information is either imported or generated for the planning purposes. The traffic layer is the main differentiating factor in the process. In the case of WCDMA different services need to be considered, the impact of the mobile speed is also taken into account. In the proposed iterative analysis method the traffic is presented as discrete mobile stations, used bit rate and MS speed being attributes to the mobile station. Each service has a speed and multipath profile dependent E_b/N_0 performance requirement and impact of link level performance is taken into account as described below. One source of traffic information can be extracted from 2G networks (provided that the operator has one). Estimates of the future demands can be based on trend analysis based on 2G traffic data.

Uplink and downlink iterations

The target in the uplink iteration is to allocate the mobile stations' transmit powers so, that the interference levels and thus the base station sensitivity values converge. In the traditional coverage planning processes the base station sensitivity value is the same for each base station. In the case of CDMA the base station sensitivity level is corrected with the estimated uplink interference level (noise rise), and therefore the base station sensitivity level is cell specific. The impact of the uplink loading to the sensitivity is taken into account with a term (1-η) where η is according to (2.15).

$$\eta = \frac{I}{I+N} = \frac{I_{own} + I_{oth}}{I_{own} + I_{oth} + N} \tag{2.15}$$

where I_{own} and I_{oth} are own cell and other cell interference, respectively, and N is the background and receiver noise. In the uplink iteration the transmit powers of the mobile stations are estimated based on the sensitivity level of the best server, service, speed and link losses. Transmit powers are then compared to the maximum allowed transmit power of the mobile stations and mobile stations exceeding this limit are put to outage. After this the interference can be re-estimated and new loading values and sensitivities for each base station are assigned. If the uplink loading is higher than the set limit, mobile stations are randomly moved from the highly loaded cell to another carrier (if spectrum allows) or to outage.

As presented in [P3] the aim of the downlink iteration is to allocate correct base station transmit powers towards each mobile station until each mobile station has received the signal with the targeted carrier to interference ratio. The carrier-to-interference-ratio of one link, n, of a mobile station $(C/I)_n$, is

$$\left(\frac{C}{I}\right)_n = \frac{p_n / L_n}{(1-\alpha)(P - v_n p_n)/L_n + I_{oth} + N} \tag{2.16}$$

Where α is the cell specific orthogonality factor, P is the total transmit power of the base station, L_n is the path loss from the own cell to the mobile station n, v_n is the voice activity factor, p_n is the power allocated to link n of a mobile station, I_{oth} is the other cell interference and N is the background and receiver noise. The estimation of the correct transmit power requires iteration, since the C/I at each mobile station depends on the powers allocated to the other mobile stations. All soft handover connections of a mobile station are maximal ratio combined. Similar iterative approach for single service has been presented in [50] and [51]. For more details on uplink and downlink iterations see [P2]and [P3].

Modelling of Link Level Performance

The issues presented in this subsection are related to the modelling of the link level simulation results in a planning tool. The idea as such is new and importance of such modelling is easy to demonstrate (for example in [P4]). This is one of the main findings of this thesis, and the author of this thesis's contribution in this area was significant.

In cellular radio network dimensioning and planning it is necessary to make simplifying assumptions concerning the multipath propagation channel, transmitter and receiver. A traditional model is to use the average received E_b/I_o ensuring the required quality of the service, which includes the effect of the power delay profile. In systems using fast power control, e.g. in WCDMA, the average received E_b/I_o is not enough to characterize the influence of the radio channel on the network performance. Also the transmit power distribution must be taken into account when modelling link level

performance in network level calculations. An appropriate approach is presented in [P1] to [P3] and [44] for the WCDMA uplink. It has been demonstrated, that due to the fast power control operating in multipath fading environment, in addition to the average received E_b/I_o requirement, an average transmit power raise is needed in interference calculations. Furthermore TPC headroom must be included in the link budget estimation to allow power control to follow the fast fading at the cell edge.

The modelling in the simulator takes multiple links into account when estimating the gains in average received and transmitted power and also in the required power control headroom due to the soft handover (SHO). The gains in SHO are achieved, firstly because of all the base stations in the active set the best received frame can be selected/combined on a frame-by-frame basis and secondly because the fast power control does not anymore have to compensate for the deepest fades. During the simulations the mobile station transmit powers are corrected for each mobile station with a voice activity factor, SHO gain and average power rise due to fast power control.

In general, it can be noted that importing or combining the system level simulation and link level simulation has been the trend when wanting to perform accurate analysis for new system features. Examples of such simulators for GSM side can be found in [52] and [53]. Novel dynamic WCDMA simulator is introduced in [54] and [55]. The simulators with this level of modelling detail are bound to perform relatively slowly; one simulation round can take several days.

The accuracy of the proposed static prediction method with enhanced power control and soft handover modelling has been questioned by operators. Therefore a simulation campaign was conducted with static simulator ([P2], [P3]) and dynamic simulator described [54] and [55]. In the case of dynamic simulator the mobile stations physically move during the simulations, and power control and other RRM functionality are modelled as accurately as possible. The results presented in [P3] show that static predictions can be utilised with reasonable accuracy especially if the bit rate is reasonably small. The work in [P3] was done up to 64 kbps. Furthermore, it can be stated that the static simulation results can be used as first QoS estimates for the WCDMA cellular network.

2.2.3 Impact of link level performance modelling on the planning result

In this section the impact of the advanced modelling in the planning tool is demonstrated. A multi-service case has been planned and analysed. Furthermore, the impact of the mobile station speed has been demonstrated. The case uses strong engineering approach, but its relevance is in the applicability of the results. In addition to that, this case demonstrates that the novel modelling supports more accurate WCDMA network planning. The author of this thesis has major contribution in publishing these results. Corresponding results cannot be found in any CDMA engineering handbooks or other references.

The results are based on work documented in [P4].

In this case study an area in Espoo, Finland was planned, the planned area being roughly 12x12 km^2, shown in Figure 2.4. In the planning phase the coverage probability requirements for the 8 kbps, 64 kbps and 384 kbps service were set to 95%, 80% and 50% or better, respectively. The planning phase started with radio link budget and site distance estimation and site location selections. In the next planning step the dominance areas for each cell were optimised. In this context the dominance is related only to the propagation conditions. Antenna tilting, bearing and site locations can be tuned to obtain clear dominance areas for cells. The dominance area optimisation is crucial for the interference, and soft handover area and soft handover probability control. The improved

soft/softer handover and interference performance is automatically seen in the improved network capacity. The final plan consists of 19 three-sectored macro sites. In the city area the uplink loading limitation was set to 75%. In case the loading was exceeded, necessary amount of mobile stations were randomly set to outage from the highly loaded cells. The user distribution used in the simulations is seen in Table 2.1.

Table 2.1. The user distribution [P4].

Service in kbps	Users per service
8 kbps	1735
64 kbps	250
384 kbps	15

Three mobile station speed cases were simulated: 3 km/h, 50 km/h and a mixed case. In the mixed case half of the users were pedestrian (3 km/h) and the other half moved with the speed of 50 km/h. The other simulation parameters are listed in Table 2.2.

Table 2.2. Parameters used in the simulator [P4].

Parameter	Value
Uplink loading limit	75%
Base station maximum transmit power	20 W
Mobile station maximum transmit power	300 mW
Mobile station dynamic range	70 dB
Shadow fading correlation between base stations	50%
Standard deviation for the shadow fading	6 dB
Channel profile	ITU vehicular
Mobile station speeds	3 km/h and 50 km/h
MS/BS noise figures	7 dB/5 dB
Soft handover window	- 6 dB
CPICH power	30 dBm
Combined power for other control channels	30 dBm
Orthogonality	50%
Activity factor speech/data	50%/100%
BS antennas	65° / 17 dBi
MS antennas	Omni / 1.5 dBi

The service distribution of Table 2.1 was used to generate the basic loading situation in the network. A total of 2000 mobile stations were generated for the simulation.

In all of the three simulation cases the cell throughput in kbps and the coverage probability for each service was of interest. Furthermore, the soft handover probability and loading results were collected. The simulation results for cell throughput and coverage probabilities are collected into Table 2.3.

The results show that the mobile station speed has an impact on both the throughput and the coverage probability. It can be seen that in the case of mobile stations moving at the speed of 50 km/h, less mobile stations can be served, the throughput is lower and the resulting loading is higher than in the case where the mobile stations are moving at the speed of 3 km/h. If the throughput values are normalised to correspond to the same

loading value, the difference is more than 20% when comparing the 3 km/h and the 50 km/h cases. The better capacity with the lower speed mobile stations can be explained with the better E_b/N_0 performance. The fast power control is able to follow the fading signal and the required E_b/N_0 target is reduced. The lower target value is reducing the overall interference level and more users can be served in the network.

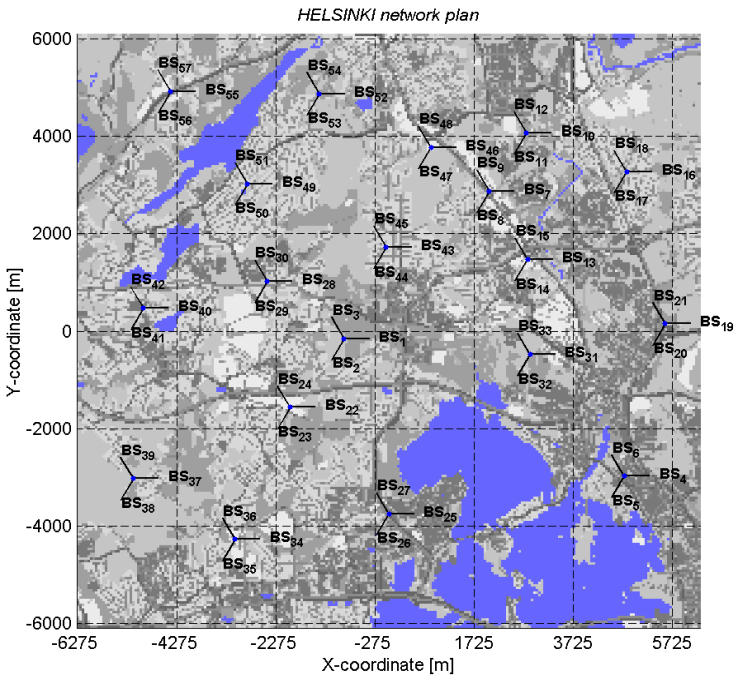

Figure 2.4. The network scenario. The area is 12x12 km^2, and it is covered with 57 cells [P4].

When comparing the coverage probability results, the faster moving mobile stations experience better quality than the slow moving mobile stations. As it is explained in [P4] the fast fading margin for the higher speed mobiles stations is reduced and thus the coverage probability improved. The impact of the speed can be seen especially if the used bit rates are high because for low bit rates the coverage is better due to a larger processing gain. The coverage is tested with a "probe" MS after the iterations have converged. Similar type of probe approach is introduced in [56]. In this thesis it is assumed that the test MS does not change the loading of the network. The soft handover overhead gives an indication of the amount of soft handover connections in the network. The total number of connections, I, in a cell can be estimated with

$$I = (1 + SHO) \cdot K_N \tag{2.17}$$

where K_N is then number of mobile stations in a cell, and SHO is the soft handover overhead value in the cell in question.

The coverage probability analysis for the downlink traffic channel is different from the uplink one. In the uplink direction the limiting factor is the mobile station maximum transmit power. In the downlink direction the limitations are dependent on the used radio resource management algorithms. One limitation in the downlink direction is naturally the total base station transmit power, and, in addition to that, another limit can be taken into use: the power limit per radio link. In Figure 2.5 there is an example of the downlink coverage analysis for the speech service. It can be seen that if the power per link limitation is selected correctly, the downlink coverage probability can be set to the same value as the uplink coverage probability. Thus, the uplink and the downlink service areas

can be balanced. The required powers per link in Figure 2.5 are the average powers and they do not include the fast fading margin.

Table 2.3 a. The cell throughput, loading and soft handover (SHO) overhead. UL = UpLink, DL = DownLink [P4].

Basic loading: MS speed 3 km/h, served users: 1805.				
cell ID	ThroughputUL kbps	ThroughputDL kbps	UL loading	SHO overhead
cell 1	728.00	720.00	0.50	0.34
cell 2	208.70	216.00	0.26	0.50
cell 3	231.20	192.00	0.24	0.35
cell 4	721.60	760.00	0.43	0.17
cell 5	1508.80	1132.52	0.75	0.22
cell 6	762.67	800.00	0.53	0.30
MEAN (all cells)	519.20	508.85	0.37	0.39
Basic loading: MS speed 50 km/h, served users: 1777.				
cell ID	ThroughputUL kbps	ThroughputDL kbps	UL loading	SHO overhead
cell 1	672.00	710.67	0.58	0.29
cell 2	208.70	216.00	0.33	0.50
cell 3	226.67	192.00	0.29	0.35
cell 4	721.60	760.00	0.50	0.12
cell 5	1101.60	629.14	0.74	0.29
cell 6	772.68	800.00	0.60	0.27
MEAN	531.04	506.62	0.45	0.39
Basic loading: MS speed 50 km/h and 3 km/h, served users: 1802.				
cell ID	ThroughputUL kbps	ThroughputDL kbps	UL loading	SHO overhead
cell 1	728.00	720.00	0.51	0.34
cell 2	208.70	216.00	0.29	0.50
cell 3	240.00	200.00	0.25	0.33
cell 4	730.55	760.00	0.44	0.20
cell 5	1162.52	780.92	0.67	0.33
cell 6	772.68	800.00	0.55	0.32
MEAN	525.04	513.63	0.40	0.39

Table 2.3 b. The coverage probability results [P4].

Basic loading: MSs 3 km/h	Test MS speed: 3 km/h	50 km/h
8 kbps	96.6%	97.7%
64 kbps	84.6%	88.9%
384 kbps	66.9%	71.4%
Basic loading: MSs 50 km/h	Test MS speed: 3 km/h	50 km/h
8 kbps	95.5%	97.1%
64 kbps	82.4%	87.2%
384 kbps	63.0%	67.2%
Basic loading: MSs 3 and 50 km/h	Test MS speed: 3 km/h	50 km/h
8 kbps	96.0%	97.5%
64 kbps	83.9%	88.3%
384 kbps	65.7%	70.2%

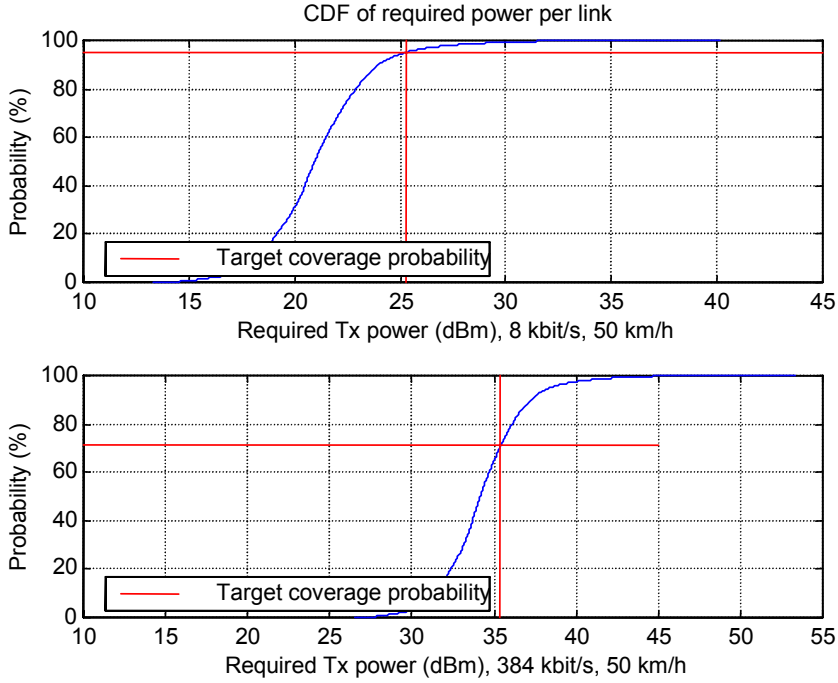

Figure 2.5. An example of the downlink coverage analysis. For the speech service (8 kbps, 50 km/h) the limit for the radio link was set to 25 dBm to achieve the 95% coverage probability. In the case of the 384 kbps and 71% coverage probability requirement the limit per radio link would be 35 dBm [P4].

The results of this section demonstrate two issues.

- It is shown that the mobile station speed as one attribute in the planning process has an impact to the capacity and quality results of the radio network plan. In terms of capacity it is seen that lower mobile station speed provides better throughput. When comparing the coverage probability results (quality) the impact of the mobile station speed is opposite. The higher speed reduces the required fast fading margin and thus the coverage probability is improved when the mobile station speed is increased.
- The accurate traffic modelling is a new challenge for the radio network planning phase. In addition to the traffic and service distribution one should be able to estimate the distribution of the mobility of the users in the network. It is clear that such a demand is not feasible. Therefore, the results presented in this section support the claim that the statistical feedback loop form the network is needed to support the pre-operational planning.

It is clear that for a thorough analysis of a network one simulation run is not enough, but multiple mobile station distributions and different traffic scenarios should be tested. Nevertheless, the results shown here indicate, that for an operator the capacity and quality optimisation of the network is more successful if, in addition to the used bearer service, the impact of mobile station speed can be used as an input.

2.2.4 Impact of site configuration on the radio network performance

Due to the fact that the WCDMA shall be capacity limited optimisation in terms of interference control already in the planning phase is essential. Also means to support fast roll out of the network are important. The study of [P5], even if applying a strong

engineering approach, demonstrates the usability of MHA. Furthermore the effect of antenna selection on the interference situation and thus the capacity is verified.

In addition to the TPC modelling, the findings of the sectorisation study have been implemented to the CDMA loading equation, which is new in literature. Furthermore, correct values (depending on service and site configuration) for variables in the equation are provided. This fact makes the work here also an important engineering reference for cellular operators.

In WCDMA networks coverage is generally uplink limited although a low base station transmit power capability combined with asymmetric data services may lead to a downlink coverage limited scenario. Capacity may be either uplink or downlink limited depending on the planned level of uplink loading, the base station transmit power capability, the traffic loading the network, and the performance of the base station and mobile terminals. There are several means to improve the WCDMA network's capacity or coverage performance. These include:

- Sectorisation
- Diversity reception
- Use of mast head amplifier
- Use of repeaters
- Use of hierarchical cell structures
- Use of roll out optimised configuration [40]
- Use of transmit diversity
- Use of beam forming

With the help of the following examples, their influence on the network capacity and coverage is demonstrated.

Sectorisation, antenna tilt and MHA study case

In this study the scenario was situated in the Shinjuku area in Tokyo, assuming all users to be indoors (this causes 12 dB additional loss to the link budget). For the multipath channel profile the ITU vehicular A channel was assumed. The 13.5 km^2 area was covered with 10 sites. The selected antenna installation height was 50 m, the propagation loss was calculated with the Okumura-Hata model, with average area type correction factor of –4.1 dB. In the simulations, omni-, three-, four- and six-sector configurations have been used, the site locations were kept fixed. The network scenario with six-sector implementation can be seen in Figure 2.6.

5 different antennas were used in the simulations with 3 dB beam widths of 120°, 90°, 65°, 33° and additionally an omni antenna. The gains of all antennas was set to 15 dBi and for the SHO window a value of –4 dB was used, i.e. all sectors whose P-CPICH is received within –4 dB of the strongest P-CPICH are included into the active set. A service mix of voice users (8 kbps), circuit switched data users (64 kbps) and packet data users (144 kbps) was assumed. The exact traffic information used in this work can be found in [P5].

This study consists of three cases.

- In the first analysis case the impact of the antenna tilting was of interest. Various antenna tilts are simulated to find the optimum.
- In the second part the influence of the usage of MHA in uplink was studied. For each sectorisation simulations with and without MHA are compared.
- In the third part the capacity improvement as a function of sectorisation and antenna selection is illustrated.

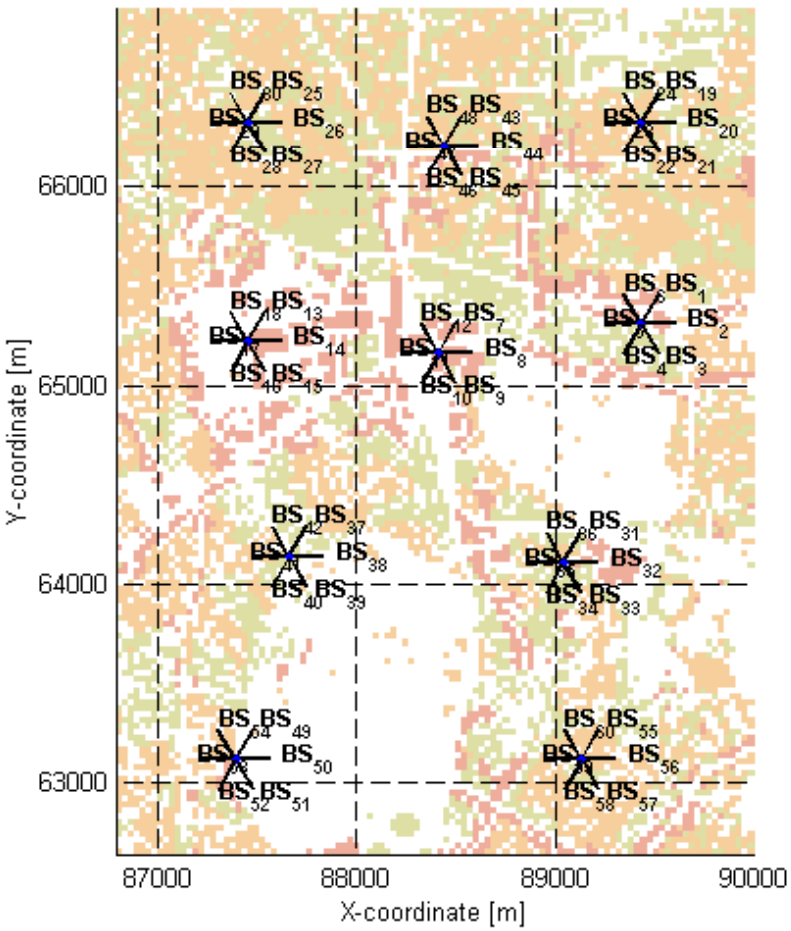

Figure 2.6. Example of a network scenario for the six sectored base stations in the Shinjuku case [P5].

In the antenna tilting study the electrical tilting was applied and with the help of the results it can be seen that an optimum tilt angle can be found, and it must be noted that the capacity and the coverage probability both have to be considered. The results of this study are collected in Table 2.4.

In these simulations the optimum tilting angle is from 7° to 10°. The relative high optimum tilt angle can be explained by the big antenna installation height (50 m). From the Table 2.4 figures can be seen the trend that by down tilting the antennas, the other to own cell interference ratio *i* is going down as the tilting is increased. This is because the antenna main beam does not deliver so much power towards the other base stations and therefore most of the radiated power goes to the area that is intended to be served by this particular base station. At the same time the network could also serve more users than without tilting the antennas. There is always some optimum value for the tilting, which depends on the environment, site and user locations and the antenna radiation pattern. If the tilting angle is too big, the service area could go down and the base station is not able to serve as big an area as without excess tilting. This is seen from the numbers of uplink coverage probability that also has some optimum value. Due to antenna radiation pattern side lobes and nulls there could be some variations of *i* and coverage probability as a function of tilting angle.

Table 2.4. Examples of the impact of the antenna tilt on the network capacity. MHA in use. MS maximum transmit power 24 dBm. In DL in case the base station maximum transmit power is exceeded, the connections are randomly put to outage [P5].

Antenna tilt	Other to own cell interference ratio, i	Served users	Soft handover overhead	UL coverage probability (outdoor to indoor) for 8/64/144 kbps
OMNI CASE				
0°	0.79	239	28%	70 / 32 / 40%
THREE SECTORED CASE, 65° antenna				
0°	0.88	575	40%	86 / 59 / 62%
4°	0.75	624	39%	91 / 71 / 72%
7°	0.59	697	36%	92 / 76 / 76%
10°	0.37	856	30%	90 / 75 / 74%
14°	0.38	787	32%	81 / 62 / 61%
FOUR SECTORED CASE, 65° antenna				
0°	1.09	604	41%	92 / 70 / 71%
4°	0.94	707	30%	95 / 81 / 81%
7°	0.72	833	26%	96 / 84 / 83%
10°	0.47	959	21%	94 / 82 / 81%
14°	0.50	886	26%	86 / 69 / 68%
SIX SECTORED CASE, 33° antenna				
0°	1.15	880	48%	93 / 76 / 76%
4°	1.03	946	49%	96 / 83 / 83%
7°	0.88	1037	45%	96 / 85 / 84%
10°	0.73	1054	41%	95 / 83 / 82%
14°	0.58	930	33%	86 / 70 / 69%

In the second part of the study the usability of a low noise masthead amplifier (MHA) is demonstrated. The MHA is used in the uplink direction to compensate for the cable losses and thus reducing the required mobile stations' transmit powers. The three- and four-sectored scenarios have been simulated with the 65° antenna and the six-sectored case applied the 33° antenna. In all cases the antenna tilt used was 7° and the maximum MS power was 27 dBm. The MHA simulation results are collected in Table 2.5.

Table 2.5. The impact of the MHA. MS maximum power 27 dBm. Antenna tilt 7°. In DL in case the BS maximum transmit power is exceeded the connections were randomly put to outage [P5].

	Other to own cell interference ratio, i	Served users in UL	Served users in DL	UL coverage probability (outdoor to indoor) for 8/64/144 kbps
THREE SECTORED CASE, 65° antenna				
no MHA	0.60	1038	807	93 / 78 / 78%
with MHA	0.61	1064	746	95 / 82 / 82%
FOUR SECTORED CASE, 65° antenna				
no MHA	0.73	1089	884	96 / 86 / 85%
with MHA	0.73	1107	846	98 / 89 / 89%
SIX SECTORED CASE, 33° antenna				
no MHA	0.88	1124	1052	97 / 87 / 86%
with MHA	0.90	1132	1021	98 / 90 / 90%
no MHA, 4 dB cable losses	0.88	1109	1057	95 / 83 / 82%
with MHA, 4 dB cable losses	0.90	1132	1016	98 / 90 / 90%

The results of Table 2.5 indicate that by using a MHA the performance in uplink can be improved also in WCDMA systems. In all the cases the number of users that can be served in uplink has been increased due to the increased sensitivity. Also the coverage probability is bigger when deploying a MHA. In the six-sectored case, the influence of MHA has also been bigger when assuming bigger cable losses in UL (4 dB instead of 2 dB). Table 2.5 however also shows that the scenarios are downlink limited, and having more MSs on the uplink actually decreases the DL performance. In all the cases the DL capacity was smaller when using a MHA in UL. The reason could be that if more users can be served in UL, the transmit powers in DL are increased due to more SHO connections and thus reducing DL capacity.

In the third analysis case, which illustrates the capacity improvement as a function of the sectorisation, each base station has been simulated as omni-site and as a site with three, four or six sectors. Furthermore, by simulating the scenarios with antennas having different beam widths, the importance of a correct antenna selection for a sectored configuration is emphasised with help of some examples. For all scenarios the MHA was in use, the maximum MS transmit power was 24 dBm and antennas were not tilted. The results related to the sectorisation study are in Table 2.6.

Table 2.6. The impact of the antenna selection in the sectorisation case. MS maximum power 24 dBm, MHA in use. No antenna tilt [P5].

Antenna 3 dB beam width	Other to own cell interference ratio, i	Served users	Soft handover overhead	UL coverage probability (outdoor to indoor) for 8/64/144 kbps
OMNI CASE				
omni	0.79	240	28%	70 / 32 / 40%
THREE SECTOR CASE				
120°	1.33	441	39%	85 / 50 / 59%
90°	1.19	461	35%	87 / 55 / 62%
65°	0.88	575	34%	86 / 59 / 62%
FOUR SECTOR CASE				
120°	1.72	489	54%	90 / 62 / 68%
90°	1.49	510	51%	92 / 67 / 72%
65°	1.09	604	41%	92 / 70 / 71%
33°	0.92	691	40%	88 / 65 / 64%
SIX SECTOR CASE				
120°	2.18	593	64%	95 / 75 / 79%
90°	1.97	627	59%	96 / 80 / 82%
65°	1.43	758	55%	96 / 80 / 81%
33°	1.15	880	48%	93 / 76 / 76%

In the case with the omni sites, coverage is very poor and only 240 users could be served. Already in uplink the network is heavily overloaded. There is almost an equal amount of MS going to outage because of too high load and because of the MS running out of power. In all the sectored cases the uplink outage reason is the MS not having enough power. However the downlink is even more limiting and more mobiles are going to outage. Table 2.6 clearly indicates that with higher sectorisation, more mobiles can be served. Another observation that can be made from the results is that for each sectorisation case the selection of the antenna beam width is important. To achieve the highest number of served users it is very crucial to effectively control the interference and soft handover overhead. If the overlap in the sectors is too big, interference leaks to the other sector directly reducing its capacity. Another effect of the antenna beam being

too wide is the waste of hardware resources and increased downlink transmit powers due to too large soft handover overhead.

In the simulations, the 65°-antenna was optimum for the three sectored case and the 33°-antenna was best for the four- and six-sectored scenario. It can be stated that with rather simple radio network planning means (antenna tilting and correct antenna selection for each scenario) the interference can be controlled and the capacity of the network improved. In the antenna tilting study the electrical tilting was applied and with the help of the results it can be seen that an optimum tilt angle can be found. In Figure 2.7 the effect of tilting to the other to own cell interference ratio (*i*) is depicted. Figure 2.8 demonstrates the impact of tilting on the speech coverage.

In the simulations presented in the study each of the base stations was optimised in a similar manner. In reality the base stations antennas are not installed at equal height and thus the optimisation of the base stations should be performed site by site.

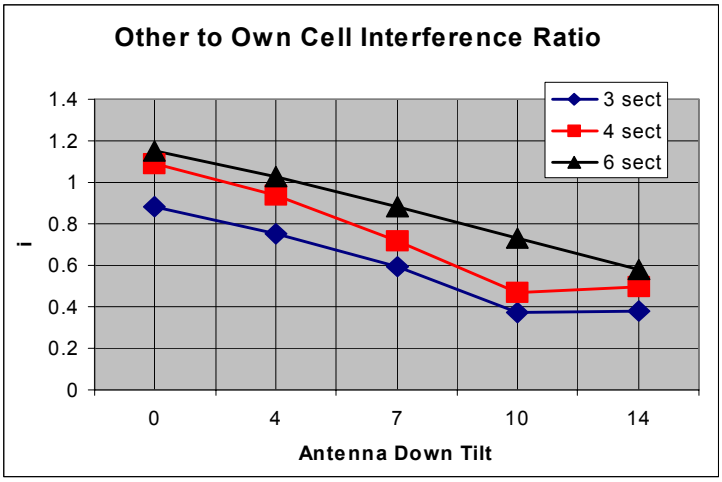

Figure 2.7. Impact of antenna tilt on interference situation. Interference wise all configurations have optimum antenna beamwidth.

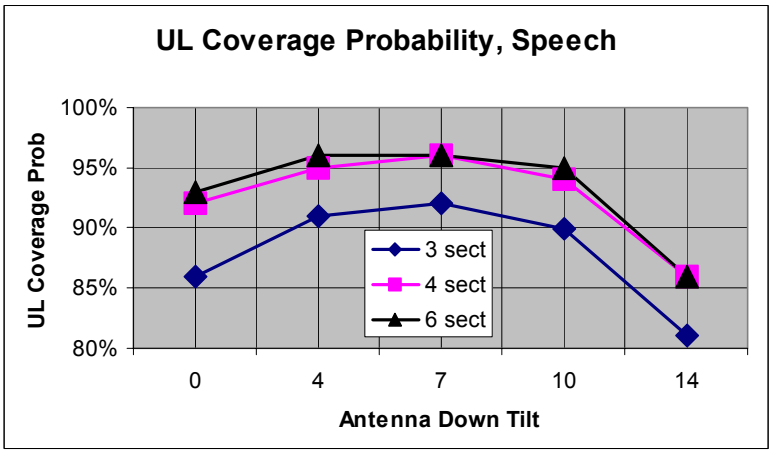

Figure 2.8. Impact of antenna tilt on uplink coverage probability (speech service). Interference wise all configurations have optimum antenna beamwidth.

In this study it has also been demonstrated that the MHA is also feasible in the WCDMA networks. However the benefit is rather small when the system is strongly downlink limited and thus the uplink sensitivity improvement is not so beneficial.

Furthermore, in the case of high uplink operation point (i.e. the interference level is high compared to the basic noise level) the MHA does not bring any gains. The results in Table 2.5 indicate that the QoS can be improved in the uplink direction in lightly loaded networks with MHA. In all of the simulated cases the coverage probability was increased when the MHA was in use. How much of the uplink capacity improvement can be utilised in the downlink direction in case of a MHA depends naturally on the current downlink loading situation and the admission and load control strategies implemented in the network.

The results of this study also clearly show that the higher sectorisation offers more capacity to the network but to achieve this the antenna selection is very crucial to effectively control the interference and soft handover overhead. For each sectorisation case an optimum antenna beamwidth exists, see Figure 2.9.

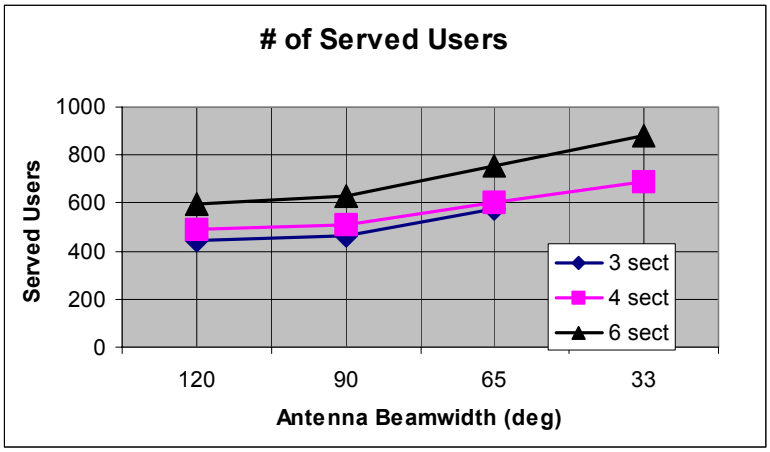

Figure 2.9. Impact of antenna beamwidth to capacity (in terms of users).

Impact of diversity on the WCDMA performance

Receive diversity provides an effective technique for both overcoming the impact of fading across the radio channel and increasing the received signal to interference ratio. The former is achieved by ensuring "uncorrelated" (i.e. low enough correlated) fading between antenna branches i.e. not all antennas experience fades at the same time. The latter is achieved by ensuring uncorrelated interference i.e. coherently combining two branches of the desired signal results in a 6 dB increase in power whereas combining two branches of uncorrelated interference results in a 3 dB increase in power. In general, the standard configuration for a WCDMA base station includes 2-branch receive diversity achieved with a single cross polar antenna (polarisation diversity) or two vertically polarised antennas (space diversity). In [P6] the diversity performance evaluation is done for TDMA system, when comparing the results with simulated results of [57] it is seen that the diversity gain in both cases is at the same level. In the case of diversity reception in WCDMA the optimal number of receiver branches depends upon the particular radio environment. Furthermore, WCDMA wideband signal results in a high delay spread resolution permitting potentially large gains from multipath diversity. In terms of uplink diversity gain multipath diversity has a significant impact on the gain that can be achieved from higher order receiving diversity. The results of [P6] are furthermore relevant also in the WCDMA case, when the number of antennas implemented at sites needs to be limited. Based on the results it can be concluded that space diversity antennas

can be replaced with polarisation diversity antennas and thus the physical number of antennas to be implemented at sites shall decrease.

When comparing results of [P1] (single cell case) and [44] (multi-cell case) it can be concluded that receive diversity improves both the uplink fast fading margin as well as the uplink E_b/N_0 requirement. Improving the E_b/N_0 requirement results in a simultaneous improvement of both service coverage and uplink system capacity. The E_b/N_0 requirement appears in both the link budget and load equation meaning that the uplink coverage and capacity are simultaneously improved.

2.3 WCDMA optimisation

The scope of this section is to introduce the network quality cycle and cost function approach in the optimisation of future networks. In Section 2.3.3 the advance analysis methods to support the quality cycle are introduced.

2.3.1 Network quality cycle [P8]

Introduction of the third generation cellular system will offer numerous possibilities for operators. Already the introduction of GPRS into GSM networks is changing the operation environment from circuit switched to the combination of real time and non real time services. The 3G traffic classes (conversational, interactive, streaming, background), QoS provisioning mechanisms and possibility for customer differentiation, together with the joint management and traffic sharing between 2G and 3G networks provide challenging playground on one hand for vendors, and on the other hand for service providers and network operators. To be able to fully utilise the resources and to focus on the service provision rather than trouble shooting, advanced analysis methods to for optimisation process are required. The high level description of the optimisation cycle is depicted in Figure 2.10.

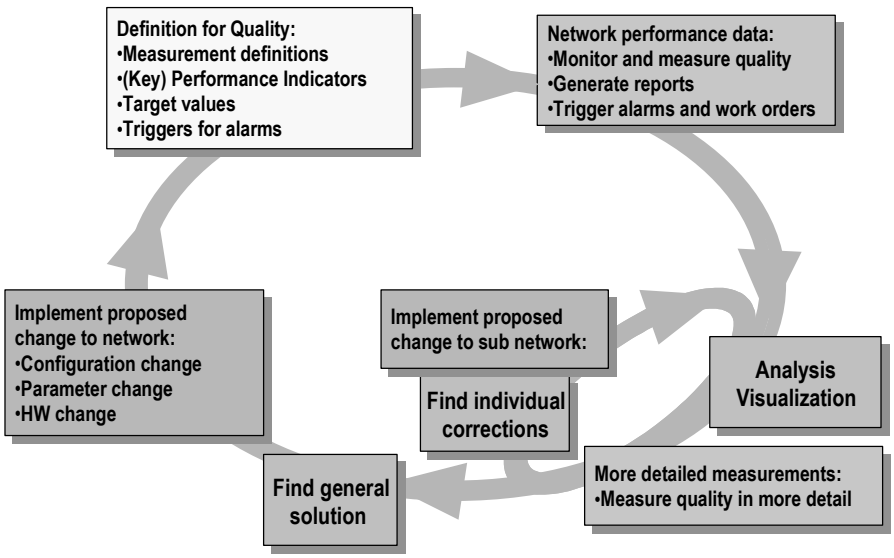

Figure 2.10. Optimisation process with the network quality cycle [P8].

The process starts with the quality definition. The overall end-to-end quality target is defined and for each service type the quality criteria are determined. The thresholds are then set for each related key performance indicator (KPI). It is important to note that

when setting the KPI targets, the operator provides the tools for capacity-quality trade-off management. Network performance data can be gathered from Network Management Systems (NMS), drive tests, protocol analysers and/or customer complaints. Network reporting tools provide statistical and pre-analysed information about the quality. Based on the network configuration and status of the network, quality in detail is analysed and individual corrections are done iteratively by solving the individual parameters affecting the reported quality. Tuning of the individual parameters or parameter sets is carried out in an iterative loop until the quality is met. Finally, in addition to tuning single parameters, the general solution has to be found. After the corrections have been implemented to the network, the quality cycle starts from the beginning.

The selection of the data for performance analysis consists of two aspects. Firstly the data is selected based on functional area (or subset of that) i.e. accessibility, reliability, traffic performance and distributions, to mention a few examples. All these functional areas are targeted to offer a picture of the end user perceived quality. Good framework for this is provided by [62]. The other aspect is the purpose of the analysis. For getting an overall performance evaluation of the network the selection of the counters and other performance indicators is different from those one would choose for optimisation or trouble shooting cases. The optimisation case is more focused and thus more problem specific indicators are required. In addition, uplink and downlink are often analysed separately. After the optimisation has been performed and the changes implemented in the network, it is essential to check the function of the optimisation target, but equally important it is to derive the overall performance distribution and compare it to the pre-optimisation case. This is done to avoid the phenomenon, that optimisation improves one subset of a functional area, but drastically decreases the performance of some of the others. If we inverse the case: general performance information gives an indication that there is degraded operation in a functional area. To be able to derive the actual problem and find a solution for it, it is mandatory to change from the generic data set to a more focused one.

The issues introduced in this section and in [P7], [P8] and [P9] concentrate on the analysis and visualisation part of the quality cycle. Due to the fact that in the future the operation of cellular networks will be strongly service driven, advanced methods for network analysis are required. Compared to the current situation with provisioning of voice and simple best effort data services only, the change in operators' tasks is enormous. Effective analysis of the voice service of 2G networks is currently challenging enough, due to the fact that the amount of data the network elements (including the mobile station itself) produces is very high. Operators' task is to filter the relevant information to a level that can be easily handled. Furthermore, the data set must include all the essential parts needed to conclude the service quality. The whole process from setting up to releasing the call must be included. Performance of hand over and power control has also impact on the quality the end-user experiences and thus items related to those must be included in the speech service analysis already today. It is easy to imagine how the amount of data explodes when the possibilities the 3G systems offer are exploited. Operators already today can benefit from the introduced neural methods. The full gain and potential can be utilized when multiple end-user services are provided, and the quality perceived by the customers need to be monitored and optimised.

2.3.2 Capacity-Quality trade-off and cost function

The role of optimisation is to provide automated or manual means to improve the performance of the network. Furthermore the task of optimisation is to understand and translate the relationship between measured network performance and set QoS targets.

The definition of performance in the case of 3G is changing; it shall be capacity-quality trade-off management, rather than traditional performance improvement. For more about the issue see [64].

With the statistical loop and cost function (CF) approach it is possible to offer automatic coverage-capacity trade-off based network management. With this concept the operator only has to set quality and capacity targets and related costs that regulate the quality-capacity trade-off. A new aspect in this area is the fact that the target of autotuning is not the best quality as traditionally defined. In some cases it might be that slightly degraded quality and the possibility to offer more traffic is more beneficial for the operators business case than the quality driven optimisation. A high level objective is also to integrate WCDMA automation with other systems such as EDGE and WLAN.

The complex operating environment and service level capacity-quality trade-off management set certain requirements for the system providing autotuning features. Figure 2.1 introduced hierarchical solution with a statistical feedback loop to optimise the performance of the two fast RRM loops. The main scope of this section is to present a concept and tools to aid the optimisation on the uppermost layer.

For an operator it is essential to utilise all available resources to improve the capacity and QoS of the radio network and for this an overall control function is required. This control function provides centralised quality monitoring, which monitors optimisation and automation subsystems. In addition, a mechanism for cost function minimisation for optimal capacity, performance and operator revenue is required. Once the cost function is minimised, the task for the network management system is to provision optimal configuration parameters at the network level. To guarantee the optimum performance of a cellular network the operator ought to have flexible means to set the QoS target based on the system KPIs and/or a cost function derived from those. In multi-radio environments (GSM-WCDMA, WLAN) it is important to have the possibility to pool the resources of the networks for optimised *capacity* and *quality* (including coverage aspects). This also requires an overall control functionality on the highest hierarchy level.

Currently manufacturers propose default values for all the parameters. These are not optimal for all conditions. Operator's task is to optimise the network cell cluster by cell cluster. This proposed concept will make the initial parameter settings less crucial: for example in the beginning of the network operation the admission control and handover control could work with very "loose" limits admitting all the users to the network. Based on the current QoS situation (KPIs at network management system (NMS)) and using the set QoS targets the relevant parameters can then be autotuned. After the parameter change the new situation is compared to the KPI history data and 'test' parameters are accepted if the change in the QoS performance (or the CF of the QoS requirements) is improved.

The mathematical formulation of the task can be seen as finding of such a combination of air interface configuration parameters based on which the KPIs are as close to the desired area as possible, see [64]. Firstly the operator sets capacity requirements for certain capacity KPIs denoted KPI_C. The requirements have "req" in the subindex. Correspondingly the operator sets quality requirements for certain KPI_Qs. The quality and capacity costs can then be calculated as in Equation (2.18)

$$QualityCost = \sum_{cells \in CLUSTER} \sum_{i} \alpha_i * f\left(KPI\_Q_i - KPI\_Q_{i,req}\right) \qquad (2.18)$$
$$CapacityCost = \sum_{cells \in CLUSTER} \sum_{i} \beta_i * f\left(KPI\_C_i - KPI\_C_{i,req}\right)$$

Figure 2.11 shows an example of a KPI cost function *f*. In this example the cost of KPI values higher than *KPI_reg* is increasing linearly. The cost functions can also take other shapes.

Total cost function to be minimised is presented in (2.19). Capacity and quality trade-off can be made using the parameter *W*. The minimisation is done by adjusting the configuration parameters, see Equaiton (2.20). The KPI values also depend on the service distribution, e.g. different costs and parameter settings will be achieved depending on the service distribution.

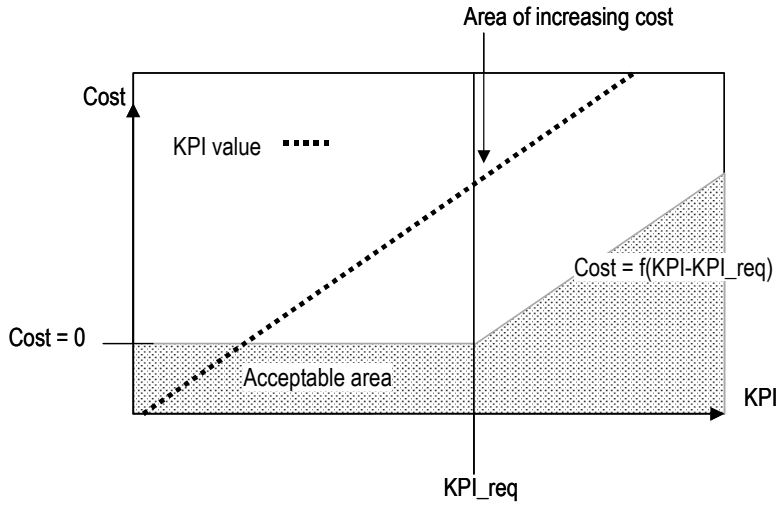

Figure 2.11. Example of a KPI cost function.

$$KPI\_C_i = f(Configuration\ parameters, Service\ Distribution) \quad (2.19)$$
$$KPI\_Q_i = f(Configuration\ parameters, Service\ Distribution)$$

$$Total\ COST = W*QualityCost + (1-W)*CapacityCost \quad (2.20)$$

This NMS level optimisation loop must interface to the network configuration and measurement data as seen in Figure 2.12. Data warehouse represents the interface to any measurement performed in the network in any network element. Configuration Management (CM) represents the database in which all the configuration parameters controlling the network are collected.

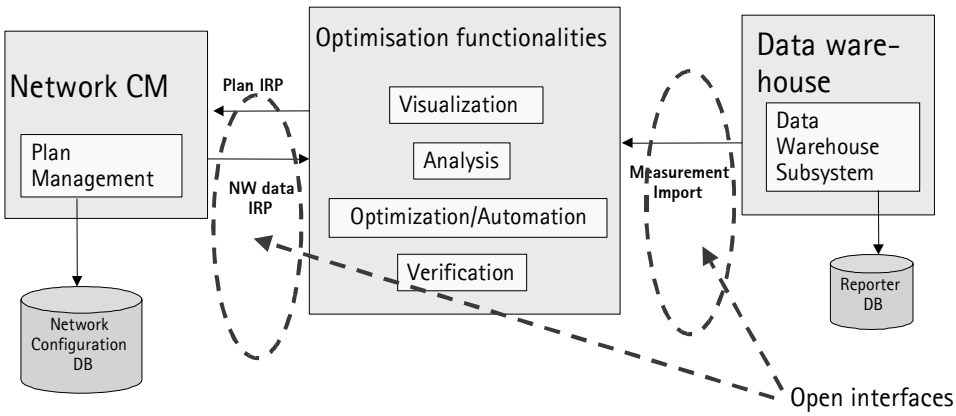

Figure 2.12. Interfaces required in the network wide optimisation (or automation) based on network statistics. CM stands for configuration management.

2.3.3 SOM analysis result example [P8]

In this section the usage of advanced neural methods in WCDMA cellular network analysis are presented. The motivation for the introduction of neural analysis on the network performance data is to provide effective means to handle multiple KPIs simultaneously. Furthermore, effective analysis methods reduce operators' trouble-shooting efforts, speed up the cycle and thus increase the network utilisation rate. In Sections 2.3.3 and 2.3.4 a microcellular example case is studied. The reason for this selection is more challenging propagation conditions than in the macrocellular case (also presented in [P8]) and furthermore, the case consisting of uplink and downlink data is more difficult to analyse with the traditional means. It is relevant to perform this type of combined analysis when general performance analysis of the network is done. Were the situation more related to trouble-shooting, one should not combine the measurements from uplink and downlink in all cases. For more details and cases see [P8].

The Self-Organizing Map (SOM) is a widely used neural network algorithm [65]. It maps a high-dimensional data manifold onto a lower-dimensional, usually two-dimensional, grid or display. The SOM has several beneficial features, which make it a useful tool in data mining and exploration. The SOM follows the probability density function of the data and is thus an efficient clustering and quantization algorithm. However, the most important feature of the SOM in data mining is the visualization property. The topology preserving property of the SOM mapping results in a display inherently visualizing the clusters in the data. The SOM based methods have been applied in the analysis of process data, e.g., in steel and forest industry [66] - [69].

The method described in [P8] has been used to analyse both uplink and downlink direction in microcellular and macrocellular network scenarios. The presented method consist of the following steps[P8]:

- Target selection
- Data pre-processing
- Cluster analysis
- Result interpretation, for more details

The data vectors of all the cells are clustered using two-phase clustering algorithm. First the SOM is trained using the data vectors. Next clustering algorithm is done for the SOM code book vectors so that exact clusters can be defined. When the *data clusters* of the cells are formed the dynamic simulator provides the input data for SOM. In this work the data clusters are further analysed by automatically generated rules in order to find the most qualitative description for the cells within a cluster. Example of this type of data presentation is in Figure 2.13.

In order to analyse sequence of data samples instead of a single data point a histogram map is computed. Histogram consists of proportions of data samples falling in each of the data clusters. These histograms describe the long-term behaviour of data sequences and they are used in the cell classification. A new SOM is generated using the histogram information as the training set. By using a clustering algorithm exact *behavioural clusters* can be generated. Example of this is in Figure 2.14.

A subset of microcellular results are presented in this section. The data used in this work has been generated using WCDMA radio network simulator [54]. Due to the lack of measured data from live network simulated data is used in the advanced analysis cases. In the case of real data there would be a possibility to analyse more KPIs simultaneously. The users in the network were using 64 kbps service and admission control was parameterised so that uplink interference level was not limiting the admission decision. The scenario consists of 46 microcells. In this scenario the multipath channel profile the ITU Outdoor to Indoor A channel was assumed. In the test scenario

the area of Helsinki was used. The propagation loss was estimated with ray-tracing , and an additional indoor loss of 12 dB was applied in areas inside buildings. For more details related to the simulation parameters and the network scenario see [P8].

For the analysis of combined uplink and downlink direction in microcellular scenario, five variables (KPIs in this case) have been selected, they are number of users (nUsr), uplink average noise raise relative to basic noise floor (ulANR), uplink frame error rate (ulFER), downlink average transmission power (dlTxp) and downlink frame error rate (dlFER). The frame error rate values are pre-processed using *tanh* function to be able to see the changes also at lower error rate level. All the parameters are also normalized to zero mean and unit variance.

Figure 2.13 shows the clustered SOM. The data samples are divided into 5 data clusters, of which the cluster 3 in the lower right corner represents data samples with high dlFER (downlink quality problems) and cluster 4 data samples with acceptable dlFER but high ulFER (uplink quality problems).

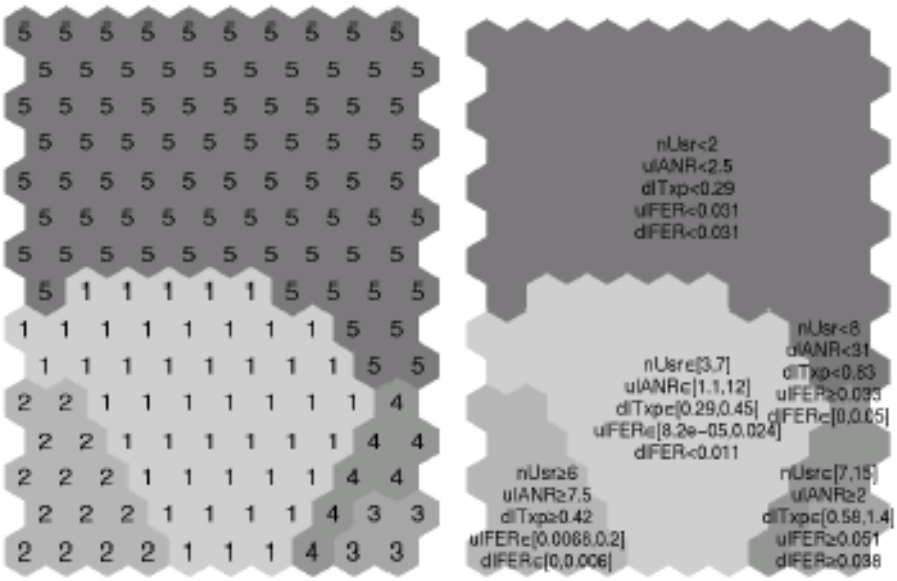

Figure 2.13. Clustered SOM for combined uplink and downlink case and rules for clusters in microcellular scenario [P8]. *Data Cluster.* Colours in the figure have no other meaning than to show the areas of the clusters.

In Figure 2.14 the corresponding histogram map and *behavioural clusters* for combined uplink and downlink data for the microcellular scenario is shown. The bars in the histograms indicate the amount of samples in data clusters of Figure 2.13. The first bar in the histogram is characterised with the rules of the data cluster 1 in Figure 2.13.

The highest proportion of samples that fall in *data clusters* 3 and 4 in Figure 2.13 is in *behavioural cluster* 4 on the histogram map, i.e. in Figure 2.14. This can be found by looking for the map nodes (i.e. hexagons) in which the 3rd and 4th bar are highest. Also, two map nodes in behavioural cluster 1 indicate high amount of samples in data cluster 3 (i.e. third bar in histogram), that is, samples with highest dlFER value in Figure 2.13. Other characteristics for data cluster 3 can be found in the lower right corner of Figure 2.13.

In the combined uplink-downlink case the dominant behavioural clusters are 2, 3 and 7. Typical for these clusters is the number of users ranging from low to medium, high correlation of the number of users and the used resources (i.e. good control of external interference) and good FER performance. Each of the cells in this area are capable to

serve the users with high probability and good quality. As can be seen from Figure 2.13 these cells fit to the rules for data clusters 1 and 5 in Figure 2.14. The geographical locations of the clustered cells are depicted in Figure 2.16.

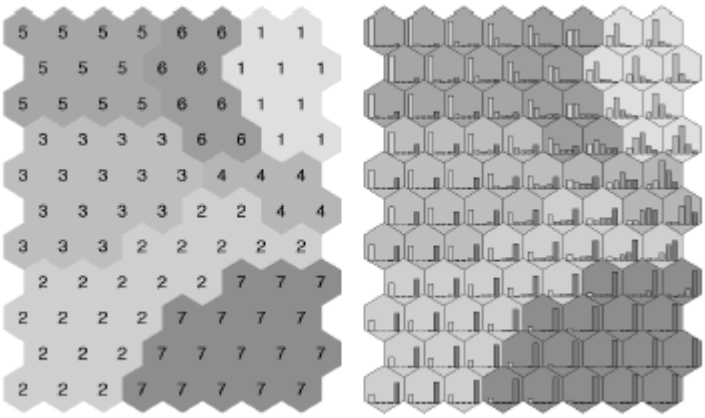

Figure 2.14. Histogram map for both uplink and downlink data of the microcellular scenario [P8]. *Behavioural cluster*.

Figure 2.15 shows how the data samples from each mobile cell have been distributed in the clusters shown in Figure 2.14. Mobile cell 44 is located in a behavioural cluster 1 near of the cluster 4 with high proportion of data samples in data cluster 3, indicating a lot of high values for dlFER, i.e. performance problems.

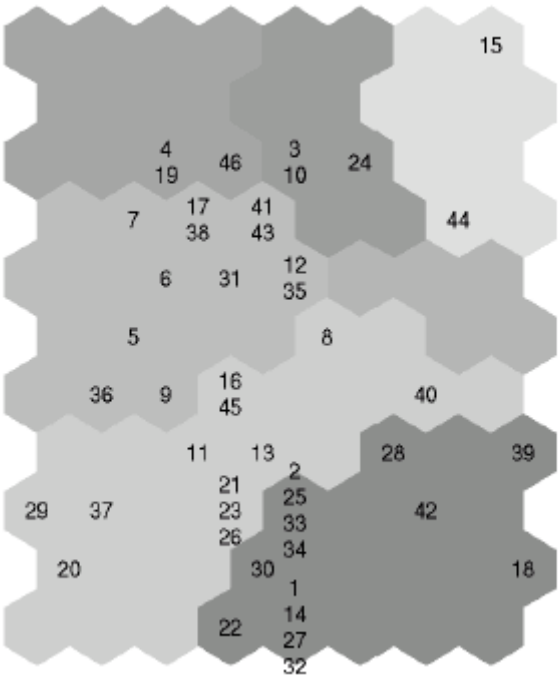

Figure 2.15. Mobile cell clustering [P8].

When the downlink information is taken into account in the clustering process, it can be seen that the geographical area covered by cells in behavioural clusters 2, 3, and 7 is very similar to the area covered by clusters 1, 2 and 6 in the uplink analysis case of [P8]. This indicates that adding the downlink information to the analysis did not bring significant new findings. This is due to the fact that the service used in the generation of

the input data was symmetric in uplink and downlink direction. Furthermore, the performance in the microcellular network is well balanced between the links. Should the services be asymmetric, the clustering results for uplink and combined uplink and downlink case were different.

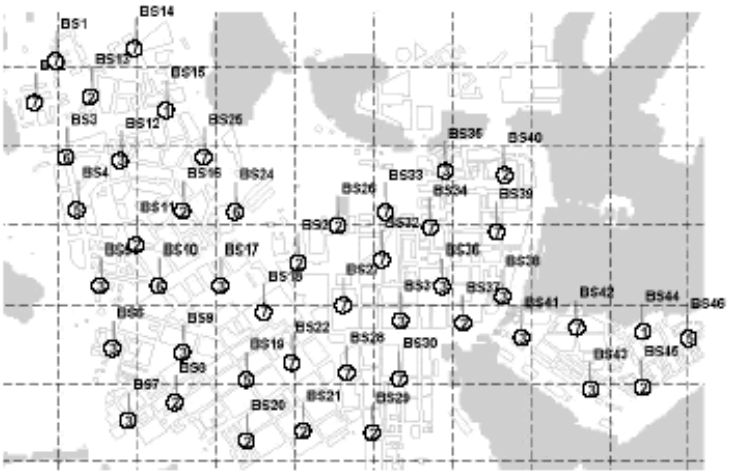

Figure 2.16. Locations of classified cells [P8].

In order to further analyse the behaviour of some mobile cells in the microcellular scenario in both uplink and downlink direction, the behaviour as a function of time, i.e. trajectories, of the cells can be obtained. Figure 2.17 shows the trajectories for cells 8, 14 and 44. Cell 8 operates initially in behavioural cluster 7 on the histogram map with almost all of the samples in data cluster 5. As can be seen from Figure 2.13 the data cluster 5 represents data samples with very small amount of users. Then, cell 8 visits the area in which data samples are distributed almost equally to data clusters 1 and 5. This is explained by a small increase in number of users. Cell 8 also shortly visits behavioural cluster 1 in the upper part of the histogram map, indicating a peak in number of samples with high ulANR. Cell 14 operates in behavioural cluster 7 with very low load through the whole analysis session, since almost all of the data samples are located in data cluster 5. In Figure 2.17 also downlink performance is included in the trend analysis. A low number of users is one strong character of this cell. Cell 44 operates very close to the problem area, that is, the behavioural cluster 4 and lower part of cluster 1 on the histogram map. In these clusters, high proportion of samples is distributed in data cluster 3 with highest dlFER.

The strength of the SOM is seen once the user has learned the meaning and content of the behavioural clusters. It is easy to distinguish the good and bad performance clusters on SOM and focus on the cells in the bad performance area. For example in Figure 2.14 the area of cluster 4 and lower edge of cluster 1 is the area of unacceptable performance. All the cells in this performance area are optimisation targets. In Figure 2.17 Cell 44 makes a visit to the bad performance area. Whether this is severe, is for the operator to decide. Furthermore it is possible to define own set of performance measures and to use those in the training of the SOM. Thus the behavioural clustering is more customised and fitting better to the wanted performance targets than with the case that is presented here.

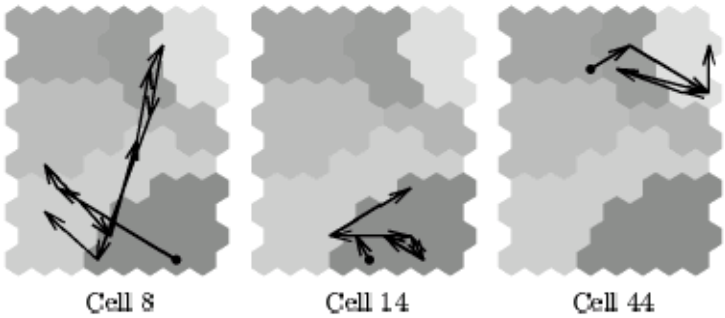

Figure 2.17. Trajectories of the cells [P8].

2.3.4 Applicability of advanced methods in optimisation [P8]

The scope of this section is to demonstrate, that the performance analysis results achieved with SOM can be explained with combined traditional analysis means and expert knowledge. In this section only one case is considered, namely microcellular. For more cases and details see also [P8]. In [P9] also examples of the actual applications how to utilise SOM with the network performance data are presented. This section merely provides an example of the reliability of the SOM analysis result.

In the analytical approach the upper bounds for the network performance has been found using equations of Section 2.2.1.1.

<u>Traditional analysis for microcellular case</u>

The strength of the SOM-based analysis is its ability to combine multiple measurements and thus provide the result in a simple format despite the fact that the input space is very complex. The motivation of this section is to perform analytical analysis on the simulation results using equations presented in Section 2.2.1.1 and cost function approach. Cost function in this context is a linear function combining different performance measures to classify the cells with traditional means. The cell specific measurements used in traditional analysis are:

- Total base station transmit power used for the traffic channels
- Number of users
- Total throughput (uplink and downlink)
- Loading
- Other to own cell interference ratio, *i*

The performance indicator *i* is used in the analysis for additional information, to improve the understanding and to provide better reference for the SOM analysis case. In live network it is not possible to extract this measurement.

Two reference figures for the cell performance can be calculated based on the input data, namely loading caused by a user and number of users a cell can serve: Used uplink E_b/N_0 value in this study was 3.5 dB and 4 dB for micro- and macrocells respectively. During the simulations the loading was set to 0.95. Frequently quoted *i* value for omnidirectional case is 55%. In [P5] and [39] more realistic values for sectored cases are presented, thus 65% for macrocellular case is used. The solely theoretical capacity values are presented in Table 2.7.

Table 2.7. Theoretical capacity values for micro- and macrocells [P8].

	Microcell	Macrocell
Number of users, upper bound	26	23
Loading/user, upper bound	0.03621	0.04063
Number of users, i included	16	14
Loading/user, i included	0.05613	0.06704

In Figure 2.18 the uplink loading is visualized. The darker the color the lower the loading in a cell. In microcellular case the water area does not cause interference problems. The cells are effectively isolated from the water and furthermore, from each other. The buildings in the propagation path provide the isolation. In Figure 2.19 the location of the mobile stations that suffer from power outage are depicted. When the uplink and downlink outage is compared with each other, it can be noted that the locations tend to correlate. Thus uplink performance and downlink performance are well in balance. When visually testing for the correlation of loading and bad quality, the situation is not straight forward: in most of the cases the loading seems not to be the reason for degraded quality, like it is was in macrocellular case [P8]. In Table 2.8 results for microcellular uplink case are introduced. Only some example cells are chosen, i.e. Cells 8, 14, 44.

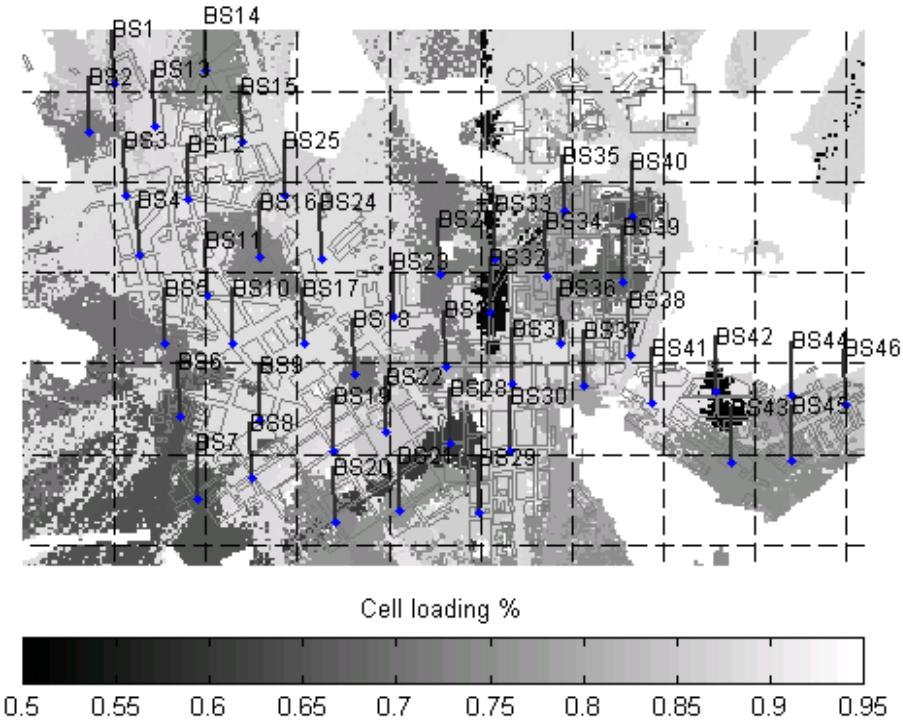

Figure 2.18. Uplink loading in microcellular case [P8].

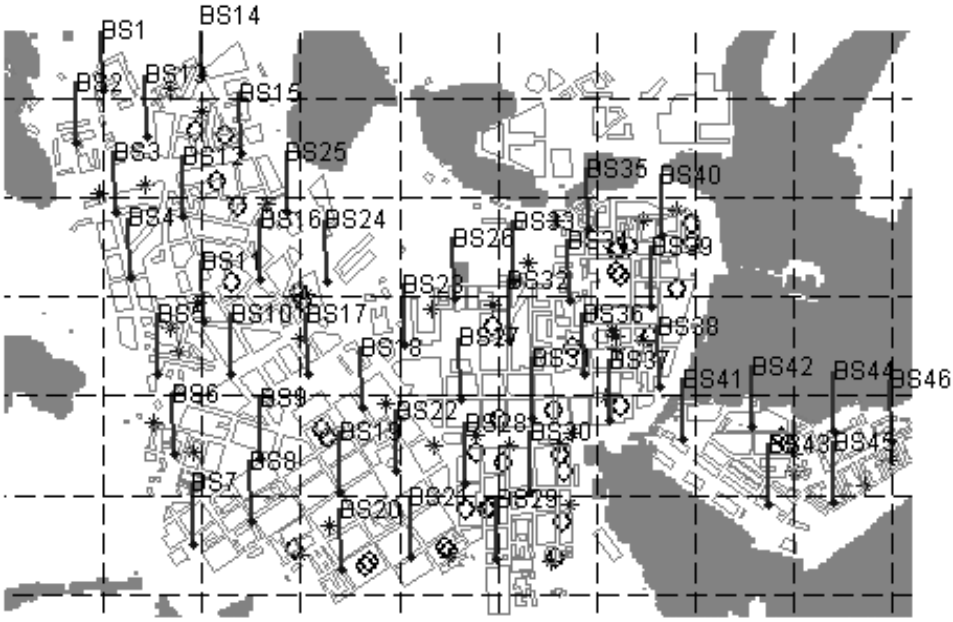

Figure 2.19. Power outage in microcellular case, * indicates uplink and ◊downlink outage.

Table 2.8. Example results from traditional analysis, microcellular case [P8].

Cell id	Bs TxP traffic [W]	Loading	Other to own cell interf. Ratio, *i*	Users UL	Users DL	Throughput UL [kbps]	Throughput DL [kbps]
8	0.40	0.88	0.16	22	22	1408	1408
14	0.25	0.75	0.13	18	18	1152	1152
44	0.39	0.88	0.15	22	22	1408	1408

All of the selected cells have relatively high loading, and significantly low *i*, compared to the often used value 55%. This indicates a very good isolation of the cells in microcellular environment. For all of these cells the loading per user is 0.04, which is very close to the upper bound value. In general, all the microcells are having well-controlled interference, only 7 cells out of 46 had *i* higher than 55%. These cells are: 3, 6, 7, 18, 24, 28, 42 and 43. When checking the position of these cells in Figure 18 of [P8] they can dominantly be located in clusters 7, 4 and 2. Behaviour in clusters 4 and 7 is close to each other, and it is characterised with a relatively high noise rise, but moderate number of users. This supports the other cell interference cause. Characteristic for cluster 2 is a low number of users, and thus the other cell interference is again dominating in the loading equation.

Cost function approach

For a more profound performance evaluation a simple function combining the interference control and throughput aspects were generated, see Equation (2.21). For the sake of simplicity, the weighting for each item in the cost function was the same. The other issue supporting the equal weighting is the fact that the same type of decision was made also in the SOM based analysis case.

$$P = f\left(\frac{Throughput\ UL}{\max Throughput\ UL}, \frac{Throughput\ DL}{\max Throughput\ DL}, i, \eta_{UL}\right) \qquad (2.21)$$

In Equation (2.21) the maximum throughput can be the theoretical upper bound or the maximum value in a cell of the network.

The uplink only analysis can be found in [P8]. When the traditional analysis is ***enhanced*** to include also ***downlink*** related information in terms of normalized power per subscriber and normalized downlink throughput the best performing cells were *8, 9*, 10, *11*, 14, 17 and *29*. The cells with *italics* being the same as in the uplink only case. When placing these cells in Figure 2.15 it can be concluded that the case seems to be rather scattered. Histogram plots indicate a different conclusion, though. Histograms of cells 8, 9, 11, 29 are very similar: first and fifth bars dominate. Characteristic for these cells according to rules of Figure 2.13 is good correlation of number of users and the resulted uplink and downlink resource usage. Cell 17 can be included into this group also. With the notation that in the case of cell 17 the number of users is in general high, rules of behavioural cluster 3 dominate. Cell 10 can be characterized as an "intermediate" cell. It has in downlink direction worse interference conditions than its neighbours and thus, the performance is slightly worse than with cells 8, 9, 11 and 17. Cell 14 is an edge cell, which explains its position in Figure 2.15.

In this section it was demonstrated that analytical means together with the expert knowledge support well the SOM based analysis. The case presented here and in [P8] is simple, comprising only of one service and limited amount of performance indicators. With live networks the situation is more complex and in that case the traditional analysis is feasible when estimating the initial performance of the network. This information is vital before the network roll out (network installation and integration). Traditional analysis provides reference data in terms of coverage, quality and capacity for the network to be implemented. Once the network is operational, the performance evaluation should be based on the analysis of the true performance data from the live network. The difficulty with this approach is the vast amount of data available. Advanced analysis methods and carefully selected data filters are needed to ease the performance evaluation work.

As a conclusion of this section it can be stated that with traditional means it is possible to support the understanding of cell classification performed by SOM. Furthermore, the comparison shows that the SOM-based results are feasible and thus they can be trusted. In this work special attention has been paid to the usability of the proposed method. One aspect of the product oriented R&D work is the technical feasibility another part is providing the new technology with high usability to guarantee the wider acceptance of the new method. Combination of these two aspects is required for successful product development.

2.3.5 Cell grouping in optimisation

In Section 2.3.4 the applicability of SOM analysis results was verified. The scope of this section is to discuss further how to utilise the clustering results based on SOM. SOM is an efficient tool for visualisation, monitoring and clustering of multidimensional data. It transforms the input vectors on a two-dimensional grid of prototype vectors and orders them. The ordered prototype vectors are easier to visualise and explore than the original data. Furthermore, SOM can be utilised to discretise the multidimensional input data and form performance space (spectrum).

The amout of parameters that control the RAN is very large. It is easy to understand that finding an optimum set of parameters for each cell manually is a tedious task when the number of cells can be thousands. Furthermore, often the operator efforts are concentrating on the trouble shooting work rather than optimisation of the RAN. The additional complication to the optimisation process arises from the fact that the network

is optimised based on measurements collected from network elements. The number of these “raw” measurements is thousands. For an operator to provide the maximum capacity (with required quality) supporting multiple traffic mixes more advanced analysis methods are required to support the configuration parameter settings. In addition, effective means to monitor and classify cells and to identify problem areas in the network are needed.

In this section, the use of the SOM in the optimisation process is described (for details see also [P7]). Figure 2.20 demonstrates the optimisation process utilising the SOM-generated performance spectrum. This feature makes it much easier for the operator to optimise the cell-specific parameters. With the help of SOM (or any other clustering method) the cells can be clustered (grouped) based on traffic profile and density, propagation conditions, cell types etc. Grouping based on multiple criteria instead of just one (like cell type) is more accurate and the operation of the network will benefit from this. First the network is started with default parameter settings. After the network has been operational in this sub-optimal mode, measurements from cells are collected. With the help of a clustering method each cell is automatically assigned to a cluster, the number of clusters being well under the number of cells in the network. How to utilise SOM as a clustering method has been demonstrated in [P7].

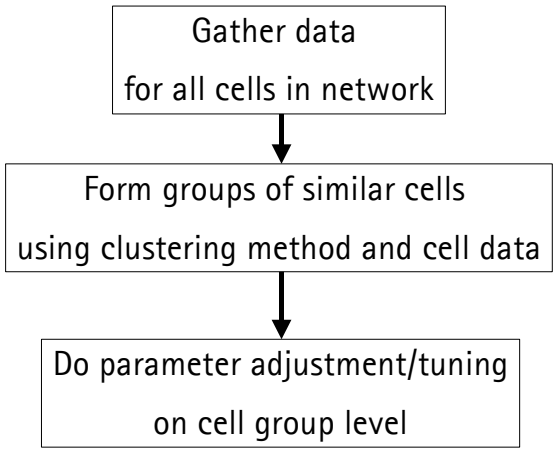

Figure 2.20. Flow chart for the methodology.

The selection of the input data is done on a functional area basis. Example of a functional area is availability. For clustering purpose availability related measurements are used as the input space for SOM. Clusters (performance spectrum) which highlight the *availability performance-space* are generated. Each cell’s behaviour is now compared to the performance spectrum and grouped accordingly. Each cell in a cell-group behaves similarly, has similar symptoms and thus should use same configuration parameter values. This simplifies and eases the optimisation process greatly. Instead of getting the network "just to work", the RAN utilisation rate can be increased. The optimisation phase will concentrate on the optimisation/automation of cell group owning a parameter set, rather than optimising each individual cell with its own selection of configuration parameter settings. This method also reduces the possibility of human error in the parameter settings and parameter provisioning, owing to the fact that part of this process, for example the selection of target cells, can be automated. Cell clusters can be utilised also to optimise only sub-set of the configuration parameters. In the trouble shooting case the problematic cells can be found rapidly using some clustering method and visualisation of the clusters. Additionally, using these visualisation properties, the operator can easily analyse what kind of cell types he has in his network with respect to

certain performance indicators and variables and combine the results with geographical relationships.

In addition to the cell grouping for parameter provisioning purposes the performance spectrum can be used as an indicator for further optimisation or autotuning activities, see also [P9]. Figure 2.21 illustrates the case. The cells in the lower left corner are in the problem area of the performance spectrum. These cells are automatically chosen for an optimisation task. This type of approach requires that the performance spectrum is connected to a set of configuration parameters. In other words: performance spectrum demonstrating cells' admission control ought to be linked to parameters controlling the admission process.

Performance spectrum also offers powerful means for optimisation verification or network trend analysis. The complexity of the radio networks is growing as well as the networks themselves. Operators will need means to analyse changes in the network rapidly, given a high number of cells, several services with different QoS criteria and a huge amount of collected performance data. Trend analysis can be performed using data averaged over various time periods, ranging from tens of seconds to days. One could for example follow one cell movement in SOM during peak traffic hours, assuming that networks are able to report cell performance frequently enough. Another possibility is to analyse networks behaviour using data collected during a whole year

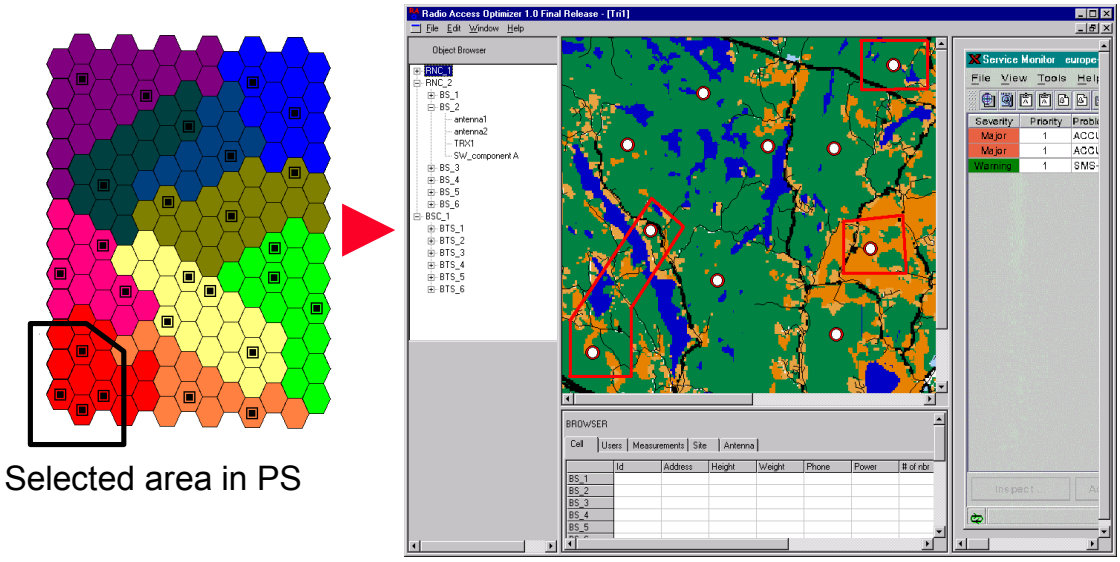

Figure 2.21. Selection for cells to be optimised/autotuned. PS stands for performance spectrum.

Figure 2.22 shows trend analysis for 32 cells, all in separate displays. There are three main groups in Figure 2.22 coloured using red, green and blue. For some cells the group membership varies during the monitored period. The advantage of this method is a highly visual representation of changes. Furthermore, the cells' behaviour can be visualized as a function of time, for example over 24 hours. Depending on the traffic mix and traffic density in the network, the performance will be different. On the performance spectrum the areas of bad performance are known and it can be easily visualized wheather the monitored performance stays out of the not wanted areas. Compared to traditional analysis methods, it is easier and faster to understand the characteristics of cell behaviour if this kind of function is used.

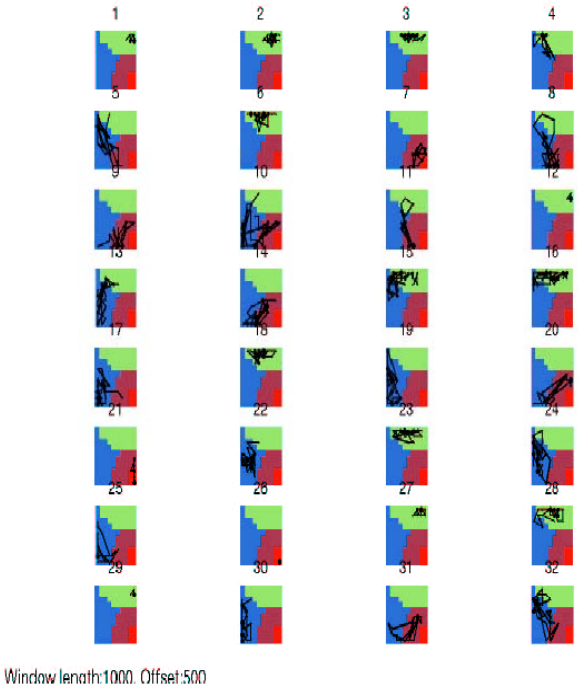

Figure 2.22. Trend analysis for 32 cells, all in separate displays [P9].

Another application for trend analysis is related to the network optimisation phase. When the network element configuration is changed, the operator normally wishes to see the effect of the change to performance. The procedure to improve network performance with SOM basically goes:

1. Collect performance data
2. Train SOM with the data
3. Analyse (This step can be done several times with different time periods)
4. Adjust parameters if needed to correct the possible problem
5. Verify adjustment effect on performance using SOM.

If once more the lower left corner is assumed to indicate malfunctioning cells, the change in the position of the cells on the performance spectrum can be detected after the optimisation, provided that the optimisation has been successful. Figure 2.23 illustrates the example.

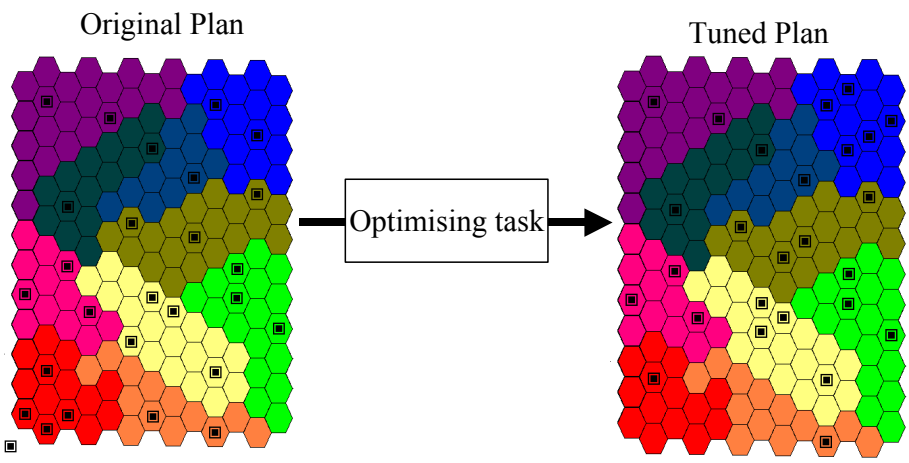

Figure 2.23. Movement of the cells in the performance spectrum as a result of optimisation or autotuning.

It is obvious that the SOM utilisation in the optimisation process covers only a small fraction of the whole process and operator's daily work. Handling the optimisation process as a whole would have been too wide a scope for this thesis. The SOM based analysis and optimisation aids support the trend required for effective WCDMA capacity utilisation. The optimisation problemacy will be much more multidimensional than with the current networks. In the case of WCDMA there will be multiple services, customer differentiation (customers with different priorities) and multiple radio access technologies to be managed simultaneously, as one resource pool. It is worth to note that essential part of the SOM utilisation lays in the pre-processing of the measured data used as input. These issues are not at all covered in this thesis, short introduction can be found in [P8].

[58], [59] and [62] provide an interesting framework and demonstrate the direction to which the network management and optimisation develops.

3 Summary of the publications

In [P1] the behaviour of the uplink closed loop (fast) power control in WCDMA system is analysed with theory and link level simulations. In this paper the impact of the fast power control to the E_b/N_0 performance and transmit power levels and thus to the capacity are addressed. This paper (single link) together with [44] (including soft handover) were the core when designing the link level modelling to the static simulator uplink. [P1] is closely related to [P2] and [P3].

[P2] introduces the first version of the static planning tool described in this thesis. The motivation for the work was to be able to examine the capacity–coverage interaction in the case of multi-service WCDMA planning. The simulation phases:

- Initialisation
- Iterations (uplink and downlink)
- Post processing
- are described and the functionality of the simulator is demonstrated with mixed service scenario.

The theory of multi-service WCDMA is supported by the simulator. Furthermore, the TPC impacts according to [P1] and [44] are modelled. As such the work was novel when first published.

[P3] contains a complete WCDMA radio network planning process description for multi-service environment. The individual phases and modelling in the process are introduced. The WCDMA specific issues in the process and modelling are emphasised. Issues related to the TPC and their impact to the dimensioning results is addressed. These issues are not found elsewhere, nor in the listed references.

Accuracy of the tools used in the radio network planning phase is essential to provide an operator with reasonable accuracy information of the required network topology. Thus the accuracy provided by the proposed tools and methods is addressed. For dimensioning the theory for uplink and downlink is provided. An example case is dimensioned and the accuracy of macrocellular dimensioning result is verified with the static simulator results, and based on the results of [P3] it can be stated that the proposed modelling is accurate enough for the purposes dimensioning is aimed for.

In the case of the static simulator the modelling description is provided in more detail than in [P2]. Furthermore, new issues like multi-carrier analysis (adjacent channel interference) and its impact on the planning process and the modelling in the simulator are discussed. In this paper the verification of the static simulation results with fully dynamic simulator in macrocellular scenario is also performed. Motivation for this comparison was to study the accuracy and quality of the radio network plan. Such a comparison has not been performed earlier, and it further shows that the novel modelling in the WCDMA planning tool is a required, in addition to the existing theory.

As a result it was demonstrated that the static simulator provides a realisation of the network with reasonable details when compared to the results provided by a fully dynamic simulator.

The scope of publication [P5] is to demonstrate with the help of static simulations the effect of

- Antenna tilting
- Sectorisation
- Antenna selection

- MHA

on the network quality and capacity. Furthermore, the paper demonstrates how site configuration change can support the evolution of the WCDMA network. Omni, three, four and six sectored cases are studied and for each case optimum antenna (in terms of beamwidth) is found. The antenna tilting can be used for the interference control in any cellular system, the effect of antenna tilting on the other to own cell interference ratio is demonstrated, and it is shown how an optimum tilt angle can be found. The use of MHA is also addressed in this paper. The findings are:

- In the case of low loading (rural areas) MHA can be used to improve the link budget (uplink)
- In the case of high interference level the benefit of the use of a MHA is negligible
- Introduction of MHA can cause the downlink capacity to decrease. Reason for this is that users at the cell edge in uplink direction get served (without MHA they are in outage) and thus they require relative large downlink powers. Since the total base station transmit power is limited, the total number of users has to be reduced.
- The use of MHA in downlink-limited situation should be avoided.

In [P4] the general targets for the radio network provision and example link budgets for WCDMA speech and 144 kbps data are introduced. Discussion on load factors and spectral efficiency are presented and the concept of soft capacity is introduced. In this paper the impact of the advanced modelling on the planning tool is demonstrated. A multi-service case has been planned and analysed. Furthermore, the impact of the mobile station speed has been demonstrated. The case uses strong engineering approach, but its relevance is in the applicability of the results. In addition to that, this case demonstrates that the novel modelling as proposed in this thesis supports more accurate WCDMA network planning. The author of this thesis has major contribution in publishing these results. Corresponding results cannot be found in any CDMA handbooks or other references. Verification of the impact of the headroom and transmit power increase on the QoS during radio network planning is among other things further studied in [P4]. Related to this the most relevant addition for this thesis is the planning example in Section 8.3.2. The conclusions based on this section are:

- Firstly, it is shown that the mobile station speed as an attribute in the planning process has an impact on the capacity and quality results of the radio network plan. In terms of capacity it is seen that lower mobile station speed provides better throughput. When comparing the coverage probability results (quality) the impact of the mobile station speed is opposite. Higher speed reduces the required fast fading margin and thus the coverage probability is improved when the mobile station speed is increased.
- Secondly, the accurate traffic modelling is a new challenge for the radio network planning phase. In addition to the traffic and service distribution one should be able to estimate the distribution of the mobility of the users in the network. It is clear that such a demand is not feasible. Therefore, the results presented in this publication support the claim that the statistical feedback loop from the network is needed to support the pre-operational planning.

The applicability of horizontal – vertical (HV) and slanted ±45° polarisation diversity scheme in comparison with the space diversity at the base station reception in a small cell environment was studied in paper [P6]. According to the measurements the slanted ±45°-polarisation diversity scheme provides the same gain as the space diversity configuration with horizontal antenna separation in areas where there are plenty of reflecting surfaces along the propagation path to turn the polarisation plane. Such environments would be urban, indoor and small cell areas. The performance of the HV scheme was slightly

worse than that of the traditional space diversity scheme. In this study cross polarisation discrimination values were also measured. The reported values range from 5 to 15 dB, depending on the line of site situation. The study was performed at 1800 MHz range, thus the results are applicable also in the case of WCDMA.

Common factor for papers [P7], [P8] and [P9] is the fact that an advanced SOM based analysis methods are introduced in the analysis of cellular networks. The conceptual work (mainly in [P8], partly also in [P7]) is not found elsewhere in literature. Main focus of [P9] is the verification of the SOM analysis results with traditional means in order to gain confidence to advanced methods.

[P7] is related to methods needed in the network optimisation phase. Due to the vast amounts of data, effective data mining methods are needed with WCDMA networks to be able to control them optimally. In this paper neural approach is applied. The SOM (self organising map) algorithm is able to perform data clustering and visualisation, both important features for operators in the optimisation phase. The method is tested in microcellular and macrocellular scenarios. From radio network optimisation point of view the main finding in this paper was in the clustering result. It is demonstrated that it is possible to find similarly behaving cells (clusters), or cells differing (malfunctioning cells) from each other. Such a clustering is beneficial in the optimisation phase. It is reasonable to assume that the RRM configuration parameters for cells in one cluster within one optimised RRM function are the same. Naturally the measurements used in the clustering phase ought to have relation with the configuration parameters. SOM application as described in this paper in the control of cellular networks is as such novel. The author of this thesis is the main contributor to the optimisation concept development presented in the paper.

In [P8] the high level optimisation process is described. In the optimisation process an analysis phase is identified. In the analysis phase a proposal for the usage of advanced neural methods was presented. The results provided by SOM were verified with combination of traditional means and expert knowledge. It can be stated that the results show a good agreement and thus the proposed method can be safely applied in the analysis of 3G cellular networks. One can say, that in this relatively simple case it was possible to generate a manual explanation for the automatic, SOM based result. Being able to understand the SOM results with traditional means increases confidence to the novel analysis and its applicability in the area of cellular networks. Demonstrating the feasibility of SOM in a telecommunication application was one of the main motivations of this paper.

[P8] consists of traditional WCDMA network analysis using analytical approach presented for example in [P3] and using statistical simulator results. A cost function was generated and using the cost function result the best (or worst) performing cells were grouped. This grouping was compared to the one proposed by SOM and similarities were noticed, but also need to explain differences with expert knowledge arouse.

During the course of this work it was noticed that traditional analysis as such is not adequate enough to provide as enhanced demonstration of the network performance as SOM provides. One reason being the fact, that the aspect of time is not present in static planning tools. The other limitation is the lack of correlation information. By traditional means it is possible to analyse one measurement at the time. The correlation (or lack of it) is determined by the planning expert, who has the knowledge of the interdependencies in the network. Correlation that is not considered normal is found manually if the number of measurements one has to consider is only few. Should the number of measurements be significantly higher, expert knowledge could not anymore aid the translation of the individual results to a combined view of the situation.

The strength of the advanced analysis methods is in the fact that multiple KPIs can be used in the analysis and the clustering of the cells is easy to visualize and understand. Furthermore, with the presented advanced methods it is possible to visualize the network performance in novel ways. Examples of these were the trend analysis and clustering including the rules to characterize each of the clusters

The traditional analysis is feasible when estimating the initial performance of the network. This information is vital before the network roll out. Traditional analysis provides reference data in terms of coverage, quality and capacity for the network to be implemented. Once the network is operational the performance evaluation should be based on analysis of the true performance data from the live network. The difficulty with this approach is the vast amount of data available. Advanced analysis methods and carefully selected data filters are needed to ease the performance evaluation work

In [P9] advanced analysis and visualisation methods to support the operator optimisation and troubleshooting tasks were introduced. The example cases were based on the SOM, but also other neural analysis and statistical methods can be applied. It was shown that with the introduction of neural algorithms to the network analysis and optimisation, the output is highly visual and these advanced methods make it possible to handle much more key performance indicators (KPIs) simultaneously than would be possible by traditional means. Furthermore, when utilizing the SOM-based clustering the behaviour of the cells can be classified and the optimisation task can be performed per cluster, rather than on a per cell basis. Also a trend analysis method based on the SOM that eases the follow-up of parameter optimisation was presented.

4 Conclusions and Discussion

The main motivation for this work was to generate tools and methods to be able to support multi-service radio network dimensioning and planning for WCDMA. Furthermore, understanding of the relevance of the radio network planning phase to the overall network performance was of interest. Due to the fact that the network performance is very heavily dependent on the actual traffic and user behaviour, it is obvious that the state of the radio network is fast changing. This causes additional challenge for the planning phase. Thus it is essential to have an immediate feedback loop from the operational network (in terms of performance measurements) to the optimisation function of the network management system. In this thesis some issues related to effective optimisation functions and process are also introduced.

This thesis consists of three parts: modelling and tools for radio network planning, process for pre-operational network planning and optimisation for the operational network.

Modelling and tools

New issue in this thesis is the modelling of the impacts of fast power control in the dimensioning and planning tool in terms of *transmit power increase* and *fast fading margin* (= *power control headroom*). Furthermore, the soft handover situation can be taken into account when estimating the performance. The capacity-quality trade-off as a result of the soft handover is pointed out also in [61]. This trade off can be effectively seen in uplink and in downlink with modelling introduced in [P1], [P4], [P3], [41] and [44]. The capacity–quality trade off is build in feature in CDMA systems and it is on the one hand providing operators possibilities, but also challenges when managing their networks.

The contribution of this thesis in terms of modelling and tools is as follows:

- Improvement of the accuracy of radio link budget by introducing power control *headroom* (also called fast fading margin)
- Improvement of loading equation by introducing a *transmit power increase* term.
- Development of theory and modelling for a planning tool capable of
  - multi-service and multi-carrier planning
  - integrated capacity and coverage analysis
  - flexible traffic distributions
  - capturing the user behaviour (service and mobile station speed) through an interface to simulated or measured link performance measures.

Radio network planning process

In the provided references radio network planning has been approached from the single service planning and dimensioning point of view, with the exception of three references, namely: [42] and [60] - [61]. In [42] the concept of total loading estimation based on contributions of individual users is introduced, but the analysis only concentrates on uplink only. In [60] the "interworking" of 8 kbps and 13 kbps CDMA speech services are considered and the problems arising from different E_b/N_0 requirements and processing gains are discussed, but the solution for the radio planning phase is not introduced.

The downlink (forward link) budget introduced in [61] is adopted from the cdmaOne (IS-95) world and it is demonstrated how the proposed approach is used in multi-service

environment. For such demonstration the simplified approach without orthogonality considerations and capacity or quality requirements is adequate. For real engineering exercise an essential aspect is the channel delay profile and its impact to the orthogonality performance. Furthermore, based on the experience gained during this work, it is claimed that the selected cell range of [61] would be is too large for WCDMA data services, if a certain QoS criteria ought to be met. Applying the process described in [P3] the correct cell range for the simulations could have been found. Simulations performed in a wrongly dimensioned network have no practical relevance; therefore all the simulation results collected to this thesis are done according to planning process described in [P3]. Thus the results presented in this thesis are highly relevant references.

Moreover, in all cases presented in this work true propagation environment and non-uniform traffic distribution is encouraged. Uniform traffic distribution and uniform SIR distribution per service are far too simplistic assumptions. Therefore in this thesis a major contribution has been done to bring accurate modelling related to the traffic channel SIR targets, both in uplink and downlink. The attributes that have an impact on SIR (E_b/N_0) in this thesis are:

- Channel profile
- Mobile station speed
- Service
- Bit rate
- BLER target

In addition to these the voice activity and orthogonality is modelled, and both of them are mobile station specific. The latter depends on the chosen channel profile and mobile station position (location in a cell). Such modelling for any systems' planning process cannot be found elsewhere in open literature.

In the area of pre-operational planning process the contribution of this thesis is as follows:

- Development of dimensioning methodology for multi-service network site density estimation, utilising the modelling of power control headroom, transmit power increase, soft handover and E_b/N_0. Furthermore, all these items are modelled as a function of terminal speed. Also microcells and macrocells are treated separately, owing to the fact that the propagation models and estimated multipath profiles (and thus orthogonality) differ.
- Development of radio network planning process for multi-service environment including site density estimation, capacity and coverage evaluation for a given traffic mixture, quality and area requirements.
- Analysis of means to improve radio network plan and thus the actual network with Mast Head Amplifier, diversity reception, sectorisation and proper antenna selection.

This thesis consists of development tools and methods to support the operators WCDMA network deployment. Due to the lack of the measured data from live network, each of the produced tools and their modelling has been verified with another tool with higher resolution and accuracy. It can be concluded that proposed modelling is adequate for each intended process phase. Furthermore, such extensive model development and verification is difficult to find in any other reference.

Whenever the operators' business strategy changes i.e. new services are introduced, pricing is changed, new areas are covered, support from the planning tool in terms of site location selections and initial quality analysis is needed. Based on the findings of this thesis the following can be concluded:

The advanced modelling proposed in the thesis brings additional accuracy to the dimensioning and the radio network-planning phase. It is admitted that the plan is only a

static snapshot of the possible performance of the network, and the simulated performance correlates strongly with the mobility and propagation modelling in the planning tool. Despite of this, it is claimed that the performance improvement from the statistical feedback loop is significantly better in the case of well-planned and analysed network, than in the case of a radio network where the plan is not at all optimised and no interference control mechanisms, like proper antenna selection, antenna tilting, base station configuration etc., are considered. In the latter case smooth network evolution to support new services is complicated and the statistical feedback loop is rather used for trouble shooting than performance improvement. Furthermore, the dimensioning and radio network planning mechanisms provide important feedback for the operator when analysing the impacts of new services on the overall network performance, expansion of the service areas, etc.

Optimisation for the operational network

In the case of WCDMA networks and multi-service environment it is important to move from offline planning to statistical optimisation as quickly as possible. The proposed trend is to move from single cell optimisation to cell cluster optimisation. To achieve this it is essential to develop advanced analysis methods to support operators' optimisation tasks. The SOM based support for the optimisation phase is also introduced into the optimisation process in this thesis. The multidimensional performance space in future cellular networks force the traditional planning process to go through some major changes. Additional challenges arise from the fact that in the case of WCDMA there will be multiple services, customer differentiation (customers with different priorities) and multiple radio access technologies to be managed simultaneously, optimally, as one resource pool. Furthermore, the high competitive situation forces operators to fast changes in service provisioning. All this will move the focus of operators daily tasks from offline planning to rapid network performance evaluation, trend analysis and optimisation based on network measurements. Therefore new analysis schemes for 3G networks are presented in this thesis. The presented, SOM based analysis tools for cellular applications are not published earlier. Furthermore, the SOM based optimisation concept is new and one of the main results in this thesis.

In the area of optimisation of the operational network the contribution of this thesis is as follows:

- Definition for optimisation target in the case of 3G. Owing to the fact that Real Time (RT) and non real time (NRT) services co-exist, new definition is required. In the case of current networks the NRT data is provided on best effort basis having no QoS targets. With 3G services the QoS for NRT is an important issue and thus the optimisation will be in the future provisioning of capacity-quality trade-off instead of quality improvement process.
- Introduction of Self Organising Map (SOM) in the analysis of cellular networks.
- Analysis of the applicability of SOM in WCDMA cellular network. The cells of the network area sorted based on a cost function approach, using traditional analysis results. This traditional sorting of cells is compared with the clustering done by SOM. The results show that the correlation is high, but the traditional analysis requires also expert knowledge to be able to achieve as good results as with SOM.
- Introduction of SOM based applications to support network capacity-quality trade-off management.

The results of this thesis show that

- Introduction of TPC headroom in the radio link budget brings an additional 0-4 dB change to the cell range estimation. With Okumura-Hata model this means 30 % in

cell range, assuming basic path loss of 150 dB, 1.5 m mobile height and 30 m base station height.

- Introduction of sectorisation effects and transmit power increase term to the loading equation makes also 30% difference in terms of number of users a cell can support when comparing omni-sectored case with 0 dB transmit power increase to a case where 3-sectored sites are implemented and 2 dB transmit power increase is assumed (speech only, full voice activity, target loading 50%).
- The power control headroom has significant impact also on the coverage probability. If the network is planned for vehicular users, but the actual customers in the network are mostly pedestrian, the slow fading margin is reduced with 2 to 4 dB. This reduction has a direct impact on the coverage probability. If the planned probability is 95%, the actual probability with simple calculations (based on [1]) is 88%. Should the initial requirement be lower, or the lognormal fading constant larger (for example in indoor environment) the difference between the planned and actual value would be larger.
- Antenna selection has strong impact on the WCDMA capacity, owing to the fact that too large sector overlap causes interference problems.
- In addition to the antenna selection, antenna tilting is an effective method for interference control, especially if the site is high.
- Antenna tilting has a strong impact on the WCDMA coverage probability; up to 10% difference is demonstrated in this work.
- Estimation of the site density based on vehicular speech traffic only, causes degraded coverage performance for low mobility speech users and all the data users.
- Site density ought to be determined based on the combination of quality (in terms of coverage probability) and service requirement, taking into account the assumptions of the speeds of the users in the area in question.
- Unlike in the cdmaOne case (see [45], page 227), the downlink can be the limiting link in the case of WCDMA. This depends on the cell type (multipath profile and thus orthogonality), service (web browsing for example causes more traffic in the downlink direction) and practical control implementations in the network (maximum allowed power per link in a cell). All these listed issues must be taken into account during the planning and optimisation processes.
- It is not the multiple access schemes alone that are going through a revolution when moving towards next generation systems. The network control process, starting from the first dimensioning and proceeding with the parameterising of radio network planning and radio resource management functions and looping back with the statistical data collection loop, is also part of the revolution.
- Optimisation for 3G multi-service environments shall be capacity-quality trade-off management, limiting factors being the cost of the network infrastructure and business plan of the operator (billing policy).
- The 3G multi-service environment will need effective analysis tools (like SOM) to cluster cells. Optimisation is done per cell cluster, not cell by cell. Cell cluster consists of cells having similar behaviour (for example similar traffic profile) or similar symptoms.
- SOM is applicable in clustering and analysis of WCDMA cells.
- SOM provides highly visual analysis results for cellular applications.
- Clustering result depends on the variables used in the analysis; there will be different cell clusters for different optimisation cases.

Future

Integrating the network management system and the static simulations or for example SOM based advanced methods for effective configuration parameter provisioning and "pre-launch network performance" estimation are the next challenges in radio network development and optimisation area. An example of the effective integration of the planning tools' functionalities into NMS is for example visualisation of statistical performance data on cell dominance areas. Furthermore, the adjacency relations can be directly generated in the NMS based on the base station coordinates and simple distance based rules. These initial lists can be later autotuned based on statistics collected from the live network. Also the WCDMA scrambling code allocation can be done in NMS without the interfacing to external planning tools. Both GSM and WCDMA standards require mobile stations to send measurement reports back to the system. These reports contain information that can be used to compensate the information generated traditionally by the planning tool, like propagation, traffic density etc. When the mobile station positioning methods are fully in use, new dimensions to optimisation tasks are opened.

The traditional roles of offline planning tools and NMS should be reconsidered. Firstly to avoid generation of features that are really not required and secondly to provide effective NMS systems that are capable to answer the needs of operators. Furthermore, together with introduction of all IP mobile world the QoS provisioning becomes very important for the operators. This directs the network control more and more from radio access network control to service control. In practise this means increased abstraction level for the operator, and new era for the network management.

This thesis concentrates on the new challenges with WCDMA networks. Furthermore, one of the main motivations of this thesis is to move away from the "analytical" control of the network, and enhance the modelling and tools to give as realistic picture of the network performance as possible. This thesis also proposes new trend for the whole network control process. The network functionalities cannot anymore be considered as individual entities, but the interaction of the entities must be considered. In the analytical, ideal world this has no relevance, but in true cellular world understanding of the interactions and network element algorithms and limitations is essential.

It can be stated that the radio access evolution towards third generation is the first big evolutionary step after the birth of cellular systems. The large step in the radio access development, the great interest in applications and services forces also the radio network planning and optimisation process to improve to fully support the offered possibilities.

After the deployment of 3G networks new challenges are ahead: Even higher bit rates shall be supported, with some possible average around 2 Mbit/s, some peaks at 20 Mbit/s and in extreme up to 200 Mbit/s. This will lead to even smaller cells, self-planning dynamic topologies, full integration of IP, more flexible use of spectrum and other resources and utilisation of precise user position. However, if the radio network control processes are carefully designed to support 3G, the step to wider variety of cell types and new set of services will be smooth and less revolutionary than what we face now when moving from 2G speech oriented networks to 3G applications and services driven cellular world.

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Errata

[P3] Equation (5)

$$\eta = \sum_k \frac{1}{1+\frac{W}{\rho_k \cdot R_k \cdot \nu_k}} \cdot (1 + i \cdot \zeta)$$

Should read:

$$\eta = \sum_k \frac{1}{1+\frac{W}{\rho_k \cdot R_k}} \nu_k \cdot (1 + i \cdot N_s / \zeta)$$

Where N_S is number of sectors

[P4] Equation (8.9)

$$\eta_{UL} = (1+i) \cdot \sum_{j=1}^{N} L_j = (1+i) \cdot \sum_{j=1}^{N} \frac{1}{1+\frac{W}{(E_b / N_0)_j \cdot R_j \cdot \upsilon_j}}$$

Should read:

$$\eta_{UL} = (1+i) \cdot \sum_{j=1}^{N} L_j = (1+i) \cdot \sum_{j=1}^{N} \frac{1}{1+\frac{W}{(E_b / N_0)_j \cdot R_j}} \cdot \upsilon_j$$

[P4] Equation (8.13)

$$BS\_TxP = \frac{N_{rf} \cdot W \cdot \overline{L} \cdot \sum_{j=1}^{N} \upsilon_j \frac{(E_b / N_0)_j}{W / R_j}}{1 - \overline{\eta_{DL}}}$$

Should read:

$$BS\_TxP = \frac{N_{rf} \cdot \overline{L} \cdot \sum_{j=1}^{N} \upsilon_j \frac{(E_b / N_0)_j}{W / R_j}}{1 - \overline{\eta_{DL}}}$$

with this change definition of N_{rf} in Equation 8.14 is valid.

[P1]

[P2]

[P3]

[P4]

[P5]

[P6]

[P7]

[P8]

[P9]

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