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ADVANCED MOBILE NETWORK MONITORING AND AUTOMATED OPTIMIZATION METHODS

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Title: Advanced Mobile Network Monitoring and Automated Optimization Methods

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Abstract: The operation of mobile networks is a complex task with the networks serving a large amount of subscribers with both voice and data services, containing extensive sets of elements, generating extensive amounts of measurement data and being controlled by a large amount of parameters. The objective of this thesis was to ease the operation of mobile networks by introducing advanced monitoring and automated optimization methods. In the monitoring domain the thesis introduced visualization and anomaly detection methods that were applied to detect intrusions, mal-functioning network elements and cluster network elements to do parameter optimization on network-element-cluster level. A key component in the monitoring methods was the Self-Organizing Map. In the automated optimization domain several rule-based Wideband CDMA radio access parameter optimization methods were introduced. The methods tackled automated optimization in areas such as admission control, handover control and mobile base station cell size setting. The results from test usage of the monitoring methods indicated good performance and simulations indicated that the automated optimization methods enable significant improvements in mobile network performance. The presented methods constitute promising feature candidates for the mobile network management system.

Keywords: monitoring, visualization, Self-Organizing Map, anomaly detection, novelty detection, intrusion detection, clustering, mobile network, WCDMA, radio resource management, optimization, auto-tuning, network management

Academic dissertation

Systems Analysis Laboratory
Helsinki University of Technology

Advanced Mobile Network Monitoring and Automated Optimization Methods

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Supervising professor: Professor Raimo P. Hämäläinen, Helsinki University of Technology
Preliminary examiners: Professor Ramjee Prasad, Aalborg University
Professor Michele Zorzi, University of Ferrara
Official opponent: Professor Jens Zander, Royal Institute of Technology (KTH)

Publications

The dissertation consists of the present summary article and the following papers:

[I] Höglund A. J. and Hätönen K., 1998, “Computer Network User Behavior Visualization using Self-Organizing Maps”, *Proc. International Conference on Artificial Neural Networks (ICANN)*, vol. 2, pp. 899-904. © 1998 IEEE

[II] Höglund A. J., Hätönen K. and Sorvari A. S., 2000, “A computer host-based user anomaly detection system using the self-organizing map”, *Proc. IEEE-INNS-ENNS International Joint Conference on Neural Networks (IJCNN)*, vol. 5, pp. 411-416. © 2000 IEEE

[III] Laiho J., Kylväjä M. and Höglund A., 2002, "Utilization of Advanced Analysis Methods in UMTS Networks", *Proc. 55th IEEE Vehicular Technology Conference (VTC) Spring*, vol. 2, pp. 726 -730. © 2002 IEEE

[IV] Höglund A., Pöllönen J., Valkealahti K. and Laiho J., 2003, “Quality-based Auto-tuning of Cell Uplink Load Level Targets in WCDMA”, *Proc. 57th IEEE Vehicular Technology Conference Spring*, vol. 4, pp. 2847 -2851. © 2003 IEEE

[V] Höglund A. and Valkealahti K., 2002, “Quality-based Tuning of Cell Downlink Load Target and Link Power Maxima in WCDMA”, *Proc. 56th IEEE Vehicular Technology Conference Fall*, vol. 4, pp. 2248-2252. © 2002 IEEE

[VI] Hämäläinen A., Valkealahti K., Höglund A. and Laakso J., 2002, “Auto-tuning of Service-specific Requirement of Received EbNo in WCDMA”, *Proc. 56th IEEE Vehicular Technology Conference Fall*, vol. 4, pp. 2253-2257. © 2002 IEEE

[VII] Valkealahti K., Höglund A., Parkkinen J. and Flanagan A., 2002, “WCDMA Common Pilot Power Control with Cost Function Minimization”, *Proc. 56th IEEE Vehicular Technology Conference Fall*, vol. 4, pp. 2244-2247. © 2002 IEEE

[VIII] Valkealahti K., Höglund A., Parkkinen J. and Hämäläinen A., 2002, “WCDMA Common Pilot Power Control for Load and Coverage Balancing”, *Proc.13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, vol. 3, pp 1412-1416. © 2002 IEEE

[IX] Valkealahti K., Höglund A. and Novosad T., 2003, “UMTS Radio Network Multi-parameter Control”, *Proc.14th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 1, pp. 616-621. © 2003 IEEE

[X] Höglund A. and Valkealahti K., 2005, “Automated Optimization of Key WCDMA Parameters”, *Wireless Communications and Mobile Computing*, vol. 5, issue 3, pp. 257-271, DOI 10.1002/wcm.212, John Wiley & Sons, Ltd. © 2005 Wiley

Contributions of the author

In papers [I-II] the author was the main contributor and writer of the papers. In paper [III] the author’s main contribution was in the clustering and anomaly detection parts of the paper.

Papers [IV-X] were created in the WCDMA Auto-tuning project 1998-2002 at the Nokia Research Center. The author was the project manager of the project and papers [IV-X] were written in collaboration with the other project members. The author was the primary author of papers [IV, V and X], in addition to being a key contributor to the papers [VI, VII, VIII and IX].

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Helsinki, March 2006

Albert Höglund

Contents of Summary

1 Introduction

The importance of managing and optimizing mobile networks is increasing with a growing amount of subscribers increasing their usage of voice and data services while the average operator revenue per subscriber is declining. By optimizing its mobile network the operator can reduce network capital expenditure (CAPEX) and operational expenditure (OPEX) and utilize its limited frequency spectrum more efficiently (Halonen, Romero and Melero (2002)). Without proper tools and methods mobile network monitoring and optimization can be tedious and difficult, since mobile networks contain a large amount of network elements that should be monitored and operated and the network elements generate extensive amounts of measurement data and are controlled by a large set of configuration parameters (Laiho, Wacker and Novosad (2001), Magnusson and Oom (2001)). This thesis attempts to ease the work of network operators by introducing and analyzing advanced network monitoring and automated optimization methods.

The mobile network monitoring and optimization domain is wide and the scope of this thesis is therefore limited. In the mobile network monitoring area the focus is on monitoring network performance using multivariate data visualization, detecting network faults and intrusions using anomaly detection methods in addition to grouping network elements to ease their optimization. In the automated optimization area the focus is set on WCDMA mobile radio access network parameter optimization using rule-based methods with the objective of improving network performance as measured in capacity and quality. The focus is not set on comparing a very extensive set of methods against each other, but rather using and developing promising methods.

The main contributions of the thesis in the area of network monitoring are developing and applying advanced monitoring, clustering and anomaly detection methods in the field of intrusion detection and mobile network monitoring. An important component in the monitoring methods and in the developed test for anomaly detection is the Self-Organizing Map.

In the area of automated mobile network optimization the contributions of the thesis are several. An extension to previous literature is introducing and validating methods for automated optimization of the WCDMA (Wideband Code Division Multiple Access) admission control. The admission control function determines the amount of traffic allowed in each base station cell. Other key contribution areas include automated optimization of WCDMA radio network parameters such as the pilot power and handover parameters. The pilot power controls the base station cell coverage area and the load distribution between different base station cells and the handover parameters control the soft-handover area or overlapping area of base station cells. Also simultaneous optimization of different parameters was validated.

The optimization methods used were rule-based and the main optimization objective was improving the network performance with regards to network quality or capacity. In conflicting situations a trade-off between capacity and quality was preformed. Statistical testing and policies describing allowed performance indicator levels and trade-off preferences were used in the optimization.

The automated optimization methods were validated using an advanced WCDMA system simulator and a real city environment scenario. The simulation results obtained with the optimization methods were in general promising with up to tens of percents of improvement in performance as measured in system traffic throughput and compared to results obtained with default initial parameter settings.

The structure of this thesis summary is as follows. Section 2 introduces relevant research in the fields of intrusion detection, advanced visualization, anomaly detection and automated mobile radio access network optimization. Section 3 reviews the thesis and presents the contribution of each individual paper and section 4 provides a summary and conclusion.

2 Literature review

2.1 Advanced Monitoring

Intrusion Detection

Building computer systems with no vulnerabilities is in practice impossible and this makes the systems vulnerable to internal attacks and abuse. Heady et al. (1990) defines an intrusion as any set of actions that attempt to compromise the integrity, confidentiality or availability of a resource. With integrity Heady et al. (1990) means that the system and its data must be complete, whole, and in a readable condition, with confidentiality that private data should be known only to the owner of the data or to those authorized by the owner of the data and with availability that the system and critical data must be available for use when the users need it. The objective of intrusion detection is to detect unauthorized access or misuse of a computer system. Intrusions can cause significant financial damages to companies and organizations, which support the development of intrusion detection methods that provide means for system operators to detect intrusions.

Lunt (1993) gives a good overview of intrusion detection techniques and Kemmerer and Vigna (2002) provides a brief history and overview on intrusion detection in general. There are two main methods for doing intrusion detection. Rule-based intrusion detection aims to detect specific behavior patterns that are known to be improper and examples on these types of methods include Kumar and Spafford (1994) and Ilgun (1993). Anomaly detection, on the other hand, aims to recognize abnormal user behavior in order to detect intrusions.

When an intrusion has been detected, two sorts of errors can be made. If a set of events is classified as an intrusion, although it is not, the classification is called a false positive. A false negative, on the other hand, is when an intrusion is not detected and is classified as a normal event. False positives are preferred to false negatives, but the number of false positives should be kept low. Rule-based misuse detection deals with predefined violations and the number of false positives are therefore normally rather limited. However, detecting intrusions outside the set of predefined violations is normally difficult with rule-based methods and this might lead to false negatives. The fundamental assumption of anomaly detection is that intrusions will be anomalous, which means that anomaly detection can be used to detect also types of intrusions that have never occurred before. However, the amount of false positives is normally higher when using anomaly detection, since also non-intrusive events can be anomalous.

Statistical anomaly detection has been used for intrusion detection for example in the Stanford Research Institute projects NIDES (2006) and Emerald (2006) in addition to for example Bayesian rule-based techniques. Also Javitz et al. (1993) and Lankewicz (1992) support the use of anomaly detection in addition to rule-base intrusion detection. Statistical anomaly detection is also the selected domain of this thesis and the thesis introduces new advanced anomaly detection and monitoring methods based on the Self-Organizing Map as we also presented in Höglund (1997, 1998) and Höglund, Hätönen and Tuononen (1998).

ISS (2006) is an example of a commercial provider of intrusion detection systems that is successfully using rule-based techniques. For example Nokia is one of many ISS technology partners and Nokia sells ISS RealSecure® intrusion-protection software integrated into its IP security platforms (Nokia, 2006a). Other commercial and research-project intrusion detection systems can be found in CERIAS (2006) in addition to an intrusion detection bibliography.

Advanced Visualization Methods

Visualization of one-, two- and three-dimensional sets of data is fairly straightforward using for example scatter plots and histograms. However, the visualization of data sets of higher dimensionality is more challenging. Preferable requirements on advanced multivariate visualization methods in this thesis are that the proportional distances between data points can be seen, which means that clusters of data points become evident and outliers can be identified.

There are many visualization and data mining methods for analysis of data and an overview can be found for example in Soukup (2002). The widely used neural network and unsupervised learning method called the Self-Organizing Map (SOM) is included in this overview and it is very useful for multivariate data clustering and visualization. The SOM was originally presented as a visualization tool in Kohonen (1981). Kohonen (1997) is the main book on the SOM and presents a large amount of theory and advanced applications of the SOM. The SOM was selected to be a key component in this study due to its popularity in multivariate data analysis, its excellent unsupervised learning capabilities, its ability to map a high-dimensional data space into a low-dimensional data space and its clustering capabilities (Kohonen, 1997). Also Vesanto (2002) showed that the SOM is very efficient for data exploration and visualization. The SOM has been applied for mobile network data analysis in Raivio, Simula and Laiho (2001), for radio network planning and in particular for finding optimal theoretical locations of base station sites in Fritsch and Hanshans (1993) and Binzer and Landstorfer (2000). Haitao and Simula (1995) used the SOM for optimal traffic shaping in telephone systems with promising results.

Particular methods that can be used for visualizing a trained SOM are the U-matrix method and the Sammon mapping. The U-matrix method used by Iivarinen et al. (1994), Kraaijveld, Mao and Jain (1992), Ultsch and Siemon (1990) and Ultsch (1993) was also used in this thesis since it was more suitable for the selected application area than e.g. the Sammon Mapping (Sammon, 1969). In the Sammon Mapping big differences in distances distort the visualization.

Anomaly Detection

Anomaly detection is also commonly called novelty detection and it is used to detect deviating and abnormal behavior. For anomaly detection, a description of normality is learnt by fitting a model to a set of normal data, and new data observations can be tested for abnormality using the model. If the model indicates a deviation of a new data observation that is greater than a predefined threshold, the observation is considered anomalous or novel. When an anomalous observation has been detected, two sorts of errors can be made. If an observation is classified as an anomaly, although it is not, the classification is called a false positive. A false negative on the other hand is when a real anomaly is not detected and is classified as a normal observation. False positives are preferred to false negatives, but the number of false positives should be kept low. False positives would correspond to Type I errors in hypothesis testing and false negatives to Type II errors when the null hypothesis is the new observation being normal (Milton and Arnold, 1990).

This section present different anomaly detection methods and their application, including simple and advanced statistical methods and neural network -based methods in addition to discussion around their advantages and disadvantages.

Examples of basic methods for finding anomalies or outliers in data of low dimensionality include histograms, scatter plots and basic statistical tests (see for example Milton and Arnold, 1990). Panossian and Ewing (1997) applied basic one-dimensional statistical testing separately on 24 variables, with a deviation of three variables indicating a failure. The method was applied to real-time failure detection for the main engine of a space shuttle. The results obtained by Panossian and Ewing

(1997) indicated that the method produced low amounts of false positives and was able to detect 99.9% of the faults in the selected application area. The disadvantage with basic one-dimensional tests is that only one-dimensional anomalies are detected and not abnormal variable combinations. A somewhat more advanced statistical method that has been used for novelty detection is the Mahalanobis method (Worden, Manson and Fieller, 2000). Worden, Manson and Fieller (2000) used the method in the area of damage detection in engineering applications. The Mahalanobis method is a traditional multivariate statistical method that takes the covariance of the variables to be tested into account. The method is unable to handle multi-clustered distributions and other than linear dependencies between variables, however. In the application area of Worden, Manson and Fieller (2000) the method worked satisfactory, but for multi-modal they recommend other methods such as kernel density estimation.

A more advanced statistical anomaly detection method is the kernel density estimation method or Parzen windows used by Bishop (1994) and Desforges, Jacob and Cooper (1998). The application area of Bishop (1994) was neural network validation when monitoring oil flow in multiphase pipelines, while Desforges, Jacob and Cooper (1998) applied kernel density estimation methods in the area of gearbox fault-detection and novel radar target identification. Both Bishop (1994) and Desforges, Jacob and Cooper (1998) reported good results. Tarassenko et al. (1995) and Nairac et al. (1997) used local Gaussian models with different variances in order to compensate for local differences in the density of multi-variate distributions. Tarassenko et al. (1995) successfully applied the method for detecting masses in mammograms while Nairac et al. (1997) successfully used the method to detect faulty jet engines. Gaussian mixture models (GMM) are more complex than the basic kernel density estimation method (Roberts and Tarassenko, 1994; Nairac et al., 1997). Roberts and Tarassenko (1994) used GMM methods for analyzing EEG signals in order to detect epileptic seizures and they obtained high performance rates.

Tarassenko et al. (1999) and Nairac et al. (1997, 1999) showed that a method based on component-wise normalization, the K-means algorithm and Euclidian distances was superior to basic Parzen window or kernel density estimation methods and GMM models when the amount of training samples was limited and the dimensionality of the data was high. Their application area was analysis of jet engine vibration data. The problem with the GMM is the large number of free parameters to be estimated when the amount of training data is limited (Tarassenko et al. (1999)). In the application areas of this thesis the dimensionality of data is also high while the amount of data stored is limited. This was the main reason for selecting a similar approach as Tarassenko et al. (1999) and Nairac et al (1997, 1999). However, instead of the K-means clustering method the Self-Organizing Map was used as the basis for the anomaly detection method. The Self Organizing Map is fairly similar to the K-means algorithm. However, it has certain advantages such as the topological ordering and its learning mechanism with data samples affecting all the model vectors and these properties make it more robust than the K-means algorithm (see e.g. Kohonen (1997) for details on the algorithm). Also Harris (1993) successfully used the Self-Organizing Map to detect machine faults in frequency measurement data. Other examples of using neural networks for anomaly detection include Kozma et al. (1994) who showed that the use of a feed-forward neural network could provide benefits in time-series anomaly detection in the application area of nuclear reactor monitoring.

2.2 Automated Mobile Radio Access Network Optimization

Mobile Radio Access Network Optimization

The leading cellular radio access technologies include Global System For Mobile Communication (GSM), Code Division Multiple Access (CDMA) and Wideband CDMA (WCDMA). Common for these is the radio resource management (RRM) function that controls the utilized capacity of the radio interface and maintains stable operation by handling functions such as admission control, power control, and handover control. Principles and details on RRM are presented by Halonen, Romero and Melero (2002) for GSM, by Holma and Toskala (2001) and 3GPP (1999a, b, c) for WCDMA and by Lee and Miller (1998) for CDMA.

There is a set of parameters controlling the radio resource management function and these parameters are normally set by when planning a mobile network. The parameters can vary between different base station cells and the operator can adjust the parameters to obtain desired performance. The objective of mobile radio access network optimization as defined in this thesis is optimizing radio resource management parameters in order to improve network capacity, maintain or improve the quality of service level desired by the operator or perform quality vs. capacity trade-off. The automated optimization is sometimes also called auto-tuning. The basic steps of the optimization process:

1. Collect performance data during system operation
2. Perform optimization
3. Implement updated parameters into the system after possible verification
4. Return to step 1

Halonen, Romero and Melero (2002) present GSM automated radio access optimization methods and examples on promising results achieved using these. The methods they presented include mobile measurement based frequency planning, measurement based adjacency planning and handover parameter optimization. The book edited by Laiho, Wacker and Novosad (2001) is focused on WCDMA network planning and optimization and in this book’s tenth chapter authored by Laiho, Höglund and Buot (2001), we tackled WCDMA automated parameter optimization in particular. There have been fewer studies on automated radio access parameter optimization for the WCDMA technology than for the GSM technology and the WCDMA radio access technology also provides a wider 3G service environment being the radio access technology of the Universal Mobile Telecommunications System (UMTS). WCDMA was therefore selected to be the main focus radio access technology of the thesis.

This chapter further presents particular WCDMA radio access optimization areas namely admission control optimization, pilot power optimization, handover control optimization and other miscellaneous WCDMA optimization in addition to validation and possible optimization system architecture solutions.

Admission Control Optimization

The admission control function of the WCDMA radio resource management determines the amount of users and traffic allowed in the base station cell and the radio resource management parameters to be optimized include the threshold for admission of new user traffic. Generally the higher the threshold, the more traffic is allowed in the cell.

Many authors have studied admission control previously. Dimitriou, Tafazolli and Sfikas (2000) introduced specific requirements for the admission control. For instance, the admission control is required to maintain quality-of-service in terms of blocking, dropping, bit error ratio, and packet delay; to adapt to changes in the system load and inter-cell interference; and to reconfigure for new services. Moreover, the admission control should be simple in design and provide minimum processing time. Viterbi and Viterbi (1993) evaluated the theoretical uplink capacity for an interference level that is 10 dB higher than the noise floor. Kim and Chang (2000) suggested that safety margins are necessary when target interference or power levels are defined for the admission control. Moreover, the study suggested that the handover control needs targets different from those used in the admission control of new calls. Also Hou and Fang (2001) suggested guard channels to be used in admission control done during handovers.

The WCDMA base station cell admission control thresholds or load-level targets can be based on throughput, interference, transmit power, or number of connections, for instance (Holma and Toskala, 2001). The power or interference-based radio resource management is more complex than the throughput-based management. However, the interference-based radio resource management allows soft capacity gains that are not achievable with the throughput-based management (Holma and Toskala, 2001). Holma and Laakso (1999) and Holma and Toskala (2001) described an interference-based admission control method.

Hämäläinen and Valkealahti (2002) presented an enhancement of this admission control method introducing an adaptive power increase estimation method using kernel regression. Knutsson et al. (1998) supported the use of power-based admission control and compared methods of single-cell and multi-cell admission controls. Their conclusion was that the gains obtained with the multi-cell admission control did not compensate for the increased complexity. Dimitriou, Tafazolli and Sfikas (2000) also found gains with multi-cell admission control. However, in this thesis single-cell power-based admission control was the selected admission control strategy.

Mueckenheim et al. (2000) suggested that the uplink interference target or threshold is set as a trade-off between blocking and dropping, which is in line with the theoretical sensitivity analysis of admission control target setting we introduced in Laiho, Höglund and Buot (2001). Pöllönen (2001), Dimitriou, Tafazolli and Sfikas (2000) and Knutsson et al. (1998) had similar ideas. This assumption was also used in this thesis. Knutsson et al. (1998) defined call dropping ten times more costly than blocking in admission control target setting. Also in this thesis dropped calls were considered as clearly more costly than blocked calls when setting the operator adjustable performance indicator weighting used in optimization. Other optimization studies related to power-based admission control optimization include Kim (1999), who considered a downlink power allocation algorithm for adjusting the total cell power and its allocation to individual users and Laiho, Höglund and Buot (2001), in which we introduced an optimization method for the dedicated capacity for non-real-time and real-time traffic.

Pilot Power Optimization

The primary common pilot channel signal power level determines the size of the base station cell area. If the pilot power is decreased the cell gets smaller and if it is increased the cell becomes bigger. Increasing the base station cell size also normally means that more mobile stations are connected to the cell in question, which means that the pilot power can be used to balance load between base station cells.

Studies on pilot power optimization include Kim, Chang and Lee (1999), Love et al. (1999), Yang and Lin (2000) and Zhu et al. (2002). Love et al. (1999) introduced a rule-based method for reducing pilot power pollution. The results obtained with the method in a field trial indicated that the method could achieve similar results to those obtained with manual optimization. Yang and Lin (2000) studied how power management can be utilized in congestion relief in loaded cells. Zhu et al. (2002) proposed a method to reduce hot spot problems with the control of pilot power based on cross-correlation measures. Kim, Chang and Lee (1999) presented a heuristic method for finding optimal pilot power values with regards to coverage and capacity in CDMA, but without presenting any validations using, for instance, simulations and multiple cells. Also in this thesis both pilot coverage and cell capacities were the main issues when performing optimization.

Handover Control Optimization

Handover control determines when and to which cell or cells the mobile station is connected. Examples of radio resource management parameters to be optimized in this area include handover window parameters controlling the soft-handover area or the overlapping area of base station cells and neighbor base station cell lists, determining the possible handover candidate cells when the mobile station needs to connect to a new base station cell when connected to a certain base station cell or cells. The handover parameters impact service coverage, quality and capacity.

Olofsson, Magnusson and Almgren (1996) and Magnusson and Olofsson (1997) presented GSM neighbor cell list optimization based on analysis of mobile station signal strength measurements and handover statistics. Their results indicated that automation is possible and that the advantages of automation are several compared to manual network planning. In Laiho, Höglund and Buot (2001), we presented two different WCDMA neighbor cell list optimization methods, one being based on mobile stations doing full ordered searches for all cells within measurement range, while the other was based on handover statistics. These methods for doing WCDMA neighbor cell list optimization added no major theoretical novelty in comparison to the ideas for the GSM technology presented by Olofsson, Magnusson and Almgren (1996) and Magnusson and Olofsson (1997).

Buot et al. (2001) and Flanagan and Novosad (2002a, 2002b) presented methods and results on soft-handover parameter optimization. Buot et al. (2001) modeled the soft-handover dynamics with a simple Markov chain to identify the adjusted critical parameters. Flanagan and Novosad (2002a, 2002b) optimized the soft-handover parameters with a gradient-descent minimization of a cost function that described blocking and total base station power. Sipilä et al. (1999) presented a more general study on soft-handover gains and their impact on WCDMA network performance.

Other WCDMA Optimization

Cell locations and antenna tilt angles are also critical in the network planning and optimization. Johnson, Khalab and Höglund (2002) presented simulation results on inter and intra operator co-existence of WCDMA hierarchical cell structure layers in a real city environment. Wacker, Sipilä and Kuurne (2002) introduced automated optimization of antenna tilt angles in WCDMA. Lee and Lee (2001) provided some ideas on how to utilize mobile station location in optimization. Flanagan and Novosad (2003) introduced gradient-descent cost function minimization–based multi-parameter optimization and their results indicated that the packet switched traffic throughput could be improved using the method.

Validation

Simulators and real network testing are the most common ways of performing validation of optimization methods. The first step before real network validation is to use simulator validation, as in many of the studies mentioned in the previous sections of this chapter. Hämäläinen, Holma and Sipilä (1999) presented an advanced WCDMA radio network simulator developed at Nokia Research Center in Helsinki. The simulator implemented many advanced features such as total power based admission control, closed-loop and outer-loop power controls, soft and hard handover controls, packet scheduler, load control, and quality manager. Examples of previous studies with the simulator include Laiho et al. (2001) and Buot and Rinne (2000). The automated radio access parameter optimization methods of this thesis were verified with this simulator.

Optimization System Architecture and Systems

Magnusson and Oom (2001) introduced an architecture for automated optimization of networks and validated it in a GSM field trial. Their main idea was that in large networks the optimization should be distributed to local agents taking care of regional tuning with centralized control. Additionally real-time computing and open interfaces should be used according to him. The results of the field trial obtained by Magnusson and Oom (2001) indicated that the architecture was fairly suitable for implementing self-tuning algorithms.

In Laiho, Höglund and Buot (2001), we presented a hierarchical structure for doing automated optimization, in which the automated optimization was split into independent parameter-subsystems and inter-dependencies between sub-systems were taken into account in higher optimization layers. Additionally we presented an example of a general cost function for measuring the network performance using key performance indicators.

An example of a commercial system that applies automated mobile network optimization can be found in the web-document Nokia (2006b) that provides a guide to a mobile network Operations Support System (OSS), the Nokia NetAct™. Nokia NetAct™ include a component for aided or automated GSM and WCDMA mobile network optimization, the NetAct Optimizer.

3 Contribution of thesis

This thesis consists of ten individual papers. In this section, the contribution of each paper is described. To clarify the picture, table 1 classifies the papers according to type of monitoring or optimization task, input variable and output parameter dimension, application area and the object of monitoring or optimization. The main tasks in the monitoring area were visualization and anomaly detection and the application areas were computer network security and mobile network operation. The particular problems tackled were intrusion detection, performance and fault monitoring and cell clustering to ease optimization. In the automated optimization task the particular application area was the WCDMA mobile network radio resource management parameter optimization.

Table 1 Classification of papers

Paper	Type of monitoring or optimization task	Input variable dimension	Output parameter dimension	Application Area	Object
[I]	Visualization	Multiple	Two	Computer Network Security	Host user
[II]	Anomaly detection	Multiple	Single	Computer Network Security	Host user
[III]	Visualization and anomaly detection	Multiple	Two&single	Mobile Network Operation	Cell
[IV]	Automated optimization	Multiple	Single	Mobile Network Operation	Cell
[V]	Automated optimization	Multiple	Single	Mobile Network Operation	Cell
[VI]	Automated optimization	Multiple	Single	Mobile Network Operation	Cell cluster
[VII]	Automated optimization	Multiple	Single	Mobile Network Operation	Cell
[VIII]	Automated optimization	Multiple	Single	Mobile Network Operation	Cell
[IX]	Automated optimization	Multiple	Multiple	Mobile Network Operation	Cell cluster
[X]	Automated optimization	Multiple	Multiple& single	Mobile Network Operation	Cell and cell cluster

3.1 Advanced Monitoring

Computer Network User Behavior Visualization using Self-Organizing Maps [I]

The amount of monitoring data generated in computer networks is enormous. Tools are needed to ease the work of system operators. Paper [I] introduces an advanced way of visualizing multidimensional computer network data that can be used in computer network monitoring, anomaly detection and ultimately in intrusion detection. The selected objects of monitoring were UNIX computer network host users. Feature selection and normalization was performed before applying the visualization algorithms on the multi-dimensional monitoring data. The visualization algorithms used were the Self-Organizing Map and the U-matrix method. Some illustrative examples, the test system used and feedback from users of it was presented in paper [I]. The monitored object is not limited to computer network host users, for example entire hosts or mobile network elements can be monitored as well.

The main extension of the paper to previous literature was applying the advanced monitoring methods Self-Organizing Map and U-matrix in the anomaly detection domain of computer network intrusion detection.

A Computer Host-based User Anomaly Detection System using the Self-Organizing Map [II]

Paper [II] extends paper [I] and introduces a method for doing automatic anomaly detection in order to detect intrusions. This method uses a test based on the Self-Organizing Map, with which it is possible to test if recent user behavior is anomalous compared to historical user behavior. It is possible to set the required heuristic probability of rejecting the hypothesis of the behavior being abnormal. Additionally the method can be used to calculate the most significantly deviating variables or features, which is quite useful if the behavior is reported abnormal. The same test system as in paper [I] was used to analyze the performance of the method. The examples from the system operation and the test user feedback indicated good performance of the method. The only negative issue with the method is when the hypothesis of the behavior being normal is falsely rejected (false positive). The amount of false positives can be controlled with the probability parameter mentioned above. The length of the training period determines how fast the method adapts to new behavior. A challenge is that the intrusive behavior should not be included in the training behavior sample in order to detect the intrusions.

A mobile network consists of a large amount of computer network hosts and the advanced monitoring methods introduced in papers [I] and [II] are applicable when monitoring mobile network hosts as well as other computer network hosts.

The main extension of the paper to previous literature such as Harris (1993) was enhancing and formalizing a Self-Organizing Map-based anomaly detection method and applying it for doing intrusion detection.

Utilization of Advanced Analysis Methods in UMTS Networks [III]

Paper [III] extends the application area of papers [I] and [II] and introduces new analysis and visualization methods for WCDMA cellular networks, another area in which the vast amount of monitoring data is a challenge for network operators.

Paper [III] suggests that a performance profile of a mobile network or network cells can be built using the Self-Organizing Map and performance indicator data collected from the network. The performance profile is called performance spectrum and can be used for cell clustering and cell behavior trend analysis. The clustering results can be used to apply the same network parameters on cells in same cell clusters, which means that network parameter optimization can be done on cell cluster level. Ideas on how to ease data visualization using red-green-blue (RGB) mapping is also provided. Certain Key Performance Indicators (KPI) are more important than others, and KPI weighting is suggested as solution to this when training the performance spectrum.

Examples on results obtained by building cell specific performance spectra and applying similar anomaly detection methods as in Paper [II] in the area of mobile network monitoring are additionally presented. The presented results provide examples on how the method is able to detect multivariate anomalies.

The main extension of the paper to previous literature was applying the above-mentioned advanced monitoring methods in the area of mobile network performance monitoring.

3.2 Advanced Mobile Network Automated Optimization

Quality-based Auto-tuning of Cell Uplink Load Level Targets in WCDMA [IV]

Paper [IV] presents automated optimization of uplink admission control load level targets. In uplink the total admission control target was measured using total uplink wideband received power. The interference-based load level targets were specific for each cell. The main uplink input variables were uplink cell load and the uplink quality indicators bad quality, blocking and packet traffic queuing. The optimization objective was to keep the quality indicators within statistically allowed levels and if not possible performing a weighted trade-off between capacity and quality.

The approach was validated using a dynamic WCDMA system simulator. The automated optimization significantly improved the performance compared to the performance obtained with fixed default parameter settings. The performance improvement as measured in cell throughput was up to 50% when the reference was the performance obtained with cautiously set fixed parameters.

The main extension of the paper to previous literature was presenting a novel algorithm for adaptive quality-based and cell-specific uplink admission control optimization and validating it using an advanced simulator and a real city scenario with promising results.

Quality-based Tuning of Cell Downlink Load Target and Link Power Maxima in WCDMA [V]

Paper [V] extends the application area of paper [IV] to downlink admission control. In downlink the downlink admission control target that was measured using total downlink wideband transmission power. In downlink the individual radio link power maxima can be adjusted in addition to the total downlink admission control target. The objective of paper [V] was automated optimization of the individual link power maxima for different cell downlink load level targets. Similar input variables as in [IV] were used; i.e. downlink cell load and the downlink quality indicators bad quality, blocking and packet traffic queuing. As in [IV], the optimization objective was to keep the quality indicators within statistically allowed levels and if not possible performing a weighted trade-off between capacity and quality.

The approach was validated using a dynamic WCDMA system simulator. The automated optimization of downlink link power maxima decreased the bad quality significantly compared to fixed parameter settings, which made a higher cell load target setting possible. The automated optimization together with the adjusted load target resulted in a significant increase in throughput in addition to a quality improvement. The increase in throughput was up to 39% compared with default conservative parameter settings. The conducted simulations support the assumption that the downlink performance can be managed and improved using the proposed cell-based automated optimization.

The main extension of the paper to paper [IV] and previous literature was applying the uplink ideas of [IV] and presenting an algorithm for adaptive quality-based and cell-specific downlink admission control optimization and validating it using an advanced simulator and a real city scenario with promising results.

Auto-tuning of Service-specific Requirement of Received EbNo in WCDMA [VI]

Paper [VI] extends the automated optimization of admission control performed in papers [IV] and [V]. Paper [VI] validates the feasibility of automated optimization of service- and bit rate-specific uplink and downlink Planned EbNo values. The EbNo requirement is the level of the received bit energy to the interference and noise density that the receiver equipment requires for proper decoding of the signal. The Planned EbNo is a vital parameter in estimating the power increase in uplink admission control, in scaling powers when the service is varying, and in rapid updating of bit rates in packet scheduling, for instance.

The uplink method was fairly straightforward, being a cell- and service- based filtered averaging of the EbNo target values of the outer loop power control. The downlink method was more complicated since the outer loop EbNo targets are not reported to the network by the mobile terminals. In downlink the method was based on average ratios of the service link powers to the total downlink transmitted power in the cell. Additionally we had to make some assumptions on the average cell orthogonality factor and inter-cell interference ratios. This means that there could be a bias in the downlink Planned EbNo values obtained using the method. However, in downlink the absolute values are not so critical and the proportional values are the most important ones.

The proposed methods were tested using a dynamic WCDMA system simulator with a deployment of macro cells on a real city region. The results showed that the proposed methods tune the initially incorrect planned EbNo values so that the throughput in the system increase for packet-switched services. The improvement in uplink was more significant, being up to 10% depending on the amount of users in the system.

The main extension of the paper to previous literature was presenting and with promising results validating optimization methods for the Planned EbNo parameter used in admission control.

WCDMA Common Pilot Power Control with Cost Function Minimization [VII]

Paper [VII] extends the automated optimization of radio resource management parameters from the admission control and power management parameters in papers [IV], [V] and [VI] to the common pilot power, a parameter controlling the cell size. The objective of the cell-based pilot power optimization in this paper was to reduce the difference in load between cells while ensuring good pilot coverage. Improving the load balance between cells helps to ease the load of overloaded cells. The load of a cell was measured using the ratio of transmitted downlink power to the maximum downlink transmission power of the cell, while the pilot coverage was evaluated as the ratio of mobile terminal handover measurements above a predefined threshold. We implemented a cost function that described the differences in load between a cell and its neighboring cells in addition to the magnitude of its pilot coverage being below the defined target coverage. A gradient descent cost function minimization was used to optimize the pilot power.

As in papers [IV], [V] and [VI], the approach was validated using a dynamic WCDMA system simulator with a deployment of macro and micro cells on a city region whose measured propagation characteristics were incorporated into the model. The results showed that the proposed control method slightly improved the air interface performance measured as a function of packet throughput.

The main extension of the paper to previous literature such as Kim, Chang and Lee (1999), Love et al. (1999), Yang and Lin (2000) and Zhu et al. (2002) was firstly introducing a novel way of taking both cell load balancing and pilot coverage into account when performing the optimization, secondly using a gradient decent cost function minimization method and thirdly validating the method using simulations in a real city environment.

WCDMA Common Pilot Power Control for Load and Coverage Balancing [VIII]

Paper [VIII] extends the cell-based automated pilot power optimization in paper [VII] so that a simple rule-based method was used instead of the gradient descent cost function minimization method. The objectives of the automated optimization were the same, i.e. to reduce the difference in load between neighboring cells while ensuring good pilot coverage. Therefore also the measurements used to determine the pilot coverage and cell load were the same, but additionally statistical testing was applied on the measurements to get the desired optimization inputs. We used an unpaired T-test to test whether there was a statistically significant difference in load between a cell and its neighboring cells and we approximated the binomial distribution with a normal distribution in order to be able to test whether the pilot coverage was below the predefined target.

Simple heuristic rules determined the direction of the automated optimization. The approach was again validated using the same dynamic WCDMA system simulator and scenario as in [VII]. The results showed that the proposed control method moderately improved the performance as measured in average cell throughput and other packet performance measures, while slightly degrading the average pilot coverage. The rule-based control method showed somewhat better performance than the gradient descent optimization method in paper [VII]. In this study the load balance was given somewhat higher priority than the pilot coverage assurance, which a real operator would not likely do. In the real case the operator would naturally set the optimization policies according to own preferences.

The main extension of the paper to previous literature and paper [VII] was using a rule-based method combined with statistical testing to optimize the pilot coverage and cell load balance and validating the method using simulations in a real city environment with moderately positive results.

UMTS Radio Network Multi-parameter Control [IX]

Paper [IX] extends the radio resource management parameter optimization from single-parameter optimization of admission control parameters and pilot power in papers [IV-VIII] to simultaneous multi-parameter optimization. The parameters included in the multi-parameter optimization were the uplink admission control target, the downlink admission control target, the downlink link power maxima, the pilot power and the addition window used in handover control.

Measurement statistics of poor quality call rate, blocking rate, power and interference levels, and terminal measurements were used in the optimization. As in papers [IV], [V] and [VIII] statistical testing was used to test for deviation of measurements from target levels. In addition to the measurements statistics, policies defining the relative costs of different statistics and allowed measurement target levels were used as input to the heuristic rules that guided the optimization. The optimization was on cell cluster level and the traffic mix circuit switched as opposite to being on cell level and packet switched or mixed circuit and packet switched in papers [IV-VIII].

As previously, the method was validated using a dynamic WCDMA system simulator with a deployment of 17 cells in Helsinki city center. The whole set of 17 cells were assumed to form a uniform cluster. The methods presented in paper [III] could also have been used to form more homogenous clusters. The method showed fairly good convergence and stable operation. The obtained results showed that the method improved overall network performance in comparison to fixed planned default values. The capacity of the network was improved up to 20% depending on the network load while the quality decreased slightly though remaining acceptable.

The main extension of the paper to previous literature and papers [IV-VIII] was extending the amount of parameters being optimized simultaneously from one to five including handover parameters, performing the optimization on cell cluster level instead of cell-level and validating the method using simulations in a real city environment with positive results.

Automated Optimization of Key WCDMA Parameters [X]

Paper [X] extends papers [IV-IX] and presents a more extensive literature survey in the area of automated radio resource management parameter optimization and in particular presents admission control related theory and references. Paper [X] gives an extensive summary on the measurements, on the single- and multi-parameter optimization methods and on the results presented in papers [IV-IX]. Additionally paper [X] introduces good results obtained in rule-based handover parameter optimization.

Due to the fact that the performance of the automated optimization methods was fairly stable also with the various load levels, different traffic mixes and different scenarios with very varying conditions the methods were considered robust. The advantages and disadvantages with cell-based and cell cluster-based optimization were discussed. A general statement of paper [X] was that the focus of the paper was set on comparing rule-based optimization methods to fixed parameter settings, and therefore the range of optimization methods compared was not large. Paper [X] further stated that similar results can likely be obtained with other optimization methods, but the rule-based optimization has the advantage of being fairly transparent to the operator. In one particular case a rule-based method was compared to the gradient descent cost function optimization method and in this case the rule-based method was slightly better. However, the main conclusion was that the significant increase in capacity obtained when using the automated optimization methods warrants their consideration as features for the network managements system.

The main extension of the paper to previous literature and papers [IV-IX] was presenting an extended literature survey in the automated radio resource management optimization area and introducing an extensive summary, discussion and small extension of the single- and multi-parameter optimization work done in papers [IV-IX].

4 Summary and Discussion

This thesis presented ten papers on mobile network monitoring and automated optimization. The first three papers were purely related to network monitoring. The application area of Papers [I] and [II] was network host intrusion detection with Paper [I] focusing on advanced visualization and Paper [II] on anomaly detection. An important component in the visualization and in the developed test for anomaly detection was the Self-Organizing Map. In Papers [III] the application area was extended to mobile network cell performance monitoring, clustering and anomaly detection. The idea to perform mobile network optimization on cell cluster level instead of cell level was introduced. The presented examples of results obtained with the methods indicate that the methods are suitable for anomaly detection, visualization and clustering.

No extensive set of visualization, clustering and anomaly detection methods was validated in this thesis, since the idea was to select the most promising ones for the selected application area based on previous research. The Self-Organizing Map was selected to be a key component in both the visualization methods and the developed anomaly detection test due to its popularity in multivariate data analysis, its excellent unsupervised learning capabilities, its ability to map a high-dimensional data space into a low-dimensional data space and its clustering capabilities (Kohonen, 1997). For example anomaly detection methods such as Gaussian Mixture Models require very large training data sets when the training data dimensionality is high (Tarrasenko et al., 1999). The amount of training data available in the application areas of this thesis was limited and the data was of high dimensionality and therefore the developed method was considered more suitable.

The feedback from the test usage of the visualization and anomaly detection methods also indicated that the methods were suitable for monitoring and able to detect the necessary anomalies. The main disadvantage with the anomaly detection method was a limited amount of false positives. In addition to real intrusions and base station faults, the method also reported other significant changes in usage patterns as anomalies. However, false positives are preferred to false negatives and the amount of false positives can be controlled with the anomaly detection threshold.

As a summary the main extension of the thesis to previous literature in the network monitoring area was developing and applying advanced monitoring, clustering and anomaly detection methods in the field of network intrusion detection and mobile network monitoring with promising results.

Papers [IV-X] tackled the area of automated mobile network parameter optimization. The selected parameter domain was WCDMA radio access parameters. Papers [IV-VI] presented results on automated admission control parameter optimization. Paper [IV] focused on uplink admission control load target optimization with results indicating performance improvements of tens of percents in base station cell voice and data capacity being possible. Paper [V] performed optimization of downlink admission control load targets with similar results. Paper [VI] performed optimization of the admission control parameter planned EbNo, with a moderate improvement in uplink performance obtained. Papers [VII-VIII] tackled the optimization of pilot power, a parameter that controls the base station cell size. The obtained results indicated that moderate improvements in performance were possible. There were no big differences in performance between the method using statistical testing and simple rules and the method using gradient descent cost function minimization. Paper [IX] presented optimization of many parameters simultaneously on cell cluster level, with improvements in performance up to 20%. Paper [X] presented an extensive summary of the single- and multiple parameter optimizations in Papers [IV-IX] and extended the single-parameter optimization to handover parameters.

The performance of the proposed rule-based automated optimization methods were compared with the performance obtained without automated optimization. No significant comparison among different optimization methods was made. One particular comparison that was made indicated no benefit of using a gradient-descent method instead of the rule-based approach in the case of pilot power optimization. The rule-based approach used in this thesis cannot be considered superior to conventional optimization methods, but the rule-based control offers the network operator a good insight into the operation logic of the optimization. The benefit of for example the gradient descent minimization is that minimum knowledge is required about the dependence of performance on the parameters. On the other hand, the choices that the algorithm makes in the parameter adjustments in the noisy mobile network system may remain obscure to the network operator.

The developed optimization methods can be considered fairly robust. They were validated in a real city simulation environment planned using realistic site locations with significant load differences among cells in addition to numerous different load conditions simulated. Both the cell-based individual parameter optimization and the cell-cluster-based multi-parameter optimization performed well under different load conditions. The optimization on cell-level can bring additional gains in performance compared with cell-cluster-based optimization, since optimal values for the individual cell-specific situation are obtained. The benefit of using the same parameter values in a cluster of homogeneous cells is in the increased stability and larger amount of measurement data.

The obtained increases in capacity are specific to the described cases and generalizing the results to real networks is not straightforward. The benefit of automated optimization depends on the choice of the initial parameters, traffic characteristics, defined policies, and the availability of performance measures. The optimization candidate methods presented in this thesis should therefore be validated in real networks before implementation.

A key challenge in real mobile networks is success in collecting and storing all the required performance measurements. Online measurements might be limited and greater stability could possibly be achieved with longer measurement averaging. Therefore, in a real mobile network, the parameters might not be optimized online in the radio network controller, but for example optimization of sets of parameters for busy-hour and for low-usage situations could take place in the network management system.

As a summary the main extension of the thesis to previous literature in the area of automated mobile network optimization the was introducing and validating methods for automated optimization of WCDMA (Wideband Code Division Multiple Access) radio access network parameters with promising results.

The main conclusion of this thesis is that the advanced monitoring and automated optimization methods presented constitute promising feature candidates for mobile network management systems, easing the work of network operators and facilitating the achievement of clear improvement in mobile network performance. The performance improvement can be seen as reduced mobile network capital and operational expenditure. However, it is of major importance to keep the monitoring and optimization system simple enough in order to keep the value of the improvement in mobile network operation and performance significantly greater than the cost of having a more complex system.

Related Patent Applications

Hätönen K., Höglund A., Miettinen M., Berg J., Kulmala K. and Torikka S., 2002, “System, device and method for automatic anomaly detection”, patent application WO0221774A1.

Höglund A., Hätönen K. and Sorvari A., 2002, “Anomaly detection system and a method of teaching it”, patent application WO0221242A1.

Höglund A., Pöllönen J. and Laiho J., 2002, “Method and device for controlling admission of users to a cellular radio network”, patent application WO2002091781A1.

Höglund A., Valkealahti K., Laiho J. and Pöllönen J., 2002, “Method and device for controlling admission of users to a cellular radio network”, patent application WO2002089512A1.

Laakso J., Höglund A., Sorvari A., Valkealahti K. and Hämäläinen A., 2003, ”Method and network element for controlling power/load in a network”, patent application WO2003071710A1.

Laiho J., Höglund A. and Novosad T., 2003, “Method and system for optimizing the performance of a network”, patent application WO2003037018A1.

Laiho J., Höglund A., Raivio K., Henriksson J., Hätönen K., Hämäläinen A. and Simula O., 2002, “Method for configuring a network by defining clusters”, patent application WO2002080458A1.

Valkealahti K., Höglund A., Parkkinen J. and Laiho J., 2003, ”Pilot channel power autotuning”, patent application WO2003036815A1.

References

3GPP (Third Generation Partnership Project), 1999a, “Requirements for support of radio resource management”, *Technical Specification 25.133*.

3GPP (Third Generation Partnership Project), 1999b, “Radio Resource Control (RRC) Protocol Specification”, *Technical Specification 25.331*.

3GPP (Third Generation Partnership Project), 1999c, “Radio resource management strategies”, *Technical Specification 25.922*.

Binzer T. and Landstorfer F. M., 2000, “Radio network planning with neural networks”, *Proc. 52th IEEE Vehicular Technology Conference*, vol. 2, pp. 811-817.

Bishop C.M., 1994, “Novelty detection and neural network validation”, *Proc. IEE Vision, Image and Signal Processing*, vol. 141, issue 4, pp. 217-222.

Buot T. and Rinne M., 2000, "Performance of WCDMA with radio resource management", *Proc. Wireless 2000, the 12th International Conference on Wireless Communications*, pp. 203-209.

Buot T., Zhu H., Schreuder H., Moon S., Song B. and Eriksson T., 2001, “Soft handover optimization for WCDMA”. *Proc. 4th International Symposium on Wireless Personal Multimedia Communications*, Aalborg, Denmark.

CERIAS, 2006, The Purdue University Center for Education and Research in Information Assurance and Security (CERIAS), available at: http://www.cerias.purdue.edu/about/history/coast_resources/intrusion_detection/

Desforges M. J., Jacob P. J. and Cooper J. E., 1998, “Applications of Probability Density Estimation to the Detection of Abnormal Conditions in Engineering”, *Proc. Inst. Mech. Eng.*, part C, vol. 212, no. 8, pp. 687-703.

Dimitriou N., Tafazolli R. and Sfikas G., 2000, “Quality of service for multimedia CDMA”, *IEEE Communications Magazine*, vol. 38, issue 7, pp. 88-94.

EMERALD, 2006, available at: http://www.csl.sri.com/projects/emerald/.

Flanagan J. A. and Novosad T., 2002a, “Automatic Selection of Window Add in a WCDMA Radio Network based on Cost Function Minimization”, *Proc. IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA)*, vol. 3, pp. 672- 676.

Flanagan J. A. and Novosad T. 2002b, “WCDMA Network Cost Function Minimization for Soft Handover Optimization with Variable User Load”, *Proc. 56th IEEE Vehicular Technology Conference Fall*, vol. 4, pp. 2224-2228.

Flanagan J. A. and Novosad T., 2003, “Maximizing WCDMA Network Packet Traffic Performance: Multi-Parameter Optimization by Gradient Descent Minimization of a Cost Function”, *Proc.14th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 311-315.

Fritsch T. and Hanshans S., 1993, “An integrated approach to cellular mobile communication planning using traffic data prestructured by a self-organizing feature map”, *Proc. IEEE International Conference on Neural Networks*, vol. 2, pp. 822-D-822-I.

Haitao T. and Simula O., 1995, “Neural adaptation for optimal traffic shaping in telephone systems”, *Proc. IEEE International Conference on Neural Networks*, vol. 4, pp. 1561-1565.

Halonen T., Romero J. and Melero J., 2002, editors, *GSM, GPRS and EDGE Performance - Evolution towards 3G/UMTS*, Wiley and Sons, 2002.

Hämäläinen A. and Valkealahti K., 2002, “Adaptive Power Increase Estimation in WCDMA”, *Proc. IEEE 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 3, pp 1407-1411.

Hämäläinen S., Holma H. and Sipilä K., 1999, "Advanced WCDMA radio network simulator", *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 951-955.

Harris T., 1993, "A Kohonen S.O.M. Based, Machine Health Monitoring System Which Enables Diagnosis Of Faults Not Seen In The Training Set", *Proc. International Joint Conference on Neural Networks (IJCNN)*, vol. 1, pp. 947-950.

Haykin S., 1999, *Neural Networks, a Comprehensive Foundation*, Macmillan.

Heady R., Luger G., Maccabe A., and Servilla M., 1990, *The architecture of a network level intrusion detection system*, Technical Report CS90-20, Department of Computer Science, University of New Mexico.

Höglund A., 1997, *An Anomaly Detection System for Computer Networks*, Master's thesis, Helsinki University of Technology, Helsinki.

Höglund A. J., Hätönen K. and Tuononen T. O., 1998, "A UNIX Anomaly Detection System using Self-Organizing Maps", *Workshop on the Recent Advances in Intrusion Detection (RAID)*, available at: http://www.raid-symposium.org/raid98/.

Höglund A. J., 1998, "An Anomaly Detection System for Computer Networks". *The Year Book of the Finnish Statistical Society*, pp. 11-29.

Holma H. and Toskala A., 2001, editors, *WCDMA for UMTS*, Wiley and Sons, 2001.

Holma H. and Laakso J., 1999, "Uplink admission control and soft capacity with MUD in CDMA", *Proc. 50th IEEE Vehicular Technology Conference Fall*, vol. 1, pp. 431-435.

Hou J. and Fang Y., 2001, "Mobility-based call admission control schemes for wireless mobile networks", *Wireless Communications and Mobile Computing*, vol. 1, issue 3, pp. 269–282

Iivarinen J., Kohonen T., Kangas J. and Kaski S., 1994, "Visualising the clusters on the Self Organising Map", *Multiple Paradigms for Artificial Intelligence (SteP)*, pp. 122-126, Finnish Artificial Intelligence Society.

Ilgun K., 1993, "USTAT: A real-time intrusion detection system for UNIX". *Proc. IEEE Symposium on Research in Security and Privacy*, pp. 16-28.

ISS (Internet Security Systems), 2006, available at: http://www.iss.net/.

Jakes, W. C., 1974, *Microwave Mobile Communications*, Wiley and Sons, New York.

Javitz H. S., Valdes A., Lunt T. F., Tamaru A., Tyson M. and Lowrance J., 1993, "Next generation intrusion-detection expert system (NIDES): Statistical algorithms rationale and rationale for proposed resolver", Technical report, Computer Science Laboratory, SRI International, Menlo Park, California, the USA.

Johnson C., Khalab J. and Höglund A., 2002, "Inter and Intra Operator Coexistence of WCDMA HCS Layers ", *Proc. 55th IEEE Vehicular Technology Conference Spring*, vol. 1, pp. 115-119.

Kemmerer R. A. and Vigna G., 2002, "Intrusion detection: a brief history and overview", *Computer*, vol. 35 , issue 4, pp. 27-30.

Kim D., 1999, "A simple algorithm for adjusting cell-site transmitter power in CDMA cellular systems", *IEEE Transactions on Vehicular Technology*, vol. 48, issue 4 , pp. 1092-1098.

Kim, D., Chang Y. and Lee J. W., 1999, "Pilot Power Control and Service Coverage Support in CDMA Mobile Systems", *IEEE Transactions on Vehicular Technology*, vol. 49, pp. 1464-1468.

Kim D. and Chang Y., 2000, "Performance of prioritized call admission strategies in cellular CDMA systems with limited receiver processors", *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, vol. 2, pp. 522-526.

Knutsson J, Butovitsch P., Persson M. and Yates R.D., 1998, “Downlink admission control strategies for CDMA systems in a Manhattan environment”, *Proc. 48th IEEE Vehicular Technology Conference*, vol. 2, pp. 1453-1457.

Kohonen T., 1981, “Automatic Formation of Topological Maps of Patterns in a Self-Organizing System”, in Oja E. and Simula O., editors, *Proc. Scand. Conf. On Image Analysis*, pp. 214-220, Helsinki, Finland, Suomen Hahmontunnistuksen Seura r.y.

Kohonen T., 1997, *Self-Organizing Maps*. Second Edition. Springer-Verlag, Heidelberg.

Kozma R., Kitamura M., Sakuma M. and Yokoyama Y., 1994, ”Anomaly detection by neural network models and statistical time series analysis”, *IEEE International Conference on Neural Networks*, vol. 5, pp. 3207-3210.

Kraaijveld M. A., Mao J. and Jain A. K., 1992, “A non-linear projection method based on Kohonen's topology preserving maps”, *Proc. 11th International Conference on Pattern Recognition (11ICPR)*, pp. 41-45, IEEE Comput. Soc. Press, Los Alamitos, CA.

Kumar S. and Spafford E. H., 1994, “A pattern matching model for misuse intrusion detection”, *Proc. 17th National Computer Security Conference*, pp. 11-21.

Laiho J., Höglund A. and Buot T., 2001, “Radio Access Network (RAN) Autotuning and Advanced Monitoring Methods”, in *Radio Network Planning and Optimisation for UMTS*, editors Laiho, J., Wacker, A. & Novosad, T., pp. 411-436, John Wiley&Sons, England.

Laiho J., Wacker A. and Novosad T., 2001, editors, *Radio Network Planning and Optimisation for UMTS*, Wiley and Sons, West Sussex, England.

Laiho J., Wacker A., Novosad T. and Hämäläinen A., 2001, “Verification of WCDMA radio network planning prediction methods with fully dynamic network simulator”, *Proc. 54th IEEE Vehicular Technology Conference Fall*, vol. 1, pp. 526-530.

Lankewicz L. B., 1992, *A nonparametric pattern recognition approach to anomaly detection*, Doctoral Thesis, Tulane University.

Lee, J. and Miller L., 1998, *CDMA Systems Engineering Handbook*, Artech House, London.

Lee W. C. Y. and Lee D. J. Y, 2001, “Optimize CDMA system capacity with location”, *Proc. 54th IEEE Vehicular Technology Conference*, vol. 2, pp. 1015-1019.

Love R. T., Beshir K. A., Schaeffer D. and Nikides R. S., 1999, “A pilot optimization technique for CDMA cellular systems”, *Proc. IEEE Vehicular Technology Conference*, pp. 2238-2242.

Lunt T. F., 1993, “A survey of intrusion detection techniques”, *Computers and Security*, vol. 12, issue 4, 405-418.

Magnusson P. and Oom J., 2001, “An architecture for self-tuning cellular systems”, *Proc. IEEE/IFIP International Symposium on Integrated Network Management*, pp. 231-245.

Magnusson S. and Olofsson H., 1997, “Dynamic neighbor cell list planning in a microcellular network”, *Proc. IEEE 6th International Conference on Universal Personal Communications Record*, vol. 1, pp. 223-227.

Milton J. S. and Arnold J. C., 1990, Introduction to Probability and Statistics. Second Edition, McGraw-Hill.

Mueckenheim J., Bernhard U., Pampel H. and Gunreben P., 2000, “Performance evaluation of connection admission control for W-CDMA networks using dynamic system simulations”, *Symposium on Personal Communications and Vehicular Technology (SCVT)*, pp. 174-177.

Nairac A., Corbett-Clark T. A., Ripley R., Townsend N. W. and Tarassenko L., 1997, “Choosing an appropriate model for novelty detection”, *Proc. Fifth International Conference on Artificial Neural Networks*, pp. 117-122.

Nairac A., Townsend N., Carr R., King S., Cowley P. and Tarassenko L., 1999, “A system for the analysis of jet engine vibration data”, *Integrated Computer aided engineering*, vol. 6, no. 1, pp. 53-65.

NIDES, 2006, Next-Generation Intrusion Detection Expert System (NIDES), available at: http://www.csl.sri.com/projects/nides/.

Nokia, 2006a, “IP Security Platforms”, available at: http://www.nokia.com/securitysolutions/whynokia.html.

Nokia, 2006b, “Make your OSS the profit centre – with Nokia NetAct™”, available at: http://www.nokia.com/BaseProject/Sites/NOKIA_MAIN_18022/CDA/Categories/Solutions/OperatorsandServiceProviders/MobileNetworks/OperationsSupportSystems/_Content/_Static_Files/make_your_oss_the_profit_centre.pdf.

Olofsson H., Magnusson S. and Almgren M., 1996, “A concept for dynamic neighbor cell list planning in a cellular system”, *Proc. Seventh IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, vol. 1, pp. 138-142.

Panossian H.V. and Ewing W. D., 1997, “Real time failure detection algorithm for the Space Shuttle main engine”, *IEEE Control Systems Magazine*, vol. 17, issue 4, pp. 16-23.

Pöllönen J., 2001, *Quality of Service Based Admission Control for WCDMA*, Master’s thesis, Helsinki University of Technology, Helsinki, Finland.

Raivio K., Simula O. and Laiho J., 2001, "Neural Analysis of Mobile Radio Access Network", *Proc. IEEE International Conference on Data Mining (ICDM)*, pp. 457-464.

Roberts S. and Tarassenko L., 1994, “A Probabilistic Resource Allocating Network for Novelty Detection”, *Neural Computation*, vol. 6, issue 2, pp. 270-284.

Sammon J. W. Jr., 1969, “A nonlinear mapping for data structure analysis”, *IEEE Transactions on computers*, vol. C-18, No. 5, pp. 401.

Sipila K., Jasberg M., Laiho-Steffens J. and Wacker A., "Soft handover gains in a fast power controlled WCDMA uplink", *Proc. 49th IEEE Vehicular Technology Conference*, vol. 2, pp. 1594-1598.

Soukup T., 2002, Visual Data Mining: Techniques and Tools for Data Visualization and Mining, *Wiley.*

Tarassenko L., Hayton P., Cerneaz N. and Brady M., 1995, “Novelty Detection for identification of masses in mammograms”, *Proc. of 4th IEE Conference on Artificial Neural Networks*, vol. 4, pp. 442-447.

Tarassenko L., Nairac A., Townsend N. and Cowley P., 1999, “Novelty detection in jet engines”, *IEE Colloquium on Condition Monitoring: Machinery, External Structures and Health (Ref. No. 1999/034)*, pp. 4/1-4/5.

Ultsch A. and Siemon H. P., 1990, “Kohonen’s self organizing feature maps for exploratory data analysis,” *Proc. International Neural Network Conference*, pp. 305–308.

Ultsch A., 1993, “Self organised feature maps for monitoring and knowledge acquisition of a chemical process”, *Proc. International Conference on Artificial Neural Networks (ICANN)*, pp. 864-867.

Vesanto J., 2002, *Data Exploration Process Based on the Self-Organizing Map*, Doctoral thesis, Helsinki University of Technology, Acta Polytechnica Scandinavica, Mathematics and Computing Series 115.

Viterbi A. M. and Viterbi A. J., 1993, “Uplink admission control and soft capacity with MUD in CDMA”, *IEEE Journal on Selected Areas in Communications*, vol. 11, issue 6, pp. 892-900.

Wacker A., Sipilä K. and Kuurne A., 2002, “Automated and Remotely Optimization of Antenna Subsystem based on Radio Network Performance”, *Proc. 5th IEEE International Symposium on Wireless Personal Multimedia Communications, (WPMC)*, vol. 2, pp. 752-756.

Worden K., Manson G. and Fieller N. R. J., 2000, "Damage Detection Using Outlier Analysis", Journal of Sound and Vibration, vol. 229, issue 3, pp. 647-667.

Yang J. and Lin J., 2000, “Optimization of power management in a CDMA radio network”, *Proc. 52nd IEEE Vehicular Technology Conference Fall*, vol. 6, pp. 2642-2647.

Zhu H., Buot T., Nagaike R. and Schreuder H., 2002, “Load balancing in WCDMA systems by adjusting pilot power”, *Proc. 5th International Symposium on Wireless Personal Multimedia Communications*, vol. 3, pp. 936-940.