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Automated optimization of key WCDMA parameters

Albert Höglund[1*,†] and Kimmo Valkealahti[2]

[1]*Nokia Networks, P.O. Box 300, FIN-00045 Nokia Group, Finland*
[2]*Nokia Research Center, P.O. Box 407, FIN-00045 Nokia Group, Finland*

Summary

This paper validates the feasibility of automated optimization of key wideband code division multiple access (WCDMA) radio resource management parameters using control methods. The parameters are regularly adjusted in order to improve performance. The parameters examined in this study include the total cell transmission power target, the received total interference target, the downlink radio link power maximums, the handover windows and the pilot channel powers. The control was based on expert-defined rules, which applied specific trade-off policies and statistics of poor quality calls, blocking, packet queuing, power and interference levels and terminal measurements to qualify the parameter values. The approach was validated using a dynamic WCDMA system simulator with a deployment of macro and micro cells on a city region. Results on automated optimization of single parameters on cell level and results on simultaneous multi-parameter optimization on cell-cluster level are presented in this paper. The use of the automated parameter optimization methods was shown to result in a significant increase of capacity in comparison to the default parameter settings. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: universal mobile telecommunications system (UMTS) radio network planning; optimization; call quality; congestion; admission control; power control; handover control; coverage

1. Introduction

The wideband code division multiple access (WCDMA) radio interface for third generation mobile networks can carry voice and data services with various data rates, traffic requirements and Quality-of-Service (QoS) targets [15]. Moreover, the operating environments vary greatly from indoor micro cells to large macro cells. Efficient use of limited frequency band in the diverse conditions requires careful setting of numerous vital network and cell radio resource management parameters such as maximum load levels and allocated common channel powers. The parameter setting is referred to as radio network planning and optimization. Once a WCDMA network is built and launched, an important part of its operation and maintenance is monitoring of performance or quality characteristics and changing parameter values in order to improve performance. The operability of the network would greatly benefit from automated monitoring and parameter tuning. The automated parameter control mechanism can be simple but it requires an objectively defined performance indicator that unambiguously tells whether performance is improving or deteriorating. Conceiving of such indicators is a major task. WCDMA network auto-tuning and advanced monitoring are discussed in Reference [26] and in particular in Reference [25], for instance.

*Correspondence to: Albert Höglund, Nokia Networks, P.O. Box 300, FIN-00045 Nokia Group, Finland.
†E-mail: Albert.Hoglund@nokia.com

This paper addresses the problem of controlling parameters such as the total cell transmission power target, the total received interference target, the downlink radio link power maximums, the handover windows and the common pilot channel powers. The parameters have direct and indirect effects on the network performance and the QoS. Various performance indicators such as real-time call quality, real-time call blocking and non-real-time traffic queuing were used for the parameter control. The main control method studied was rule-based control, but gradient-descent cost-function minimization was also considered in one specific case. The automated parameter control methods were verified with an advanced WCDMA radio network simulator developed at Nokia Research Center in Helsinki [11].

The performance of the proposed control methods was compared with the performance obtained without automated optimization. Comparisons among different optimization methods were not made, expect for one case. Presumably, similar results can be obtained with other valid and warranted optimization methods. However, the approaches differ in their practicability and adoption by the network operator. The advantage of our methods lies in the explicated operation that supports understanding of regularities in the network.

The conducted simulations support the assumption that the performance can be managed and improved by the proposed cell-based and cell-cluster-based automated optimization. The increase in system throughput compared with throughput with default parameter setting was significant.

The structure of the paper is as follows. Section 2 describes admission control methods of the WCDMA system and surveys previous work on WCDMA parameter optimization. Section 3 introduces the measures and statistics that were applied to drive the optimization. Section 4 is devoted to the parameter optimization methods that were validated in this study. Section 5 describes the network simulator. The results are presented in Section 6, which is followed by discussion and conclusions in Section 7.

2. Background

2.1. Admission Control

The radio resource management controls the utilized capacity of mobile networks and maintains stable operation by handling functions such as admission control, power control and handover control. The principles of radio resource management in WCDMA are described in Reference [15] in general and in detail in 3GPP specifications such as References [35–37], for example. Lee and Miller provide a good introduction to the CDMA in Reference [29]. The key function of radio resource management with regard to this paper is admission control, and this function is therefore presented more in depth.

The cell load-level targets used in the admission control can be based on throughput, interference, transmit power or a number of connections, for instance (Reference [15]). The performance of a WCDMA cellular radio network is highly dependent on the amount of interference in the system. High interference reduces cell sizes and increases the power outage probability of the user connection both in uplink (UL) and downlink (DL). The interference increases with the number of admitted users in the system. This means that there is a trade-off between capacity and coverage and between capacity and QoS. The task of admission control is to ensure that the trade-off is optimum. Many authors have studied admission control previously. Study in Reference [4] introduced specific requirements for the admission control. For instance, the admission control is required to maintain QoS 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. Study in Reference [42] evaluated the theoretical uplink capacity for an interference level that is 10 dB higher than the noise floor. Study in Reference [23] 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, study in Reference [17] suggests guard channels to be used in admission control done during handovers. Study in Reference [24] supported the use of power-based admission control and compared methods of single-cell and multi-cell admission controls. The conclusion was that the gains obtained with the multi-cell admission control did not compensate for the increased complexity. Gains with multi-cell admission control were also found in Reference [4]. Study in Reference [33] suggested that the uplink interference target is set as a trade-off between blocking and dropping. Similar ideas were suggested in studies in References [4] and [24], which defined call dropping ten times more costly than blocking.

The interference-based radio resource management (total-transmission-power-based in downlink) is more complex than the throughput-based management. However, we adopted the interference-based radio resource management as it allows soft capacity gains [15] that are not achievable with the throughput-based management. The increased complexity favors the use of automated optimization methods to obtain fully utilized capacity while maintaining the stability of operation. The applied cell-based admission control method is described in References [15,16]. The method admits new allocation of uplink resources if

$$PrxTotal + \Delta PrxTotal < PrxTarget \qquad (1)$$

in which *PrxTotal* denotes the current level of the total received interference, Δ*PrxTotal* denotes the estimated change in the interference with the new resource allocation and *PrxTarget* is the optimum level of interference as set by network planning, for instance. The change in *PrxTotal* is calculated with formula

$$\Delta PrxTotal = \frac{PrxTotal}{1 - \eta - \Delta L}\Delta L \qquad (2)$$

in which η is the uplink load factor defined as

$$\eta = 1 - \frac{PrxNoise}{PrxTotal} \qquad (3)$$

and ΔL the estimated change in load factor,

$$\Delta L = \frac{1}{1 + \frac{W}{\upsilon \cdot E_b/N_0 \cdot R}} \qquad (4)$$

In Equations (3) and (4), *PrxNoise* is the system noise floor, W is the chip rate, R is the bit rate, E_b/N_0 is the assumed ratio of the received bit energy to noise and interference density that the receiver equipment of new connection requires for proper decoding of the signal and υ is the assumed voice activity of the new connection. Interference-based admission control is illustrated in Figure 1.

In downlink the admission control is similar. New resources can be allocated if

$$PtxTotal + \Delta PtxTotal < PtxTarget \qquad (5)$$

in which *PtxTotal* denotes the current total transmission power, Δ*PtxTotal* denotes the estimated change in the power with the new resource allocation and

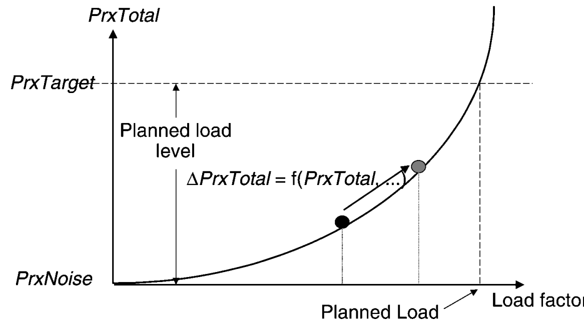

Fig. 1. Interference-based admission control in uplink. *PrxTotal* denotes the total UL wideband received power, for which *PrxNoise*, the noise floor, is the minimum level. *PrxTarget* denotes the admission control and packet scheduler target interference level. Allocating resources to the users requires estimation of changes in *PrxTotal* with changing load.

PtxTarget is the optimum total power. Δ*PtxTotal* can be equal to the estimated initial link power, the measured average power or the allocated maximum link power for the particular service and cell. In this study, we conservatively used the maximum service power.

2.2. Previous Work on WCDMA Parameter Optimization

Our previous work on WCDMA parameter optimization includes studies on pilot power optimization [40,41], optimization of admission control and power parameters [13,14] and multi-parameter optimization including optimization of handover parameters [39]. These studies form the basis for this paper. Other studies on pilot power optimization include References [22,31,44,45]. Study in Reference [22] presented a heuristic method for finding optimal pilot power with regard to coverage and capacity in CDMA, but without presenting any validations using, for instance, simulations and multiple cells. In study of Reference [31], a rule-based method for reducing pilot power pollution was presented and the results obtained with it in a field trial indicated that the method could achieve similar results to those obtained with manual optimization. Reference [44] studied how power management can be utilized in congestion relief in loaded cells. Study in Reference [45] proposed a method to reduce hot spot problems with the control of pilot power based on cross-correlation measures. Studies in References [3,5,7] presented methods and results on soft-handover parameter optimization. In Reference [3] the soft-handover dynamics were modeled with a simple Markov chain to identify the adjusted critical parameters. Studies in References [5,7] optimized the soft-handover parameters with a gradient-descent minimization of a cost function that described blocking and total base station power. A more general study on soft-handover gains and their impact on WCDMA network performance was presented in Reference [34].

Study in Reference [8] presented adaptive power increase estimation in WCDMA using kernel regression. Study in Reference [9] presented results on optimization of UL and DL planned E_b/N_0, which is a vital parameter in estimating the power increase in uplink admission control (3), in scaling powers (15), and in rapid updating of bit rates in packet scheduling, for instance. Study in Reference [21] considered a DL power allocation algorithm for adjusting the total cell power and its allocation to individual users. Study in Reference [43] introduced automated optimization of antenna tilt angles in WCDMA. Advanced analysis methods for analyzing the performance of Universal Mobile Telecommunications System (UMTS) networks and doing cell clustering were provided in References [28] and [25]. Inter and intra operator co-existence of WCDMA hierarchical cell structure cell layers was presented in Reference [20]. Some ideas on how to utilize location in optimization were provided in Reference [30]. An architecture for auto-tuning networks including a GSM field trial was presented in Reference [32]. The idea in Reference [32] was that in large networks the auto-tuning should be distributed to local agents taking care of regional tuning with centralized control in addition to using real-time computing and open interfaces. No clear conclusion could be drawn from the results of the field trial in Reference [32], except for an indication of the architecture being suitable.

3. Measurements and Statistics

3.1. UL and DL Poor Quality

The general call quality in a cell was described as the ratio of active connections suffering from increased block error rate (BLER) among all active connections in the cell. The strongest cell in the active set determined the cell, to which the measurement was associated. The connections have specific BLER targets that depend on the service used. If the ratio of connections significantly exceeding their BLER targets was significantly higher than a predefined allowed level, the cell showed increased poor call quality. Only real-time services with planned coverage in the entire cell were monitored for call quality. The significance of increased poor call quality in a cell was analyzed with the Equation:

$$S_{PQ} = \frac{R_{PQ} - T_{PQ}}{\sqrt{T_{PQ}(1 - T_{PQ})/N_{PQ}}} \tag{6}$$

which describes the sample-size (N_{PQ}) corrected deviation of ratio R_{PQ} from allowed ratio T_{PQ} of connections with increased block error rate. The formula basically divides the ratio difference estimate by its expected standard deviation giving, thus, the number of standard deviations that the measured ratio deviates from the allowed ratio. The criteria used for determining whether a cell suffered from significant poor quality was that S_{PQ} should be higher than two and N_{PQ} higher than $5/R_{pq}$. The former condition was based on the 98th percentile of the normal distribution, giving a 2% probability of incorrectly showing poor quality, and the latter condition indicated that there was a sufficient sample for estimating the ratio R_{PQ} accurately. The computation of poor quality was similar in UL and DL. However, no terminal reporting of the correctness of received blocks in the DL was assumed. Instead, the transmitted frames during link power outage were considered erroneous. The allowed level of poor quality ratio was 2% in UL and DL. The statistics were separate for UL and DL and were denoted $S_{PQ,UL}$ and $S_{PQ,DL}$.

3.2. UL and DL Congestion

The congestion was described with ratios of blocked real-time calls and queued packet calls. The blocking ratio was the ratio of blocked real-time calls to the total number of real-time call admission requests in the cell. The blocking ratio was measured separately for UL and DL. The blocking ratio comprised of calls blocked due to an unsatisfied condition (1) for UL and (5) for DL in addition to lack of hardware channels or scrambling codes. The packet queuing ratio was the ratio of queued packet calls to the total number of packet users in the cell measured at specific intervals. The packet queuing ratios were measured separately in UL and DL.

In small amounts call blocking and packet queuing were regarded as normal. Congestion occurred if blocking or queuing ratios exceeded significantly certain allowed levels. The significance of increased blocking or queuing ratio was measured with Equations similar to Equation (6). If Equation (6) exceeded

2 and the sample size was sufficient then the cell showed increased congestion with the particular blocking or queuing ratio. The allowed level of blocking ratio was 2% and that of queuing ratio 5%. The blocking statistics derived from Equation (6) were denoted $S_{BL,UL}$ and $S_{BL,DL}$ for UL and DL. The queuing statistics were denoted $S_{QE,UL}$ and $S_{QE,DL}$.

3.3. Common Pilot Coverage

In the universal mobile telecommunications system, the terminal measures and reports the received level of the primary common pilot energy-per-chip-to-total-wideband-interference-density ratio, or E_C/I_0, for the selection of call setup or handover cells. The primary common pilot power determines the cell coverage area and thus, the average number of terminals connected to the cell. If the pilots of all cells are too weak for a terminal to decode any of their signals, call setup is not possible. The minimum pilot strength is specific to the receiver electronics. Therefore, the specifications of the Third Generation Partnership Project require that the terminal must be able to decode the pilot from a signal with E_C/I_0 of -20 dB [35]. Quality receivers can cope with ratios several decibels lower than that. Too good coverage is not desirable either as it indicates unnecessarily high common pilot powers, consuming the limited power capacity of cells. The consumption is even compounded if the powers of other common channels are scaled with respect to the common pilot power.

We measured the pilot coverage as the ratio of reported E_C/I_0 that exceeded -18 dB. Only the strongest E_C/I_0 was included in the coverage ratio from a single report of a terminal. We considered 98% coverage ratio as an optimal target. The test statistic of the difference between the cell coverage ratio and target coverage ratio was derived from Equation (6). The common pilot coverage was regarded as significantly smaller or larger than the target if the test statistic was lower than -2 or higher than 2 respectively and the sample size was sufficient.

3.4. UL Load, DL Load and the Load Balance Statistics

The cell-specific UL and DL loads were measured with the geometric averages of cell *PrxTotal* and *PtxTotal* respectively. A load balance statistic was calculated for each cell, in order to test whether a load in a certain cell differed from the load in neighboring cells. The statistic was based on the *PtxTotal* measurement divided by the target transmission power *PtxTarget*. The target power depends on the maximum transmission power of the cell and differs among macro cells and micro cells. The cell load was thus, commensurate among different cell layers. As the capacity is in general more limited in DL than in UL [15], we saw that measuring of the DL load balance was sufficient for our purpose. The load was sampled separately for each cell. Three counters were kept for each cell. The first collected the number of samples, the second collected the sum of the sample values and the third collected the sum of the squared sample values. Denote the counter values of cell i by N_i, S_i and T_i respectively. The sample mean and variance of the load in cell k was obtained with Equation

$$m1 = \frac{Sk}{Nk} \tag{7}$$

and

$$v1 = \frac{Tk}{Nk} - m1^2 \tag{8}$$

The statistics for the load in the neighboring cells of cell k were obtained with

$$m2 = \frac{\sum_i Si}{\sum_i Ni}, i \neq k \tag{9}$$

and

$$v2 = \frac{\sum_i Ti}{\sum_i Ni} - m2^2, i \neq k \tag{10}$$

Neighbor cells are normally defined during network planning and optimization (see for example Reference [26]). The test statistic of the difference between the own-cell and neighbor-cell loads was obtained with Equation

$$t' = \frac{m1 - m2}{\sqrt{\frac{v1}{Nk} + \frac{v2}{\sum_{i \neq k} Ni}}} \tag{11}$$

3.5. Costs

Costs were defined to enable trade-offs between capacity and quality. The cost of congestion was based on blocking and queuing statistics:

$$CostCongestion\,(x) = f(S_{BL,x}) + 0.25 \times f(S_{QE,x}) \tag{12}$$

in which $x = UL, DL$ depending on the link direction. The threshold function $f(S)$ was defined as

$$f(S) = \max(S - 2, 0) \quad (13)$$

in which the maximum operator and subtraction with two zeroed insignificant values of the statistic. Equation (12) shows that the cost of packet queuing was only one-fourth of the cost of blocking a real-time user. The cost of poor call quality was defined to be five times higher than the cost of blocking in Equation (12):

$$CostQuality\,(x) = 5 \times f(S_{PQ,x}) \quad (14)$$

If *CostCongestion* is greater than *CostQuality* then congestion is more costly than poor quality in the cell. If the reverse is true then poor quality is more costly than congestion.

4. Parameter Optimization

4.1. Power Parameters *PrxTarget, PtxTarget, CPICHToRefRABOffset* and *PtxDLAbsMax*

The admission control parameters selected for optimization were *PrxTarget*, *PtxTarget*, *CPICHToRefRABOffset* and *PtxDLAbsMax*. Our previous studies on their optimization showing significant capacity gains were reported in References [13,14]. *PrxTarget* and *PtxTarget* determine the amount of traffic allowed in the cell. If the targets are too low, the capacity of the network is not fully utilized. On the other hand, if the targets are too high, too many connections are admitted in the cell with increased interference as a consequence. The increased interference causes poor call quality or even dropping of calls. In UL, terminal power outage causes poor call quality. In DL, poor quality occurs in connections whose required link transmission power exceeds the maximum connection-specific link power. Moreover, outage of total cell power causes poor call quality. The parameter *CPICHToRefRABOffset* defines the maximum link transmission power for a selected reference radio access bearer, for example, 12.2-kbps speech service, as a corresponding fraction of the cell common pilot power *PtxPrimaryCPICH*. The maximum link powers of other services are obtained by scaling the reference maximum power with the ratio of bit rates, R/R_{ref}, and the ratio of DL E_b/N_0 requirements, ρ/ρ_{ref}, between the reference and a particular service:

$$Ptx\,Max = \frac{PtxPrimaryCPICH}{CPICHToRefRABOffset} \frac{\rho \cdot R}{\rho_{\mathrm{ref}} \cdot R_{\mathrm{ref}}} \quad (15)$$

Equation (15) produces similar cell coverage for all services it is applied to. The coverage of high-bit-rate services can be limited with the parameter *PtxDLAbsMax*, which defines the absolute maximum link power for any service.

The UL power target *PrxTarget* was adjusted separately in each cell based on the UL poor quality and congestion situation in the cell. The simplified rule was that *PrxTarget* was increased or decreased by 0.5 dB if *CostCongestion* (UL) was higher or lower than *CostQuality* (UL) respectively. Moreover, increasing *PrxTarget* required that average *PrxTotal* was at most one decibel lower than *PrxTarget*, which supported the interpretation that increased congestion was due to low *PrxTarget*. The rules actually implemented, described in References [14] and [26], were more complex but in practice not significantly different from the simple rule above.

Parameter *CPICHToRefRABOffset* for the DL link power maximum determination was adjusted if there was either significant DL poor quality or congestion. The simplified rule was that *CPICHToRefRABOffset* was increased or decreased by 0.5 dB if *CostCongestion* (DL) was higher or lower than *CostQuality* (DL) respectively. The rules actually implemented and described in Reference [13] were somewhat more complex but in practice not significantly different from the simple rule above.

PtxDLAbsMax was set equal to the maximum power, *PtxMax* of Equation (15), of the service with the highest power requirement planned to have coverage in the entire cell, which was the 64-kbps circuit-switched-data service. *PtxDLAbsMax* was calculated online using the current optimized *CPICHToRefRABOffset* with Equation (15).

The selection of *PtxTarget* was based on the assumption of *PtxTotal* being normally distributed and an allowed 2% probability of total power outage. *PtxTarget* was set equal to the maximum base station power minus two times the measured standard deviation of *PtxTotal*.

4.2. Common Pilot Power *PtxPrimaryCPICH*

Our previous studies on the optimization of *PtxPrimaryCPICH* were reported in References [40,41]. *PtxPrimaryCPICH* defines the power of the primary common pilot channel in the cell. Increasing or decreasing the pilot power makes the cell larger or smaller. Thus, the adjusting of pilot powers can be applied to balance the cell load among neighboring cells. The common pilot power was controlled to balance load among neighboring cells and provide sufficient signal reception for the terminals.

In the rule-based method of Reference [40], the pilot power of a cell was increased or decreased by 0.5 dB if the cell load was significantly lower or higher than the neighbor-cells load as indicated by statistic (11). If the load was not significantly unbalanced among the cells, but the pilot signal reception was significantly lower or higher than the target, the pilot power was increased or decreased by 0.5 dB respectively. The pilot power was limited between 3% and 15% of the maximum base station power.

In Reference [41], a gradient-descent method was used to minimize a cost function, which was the sum of a coverage statistic and a load statistic. The two statistics described similar performance features as the statistics used in the rule-based method presented above, that is, the deviation of the coverage from the target and the deviation of the cell load from the load in the neighboring cells. In contrast to the rule-based method, with which fixed parameter adjustments were used, the gradient-descent method recomputed the adjustment at every iteration step of the optimization. The better the changes in the cost function followed the changes in the parameter value, the larger was the magnitude of adjustment, which theoretically allowed faster convergence to the optimum in comparison to the rule-based method with the fixed adjustment.

4.3. Handover Parameters *AdditionWindow* and *DropWindow*

AdditionWindow determines cell addition to the active set of a terminal. If the active set is not full and the received pilot signal is higher than that of the strongest cell in the active set subtracted with *AdditionWindow*, the addition is performed. *DropWindow* determines cell dropping from the active set. An active-set cell is dropped if its received pilot signal is lower than that of the strongest cell subtracted with *DropWindow*. The parameters have an effect on the average size of the terminal active sets and on the average level of soft-handover overhead.

If *AdditionWindow* is set to a too high value, the active set sizes of the terminals are too large on the average, which can cause increased DL-based congestion due to

- insufficient physical (channel elements) and logical (codes) resources, and
- increased base station total transmission powers due to many links.

If *AdditionWindow* is set to a too low value, the active set sizes of the terminals are too small on the average, which can cause increased UL interference, poor quality and congestion. The calls from terminals on the cell border can also show increased poor quality due to power outage.

The soft-handover parameter control was a compromise between DL congestion on one hand and UL blocking and bad quality on the other hand. *AdditionWindow* and *DropWindow* were increased by 0.5 dB if

$$\begin{aligned} &\mathit{CostQuality}\,(\mathrm{UL}) + \mathit{CostCongestion}\,(\mathrm{UL}) \\ &\quad > \mathit{CostCongestion}\,(\mathrm{DL}) \end{aligned} \tag{16}$$

If the cost balance was reverse, the parameters were decreased by 0.5 dB.

The *ReplacementWindow* and handover timers were not tuned in this study, since controlling these parameters had a low impact on the studied WCDMA performance.

4.4. Rule-based Multi-Parameter Optimization

We introduced the rule-based multi-parameter optimization in Reference [39]. The method applied simultaneously the control rules described in subsections 4.1 to 4.3. However, the rules were simplified by omitting the load statistic (11) from the rule of pilot control described in 4.2. The rules were independent so that simultaneous operation was possible without conflicting control actions.

5. Network Simulator

The automated control methods were verified with an advanced WCDMA radio network simulator developed at Nokia Research Center [11]. The simulator was able to model various cell deployments. A set of mobile terminals moved in the area with constant speed and, with random intervals, made calls of different services: voice, circuit-switched data and packet-switched data. The main differences between voice and circuit-switched-data calls were in the bit rates and that the former had talk spurt silence periods. The data rates of voice and circuit-switched-data calls were fixed but packet data rates could vary. The simulation step was one frame or 10 ms, at which the transmission powers, received interferences and signal-to-interference ratios were recalculated for each connection in UL and DL. The method of Reference [10] was used to obtain correctness of received frames from signal-to-interference ratios. 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. Previous studies with the simulator are described in References [27] and [2], for instance.

Three main simulation scenarios were used in this study. They were a micro-cell-scenario (Figure 2), a macro-cell-scenario (Figure 3) and a mixed scenario with both micro and macro cells (Figure 4). For the micro cell scenario, an area of $9\,\mathrm{km}^2$ of downtown Helsinki was planned with 46 micro cells, while in the mixed cell scenario the same area was planned with 32 macro cells in addition to the 46 micro cells. In the pure macro-cell scenario a subset of the area was planned with 17 macro cells (Figure 3). In Figures 2, 3 and 4 the bars depict cells by pointing to the principal direction of antenna pattern, except for cells with omni directional antennas that are vertically depicted.

The main parameters used in the simulations are presented in Table I. The channel multi-path profile was that of ITU Outdoor-to-Indoor A [38] with two-path propagation in the micro cell scenario and that of ITU Vehicular A [38] with five-path propagation in the macro and mixed cell scenarios. The path gains are shown in Table I. Signals from the same base station cell propagating along the same path were totally orthogonal; that is, they did not interfere with each other. For example, for the ITU Vehicular A model the DL orthogonality factor [15], computed from the path gains, was 60%. The propagation loss was calculated using the Okumura–Hata model with average correction factor of $-6.2\,\mathrm{dB}$. The shadow fading process conformed to the buildings, streets and water areas. Short-term fading with 7 dB deviation was added to the process. The fast fading process was that of Jakes [19]. The mobile stations were uniformly distributed along the streets of simulated area and they made new calls according to a Poisson inter-arrival distribution. The packet size of packet calls was generated according to a Pareto distribution. The service of new calls was generated according to the probabilities shown in Table I.

The simulation step was one frame or 10 ms, at which the transmission powers, received interference

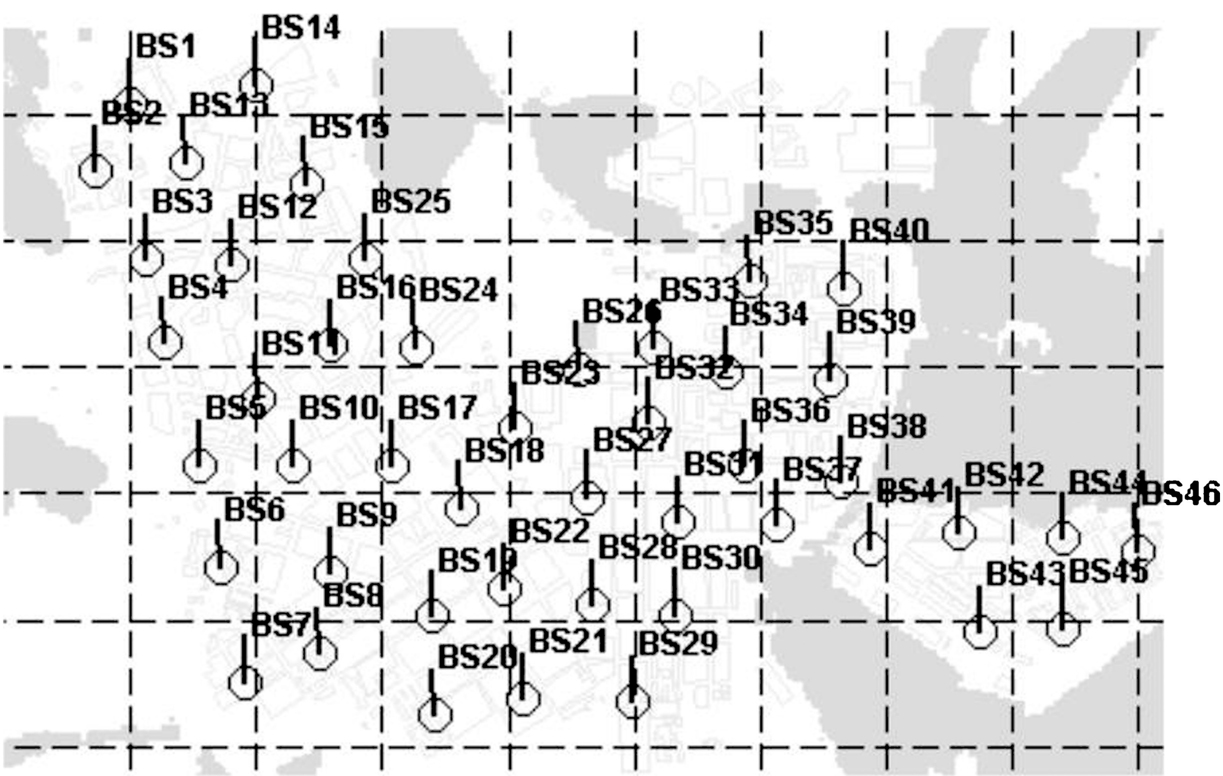

Fig. 2. The micro cell scenario with 46 micro cell sites deployed in a Helsinki city center area having the size of approximately $9\,\mathrm{km}^2$. Water areas are shown in gray.

Fig. 3. The pure small macro cell scenario with five three-sector and two one-sector macro cell sites in Helsinki center area. Water areas are shown in blue. Average site distance roughly 910 m. Subset of 32-cell scenario in Reference [26].

and signal-to-interference ratios were recalculated for each connection in the DL. The method of Reference [10] was used to obtain the correctness of received frames from signal-to-interference ratios.

The call parameters were selected to produce a high system load and load the system up to the target level of the DL transmission power and UL total received power. The simulation time was 300 seconds. In the simulations, the planned pilot power was 1 W in the macro cells and 200 mW in the micro cells, which was 5% of the maximum base station power [26]. The fact that the simulated environment was a real city environment planned using realistic site locations lead to quite significant differences in the load of different cells, with some of the cells being clear hot-spot cells.

6. Results

6.1. Automated Cell-Based Optimization of *PrxTarget*

In Reference [14], we presented results for the optimization of *PrxTarget*. One simulation was done using the macro-cell scenario in Figure 3 and two simulations with different service mixes using the micro-cell scenario in Figure 2. In general the results improved significantly compared with fixed parameter

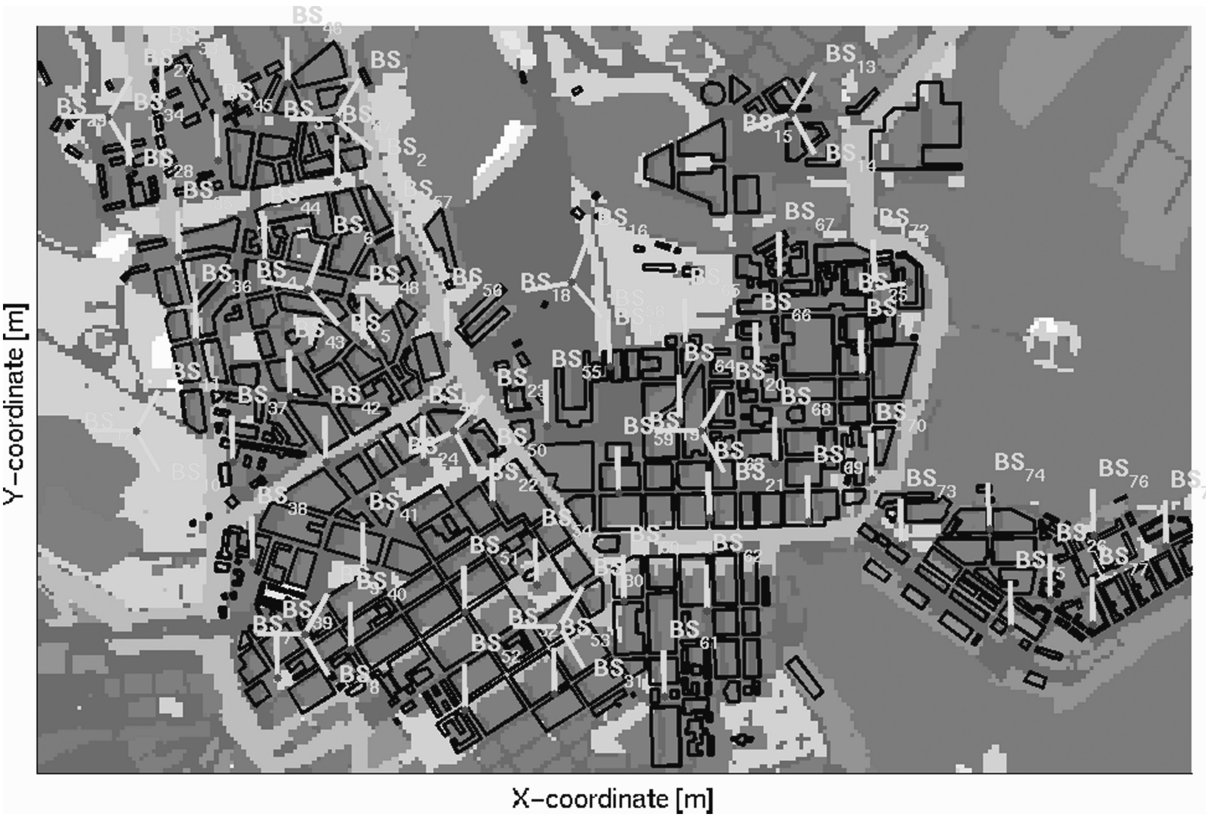

Fig. 4. Mixed micro and micro case with 32 macro cells and 46 micro cells deployed in Helsinki center area.

settings and in particular for cautiously made parameter settings. The results in Table II show that the auto-tuning improved the system performance. The UL throughput increased 48–57% compared with the conservative noise-rise target of 4 dB (60% loading), 16–25% compared with the 6-dB *PrxTarget* (75% loading) and 2–10% compared with the 8-dB *PrxTarget* (84% loading). The degradation in real-time call quality was minor, while the real-time call blocking decreased significantly [14].

6.2. Automated Optimization of *CPICHToRefRABOffset, PtxDLAbsMax* and *PtxTarget*

In Reference [13] we presented results for the optimization of *CPICHToRefRABOffset* and *PtxTarget*. Two fixed settings of *CPICHToRefRABOffset* were validated using the micro scenario in Figure 2. In comparison with fixed *CPICHToRefRABOffset* values, the auto-tuning decreased the bad quality significantly, which made it possible to increase the *PtxTarget*. The adjustment of *PtxTarget* together with the autotuning of *CPICHToRefRABOffset*, made a significant increase in throughput possible (up to 39% compared with default parameter settings) in addition to a quality improvement [13].

6.3. Automated Optimization of the Primary Common Pilot Power

We presented results for the optimization of the pilot power using a rule-based method in Reference [41] and a gradient descent optimization method in Reference [40]. The mixed-macro-and-micro-cell scenario depicted in Figure 4 was used in the simulations. Table III shows the improvement of DL packet performance measures obtained with the two auto-tuning methods. The performance improved but the improvement was not great. The rule-based control method showed better performance than the gradient descent optimization method. Table IV shows that the average DL total transmission powers (*PtxTotal*) were similar with and without the gradient descent minimization, but increased when the rule based-optimization was applied. The increased total base

Table I. Selected parameters used in the simulation studies.

Parameter	Value
Chip rate	3.84 MHz
Frequency	2.0 GHz
Bandwidth	5.0 MHz
Base station cell maximum transmission power	Micro 4 W, Macro 20 W
CPICH transmission power	Micro 0.2 W, Macro 1 W
Power control dynamic range in UL and DL	65 dB and 20 dB
Base station antenna cell and gain, macro	65°, 17.5 dBi
Base station antenna cell and gain, micro	Omni, 11.0 dBi
Mobile station antenna cell and gain	Omni, 0.0 dBi
DL and UL system noise	−99.9 dBm and 102.9 dBm
Minimum coupling loss with O-H model	−50 dB
Propagation loss model	Okumura-Hata
Shadow fading deviation	7 dB
Multi-path propagation gains, micro cases	94 and 6%
Multi-path propagation gains, macro and mixed cases	51, 30, 11, 6, 3%
Mobile station speed	3 km/h
Number of mobile stations	5000–11 000
Call arrival rate for a mobile station	2 per minute
Probability of voice service	0–40%
Probability of circuit-switched service	0–10%
Probability of packet service	0–90%
Average voice call length	120 s
Average discontinuous transmission period	3.0 s
Average CS RT 64 kb/s data call length	10 s
Mean number of packets in DL packet call	100
Mean number of packets in UL packet call	1
Mean packet size in UL packet call	8150 bytes
Mean packet size in DL packet call	81.5 bytes
Voice data rate	8 kb/s
Circuit-switched data rate	64 kb/s
Packet data rates	8, 12, 64, 144, 512 kb/s
Voice and CS data outer loop BLER target	1%
Packet-switched data outer loop BLER target	20%
Handover control add window	1 or 3 dB
Handover control drop window	3 or 7 dB
Admission control total DL tx power target, *PtxTarget*	Micro 2 and macro 10 W
Admission control total UL rx power target, *PrxTarget*	6 dB
CPICHToRefRABOffset	5.5 dB
Auto-tuning interval	20 s
Simulation time	600 s or more

station powers explain the improved performance of the rule-based optimization. This can be taken as an indication that the load was more evenly distributed. As the target pilot coverage was 98%, the results in Table IV show that the coverage deteriorated with the auto-tuning. The coverage could be improved by increasing its weight in the cost function and by adjusting the rule priorities.

Table II. Improvement of system throughput with *PrxTarget* optimization in comparison to fixed setting of *PrxTarget*.

Scenario	Improvement with respect to fixed *PrxTarget*		
	4 dB	6 dB	8 dB
Macro cell	57%	25%	10%
Micro cell 1 (NRT PS and RT speech)	52%	21%	6%
Micro cell 2 (NRT PS and RT CS data)	48%	16%	2%

Table III. Improvement of packet performance with pilot power optimization [40,41] compared with initial pilot power setting.

	Rule-based method	Gradient-descent cost function minimization
Total throughput	4%	1%
Active session throughput	21%	5%
Allowed bit rate	31%	9%
95th packet delay percentile	5%	2%

Table IV. Performance results of pilot power optimization [40,41].

	No optimization	Rule-based method	Gradient-descent cost function minimization
Macro *PtxTotal* (std) [W]	9.0 (2.0)	9.4 (1.3)	8.8 (2.2)
Micro *PtxTotal* (std) [W]	1.9 (0.3)	1.9 (0.2)	1.9 (0.3)
Macro pilot power (std) [W]	1 (0)	1.6 (0.9)	1.0 (0.4)
Micro pilot power (std) [W]	0.2 (0)	0.24 (0.15)	0.2 (0.09)
1—macro coverage [%]	1.6	2.3	2.8
1—micro coverage [%]	1.3	3.5	2.4

6.4. Automated Optimization of Soft Handover Parameters

The optimization of the addition window and drop window decreased the number of blocked speech-service calls by 10% and circuit-switched data calls by 11% while the quality of the calls did not deteriorate at all.

The optimization was also repeated in a hardware-limited scenario, in which the number of simultaneous channels was limited to 32 in per cell. This was to verify the supposition that the addition window control reduces the blocking due to insufficient channels, which are the anticipated limiting resource in the first WCDMA networks. The results were similar to those with the power-limited scenario. The number of blocked speech calls decreased by 11% and the number of blocked circuit-switched data calls decreased by 13%. The total increase in utilized capacity due to optimization was 15%. The quality was not a problem, as the power resources were sufficient owing to the limited number of users in the cells.

6.5. Automated Multi-parameter Optimization

We presented results for cell-cluster-based multi-parameter optimization using rule-based methods in Reference [39]. The general performance in the network with and without control is given in Table V. The upper number in each row is the result obtained with the initial parameters and the lower number is that with control. The first and second rows show that the number of started calls was increased significantly with control (subject to sufficient traffic). The next four rows show that the ratio of poor quality calls was at most 1.0% with the initial parameters and 2.2% with control. The call quality was regarded as poor if over 2% of the frames were incorrectly received when averaged over the whole phone call. The last two rows show that the blocking ratio was significantly reduced when using the control. Requiring that at most 5% of the calls are either blocked or suffer from poor quality then the number of subscribers that the network tolerated was between 1000 and 2000 with the initial parameters. With control, the number was increased to between 2000 and 3000. The quality of calls was too good by the standard of defined policy with the initial parameters, which was reflected in high blocking. The capacity was much improved by trading off quality for reduced blocking. Taking into account a 2.5-dB difference in signal level requirements between the 8- and 64-kbps services, the combined improvement of capacity was 9% with 2000, 17% with 3000, and 19% with 4000 subscribers.

Table V. General network performance with and without simultaneous control of the parameters.

Indicator	Number of subscribers			
	1000	2000	3000	4000
Started speech calls	14 000	26 000	33 000	39 000
	14 000	28 000	40 000	52 000
Started CS calls	5800	11 000	14 000	17 000
	5800	12 000	16 000	19 000
Poor quality speech calls UL (%)	0.2	0.2	0.3	0.2
	0.2	0.3	0.6	0.9
Poor quality speech calls DL (%)	0.1	0.2	0.2	0.4
	0.3	0.2	1.2	1.9
Poor quality CS calls UL (%)	0.3	0.7	1.0	0.9
	0.5	1.2	2.1	2.2
Poor quality CS calls DL (%)	0.1	0.1	0.0	0.0
	1.8	0.9	1.0	1.0
Blocked speech calls (%)	0.6	8.2	20	30
	0.5	0.8	3.8	6.9
Blocked CS calls (%)	0.6	8.0	21	31
	0.4	1.7	10	21

CS, circuit-switch data.

7. Discussion and Conclusions

The automated optimization of key WCDMA parameters benefits the improving of inaccurate or even incorrect parameter values and increases the network capacity, especially, in the case when the operator has chosen to set the parameter values cautiously to ensure that required quality criteria are met. For instance, *PrxTarget* or *CPICHToRefRABOffset* that has been set to a too high level can result in poor quality or link power outage of calls in the cell. In such cases, observed poor quality makes the control algorithm reduce the parameter value until the quality is at the required level. The obtained increases in capacity are specific to the described cases and generalizing the result to real networks is not straightforward. The benefit of control depends on the choice of the initial parameters, traffic characteristics, defined policies and the availability of performance measures.

We showed that the parameters could be optimized on a per-cell basis or a per-cell-cluster basis. 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. In a network of diverse cell properties and many layers, the clustering of cells is thus, an additional task. The clustering can be based on performance measures and parameters with conventional methods such as the k-means algorithm or the self-organizing map [28].

The simulated environment was a real city environment planned using realistic site locations. These issues lead to quite significant differences in the load among different cells. The blocking and queuing occurred mainly in few overloaded hot-spot cells. Additionally, different load conditions were tried, for instance, in the simultaneous multi-parameter optimization. Both the cell-based individual parameter optimization and the cell-cluster-based multi-parameter optimization worked fine under different load conditions. This indicates that the methods are robust. 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. Thus, the parameters would be optimized for average load conditions, and the optimization would not tackle rapid differences in load conditions.

The performance of the proposed control methods were compared with the performance obtained without automated optimization. Comparisons among different optimization methods were not made, expect for one case. The rule-based approach is not necessarily superior to conventional optimization methods, such as the gradient-descent minimization [5–7] in terms of convergence speed, stability or robustness. The gradient-descent algorithm utilizes stochastic search, that is, random perturbations of parameters to find the optimum values. The gradient-descent algorithm also controls the magnitude of parameter adjustments allowing improved convergence rate. The benefit of stochastic search 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 rule-based control is based on expert knowledge, according to which the rules are constructed. The rules likely require revision of details in the beginning of operation. However, the approach offers the network operator a good insight into the regularities of system, which may prove valuable in solving problem situations. For instance, the multi-parameter optimization with the gradient-descent optimization described in Reference [6] resulted in an improved packet throughput. However, the optimum parameter values, with which the improvement was obtained, may seem peculiar and the reason for the improvement may not be clear for the expert. This study showed no benefit of using the gradient-descent method instead of the rule-based approach in the case of pilot power optimization. The result is thus in favor of the rule-based control.

To conclude, the automatic optimization of several WCDMA parameters was described. The optimization was guided by heuristic rules, commensurate performance indicators and trade-off policies. The methods were shown to produce a significant increase in capacity in comparison to the default parameter settings, both in the case of single-parameter and multi-parameter optimization. As implemented into the network management system, the proposed method constitutes a beneficial feature that could reduce the operational and capital expenditures of the network operator.

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Authors' Biographies

Albert Höglund received the M.Sc. (Tech.) degree in Operations Research from Helsinki University of Technology in 1997 and the M.Sc. (Econ.) degree in computational finance from the Swedish School of Economics and Business Administration, in 2001. He worked as research engineer and senior research engineer at Nokia Research Center, from 1996 to 2002. Currently, he works as senior business analyst at Nokia Networks. His research interests include network management, network optimization and portfolio management.

Kimmo Valkealahti received the M.Sc. (Tech.) and D.Sc. (Tech.) degrees in Computer Science from Helsinki University of Technology in 1992 and 1998 respectively. From 1991 to 1998, he worked at Helsinki University of Technology as research associate. He worked as research engineer at Nokia Research Center from 1998 to 2000. Since 2001, he has worked as a consultant for Nokia Research Center. His research interests include network management, network optimization and data mining.