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ABSTRACT

Code-division multiple access has been widely accepted as the major multiple access scheme in third-generation mobile communication systems. Wide-band CDMA and its hybrid associate time-division CDMA are key elements of the IMT2000 framework of standards. Since the beginning of the 1990s there has been enormous research activity in analysis of the soft (i.e., interference limited) capacity of these CDMA-based systems. Optimal usage of the soft capacity to provide, maintain, and guarantee QoS for different service classes is now becoming a very important issue. Therefore, interest in radio resource allocation has recently increased. This article presents an overview of RRA schemes (primarily for CDMA-based systems) that are flexible, support traffic services with various QoS requirements, minimize call/session blocking and dropping probabilities, and have acceptable radio resource utilization.

INTRODUCTION

Radio resource allocation (RRA) algorithms aim to optimally use the “soft” code-division multiple access (CDMA) capacity. What is included in RRA?

Denote with \( M(t) \) the number of active mobiles in the coverage area. This number changes depending on the offered load. The set of all base stations (BSs) is \( B = \{1, 2, ..., B\} \). \( C = \{1, 2, ..., C\} \) is the numbered set of all available channels. The gain matrix \( G \), which describes the radio environment, is defined as \( G = \{G(t), i, j\}_{B \times M(t)} \). \( G(t), i, j \) is the link gain between base station (BS) \( i \) and mobile station (MS) \( j \) that changes with the mobile’s movement.

RRA algorithms consider the link gain matrix \( G \) and perform the following tasks (Fig. 1):

- Assign one or more (e.g., soft handoff) BS from set \( B \). Call admission control (CAC) decides if and where the new (or handed over) session is accepted or rejected.
- Assign one or more channels (e.g., codes for wideband CDMA, WCDMA, and combination code-timeslot for time-division CDMA, TD-CDMA) from set \( C \). The rate scheduler assigns appropriate code for the session, and the time scheduler (TS) decides when these resources can be used.
- Assign transmitting power for the BS and mobile. The power scheduler decides the appropriate power level considering the radio channel conditions and required session quality.
- Differentiate in resource allocation between several traffic classes. TS decides the time moment and the amount of used resources based on the session's quality requirements.

RRA algorithms should maximize the number of satisfied users within the available radio bandwidth. A user is satisfied if its session quality is under the acceptable level for an insignificant amount of time (see a more elaborate definition in the section about CDMA capacity). Considering all these assignments, the dynamic nature of the link-gain matrix \( G \), and the wide range of quality requirements, the RRA algorithms must perform very complex tasks.

As shown in Fig. 1, a resource estimator (RE) controls the RRA algorithms, represented by the dotted arrows. The solid arrows present the flow of user information. The RE has several inputs such as the measured interference conditions, radio channel characteristics, current load in the BSs, sessions’ traffic characteristics, and quality requirements. With these inputs and its built-in capacity models, the RE performs the following control tasks:
• The radio channel characteristics and session quality requirements are used for optimal power and rate allocation.
• The current BS load, session traffic characteristics, and quality requirements are used to control the time scheduler.
• With the built-in capacity models, the RE assists CAC in accepting or rejecting new (or handoff) sessions.

The following sections explain the RRA algorithms shown in Fig. 1 in more detail. The section about CDMA capacity presents the main factors that influence uplink (UL) and downlink (DL) system capacity. The analytical models can be built in CAC and the RE, and used for decisions whether new/handoff sessions are accepted or rejected. The next section shows several methods for power and rate adaptation for optimal usage of the soft CDMA capacity. It also shows dynamic channel allocation of time slots for TD-CDMA-based systems. The following section addresses UL and DL CAC algorithms. The bandwidth reservation technique is elaborated in the last section as a possible solution for maintaining required quality during MS movement. The article concludes with a summary and recommendations.

**CDMA Capacity Analysis**

The analysis presented here is kept on a fairly simple level because it aims to present only the crucial factors that define the soft CDMA capacity. In more detail, the capacity analysis assumes:
• Total system bandwidth $W$.
• One service with transmission rate $R$, quality target for the transmitted energy per bit vs. interference ratio $E_b/N_0 > \mu$ and averaged channel activity factor $P_{on}$. It should be noted here that due to different receiver algorithms at the MS and BS, the quality target is different for UL and DL.
• Perfect power control. In UL this means equal received power $P_{0,rx}$ at the BS from all mobiles belonging to that cell. In DL it means that all mobiles in the cell have reached the same $E_b/N_0$ target.
• Uniform traffic distribution with $N$ users/cell.

The major interference comes from the first two tires around the reference cell. The quality requirement in the UL direction can be calculated (not accounting for thermal noise) as

$$E_b = \frac{I_0}{I_0}$$

$$\frac{W}{R} P_{0,rx} \left( N - 1 \right) P_{0,rx} + \sum_{i=1}^{12} N \sum_{j=1}^{1} P_{j,rx} + \sum_{j=1}^{2} P_{j,rx} \geq \mu_{ul}$$ (1)

$P_{j,rx}$ is the interference power from user $j$ received at the reference BS but power-controlled by its own BS. The total outer-cell interference is a summation of log-normally-distributed random variables. For large $N$ the outer-cell interference is usually modeled with Gaussian random variables with mean and standard deviation that depends on number of users, radio channel characteristics, and service activity.

Similarly, the downlink $E_b/I_0$ requirement for the desired user $i$ is calculated as

$$\frac{W}{R} P_{0,rx} \left( 1 - \gamma \Phi_0 \right) P_{0,rx} + \sum_{j=1}^{1} P_{j,rx} + \sum_{j=1}^{2} P_{j,rx} \geq \mu_{ul}$$ (2)

Equation 2 differs from Eq. 1 in the following:
• $P_{0,rx}$ is the total power received at the desired mobile from its own cell, while $P_{j,rx}$ is the total power received from the $j$th interfering BS located in the first or second tier.
• $\gamma$ is the portion of the BS’s maximum transmitting power $P_{max}$ devoted to all traffic channels $(1 - \gamma$ is devoted to the pilot channel). $\Phi_0$ is the portion dedicated to the desired user.
• Considering the maximum BS transmission power $P_{max}$ and the DL power control, there is the additional constraint

$$\sum_{i=1}^{N} P_{on} \Phi_{1i} \leq 1$$

along the quality restriction in Eq. 2.

• $\rho$ is the orthogonality factor (usually between 0.4 and 0.9) accounting for residual own-cell interference.
• The outer-cell interference cannot be modeled with Gaussian random variables since the number of interference sources is smaller (18) than in the UL case.

Denote with $P_{outage} = P_i(E_b/I_0 < \mu)$ the probability that a call has bad quality (UL or DL). From this definition it follows intrinsically that $P_{outage}$ increases for higher-quality targets $\mu$. WCDMA capacity is usually defined as the maximum number of users $N$ for $P_{outage} <$ 0.05. The “soft” WCDMA capacity comes from the drastic influence of the quality requirements on $P_{outage}$ (and consequently the capacity) and from the desired upper bound for $P_{outage}$.

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1 For a hexagonal cellular network there are 6 and 12 cells in the first and second tier, respectively.
From the definition of $P_{\text{outage}}$, Eqs. 1 and 2, and Fig. 2, the most important factors that influence UL and DL CDMA capacity are the $E_b/I_0$ target, transmission rate (i.e., processing gain $W/R$), channel activity, and number of users. Note that for $P_{\text{outage}} = 5$ percent we can have twice as many users when the activity is decreased from 1 to 0.5. Furthermore, the lower the transmission rate (i.e., the higher the processing gain $W/R$), the higher the number of users we can have in the system.

Additionally, the power control error is also one of the most important factors that have an impact on system capacity. The effects of the power control error are modeled and investigated in [1], and are not further elaborated here. However, it should be noted that a small increase in the power control error has a significant impact on capacity. For example, the authors in [1] report UL capacity loss of 28 and 58 percent (relative to perfect power control) for standard deviation of power control error 1 dB and 2 dB, respectively.

The analysis and relations presented here can be built in the CAC for deciding the amount of traffic load accepted in UL and DL. The RE can use the relations defined by these models for controlling the power and rate assignments (see power and rate adaptation in the next section) and for defining the available capacity for the time scheduler.

**Radio Resource Allocation for WCDMA and TD-CDMA**

The previous section indicated that the received useful power and transmitted data rate (Eqs. 1 and/or 2) have huge effects on the received $E_b/N_0$ and consequently on capacity. Accurate and fast$^2$ power control can compensate for bad radio channel conditions and keep the received $E_b/N_0$ above the target level. However, in a bad radio link (e.g., low radio link gain $G(t_0)$ at time moment $t_0$), the source can transmit with high power levels, causing extensive interference to other ongoing sessions. It is possible to gain in capacity by limiting the maximum transmit power during these bad radio channel conditions and also adjust the transmission rate for the required $E_b/N_0$? This possibility is investigated in [2] with two alternatives for power and rate adaptation in bad radio channel conditions:

A1) Power and rate adaptation:
In the case of bad conditions the transmitting power is limited to $S_{\text{max}}$ while the transmission rate is reduced to meet the QoS requirement.

A2) Truncated rate adaptation:
In the case of bad conditions the transmission is suspended. Otherwise, the data rate is adapted with a fixed transmission power $S'<S_{\text{max}}$.

The power gain of solution A2 is larger than that of A1, although A2 introduces time delay when the channel gain is low. Therefore, it is advantageous to use A1 for voice service and A2 for data services since they can tolerate higher delay. The analysis in [2] shows that the power gain depends on the radio channel profile. This gain can be translated in capacity increase when A1 is used for voice and A2 for data while still maintaining the same average data rates and bit error rate requirements. However, a procedure for defining and optimizing the power threshold $S_{\text{max}}$ is not proposed.

The latter issue is extensively addressed in [3], where the throughput and delay are studied as functions of both power and processing gain. The investigated model accounts for traffic burstiness, retransmissions, and queuing delay. An important result of this analysis is that optimization of the powers and processing gains assigned to the voice and data service classes can provide a significant expansion in the capacity region over a fixed allocation.

$^2$ In UMTS the power control commands have frequency of 1500 Hz.

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![Figure 2](image-url)

**Figure 2.** $P_{\text{outage}}$ in the uplink for 3.3 dB quality target, processing gain 256 and 341.3, and Gaussian assumption for the total interference.

![Figure 3](image-url)

**Figure 3.** DL/UL switching point configurations for UMTS TDD mode.
The power and rate adaptation algorithms explained above can be implemented in the power/rate scheduler presented in Fig. 1. The necessary radio channel characteristics can be provided by the RE and the built-in capacity models in CAC, and/or the RE can translate the gain from optimal power and rate allocation into better capacity estimation and utilization.

In TD-CDMA the resource allocation also has a time slot assignment. Each time slot in the TDMA frame can be allocated either to UL or DL (Fig. 3). Thanks to this flexibility the time-division duplex (TDD) mode can be adapted to different environments and deployment scenarios. Additionally, pooling of CDMA codes and TDMA time slots gives higher granularity.

The RRA algorithms discussed in the following paragraphs dynamically assign time slots, or more precisely a combination of time slot and code, which is specific for TD-CDMA systems. They have been investigated within the ACTS project Future Radio Wideband Multiple Access System (FRAMES) [4, Ch. 7]. The three algorithms are:

- Centralized resource allocation
- Intrabunch resource allocation algorithm
- Interference matrix-based allocation algorithm
- Decentralized resource allocation
- Channel segregation algorithm

The centralized approach assumes a wireless system based on a limited number of remote access units (RAUs) connected to a central unit (CU), as shown in Fig. 4. This group of cells is called a bunch. The RAUs share measurement and status information for the purpose of dynamic resource allocation. In UMTS terminology the RAUs are node Bs and the CU can be associated with the RNC.

Intrabunch allocation is based on measurements of the radio link gain matrix \( G = [G(i,j)]_{B \times M} \) described in the introduction, but here \( B \) denotes the number of RAUs. Each mobile performs DL path loss measurements on the beacon channel transmitted by all RAUs within the same bunch. From these measurements the CU constructs the gain matrix that is used in the time slot allocation. The resource allocation algorithm goes as follows:

1) Choose a free time slot randomly or by some heuristic algorithm.
2) From the gain matrix \( G \) calculate/estimate received signal-to-interference ratio (SIR) for all existing sessions on that time slot. During this process, a distributed constrained power control (DCPC) algorithm iteratively searches for a set of transmission powers that can satisfy all \( E_b/N_0 \) targets for the sessions using that time slot.
3) If the power set is found (i.e., all \( E_b/N_0 \) targets can be satisfied) the time slot is allocated. If not, temporarily assign the next free time slot to the new user and repeat from 2. Abort when there are no more slots to try.

The performance of the proposed bunched system is better for larger bunch size (at a cost of higher CU processing power) and depends on the mobile’s measurement capability. The latter causes incomplete link gain matrix \( G \) and consequently less accurate \( E_b/N_0 \) estimations. Additionally, a communication is required between CUs from different bunches (Fig. 4) to coordinate the time slot and code allocations at the bunch border. This is a small drawback of the centralized approach. Nevertheless, the feasibility check if all collocated \( E_b/N_0 \) targets can be satisfied is a good approach to defining whether this time slot can be allocated and afterward provide acceptable quality.

The Interference matrix-based allocation algorithm is different from the intrabunch scheme because it uses the concept of zones. A zone is the area homogeneously covered by one or several RAUs, as shown in Fig. 5. The time slots used by an MS located in one zone might be blocked for usage by another MS in the same or some of the surrounding zones. For example, the MS is in Zone2 and RAU2 is chosen for the uplink allocation (Fig. 5). Then the following two blocking policies are defined:

- Polite policy: Block the time slot for pairs \((\text{Zone}^3, \text{RAU})\) that can be interfered with by our allocation. In the example, the pairs are \((\text{Zone}_1, \text{RAU}_1)\), \((\text{Zone}_2, \text{RAU}_1)\), \((\text{Zone}_3, \text{RAU}_1)\), \((\text{Zone}_4, \text{RAU}_1)\) and \((\text{Zone}_5, \text{RAU}_1)\).
• Aggressive policy: Block the time slot for pairs (Zone\textsuperscript{4}, RAU) that could interfere with our link. The pairs are (Zone\textsubscript{2}, RAU\textsubscript{1}), (Zone\textsubscript{3}, RAU\textsubscript{1}), (Zone\textsubscript{3}, RAU\textsubscript{3}), and (Zone\textsubscript{4}, RAU\textsubscript{3}).

The time slot allocation algorithm in the CU performs the following tasks:

• Finding the a priori free time slot.
• The CU evaluates which zones would be blocked (according to polite or aggressive policy) with the new allocation. Additionally, a score is kept for the chosen time slot which is increased each time the CU evaluates a zone that is already blocked.
• The time slot with the highest score is selected. The scoring idea is based on reusing the same time slot whenever possible.

The zone principle seems an attractive idea since in a real network with small cells (for higher capacity), which usually have irregular shape, a large overlap between the cells is possible.

The channel segregation algorithm as a decentralized approach aims to avoid the high processing power demand at the CU, interbunch communication for time slot allocation at the bunch border, and extensive radio network planning. It also avoids requirements for knowledge about link gain matrix \(G\) due to its self-adaptive learning capability. The basic algorithm is implemented as follows:

• Each base station assigns a priority value for each time slot according to a priority function. This priority function gives the relationship between the priority value and the interference level experienced on the time slot.
• The priority list of the time slot at each base station is updated considering a time-geometrical window formula that weights the new priority value, and also old priority values.
• The base station utilizes resources from the slot with the highest priority.

The results presented in [4] show the self-learning capability of the algorithm and capacity gain compared with pure random time slot allocation. However, this algorithm requires further study to show the algorithm’s efficiency in mixed traffic scenarios and higher data rates, and its functioning with intracell handoffs.

### UPLINK AND DOWNLINK ADMISSION CONTROL

The number of users in the system, \(N\), strongly influences system capacity, as discussed earlier. From the capacity analysis presented previously, decision rules can be defined and implemented in CAC and/or the RE entity to avoid overload situations and for stable system operation. One typical example of this approach is presented in [5] for the DL. An interesting result of this study is the theoretical limit \(N_{\text{limit}}\) for the number of users in DL. \(N_{\text{limit}}\) depends on several parameters such as DL orthogonality factor, soft handoff area and gain, \(E_b/N_0\) target, and radio link characteristics. When this limit is reached the DL BS transmission power becomes infinite.

Therefore, the DL load should be kept with a safety margin below \(N_{\text{limit}}\).

In reality the DL BS transmission power is upper-bounded with \(P_{\text{max}}\). Thus, DL CAC criteria could be to:

• Accept a new/handoff session if the total transmission power is smaller than a predefined threshold (with a safety margin lower than \(P_{\text{max}}\)).
• Accept a new/handoff session if the DL transmission power per traffic channel is smaller than a predefined threshold.

Subsequently the question arises of which CAC criteria is more advantageous.

The analysis in [6] gives a performance comparison in terms of voice call blocking and dropping probabilities between these two CAC alternatives. A WCDMA system in an urban (8 x 8 Manhattan grid) environment is modeled with a DCPC algorithm in the DL. The simulation results show that strategy has lower dropping probability than the other strategy, especially for higher loads. This is due to the higher flexibility in the DL power allocation when the constraint is on the total DL transmission power and not on the transmission power per channel. Additionally, the effect of involving the surrounding BSs in the CAC decision is compared with the case when this decision is taken only at the home cell. In this case the dropping probability is only improved (although more signaling appears in the core network) for extremely high load scenarios. For low and moderate loads the gain introduced by the consultations with surrounding cells is insignificant.

Similar approaches can be found for UL CAC algorithms. A typical example is the study shown in [7], where the following two approaches are presented:

• Number-based CAC (NCAC): A new call is blocked if \(N\) users already occupy the home BS. For example, the number of ongoing sessions can be measured by the RE in Fig. 1.
• Interference-based CAC (ICAC): A new call is blocked if the observed interference level (from interference measurements at the RE in Fig. 1) exceeds a predefined threshold \(I_{\text{block}}\).

The blocking and outage\textsuperscript{3} probability in the case of NCAC and ICAC are derived analytically. The presented simulation results for blocking and outage probabilities are in very close agreement with the analytical approach and show similar performance for both ICAC and NCAC. A procedure for defining the optimal threshold for \(N\) (for NCAC) and \(I_{\text{block}}\) (for ICAC) is not presented. However, this study shows interesting results about the influence of environment parameters such as path loss, shadowing, and traffic’s spatial distribution and transmission rate on the thresholds required for the two CAC algorithms. The interference threshold \(I_{\text{block}}\) is much more robust than the threshold for the number of users when the system parameters stated above are changed. ICAC requires more complex implementation at the BS’s hardware and may suffer performance degradation due to interference measurement error. However, ICAC is more flexible because its admission

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\textsuperscript{3} If several RAUs cover the current zone then block all the zones covered by these RAUs, the current RAU excepted.

\textsuperscript{4} These zones are covered by at least two RAUs of which at least one is the current RAU.2

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The bandwidth reservation scheme can overestimate the amount of reserved bandwidth. By predicting the mobile’s movement, which is difficult to implement in a real network, the overestimation can be reduced.

threshold is slightly changed while the threshold for NCAC must be specifically redesigned for changes in propagation parameters, traffic spatial distributions, and transmission rates.

**Figure 6. Bandwidth reservation along the mobile’s movement.**

### SUMMARY AND RECOMMENDATIONS

This article has addressed RRA issues for the future mobile communication systems, especially the WCDMA and TD-CDMA modes of the Universal Mobile Telecommunications System (UMTS). A set of RRA algorithms is proposed that consist of resource estimation, QoS-aware scheduling, power and rate allocation (plus time slot allocation for TD-CDMA), and CAC. The RE is the crucial part of this framework. How to combine the interference measurements with the current load situation and QoS requirements of the existing traffic classes to control CAC, QoS-aware scheduling, or channel allocation is also a very interesting issue for further research. In the future all these interactions between the RE and the other parts of the RRA framework should be well defined.

A UL and DL capacity analysis/estimation is shown for a CDMA-based radio interface that can be used for calculation of the available resources. The total interference (i.e., number of users), power control error, quality requirement, and transmission rate are among the most important factors in defining the capacity limit.

Several techniques for power/rate and time slot allocation were presented for maximizing the carried load within a certain radio bandwidth. How to translate the gain from optimal power, rate, and time slot allocation into capacity expansion is an area for further research.

Furthermore, downlink and uplink CAC algorithms are briefly discussed as methods for limiting the accepted load and avoiding rapid decrease in the quality of ongoing sessions. This is crucial for CDMA-based systems since capacity is interference limited. Optimization procedures for the CAC thresholds should be investigated in the future.

Although the time scheduling was proposed in the set of RRA algorithms mainly for QoS differentiation, the interactions of this scheduler with the CAC, power and rate scheduler, and...
RE should be well defined. Additionally, the gain achieved by the scheduling algorithm should be translated into capacity increase. This is also an area for further research.

Finally, the bandwidth reservation technique was elaborated as a tool for maintaining the required quality during the MS movement.

REFERENCES


BIOPHGRAPHIES

LIUPCO JORGUSEKSI received his Dipl.Ing. degree in 1996 in the field of microelectronics and telecommunication at University St. Cyril and Metodij, Skopje, Republic of Macedonia. In December 1997 he joined the Telecommunications and Traffic Control Systems Group of Delft University of Technology (DUT), The Netherlands, where he was involved in the ACTS project FRAMES investigating dynamic radio resource allocation algorithms for third-generation mobile communication systems. In April 1999 he joined the mobile networks department at KPN Research, Leidschendam, The Netherlands, where he works as an applied scientist on RRA algorithms for GPRS, UMTS, and WATM. Currently he is pursuing his Ph.D. degree at the Center for PersonKommunikation, Aalborg University, Denmark, in QoS-aware RRA algorithms for future-generation mobile communication systems.

ERIK FLEDDERUS studied at the University of Twente. He received his Master’s and Ph.D. degrees in applied mathematics in 1993 and 1997, respectively, both in the field of mathematical modeling in fluid mechanics. Since then he has worked at KPN Research on various topics, including radio propagation in microcells, capacity enhancement techniques in GSM, and multiuser detection in UMTS. In 1998 he was a program manager for the GSM projects within KPN Research, and he worked extensively on capacity and coverage models for UMTS. In 2000 he became project leader of a project involving planning and QoS issues for UMTS, thereby relating radio, core, and end-to-end aspects. In addition, he is coordinator and project leader of a European research proposal for the IST program MOMENTUM, leading a consortium of Germain and Portuguese partners. This project is targeted to run for two years and will be finalized in 2002. His research interest is mathematical modeling in mobile communications, including capacity and QoS modeling for UMTS, radio network planning, and radio propagation.

JOHN FARGEROTU received a B.S.E.E. degree from the University of Maryland, College Park, in 1982 and an M.S.E.E degree in communications engineering from George Washington University, Washington, D.C., in 1986. He received his Ph.D. from Delft University of Technology in 1998. He is currently head of the Wireless Communication Section at CSEM, Neuchatel, Switzerland, where his research interests include wireless communication, modulation and coding, satellite communication, and networking. In 1999 he served as Technical Program Chair for IEEE VTC ’99 Fall, Amsterdam, The Netherlands. As a principal scientist in the Satellite Communications Branch of the NATO C3 Agency (NC3A), The Hague, The Netherlands, he was a member of the SATCOM Post-2000 team, evaluating SATCOM requirements, options, and technologies for the future, as well as the ATM project teams, where the focus of his work was on the integration of ATM and SATCOM, networking and performance analysis, and characterization. From 1985 to 1990 he was a senior engineer and task leader at Stanford Telecommunications, Inc., Reston, Virginia, where he led a team of engineers in communication subsystem design and analysis.

RAMOJI PRAJAG (SM) received a B.Sc. (Eng) degree from Bihar Institute of Technology, Sindri, India, and M.Sc. (Eng) and Ph.D degrees from Birla Institute of Technology (BIT), Ranchi, India, in 1968, 1970, and 1979, respectively. In February 1988 he joined the Telecommunications and Traffic Control Systems Group of Delft University of Technology (DUT), The Netherlands, where he was actively involved in the area of wireless personal and multimedia communications (WPMMC). He was head of the Transmission Research Section of the International Research Centre for Telecommunications Transmission and Radar (IRCTR) and also program director of the Centre for Wireless Personal Communications (CEWPC). Now he is Wireless Information Multimedia Communications chair and co-director of Center for PersonKommunikation, Aalborg University, Denmark, since June 1, 1999. He has published over 300 technical papers, and authored and co-edited *CDMA for Wireless Personal Communications, Universal Wireless Personal Communications, Wideband CDMA for Third Generation Mobile Communications, and OFDM for Wireless Multimedia Communications* (Boston: Artech House). His research interest lies in wireless networks, packet communications, multiple access protocols, adaptive equalizers, spread-spectrum CDMA systems and multimedia communications.