UPGRADE
The European Journal for the Informatics Professional
http://www.upgrade-cepis.org
Vol. V, No. 1, February 2004

UPGRADE is the European Journal for the Informatics Professional, published bimonthly at <http://www.upgrade-cepis.org/>

Publisher
UPGRADE is published on behalf of CEPIS (Council of European Professional Informatics Societies, <http://www.cepis.org/>) by NOVÁTICA <http://www.ati.es/novatica/>, journal of the Spanish CEPIS society ATI (Asociación de Técnicos de Informática <http://www.ati.es/>).
UPGRADE is also published in Spanish (full issue printed, some articles online) by NOVÁTICA, and in Italian (abstracts and some articles online) by the Italian CEPIS society ALSI <http://www.alsi.it> and the Italian IT portal Tecnoteca <http://www.tecnoteca.it/>.
UPGRADE was created in October 2000 by CEPIS and was first published by NOVÁTICA and INFORMATIK/INFORMATIQUE, bimonthly journal of SVI/FSI (Swiss Federation of Professional Informatics Societies, <http://www.svifsi.ch/>).

E-mail addresses for editorial correspondence: <rfcalvo@ati.es>, <nicolet@acm.org> or <rcarniel@dgt.uniud.it>

E-mail address for advertising correspondence: <novatica@ati.es>

Upgrade Newslist available at <http://www.upgrade-cepis.org/pages/editinfo.html#newslist>

ISSN 1684-5285

Next issue (April 2004):
"Unified Modeling Language (UML)"

Wireless Networks - Telecommunications' New Age

Guest Editors: Mehmet Ufuk Çaglayan, Vicente Casares-Giner, and Jordi Domingo-Pascual

Joint issue with NOVÁTICA*

Mosaic

* This monograph will be also published in Spanish (full issue printed; summary, abstracts and some articles online) by NOVÁTICA, journal of the Spanish CEPIS society ATI (Asociación de Técnicos de Informática) at <http://www.ati.es/novatica/>, and in Italian (online edition only, containing summary abstracts and some articles) by the Italian CEPIS society ALSI and the Italian IT portal Tecnoteca at <http://www.tecnoteca.it>.

Capacity in WCDMA Cellular Systems: Analysis Methods

Luis Mendo-Tomás

This paper surveys the available methods for analysing the capacity of the radio interface in WCDMA (Wideband Code Division Multiple Access) cellular systems, and the related aspects of power control, base-station assignment, load control, simulation and planning.

Keywords: Capacity, Cellular Systems, Code Division Multiple Access, Power Control.

1 Introduction

The WCDMA (Wideband Code Division Multiple Access) radio interface is based on DS-CDMA (Direct Sequence Code Division Multiple Access) with an approximate bandwidth of 5 MHz. The performance of the radio interface in cellular CDMA systems is difficult to analyse, due to the trade-off between coverage and capacity, caused by the interference-limited nature of these systems. As a result, power control takes on a fundamental role. Power control is closely linked to the assignment of mobile users to base stations, load control and congestion control. For a description of the general characteristics of DS-CDMA cellular systems and the WCDMA radio interface the reader is referred to [13]. Furthermore, because of the inherent complexity of these systems, it is often necessary to resort to simulation in order to obtain meaningful results. The remainder of this paper provides an overview of existing literature on these concerns, before closing with an outline of available techniques for capacity analysis and planning.

For simplicity's sake, CDMA network analyses or simulation studies are usually split into two stages:

- *Link Level:* Analyses the link between a mobile terminal and its serving base station or stations (soft hand-off)
- *System Level:* Using the characterization obtained at the link level, this models the functioning of the cellular network, taking into account the environment, radio network configuration and traffic distribution.

At link level, aspects such as modulation, coding, closed-loop power control, channel estimation and diversity are considered, while the system level is concerned with required transmit powers, base-station assignment, load control, coverage, traffic and capacity.

2 Power Control

Early works on power control in radio networks were oriented towards systems with orthogonal channels and frequency reuse.

Power control in CDMA, which is achieved by open-loop, closed-loop and outer-loop procedures [13], can be studied from two different viewpoints: link-level and system-level. In the former, the performance of the closed loop is analysed, usually by means of simulation. Initial studies considered received level based power control. More recent work focuses mainly on signal/interference ratio (SIR)-based power control [1], which is more effective, in spite of stability problems.

System-level effects of the closed loop are analysed in [25] and [24] by means of simulations. These effects are caused by the interaction of the closed loop with the fast variations in the channel attenuation produced by multipath propagation, and can be characterized by a small set of parameters, described in [13]. This characterization is important when assessing system capacity; nevertheless, many capacity analyses ignore these effects. [23] examines power control in conjunction with transmit diversity.

The system-level approach to power control is essentially aimed at determining the optimal power values as a function of the state of the cellular network. A simplified model which does not take into account the previously mentioned closed-loop effects is commonly used. In these conditions the power control problem is equivalent to a linear equation system. Power control in the uplink of a cellular network with conventional (mono-user) receivers using this type of simplified model is analysed in [9]. This work also shows that the dimension of the equation system can be greatly reduced in the uplink of a mono-service network, and [11] applies this idea to multi-service networks by means of an approximation valid for high processing gains. [20] shows that dimension reduction can be achieved in multi-service networks without the need for such an approximation, in both the uplink and the downlink. A downlink power control algorithm based on dimension reduction is proposed in [16] for a mono-service network, and in [20] it is generalized to the multi-service case. [10] and [32] consid-

Luis Mendo-Tomás received his MSc. and PhD. degrees in Telecommunication Engineering from the *Universidad Politécnica de Madrid*, Spain, in 1997 and 2001, respectively. He has worked in radio network planning and is currently carrying out research work at the *Universidad Politécnica de Madrid*. He is co-author of two textbooks on CDMA cellular systems and has published several papers in the fields of CDMA system capacity and power control. His current research interests include CDMA networks, tele-traffic and Monte Carlo methods. He received a national prize from the *Colegio Oficial de Ingenieros de Telecomunicación* (Spanish National Board of Telecommunications Engineers) for his PhD. thesis, and two national awards for his MSc. thesis.
<lmendo@grc.ssr.upm.es>

er an uplink power control algorithm, combined with optimal base-station assignment (see *Section 3*). The convergence rate of this algorithm is investigated in [14]. [29] and [33] propose methods to accelerate this convergence. [31] unifies most of the previous algorithms in a common theoretical framework.

Consideration of closed-loop effects transforms the power control problem into a non-linear equation system. In [18] two power control algorithms are proposed for the uplink and the downlink respectively, valid in the general case with the aforementioned closed-loop effects. These algorithms generalize those in [31] and [20], and their convergence is demonstrated under mild conditions.

The impact of multi-user receivers on power control and capacity is at an early stage of study. [26] presents an algorithm which uses the simplified uplink model to jointly determine transmit powers and the optimal linear multi-user receiver.

A recent line of research addresses the issue of power control for data communications, taking into account the fact that user satisfaction does not depend solely on achieving the required SIR, but depends also on other parameters such as transmit power (which impacts on battery duration) or transmission delay [2]. [22] provides an overview of this line of research.

3 Base-station Assignment

The assignment of users to base-stations in CDMA systems has a great influence on capacity. In most capacity analyses, an assignment based on minimum attenuation is assumed. The notion of adapting assignment to system load conditions in order to increase capacity was first introduced in [9]. This idea is developed in [10] and [32] for a system with conventional receivers, using the simplified model without closed-loop effects. A simple characterization of optimal assignment is obtained, and a decentralized iterative algorithm is derived that converges to that assignment and its associated transmit powers. [19] proposes a non-iterative centralized algorithm that determines optimal assignment and transmit powers, the complexity (number of required operations) of which is a polynomial function of the number of users and base stations, and which shows the resulting capacity increase by means of simulation. [30] studies the optimal assignment and transmit powers considering the latter as discrete variables.

The optimal assignment in the downlink, or in the uplink with closed-loop effects, has been far less studied due to the fact that characterization is not as simple as in the case of a simplified uplink.

4 Admission and Congestion Control

Admission and congestion control in Third-Generation networks is more complicated than in voice-only oriented cellular systems, due to the introduction of packet-switching in the radio interface, and also due to the fact that, being interference-limited, CDMA does not have a "hard" capacity limit.

Several admission control techniques have been proposed for CDMA systems. Most studies consider memory-less control methods, based solely on observing the network when a new call arrives.

5 Simulation

The simulation of the cellular network is accomplished in two steps; at link and system levels. The main parameter acting as an interface is the average value, in terms of multipath variations, of the bit energy to noise spectral density ratio (E_B/N_0), or of the equivalent SIR, necessary to achieve a desired link quality under a given set of conditions. (It can be demonstrated that, irrespective of the quality parameter used, achieving a given quality is, under mild conditions, equivalent to achieving a certain E_B/N_0 value at the receiver, or a permitted combination of E_B/N_0 values at the receivers in the case of diversity reception [18, sect. 3.3.2 y 3.4].) In systems with closed-loop power control, in order to characterize the link from a system-level point of view it is also necessary to take into account the instantaneous transmit power distribution [13, sect. 8.3.2] because of the aforementioned effects.

System-level simulations are classified as *dynamic* or *static* depending on whether time-evolution is modelled in the system or not. Static simulations, while providing less information, are more commonly used in both capacity analyses and radio planning tools [17] due to their shorter simulation time.

6 Capacity Analysis Methods

6.1 Early Studies

The first capacity analyses in DS-CDMA cellular systems considered a single service class, focusing on transmission and propagation aspects while assuming a fixed spatial distribution of users with an ongoing call, thus ignoring load variability.

The classical capacity analysis [7], oriented toward the American IS-95 CDMA system, assumes a uniform deterministic user distribution, modelling the random variability of shadow fading and voice activity (a user only speaks during approximately 40% of the call duration, which is exploited to reduce transmission power in the inactivity periods). Base-station assignment is carried out on a minimum attenuation basis, and it is assumed that the power control sets the received signal level (not the SIR) at the same value for all users, regardless of transmit power restrictions. Similar hypotheses form the basis of other studies. [15] considers shadow and multipath fading, modelling IS-95 coding, modulation, diversity and power control by means of a combination of theoretical development and simulation.

6.2 Load Variability and Multiple Services

Load variability is considered in [27], modelling the number of users with an on-going call in each cell as a Poisson distributed random variable, but making the slightly unrealistic assumption that this number is the same in all cells [6]). This constraint is removed in [5], which extends the analyses of [7] and [27]. Load variability is also modelled in [6]. Both studies limit themselves to the uplink with minimum-attenuation assignment and a single service. In [4] the outage probability is calculated in an analytical manner, modelling traffic as a Poisson spatial point process, and making significant simplifications.

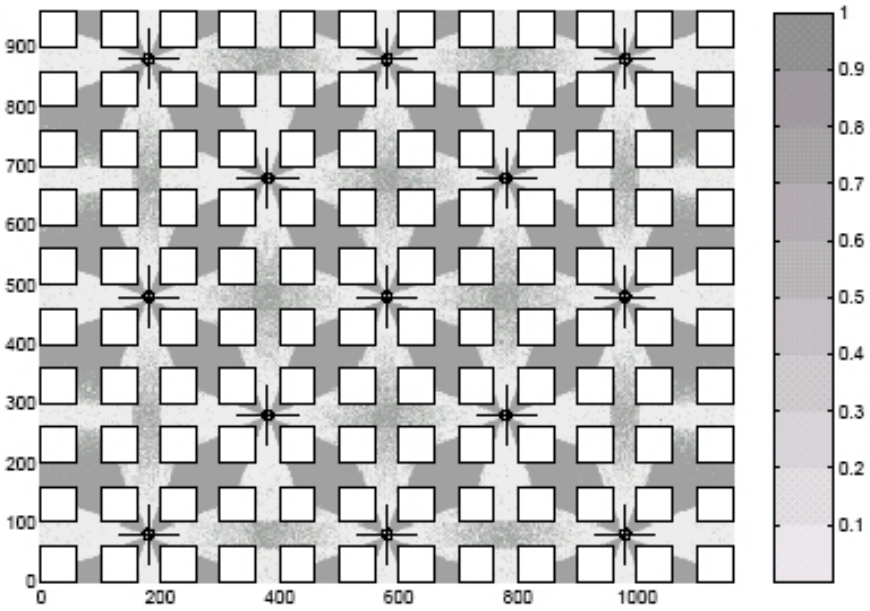

Figure 1: Probability of a User Being in Hand-off as a Function of Position.

6.3 Capacity with Multiuser Receivers

Existing studies on the capacity of networks with multiuser receivers rely on significant simplifications, such as considering a single isolated cell, assuming symbol-synchronization or performing an asymptotic analysis for very large processing gains [12].

6.4 Capacity Analysis Based on Simulation

System-level static simulations are normally employed to assess CDMA capacity. The simulation consists of a number of independent 'snapshots' or *realizations*. In each realization active users are generated according to a traffic model; their attenuation matrix is computed, and the base-station assignment and power control algorithms are run, considering any admission or load control policies to be applied. Attenuation is computed with the usual propagation models and a random shadow fading component is added. Several studies [3] have shown the importance of adequately modelling the shadowing correlation. The traffic characterization in Third-Generation networks is complicated by the existence of multiple service classes, both circuit-switched and packet-switched. This results in a large number of traffic parameters that must be defined in order to characterize the load offered to the network [18]

The system is said to be in outage when not all users can be served with the required quality. Alternatively, outage can be defined as an individual concept related to each particular user. In principle this is more attractive, because it provides local information, but this approach needs to consider load admission and load control criteria which are not standardized and thus may vary significantly from one network to another. For this reason, some simulations consider only overall outage [18] [21].

In each realization key parameters are recorded in order to estimate outage probabilities and other relevant performance indicators in a final processing stage. Usually the main goal of the simulation is to characterize the traffic capacity region, defined as the set of all combinations of values for the traffic parameters such that a given outage probability is not exceeded.

Figures 1 and 2 show how some examples of the kind of results that can be obtained from static simulations. The simulation scenario is an urban microcellular environment [18]. The first figure represents the probability of a user being in hand-off as a function of position. Note the hand-off areas between two sectors, and the more diffuse ones involving different sites. The second figure shows transmitted power (dBm) histograms in the uplink for different bearer-service classes. The services considered are voice, circuit-switched data or LCD (Long Constrained Delay) and packet-switched data or UDD (Unconstrained Delay Data) with different binary rates. The microcellular nature of the network can be seen in the existence of two lobes, corresponding to line-of-sight (LOS) and non-line-of-sight (NLOS) areas; and higher rate services are seen to require larger transmit powers. A peak is also observed corresponding to the minimum transmit power.

7 Radio Planning

The radio planning process in CDMA cellular systems is significantly different from classical planning, mainly due to the relationship between coverage and capacity.

CDMA soft hand-off has an important impact on planning tasks. The number of mobiles in soft hand-off has an influence on the number of channel elements that are required at the base station. On the other hand, soft hand-off brings diversity reception in both uplink and downlink, which reduces the necessary reception margins and extends coverage, although it may increase downlink interference. System-level closed-loop effects also vary according to the hand-off state of the mobile

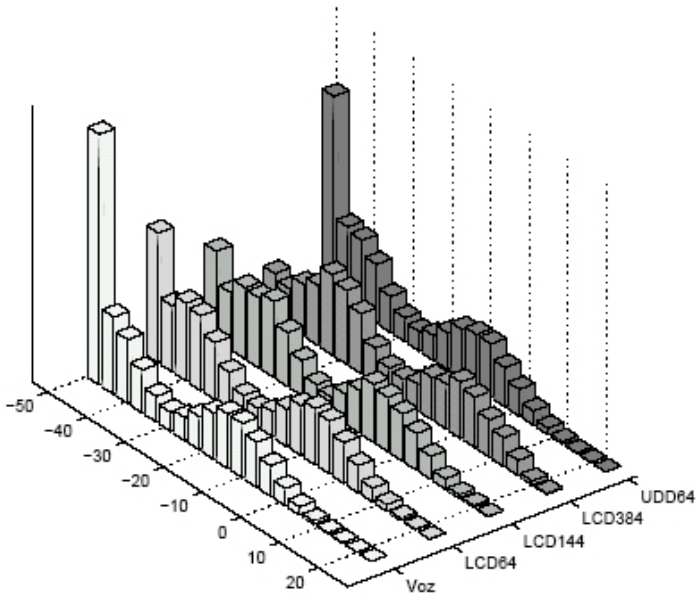

Figure 2: Uplink Transmit Power per Bearer Service.

[24]. The proportion of mobiles in a soft hand-off state can be controlled by means of system parameters, and must be selected as a trade-off value.

Sectorization techniques and hierarchical cell structures can also be applied in CDMA. Usage of the same frequency band in both cell layers is possible but requires network parameters to be adjusted accordingly.

Radio planning significantly affects system capacity. To maximize the latter it is necessary to optimise various parameters such as site location, antenna tilt or antenna beamwidth [28].

7.1 Stages of Radio Planning

Classical planning methods based on link budgets do not adequately describe such aspects as the random nature of system load or the effect of a combination of several simultaneous services on the network. This analysis is even more difficult in the downlink and therefore requires further approximations. This type of technique, or more elaborate ones [8], can be applied for an initial, approximate dimensioning, but detailed radio planning based on simulation is required in order to obtain more precise results [17, sec. 3.3]. The results of the simulation process must be detailed enough to indicate which parameters should be changed, and in which direction. Since almost all the parameters involved in radio planning belong to the system level, simulations are carried out at that level, using results from link level simulations as input.

8 Unsolved Problems

The influence of certain aspects such as smart antennas, multiuser detection or transmission-reception diversity (Multiple-Input Multiple-Output systems, or MIMO) on capacity has yet to be sufficiently studied. Similarly, research on more elaborate admission control algorithms is still required. The problem of optimal assignment has not been studied in the downlink, in spite of its importance when dealing with highly asymmetric traffic.

References

[1] S. Ariyavisitakul. Signal and interference statistics of a CDMA system with feedback power control – Part II. IEEE Transactions on Communications, 42(2/3/4):597–605, February/March/April 1994.

[2] N. Bambos and S. Kandukuri. Power-controlled multiple access schemes for next-generation wireless packet networks. IEEE Wireless Communications, pages 58–64, June 2002.

[3] K. S. Butterworth, K. W. Sowerby, A. G. Williamson, and M. J. Neve. Influence of correlated shadowing and base station configuration on in-building system capacity. In IEEE Vehicular Technology Conference, volume 2, pages 850–855, May 1998.

[4] C. C. Chan and S. V. Hanly. Calculating the outage probability in a CDMA network with spatial Poisson traffic. IEEE Transactions on Vehicular Technology, 50(1):183–204, January 2001.

[5] G. E. Corazza, G. D. Maio, and F. Vatalaro. CDMA cellular systems performance with fading, shadowing, and imperfect power control. IEEE Transactions on Vehicular Technology, 47(2):450–459, May 1998.

[6] J. S. Evans and D. Everitt. On the teletraffic capacity of CDMA cellular networks.
IEEE Transactions on Vehicular Technology, 48(1):153–165, January 1999.

[7] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, Jr, and C. E. Wheatley, III. On the capacity of a cellular CDMA system. IEEE Transactions on Vehicular Technology, 40(2), May 1991.

[8] S. Hanly and R. Mathar. On the optimal base-station density for CDMA cellular networks. IEEE Transactions on Communications, 50(8):1274–1281, August 2002.

[9] S. V. Hanly. Information Capacity of Radio Networks. PhD thesis, Cambridge University, August 1993.

[10] S. V. Hanly. An algorithm for combined cell-site selection and power control to maximize cellular spread spectrum capacity. IEEE Journal on Selected Areas in Communications, 13(7):1332–1340, September 1995.

[11] S. V. Hanly. Congestion measures in DS-CDMA networks. IEEE Transactions on Communications, 47(3):426–437, March 1999.

[12] S. V. Hanly and D. Tse. Power control and capacity of spread-spectrum wireless networks. Automatica, 35(12): 1987–2012, December 1999.

[13] H. Holma and A. Toskala, editors. WCDMA for UMTS. John Wiley and Sons, 2000.

[14]
C. Y. Huang and R. D. Yates. Rate of convergence for minimum power assignment algorithms in cellular radio systems. ACM Wireless Networks, 4(3):223–231, April 1998.

[15]
A. Jalali and P. Mermelstein.Effects of diversity, power control, and bandwidth on the capacity of microcellular CDMA systems. IEEE Journal on Selected Areas in Communications, 12(5), June 1994.

[16]
D. Kim. A simple algorithm for adjusting cell-site transmitter power in CDMA cellular systems. IEEE Transactions on Vehicular Technology, 48(4):1092–1098, July 1999.

[17]
J. Laiho, A. Wacker, and T. Novosad, editors. Radio Network Planning and Optimisation for UMTS. John Wiley and Sons, 2001.

[18]
L. Mendo. Capacity in W-CDMA Cellular Systems (in Spanish). PhD thesis, Escuela Técnica Superior de Ingenieros de Telecomunicación, Universidad Politécnica de Madrid, December 2001.

[19]
L. Mendo and J. M. Hernando. An efficient algorithm for determination of the optimum base-station assignment in cellular DS-CDMA systems. Accepted in IEEE Transactions on Communications.

[20]
L. Mendo and J. M. Hernando. On dimension reduction for the power control problem. IEEE Transactions on Communications, 49(2):243–248, February 2001.

[21]
L. Mendo and J. M. Hernando. Uplink and downlink traffic capacity performance in WCDMA systems. In Wireless Design Conference, volume 1, pages 117–120, May 2002. See also Wireless Europe, September 2002, p. 14.

[22]
D. M. Novakovic and M. L. Dukic. Evolution of the power control techniques for ds-cdma toward 3G wireless communication systems. IEEE Communications Surveys, fourth quarter 2000.

[23]
M. Raitola, A. Hottinen, and R. Wichman. Transmission diversity in wideband CDMA. In IEEE Vehicular Technology Conference, May 1999.

[24]
K. Sipilä, M. Jäsberg, J. Laiho-Steffens, and A. Wacker. Soft handover gains in a fast power controlled WCDMA uplink. In IEEE Vehicular Technology Conference. IEEE, May 1999.

[25]
K. Sipilä, J. Laiho-Steffens, A. Wacker, and M. Jäsberg. Modelling the impact of the fast power control on the WCDMA uplink. In IEEE Vehicular Technology Conference. IEEE, May 1999.

[26]
S. Ulukus and R. D. Yates. Adaptive power control and MMSE interference suppression. ACM Wireless Networks, 4(6): 489–496, 1998.

[27]
A. M. Viterbi and A. J. Viterbi. Erlang capacity of a power controlled CDMA system. IEEE Journal on Selected Areas in Communications, 11(6):892–899, August 1993.

[28]
A. Wacker, J. Laiho-Steffens, K. Sipilä, and K. Heiska. The impact of the base station sectorisation on WCDMA radio network performance. In IEEE Vehicular Technology Conference Fall, volume 5, pages 2611–2615. IEEE, 1999.

[29]
J. T. Wang. Power adjustment and allocation for multimedia CDMA wireless networks. Electronics Letters, 38(1):54–55, January 2002.

[30]
C. Wu and D. P. Bertsekas. Distributed power control algorithms for wireless networks. IEEE Transactions on Vehicular Technology, 50(2):504–514, March 2001.

[31]
R. D. Yates. A framework for uplink power control in cellular radio systems. IEEE Journal on Selected Areas in Communications, 13(7):1341–1347, September 1995.

[32]
R. D. Yates and C.-Y. Huang. Integrated power control and base station assignment. IEEE Transactions on Vehicular Technology, 44(3):638–644, August 1995.

[33]
W. R. Zhang, V. K. Bhargava, and N. Guo. Power control by measuring intercell interference. IEEE Transactions on Vehicular Technology, 52(1):96–106, January 2003.

