Asynchronous Wideband CDMA for IMT-2000

Harri Holma[1], Antti Toskala[1] and Matti Latva-aho[2]

[1] **Nokia Telecommunications, New Radio Systems, P.O.Box 300, FIN-00045 Nokia Group, FINLAND**

[2] **University of Oulu, Centre for Wireless Communications, P.O.Box 444, FIN-90571 Oulu, FINLAND**

I. INTRODUCTION

This paper presents an overview of the wideband CDMA concept which was chosen in ETSI (European Telecommunications Standards Institute) in January 1998 as a basis for UMTS air interface for FDD (Frequency division duplexing) operation. UMTS is the 3rd generation mobile communication system specified within ETSI. This paper is organized as follows. First, the background of WCDMA is presented in Section II. An overall description of WCDMA physical layer is given in Section III. Logical channels and dedicated physical channels are described in Sections IV and V. Service multiplexing and coding is introduced in Section VI. Common physical channels are presented in Section VII. Asynchronous base station operation is described in Section VIII. Inter-frequency handovers for utilizing hierarchical cells are presented in Section IX followed by an introduction of packet access solution in Section X. In Section XI support for adaptive antennas is considered and conclusions are drawn in Section XII.

II. BACKGROUND OF WCDMA

In this section an introduction of European research activities towards 3rd generation systems is presented. RACE I (Research of Advanced Communication Technologies in Europe) program started basic 3rd generation research work in 1988. This program was followed by RACE II with development of CDMA based CODIT (Code Division Testbed) and TDMA based ATDMA (Advanced TDMA Mobile Access) air interfaces 1992-1995. Wideband air interface proposals were studied also in a number of industrial projects in Europe, see e.g. [1]. The European research program ACTS (Advanced Communication Technologies and Services) started in the end of 1995 to support mobile communications research and development. Within ACTS the project FRAMES (Future Radio Wideband Multiple Access System) was set up with an objective to define a proposal for a UMTS radio access system. The main industrial partners in FRAMES project are Nokia, Siemens and Ericsson. Based on an initial evaluation phase in FRAMES, a harmonized multiple access platform was defined consisting of two modes [2][3]: FMA1, a wideband TDMA [4] and FMA2, a wideband CDMA [5][6]. FRAMES wideband CDMA and wideband TDMA proposals were submitted to ETSI as candidates for UMTS air interface.

The proposals for UMTS air interface were grouped into five concept groups in ETSI in June 1997. One of the concept groups studied WCDMA air interface. This group was formed around WCDMA proposals from FRAMES/FMA2, Fujitsu, NEC and Panasonic. During the WCDMA concept group work the WCDMA concept was developed with contributions from several companies from Europe, from Japan and from US. The physical layer of WCDMA uplink is mainly adopted from FRAMES/FMA2 while downlink solution is based on Japanese contributions.

ETSI made the decision between the concept groups in January 1998 [7]. WCDMA was chosen to be standardized for UMTS air interface on paired bands, i.e. for FDD (frequency division duplexing) operation. Detailed standardization of WCDMA is now going on within ETSI.

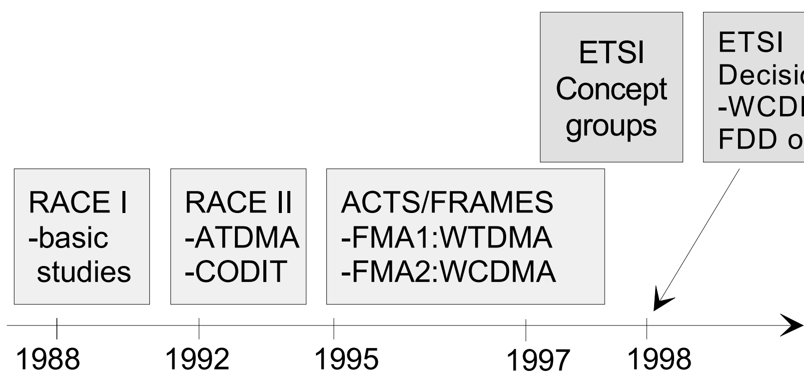

Figure 1. European research programs towards 3rd generation systems and ETSI decision.

In order to validate the performance of wideband air interface solutions, testbeds were developed within European companies [8]. Nokia and Ericsson are also involved in NTT Docomo WCDMA trial network development in Japan.

Asynchronous wideband CDMA is not only considered in Europe but also in Korea and in Japan for IMT-2000 air interface [9] [10] [11] [12] [13]. One of the targets of the ETSI decision was the possibility to have a common global air interface based on the asynchronous wideband CDMA.

III. Overall description of physical layer

The main features of WCDMA are summarised in Table 1.

Table 1. Main parameters of WCDMA.

(DL = downlink, UL = uplink)

Multiple access method	DS-CDMA
Duplexing method	Frequency division duplex (FDD)
Base station synchronization	Asynchronous operation
Chip rate	4.096 Mcps, optionally 8.192 and 16.384 Mcps
Frame length	10 ms
Service multiplexing	Multiple services with different quality of service requirements multiplexed on one connection
Multirate concept	• Variable spreading factor and multicode • Rate matching at layer L1 with repetition coding or puncturing • Continuous transmission in the uplink • Multirate with discontinuous transmission in the downlink • Rate changes dynamically frame-by-frame
Rate detection	• Rate information in each frame protected with a block code and/or • Blind rate detection
Interleaving	Intra-frame / inter-frame interleaving
Spreading factors	4 to 256
Spreading codes	UL: Orthogonal variable spreading codes, long scrambling codes, optional short scrambling codes DL: Orthogonal spreading codes, long scrambling codes
Modulation	UL: Dual channel QPSK with complex scrambling DL: QPSK
Pulse shaping	Root raised cosine, roll-off = 0.22
Intra-frequency handover	Mobile controlled soft handover
Inter-frequency handovers	Hard handover
Inter-frequency measurements	Dual receiver / slotted mode
Detection	UL/DL: Coherent detection (reference symbol based)
Power control	UL: Open loop and fast closed loop DL: Fast closed loop

Diversity	Multipath diversity with Rake, antenna diversity in the uplink, macro diversity

WCDMA base station system is asynchronous with no dependence on external systems like GPS to obtain synchronization. Multiple bit rates are achieved through variable spreading factors, multicode or a combination of them in both uplink and downlink. Bit rates from a few kbps up to 2 Mbps can be provided with good bit rate granularity with the basic chip rate of 4.096 Mcps. The chip rate can be generated from a common clock with GSM in GSM-UMTS dual mode terminals. The carrier spacing has a raster of 200 kHz and the carrier spacing can vary from 4.2 to 5.4 MHz. The different carrier spacings can be used to obtain suitable adjacent channel protections depending on the interference scenario. In Figure 2 is shown an example operator bandwidth of 15 MHz with three cell layers. Larger carrier spacing can be applied between operators' bands than within one operator's band in order to avoid inter-operator interference.

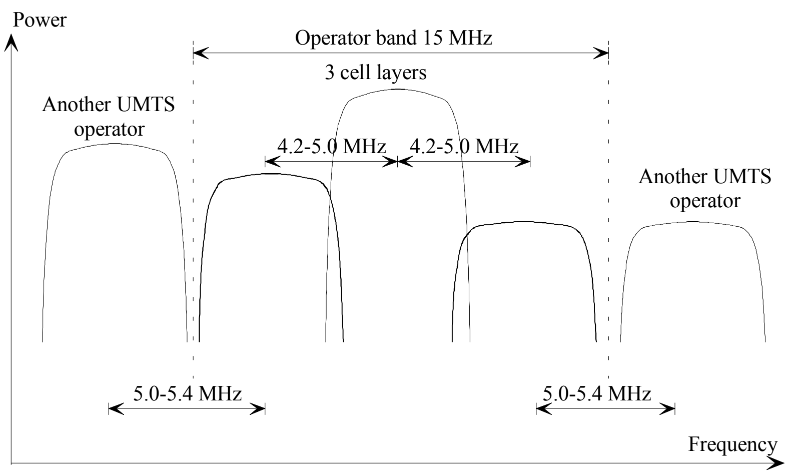

Figure 2. Frequency utilization with WCDMA.

Inter-frequency measurements and handovers are supported by WCDMA to efficiently utilize several cell layers and carriers. Those measurements and handovers are presented in Section IX.

Only frequency division duplexing (FDD) is considered in this paper. According to ETSI decision time division duplexing (TDD) UMTS will be based on a TD-CDMA (Time Division CDMA) proposal where a TDMA component has been included in addition to CDMA.

IV. LOGICAL CHANNEL STRUCTURE

WCDMA basically follows the ITU recommendation ITU M-1035 in the definition of logical channels. The following logical channels are defined for WCDMA.

The three different common control channels are available:

- BCCH (Broadcast control channel) carrying system and cell specific information,
- PCH (Paging channel) for messages to the mobiles in the paging area,
- FACH (Forward access channel) for massages from the base station to the mobile in one cell.

In addition there exists two other channel types:

- DCCH (Dedicated control channel) covers the two dedicated control channel stand-alone dedicated channel (SDCCH) and associated control channel (ACCH),
- DTCH (Dedicated traffic channel) for point-to-point data transmission in the uplink and downlink.

V. DEDICATED PHYSICAL DATA CHANNEL (DPDCH) AND DEDICATED PHYSICAL CONTROL CHANNEL (DPCCH)

Dedicated physical data channel (DPDCH) is used to transmit data generated at layer 2 and above. Figure 3 shows the principle of the frame structure for the uplink DPDCH. Each DPDCH frame on a single code carries $160*2^k$ bits ($16*2^k$ kbps), where k=0,1...6, corresponding to a spreading factor of $256/2^k$ with the 4.096 Mcps chip rate. Multiple parallel variable rate services (=dedicated logical traffic and control channels) can be time multiplexed within each DPDCH frame. The overall DPDCH bit rate is variable on a frame-by-frame basis.

In most cases, only one DPDCH is allocated per connection, and services are jointly interleaved sharing the same DPDCH. However, multiple DPDCHs can also be allocated e.g. to avoid a too low spreading factor at high data rates.

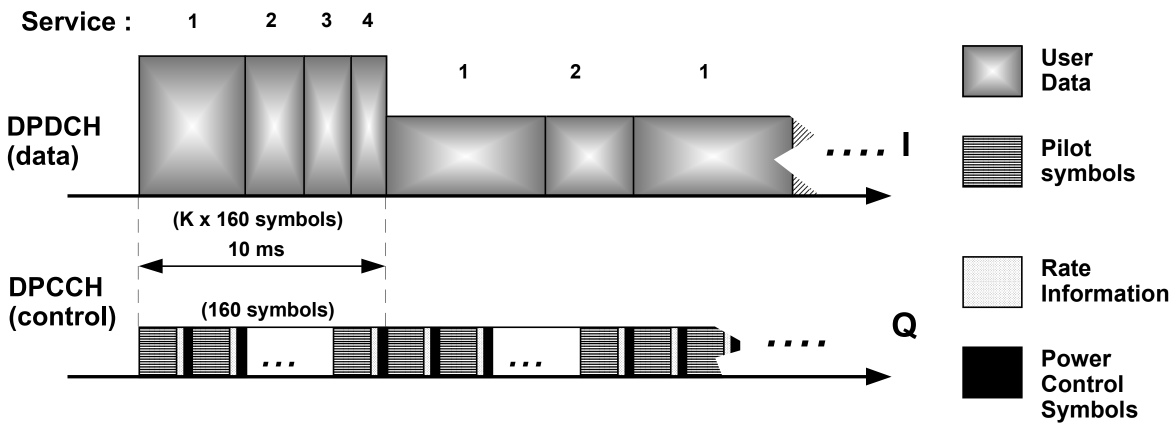

Figure 3. WCDMA uplink multirate transmission.

Dedicated physical control channel (DPCCH) is needed to transmit pilot symbols for coherent reception, power control signalling bits and rate information for rate detection. Two basic solutions that were considered in WCDMA for multiplexing physical control and data channels are time multiplexing and IQ/code multiplexing. A combined IQ and code multiplexing solution (Dual channel QPSK) is used in WCDMA uplink to avoid EMC (electromagnetic compatibility) problems with discontinuous transmission. In downlink time multiplexed physical control channel is used. The uplink solution is adopted from FRAMES/FMA2 work and the time multiplexed downlink solution is based on Japanese contributions.

First, the uplink solution of WCDMA is presented. The major drawback of time multiplexing control channel is the EMC problems that arise when discontinuous transmission (DTX) of user data is used. One example of service with DTX is speech. During silent periods no information bits needs to be transmitted which results in pulsed transmission as control data must be transmitted in any case. This is illustrated in Figure 4. As the rate of transmission of pilot and power control symbols is in the order of 1-2 kHz, they cause severe EMC problems both to external equipment and internally within the terminal. This EMC problem is more difficult in uplink direction since a mobile station can be close to other electrical equipment, like hearing aids.

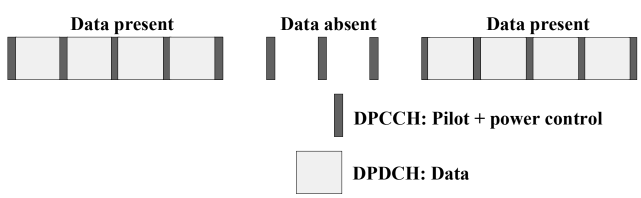

Figure 4. Illustration of pulsed transmission with time multiplexed control channel.

IQ/code multiplexed control channel is shown in Figure 5. Now as pilot and power control are on a separate channel no pulse like transmission takes place. Interference to other users and cellular capacity remains the same as in time multiplexed solution. In addition, link level performance is the same in both schemes if the energy allocated to pilot and power control is the same.

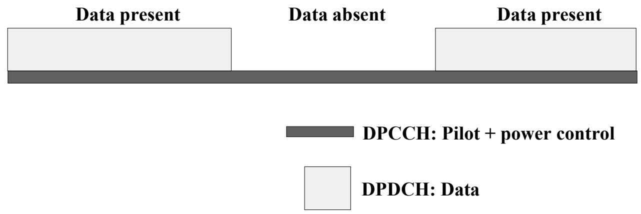

Figure 5. Illustration of parallel transmission of DPDCH (dedicated physical data channel) and DPCCH (dedicated physical control channel) when data is present/absent (DTX).

The signal constellation of IQ/code multiplexing before complex scrambling is shown in Figure 6. The same constellation is obtained after descrambling in the receiver when the decisions are made.

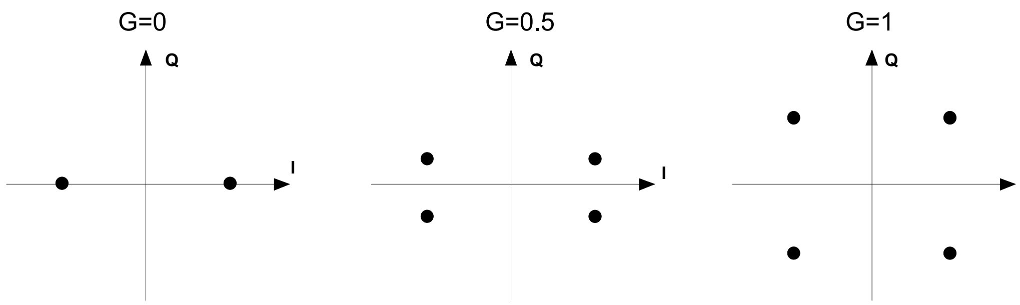

Figure 6. Constellation of IQ/code multiplexing before complex scrambling. G is power difference between DPCCH and DPDCH.

IQ/code multiplexing leads to parallel transmission of two channels and therefore attention must be paid to modulated signal constellation and related peak-to-average power ratio (crest factor). In Figure 6 peak-to-average ratio is changing when *G* is changed. By using the spreading modulation solution shown in Figure 7 the transmitter power amplifier efficiency remains the same as for QPSK transmission in general.

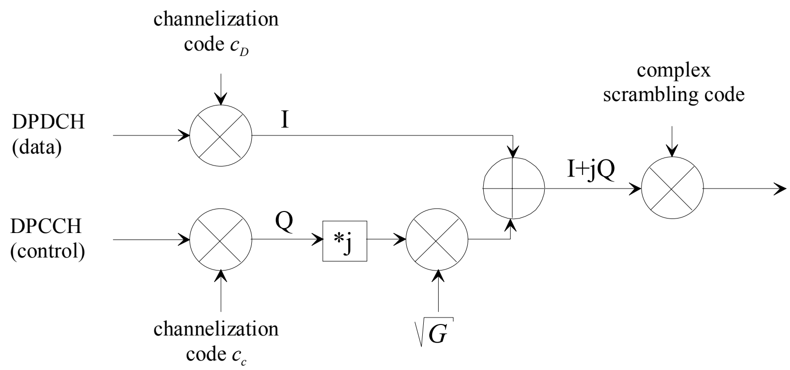

Figure 7. IQ/code multiplexing with complex scrambling.

Moreover, the efficiency remains constant irrespective of the power difference *G* between DPDCH and DPCCH. This can be explained with Figure 8 showing the signal constellation for IQ/code multiplexed control channel with complex spreading. In the middle constellation with *G*=0.5 the possible constellation points are only black ones or only gray ones during one symbol period. The constellation of those black points or of those gray points is the same as rotated QPSK. Thus the signal envelope variations with complex spreading are very similar to the QPSK transmission for all values of *G*. The IQ/code multiplexing solution with complex scrambling results in power amplifier output backoff requirements which remain constant as a function of power difference. Furthermore, the achieved output backoff is the same as for one QPSK signal.

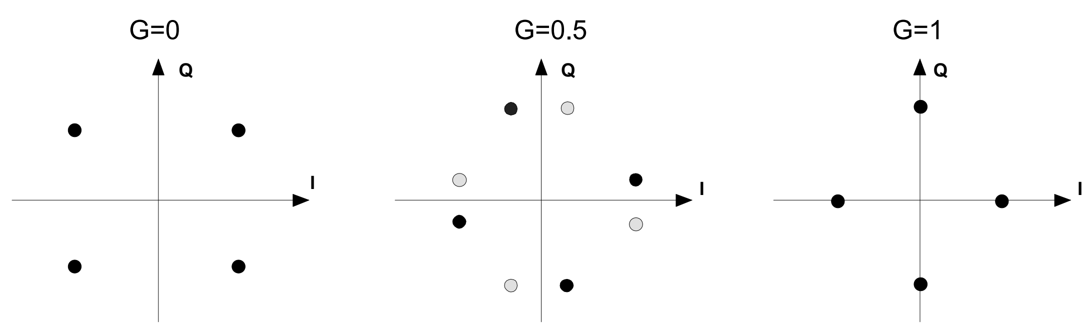

Figure 8. Signal constellation for IQ/code multiplexed control channel with complex scrambling. G is power difference between DPCCH and DPDCH.

Instead of applying combined IQ and code multiplexing of control data it is possible to use pure code multiplexing. With code multiplexing a multicode transmission occurs with parallel control and data channels. This approach increases envelope variations of the transmitted signal and sets higher requirements for power amplifier linearity. Especially for low bit rates, like for speech, control channel can have an amplitude of more than 50 % of the data channel which causes more envelope variations than the combined IQ/code multiplexing solution.

Dual channel QPSK has been considered for WCDMA uplink in [14]. It is shown that pilot symbol aided dual channel QPSK has lower envelope variations than the corresponding solution with continuous pilot channel. Continuous pilot channel increases peak-to-average ratio of the transmitted signal.

In WCDMA downlink DPDCH and DPCCH are time multiplexed. The EMC problem caused by discontinuous transmission is not considered difficult in downlink since first, there are signals to several users transmitted parallel at the same time and second, base stations are not so close to other electrical equipment, like hearing aids.

Connection dedicated pilot symbols are used in WCDMA downlink to support adaptive antennas and to support downlink fast power control. Another possibility to support coherent reception at the mobile station would be the use of a common downlink pilot channel. Common pilot would have an advantage of lower pilot overhead for low bit rates but downlink fast power control and adaptive antennas are difficult to support with common pilot. For downlink fast power control the mobile station needs to estimate the received SIR. If the connection bit rate is variable and there is no connection dedicated pilot, SIR estimation is difficult. Common downlink pilot cannot be used for SIR estimation with fast power control because the transmission power of the dedicated channel changes compared to common pilot. With downlink adaptive antennas the channel estimation for coherent reception at the mobile station should be done from the signal that is transmitted through the same adaptive antenna pattern as the user data. Common pilot cannot be used for channel estimation since it is transmitted through a different antenna and it may experience different multipath propagation than user data.

VI. SERVICE MULTIPLEXING, CODING AND RATE MATCHING

Multiple services of the same connection are multiplexed on one dedicated physical data channel (DPDCH). Multiplexing may take place either before or after the inner or outer coding as illustrated in Figure 9.

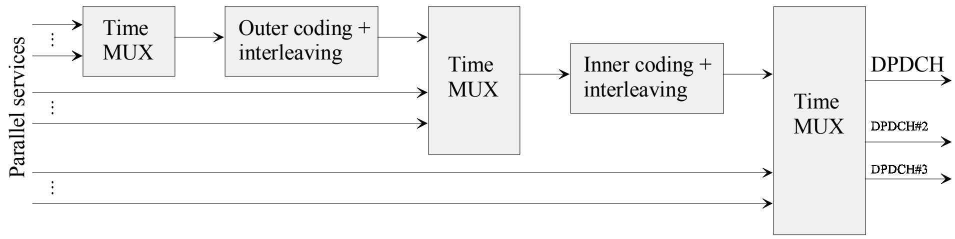

Figure 9. Service multiplexing in WCDMA.

After service multiplexing and channel coding, the multi-service data stream is mapped to one DPDCH. If the total rate exceeds the upper limit for single code transmission, several DPDCHs can be allocated.

A second alternative for service multiplexing would be to treat parallel services completely separate with separate channel coding/interleaving and mapping to separate DPDCHs in a multicode fashion. With this alternative scheme, the power and consequently the quality of each service can be separately and independently controlled. The disadvantage is the need for multicode transmission which will have an impact on the mobile station complexity. Multicode transmission sets higher requirements for the power amplifier linearity in transmission and more correlators are needed in reception.

For BER=10^{-3} services, convolutional coding of rate 1/3 is used. For high bit rates a code rate of 1/2 can be applied. For higher quality service classes outer Reed Solomon coding is used to reach the 10^{-6} BER level. Retransmissions can be utilized to guarantee service quality for non-real time packet data services.

After channel coding and service multiplexing, the total bit rate can be almost arbitrary. The rate matching adjusts this rate to the limited set of possible bit rates of a DPDCH. Repetition or puncturing is used to match the coded bit stream to the channel gross rate. The rate matching for the uplink and for the downlink are introduced below.

For the uplink, rate matching to the closest uplink DPDCH bit rate is always based on unequal repetition (a subset of the bits repeated) or code puncturing. In general, code puncturing is chosen for bit rates less than ≈20% above the closest lower DPDCH bit rate. For all other cases, unequal repetition is done to the closest higher DPDCH bit rate. The repetition/puncturing patterns follow a regular predefined rule, i.e., only the amount of repetition/puncturing needs to be agreed on. The correct repetition/puncturing pattern can then be directly derived at both the transmitter and receiver side.

For the downlink, rate matching to the closest DPDCH bit rate, using either unequal repetition or code puncturing, is only done for the highest rate (after channel coding and service multiplexing) of a variable rate connection and for fixed-rate connections. For lower rates of a variable rate connection, the same repetition/puncturing pattern as for the highest rate is used and the remaining rate matching is based on discontinuous transmission where only a part of each slot is used for transmission. This approach is used in order to simplify the implementation of blind rate detection in the mobile station.

VII. COMMON PHYSICAL CHANNELS

Common Control Physical Channel (CCPCH)

WCDMA defines two downlink physical channels to carry the downlink common control logical channels (BCCH, PCH, and FACH), the primary and secondary common control physical channels (CCPCH).

The primary physical channel for common control carries the BCCH. It is of fixed rate and is mapped to DPDCH in the same way as the dedicated traffic channels. The primary CCPCH uses the same channelization code in all cells. A mobile terminal can thus always find the BCCH, once the base station unique scrambling code has been detected during the initial cell search.

The secondary physical channel for common control carries the PCH and the FACH in time-multiplex within the super-frame structure. The rate of the secondary CCPCH may vary cell to cell and is set to provide the required capacity for the PCH and the FACH in each specific environment. Channelization code of the secondary CCPCH is transmitted on the primary CCPCH.

Synchronization channel (SCH)

The synchronization channel (SCH) consists of two sub channels, the primary and the secondary SCH. Figure 10 illustrates the structure of the SCH.

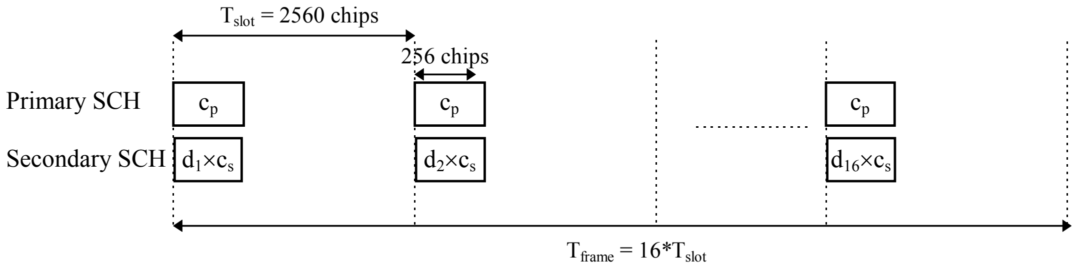

Figure 10 Structure of the synchronisation channel (SCH).

c_p = primary synchronization code

c_s = secondary synchronization code

$d_{1,\ldots 16}$ = modulation of secondary SCH

The primary SCH consists of an unmodulated code of length 256 chips, the primary synchronisation code, transmitted once in every slot (each frame of length 10ms is devided into 16 slots). The primary synchronisation code is the same for every base station in the system and is transmitted time-aligned with the slot boundary as illustrated in Figure 10.

The secondary SCH consists of one modulated code of length 256 chips, the secondary synchronisation code, transmitted in parallel with the primary SCH. The secondary synchronisation code is chosen from a set of 16 different codes $\{c_1,c_2,\ldots,c_{16}\}$ depending on to which of the 16 different code groups the base station downlink scrambling code c_{scramb} belongs.

The secondary SCH is modulated with a binary sequence d_1, d_2, ..., d_{16} of length 16 bits which is repeated for each frame. The modulation sequence, which is the same for all base stations, has good cyclic autocorrelation properties.

SCH is multiplexed with the DPDCH/DPCCH and CCPCH after long code scrambling is applied on DPDCH/DPCCH and CCPCH. No scrambling is used on SCH. Consequently, the SCH is non-orthogonal to the other downlink physical channels.

Random access

The need for a fast and efficient random access scheme is more important for the UMTS system than in the 2nd generation mobile communication systems. The reason is the expected increase in packet transmission, for which fast and efficient random access is a key requirement.

The structure of the random access burst is shown in Figure 11. The random access burst consists of two parts, a preamble part of length 16*256 chips (1 ms) and a data part of variable length.

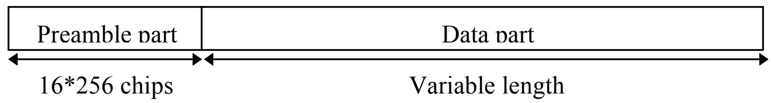

Figure 11. Structure of WCDMA random access burst.

The WCDMA random access scheme is based on a slotted ALOHA technique with the random access burst structure shown in Figure 11. Before the transmission of a random access request, the mobile terminal should carry out the following tasks:

- Achieve chip, slot, and frame synchronisation to the target base station from the synchronization channel (SCH) and obtain information about downlink scrambling code also from SCH.
- Retrieve information from BCCH about the random access code(s) used in the target cell/sector.
- Estimate the downlink pathloss, which is used together with a signal strength target to calculate the required transmit power of the random access request.

It is possible to transmit a short packet together with random access burst without a need to set up a scheduled packet channel. No separate access channel is used for packet traffic related random access, but all traffic shares the same random access channel. More than one random access channel can be used if the random access capacity requires such an arrangement. The performance of the selected solution is presented in [15].

VIII. ASYNCHRONOUS BASE STATIONS

Base stations in WCDMA need not be synchronized and therefore no external source of synchronization, like GPS, is needed for the base stations. This aspect is considered important especially for fast deployment of small indoor base stations. Asynchronous base stations must be taken into account when designing soft handover algorithms and when implementing position location services. These two aspects are considered in this section.

Before entering soft handover mobile station measures observed timing differences of the downlink synchronisation channels (SCH) from the two base stations. The structure of the SCH was presented in Section VII. Mobile station reports the timing differences back to the serving base station. The timing of a new downlink soft handover connection is adjusted at the resolution of one symbol, i.e., the dedicated downlink signals from the two base stations are synchronized with an accuracy of one symbol. That enables the mobile Rake receiver to collect the macro diversity energy from the two base stations. Timing adjustments of dedicated downlink channels can be made with a resolution of one symbol without losing orthogonality of downlink codes with the aid of the orthogonal code tree structure.

Position location capability of WCDMA network can be utilized for a large number of applications in addition to locating emergency calls. When starting soft handover the mobile station reports the measured timing differences to the base station. Since also the propagation delay between the mobile and the base station is known by measurements at the base station, base station system can determine the actual timing differences between base stations using information from soft handovers. This information is one example how the position location services can be implemented in WCDMA without need for base station synchronization. It is enough to know the timing differences between base stations, synchronization is not required.

IX. INTER-FREQUENCY HANDOVERS

Inter-frequency handovers are needed for utilization of hierarchical cell structures; macro, micro and indoor cells. Several carriers and inter-frequency handovers may also be used for taking care of high capacity needs in hot spots. Inter-frequency handovers will be needed also for handovers to 2nd generation systems, like GSM or IS-95. In order to do inter-frequency handovers an efficient method is needed for making measurements on other frequencies while still having the connection running on the current frequency. Two methods are considered for inter-frequency measurements in WCDMA, namely, dual receiver and slotted mode approaches.

Dual receiver approach is considered suitable especially if mobile terminal employs antenna diversity. During the inter-frequency measurements one receiver branch is switched to another frequency for measurements while the other keep receiving from the current frequency. The loss of diversity gain during measurements need to be compensated with higher downlink transmission power. The advantage of dual receiver approach is that there is no break in connection in the current frequency but the fast closed loop power control loop is running all the time.

Slotted mode approach is considered attractive for the mobile station without antenna diversity. Slotted mode solutions and their performance have been presented in [17].

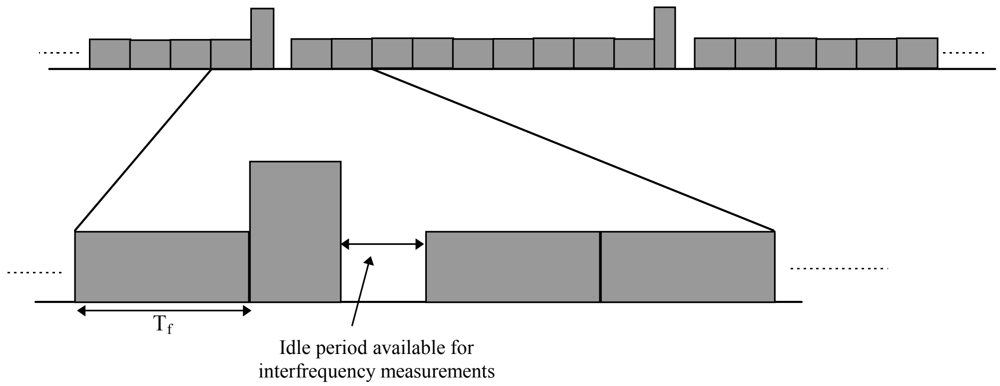

Figure 12. Slotted mode for inter-frequency measurements in WCDMA mobile station

X. PACKET ACCESS

Due to the varying characteristics of packet data traffic in terms of packet size and packet intensity, a dual-mode packet-transmission scheme is used for WCDMA. With this scheme, packet transmission can either take place on a common fixed rate channel or on a dedicated channel.

When using uplink common channel, a packet is appended directly to a random access burst. Common channel packet transmission is typically used for short infrequent packets, where the link maintenance needed for a dedicated channel would lead to unacceptable overhead. Also the delay associated with a transfer to a dedicated channel is avoided. Note that, for common channel packet transmission, only open loop power control is active. Common channel packet transmission should therefore be limited to short packets that use only a limited amount of capacity. Figure 13 illustrates packet transmission on a common channel.

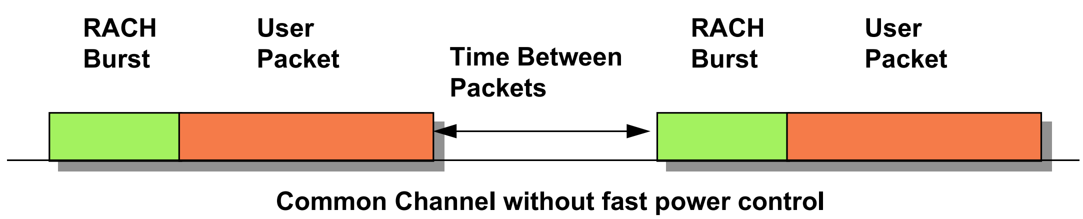

Figure 13. Packet transmission on common channel.

When using a dedicated channel, an initial random access request is used to set up a dedicated channel for the packet transmission. On this dedicated channel, closed loop power control is in operation. The dedicated channel can either be set up for the transmission of a single packet or for the transmission of a sequence of packets (multi-packet transmission).

XI. SUPPORT FOR ADAPTIVE ANTENNAS AND MULTIUSER DETECTION

The use of adaptive antennas is also a potential technology for achieving the high capacity and range gains needed for the extensive use of high bit rate services in the third generation cellular systems, while having wide coverage. Current commercial DS-CDMA standards do not support downlink adaptive antennas because of the use of a common pilot code for downlink coherent detection. On the other hand, with the use of connection dedicated pilot bits, the WCDMA concept allows the use of adaptive antennas on both uplink and downlink.

The connection dedicated pilot symbols are needed when the user data is transmitted via varying antenna radiation pattern and the common channels with pilot symbols are transmitted with a fixed antenna radiation pattern, typically either using a sectorised or an omnidirectional antenna. As the antenna patterns are not the same then the channel estimate derived from a common pilot cannot be used anymore and thus pilot symbols are needed to facilitate coherent detection. The achievable capacity gains with adaptive antennas have been studied in [17].

Interference cancellation type multiuser detectors require coherent reception. Due to time-multiplexed pilot bits, channel can be estimated reliably and interference cancellation can be used. It should be noted that unlike linear interference suppression schemes, the interference cancellation techniques do not require short scrambling codes when applied to the sampled wideband signal. An extensive list of references on multiuser detection schemes is given, e.g., in [18].

XII. CONCLUSIONS

An overview of the ETSI WCDMA was presented. WCDMA is based on contributions from a large number of companies from Europe, Japan and US. This air interface solution is able to offer speech and multimedia services with different transmission rate and service quality requirements. Physical layer offers flexible multirate transmission capabilities and service multiplexing scheme. Efficient support for packet access has been implemented with dual mode packet transmission scheme supporting various multimedia services. WCDMA sets low requirements on mobile terminal complexity thus making it possible to produce attractive cost efficient terminals also for high bit rate packet applications with an additional 2nd generation system functionality. High bit rate transmission without multicode transmission and low requirements on the power amplifier linearity make the mobile terminal implementation cost efficient. Asynchronous operation of base stations makes the deployment of the indoor base stations fast because no external clocking sources are needed. Soft handover algorithms are designed for asynchronous base station operation. In the development of WCDMA attention has also been paid to flexible and efficient frequency utilization with variable carrier spacing. Inter-frequency measurements and handovers make it possible for operators to utilize hierarchical cell structures.

ACKNOWLEDGEMENTS

The authors would like to acknowledge colleagues within ACTS FRAMES project and also members of ETSI WCDMA concept group.

REFERENCES

[1] T. Ojanperä, K. Rikkinen, H. Häkkinen, K. Pehkonen, A. Hottinen, J. Lilleberg. "Design of a 3rd Generation Multirate CDMA System with Multiuser Detection, MUD-CDMA", Proc. of the IEEE ISSSTA'96, Vol. 1, pp. 334-338, Mainz, Germany, September 1996.

[2] T. Ojanperä, J. Sköld, J. Castro, L. Girarg, A. Klein. "FRAMES- Hybrid Multiple Access Technology", Proc. of the IEEE ISSSTA'96, Vol. 1, pp. 320-324, Mainz, Germany, September 1996.

[3] T. Ojanperä et.al. "Comparison of Multiple Access Schemes for UMTS" Proc. 47th IEEE Veh. Techn. Conf, pp. 490-494, VTC'97, Phoenix, AZ, USA, May 1997.

[4] A. Klein., R. Pirhonen, J. Sköld, R. Suoranta. "FRAMES Multiple Access Mode 1 - Wideband TDMA with and without Spreading", Proc. IEEE Int. Conf. on Personal Indoor and Mobile Radio Commun., pp. 37-41, PIMRC'97, Helsinki, Finland, September 1997.

[5] F. Ovesjö, E. Dahlman, T. Ojanperä, A. Toskala, A.Klein. "FRAMES Multiple Access Mode 2 - Wideband CDMA", Proc. IEEE Int. Conf. on Personal Indoor and Mobile Radio Commun., pp. 42-46, PIMRC'97, Helsinki, Finland, September 1997.

[6] E. Dahlman, A. Toskala, M. Latva-aho. "FRAMES FMA2, A Wideband-CDMA Air-interface for UMTS", Proc. 2nd CDMA International Conference (CIC), pp. 588-592, October 21-24, Seoul, Korea.

[7] "Agreement reached on radio interface for third generation mobile system, UMTS", press release by ETSI, January 29,

1997.

[8] K. Pajukoski, J. Savusalo. "Wideband CDMA Test System", Proc. IEEE Int. Conf. on Personal Indoor and Mobile Radio Commun., pp. 669-672, PIMRC'97, Helsinki, Finland, September 1997.

[9] W. Oh, A. Choi, T. Lee, B. Ahn, Y. Park. "Implementation of a Mobile Multimedia Testbed based on W-CDMA", Telecommunications Review, SK Telecom, Vol.7, No.2, 1997, pp. 197-218.

[10] S. Bang, H.-R. Park, Y. Han. "Performance Analysis of a Wideband CDMA System for FPLMTS", Proc. 47th IEEE Veh. Techn. Conf, pp. 830-834, VTC'97, Phoenix, AZ, USA, May 1997.

[11] N. Nakajima, F. Adachi. "Wideband DS-CDMA for 3rd Generation Mobile Communication System", Telecommunications Review, SK Telecom, Vol.7, No.2, 1997, pp. 178-187.

[12] S. Onoe, K. Ohno, K. Yamagata, T. Nakamura. "Wideband CDMA Radio Control Techniques for Third Generation Mobile Communication Systems", Proc. 47th IEEE Veh. Techn. Conf, pp. 835-839, VTC'97, Phoenix, AZ, USA, May 1997.

[13] M. Sawahashi, F. Adachi. "Wideband CDMA Mobile Radio Access for IMT-2000", Proc. 2nd CDMA International Conference (CIC), pp. 571-576, October 21-24, Seoul, Korea.

[14] R. Seong, K. Sugbong, G. Jeong, S. Jeong. "Pilot Symbol Aided Dual-Channel QPSK for CDMA Reverse Link", Proc. 2nd CDMA International Conference (CIC), pp. 174-178, October 21-24, Seoul, Korea.

[15] A. Toskala, E. Dahlman, M. Gustafsson, M. Latva-aho, M.J. Rinne. "Frames Multiple Access Mode 2 Physical Transport Control Functions", Proc. ACTS Summit 1997, Aalborg, Denmark, October 1997.

[16] M. Gustafsson, K. Jamal, E. Dahlman. "Compressed Mode Techniques for Inter-frequency Measurements in a Wideband DS-CDMA System", Proc. IEEE Int. Conf. on Personal Indoor and Mobile Radio Commun., pp. 231-235, PIMRC'97, Helsinki, Finland, September 1997.

[17] A. Naguip, A. Paulraj, T. Kailath, "Capacity Improvement with Base Station Antenna Arrays in Cellular CDMA", IEEE Trans. on Vehicular Tech., Vol 43, No.3, August 1994, pp. 691-698.

[18] M. Juntti, S. Glisic, "Advanced CDMA for Wireless Communications", pp. 447-490 in book by S. Glisic, P. Leppänen, "Wireless Communications", Kluwer Academic Publisher, 1997.

Biographies

HARRI HOLMA joined Nokia Research Center 1994 and received his M.Sc. with honours from Helsinki University of Technology 1995. Since 1994 he has been working with 3rd generation WCDMA air interface with special interest on radio network performance and advanced receiver structures. In January 1998 he joined New Radio Systems at Nokia Telecommunications and is currently working as Senior Research Engineer with WCDMA radio network development.

ANTTI TOSKALA received his M.Sc. degree in 1995 from Tampere University of Technology, Finland. He joined the Nokia Research Center in 1994, where he was involved with WCDMA system studies. In September 1995, he joined the ACTS FRAMES project being then in the later phase of the project as team leader for the work package which resulted for the FMA2 W-CDMA concept. During 1997, he was working at the Radio Communications laboratory at Nokia Research Center as a Senior Research Engineer and CDMA Specialist participating in the ETSI SMG2 UMTS standardization work. In SMG2, he worked as a Secretary for the ETSI SMG2 WCDMA concept group. Currently he is with New Radio Systems at Nokia Telecommunications working as Standardisation Manager with European wideband CDMA standardisation process.

MATTI LATVA-AHO received his M.Sc. (E.E.) and Lic.Tech. degrees from the University of Oulu in 1992 and 1996, respectively. From 1992 to 1993, he was a Research Engineer at Nokia Mobile Phones, Oulu, Finland. Since October 1993 he has been a Research Scientist in the Telecommunication Laboratory at the University of Oulu, where he is currently pursuing the Ph.D. in electrical engineering. In June 1997 he joined the Centre for Wireless Communications of the University of Oulu. His main interests are in CDMA and multiuser communications.