7.2 A CDMA Air-interface for Mobile Access

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7.2.1 Project Rationale

A three year project funded through the U.K. DTI/EPSRC LINK Personal Communications Programme (PC019) was established in 1992 in order to carry out a rigorous evaluation of CDMA for third generation mobile radio systems, culminating with a field trial demonstration of the selected DS-CDMA architecture. Members of the consortium included AT&T NS UK Ltd, Hewlett Packard Laboratories (Bristol) and the Universities of Bradford and Bristol, with approximately 25 man years of funded effort spread throughout the partners. The key objectives of the project were as follows:

- Study of UMTS requirements - teleservices and bearers.
- Comparative study of frequency hopping (FH) and direct sequence (DS) CDMA for UMTS service provision.
- Design and development of a DS-CDMA field trial system.
- Demonstration of a working DS-CDMA radio link, with a subset of the proposed UMTS services.

7.2.2 Service Requirements for UMTS

The Universal Mobile Telecommunications System (UMTS) was taken as the target European Personal Communication System for this project. The diverse range of teleservices and environments envisaged for UMTS were studied by the consortium, and number of key teleservice attributes were identified. In particular, bit throughput, error rate, connection duration, delay, and occupancy was evaluated [14, 15] for a wide range of teleservices encompassing both low and high bit rate voice and audio, as well as, data transfer, graphics and video services, in order to ascertain the radio bearer requirements. To satisfy these requirements, the bearer classifications within the IBC Common Functional Specification D730 was adopted by the consortium. Here there are essentially two types of bearer service - circuit mode and packet mode. The former provides a predetermined amount of transmission capacity on an exclusive basis for the duration of the call. Packet mode provides a variable bit throughput by the use of packets and connections by routing. This activity thus provided the baseline specification for the project, as well as highlighting the need for a completely new air interface specification in order to fully support the UMTS Vision [16].

7.2.3 Assessment of DS and FH CDMA for UMTS

In order to assess the most appropriate spreading technique for a CDMA based UMTS implementation, the capacity, hardware complexity, network management issues and overall quality of service (QoS) aspects of both DS and FH CDMA were appraised. The architecture of the LINK CDMA test bed was then based on the outcome of these studies.

7.2.3.1 Traffic Capacity

The results reported in literature indicate that both DS and FH can potentially support high traffic loads for voice only communications, although the figures given differ widely. The results of both DS and FH capacity simulation carried out as part of this study [17,18] indicated that the traffic capacity that could be supported by slow FH was equivalent to, or better than, a DS system. This result is summarised in graphical form in figure 3.1 where it can be seen that the FH scheme could offer 24 users/MHz/cell compared to 21 users/MHz/cell with DS. However, given the error bounds of this type of approach, the result does not indicate a significant advantage either way.

The sensitivity of these capacity figures to variations in system parameters was the focus of much of the simulation work. The results indicated that DS is extremely sensitive to, for example, variations in the propagation environment and power control errors. This is clearly a difficult issue for any future DS-CDMA system and should be given careful consideration if a DS solution is selected for UMTS.

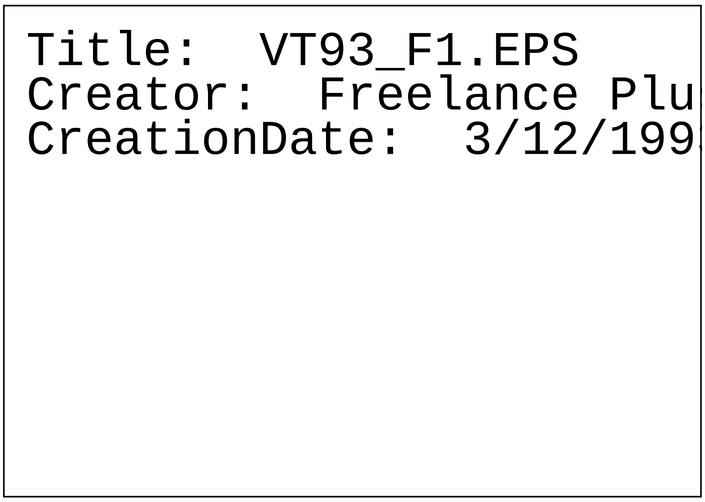

Figure 7.2.1: Performance Comparison of DS and FH CDMA

• Total number of base-stations: 37

• Path loss exponent: 4

• Log-normal shadowing std. dev.:8dB

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• Power control: Shadowing & path loss.

• Power control error (std. dev.): 0 dB

• Handover margin: 0 dB

• Voice activity factor: 0.5

• Cell sectorisation: None

• Antenna diversity: Dual

• Spreading/hopping bandwidth: 1 MHz

7.2.3.2 Hardware

The choice of CDMA scheme, specifically direct sequence, or fast or slow frequency hopping, will influence heavily the design and implementation of both mobile station and base station transceiver hardware. The power consumption, size and cost constraints of present state-of-the-art integrated circuit (IC) technology were taken as the starting points from which to base predictions for the potential UMTS hardware [17]. These can be briefly summarised as follows:

DS-CDMA

- DS chip sets are readily available providing a very flexible solution.
- The need for a Rake receiver increases complexity significantly.
- Power consumption and cost increase significantly with bandwidth.

FH-CDMA

- Limitations of RF synthesiser technology restrict FH to less than 1khop/sec, i.e. slow frequency hopping.
- A digital solution is possible (exploiting commonality with DS) enabling the hop rate to increase.

Given that the system performances of DS and FH are found to be basically equivalent, or at least complementary for certain scenarios, then it was expected ultimately that the hardware considerations of cost, size and power consumption will be evenly matched for both DS and FH.

7.2.3.3 Network Infrastructure Management

CDMA potentially offers complete frequency reuse within each sector or cell, thereby considerably easing the task of network planners, but the network topology may impose other restrictions. These problems were considered in the context of a mixed cell environment with both handover and signalling overheads. The following conclusions were drawn from this activity:

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- The need to support a comprehensive set of UMTS teleservices will require a large bandwidth to be allocated to each operator within a given geographic area.
- A mixed cell architecture will require CDMA to operate with different frequency bands unless alternative near-far resistant techniques are considered.
- Multiple operators and the need for a contiguous bandwidth could limit the maximum allocation for DS-CDMA to as little as 5MHz.
- Initial studies show that the signalling overhead for the seamless, or soft handover, offered with Qualcomm's DS-CDMA system is no greater than with the hard handover procedures of GSM. However, the network traffic would be increased in proportion to the number of base-stations involved.
- The tight power control requirements for DS-CDMA increase the signalling overhead.

7.2.3.4 Quality of Service

The definition of ‘Quality of Service’ (QoS) adopted followed established CCITT practices, although this was extended to include such parameters as spectral efficiency. The project output [19] was a set of QoS parameters, together with target values. These ranged from specifying a maximum BER of 10-3 for speech to a handover success rate of greater than 99.95%. Of particular interest was how these parameters could be traded off with each other, e.g. spectral efficiency or system capacity versus SNR. The extent and ease of this process was itself considered an important quality aspect of system implementation.

7.2.3.5 Selection of Spreading Technique for LINK CDMA Demonstrator

Although many of the issues associated with the selection of either a DS or FH air interface for UMTS remain unanswered, the results summarised above indicated that there would appear to be nothing to choose between the two techniques in terms of available traffic capacity and hardware implementation. Thus, on balance it was decided that DS would offer the better, lower risk solution at this point in time. This argument was based upon the amount of background work already carried out with DS, i.e. Qualcomm and CoDiT, and the level of support for this technique from hardware manufacturers, i.e. chip-sets aimed specifically at DS applications. This is not to say that there is no future with FH CDMA [20].

7.2.4 Test Bed Specification & Design Issues

Key parameters defining the channel structure and air interface specifications of the 8.2Mchip/s of the LINK CDMA test bed are given in figure 7.2.2 and table 7.2.1 respectively.

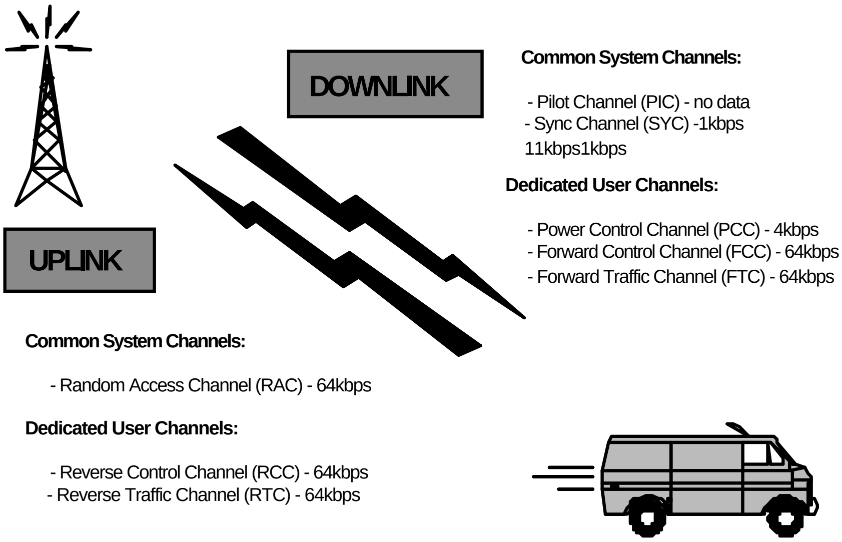

Figure 7.2.2 LINK CDMA Channel Structure

Original plans included the production of two base station (BS) and two mobile station (MS) units connected together through the fixed network via a Mobility Manager (MM). However, in order to obtain meaningful test bed results within the time period and with the resource limitations, the configuration was restricted to a single base station and mobile station as shown in figure 7.2.3. Although much of the software was written and tested to support an ISDN interface, there was insufficient time to complete the system integration, and hence the fixed terminal interface was reduced to an analogue telephone or 64 kbps data interface. Since the aim of this assessment was principally to evaluate the radio link performance, the loss of the ISDN call set-up facility in no way devalues the results obtained.

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		Downlink	Uplink
Channel Structure:		All defined as separate physical channels with a unique PN code assignment.	
	System	**PIC** - Pilot PN sequence with no data. • **SYC** - 1kbps continuous data channel carrying essential system information, e.g. system timing reference.	**RAC** - Random access channel for call set-up. Non-continuous with a burst transmission rate of 64kbps.
	User	**PCC** - Variable rate (≤4kbps) to control MS Tx power during a call. **FCC** - Carries all signalling and control messages to MS including paging. Non-continuous at 64kbps. **FTC** - Supports continuous user traffic with Bearer A or B.	**RCC** - Carries all signalling and control messages to BS. Non-continuous at 64kbps. **RTC** - Supports continuous user traffic with Bearer A or B.
PN Code Assignment:		All codes synchronised to timing reference at MM.	
	System	Augmented m-sequence with each BS assigned a fixed phase offset. • Length = 2^{17} chips (16msec period).	As for user channels below.
	User	Long m-sequence with each user assigned a unique phase offset based on user ID. Each channel is then given a further fixed offset. • Length = 2^{29}-1 chips (65.5 sec period).	
Error Control Coding		_ rate, constraint length 7 convolutional code (industry standard) on all channels except PIC and PCC.	
Block Interleaving		12msec frame for Bearer A (speech) and 36msec frames for Bearer B (data).	
Modulation & Spreading		QPSK with a preferred pair of PN sequences.	BPSK with RAC/RCC in phase quadrature with the RTC.

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Pulse Shaping	33 Tap digital FIR filter (3dB signal BW ♠ 8MHz)	
Chipping Rate	8.192MHz	
RF Carrier Frequency	1823MHz	1727.5MHz

Table 7.2.1: Air interface parameters.

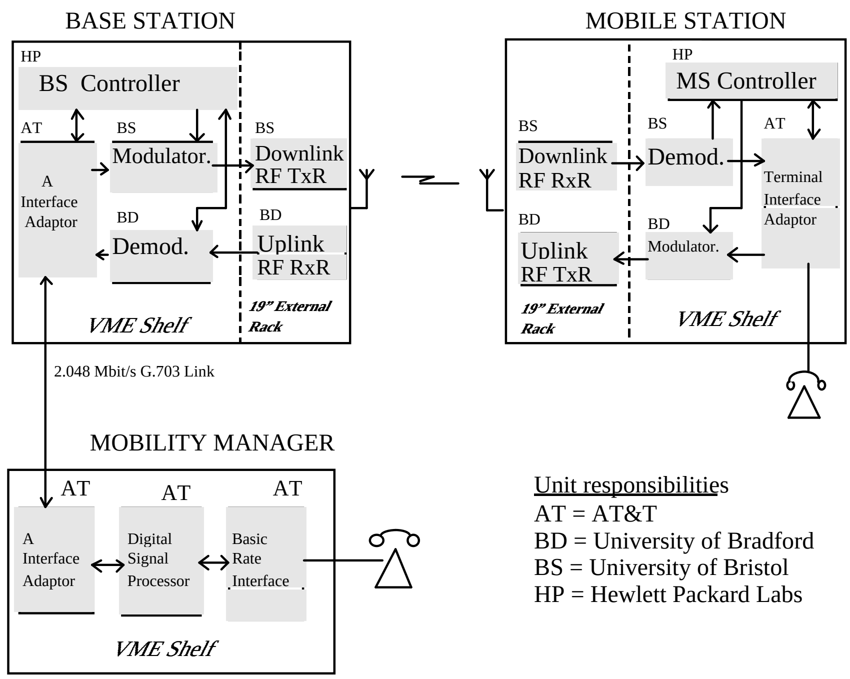

Figure 7.2.3 Partitioning of LINK CDMA Test Bed

7.2.4.1 Downlink Design

Here the BS digital modulators produce the encoded, interleaved, spread and filtered signals which are combined in analogue form at baseband before being upconverted in quadrature directly to RF and transmitted. The received signal at the MS is mixed down to a first IF at 70MHz where AGC is carried out, prior to the final downconversion process to quadrature baseband and subsequent analogue-to-digital conversion. Thereafter follows the process of extracting the user data from the spread signal, the key modules of which are illustrated in figure 4.3.

Crucial to this whole process is the acquisition and tracking of the Pilot signal. This synchronisation task is on a number of levels and can be broken down as follows:

1. Acquire the Pilot PN code from the strongest BS signal (coarse acquisition).
2. Acquire and track carrier and provide necessary AFC for the 70MHz local oscillator.
3. Recover and track clocks, synchronising with the downlink data.
4. Generate estimates of the channel coefficients (amplitude, phase and time) for coherent Rake reception.
5. Demodulate SYC to extract system timing and align long PN code generators as well as establish frame synchronisation.

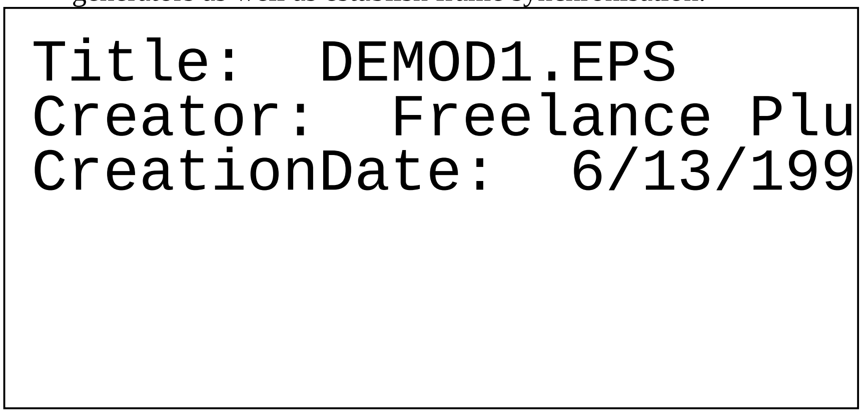

Figure 7.2.4 MS demodulator.

Central to this is the Pilot Matched Filter (PMF) which generates the complex impulse response from the received Pilot signal. This employs an FIR filter structure with the locally generated Pilot PN sequence forming the filter coefficients. The filter is 128 spreading chips long giving an impulse response of 15.6msec which is sufficient to enable all significant multipath activity to be detected and utilised. This is carried out by the Peak Search and Sort process which extracts the strongest multipath components (up to a maximum of four) and passes the channel coefficient data to an embedded DSP which programs the Rake receivers. Each of the Rake receivers comprises up to four paths, or tines, each consisting of a programmable delay block, serial despreader and complex coefficient multiply. The time-aligned outputs are then combined in a maximal ratio sense before the final demodulation process extracts the data. During handover, a second Pilot Matched Filter detects and tracks another BS. The DSP simply treats the outputs as additional multipath which are combined in the Rake receiver in the same manner.

In order to maximise the resolution of the multipath signals, the PMF outputs are averaged over a number of integration cycles. The choice for the number of cycles is a compromise between providing sufficient dynamic range in the filter to detect the signals and being fast enough to follow the rapidly changing phase. To allow further investigation, the integration period can be varied between 1, 0.5 and 0.25msec, providing coefficient update rates of 1, 2 and 4kHz respectively.

7.2.4.2 Uplink Design

The uplink air interface and receiver design are very similar to those for the downlink. The principal differences are that no pilot channel is available and that BPSK rather than QPSK modulation is used. In addition, the uplink requires accurate power control in order to take into account the distance of the MS transmitter from the BS.

The uplink receiver is a coherent rake structure with four tines, as illustrated in figure 4.4. The signal received at the base station is down-converted from 1727.5 MHz to baseband via a 70 MHz IF. It is then converted to digital as a complex baseband signal, sampled at 24.576 MHz. As in the downlink receiver, a parallel estimate of the channel impulse response is formed from the averaged outputs of a filter matched to the incoming PN sequence. Because no pilot sequence is transmitted the filter must obtain its taps from the traffic channel PN sequence. A decision feedback loop is therefore required, to remove the effect of the traffic channel data. The matched filter used is half the length of that used in the downlink, providing a 7.8 microsecond window on the channel impulse response.

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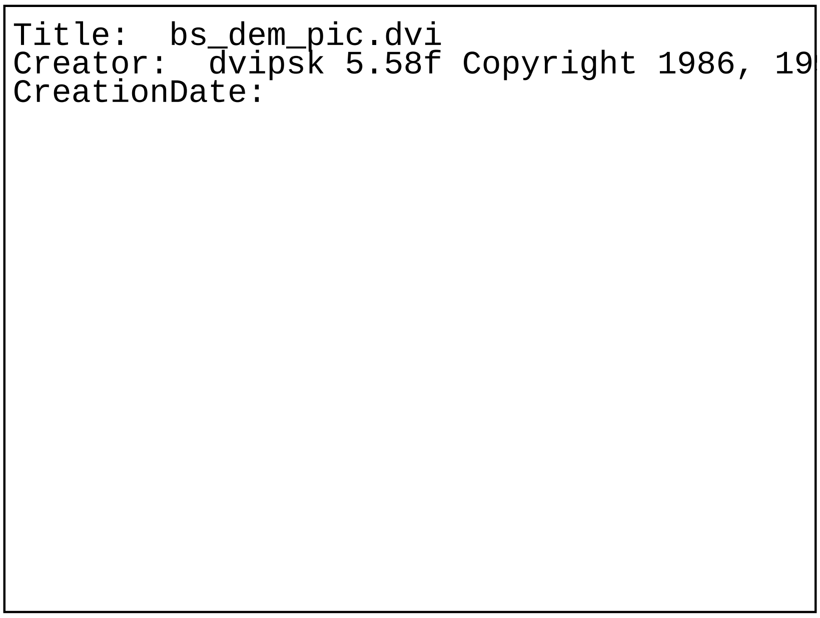

Figure 7.2.5 Coherent Rake Receiver for Uplink

Since there is no pilot channel on the uplink, there is a 180 degree ambiguity in the phase of the recovered channel estimate. This must be resolved before de-interleaving and decoding in order that the symbols from different base stations may be combined during handover. The phase ambiguity is resolved through the transmission of regular polarity symbols, using the (code separated) reverse control channel. The overhead required to transmit these symbols is small (<0.2 dB performance degradation). In addition, no carrier frequency recovery is done in the base station receiver. Instead the system relies upon a frequency extraction and re-transmission loop in the mobile station. Because of this, the frequency offset at the base station receiver is guaranteed to be no greater than twice the Doppler frequency plus the inherent frequency tolerance of the oscillator (<1ppm). This greatly simplifies the design of the coherent uplink.

The base station receiver uses a reduced search algorithm for acquisition of the mobile. This is possible because the phase of the PN sequence in the mobile is set using system timing information recovered from the downlink SYC channel. This phase and that of the PN sequence in the base station should therefore be the same, to within the round-trip delay over the radio link. Once the PN sequence has been acquired, carrier phase is tracked by means of the matched filter channel estimate, as described above for the downlink. There is also a simple loop which tracks any clock offset by adjusting the receiver PN sequence timing so that the largest peak of the channel estimate is forced to a fixed position in the channel estimate vector.

In order that system capacity is maximised, the transmissions from a mobile station are power controlled by a fast accurate closed loop. The loop uses the downlink PCC channel to send a stream of power control commands. Each command is a single bit, indicating that the mobile should either "turn up" or "turn down" its power. The bit rate may be set to one of a range of values, the greatest being 4 kbps. These bits are generated in the base station receiver, by comparing an estimate of the post-despreading signal-to-noise ratio with a preset threshold. The power control step in the mobile may be set to either 1 or 2 dB. The mobile station has an 80 dB range in its output power.

7.2.4.3 Mobility Manager Design

The mobility manager provides the interface (control and user) between the fixed ISDN terminal equipment and the base station(s) via 2.048 Mb/s G.704 links. In particular, the MM converts the speech/data to a format that is acceptable to interface with the radios, i.e. convolutional encoding/ Viterbi decoding for all control/traffic channels and the interleaving/de-interleaving function. In addition, it can support the diversity handover function as the mobile station passes from one base station operational region to another.

7.2.5 Validation and Test Bed Performance

Testing was broken down into four phases:

- Phase 1 - Basic error rate measurements performed on the bench with the multipath simulator. These were carried out at the unencoded rate of 128kbps.
- Phase 2 - As with Phase 1 but at 64kbps with coding and interleaving.
- Phase 3 - Radiating tests in the laboratory.
- Phase 4 - Repeat of Phase 3 test but fully mobile in various outdoor environments.

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Title: BER1.EPS
Creator: Freelance Plu
CreationDate: 12/12/19

Figure 7.2.6 Uplink BER measurements with the channel simulator.

At the time of writing, only Phase 1 and 2 have been completed to any extent, with radiating tests limited to the laboratory environment [21]. One of the many basic sets of BER measurements is given in figure 7.2.6 for the uplink using a multipath channel simulator developed by the consortium. This provides up to 9 parallel paths, each having its attenuation controlled either manually or via a PC. Instantaneous bandwidth in excess of 10MHz is provided together with delays in the range 5ns to 1000ns; Doppler can also be added to one of the paths.

The different curves shown in figure 7.2.6 represent four simulated channels. Note that no power control is employed and that the averaging process in the channel estimator is over 32 channel filter outputs. This corresponds to a period of 0.25msec or an update rate of 4kHz. The static channel employed increasing numbers of fixed, equal amplitude paths with offsets from the undelayed path (single path) of 250nsec and 500nsec respectively. This ensures that no paths are within a single chip period. The single path offers an additive white Gaussian noise (AWGN) channel. Using equal amplitude paths in the multiple path channels provides a "worst case" scenario. The Doppler path is a single path with a fixed amplitude and a 150Hz offset.

The system performs best with the single static path channel, as expected. There is an implementation loss (relative to the theoretical performance of a perfect coherent receiver on an AWGN channel, also shown on the graph) of between 1 and 2dB. This implementation loss is slightly worse for high BERs than for low ones, being around 1.5dB at a BER of 10-2, a possible operating point for the coded system.

The BER over a static two path channel is only slightly worse than for a single path channel. This proves the rake receiver to be giving a multipath gain. Without the rake a degradation of at least 3dB would be inevitable. A further and more severe degradation is apparent when the channel moves to three static paths. The degradation is about 1dB. When a 150Hz frequency offset between mobile and base station is included, the performance for a single path is slightly worse. This is because the channel estimation loop is too slow to track the changing carrier phase accurately. There is however no cycle slipping and no irreducible BER.

7.2.6 Conclusions

The results obtained to date by the consortium illustrate that a DS-CDMA radio link based on a single mobile, base station and mobility manager for a sub-set of the UMTS teleservices is viable. The system supports two common channels (pilot and synchronisation) and three channels per user (power control, forward control and forward traffic) on the downlink. On the uplink it supports a common random access channel and two channels per user (reverse control and reverse traffic). All channels on the same link are code separated with a common chipping rate of 8.192 Mchip/s. The mobility manager architecture can support several base stations, handling ISDN control signals, converting between line and radio signal formats including coding and interleaving, and supporting diversity handover.

A range of special test equipment and assessment tools was developed to support the design of future generation CDMA systems, and employed here to facilitate bit error rate testing over a multipath simulator with and without coding and interleaving. This clearly demonstrating the need for these functions, and the trade off between channel estimator averaging time and Doppler tracking capability. Further, the diversity gain of the Rake receiver was clearly demonstrated. In addition, the robustness of the synchronisation process and the effects of varying the power control loop update rate were also demonstrated

Many potential follow-on activities have been identified, both for exploiting the test-bed as a facility and building on the spirit of collaboration which has been built up among the partners.

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