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# A Comparison of CDMA Techniques for Third Generation Mobile Radio Systems

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***Abstract*- Code Division Multiple Access (CDMA) is now regarded by many as the most viable candidate air interface for future third generation mobile radio systems. The main thrust of research to date has been directed towards direct sequence (DS) CDMA, although recent work has shown that the claimed advantages of DS also apply to frequency hopping (FH) CDMA. Therefore, in this paper a comparison is made between both DS and FH spreading techniques based upon the stringent requirements of proposed third generation mobile radio systems in Europe. Given the many criteria against which this comparison is made, the outcome is slightly in favour of DS-CDMA.**

## I. INTRODUCTION

A three year project funded through the U.K. DTI/SERC LINK Personal Communications Programme 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 architecture. The currently proposed third generation standards are the CCITT Future Public Land Mobile Telecommunications System (FPLMTS) and the European Universal Mobile Telecommunications System (UMTS) [1]. The aim of these systems is to support universal personal communications on an unprecedented scale, offering users worldwide coverage of a wide range of different services (speech, video, data, etc.) through a variety of subscriber terminals.

The requirements for these third generation systems far exceed those of current second generation wireless networks, and can only be satisfied by employing a very flexible air interface. The currently favoured candidates include both TDMA and CDMA. If either of these is to be universally accepted as the sole air interface to take wireless communications into the 21st Century, they will have to meet a number of stringent criteria as follows:

- **Capacity** - support for the required level of user traffic.
- **Hardware** - provision of low cost, compact and power efficient user terminals.
- **Flexibility** - support for a wide range of services with varying bit rates.
- **Quality of Service (QoS)** - provision of a high performance and low cost service.

These criteria cannot be considered in isolation, since they are all interdependent, e.g. one proposed scheme may be able to support a very high level of user traffic, but only at a certain cost in terms of hardware complexity, etc., possibly prohibiting its selection. The sensitivity to errors in the power control mechanism or handover procedure, for example, should also be taken into consideration, since a sharp degradation in capacity or QoS in a realistic system implementation will be inadmissible.

The first phase of the LINK project focused on the service requirements for UMTS, and the output has been a clear definition of the range of potential services which could be offered [2].

The second phase has dealt with the system definition, and this included studies on traffic capacity, handset and base-station complexity, network infrastructure management and QoS issues. It was decided at the outset to evaluate both direct sequence (DS) and frequency hopping (FH) spreading techniques, delaying a decision on the most suitable for the UMTS standard until the completion of these studies at the end of the first year of work.

This paper summarises the outputs of some of these studies and outlines the decision process by which the consortium selected the CDMA architecture for implementation. This process was based upon the criteria described above.

## II. TRAFFIC CAPACITY

There have been numerous studies into the traffic capacity that can be supported by a CDMA system for voice only communications, and comparisons made with current generation technology. The analysis tools employed, and the results presented differ widely, although the emerging consensus is clear; CDMA is an attractive candidate for third generation systems. However, unlike current generation CDMA proposals, the candidate CDMA architecture for UMTS will have to support a number of new services in variety of different propagation environments, ranging from indoor picocells to rural countryside.

Any rigorous capacity analysis should include the actual traffic requirements, although these are extremely difficult to predict at this stage (see [2]). Therefore, in this initial study, the capacity of a voice only system was assessed, leaving out the data services until a better traffic model of the expected service mix is available.

### *A. DS-CDMA Analysis*

Recent studies into CDMA performance claim that DS-CDMA offers the solution to long term capacity demands for wireless personal communications [3]. These claims have been substantiated largely through simulation and, more recently, by field trials [4], and so there is growing evidence to support earlier capacity forecasts. One issue which is still to be fully understood is the sensitivity of DS-CDMA to system imperfections, e.g. errors in the power control mechanism. This was the main motivation for developing a Monte Carlo simulation of the multiple user cellular network. A similar approach has been adopted by many authors [5], since analytical solutions to the sensitivity issue can be extremely complicated.

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The basic philosophy behind the Monte Carlo approach is to generate a large number of random deployments of mobile users under realistic loading conditions. Using the co-ordinates of the base-station (BS) antennas, it is then possible to assign mobiles to BSs. The decision is based upon the shadowing and path loss experienced, and the selected BS is the one which maximises the received signal power, i.e. perfect handover.

For each deployment, a carrier-to-interference ratio (C/I) can be calculated, and after many runs the complete cumulative distribution (CDF) of the C/I values produced. Given the C/I threshold for a particular bit error rate (BER) performance, the outage probability can then be generated, i.e. the percentage of time that the C/I falls below the given threshold. A 1% outage is a commonly accepted value. The model can include the effects of slow and fast fading, errors in the power control mechanism, voice activity, different path loss models, etc.

Only the uplink has been studied in any detail, and an $E_b/N_0$ threshold of 7dB was adopted to provide a BER performance of $10^{-3}$. This is the value quoted by Qualcomm [3] and has been employed almost exclusively in recent DS-CDMA publications.

## *B. FH-CDMA Analysis*

In a frequency hopping system, the effect of narrowband hopped interference on the receiver performance is hard to predict. The interference cannot be considered simply as noise, and an absolute C/I threshold cannot be set.

The approach taken involved developing a simulation of a narrowband modem (16APSK and $\pi/4$ QPSK) operating over a frequency hopped channel. This model, and the associated channel coding, is more fully described in [6].

In order to analyse the impact of a loaded system, a multiple user scenario must be set up to simulate the effect of the out-of-cell interference. This was achieved by generating a reference file for a given network topology, cell loading, propagation environment, voice activity, etc., and adding this directly into the link simulation at run-time. The criteria used to define outage is when the link BER is above a threshold of $10^{-3}$. In the results to follow, a single outage is measured over a period of $10^4$ information bits, and this is repeated to generate the overall outage statistics.

The FH-CDMA scheme considered here is described in more detail by Purle *et al* [6]. Slow frequency hopping (SFH) has been adopted since this offers several advantages when compared to fast hopping (FFH). Firstly, practical hopping radio frequency (RF) synthesisers can be realised, as well as relaxing the requirements for the associated acquisition, tracking and despreading subsystems. Finally, and most importantly, slow hopping offers the potential for synchronous operation within a cell. This is an extremely desirable feature since it effectively removes the intra-cell interference component, greatly improving performance.

## *C. Results*

Figure 1 contains the outage results for the DS and FH-CDMA simulations as described above. The common parameters are as follows:

| | |
|---|---|
| • Total number of base-stations: (hexagonal geometry) | 37 |
| • Path loss exponent: | 4 |
| • Log-normal shadowing std. dev.: | 8 dB |
| • 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 |

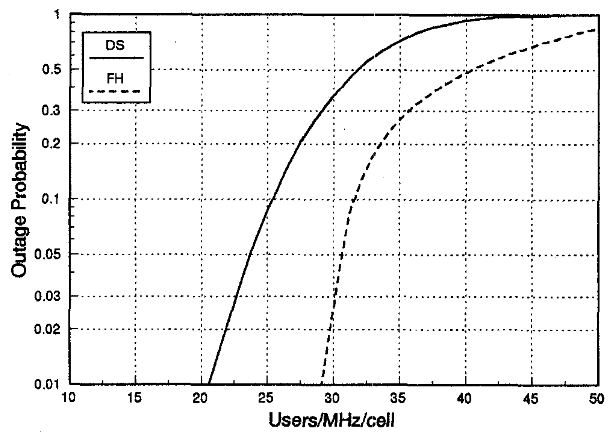


*Figure 1: Performance comparison of DS and FH-CDMA.*

The DS simulation is based upon a narrowband CDMA system [3], with an 8kbps data rate and a spreading bandwidth of 1MHz corresponding to a processing gain of 21dB. The graph indicates that the DS-CDMA system could support approximately 21 users/MHz/cell with a 1% outage.

Increasing the spreading bandwidth increases the number of users that can be supported, and the corresponding simulation run-times, but the spectrum efficiency in terms of users/MHz/cell would, intuitively, remain the same. In fact, there is an improvement in performance due to the larger number of users enhancing the quality of the resulting statistics. However, since the analysis is primarily concerned with a direct comparison with FH, a basic 1MHz spreading bandwidth has been adopted.

Since the spreading bandwidth for any candidate UMTS DS-CDMA system is likely to be in the order of 5-10MHz and will exhibit very different fast fading statistics, no fast fading component has been included in this generic simulation.

The FH curve has been produced for QPSK modulation with half rate convolutional encoding and an interleaving delay of 40msec. A basic data rate of 10kbps has been employed, allowing for 8kbps speech with a 2kbps control overhead. The transmission symbol rate is 10kbaud, and with Root Raised Cosine Tx-Rx filtering ($\alpha$=0.6) allowing a channel spacing of 16kHz, this provides a total of 62 channels in a 1MHz bandwidth. Fast fading with a normalised Doppler of 0.01 has been employed, and the graph indicates that approximately 29 users/MHz/cell can be supported with a 1% outage.

Given the error bounds for this type of simulation, these results would indicate that FH potentially has the higher spectrum efficiency in terms of users/MHz/cell. This can largely be attributed to the synchronous operation within a cell, effectively removing the intra-cell interference.

Much of the work to date has focused on the FH analysis in order to enable a competitive comparison to be made with the more widely researched DS technique. This has produced some encouraging results, indicating that slow FH can rival DS when considering traffic capacity alone. The increase in capacity by introducing antenna sectorisation at the base-station has not been considered, although it is expected that this will have a similar effect for both systems. The impact of sensitivity is the subject of continuing study.

## III. 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. For this reason an assessment was made of the impact of any technological advances or limitations on the eventual transceiver architectures. 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.

Considering FH first, the aspect that sets it aside from other systems is the use of a hopping frequency synthesizer. Traditionally this has been realised as a hopped RF synthesizer, and because of the limited dynamics of the phase-locked loops employed, the achievable hop rates have been restricted to what is effectively slow hopping. With the advent of direct digital synthesizer techniques, and very recent digital up/downconverter technology (e.g. from Stanford Telecom, Harris Semiconductor), fast baseband and intermediate frequency hopping has become attainable, and this has enabled the concept of compact commercial FH equipment to be entertained.

While the present power consumption and size of the chip sets precludes the immediate realisation of prototypes that fulfil the specifications of a commercial handset (a basic voice only terminal), it is envisaged that advances in IC fabrication techniques, such as reduction of semiconductor feature sizes and the advent of new geometries, will remedy this situation by circa 2000. For FH, the frequency switching rate and power drain limitations of RF synthesizers have been resolved by the introduction of fast, although at present still unacceptably high power dissipation, digital signal processing (DSP) electronics.

DS systems have received much publicity in the last few years (e.g. Qualcomm, PCN America), and substantial amounts of time, effort and capital have been put into developing and evaluating fully functioning mobile communications networks. Whole DS chip sets have been produced (Stanford Telecom) which provide high levels of flexibility in terms of chipping rates, data rates, and modulation and coding schemes supported. Indeed the very flexibility has enabled various blocks to be considered for FH applications. However, to date the realisation of long battery life (arbitrarily >24hours, say) handsets has been precluded by the heavy power consumptions of the DSP blocks. With interest being shown increasingly in higher chipping rate (10-20Mchips/sec) systems, the power drain problem is exacerbated for the hardware designers.

Present difficulties aside, it is considered that broadband CDMA handheld terminals will be feasible by the time third generation systems come on-line. Furthermore, given that the system performances of DS and FH are found to be basically equivalent, or at least complementary for certain scenarios, then it is expected ultimately that the hardware considerations of cost, size and power consumption will be evenly matched for both DS and FH.

## IV. FLEXIBILITY

The flexibility criteria covers a broad range of issues including the support of higher rate services, operation in a mixed cell environment, and the support of multiple operators.

Third generation systems will offer a variety of new teleservices with a range of user bit rates. These will range from high speed data and videophones, to fax and low rate data, although it is likely that voice will remain as the dominant service. Clearly, the challenge facing system designers is the support of enhanced services (≥64kbps), and for both DS and FH-CDMA a number of options are available. For DS these include:

- Trade-off processing gain for an increased data rate in the same spreading bandwidth.
- Utilise different spreading bandwidths to match the required data rate, resulting in DS overlaying DS.
- Pair up basic channels until the required data rate is achieved. This could be in separate frequency channels or within the same channel allocation.

Similarly for FH:

- Increase the transmission rate as required. This would probably preclude the use of equalisers.
- Employ a multi-level modulation format, allowing variable rates but with the same transmission symbol rate.
- Pairing multiple hop channels.
- Combine FH with an adaptive TDMA architecture.

The advantages and disadvantages of these schemes involve a number of issues: hardware complexity, signalling overheads, effect on system capacity, support of handover, etc. The most suitable solution is the subject of on-going investigation. The choice between DS and FH on this particular issue is very hard to resolve since this is a relatively new area for both techniques, and considerable further study is still required.

An increasingly important aspect for network planners is the availability of sophisticated planning tools to ensure the efficient deployment of a network [7]. CDMA, both DS and FH, offers the potential for complete frequency reuse in each cell, thus greatly simplifying the frequency planning aspects of any planning tools.

The support of increased user traffic in urban city centres requires the introduction of small outdoor microcells and indoor picocells, with ranges of up to 200m and 50m respectively. The support of high speed users is still likely to require the use of overlaid macrocells due to the problems of handing over such users as they travel through the microcellular network.

This poses problems to the CDMA system designer since the higher power users in the larger macrocells could severely interfere with the lower power users in the microcells if they were in the same band. This is a general problem facing CDMA schemes, commonly referred to as the *near-far* problem, and may require the support of separate frequency channels in the different cells. This will reduce the amount of spreading bandwidth available for a single channel. The expected immunity of FH to the near-far effect is an advantage over DS.

WARC'92 has allocated a total bandwidth of 230MHz in the 2GHz band specifically for the development of third generation mobile radio systems. In order to satisfy the requirements for competition, a number of network operators will be required to coexist in the same areas. Using traditional coexistence regulations, each operator will be assigned different frequency channels, and in the case of a mixed cell architecture as described above, separate channels also for the different cell types. This very quickly limits the maximum channel bandwidth allocation that can be made available, e.g. between 5 and 10MHz, and is a particular problem with DS-CDMA which requires a contiguous bandwidth allocation. FH would be more flexible in this case.

The minimum bandwidth requirements for successful DS-CDMA operation in urban environments is the subject of on-going research [8], and the results will have a significant effect on the flexibility of a DS-CDMA architecture.

## V. Quality of Service

There are a number of issues affecting the quality of service offered by candidate architectures for UMTS. These include handover and the robustness to system errors.

Handover is a key issue in this debate, and in particular the application of soft handover [3,9] to improve the call quality as the mobile moves from one cell, or sector, to another. In this mode of operation, the call is handled by two or even three BSs at the same time, significantly reducing the chance of a dropped call as experienced with traditional handover techniques. Also, on average, the user will transmit less power, thereby contributing less interference, and enhancing the overall system capacity.

DS would appear to be inherently able to support this type of handover, although the exact overheads in terms of hardware complexity, signalling and increased network traffic have yet to be fully assessed.

The support of soft handover with FH is an issue requiring further study, although cannot be ruled out at this stage. Overall, DS has the advantage on this issue.

The sensitivity of DS-CDMA to system errors [5] is a disadvantage of this technique, and is as a consequence of its susceptibility to the near-far effect. The impact of wider spreading bandwidths will mitigate this to some extent [10], e.g. the effect of errors in the power control mechanism. The application of near-far resistant techniques is another possibility receiving a lot of interest at the moment [11]. FH would appear to be more robust to these type of errors, and could therefore offer a more reliable service, although this issue is the subject of continuing investigation.

## VI. Discussion

This paper has considered many aspects of future third generation mobile radio systems, and attempted to consider the application of both DS and FH-CDMA systems. This has shown that, although exhibiting very different characteristics, the selection of the most suitable scheme for the third generation UMTS standard is very difficult. This is partly because many of the issues raised have not been addressed in any detail to date.

The work carried out so far within the LINK CDMA project has spent some time determining the key issues which have a direct impact on future mobile radio systems, and has attempted to rigorously assess CDMA in this context. The work has demonstrated that on the most critical issues of traffic capacity and hardware, there would appear to be nothing to choose between the two spreading techniques. On balance however, the consortium has decided to focus the remaining two years of the project on a DS architecture, with the intention of demonstrating a subset of the UMTS services in a number of key environments.

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