The IST project MATRICE on MC-CDMA transmission techniques for future cellular systems

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This paper presents an overview of the European IST project MATRICE (MC-CDMA Transmission Techniques for Integrated Broadband Cellular Systems, IST-2001-3220), describing its tasks, goals and preliminary achievements. The main focus of the MATRICE project is the definition of a new air-interface for future cellular mobile radio systems based on Multicarrier-CDMA modulation techniques and the study of its key building blocks like receiver algorithms and flexible TX components. The nine European partners participating in this project are CEA-LETI (F), France Telecom (F), Instituto de Telecommonicaçõ (P), Mitsubishi Electric ITE-TCL (F), University of Madrid (E), University of Surrey (UK), STMicroelectronics (CH), INSA-IETR (F) and Nokia (D).

1. Introduction

The European third generation terrestrial mobile system (UMTS-UTRA) is currently being deployed and its enhancements standardized. This system offers a large variety of services (circuit switched and packet switched services, low to high bit rates), as well as a greater spectral efficiency compared to second-generation systems such as GSM. Commercial networks are now being launched to provide basic UMTS functionality, using today's technology. This evolution from 2G to 3G already represents a change in many aspects: new technology, change of focus from voice to mobile multimedia, and simultaneous support of several Quality-of-Service (QoS) classes in a single radio interface. Despite the high capacity foreseen in this 3G technology, the rapid growth of Internet services and increasing interest in portable computing devices are likely to create even larger demands for high-speed wireless data services, presumably with aggregated information bit rates of more than 2-20 Mbps in a vehicular environment and 50-100 Mbps in indoor to pedestrian environments, using 50-100 MHz bandwidths. Especially in the downlink, high throughput is needed since the number of downloads of large data files from web sites and servers will increase and broadcast / multicast services may become a reality. Future 4G systems will need to accommodate these requirements. The European vision for this new generation is one of a fully Internet Protocol (IP)-based integrated system, offering a full range of simultaneously active services, anytime, anywhere, supporting multiple classes of terminals.

The provision of such high bit rates requires the development of new technologies. One of the most promising candidate techniques for achieving high data rate transmission in a mobile environment is multi-carrier CDMA (MC-CDMA), which divides a wide signal bandwidth into several sub-channels, where several information bearing signals can coexist in the same frequency range by using code separation. Research at several universities and R&D laboratories has already pointed to MC-CDMA as a potential technique for the broadband component of future cellular systems. However, to provide a comprehensive picture for the standardisation of future broadband mobile systems, considerable work is still required, particularly with respect to the integration of several processing techniques like access, coding, equalisation and resource allocation.

The paper is structured as follows: Section 2 provides the objectives of the MATRICE project. Section 3 extensively describes the tasks and goals of the workpackages. Section 4 shows the initial results of the project, and Section 5 concludes the paper.

2. OBJECTIVES

The work carried out in the MATRICE project focuses on the definition of a realistic architecture for a broadband 4G wireless system based on an MC-CDMA technique. Its innovative aspects allow it to do the following:

- To define the performance of MC-CDMA schemes at the physical layer and define a link level chain that is realistic for the broadband component of 4G cellular systems.
- To devise efficient Medium Access Control (MAC)-layer protocols that explore the properties of MC-CDMA schemes.
- To quantify signal-processing resources in the schemes investigated and define the architecture of a radio transceiver for future 4G cellular systems.
- To implement a hardware demonstrator showing the feasibility of the defined radio transceiver.

3. PROJECT OVERVIEW

3.1. Introduction

In order to achieve these objectives, the MATRICE project utilizes 5 technical operational areas (workpackages, WPs) under the administration of a management workpackage (WP0) and the addition of a dissemination workpackage (WP7). The tasks and goals of the WPs are summarized in Table 1.

WP0	MANAGEMENT
WP1	4G REFERENCE SCENARIO DEFINITION: - Capture the system requirements for a future mobile radio system
WP2	SIMULATION PLATFORM: FUNCTIONAL SPECIFICATION: - Define and specify the link level and system level simulation platform
WP3	PHYSICAL LAYER PLATFORM AND SIMULATION: - Set up a physical layer simulation platform to evaluate the performance of physical layer algorithms
WP4	RADIO LINK LAYER PLATFORM AND SIMULATION: - Set up a radio link layer simulation platform to evaluate the performance of key radio resource management algorithms
WP5	COMPLEXITY EVALUATION: - Perform a complexity evaluation of key layer1 and radio link layer algorithms including fix point implementation
WP6	RECONFIGURABLE RADIO TRANSCEIVER: - Develop a reconfigurable radio transceiver to demonstrate key algorithms and functionalities
WP7	Dissemination

TABLE 1: WORKPACKAGES OF MATRICE.

We have detailed the operational areas in order to provide an overview of the MATRICE project and its technical approach.

3.2. 4G Scenario Definition

The first operation area aims at defining the 4G scenarii to be used as a common basis for the overall project. These scenarii provide basic assumptions and requirements for 4G systems in terms of user and service requirements, deployment scenarii, spectrum issues, interoperability and co-existence constraints, which will set the scene for the design of the MATRICE air interface.

Several technologies are evolving and emerging and are analysed inside this WP. The combinations of these technologies represent a very flexible and powerful platform, which will support future requirements of services and applications. Still, it is clear that there is a need to develop new radio interface concepts that may support higher data rates with higher mobility than 3G or Wireless Local Area Network (WLAN) systems. Thus, the MATRICE project aims at designing a system based on MC-CDMA with high bit rates and high mobility capabilities in geographically restricted areas, capabilities which allow for a complement-type scenario in the ITU-R vision, as opposed to the all-round type scenario (see Fig. 1a and 1b). The following set of target throughputs has already been identified:

— 50 Mbps at 3 km/h in indoor office and home environments;
— 20 Mbps at 60 km/h in urban environments; and
— 10 Mbps at 300 km/h in high-speed environments including trains.

We have assessed the spectrum requirements based on preliminary traffic and system assumptions. Based on these evaluations, we propose a system bandwidth of 50 MHz and view the 5 GHz band as a good candidate to welcome a new mobile system such as MATRICE. Furthermore, since this new system aims at complementing existing systems in terms of coverage and services, system requirements mainly focus on interoperability issues with 3G (UMTS) and WLAN systems. Consequently, the sampling rates and the system bandwidth of the MATRICE air-interface should be multiples of the ones used with UMTS.

The MATRICE project will focus on Time Division Duplex (TDD), which offers potential benefits for pre-filtering, dynamic channel allocation, and adaptive antennas techniques. MATRICE takes into account the disadvantages of a TDD-based system, such as potential problems with larger cells and higher velocities, during the development and evaluation process. Furthermore, MATRICE will assume IP-based core networks, which will simplify integration in future networks.

The four QoS classes of UMTS (i.e., the conversational, the streaming, the interactive and the background classes) should, at the very least, be supported; however, MATRICE will require greater flexibility of QoS support in order to cope with emerging future services.

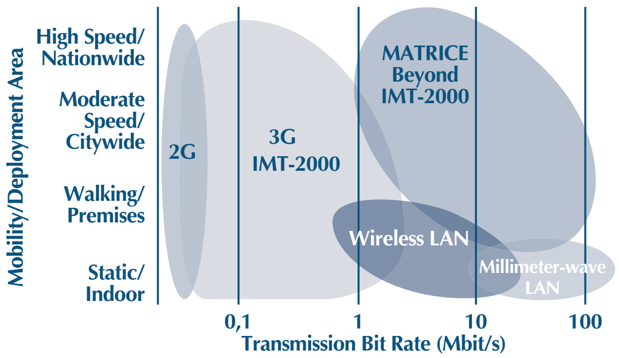

FIGURE 1A: COMPLEMENT-TYPE SCENARIOS BY ITU-R VISION.

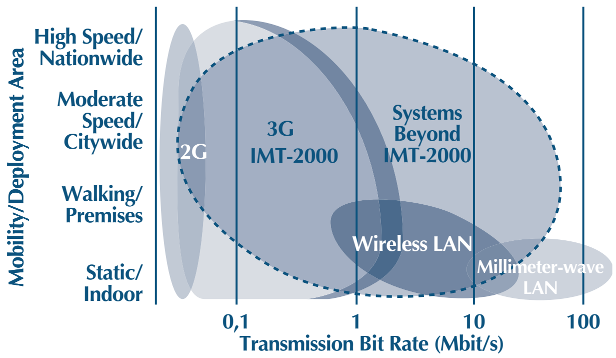

FIGURE 1B: ALL-ROUND TYPE SCENARIOS BY ITU-R VISION.

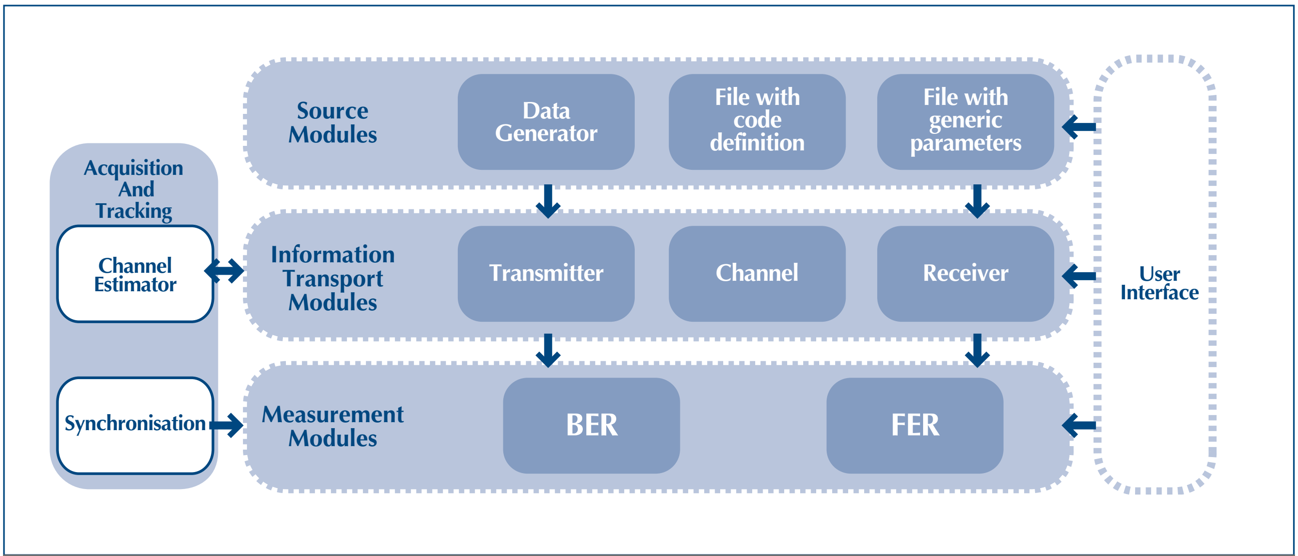

Figure 2: Main blocks of the physical layer reference platform.

Finally, this workpackage will provide a methodology for the evaluation of the MC-CDMA radio interface. We will define evaluation criteria and common assumptions, such as test environments, deployment models and services as a basis for overall performance evaluation of the project.

3.3. Simulation Platform Specification

This technical area aims to define the main guidelines for the development of the simulation platforms. We developed these guidelines with two main concerns in mind:

— that the work produced by the different partners contribute in a unified way to the overall goal of the project with a minimum overhead concerning format adaptations and conversions, and
— that the work produced in the simulation workpackages be easily used by the hardware developers.

In this sense, this WP defines:

i) *The interfaces for all simulation platforms*. For the physical layer, we have defined two different reference simulation chains: a reference platform acting as a performance benchmark and advanced platforms incorporating novel algorithms. For higher-layer models, we have created a complex hierarchical simulation model, supporting a full loop simulation based on a custom simulation tool. Notice that these "platforms" already incorporate a coarse system partitioning, defining key blocks, and their interfaces.
As an example, Figure 2 depicts the main blocks of the advanced simulation platform for the physical layer.

ii) *The design flow specification and information exchange between the physical and higher layers.* This covers the analysis of MC-CDMA requirements and their specific properties as compared with other systems, as well as the definition of the parameters able to be configured for differentiating various types of requirements. This information is essential for higher layers.

The overall simulation chains will be described in SystemC [5]. The project will fully use its multiple abstraction levels to integrate and develop the MC-CDMA principle.
This workpackage further defines procedures for the documentation and delivery format of every software module, including testing and integration procedures. It defines the

multiple layer validation approach, providing the flexibility required for consistent individual partner development.

3.4. Physical Layer

The studies conducted within the physical layer workpackage consist of an evaluation of MC-CDMA techniques in order to fulfill the requirements of the communication scenarios defined in WP1. We will continue to develop several simulation platforms with the intention of evaluating advanced transmission and reception techniques in the uplink (UL) and the downlink (DL) throughout the life of the project.

Following the simulation platforms reference model developed in WP2, we focus on the first step of separate UL and DL reference simulation platforms with state-of-the-art MC-CDMA algorithms, together with perfect synchronisation and perfect channel estimation. These two platforms aim at allowing a fair comparison between competing advanced algorithms from the different partners by simply replacing some modules of the common reference platform by these advanced modules.

For the DL reference platform, MC-CDMA's performance and inherent flexibility has made it a challenging candidate for a 4G air interface [3][4]. Figure 3 shows the block diagram of an MC-CDMA downlink transmission with the *k*-th mobile terminal (MT) receiving the data transmitted in the presence of *K* active users from the base station (BS). For each user *k* in the set of *K* active users, a binary source generates a random stream of binary information $b_k(i)$ that is encoded, using either a convolutional encoder or a turbo-encoder, into a block of coded bits $c_k(i)$. Puncturing allows a reduction of the coded block size to match the frame size requirements. After channel interleaving, a mapping function builds a complex data symbol $d_k(j)$ that may belong to a BPSK, QPSK, 8-PSK, 16-QAM or 64-QAM alphabet. We jointly spread the data symbols of all users with user-specific orthogonal spreading sequences taken from a set of Walsh-Hadamard sequences. The orthogonality among spreading sequences of different users allows them to transmit at the same time over the same frequency band. The resulting chip stream $e(l)$ is frequency multiplexed to benefit from frequency diversity while de-spreading. A framing operation introduces null symbols on the sub-channels at both

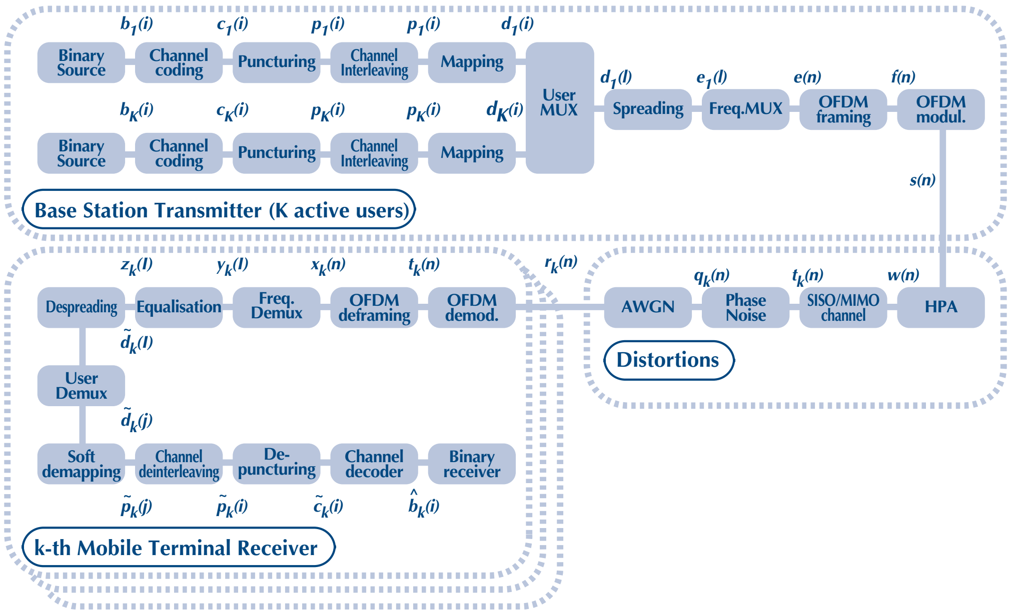

FIGURE 3: MC-CDMA DOWNLINK TRANSMISSION BETWEEN BS AND K-TH MT (DL REFERENCE PLATFORM).

edges of the Orthogonal Frequency Division Multiplex (OFDM) spectrum in order to avoid aliasing. Then, OFDM modulation takes place using an inverse Fast Fourier Transform (FFT), and a guard interval is inserted. A non-linear high-power amplifier (HPA) then power amplifies the generated multi-user symbol $s(n)$ before its transmission over a Single-Input Single-Output (SISO) channel. The multipath propagation of the transmitted signal over the mobile radio SISO channel destroys the code orthogonality among users' signals, which creates Multiple Access Interference (MAI).

Considering the reception at MT k, a phase noise resulting from impairments of synchronisation, local oscillator imperfections, and Additive White Gaussian Noise (AWGN) may corrupt the received signal $r_k(n)$. After guard interval removal, the received signal is OFDM demodulated, and an OFDM de-framing operation extracts the multi-user observation signal $x_k(n)$. Frequency de-multiplexing gathers the chips belonging to the same complex data symbol. Then, single-user detection is carried out on the basis of a one-tap-per-carrier equalisation followed by a de-spreading according to the spreading sequence of user k, thus mitigating, part of the MAI. This yields the complex observation $\tilde{d}_k(i)$ that is specific to user k, a soft-demapping followed by channel de-interleaving and de-puncturing rebuilds estimates $\tilde{c}_k(i)$ of coded bits $c_k(i)$ that are decoded, either with a convolutional decoder or with a turbo-decoder, to provide hard estimates $\hat{b}_k(i)$ of information bits $b_k(i)$.

Starting from the UL and DL reference platforms, MATRICE research activities for the advanced platforms cover several areas: space-time-frequency coding, beamforming, channel pre-equalisation, multi-user detection, system and signal design, channel estimation, synchronisation, sensitivity to non-linear amplifiers, system level studies, and complexity reduction.

When antenna arrays at the transmission and reception sides are used, a space-time-frequency coding scheme can improve the performance of MC-CDMA systems by utilizing the space diversity [6]. Alternatively, antenna arrays can be used at the transmission or at the reception to perform beamforming, *i.e.*, to point the main lobe of the antenna diagram in the direction of the desired user while limiting the interference to or from other users. Thus, the user separation in space can lessen the MAI. In the MATRICE project, we consider different types of beamforming, mainly at the BS where an additional complexity is tolerable [11]. A comparison of antenna array techniques used for diversity or beamforming is also in the scope of the project. For that purpose, we also consider a realistic Multiple-Input Multiple-Output (MIMO) channel model.

An interesting feature of the TDD mode is the ability to benefit from almost unchanged channel characteristics between consecutive UL and DL transmission intervals (the lower the velocities, the better this statement holds). Therefore, it is possible to use the channel estimates computed by the receiver during one link to pre-equalise at transmission during the other link. Pre-equalisation is especially interesting in the UL as it avoids channel estimation at the BS, which cannot be performed with a good spectral efficiency using conventional techniques [7] [8].

The design of an MC-CDMA signal must satisfy several constraints such as good spectral efficiency, low variation of the transmitted signal envelope, and robustness to the degradations caused by the propagation through the mobile radio channel. For example, it is possible to select the spreading sequences for DL and UL MC-CDMA systems with the aim of jointly minimizing the dynamic range of the transmitted multi-carrier signal envelope and the MAI [8]. Alternatively, the use of spheroid functions as spreading sequences allows an increase in spectral efficiency by avoiding the use of a guard interval [10].

As far as multi-user detection techniques are concerned, MATRICE aims to mitigate the MAI at the receiver side using knowledge of every user's transmission characteristics (such as the spreading sequence or the power). MATRICE analyses both linear and non-linear filtering techniques such as parallel interference cancellation (PIC) or successive interference cancellation (SIC). It also investigates Maximum Likelihood detection using sphere decoding, as it provides the optimal performance needed to evaluate other techniques, and its computational complexity can be simplified to allow a practical implementation [12]. When MTs transmit asynchronously in the UL, the introduction of a decorrelation process can increase the performance of a multi-user detection scheme [13].

Finally, an additional result of the physical layer studies will be the specification of the physical layer key parameters (such as the FFT size, the spreading type, the modulation alphabet and the coding rate) in order to cope with the diverse envisaged transmission scenarios.

3.5. Radio Link Layer

We envisage the MATRICE radio access network to be an entity within an all IP core network and thus become an infrastructure that will evolve to provide end-to-end connectivity to WLAN networks, Digital Video Broadcasting (DVB) multicasting services, and the global Internet, amongst others. In addition, current trends suggest that future applications will require greater bandwidth on demand, at any time and at any given place. These system requirements pose a direct impact on the design of the Link Layer, providing the impetus for maximizing the use of available resources and seamless interoperability with an all-IP network, while still complying with the original IP design philosophy.

Essentially, this workpackage will focus on the design and development of the Link Layer, in particular to develop an evaluation tool to investigate Radio Resource Management (RRM) algorithms that include power control, handover, and call admission control. Moreover, it will approach Dynamic Resource Allocation (DRA) problems and develop an IP convergence layer. We will develop a dynamic system level simulator that will model the channel environment, user mobility, and packet session scheduling, and that will support the transport of IP packets. Each of the Link Layer entities will be integrated into the platform and optimised to maximize the system capacity over a MC-CDMA air-interface, based on the scenarios defined in WP1.

The Radio Link workpackage will explore DRA schemes that attempt to maximize the use of the available transport channels, given that the link quality is time varying depending on the propagation environment. This will be connected to the IP convergence layer, in QoS aspects. Presently, networks offer minimal QoS provisioning. Future networks will provide preferential treatment to traffic in order to accommodate real-time traffic. Current efforts are assuming a DiffServ QoS mechanism at layer 3 to provide the QoS classes defined in MATRICE.

Roaming between IP entities also needs to be addressed. Per hop forwarding protocols and cellular IP are active research areas, but, from a user's perspective, the handover at higher layers must be transparent. In this workpackage, the IP convergence layer will provide support to future emerging networks in terms of QoS and mobility management.

Moreover, there will be close interaction with the Physical Layer aspects. The combined efforts of both work areas will focus on developing a link level interface so that implications from physical layers can be supported and the impact on system level performance can be evaluated. Furthermore, there will be close collaboration with other technical areas, especially complexity analysis and implementation. We will subject the RRM algorithms to a complexity evaluation, as the computational effort is also regarded as an integral part of the overall performance measure in this project. In addition, we will integrate the MAC layer functionality into the hardware prototype developed in the project.

3.6. Complexity Analysis

We have set up a specific task for evaluating the complexity of the MC-CDMA system developed by the project. It runs parallel to and works in close relationship with workpackages 3, 4 and 6, and its tasks can be split into two main aspects. One part provides input throughout the system development process and allows for early algorithm evaluation and possible selection or rejection, optimisation opportunities and possible split or combination of tasks. The other part supports the hardware platform development first by providing complexity figures at an implementation level to size the prototype quickly, and later by investigating architectural optimisation issues more deeply.

All these tasks are performed in a coherent way in line with the design methodology, using SystemC as the core language throughout the development. We introduce the concept of "abstraction levels", which aims at splitting the design in several steps, so as to focus sequentially on various aspects of the system, while keeping a common design flow. Hence, from a purely functional description level, each model runs through several refinement levels where issues like system partitioning, HW/SW split, timing, HW synthesis or DSP implementation are investigated. Simultaneously, complexity can be evaluated in line with these abstraction levels. On a system functional level, the number of operations together with memory size requirements are the only metrics of interest, but as each model is further refined, figures like bus traffic, latency, resource sharing, or parallelism impact the overall complexity as well.

How to perform complexity evaluation, especially knowing which metrics to use, is related to its purpose during each phase of the system development. When performing early algorithms comparison and selection, operations and memory size are relevant metrics. However, when investigating architecture exploration, other items like memory type or even reconfigurability capabilities, are of interest as well. It is important to note that, in the context of MATRICE, we investigate architectural issues in a completely open way, i.e., without any predefined architecture. Determining the best mapping of the developed system is part of the workpackage target, in addition to submitting a HW/SW split of the key building blocks.

As introduced above, the work breakdown and scheduling of MATRICE allows this workpackage not only to provide deliverables after the design of physical layers (WP3) and MAC layers (WP4) for MC-CDMA, but also to feedback relevant information periodically, in line with the internal development phases. From the initial UL and DL reference platforms, high-level complexity figures work as inputs to help in the selection of advanced algorithms. The most relevant advanced algorithms are further evaluated by means of fixed-point design leading to a more accurate complexity evaluation. In WP6 even lower level issues are investigated in a step-by-step approach, from the prototype dimensioning to implement a simplified chain, down to architectural optimisation of the final system to be validated.

3.7. Validation Platform

A final technical workpackage is responsible for the implementation of the baseband hardware demonstrator of the project. The aim is to develop a reconfigurable transceiver incorporating the set of algorithms and functionalities selected from the work in WP3 and WP5. A hardware platform provided by Hunt Engineering, which contains DSP (C6x) and FPGA (Xilinx) daughter boards [13], provides the basis for the demonstrator.

The main specifications of the system that we will implement are as follows:

- TDD mode. DL and UL transmission will be supported in order to evaluate algorithms that take advantage of channel reciprocity (e.g. pre-equalisation and beamforming).
- Implementation of all baseband modules, from synchronization, FFT / IFFT, spreading / despreading to a turbo-decoder and
- Intermediate Frequency (IF) transmission through a hardware channel emulator.

We have currently assumed the system bandwidth and the target bit rate as 20 MHz and up to 50 Mbit/s, respectively.

We split platform development into two phases. The first version of the demonstrator will implement a conventional MC-CDMA receiver structure based on a single user Equal Gain Combining (EGC) detector. It will be available by the end of December 2003. The second version of the platform is much more ambitious, foreseen to implement advanced algorithms such as multi-user detection, pre-equalisation schemes and duo-binary turbo decoders. We will select the algorithms to be implemented in the platform in September 2003. We will perform a final demonstration of the complete system including a video streaming application at the end of the project in December 2004.

4. INITIAL RESULTS

Since the start of the project, we have reached several intermediate project milestones, some of which we have reported previously in relevant areas. For instance, during the first phase, we investigated the requirements and scenarios for a broadband component of future mobile radio systems. The ITU complementary scenario (see Fig. 1), the scenario we have chosen, provides high data rates to high mobility users. Based on this requirement, we have achieved further developments of the MC-CDMA-based air interface. The working assumption for these developments is the deployment of a TDD-based multiplexing scheme without completely disregarding the FDD mode for comparison reasons.

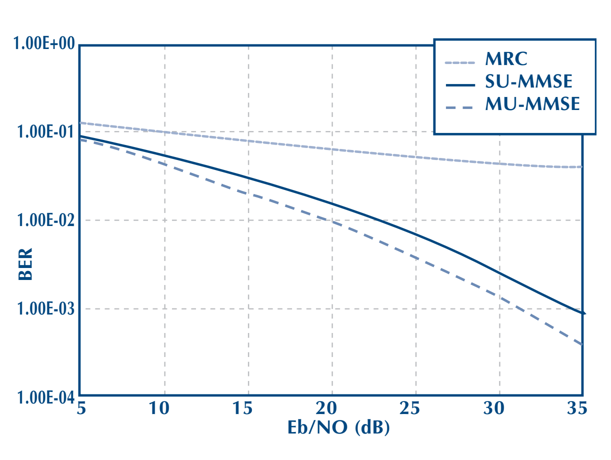

FIGURE 4: MATRICE V0 DL EXAMPLE SIMULATION RESULTS IN A BRAN A CHANNEL WITH SINGLE USER AND MULTI USER MMSE DETECTION.

A SystemC based design flow provides the basis for the algorithm development and optimisation. The first complete reference (V0) simulation chain in SystemC is available and first simulations have already been performed.

Fig. 4 shows the first DL simulation results using the MATRICE V0 SystemC simulation chain and compares the performance of three different detection techniques.
Currently, enhanced simulation chains are under development, including a configurable multilink 3GPP/3GPP2 MIMO channel model in SystemC. These enhanced chains will include more sophisticated demodulation and synchronisation techniques together with multi antenna processing algorithms.

5. CONCLUSION

The IST MATRICE project represents an important European effort towards the definition of an air interface for mobile radio systems beyond 3G in the scope of the 5th European Research Framework. It advocates that future mobile radio systems complement existing mobile radio systems and wireless local area network systems in the operational area of high mobility with high data rates. Thus, an easy integration of the new air interface based on a MC-CDMA type of modulation into existing mobile radio systems will be of crucial importance for the success of a developed new air interface concept based on MC-CDMA.

6. ACKNOWLEDGMENTS

This work has been performed in the framework of the IST project MATRICE (IST-2001-32620), which is partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues from CEA-LETI, France, STMicroelectronics N.V., Switzerland, Nokia

GmbH, Germany, Mitsubishi Electric ITE, France, UPM, Spain, FTR&D, France, University of Surrey, UK, INSA-IETR, France and Universidade de Aveiro/Instituto de Telecomunicações, Portugal.

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