# (5) Advanced Topics in MIMO-OFDM Systems

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*At DoCoMo Euro-Labs, we are concentrating on studies of OFDM and MIMO with a view to realizing Fourth-Generation mobile communication systems with high-speed and high-capacity wireless access. When MIMO-OFDM systems are applied to mobile communications, there are numerous issues that have to be addressed, including improvement of the required signal-to-noise ratio to achieve adequate coverage outdoors, as well as reduction of the signal processing load, taking into account the processing capabilities of future mobile devices. In our studies, we are bringing these issues to light and striving for technologies that can be used to solve them, such as OFDM channel estimation, multi-user detection, peak power reduction, channel coding, space-time signal processing, and adaptive beamforming.*

## 1. Introduction

Rapid progress in the development of device technology has made it possible for digital equipment to handle diverse multimedia content such as speech, music and video. We envision that future mobile communications will be able to provide this type of content, which can be accessed seamlessly, at higher speed and with higher quality. The requirements of Fourth-Generation (4G) mobile communications are substantially higher than those of Third-Generation (3G) mobile communications (IMT-2000: International Mobile Telecommunications-2000). In order to meet these requirements it will be necessary to implement wireless access technology that is higher speed and has higher capacity without sacrificing the features of existing 2nd and 3rd Generation systems in terms of their service areas, mobile terminal size, ease of use, or cost.

If the target transmission speed of 4G systems is set to 100 Mbit/s, it will become necessary to use frequency bands of 50–100 MHz, which exceeds the bandwidth of current systems [1]. When transmitting broadband signals, a large number of propagation paths will contribute to the received signal. In such a severe multipath environments, better performances are obtained with Orthogonal Frequency Division Multiplexing (OFDM) than with single carrier modulation used in 3G systems. Furthermore, Multiple Input Multiple Output (MIMO) technology which involves the use of multiple antennas can be used to increase the capacity (i.e., speed) of data transmission in a given frequency band. Therefore, with a view to the future realization of 4G systems, we are conducting a variety of studies to improve transmission speeds and increase the efficiency of bandwidth use by focusing on technology relating to MIMO and multi-carrier schemes such as OFDM.

Specifically, we have proposed a solution for MIMO-OFDM channel estimation, which supports high velocities of the mobile terminal, even at severely distorted channels. For OFDM with spreading, we have made new proposals for detection schemes aimed at improving the Bit Error Rate (BER). Furthermore, since multi-carrier systems cause peak power problems, we have proposed a scheme for analyzing peak reduction techniques, and a channel coding technique suitable for OFDM systems.

For MIMO systems, we have proposed a transmit diversity scheme in which different data sequences are transmitted from transmitting antennas with temporal, spatial and frequency correlations. To perform coherent detection in MIMO systems, a large number of pilot signals are needed for channel estimation. This has an adverse effect on efficiency. We have therefore proposed a new scheme for differential space-time modulation that makes these pilot signals unnecessary and allows the available bandwidth to be used very efficiently. Also, in the field of directional transmission, we have proposed a beamforming technique that uses long term channel knowledge and a space-time signal processing method that improves performence by signal processing in time and space directions in transmitter.

## 2. Multi-carrier Systems for Broadband Wireless Access

With the development of Digital Signal Processing (DSP) technology and the desire for broadband connectivity even over severely dispersive channels, multi-carrier modulation appears to be a technology whose time has come. OFDM offers efficient implementation through the application of the Fast Fourier Transform (FFT). Moreover, by inserting a cyclic prefix, an equalizer can be omitted. How multi-carrier systems can be implemented in future mobile communication systems is the subject of current research.

## 2.1 Performance Enhancement of MC-CDMA

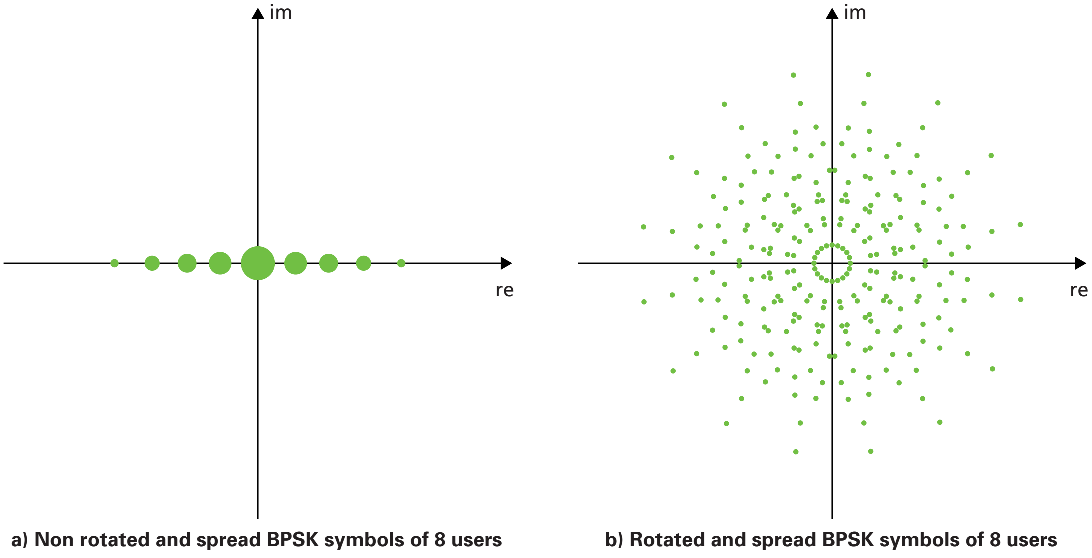
For Multi Carrier-Code Division Multiple Access (MC-CDMA), OFDM is combined with CDMA by spreading the data across subcarriers in the frequency direction. If these spread subcarriers are subject to independent fading, diversity can be utilized. That is, if one subcarrier is in a deep fade, its information is lost. However, other subcarriers which are received with better quality may compensate for that. Since the information is spread over many subcarriers, diversity can be utilized. On the other hand, orthogonality of the spreading codes will be lost which causes multiple access interference. By using a Multi-User Detector (MUD) the performance degradation due to multiple access interference can be reduced.

We are working on advanced detection schemes to push detection for MC-CDMA towards the theoretical limit, which is the single user bound. One approach is based on iterative processing, i.e. applying the "turbo" principle. In particular, we are investigating a soft interference canceller [2], which cancels the multiple access interference weighted by reliability information provided by the channel decoder from the previous iteration.

The performance of MC-CDMA with MUD can be improved by using rotated spreading sequences instead of conventional Walsh-Hadamard sequences. If the spreading codes are Walsh-Hadamard sequences, the distribution of the signal space is limited to nine distinct constellation points, as shown in **Figure 1** a), for a Binary Phase Shift keying (BPSK) modulated signal with unrotated spreading, a Spreading Factor (SF) of 8, and eight users. Here, the area size of each distribution point corresponds to degree of signal overlapping. Note that, about 20% of all subcarriers are equal to zero, i.e. no signal is transmitted on these subcarriers. On the other hand, a more favorable distribution of the signal space is obtained if rotated transforms are used, shown in Fig.1 b). The spread signal is distributed on 256 points in the complex plane, so each signal point is uniquely defined. Hence, the signal energy is distributed more equally across subcarriers, which allows to exploit diversity more efficiently. By using rotated transforms, up to 3dB in $E_b/N_0$ for an uncoded system can be gained. For a coded system with rate of 2/3, about 1dB can still be gained, while with a coding rate of 1/2 no difference between rotated and unrotated spreading is observed [3]. So, it can be concluded that MC-CDMA with rotated spreading sequences is of advantage for high code rates. In [4] we have verified that these gains can also be achieved if realistic channel estimation is taken into account.

## 2.2 MIMO-OFDM Channel Estimation

A received OFDM frame may be viewed as a two Dimensional (2D) grid, where each field specifies a certain subcarrier $i$ and OFDM symbol $l$. The received signal in each field is a complex value $Y_{l,i} = H_{l,i} X_{l,i} + N_{l,i}$. In order to detect $X_{l,i,}$ the Channel Transfer Function (CTF) $H_{l,i}$ must be estimated in the entire frame. For multi-carrier systems the channel response is typically correlated in two dimensions, in time and frequency. By invoking the sampling theorem, the 2D channel response



a) Non rotated and spread BPSK symbols of 8 users

b) Rotated and spread BPSK symbols of 8 users

Figure 1 Distribution of the spread MC-CDMA signal in the complex plain can be reconstructed by "sampling" the CTF in the 2D plane. This sampling operation is realized by periodically inserting pilots in the time-frequency grid, termed Pilot-symbol Aided Channel Estimation (PACE).

The application of the sampling theorem is intuitively appealing, since it yields the minimum possible 2D pilot spacing given the characteristics of a certain channel and the OFDM system parameters. In order to implement PACE, 2D filtering algorithms have been proposed based on Wiener filtering. Unfortunately, such a 2D estimator structure may be too complex for practical implementation. To reduce the complexity, two cascaded 1D estimators in time and frequency may be used instead as indicated in **Figure 2**, termed two times one dimensional (2x1D) PACE [5]. In the 1st step, the channel is estimated at pilot positions in the first dimension, which in Fig.2 is the frequency direction, to yield tentative estimates of all subcarriers. In the 2nd step, the channel is estimated in the time direction using the tentative estimates of the 1st stage, to yield the final estimate.

For MIMO systems, $N_t$ channels, corresponding to $N_t$ transmit antennas, need to be estimated. If PACE is to be used for MIMO-OFDM channel estimation, it requires about $N_t$ more pilot symbols than a comparable single transmit antenna system. Thus, the efficient use of pilot symbols becomes even more important. We believe that the realization of 2x1D PACE makes it possible to keep the pilot symbol overhead at an acceptable level, while maintaining a practicable estimator complexity, even at high velocities of the mobile terminal. So, 2x1D PACE provides an efficient means of putting MIMO-OFDM systems into practice. To this end, we have proposed a 2x1D PACE scheme suitable for MIMO-OFDM systems [6], [7]. Furthermore, we have developed an algorithm which can efficiently separate $N_t$ superimposed signals, corresponding to $N_t$ transmit antennas, by exploiting the properties of the Discrete Fourier Transform (DFT) [8].

### 2.3 Peak Power Reduction for OFDM

OFDM suffers from high signal peaks, which originate from the superposition of subcarriers. The high power amplifier heavily distorts all signal parts that come close to or exceed saturation. The distortion causes Inter-Carrier Interference (ICI) and out-of-band radiation. While ICI disturbs the transmitted signal and degrades the BER, out-of-band radiation disturbs signals on adjacent frequency bands and should also be avoided.

The peaks can be reduced by digital signal processing at the transmitter. Distortion techniques usually clip the peak amplitudes of the signal. Furthermore, it is necessary to limit the out-of-band radiation without significant increase of required $E_b/N_0$ by filtering the clipped signal before amplification and transmission.

**Figure 3** compares the performance of different clipping techniques for QPSK modulation, namely non-recursive clipping and recursive clipping [9], [10], and Active Constellation Extension (ACE) [11]. The y-axis shows the out-of-band radiation. The x-axis informs about the ICI, which corresponds to a loss in signal to noise ratio $E_b/N_0$, referring to the undistorted signal's $E_b/N_0$. Whereas the out-of-band radiation can be easily reduced by several decibels, it is quite difficult to achieve a very low out-of-band radiation for any of these clipping techniques. This is even more difficult for higher order modulation schemes [12].

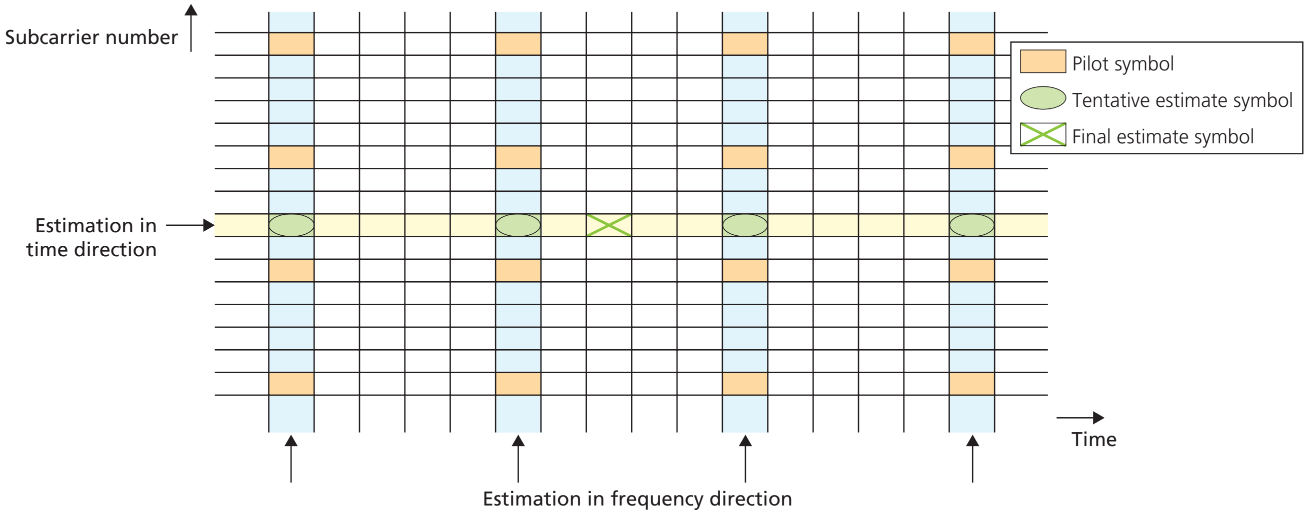


**Figure 2 Principle of 2x1D PACE**

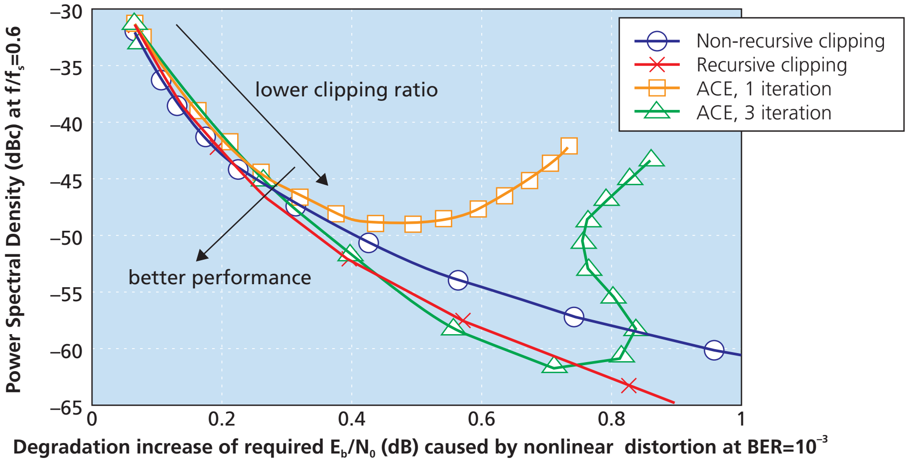


**Figure 3** Performance comparison of some clipping techniques for uncoded QPSK modulation and transmission over an AWGN channel

## 3. The Turbo Principle for Iterative Detection of Coded Data

Since their invention ten years ago, turbo codes have revolutionized the field of error control coding [13]. The idea of this turbo principle can be applied to a large variety of detection problems. We focus on ways to obtain a very flexible (adaptive coding rate), powerful but still relatively simple Forward Error Control (FEC) coding scheme which can be detected using the turbo principle. Particularly, we look at iterative demapping for bit-interleaved coded modulation where the Quadrature Amplitude Modulation (QAM) demapper is regarded as the inner constituent “code” [14] (see **Figure 4**). However, turbo gains in this scheme are only possible for special mappings of bits to QAM symbols which are different from Gray mapping. We have developed an algorithm to find such optimized mappings. With these mappings we obtained similar performance as with conventional turbo codes at a significantly lower detection complexity. Moreover, we have considered rate 1 recursive precoders for further performance improvement without rate loss. Performance results are shown in **Figure 5**. Our new mappings outperform Gray mapping and previously proposed mappings such as set partitioning. The turbo code as used in Universal Mobile Telecommunications System (UMTS) shows earlier convergence but a higher error floor. An error floor can be avoided by using a rate 1 precoder.

## 4. Multiple Antenna Systems

### 4.1 Transmit Diversity for MIMO-OFDM

Results from information theory show that the capacity of a wireless system can be significantly increased if multiple antennas are used at the transmitter and the receiver MIMO [15]. Therefore, future wireless systems will be equipped with multiple antennas at least at the base station. Several strategies exist in order to exploit the capacity increase offered by a MIMO channel.

If the channel is unknown to the transmitter, the theoretically optimum transmission technique for high data rate transmission in a MIMO channel—under the assumption that the antennas are separated far enough in order to guarantee independently fading channels from each transmit to each receive antenna—is spatial multiplexing. Here, independent data streams are transmitted simultaneously from multiple transmit antennas. Spatial multiplexing requires at least as many receive antennas as transmit antennas. Receivers are relatively complex. Furthermore, the performance of spatial multiplexing degrades in the case of channel imperfections such as spatial correlations or keyhole effects. A more robust multiple transmit antenna technique is spatial diversity which can be obtained using space-time or space-frequency codes. The idea is to transmit the same information via different antennas in such a way that the receiver is able to combine the contributions from all transmit antennas constructively. The reliability of the wireless link is improved, which enables higher data rates by using higher order modulation or lower coding rates. Orthogonal designs,

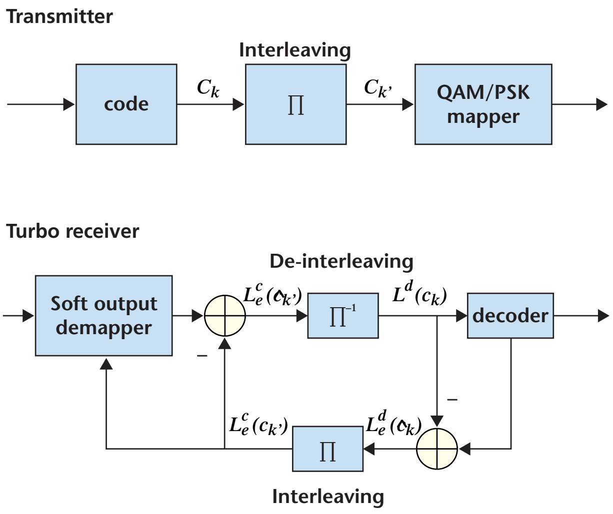


**Figure 4** Configuration of the proposed transmitter for bit-interleaved coded modulation and the turbo receiver for iterative demapping and decoding

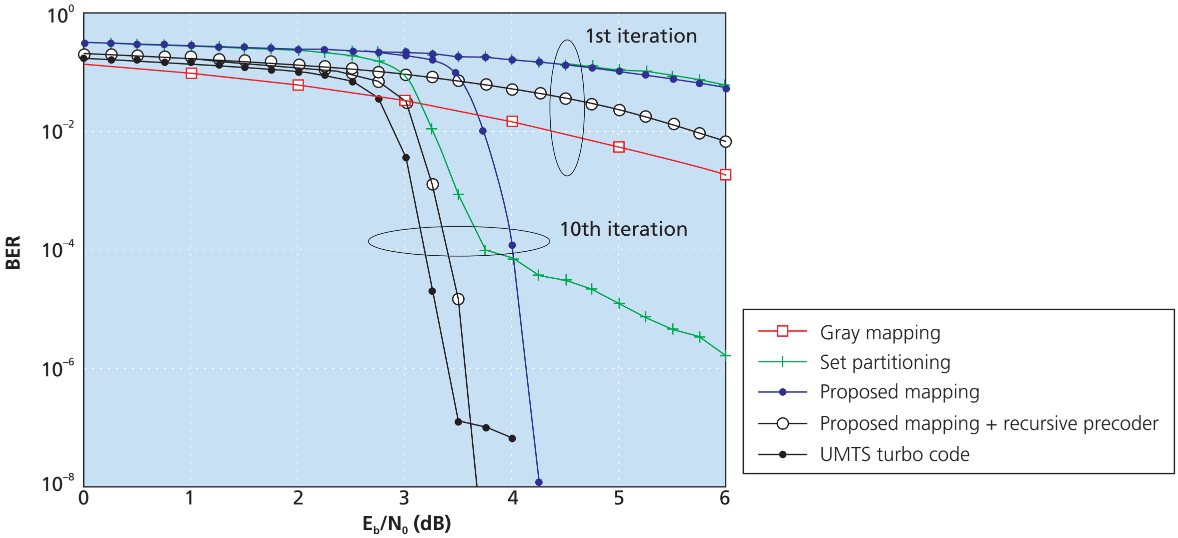


**Figure 5 Performance of bit-interleaved coded modulation with iterative demapping**

i.e. transmit matrices with orthogonal columns, can be used as a transmit diversity technique where essentially a simple combiner at the receiver transforms the fading MIMO channel into an equivalent Single Input Single Output (SISO) channel with a lower variance of the Signal to Noise Ratio (SNR).

We have proposed methods for the application of orthogonal designs in OFDM or MC-CDMA [16]-[19]. In order to allow a simple receiver which does not produce intersymbol interference, the channel needs to meet certain requirements relating to coherence time and coherence bandwidth. In our proposal, the elements of orthogonal designs are mapped to both different OFDM symbols and neighboring subcarriers taking into account coherence time and coherence bandwidth of the channel. This results in a simple and powerful orthogonal space-time-frequency coded system.

Furthermore, we have proposed a turbo detector for orthogonal transmit diversity [18]. Previous publications had shown that due to the orthogonal structure of orthogonal designs no extrinsic information can be obtained on the symbol level and that, therefore, turbo iterations cannot be effective. Similar to the iterative demapping technique described above, we have derived optimized mappings of bits to transmit symbols which enable significant turbo gains even with orthogonal designs at relatively low complexity.

The multiple antenna transmission techniques discussed so far require channel estimation at the receiver. Channel estimation is more difficult in multiple transmit antenna systems than in single antenna systems since more coefficients have to be estimated and the transmit power of the pilots has to be distributed over several antennas. At least, more pilot symbols are required. Therefore, differential transmit techniques are attractive alternatives since they can be detected non-coherently without any channel estimation. Differential unitary space-time modulation has been proposed in [20]. Here, bits are mapped on a unitary matrix $C_k$. The transmit matrix is obtained by differential encoding of $C_k$ with the previously transmitted matrix $C_{k-1}$. Unitary matrices are usually constructed based on PSK constellation elements. However, the distance properties of M-ary PSK are only advantageous up to M=8. For higher order modulation it is better to code the information in both phase and amplitude. Therefore, we have developed a differential multiple transmit antenna scheme where unitary space-time modulation is extended by a differential cyclic amplitude modulation on matrix basis [21] (see **Figure 6**). We have derived a completely non-coherent soft-output detector for the scheme which in contrast to most soft-output detectors for differential schemes does not require any knowledge about the channel state or its statistics. The proposed scheme significantly outperforms unitary space-time modulation at high bandwidth-efficiencies particularly in time-varying channels or frequency-selective multicarrier channels. At the same time it has lower detection complexity.

### 4.2 Adaptive Beamforming

If the transmitter has knowledge of the long-term channel properties, we can apply beamforming techniques in order to concentrate the transmit energy in dimensions where the information can be transmitted most efficiently. A powerful beamforming technique is Eigenbeamforming where the antenna

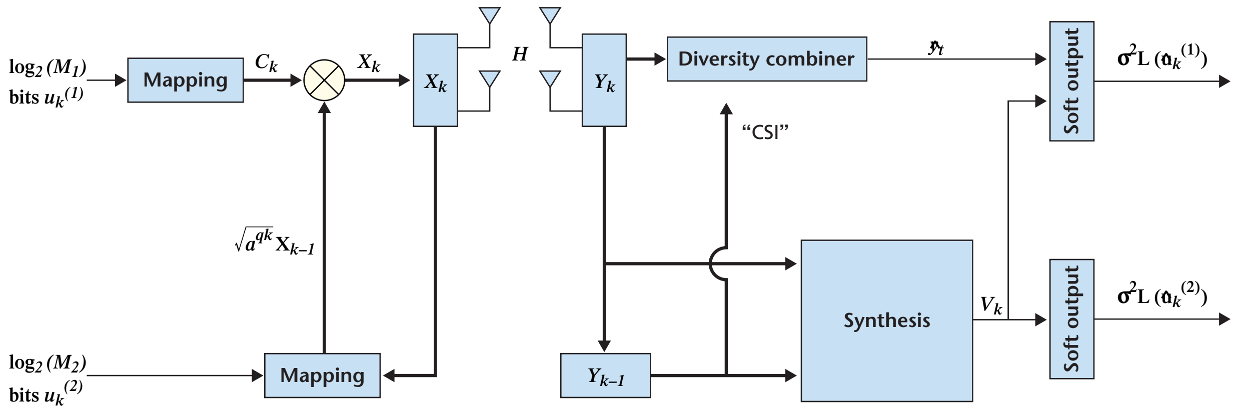


**Figure 6 Bandwidth-efficient differential space-time modulation**

weights are given by the Eigenvectors of the spatial covariance matrix. We proposed transmit processing techniques which combine Eigenbeamforming and MIMO concepts such as spatial multiplexing and transmit diversity [22]. We derived criteria and algorithms for adaptive transmission with the optimum number of Eigenbeams and optimum power and data rate allocation to the Eigenbeams.

As another possibility to make use of channel knowledge at the transmitter, we have developed a space-time transmit processing which avoids or reduces the effect of interference due to a delay spread of the channel which exceeds the guard interval [23]. By applying the proposed scheme to the downlink, the receivers (i.e. the mobile terminals) can be kept simple without the need for complex operations like equalization.

## 5. Conclusion

This article summarized the status and achievements of research in wireless communications at DoCoMo Euro-Labs. We will continue to carry out research on 4G, and we will collaborate with excellent European research institutes in those fields. We hope to achieve a global impact and to contribute to the realization of 4G systems.

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## ABBREVIATIONS

2D: 2 Dimensiona1
ACE: Active Constellation Extension
AWGN: Additive White Gaussian Noise
BER: Bit Error Rate
BPSK: Binary Phase Shift Keying
CDMA: Code Division Multiple Access
CTF: Channel Transfer Function
CSI: Channel State Information
DFT: Discrete Fourier Transform
DSP: Digital Signal Processing
$E_b/N_0$: Signal energy per bit to background noise power spectrum density ratio
FFT: Fast Fourier Transform
ICI: Inter Carrier Interference
IMT-2000: International Mobile Telecommunications-2000
MC-CDMA: Multi Carrier-Code Division Multiple Access
MIMO: Multiple Input Multiple Output
MUD: Multi User Detection
OFDM: Orthogonal Frequency Division Multiplexing
PACE: Pilot symbol Aided Channel Estimation
PSK: Phase Shift Keying
QAM: Quadrature Amplitude Modulation
QPSK: Quadrature Phase Shift Keying
SF: Spreading Factor
SISO: Single Input Single Output
UMTS: Universal Mobile Telecommunications System