4MORE: An Advanced MIMO Downlink MC-CDMA System

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ABSTRACT

The IST 4MORE project defines a multicarrier code division multiple access (MC-CDMA) radio system with multiple mobile users and advances this one step towards implementation through the design of a System on Chip (SoC) for a 4G terminal employing multiple antennas, based on MC-CDMA. In this contribution we present results of the simulated downlink scenario, which is the base for the designed demonstrator. We cover different channels, various modulation schemes, coarse time synchronization, carrier frequency offset tracking and finally the effect and countermeasures which are needed for RF impairments. The implemented air interface offers transmitting 5.5 bits/s/Hz over two spatial parallel multiplexed data streams.

I. INTRODUCTION

The 4MORE project aims at advancing one step towards implementation for a 4G terminal employing multiple antennas through the design of a System on Chip (SoC). The system is based on MC-CDMA. In order to increase capacity and/or diversity, systems with four antennas at the base station and two at the mobile station are considered. This results in a 2x4 antenna system for the uplink and a 4x2 system for the downlink. Different techniques have been compared in the predecessor project for both uplink and downlink. The choices lead to the MC-CDMA technique for downlink and spread spectrum multi carrier multiple access (SS-MC-MA) for uplink. SS-MC-MA has been selected mainly to reduce the complexity of synchronization and UL channel estimation for all users and is investigated in [4].

MC-CDMA systems have been extensively investigated [1] for the down- and uplink. The general advantage versus a pure OFDM system is the additional degree of freedom for the dynamic resource allocation schemes in the MAC layer. The diversity gain in flat and static channels is small. On the other hand a low degree of diversity means that multiple access interference does not degrade the performance significantly despite the use of simple detectors and in addition the channel estimation algorithm can be simple as well. The simplicity has enormous significance considering that the IST 4MORE project will present a demonstrator at the IST summit in 2006 including RF air interfaces with four antennas at the base station and two mobiles each equipped with two antennas.

The results presented in this contribution correspond to simulation results in order to evaluate the physical layer performance of the demonstrator. The simulations include channel estimation, synchronization, RF impairments and compensation algorithms for the last ones.

The document is organised as follows. Section II gives a description of the system model followed in Section III by the slot and frame structure as well as system parameters. In Section IV we highlight the main problems that we encountered in the setup of our MC-CDMA MIMO demonstrator system. Simulation results and discussion about the findings are covered in Section V.

II. SYSTEM MODEL

Figure 1 shows a simplified MC-CDMA system for the downlink. The bits from each user $j$ are encoded by a convolutional channel encoder and then modulated to complex data symbols. The complex modulated data signals $d^{(j)}$ of each user $j$ are spread with a Walsh-Hadamard sequence $c^{(j)}$ of length $L$, where the maximum number of users is $K_{\text{max}} \leq L$. The spread data signal $s$ is then split into two data streams and each is fed into one Alamouti STBC encoder.

Figure 1: SISO MC-CDMA transmitter system for the downlink
which may carry a cyclic prefix. i.e. as illustrated in Figure 2.

The spatial scheme used for the 4-transmit and 2-receive antennas in the downlink is the double Alamouti scheme [2] from the number of UL slots allowing the operator to deal with asymmetrical traffic needs of the users. The allocation from the propagation channel.

Then the data streams are sent over two pairs of antennas to the mobile users. At the receiver, the signals from the two antennas are submitted to space-time combining based on minimum mean square error (MMSE) criterion. The mobile users have to deal with data symbols which are spread twice, by the CDMA unit and by the Alamouti scheme. Therefore, the received data is equalized twice, once by the space-time equalizer based on MMSE and afterwards by an equal gain combiner (EGC).

III. FRAME STRUCTURE

In the following, the parameters and the frame and slot structure of the 4MORE system are described in order to allow a quick understanding of the system. The main goal of the proposed set of system parameters is to provide flexibility to the frame structure to allow either an optimisation of the spectral efficiency using an extended slot size or pre-filtering solutions based on the TDD channel reciprocity by using a short slot size. The TDD frame structure describes different antenna systems either a 2x2 or a 4x2 (TxxRx) system. The 2x2 system is used for backwards compatibility and fallback solution. The chosen frame represented by Figure 3 is a 10 ms frame made of 15 slots of 0.667 ms as it is defined for UMTS. Each slot is dedicated either to uplink (UL) or to downlink (DL) communications. The number of DL slots can be different from the number of UL slots allowing the operator to deal with asymmetrical traffic needs of the users. The allocation of UL and DL slots in the frame is determined by the network and can change at each new frame depending on traffic conditions. The base station (BS) regularly informs in advance each MT (mobile terminal) through a control channel about the allocation that has been chosen for the next frames.

Each UL and DL slot is composed of several symbols along the frequency and time dimensions of the OFDM frame. These symbols may be synchronisation or pilot symbols (represented in blue in this example) or data symbols (represented in green). The duration of each symbol includes the duration of the OFDM symbol itself i.e. $T_{FFT}$, plus the duration of the OFDM guard interval, $T_g$, which may carry a cyclic prefix.

Assuming a sampling frequency denoted as $f_s$, the number of samples composing one OFDM symbol and the number of samples composing one guard interval, respectively denoted as $N_{FFT}$ and $N_g$ are defined as:

$$N_{FFT} = T_{FFT}/f_s$$

$$N_g = T_g/f_s$$

(1)

$T_g$ and $T_{FFT}$ are generally set up according to other system parameters such as the maximum delay spread of the propagation channel.

At the end of each slot, a TDD guard time, represented here in red, is usually introduced so as to avoid that UL and DL communications interfere each other. During this guard time, no information is transmitted. The duration of this TDD guard time $T_G$ is related to the cell range as it corresponds to the maximum round trip delay, i.e.:

$$T_G \geq 2 \frac{R}{c}$$

(2)

where $R$ is the size of the communication area (e.g. the cell size in cellular environments) and $c$ is the light celerity. The TDD guard time has thus not necessarily the same duration than the OFDM symbols.

A drawback of this conventional scheme is that the guard time is still introduced between two consecutive slots dedicated to the same link, i.e. two consecutive UL slots or two consecutive DL slots. In that case, even if no interference can occur between these slots, the time period $T_G$ is not used for transmission, which results in an inefficient usage of the available data rate. In the 4MORE frame structure depicted in Figure 4, the duration of the TDD guard time between these consecutive slots is used to transmit useful OFDM symbols. This results in an extended downlink slot, which increases the useful data rate. To achieve it, the TDD guard time is set to be an OFDM symbol duration, i.e.,

$$N_G = T_G/f_s = N_{FFT} + N_g$$

(3)

Figure 2: Double Alamouti scheme for a 4 transmit antenna system

Figure 3: Conventional frame and slot structures in a TDD system.

Figure 4: 4MORE frame structure with extended slots.
In addition, as some pilots may become useless in an extended slot, they may be replaced by data symbols.

**Time slot structure**

To match the functionalities targeted by the 4MORE demonstrator, additional constraints have been taken into account.

For the downlink 4x2 MIMO MC-CDMA transmission,
- One OFDM symbol per slot is devoted to synchronisation (in yellow). This symbol is composed of 10 repetitions of a \((N_{\text{FFT}} + N_d)/10\) chip long sequence,
- Full OFDM pilot symbols are inserted in the slot to regularly estimate the channel at the moving terminal (in red),
- Each time the channel estimation is processed, 2 full OFDM symbols are needed to estimate the channels from the 4 transmit antennas;
- Two-dimensional spreading \((S_F=S_{FFSFT})\) requires a number of OFDM data symbols and a number of data modulated carriers, which are both a multiple of a power of 2.

The chosen time structure for the downlink allowing \(S_F=8\) is represented in Figure 5.

**Figure 5: Timeslot structure for the downlink allowing \(S_F=8\).**

**Frequency frame structure**

The number of continuous pilot sub-carriers required for efficient carrier frequency offset calculation and compensation is \(N_p=22\) carriers per OFDM symbol. The pilots are the same on each transmit antenna. The frequency structure of each OFDM data symbol is obtained as depicted in Figure 6.

**Figure 6: OFDM symbol structure in downlink.**

**Channel modelling**

In the simulations the MIMO BRAN A and BRAN E channels are based on 3GPP/SCM definition [3] for a MIMO channel exploiting multipath angular characteristics. The model parameters are adapted to the 5.15 GHz carrier frequency and use the BRAN E channel average power delay profile (APDP) which refers to a typical outdoor urban multi-path propagation. The BRAN A APDP which refers to an indoor scenario is also adapted to the 5.15GHz carrier frequency. The velocities that are studied are 3 km/h for BRAN A and 60 km/h for BRAN E channels. QPSK, 16QAM and 64QAM modulations associated with convolutional channel code of different rates are considered.

**IV. MODELLING OF RF IMPAIRMENTS**

For up/down frequency conversions to/from RF band a double (two-step) direct conversion was preferred to Intermediate Frequency (IF) conversion in order to reduce equipment costs. Base-band signal is directly up-converted to L-band (1.2 GHz) and afterwards to RF frequency (5.2 GHz). Impairments caused by RF front-end processing, that is, distortions from the base-band point of view, were analyzed and measured for the RF front-end specifically designed for the purposes of IST-4MORE project. RF impairments are modelled in the simulation chain in order to assess the degradation they may cause and to evaluate the necessity for their potential compensation.

For that purpose, non-linear AM to AM distortions of High Power Amplifer (HPA) were modelled at the transmitter. At the receiver, amplitude and phase imbalances of in-phase and quadrature (I and Q) branches were modelled, as well as the relative delay between them. This delay is caused by the difference in length of the internal cabling (up to 800 ps) and, consequently, the mismatch of a fractional part of chip rate in the sampled signals. This degradation is found to be a limiting factor for satisfactory performance of dense modulation modes and digital compensation with frequency dependent filtering per branch is performed to minimize its effect. Besides I and Q mismatches, phase noise from the RF to L-band receiver was modelled. An Automatic Gain Control (AGC) module that maintains the level of input signal at some nearly constant mean power value follows RF impairments. The performance results in terms of BER show that degradation due to RF impairments and AGC is almost negligible, except for the I/Q frequency dependent delay that has to be minimized either by careful adjustment of cables or digital compensation.

**V. SIMULATION RESULTS**

In Table 1 the main system parameters are outlined that are used perform the simulations. For coarse time/frequency synchronization one OFDM symbol is assumed. The channel estimation is performed based on full pilots. Observations on full-pilot symbols are correlated with pilot sequences and correlation results on each sub-carrier are averaged over time, i.e., over two consecutive full pilot OFDM symbols. A Wiener filtering in the frequency domain is then performed. The Wiener filter takes into account the maximum tap delay of the multi-path channel. Time interpolation is finally performed between pairs of pilots. The double Alamouti scheme uses two pairs of transmit antennas, each pair applies a single MC-CDMA data stream. The spatial multiplexed signals interfere with
each other and the interference is encountered by an MMSE detector.

Each spread data stream is equalized by an equal gain combiner (EGC) before despreading. The initial data symbols are interfered twice by neighbouring data signals because of the spreading and by neighbouring spatial data streams. We perform block spreading that says the spread data symbols, chips, are not interleaved over the subcarriers to increase diversity. By this we keep the correlation high between the chips of a single block and therefore the multiple access interference low.

In all presented figures except Figure 11 the synchronization is assumed to be perfect and carrier frequency offset (CFO) is null.

The performances achieved by the simulation chain for a reference scenario, that we called “best setup”, where perfect channel estimation is assumed and no automatic gain control (AGC) or radio frequency (RF) impairments exist, are represented in Figure 7. This picture shows the performance regarding both BRAN channels, for a system using three different constellations, QPSK with a rate of R=1/2, 16-QAM with a rate of R=2/3 and 64-QAM with a rate of R=3/4 and all three modes were performed with three different system loads (single user, half load and full load).

In Figure 8 we compare for the channel BRAN A the effect of real channel versus the perfect channel estimation always for the same code rate of R=1/2, but for different modulation schemes. Keeping the same channel code allows us to focus only on the impact of the channel estimation on the different modulation schemes. In general, systems with higher modulation are expected to be more vulnerable for channel estimation errors. On the other hand, the SNR working point for the channel estimation is higher for higher modulation alphabets. Therefore, the impact of channel estimation errors reduces due to the lower mean square error caused by the channel estimator. The gaps between the various loaded systems for QPSK and 16-QAM decrease, as the working point of the SNR is about 14 dB higher, and about 20 dB higher comparing 64-QAM against QPSK. The lower levels of noise which are vulnerable for channel estimation errors. On the other hand, the EGC detector profit from the higher working point of the 16-QAM system. Latter is also very visible for 64-QAM for perfect channel estimation, where all curves overlap.

In Figure 9 we compare the effect of an activated AGC controller with real channel estimation versus the perfect setup. An abnormal behaviour is observed regarding single user performance in the system using 64-QAM when AGC is activated. Apart from this, all performance gain or loss caused by AGC is always less than 0.75 dB for all considered scenarios. The deviation for single user comes from the fact that the signal at the receiver input presents large variations, as powers for user data and pilots are quite different. A preliminary version of the AGC was not designed to adapt to this type of signals, and therefore it is cutting the pilots and amplifying the data signal at the same time, causing two problems. First, data signal amplification or variation, which produces wrong noise sigma value at the equalizer, and second, wrong channel estimation due to corrupted pilots. Nevertheless, the AGC still works for a half loaded system, as amplitude variations between data and pilots in that scenario are small enough.

In Figure 10 we compare the effect of RF impairments with real channel estimation versus the perfect setup. The RF impairments are modelled both at transmitter (HPA) and receiver sides (phase noise and I/Q gain, phase and delay mismatches). For the evaluation of RF impairments, we assumed both components (Tx and Rx) simultaneously active. The degradation is minimized including IQ delay compensation. Nevertheless, the phase noise of 4MORE RF front-end prohibits the use of higher modulation alphabets, and the error floor can be observed for 64QAM.

In Figure 11 we investigate the impact on the BER of the Carrier Frequency Offset compensation together with coarse time synchronization. In those simulations, we assume a CFO of 17% of the subcarrier spacing (except for reference curve where CFO is null). Indeed the stability of the reference oscillator in the 4MORE demonstrator is ±1ppm). QPSK modulation and a BRAN E channel with real channel estimation are assumed. For one curve we assume real time synchronization.

The synchronization is done on both receive antennas at a time by comparing, at each chip n, a metric to a threshold (the choice of the threshold is out of the scope of this paper). The metric is computed thanks to a 128 chip long autocorrelation. The CFO estimation method is based on the phase of the complex correlation between two consecutive received versions of a training symbol, thanks to continuous pilots. In Figure 11 we present results for estimations averaged over 6 and 24 symbols.

As a first result we can note that neither compensating the CFO before FFT nor after FFT is sufficient to reach the performance of a non corrupted system, whereas the estimation is averaged on the maximum number of symbols (i.e. 24). When compensating before and after FFT, 6 symbols are enough to compensate all the offset. Concerning synchronization, the presented method allows synchronizing perfectly the received signal.
Channelisation bandwidth $B_C$ 50 MHz
Max delay spread $\Delta$ 4 $\mu$s
Cell radius $R$ < 1 km
Guard time $G$ > 6.66 $\mu$s
FFT size $N_{FFT}$ 1024
Slot duration $T_{slot}$ 0.667 ms
Frame duration $T_{frame}$ 10 ms, 2 ms, ...
Extended slot duration $T_{slot}$ 0.667(F+1) ms
Sampling frequency $f_s=1/T_S$ 61.44 MHz
Number of samples per nominal slot $N_S$ 40960
Number of OFDM symbols per slot $N_T$ 32F+31
Guard duration $T_G$ 4.16 $\mu$s
Guard interval in samples $N_G$ 256
UL/DL guard time $T_G$ 20.8 $\mu$s
UL/DL guard time in samples $N_G$ 1280
Number of DL modulated sub-carriers $N_C$ 695
Occupied bandwidth in DL $B_O$ 41.7 MHz
Number of DL OFDM data symbols $N_{D,Symbol}$ 24 / 20
Number of DL OFDM pilot symbols $N_{P,Symbol}$ 6 / 10
Number of DL data sub-carriers $N_D$ 672
Number of DL pilot sub-carriers $N_P$ 22
Maximum (Simulated) total spreading factor in DL $S_F$ 256(32)
Maximum (Simulated) spreading factor in frequency DL $S_{FF}$ 32(32)
Maximum (Simulated) spreading factor in time DL $S_{FT}$ 8(1)

Table 1: System parameters
VI. SUMMARY
We presented results for the MIMO MC-CDMA downlink system of the IST-4MORE project. The simulation results are used to validate the demonstrator that will be shown at the IST summit in 2006. The 4MORE concept focuses on simple algorithms (due to hardware and time constraints) to equalize the signal (EGC), to estimate the channel by linear interpolation and to combine the two spatially separated data streams by an MMSE detector. It is interesting to note that for high modulation schemes, like 64-QAM the difference between single user bound and the full load case is negligible as long as the channel is very well estimated. This is especially emphasized by comparing the results for activated impairments (Figure 9 and 9) versus the perfect setup (Figure 7 and 7).

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REFERENCES