Space-Time-DFE for Adaptive Array Antennas in 4G Wireless Communications
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Abstract
The feasibility of a space-time decision feedback equalizer applied to the uplink of a 12.8 Mbit/s QPSK-system is demonstrated by means of link and system level simulations of real-world-like propagation and cell scenarios. Even for small antenna arrays of only 4 sensors an SDMA gain of 67% is achieved, i.e. 5 users per cell may be loaded to only 3 carrier frequencies. For scenarios with omnidirectional coverage, uniform circular arrays present better performance than uniform linear arrays.

1 Introduction
Fourth generation (4G) mobile communication systems will support high data rates in the range of 10 Mbit/s or above [Moh00]. The radio channels on which these systems will operate introduce severe intersymbol interference (ISI), which has to be mitigated. On the other hand, the overall spectrum efficiency (bits/sec/Hz) of the radio network has to be as high as possible. This requires an appropriate modulation scheme that is resistant against co-channel interference (CCI). An optimum system performance requires the adoption of a well-designed strategy for both equalization and CCI-suppression. Due to the high symbol rate only relative simple transceiver algorithms can be implemented.

The common modulation format postulated for 4G is multi-carrier accommodating straightforward frequency domain equalization [Sam02]. However, multi-carrier suffers from the large peak-to-mean-power ratio of its transmission signal imposing some expense in the power-amplifier and from strong requirements on the carrier phase synchronisation. Alternatives arise from the combination of robust single-carrier modulation with sub-optimum space-time equalization of moderate complexity. A beamformer connected with a MLSE of low state number is one possible choice for an appropriate space-time equalizer [Heb02]. Another technique relies on the decision feedback concept.

The decision-feedback equalizer (DFE) is an attractive method for equalization in high rate single carrier systems, as it performs well at moderate implementation costs. With minor extensions, the DFE can additionally exploit the spatial characteristics of the mobile propagation channel using antenna arrays [Tra00]. Such joint equalization in both spatial and temporal domains exhibits advantages over simple combination of adaptive beamforming and traditional equalization, since it offers more degrees of freedom against the hindrances mentioned above. In the following we restrict ourselves to the investigation of the uplink, i.e. the array antenna and the DFE-receiver are located at the base station.

Packet data based systems like 4G wireless local area networks usually employ a preamble for receiver synchronization and adaptation purpose. While the DFE itself is easy to map onto hardware, the fast adaptation of its filter coefficients during the preamble phase is a more difficult task. Because it is part of the critical path of packet decoding, quick computation of the coefficients is essential. Here, the Fast Kalman sequential adaptation algorithm is investigated.

2 Radio Interface and Transceiver Layout
A TDD scheme is considered with a transmission frame of 0.2 ms duration, structured in training period, payload phase and guard as shown in Fig. 1. The short frame length assures stationary propagation conditions during the complete frame period. The symbol rate is 7.68 MHz. The training period consists of a complex-valued Gold sequence of 128 symbols. Gold sequences are chosen because of their good cross-correlation characteristics, which allow the base station to separate users allocated on the same frequency at the same time. A length of 128 symbols is demonstrated to be long enough for the adaptation algorithm to converge.

The effective payload rate is 1280 data symbols per frame, which corresponds to 6.4 Msym/s. QPSK modulation is used, so that a data rate of 12.8 Mbit/s is achieved. A FDMA scheme is considered for the re-

| 128 pilots | 1280 payload symbols | 128 guard |

Fig 1: Transmission frame
source allocation among different common shared packet channels in a cell. Moreover, multiple usage of the same frequency at the same time within a cell or within adjacent cells is proposed by applying smart antennas, leading to SDMA schemes. Temporal resource allocation with TDMA structures could additionally been considered in order to further enhance the system flexibility.

The proposed space-time receiver is depicted in Fig. 2. The I/Q-demodulated complex baseband-signals delivered by the M branches of an antenna array are processed by feedforward filters (FFF) and combined at sample rate. The ISI remaining in this sample rate signal is cancelled by the output of a feedback FIR filter (FBF), which is running on sliced symbols. The FFFs are T/2-fractionally spaced FIR filters. A fractionally-spaced structure is used because of its insensitivity to sampling phase offset and superior performance for channels with strong frequency-selective fading. A fixed total number of filter tap coefficients are allocated to the feedforward filters of all branches. The FFFs have been dimensioned with overall 24 filter tap coefficients as a trade-off between performance gain versus computational complexity. 5 filter taps were allocated to the FBF. Thus, a channel memory of only 4 symbol durations (about 0.52 µs) can be emulated by the FBF, which seems to be small compared to the impulse response duration of typical radio channels. However, the use of adaptive antennas results in a reduction of the virtual delay spread observed by the feedback part. Correspondingly, intersymbol interference is reduced due to the suppression of received signal components of large excess delay. Therefore, a shorter effective channel memory can be reasonably considered.

The recursive least squares algorithm (RLS) and its Fast Kalman derivate have been investigated for DFE adaptation. The latter makes use of a shift invariance property of the data matrix [Fal78]. Both adaptation methods offer similar performance in terms of accuracy and convergence. The Fast Kalman offers lower computational complexity for up to 4 sensors if T/2-fractionally spaced FFFs are employed. For larger sensor numbers the RLS is more favorable.

3 Performance on Link-Level

The link-level performance of the suggested space-time equalizer is investigated by means of computer simulations. For this purpose a statistical channel model including the directional characteristics of the real-world propagation channel is required.

Signals transmitted from different users experiment different realizations of the directional multipath channel, which is kept time-invariant during a complete transmission frame length and newly tossed for the next frame. The WSSUS-type directional channel simulator used here characterizes the multipath propagation by means of excess delays, direction-of-arrival (DOA) at the BS antenna array and mean powers of the multipath components. The model simulates a single-input-multiple-output (SIMO) multipath channel corresponding to an uplink radio link. More information dealing with the background, the application and the real-world-like configuration of this channel simulator can be found in [Mar98]. The model parameters used here are derived based on reports from sounding experiments in industrial environments in the 5 GHz band [Tra00]. The applied model settings result in a mean delay-spread of 0.32 µs and a mean angular spread of 20 degrees.

Simulations with the proposed receiver structure have been run in order to investigate the level of CCI resistance possible with space-time DFE. For this purpose, 2 users were allocated at the same frequency.

Fig. 4 and Fig. 5 show the measured bit error rates (BER) for uniform linear arrays (ULA) of 4 and 8 sensors spaced with λ/2. In each case the line-of-sight (LOS) broadside angle of the desired user is 30°. The interferer is placed in three different broadside angles (-30°, 0° and 30°). The investigated interference conditions yield CIR values from -20 to 0dB. A background noise level modeled with a SNR = 20 dB is assumed.

![Fig. 4: BER in case of an ULA with 4 sensors](image-url)
Fig. 6: Geometries of array antennas

Obviously, the receiver can take advantage of the multipath characteristics of the propagation channel to discriminate signals arriving from different sources even if they are seen under the same LOS-angle. Although the BER performance for the 8-sensor case is significantly better than for 4 antenna elements, the lower base station receiver complexity of the latter configuration could make this solution even more suitable for applications for which channel conditions are not extremely unfavorable.

From additional simulation results (not shown here) it can be concluded that the degree of the FBF is not a determinant factor for the performance in space-time configurations. This can be explained by the fact that the equalization capabilities of the FBF can be at least partially supported by spatial filtering. By nulling out multipath components arriving at the sensor array with a large excess delay, the FBF is relieved from postcursor suppression. Thus, this filter is rapidly overdimensioned.

Other array geometries than the ULA may improve the performance. Here, uniform circular arrays (UCA) and sectorized uniform linear arrays (SULA) are investigated. Both structures cover not only a sector of the cell, as intended for a ULA, but the whole cell by receiving signals impinging in the array from all possible directions of arrival. Hence, 24 sensors were considered for these array arrangements to cover the three sectors, for a fair comparison with the 8-sensor ULA case. Fig. 6 depicts the three array geometries used in this simulation. In the UCA and SULA cases all sensors will jointly process the impinging wavefronts resulting in a performance gain compared to the ULA case.

To validate this, both the user and the co-channel interferer are positioned under angles of 60° relative to the broadside of the different sensor arrays. The simulation results are shown in Fig. 7. The best performance is obtained for the UCA. For the ULA, worse results are obtained as for both users located at 30°. This is due to the fact that the ULA offers a lower angular resolution as it steers the beam off-broadside. This explains also the better performance of the UCA compared to the SULA, since the former has uniform resolution as it steers around the full angular range.

4 Performance on System Level

In order to investigate the performance of the proposed equalizer at a system deployment level, the statistical distribution of the interference situations at link level has to be taken into consideration. The system level simulation approach consists of distributing users inside a cell, such that a maximum of two mobile equipments are simultaneously allocated to a single frequency. In this SDMA case, the capacity of the system is improved by 100% in comparison to conventional system deployment, which allocates only one user per carrier.

The CIR for a specific configuration is calculated according to a path-loss of 38 dB per decade. Lognormal shadowing with a variance of 10dB is taken into account. Users are uniformly distributed inside the cell area. An ideal frequency allocation is considered, which maximizes the minimum observed CIR value for each configuration. According to this optimum user-frequency allocation, the BER for the worst CIR case in the cell is calculated based on the relative angle between both users and making use of the BER values from the link level simulations. Each case is matched to the most critical similar situation investi-
Simulations for 1, 2 and 3 carrier frequencies per cell are performed. By using an efficient dynamic channel allocation (DCA) scheme, low CIR-values in a cell can be avoided, i.e. taking advantage of the better BER performance for higher CIR. Fig. 8 depicts the results from the simulations performed for an 8-sensor ULA. The curves show the cumulative distribution function of the BER values observed by the users in the cell for 1 (bottom), 2 (middle) and 3 (top) available carrier frequencies. This figure considers a total allocation of cell resources, i.e. 2 users per frequency (full loading).

An approach that will result in improved system performance – lower probability of large BER values – is partial loading. For full loading, 90% of the users will receive data with a BER better than $10^{-2}$ if 8 sensors and 2 frequencies are available at least. Appropriate channel coding schemes like Turbo-Codes can reduce the BER to values suitable for data transmission. For the partial loading situation, the system performance is significantly improved. In 90% of all cases BER values of $4 \times 10^{-1}$ or better for 8 antennas and of $10^{-2}$ or better for 4 antennas are achieved. The SDMA approach would work with sufficient performance even with small arrays if partial loading is applied!

5 Conclusions

The feasibility of the proposed space-time DFE in the uplink of a 12.8 Mbit/s QPSK-system is demonstrated. Even for small antenna arrays of only 4 sensors an SDMA gain of 67% is achieved, i.e. 5 users per cell may be loaded to only 3 carrier frequencies. A larger SDMA gain of 100% (2 users per carrier) requires 8-sensor arrays. For scenarios with omnidirectional coverage, UCAs present better performance than ULA sensor configurations. Further research results proposing another suitable receiver structure based on the combination of a reduced-state MLSE and a space-time beamformer are presented in [Jon03].

References


