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Mikael Sternad, Sorour Falahati, Uppsala University, Uppsala, Sweden and
Tommy Svensson, Chalmers University of Technology, Göteborg, Sweden

Adaptive OFDMA/TDMA Transmission at Vehicular Velocities

***Abstract*—Within the EU FP6 Integrated Project WINNER, adaptive transmission is investigated as a key technology for boosting the spectral efficiency of a new radio interface for 4G systems. Adaptive allocation of time-frequency bins in an OFDM-based system offers a significant potential, but also poses challenges. Within work package 2 of WINNER, we study critical issues such as the feasibility of adaptive transmission over fading downlink/uplink channels to/from vehicular terminals, the corresponding required channel prediction accuracy, and the required feedback control bandwidth. This paper summarizes recent results obtained within WINNER, and related results obtained within the Swedish Wireless IP project.**

***Index Terms*—4G mobile wireless systems, adaptive transmission and multiple access, Orthogonal Frequency Division Multiplexing (OFDM), spectral efficiency.**

Introduction

Adaptive systems allocate (schedule) time/frequency/antenna resources based on channel quality and user requirements. They enable efficient resource utilization and multi-user scheduling gains, when channels to different terminals fade independently. In systems based on OFDMA/TDMA, time-frequency resources (bins) are allocated. This provides a flexible small-scale granularity of the resources, ideal for transmitting small as well as large packets.

Based on results obtained within the Swedish Wireless IP project[1], we are assessing the feasibility of such methods in novel broadband radio interfaces within the EU FP6 Integrated Project WINNER[2].

We here investigate adaptive downlinks and uplinks based on fast scheduling and link adaptation, with a non-adaptive fall-back mode. Allocation of fast fading channels requires channel prediction: The SINR (signal to interference and noise ratio) at time $t+L$ must be predicted, for all potential resources.

In the proposed downlink, each terminal predicts the SINR over a major part of the total bandwidth. All active terminals then report e.g. suggested modulation formats over a shared uplink control channel. A scheduler, located close to one or several radio access points over which it has control, then allocates the downlink resources in a subsequent set of time-frequency bins.

In uplinks designed in a similar way, one has the problem that channels from each potential user will have to be estimated and predicted. In a system using FDD (frequency division duplexing), the estimation would have to take place at the access point, and be based on pilots transmitted by all active terminals. To avoid unacceptable pilot overhead, these pilots must be transmitted simultaneously, by overlapping pilots. This is related to the problem of estimating channels from multiple antennas [9].[3]

There are four main challenges in designing such a system:

1. *The channel prediction quality for mobile terminals*. A higher terminal velocity, and also a higher transmission carrier frequency, implies the need to predict the state of the short-term fading over

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[1] www.signal.uu.se

[2] This work has been performed in the framework of the IST project IST-2003-507581 WINNER, which is partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues.

[3] This problem can be avoided in TDD systems, where the uplink channel power could be predicted by each terminal by predicting the downlinks.

a higher fraction of a wavelength.

2. *The channel prediction quality in uplinks*, based on overlapping pilots from active users.
3. *The required feedback data rate*. The larger the bandwidth of interest, and the finer the granularity of the time-frequency resource allocation, the higher will the required feedback data rate be.
4. *Frequency synchronization* of all uplink transmissions, to avoid significant intercarrier interference.

The present contribution investigates the first two issues. We explore adaptive OFDMA/TDMA transmission designed at 5 GHz. Adaptive transmission to vehicular users over OFDMA/TDMA downlinks has earlier been investigated in [1] and [2] for a more narrowband system of 5 MHz bandwidth at 1.9 GHz.

FDD DOWNLINK AND UPLINK

A total bandwidth of 51.2 MHz in both uplinks and downlinks has been assumed. We use OFDM sub-carriers of width 50 kHz, with symbol length 20 μs and guard space of 2.5 μs. The system utilizes 200 kHz by 337 μs time-frequency bins (4 subcarriers by 15 symbols) that are exclusively allocated to users in a cellular environment. The total bandwidth is split into 10.4 MHz sub-bands (52 bins wide) called contention bands, and each terminal is in competition for bins in one or several contention bands. The design goal is to use adaptive transmission, based on link adaptation and scheduling, for terminals with velocities up to 70 km/s. For the minority of terminals with higher velocities, one would have to use a non-adaptive fallback mode based on coding and interleaving.

The frame structure of the downlink and the uplink is designed to support half-duplex terminals, and still obtain a fast feedback loop. Thus a short required prediction horizon is obtained, but still adequate time to perform scheduling, channel estimation/prediction, and preparation of the transmission.

Downlink

The downlink transmission is partitioned into slots of 15 OFDM symbols, and is designed so that the transmission of slot i+2 is based on prediction of the channel power and the interference during the later part of slot i. This is done at symbol 13 within the slot, which contains only pilot information. Each terminal contains a set of channel predictors in the form of state space estimators, as outlined in the next section. The required prediction horizon, to the far end of slot i+2, is thus 32 symbol times, or 720 μs. The control information that describes how the 200 kHz bins are allocated to users, is coded within OFDM symbol 6 of slot i+2. It utilizes a safe modulation-coding scheme that is detectable by all users within the cell. OFDM symbol 11 contains control information for the uplink transmission of the next slot, coded and modulated in a similar way. The other 48 symbols within each bin contain payload data modulated and coded in a way appropriate for each designated user.

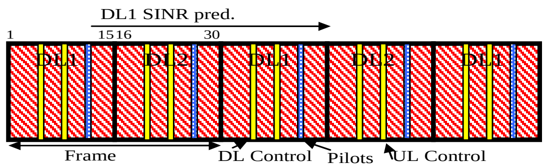

Figure 1. Downlink frame structure.

The uplink

The uplink is also partitioned into slots of 15 OFDM symbols, and is designed so that the allocation of bins within slot i+2 can be based on received uplink transmissions at the end of slot number i. The last symbol of each slot consists of overlapping pilots transmitted by all users in the contention band. The channel prediction is based on this and earlier overlapping pilots. The required prediction horizon to the far end of slot i+2 is thus 29 symbol times, or 652 μs. The uplink also carries the feedback information required to control the downlink, within symbol 10 and 11. Payload data within 200 kHz bins of the slots are allocated exclusively to users, using link adaptation based on the short-term fading. Slow power control, which equalizes the average received uplink power, is assumed.

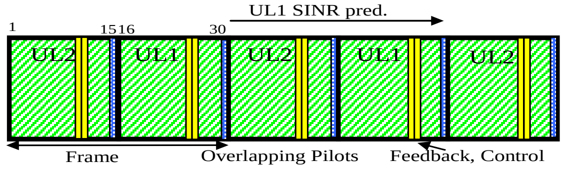

Figure 2. Uplink frame structure.

PREDICTOR PERFORMANCE

The performance of the predictors is crucial for the whole proposed adaptive scheme

For the downlink, the Kalman state-space algorithm described in [3] has been utilized to predict the complex channel for each 50 kHz subcarrier. Based on the predicted complex channel, an unbiased quadratic predictor [3],[5],[6] has thereafter been used to predict the channel power. The Kalman predictor utilizes the correlation of the channel in the frequency domain by predicting 8 subcarriers (400 kHz) in parallel. Autoregressive models of order 4 are used to model the channel correlation properties in the time domain. They are adjusted to the Jakes fading statistics, with the maximal Doppler frequency assumed to be known. In downlinks, the control symbols were also utilized in decision-directed mode, to improve the channel estimation and prediction, as described in [3]. When using the low-complexity GCG algorithms [10], as proposed in [3], the computation time available within the frame structure is adequate.

In uplinks, a generalization of the Kalman algorithm of [3], described in [4], is utilized. In a Kalman estimator based on overlapping pilots, separate sets of states are used for describing the channel of each user. The autoregressive models that describe the fading statistics of each user are adjusted individually to the velocity of the users [4].

These algorithms have been applied on channels with Vehicular-A power delay profile and noise with known power. Almost identical results were obtained also for flat Rayleigh fading channels.

Figs. 3-5 show the normalized prediction error variance as a function of the prediction horizon, measured in carrier wavelengths, for different values of the SNR. Fig. 3 shows the performance in the downlink. The prediction accuracy depends on the horizon in wavelength, which in turn depends on the vehicle velocity *v* and the carrier wavelength, via

$$vD/\lambda \quad ,$$

for a given horizon D in time. The predictability also depends on the SNR. For a given SNR, there is a maximum value of the velocity that allows reliable adaptive transmission. For combinations of velocities and SNRs beyond such a boundary, non-adaptive transmission must be used.

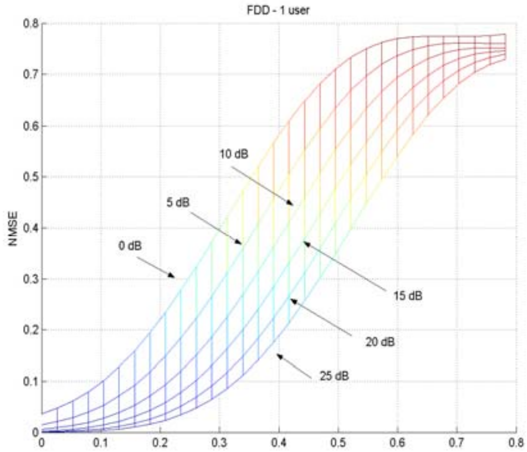

Figure 3. Prediction accuracy in terms of the complex normalized prediction error, as a function of the prediction horizon scaled in carrier wavelengths, and as function of the SNR. Results for FDD downlink over a Vehicular-A channel, using a Kalman algorithm that utilizes 8 subcarriers in parallel.

Fig. 4 and Fig. 5 show the same results but for FDD downlinks, where 2 users and 8 users simultaneously transmit overlapping pilots, all with the same average received power. In the here presented results, all users have the same velocity and travel through the same type of propagation environment, but their channels were generated as independent realizations from this channel statistics.

The results indicate that prediction based on overlapping pilots will decrease in accuracy with an increasing number of users, but this decrease is rather modest. Channel predictions in FDD uplinks, where not too many users occupy each contention band of the total bandwidth, thus seems feasible. A basic assumption on which this conclusion is based is of course that the tight feedback loop outlined here is feasible when all practical aspects are taken into account.

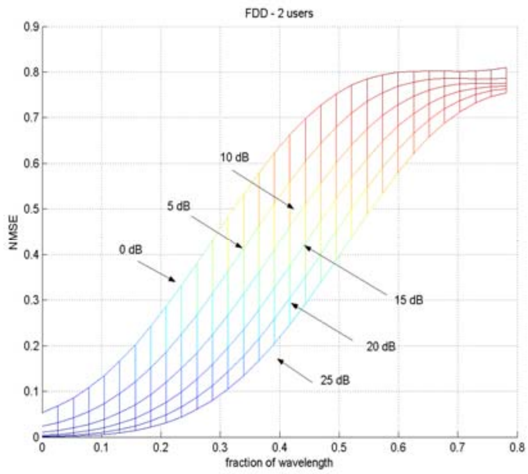

Figure 4. Prediction accuracy in terms of the complex normalized prediction error, as a function of the prediction horizon scaled in carrier wavelengths, and as function of the SNR. Results for FDD uplink over a Vehicular-A channel, using a Kalman state-space algorithm for overlapping uplink pilots, that utilizes 8 subcarriers in parallel. Average result for two simultaneous uplink users in the contention band is shown.

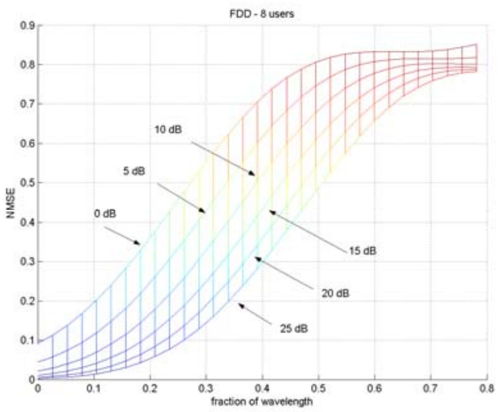

Figure 5. As for Fig. 4, with 8 simultaneous uplink users transmitting overlapping pilots.

Table I below summarizes the required prediction horizons scaled in wavelengths, for the considered FDD system operating at 5 GHz. The horizon as a fraction of λ is then

$$v\text{ [km/h] } x\ D \text{ [ms] } / 216 \ .$$

Table I. Required prediction horizon as fraction of wavelength for terminals with different velocities.

	Maximal horizon	35 km/h	50 km/h	70 km/h
Downlink	0.72 ms	0.12	0.17	0.23
Uplink	0.65 ms	0.11	0.15	0.21

One can now compare these required prediction horizons to the results in Fig. 3-Fig. 5. Earlier research has indicated that normalized prediction accuracy levels of 0.1 result in a rather small reduction of the performance of adaptive feedback loops, in single-user systems [7] as well as in multiuser adaptive transmission that utilizes proportional fair scheduling [8]. In Fig. 3 – Fig. 5, it is seen that these performance levels are attained at vehicular velocities for reasonable values of the SNR, for the prediction horizons required in Table I.

Simulation Results

Fig. 6 illustrates the multiuser scheduling gain obtained when eight users share the channel, and are allocated bins adaptively.

In Fig. 6, the users all move at 35 km/h. Link adaptation and scheduling are based on the predicted power in the scheduled bins. Link adaptation is here performed using 8 modulation-coding rates, from BPSK rate ½ to 64-QAM rate 5/6. All active terminals predict the channels for all bins, and report the resulting rates via the uplink feedback channel The scheduler allocates each bin to the user who reports the highest rate, relative to its own average. Vehicular-A channel statistics, and the transmission parameters specified earlier for the OFDM system, are used.

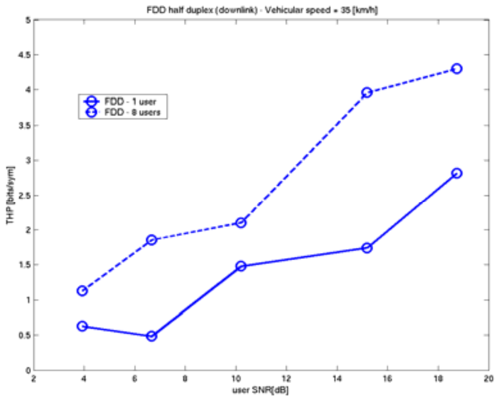

Figure 6. Throughput in bits per payload symbol, as a function of the average SNR, for an adaptive FDD half duplex downlink with one user (solid) and for eight users who obtain resources by proportional fair scheduling (dashed).

In Fig. 7, all terminals receive transmission with an average SINR of 16 dB, and all have the same velocity, either 35 km/h or 70 km/h. All channels have 3GPP Typical Urban power delay profiles. In this case, un-coded 4QAM, 16-QAM or 64-QAM is utilized for the payload symbols.

In this second example, the prediction uncertainty is taken into account with methods described in [7], and the aim is to attain a target bit error rate of 0.001. The prediction error levels are obtained from Table I and Fig. 3. All active terminals feed back the suggested modulation rates to the scheduler, which gives time-frequency bins to the users with the highest rates, relative to their own average rates, as in the first example. This is a variant of proportional fair scheduling.

As seen in Fig. 7, there is a significant multi-user diversity gain as the number of users is increased. The decrease in spectral efficiency due to incorrectly predicted channel states is rather modest for velocities up to 70 km/h when the link adaptation is based on uncoded M-QAM. Furthermore, there is an interesting synergy between the multi-user diversity effect and the effect of prediction inaccuracy: when the number of active users is increased, the impairment of the spectral efficiency due to prediction inaccuracy decreases, in relative terms.

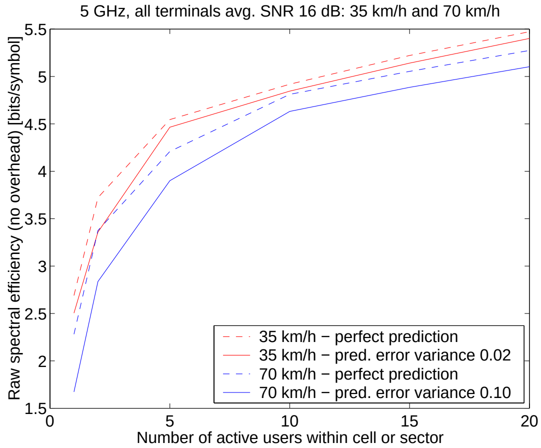

Figure 7. Average number of bits per payload symbol, as function of the number of simultaneous downlink users, all having average SNR 16 dB.

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