CHANNEL ESTIMATION AND PREDICTION FOR ADAPTIVE OFDMA/TDMA UPLINKS, BASED ON OVERLAPPING PILOTS

Mikael Sternad and Daniel Aronsson

Signals and Systems, Uppsala University, Box 528, SE-75120 Uppsala, Sweden

ABSTRACT

In adaptive wireless packet transmission for multiple users, resources are allocated based on measurement and feedback of the channel qualities. Uplink channels of adaptive OFDM systems that use FDD have to be estimated and predicted based on uplink pilots transmitted by all active users. To prevent a prohibitive pilot overhead, the use of overlapping (simultaneously transmitted) pilots is considered here. Kalman estimators and predictors can efficiently utilize the channel correlation in time and frequency to obtain estimates. The estimates have higher error than in the downlink case where overlapping pilots are not needed. However, the estimation and prediction MSE increases rather slowly with the number of simultaneous users. The results indicate that the accuracy is adequate for control of an adaptive transmission loop.

1. INTRODUCTION

Adaptive systems for wireless transmission allocate (schedule) time/frequency/antenna resources based on channel quality and user requirements. They enable efficient resource utilization and multiuser diversity gains. In systems based on OFDMA/TDMA, time-frequency resources (bins), consisting of a number of adjacent subcarriers and a number of OFDM symbols, are allocated. This enables the use of a flexible small-scale granularity of the resources, ideal for transmitting small as well as large packets.

For mobile users, the SINR (signal to interference and noise ratio) will vary between bins both in frequency (due to frequency selectivity), and in time (due to fading). The variability is mostly independent for different terminals. We therefore obtain a significant multiuser diversity gain if bins are allocated to the terminals with the best SINR. The total throughput will then increase with the number of active users. However, due to feedback delays, allocation of fading channels requires channel *prediction:* At time t, the quality of the channel must be predicted for the time $t + L$ when the resources are to be allocated.

The research has been performed within the Wireless IP project [1], funded by the Swedish Foundation for Strategic Research.

The feasibility of adaptive transmission in the downlink, based on channel prediction, has been studied in [2] and [3]. A hypothetical FDD (frequency division duplex) system at 1.9 GHz, with 5 MHz bandwidth and users with velocities up to 100 km/h was investigated[1]. The feedback loop considered in [2, 3] is designed to be fast, with a feedback delay L of only 2 ms. Channel prediction over these horizons can be performed in the time domain [4, 5] or in the frequency domain [6]. In both cases, one obtains a typical channel power prediction normalized mean square error (NMSE) of 0.1 for prediction horizons corresponding to 1/3 carrier wavelengths, which at 1.9 GHz corresponds to the required horizon of 2 ms for terminals moving at 100 km/h. Link adaptation and multiuser scheduling can be performed with only a small performance degradation for such prediction accuracies. Significantly larger prediction errors would however impair the performance considerably [7].

This paper will consider the problem of estimating and predicting channels in the corresponding uplinks (terminals to base station). The less challenging downlink scenario, where overlapping pilots are not used, was considered in [6]. In an adaptive OFDMA/TDMA uplink of an FDD system, channel estimators at the base station have to predict the uplink channels over the *whole* frequency band for *all* active terminals[2], in order to fully utilize multiuser diversity. Since in each bin only one user (at most) sends data, a pilot-aided approach has to be used, but since all terminals will have to send pilots, the number of received pilot symbols per bin will be proportional to the number K of active terminals. If these pilots were transmitted in orthogonal (non-overlapping) patterns, the pilot overhead would increase proportionally to K. Pilot symbols would fill up a major part of each bin when the number of users K is large.

We will here investigate the alternative of using *overlapping pilots*: All active users send pilots at the same time-frequency positions. Assuming adequate time- and frequency synchronization, they will be received simultaneously by

[1]Designed for the possible future use of 4G radio interfaces within the spectral bands today allocated to 3G systems.

[2]In a TDD systems, the terminals could predict the downlink channel power, based on the common downlink pilots, for the time-slot of uplink transmission (assuming channel reciprocity). Interference would have to be estimated separately at the base station.

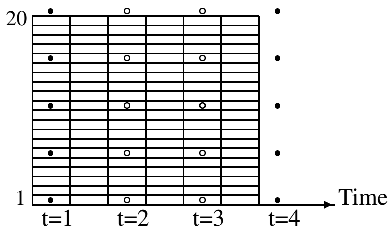

Fig. 1. One of the time-frequency bins of the investigated system, containing 20 subcarriers with 6 symbols each. Known 4-QAM pilot symbols (black) and 4-QAM control data symbols (rings) are placed on four pilot subcarriers. The modulation format for the other (payload) symbols is adjusted adaptively. The bin is assumed to be exclusively allocated to one out of K users. All payload symbols within a bin use the same modulation format.

the base station. The pilot overhead will then not increase with the number of users. The problem of using overlapping pilot patterns for multiuser uplinks is similar to the use of overlapping pilots to estimate channels in OFDM systems with multiple transmit antennas. The required pilot density for this case is derived in [8].

We outline and investigate a solution to the problem of predicting MISO OFDM channels based on overlapping pilots and non-overlapping control data symbols. It represents a generalization of the downlink Kalman predictor scheme outlined in [6] to the case of multiuser channels within each bin.

2. ASSUMED ADAPTIVE OFDMA/TDMA UPLINK

The use of FDD in a base station infrastructure with sectored antennas is assumed.

The available uplink bandwidth within a sector (cell) is assumed to be partitioned into *time-frequency bins* of bandwidth Δf_b and duration T. These bins are assumed to be exclusively allocated to one of K users. We here assume $T = 0.667$ ms and $\Delta f_b = 200$ kHz, which is appropriate for stationary and vehicular users in urban or suburban environments [3]. We also assume a subcarrier spacing of 10 kHz, a cyclical prefix of length 11 μs and an OFDM symbol period (including cyclic prefix) of $T_s = 111\mu$s. Thus, each bin of 0.667 ms $\times$ 200 kHz carries 120 symbols, with 6 symbols of length 111μs on each of the 20 10 kHz subcarriers. Of these 120 symbols, four locations are reserved for overlapping pilot symbols, assumed to be 4-QAM symbols. Furthermore, 8 symbols are allocated for control information, that utilizes a fixed modulation (here assumed to be 4-QAM), leaving 108 payload symbols, for which adaptive modulation and coding is used. The 12 pilots and control symbols are located within each bin as indicated by Fig. 1. Pilot symbols and control symbols are transmitted over every fifth subcarrier, here denoted *pilot subcarriers*. We assume perfect time and frequency synchronization.

The uplink channel within the whole bandwidth has to be estimated for each and every active user. The channel estimates are used for two purposes: coherent detection of payload symbols (in bins addressed to that user), and channel power prediction (all bins).

3. CHANNEL ESTIMATION

The received scalar complex-valued baseband signal $y_{n,t}$ on the pilot subcarrier n at the pilot/control data locations (t=1,2,3, ...) is described by

$$y_{n,t} = \sum_{k=1}^{K} s_{k,n,t} h_{k,n,t} + v_{n,t} \quad , \tag{1}$$

where the time index t will here be incremented in steps of two symbol times $2T_s = 222\mu$s. Here, $s_{k,n,t}$ is the pilot or control data symbol from user k, $h_{k,n,t}$ is the scalar complex channel from user k and $v_{n,t}$ represents noise and interference.

In situations with $K > 1$ uplink users, the channels $h_{k,n,t}$ are more numerous than the available received signals $y_{n,t}$, so direct least squares estimates $h_{k,n,t}$ cannot be obtained. Such estimates are normally the basis for 1-D Wiener and 2-D Wiener channel estimators [9, 10]. However, an MMSE solution can be obtained by introducing priors or estimates of the correlation of the channels between the frequencies n and/or between different times. In [6] we showed that p parallel subcarriers for one user can be modelled

$$\begin{aligned}
x_{t+1}^{(u)} &= \mathrm{diag}_p(\mathbf{F}^{(s)})x_t^{(u)} + \mathrm{diag}_p(\mathbf{G}^{(s)})e_t^{(u)} \\
&= \mathbf{F}^{(u)}x_t^{(u)} + e_t^{(u)} \\
h_t^{(u)} &= \mathrm{diag}_p(\mathbf{H}^{(s)})x_t^{(u)} = \mathbf{H}^{(u)}x_t^{(u)} \\
y_t &= \mathrm{diag}_p(s_{n,t})\mathrm{diag}_p(\mathbf{H}^{(s)})x_t^{(u)} + v_t = \varphi_t\mathbf{H}^{(u)}x_t^{(u)} + v_t
\end{aligned}$$

diag_p represents a block diagonal matrix of p blocks. (s) is for *subcarrier*, and (u) is for *user*. One single subcarrier is modelled by an AR4 model, in state space form $x_{t+1}^{(s)} = \mathbf{F}^{(s)}x_t^{(s)}, h_t^{(s)} = \mathbf{H}^{(s)}x_t^{(s)}$. This model is either fit to a Jakes doppler spectrum (when measurements are performed on flat Rayleigh fading channels), or to a doppler spectrum that is flat for all frequencies beneath the doppler frequency [11] (when measured channels are used). For the uplink case, we expand the above model to

$$\begin{aligned}
x_{t+1} &= \mathrm{diag}_K(\mathbf{F}^{(u)})x_t + \mathrm{diag}_K(\mathbf{G}^{(u)})e_t = \mathbf{F}x_t + e_t \\
h_t &= \mathrm{diag}_K(\mathbf{H}^{(u)})x_t = \mathbf{H}x_t \\
y_t &= [\varphi_{t,1}\varphi_{t,2}\dots\varphi_{t,K}]\mathrm{diag}_K(\mathbf{H}^{(s)})x_t + v_t,
\end{aligned}$$

where $\varphi_{t,k}$ denotes the regressor matrix for user k. The state x_t is composed of the individual users states $x_t^{(u)}$ stacked on top of one another. When pilots are sent (t=1,4,7,...) all K regressor matrices $\varphi_{t,k}$ hold known pilot symbols. At all other time instants, *only* the regressor matrix whose user is scheduled for sending data in that particular bin holds symbols. These symbols are estimated based on the previous one-step prediction, i.e the filter operates in decision directed mode. Iterating the Kalman filter equations gives the estimate $\hat{h}_{t|t} = \mathbf{H}\hat{x}_{t|t}$, and the predictor estimate $\hat{h}_{t+L|t} = \mathbf{H}\mathbf{F}^L\hat{x}_{t|t}$.

Thus, the user which is scheduled for traffic obtains a data-based update while the channel estimates from other users are propagated by model-based prediction. Incorrect symbol detection may lead to error propagation events, but these will be terminated at the next pilot position.

4. CHANNEL POWER PREDICTION

The square of the predicted complex tap constitutes a biased prediction of the channel power [4]. If $h_{k,n,t}$ has zero mean, an unbiased quadratic prediction estimate of the power $p_{k,n,t+L}$ on the pilot subcarrier n is obtained as

$$\hat{p}_{k,n,t+L|t} = |\hat{h}_{k,n,t+L|t}|^2 + \sigma_h^2 - \sigma_{\hat{h}}^2 \ , \qquad (2)$$

where σ_h^2 and $\sigma_{\hat{h}}^2$ are the variances of $h_{k,n,t}$ and $\hat{h}_{k,n,t+L|t}$, respectively.

An appropriate measure for evaluating power prediction algorithms is the normalized mean square power estimation error (NMSE)

$$\text{NMSE} = \frac{E||h_{k,n,t}|^2 - \hat{p}_{k,n,t|t-L}|^2}{E|h_{k,n,t}|^4} \ , \qquad (3)$$

where the performance target is here selected to NMSE=0.1, as explained in Section 1.

5. EVALUATION ON RAYLEIGH FADING CHANNELS

The methods outlined in Section 3 and 4 are here evaluated on simulated flat Rayleigh fading 5 MHz channels at carrier frequency 1900 MHz. The terminals have velocity 50 km/h, so the maximal Doppler frequency f_D is 87 Hz and $f_D T_s = 0.010$. The noise $v_{n,t}$ is uncorrelated in time and among subcarriers, with known variance $\sigma_{v,n}^2$. The 5 MHz bandwidth is partitioned into 25 bins. We begin by using 25 parallel estimators, which each uses $p = 4$ pilot subcarriers. Thus, one estimator is used for each bin width. The case for $K = 1$ user then corresponds to the downlink Kalman estimator of [6].

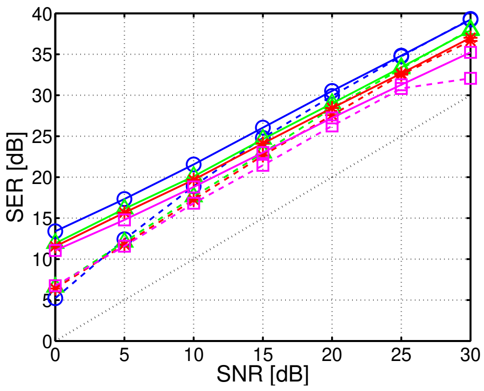

Fig. 2. Channel signal to estimation error ratio (SER) for Jakes flat fading channels at 50 km/h. Results displayed as a function of the SNR per user, obtained within the bins that were scheduled to that user. Filter estimates $\hat{h}_{k,n,t|t}$ are obtained when using correct regressors (solid) and when using estimated uncoded 4QAM downlink control symbols (dashed). The SER versus SNR for a single uplink user who utilized all bins is given by the top blue line (circles). Average SER's for two (green, triangles), four (red, stars) and eight scheduled users (magenta, squares). Dotted line: SER=SNR.

We first investigate the Channel Signal-to-Estimation error Ratio (SER) of the estimator output, defined by

$$\text{SER} = \frac{E|h_{k,n,t}|^2}{E|\tilde{h}_{k,n,t|t}|^2} \qquad (4)$$

where $\tilde{h}_{k,n,t|t} = h_t - \hat{h}_{k,n,t|t}$. The Kalman estimator uses autoregressive models of order 4, that are adjusted to the Jakes fading spectrum. Correct noise and channel covariances are used. The resulting SER is shown in Fig. 2 as a function of the SNR per user, $E|h_{k,n,t}|^2/\sigma_{v,n}^2$, that was obtained in the bins actually allocated to the users. All users have the same average SNR (due to slow power control) and the bins are allocated to the user with the best SNR.

Performance above the dotted line SER=SNR means that the detection performance will essentially be determined by the noise level, not by the channel estimation inaccuracy. The filter performance deteriorates with an increasing number of uplink users, but the decrease is rather small. No catastrophic performance reduction occurs for $K = 8$, when the number of users is larger than the number $p = 4$ of measured subcarriers in the Kalman estimator. The performance reduction due to error propagation in decision-directed mode is also illustrated for uncoded 4 QAM control symbols (dashed lines). The effect is much smaller if coded symbols are utilized and decoding and estimation are performed iteratively, in a turbo mode.

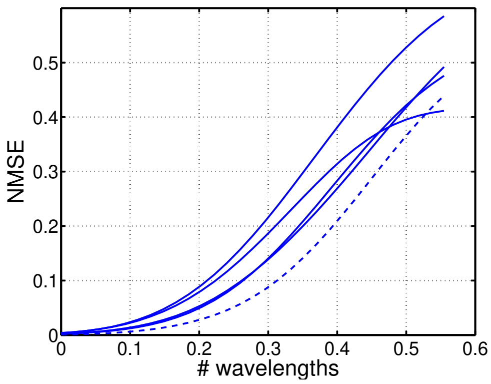

Fig. 3. Prediction NMSE as function of the prediction horizon at SNR 20 dB on Jakes flat fading channels for Kalman predictors that use $p = 4$ subcarrier measurements. Results for four uplink users. Compare to one user (dashed).

Figure 3 shows the prediction performance with four uplink users. The target NMSE=0.1 is here fulfilled for all users for prediction horizons of 0.21 wavelengths[3]. This is smaller than the 0.3 wavelengths attained for a single user. In the target system, the maximal vehicle speed for which adaptive transmission can be used would therefore be lower for the uplink than for the downlink.

6. MEASURED CHANNELS

We finally illustrate the noise reduction properties on two 5 MHz channel measured in suburban Stockholm at 1900 MHz. One of the channels has a 3 dB coherence bandwidth of 6.4 MHz. The mobile travels at 92 km/h, corresponding to a maximal Doppler frequency of 161 Hz. The other channel has a 3 dB coherence bandwidth of 3.9 MHz. This mobile travels at 89 km/h, corresponding to a maximal Doppler of 157 Hz.

The channel is estimated as described in [5] and this estimate is used as the true channel.[4] One estimator is used for each bin width of 20 subcarriers (4 pilot subcarriers). Thus, $p = 4$. The resulting SER is shown in Fig. 4 as a function of the SNR. The performance degradation compared to the flat Rayleigh fading channels is 2–3 dB. Model mismatch causes the curves to fall off somewhat at high SNRs.

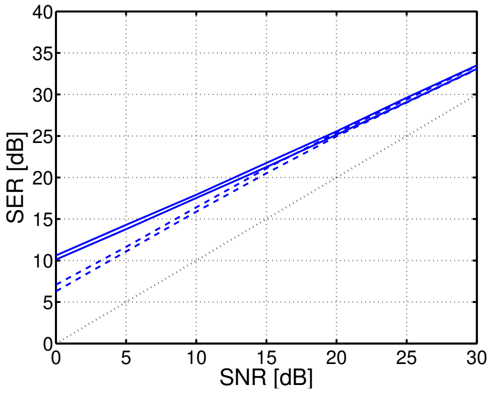

Fig. 4. Channel signal to estimation error ratio (SER) as a function of the SNR for two uplink users who experience the two measured channels. Kalman filter estimates $\hat{h}_{k,n,t|t}$ are obtained when using correct regressors (solid) and when using estimated uncoded 4-QAM downlink control symbols in decision- directed mode (dashed).

7. REFERENCES

[1] Online: www.signal.uu.se/Research/PCCwirelessIP.html.

[2] M. Sternad, T. Ottosson, A. Ahlén and A. Svensson, “Attaining both coverage and high spectral efficiency with adaptive OFDMA downlinks,” *IEEE VTC 2003-Fall*, Orlando, Fla, Oct. 2003.

[3] W. Wang, T. Ottosson, M.Sternad, A. Ahlén and A. Svensson, “Impact of multiuser diversity and channel variability on adaptive OFDM” *IEEE VTC 2003-Fall*, Orlando, Fla, Oct. 2003.

[4] T. Ekman, M. Sternad and A. Ahlén, “Unbiased power prediction on broadband channels,” *IEEE VTC 2002-Fall*, Vancouver, Canada, Sept. 24-28 2002.

[5] T. Ekman *Prediction of Mobile Radio Channels. Modeling and Design* PhD Thesis, Signals and Systems, Uppsala University, Sweden, 2002. Online: www.signal.uu.se/Publications/abstracts/a023.html

[6] M. Sternad and D. Aronsson, “Channel estimation and prediction for adaptive OFDM downlinks,” *IEEE VTC 2003-Fall*, Orlando, Fla, Oct. 2003.

[7] M. Sternad and S. Falahati, “Maximizing throughput with adaptive M-QAM based on imperfect channel predictions,” *IEEE PIMRC*, Barcelona, Spain, Sept. 2004.

[8] G. Auer, “Analysis of pilot-symbol aided channel estimation for OFDM systems with multiple transmit antennas, *IEEE ICC 04*,” Paris, June 2004.

[9] P. Hoeher, S. Kaiser and P. Robertson, “Two-dimensional pilot-symbol-aided channel estimation by Wiener filtering,” *IEEE ICASSP*, 1997, pp. 1845-1848.

[10] O. Edfors, M. Sandell, J-J van de Beek, S.K. Wilson and P.O. Börjesson, “OFDM channel estimation by singular value decomposition,” *IEEE Trans. Comm.*, vol. 46, 1998.

[11] Y. Li, L.J.Cimini and N. Sollenberger, “Robust channel estimation for OFDM systems with rapid dispersive fading channels,” *IEEE Trans. on Commun.*, vol. 46, pp. 902-915, 1998.

---

[3] The corresponding prediction horizon for eight users (i.e twice the number of parallel subcarriers) is 0.18 wavelengths.

[4] We thank Ericsson Research for providing measurements and Torbjörn Ekman for providing the estimated channel.