PROGRESS REPORT ON ADAPTIVE OFDM

AND

CHALLENGES FOR THE UPLINK

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http://www.signal.uu.se/Research/PCCwirelessIP.html

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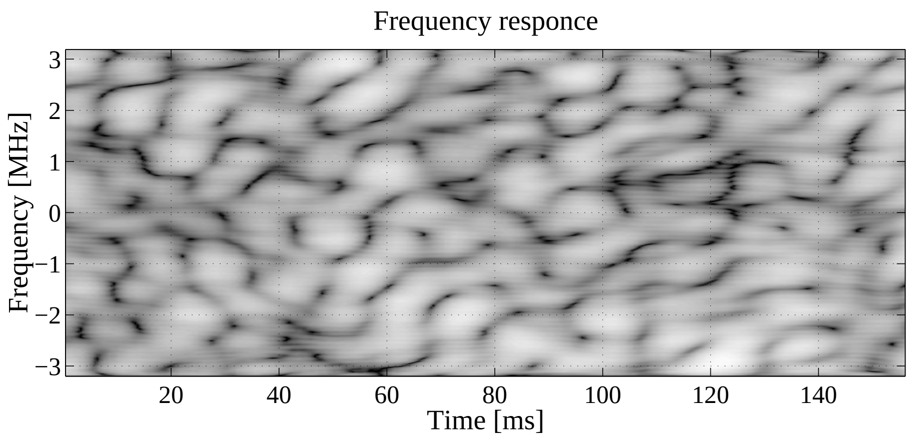
Main points:

1. Adaptive OFDM downlink designed for 2 GHz.
2. Evaluation of the downlink:
   - Effect of prediction inaccuracy
   - The feedback control bandwidth demand
   - Estimate of total overhead and losses
3. Preliminary study of system capacity
4. Research challenges for a corresponding uplink.

Challenges:

- Can the channel variability be exploited when the bandwidth is large?
  Strategy: allocate time-frequency bins (exclusively) in the downlink, OFDM.



- High data rate in a frequency selective channel (OFDM attractive in downlink).
- Adaptation to fast fading could require unrealistic feedback control data rates.
- Slow fading may give problems with QoS.
- Channel prediction required, due to delay in the feedback loop
  (design aim-point 100 km/h).

An adaptive OFDM-downlink

Assume FDD and a slotted OFDM-downlink in one sector.

The bandwidth B is used by K active users (terminals).

Partitioned into **time-frequency bins**.

- In time slot j, all active terminals predict the SINR at time slot $j+3$ for *all* time-frequency bins.
- Based on these predictions, the terminals suggest appropriate modulation levels for all bins of time slot $j+3$.
- Scheduling is then performed (centralized for all sectors at site).
- Allocation decisions for time slot $j+3$ are broadcast. (Modulation rates as suggested by the appointed terminals.)

Design of downlink in cellular FDD-system at 2GHz:

(Studied together with T. Ottosson, A. Ahlén and A. Svensson, Paper 2, VTC03-Fall)

- **OFDM**, with 100 μs symbols, 11 μs cyclic prefix, 10 kHz subcarriers.
- **Time-frequency bins of 0.666 ms x 200 kHz**, or 6 symbols x 20 carriers (120 symbols) are allocated exclusively to users.
- **Adaptive modulation, with 1-8 bits per symbol** (BPSK - 256 QAM), possibly with trellis-coded modulation. 4 pilots och 8 downlink control symbols per bin always use 4-QAM. These are used for the channel estimation.
- **Each user predicts the whole bandwidth three slots (2 ms) ahead**.
- Appropriate modulation levels (based on the SINR predictions) are reported by all active users for all bins via the uplink.
- A scheduler, located at the base station allocates the resources, and the slot, with 25 bins, is transmitted. **Fast link-level retransmission $\approx$ 2 ms** is utilized.

Outline of downlink in cellular FDD-system:

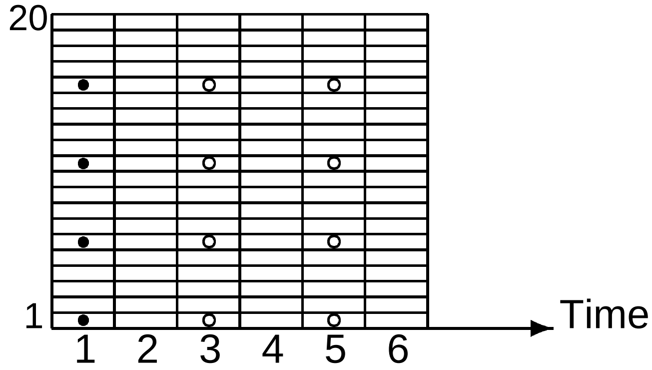


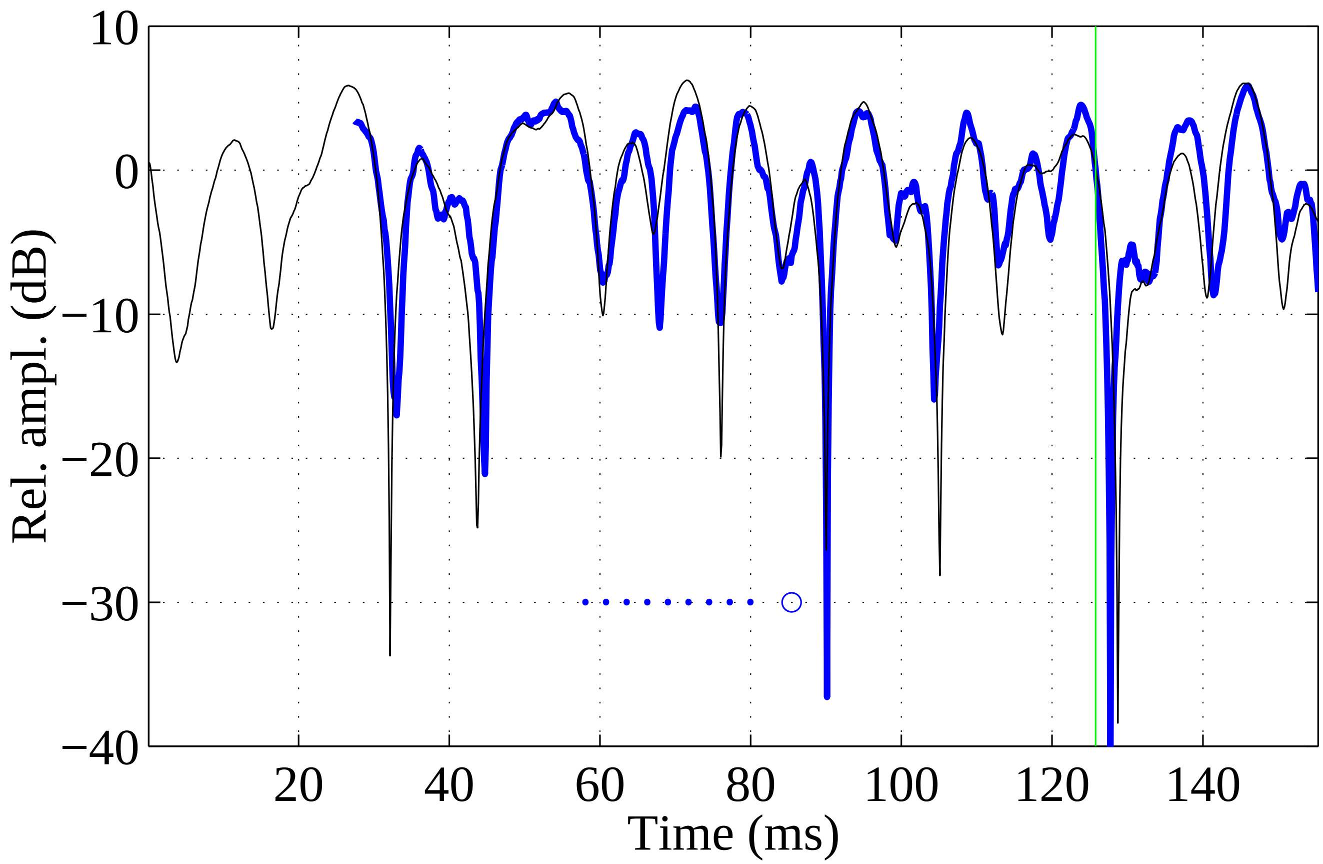
Figure 1: One of the time-frequency bins, containing 20 subcarriers with 6 symbols each. Known 4-QAM pilot symbols (black) and 4-QAM downlink control symbols (rings).

Channel estimation performed by low-complexity Kalman filtering (Wiener-LMS-like algorithms) at pilot and control locations. (Paper 3, VTC-Fall 2003).

Channel estimates are used for

- **Coherent detection of payload symbols.** 2D curve fitting within bins.
- **Noise reduced inputs to long-range predictor** (performed in time domain).

Channel power prediction



Predict the channel power (and interference power) over a horizon corresponding to 0.3 wavelengths (=2 ms at 2 GHz carrier and 100 km/h terminal velocity.)

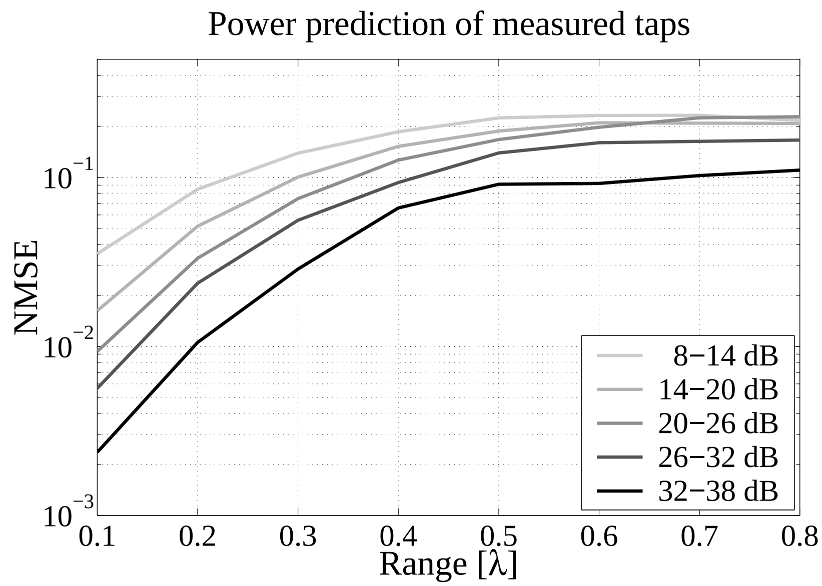
Power prediction algorithms

Result of work with Torbjörn Ekman and Anders Ahlén (e.g. TE PhD thesis)

- The significant taps of the impulse response are predicted, based on previous tap estimates. (Prediction in the frequency domain of the OFDM channels seems to perform similarly.)
- Best performance attained by a **bias-compensated squared FIR tap-estimate.**
- **Noise reduction** of the regressors (the previous tap estimates) should be done with care!
- Do not use a predictor with too many adjustable coefficients.

Prediction of tap powers, 41 channels

Predictability for different horizons and different regressor quality:



Median of the power prediction NMSE as function of the prediction horizon for cases with different estimation error power (CEER) on the regressors.

Bias compensated quadratic predictor with 8 coefficients. Smoothed regressors.

Predictability increases with decreasing estimation errors (noise) on regressors.

Predictability of the channel power

The performance of the predictor is indicated by the normalized power prediction error (NMSE)

$$\sigma_p^2 = \frac{E||g_n|^2 - \hat{p}_{n|n-L}|^2}{E|g_n|^4}$$

- $\sigma_p^2 = 0.001$: Essentially perfect prediction.
- $\sigma_p^2 = 0.01$: Attainable for $L = 0.1$ wavelengths.
- $\sigma_p^2 = 0.1$: Attainable for $L = 0.33$ wavelengths **(=2 ms at 2 GHz, 100 km/h)**.
- $\sigma_p^2 = 0.5$: Obtained when $\hat{p}_{n|n-L} = E|g_n|^2$ for Rayleigh fading.

Interesting property:

The **relative** standard deviation of the prediction error $\sigma_p(\hat{p}_{n|n-L})/\hat{p}_{n|n-L}$ **increases** when $\hat{p}_{n|n-L}$ decreases, i.e. when we predict into a fading dip.

Link adaptation

Optimize number of bits within correct bins (link-level frames):

Based on the predicted SINR $\hat{\gamma}$, the terminal selects the modulation format k_i that results in the highest spectral efficiency

$$\eta(\hat{\gamma}) = G_c G_p \, k_i (1 - P_{f,i}(\hat{\gamma})) \quad \text{bits/s/Hz} \, . \tag{1}$$

$$P_{f,i}(\hat{\gamma}) = 1 - (1 - P_{e,i}(\hat{\gamma}))^{108} \, , \tag{2}$$

where $P_{e,i}$ is symbol error rate for uncoded M-QAM.

Overhead factor $G_c = 100/111$ is due to the cyclic prefix

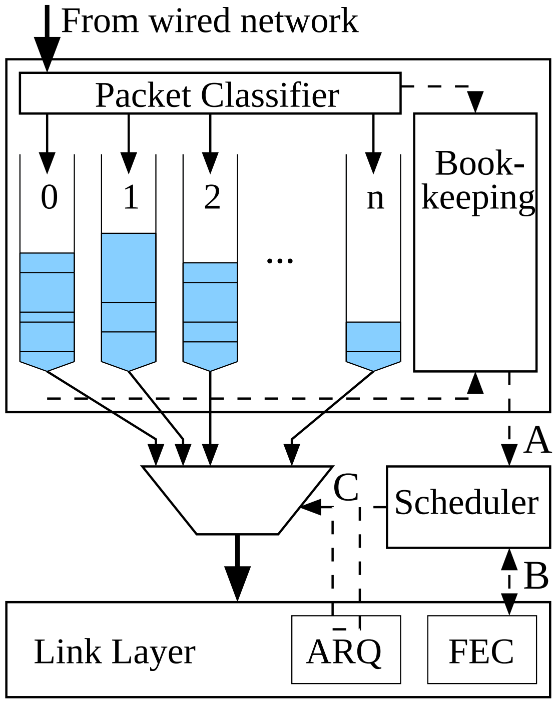
$G_p = 108/120$ is due to the 12 pilots and control symbols per bin.

Modulation rate limits for uncoded M-QAM:

Table 1: Optimized switching levels γ_i

i	Modulation	k_i	γ_i (dB)
0	BPSK	1	$-\infty$
1	4-QAM	2	8.701
2	8-PSK	3	14.58
3	16-QAM	4	16.84
4	32 Cross-QAM	5	20.46
5	64-QAM	6	23.59
6	128 Cross-QAM	7	26.86
7	256-QAM	8	29.94

Scheduling



- Buffering per flow (different users and traffic classes.)
- Channel quality weighted against priority, QoS-demands.
- Link level retransmission is given highest priority.

Simple scheduling principles for theoretical evaluation

(These strategies do not take buffer levels and priorities into account.)

Of users $u = 1 \ldots K$, select according to

- $\max_u \hat{\gamma}_u$: **Maximal throughput**.

  Neglects users far from base station.

- $\max_u \hat{\gamma}_u / \bar{\gamma}_u$: **Highest SINR relative to own average.**

- $\max_u \hat{\gamma}_u$/average_throughput (Proportional Fair Scheduling)

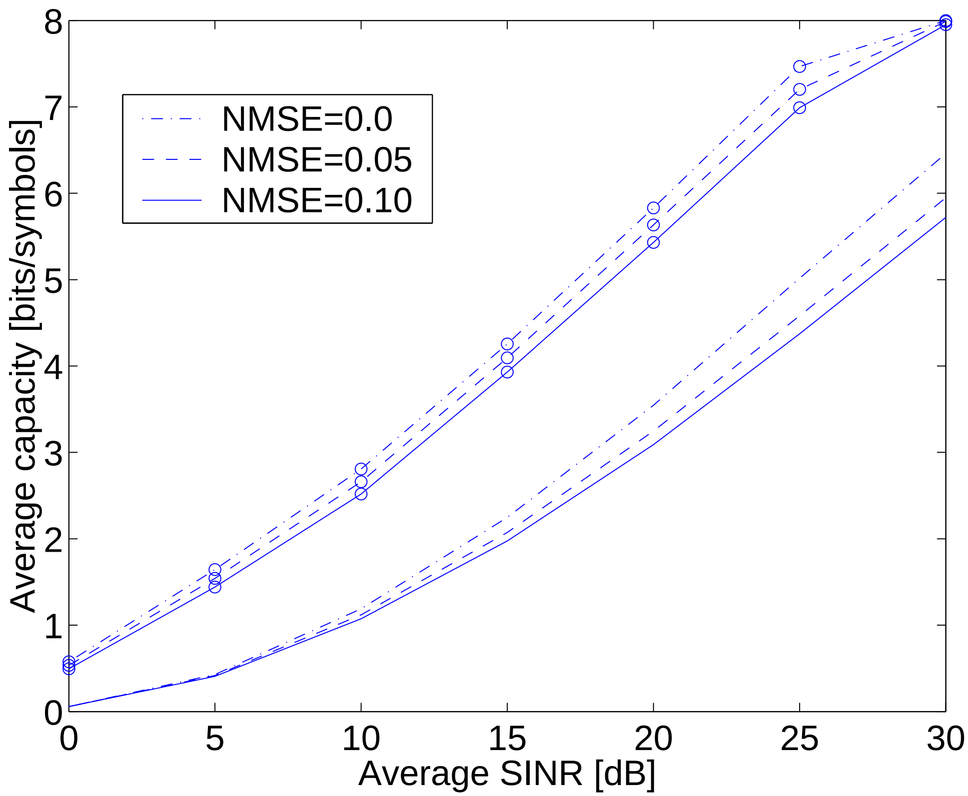
Simple algorithms appropriate for more realistic cases:

coming PhD thesis by Nilo Casimiro Ericsson.

Bayesian methods that take uncertain buffer inflows into account,

presented in coming PhD thesis by Mathias Johansson.

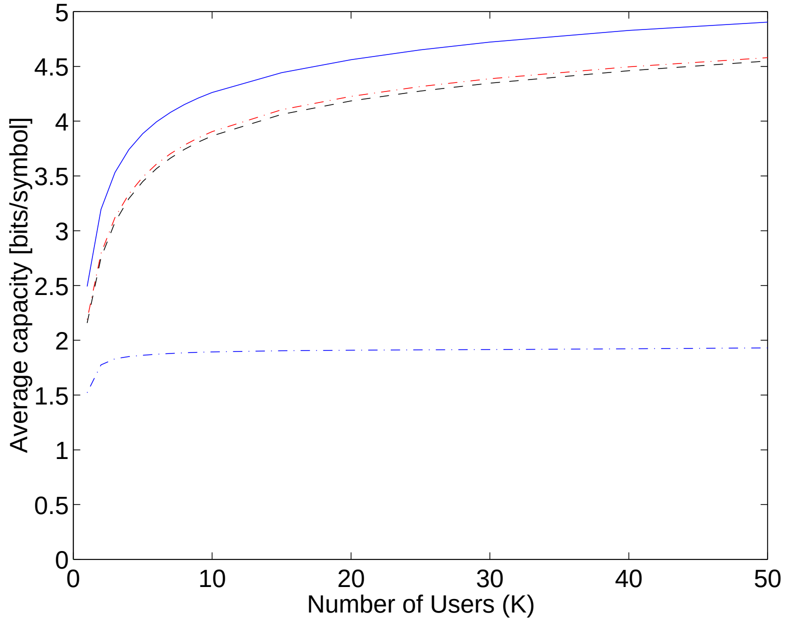
Spectral efficiency vs. SNIR with prediction errors:



Average capacity as a function of the average SINR, equal for all users, with $K = 1$ active users (lower curves) and $K = 20$ terminals (upper curves with rings).

Not much loss for a power prediction NMSE 0.1, compared to perfect prediction.

Spectral efficiency with prediction errors:



Spectral efficiency for average SINR 16B (same for all) when selecting the highest SINR out of K independent Rayleigh fading users. Solid: Perfect prediction. Dash-dotted: prediction NMSE 0.1, with optimized rate limits. Dashed: prediction NMSE with rate limits adjusted for perfect prediction. Lower dash-dotted: NMSE 0.495. **Conclusions:**

1. Rate limits optimized for perfect prediction are adequate.

2. Not much multiuser diversity is lost at prediction NMSE 0.1. (We loose everything at NMSE 0.5 !)

Summary of estimated losses:

Bits/s/Hz/sector, when all users have equal SNR 16 dB, and loss factors:

	K=1	K=2	K=5	K=10	K=20
Ideal case, see VTC03-1	**2.492**	**3.195**	**3.886**	**4.262**	**4.561**
Loss due to variability with bin:	0.87	0.92	0.95	0.96	0.973
Loss due to pred. error NMSE 0.1:	0.878	0.874	0.898	0.916	0.926
Cycl. prefix, training, control $(G_c G_p)$:	0.811	0.811	0.811	0.811	0.811
Link level overheat (18 bits/bin)	0.93	0.948	0.957	0.961	0.964
Payload spectral eff. if all users at 16 dB:	**1.436**	**1.975**	**2.573**	**3.039**	**3.213**
Sector capacity at **full load** , eq.reuse 1.73 $\approx$	0.83	1.14	1.49	1.76	1.86

Control bandwidth demand

Downlink: Adequate with 8 4QAM-symbols.

- Downlink user numbers (ca 5-8 bit incl. coding)
- Indicate user to send in uplink (ca 5-8 bit)

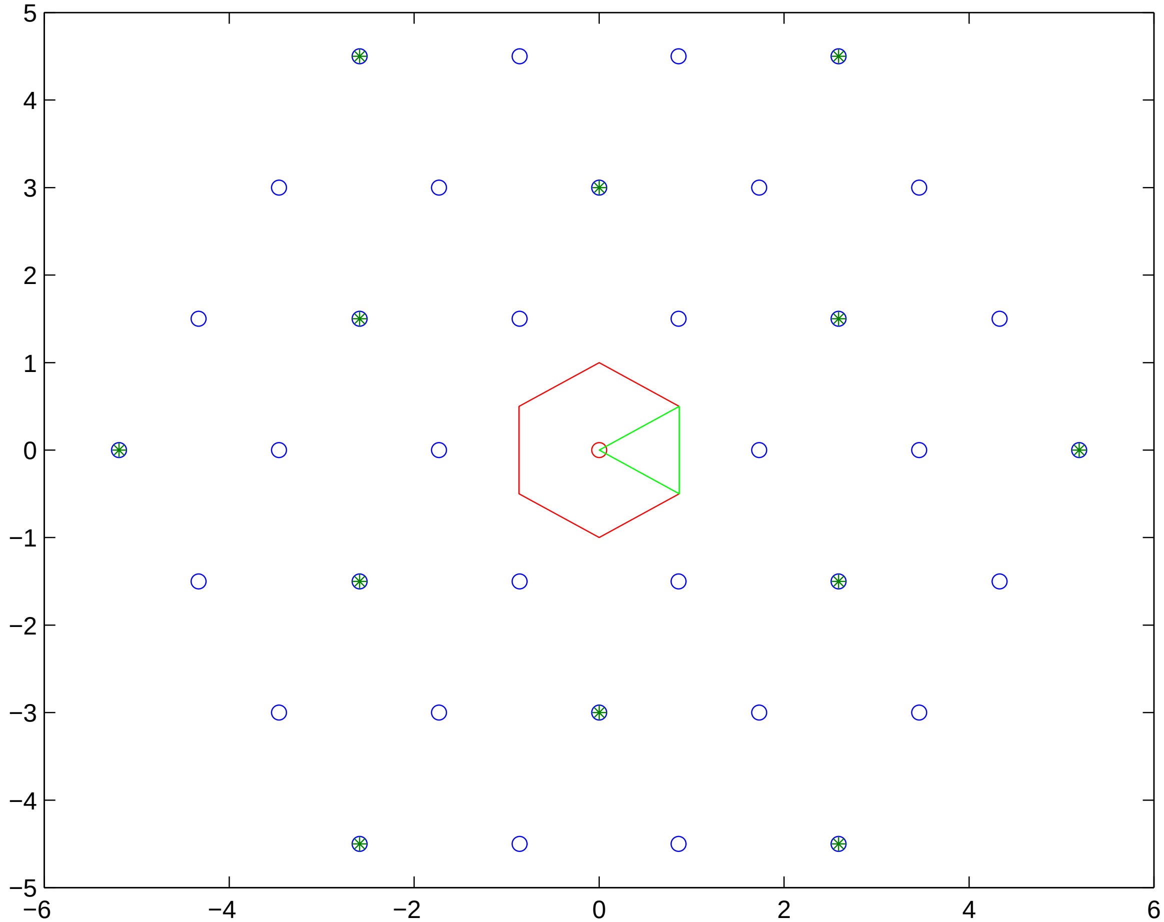
Uplink: All K active terminals indicate desired modulation rate. (N levels) for all b bins in slots of duration T. A “dumb” implementation:

$$B_{uc} = Kb\log_2(N)\frac{10^{-3}}{T} = 112 \times K \quad \text{[kbits/s]} \ .$$

for $N = 8, b = 25$ (0.2x25=5MHz), $T = 0.666$ms.

Can easily be reduced by factor 10 by using correlation in time, in frequency, and the rare use of most modulation levels.

Hexagonal cellular system, 60 degree sectors:

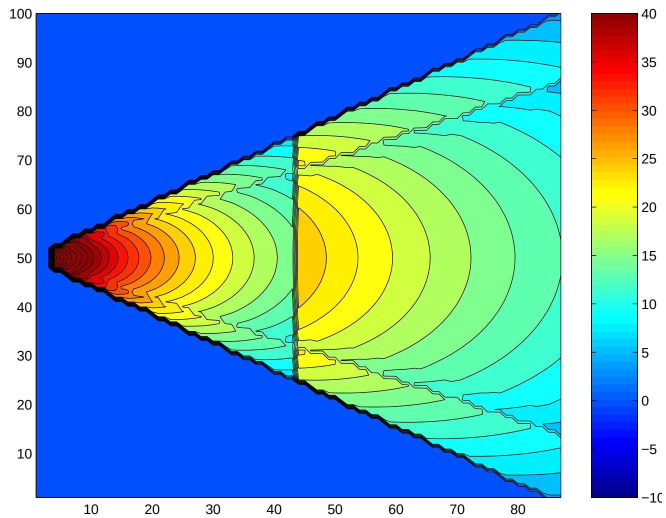


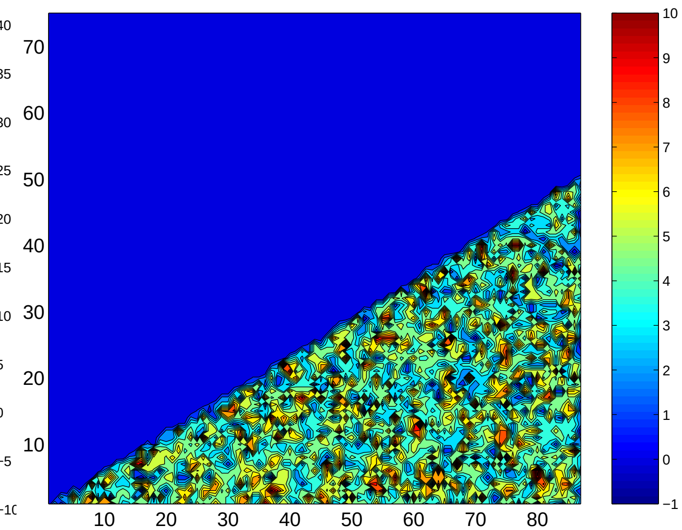
Interference control

High spectral efficiency demands **both reuse close to 1 and low co-channel interference.** Two principles are suggested (VTC03-Fall, Paper 2:):

- Reuse 1 in inner part of sector, reuse 3 in outer part.
- Coordinated scheduling between sectors of the same base station.

. **SIR distribution:** **Distr. of bins when $\max_u \hat{\gamma}_u / \bar{\gamma}_u$ selected:**





Sector throughput (preliminary evaluation)

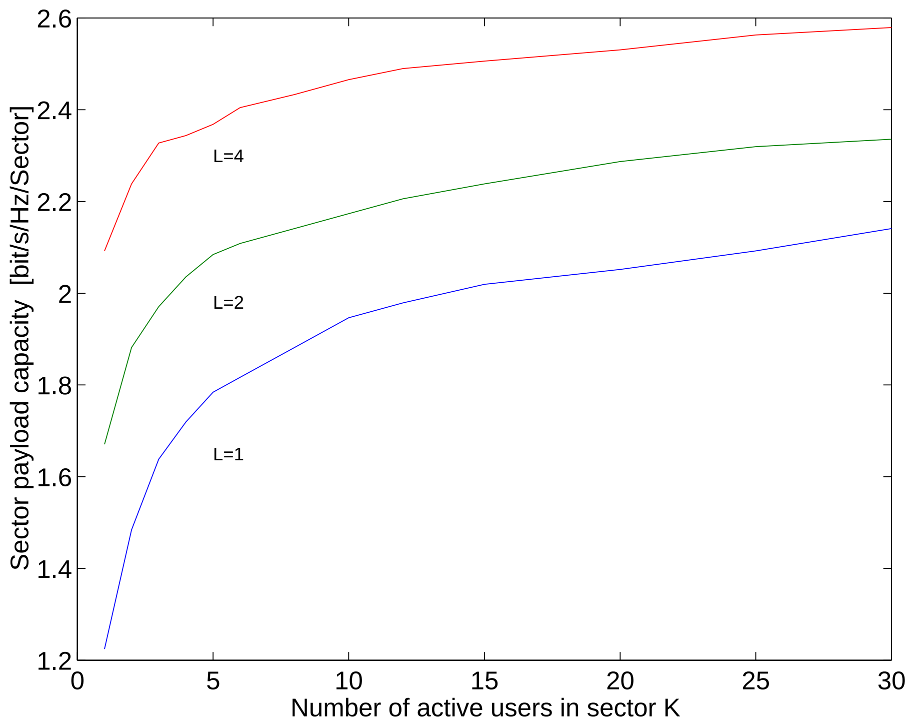


Figure 2: Estimated sector capacity with Rayleigh fading (no shadow fading). Two zones, limit 0.7 of radius **(reuse 1.73). OFDM-overhead factor 0.81** (prefix, downlink control). K **users**, all with L **antennas**, with Maximum Ratio Combining. Each data point based on 10000 realizations. Load factor in interfering cells $\ell = 1$ and path loss exponent $\alpha = 4$.

Challenges for the Uplink 1

Can a similar adaptive OFDM scheme work also in uplinks?

In a FDD system, the base station would have to predict the channels of all terminals competing access, over the whole bandwidth to be allocated. This would result in two difficulties:

- Continuous uplink transmission of pilots over a large band would risk draining terminal batteries.
- To avoid cluttering the band with pilots, we would require simultaneous (overlapping) pilots. This generates a challenging channel estimation and prediction problem.

Furthermore

- The transmission from all terminal would have to be well synchronized in frequency, to avoid significant inter-carrier interference.

Challenges for the Uplink 2

In a TDD system, we could predict the uplink channels from measurements of the downlink.

- Terminals will then need to send pilots only in bins allocated to them. This preserves battery power.
- Channel estimation and prediction from overlapping pilot patterns is avoided.

However,

- The required prediction horizon (in time) will be longer than in a corresponding FDD system. (Depends on the switching frequency between uplink and downlink transmissions.)
- Downlink pilot transmission is interrupted by the uplink periods. This will reduce the accuracy of downlink estimation and uplink prediction.