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An OFDM based System Proposal for 4G Downlinks

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1 Introduction

Higher spectral efficiency will be a key feature of any acceptable radio interface beyond 3G. A promising approach for the downlink, is to adaptively multiplex user data onto an OFDM transmission system. This will minimize interference between users within a cell and efficiently allows users to share the total bandwidth. In such a system, spectral efficiency can be improved by allocating the time-frequency resources based on throughput requirements, quality of service constraints and the channel qualities of each user. A scheduler, which optimizes the resource allocation for multiple active users, becomes a key element in the system. In present CDMA systems, the spectral efficiency decreases with an increasing number of active users having conventional detectors. This is caused by intra-cell interference due to imperfect orthogonality of the downlinks. In an adaptive multiplexing and OFDM system, where orthogonal time-frequency resources are given to the user who can utilize them best, the spectral efficiency will instead *increase* with the number of active users. This *multiuser diversity* effect [1] is quantified and illustrated by analytical results in Section 3, assuming independently frequency-selective fading channels, and an adaptive joint multiplexing and modulation scheme, which is optimized in a novel way.

Designing an adaptive multiuser multiplexing and OFDM system that works also for vehicular users and wide area coverage scenarios is a challenging task [2]. In Section 2 below, we outline such a system.[1] It assumes FDD, a base station infrastructure and a tight reuse of the bandwidth. The quality of downlink channels must in such a solution be predicted by the terminals, and reported to the system. A potential problem is that the required amount of feedback information might become unreasonably large. The uplink control bit rate increases with the granularity of the resource partitioning of the downlink, i.e. with the size of time-frequency bins that may be adaptively allocated to different users. An important issue is whether resources can be partitioned into bins that are large enough to keep feedback data rates at reasonable levels, while the reduction in spectral efficiency due to channel variability *within* these bins, caused by frequency selectivity and time variation, remains acceptable. According to our results it can in fact be done up to reasonably high vehicle speed.

2 The adaptive downlink

The available downlink bandwidth within a base station sector is assumed to be slotted in time. Each slot is partitioned into b time-frequency bins of bandwidth Δf_b and duration T. These resources are shared among K active terminals.

During slot j, each terminal predicts the signal to interference and noise ratio (SINR) for all bins, with a prediction horizon mT which is larger than the time delay of the transmission control loop. All

[1]The system serves as a focus for research within the Wireless IP project [3], supported by the Swedish Foundation for Strategic Research SSF.

terminals then signal their predicted quality estimates on an uplink control channel. They transmit the suggested appropriate modulation format to be used within the frequency bins of the predicted time slot $j + m$. A scheduler that is located close to the base station then allocates these time-frequency bins exclusively to different users and broadcasts its allocation decisions. In the subsequent downlink transmission of slot $j + m$, the modulation formats used are those which were suggested by the appointed users.

The bin size T (ms) $\times\Delta f_b$ (kHz) should be selected so that all payload symbols within a bin can be given the same modulation format, without too large reduction in spectral efficiency relative to an ideal case with a completely flat and time-invariant channel within each bin. Assuming a design vehicle speed of 100 km/h (Doppler $f_D = 174$ Hz at 1900 MHz), we here select $T = 0.667$ ms and $\Delta f_b = 200$ kHz.

A cyclic prefix of length 11 μs is introduced. It eliminates intersymbol interference if paths more than 3.3 km longer than the shortest path are insignificant. We here also select a sampling period 0.20 μs, subcarrier spacing of 10 kHz, and a symbol period of 111 μs. Thus, we assume each time-frequency bin of 0.667 ms $\times$200 kHz to carry 120 symbols, with 6 symbols of length 111 μs on each of the 20 10kHz subcarriers. Of the 120 symbols, 12 are for training and downlink control, leaving 108 payload symbols [2].

For the payload symbols, we utilize an adaptive modulation system that uses $N = 8$ uncoded modulation formats: BPSK, 4-QAM, 8-QAM, 16-QAM, 32-QAM 64-QAM, 128-QAM, and 256-QAM. No transmit power adjustment is used to fine-tune the SINR, since this provides only minor improvements [4] and would require a large amount of feedback.

3 Analysis and results

We now estimate the resulting spectral efficiency for best effort services under some simplifying assumptions. The channel is assumed flat and time-invariant AWGN within bins and independent Rayleigh fading between bins[2]. All K users are assigned equal average received power[3] and channels to different users fade independently. Accurate SINR predictions and channel estimation are used for symbol detection. Finally, all users always have data to transmit, and the allocated bins are fully utilized by their designated users.

The here assumed scheduler works as a selection diversity scheme, where the user with the best predicted SINR out of all K users will transmit in a bin. In the receiver we assume *maximum ratio combining* (MRC) with L *antennas*.[4] The resulting pdf of the received SINR (γ) after MRC and multiuser selection diversity can then be calculated analytically.

The SINR limits for selecting the appropriate M-QAM format have been optimized to maximize the number of bits that arrive in correct bins (in which all payload symbols are detected correctly). We believe this is a useful and novel approach to the optimization of adaptive modulation schemes. The spectral efficiency when using adaptive modulation will then be obtained by a weighted average over the N modulation formats, weighted by the probabilities that those particular formats will be utilized, and also by the corresponding frame acceptance rates. This raw spectral efficiency η must in our target system be multiplied by $100/111$ due to cyclic prefixes and by $108/120$ due to the 12 pilots and control symbols per bin. The resulting payload spectral efficiency, or sector capacity, is $C \approx 0.81\eta$ [bits/s/Hz]. The overall system capacity also must take frequency reuse into account; an issue which is still under consideration.

[2]Such a channel is sometimes referred to as a block Rayleigh fading channel where a block in our case contains the symbols in a time-frequency bin.

[3]This assumed power control scheme is wasteful from a system capacity perspective. The capacity of the proposed adaptive downlink with a better power control strategy is evaluated by Monte-Carlo simulation for an interference-limited environment in [2].

[4]Equivalently, we could assume downlink beamforming with L transmit antennas, but this variant would require much more control information.

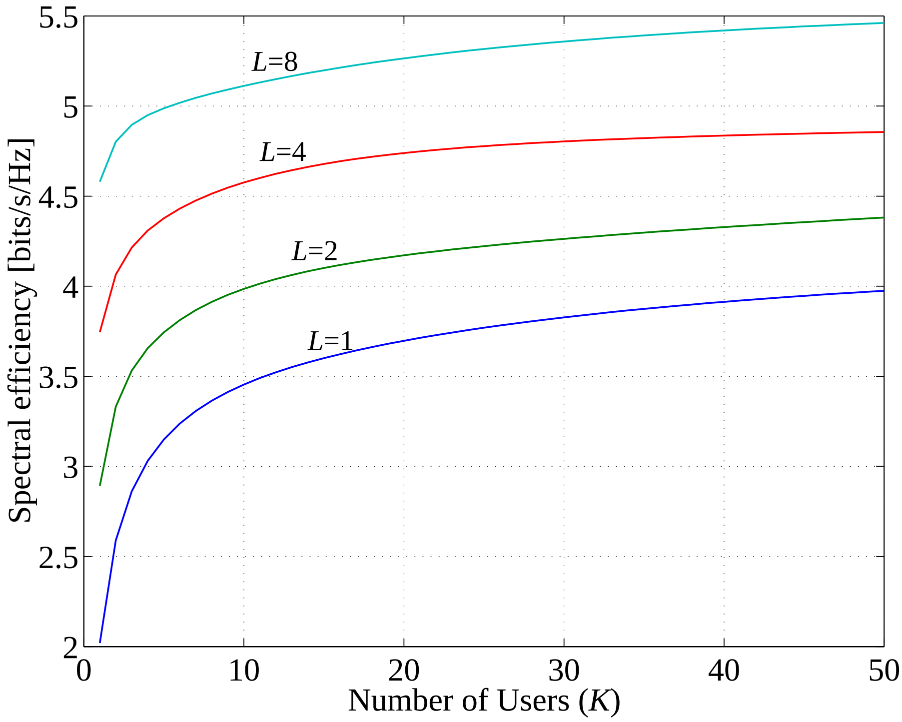

Figure 1: Payload spectral efficiency C at SINR 16 dB per receiver antenna, when using adaptive multiplexing and modulation with Lth order MRC diversity in the mobile and Kth order of selection diversity between the users.

The sector capacity is evaluated numerically in Figure 1 for an average symbol energy to noise ratio of $\bar{\gamma} = E(\gamma) = 16$ dB per receiver antenna, for all users. There is a notable improvement with an increasing multiuser selection diversity and of course also an increase with the number of receiver antennas.

The spectral efficiency saturates for a high number of users, when most bins are occupied by users who can utilize a high modulation format. The addition of more receiver diversity branches (larger L) decreases the OFDM channel variability [5]. Here, this tends to decrease the multiuser diversity effect.

Our proposed system has also been simulated on the channels used for UMTS performance evaluation. These channel models are more realistic and takes into account correlation between time-frequency bins and channel variation within each bin. The simulations show that the degradation compared to the results in Figure 1 is insignificant for vehicle speeds below 120 km/h [6]. Other time-frequency bin sizes have also been evaluated and the results show that the proposed bin size of 0.667 μs times 200 kHz makes a good compromise between spectral efficiency and feedback information rate.

4 On spreading and OFDM in the downlink

We above outlined a downlink proposal that utilizes uncoded adaptive OFDM. Among other alternative solutions, several research groups have proposed 4G downlinks based on different combinations of OFDM and CDMA. In [7], a detailed comparison has been carried out between the following schemes:

MC-CDMA User bits are spread to N chips, the chip sequences from different users are added and then mapped to different subcarriers of the same OFDM symbol. This is spreading over frequency.

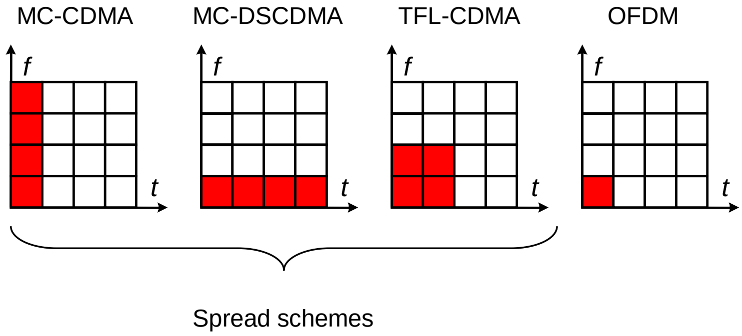

Figure 2: Various combinations of spreading and OFDM transmission with 4 chips per bit. The red/dark areas represent the time-frequency resources used for each transmitted bit. In the spread schemes, several users share these resources.

MC-DSCDMA User bits are spread to N chips, the chip sequences from different users are added and then mapped to different consecutive OFDM symbols on the same subcarrier. This is spreading over time.

TFL-CDMA User bits are spread to N chips, the chip sequences from different users are added and then mapped to a rectangular OFDM time-frequency bin of size N. This is spreading over both time and frequency.[5]

OFDM This is ordinary OFDM without spreading (and without adaptive modulation).

All the systems has N subcarriers. The systems are illustrated in Figure 2 for the case of 4 chips per bit (in the spread schemes).

The impact of frequency-selective fading on these different systems are quite different. For many practical mobile radio channels with high mobility, the coherence bandwidth is significantly smaller than the spread bandwidth for MC-CDMA, and the coherence time may also be smaller than the spread symbol time in MC-DSCDMA. In TFL-CDMA, the area that a symbol occupies can be adjusted to better fit the coherence time and bandwidth, but this area may still exceed a coherence bandwidth in frequency and/or a coherence time time. Thus, the spread schemes will in most cases result in multiuser interference (MUI) but will also provide diversity gains if appropriately detected. With pure OFDM, outer channel coding must be used to obtain diversity, but this scheme is free from multiuser interference. All these systems have been evaluated for UMTS channel models. Outer convolutional coding with rate 1/2 was used in all systems. Pure OFDM significantly outperforms all the other schemes and MC-CDMA and MC-DSCDMA has very bad performance due to extensive MUI, when the systems are fully loaded. For low load, all system perform quite similar.

Of course, all the systems with spreading, can be improved by multiuser detection and/or equalization. However, at best their performance can approach that of pure OFDM when the same outer channel encoder is used. But then, the complexity of the spread schemes are much higher. Moreover, it is quite straight forward to use adaptive modulation with pure OFDM as in our proposal above, while this might be very difficult with the spread schemes since the channel will not be flat for each transmitted symbol. We therefore conclude, that we have difficulty in finding any advantage at all, from introducing a spreading component in a scheme like the one we propose in this paper. The situation for an uplink, may however be quite different but is not within the scope of this paper (a good topic for further study).

[5]TFL is an abbreviation for time-frequency localized.

5 Summary and conclusion

Adaptive multiplexing and OFDM transmission based on predicted channels seems to be a very promising technique for the downlink in future high mobility and wide area coverage systems. In this paper, we show that with a reasonable number of users and at least two receiver antennas, it is possible to reach a sector capacity in excess of 4 bits/s/Hz, which is far better than current 3G systems. This is however obtained with a very simple scheduler that does not take quality of service and fairness into account. More advanced scheduling must be done in a practical system and this will reduce the capacity at the expense of quality of service and fairness. An issue that seems to be difficult though is to find a proper criteria for optimizing the scheduler since such a criteria will depend on the business models that operators will use.

In the final paper, we will discuss the whole system in some more detail.

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