AN OFDM BASED SYSTEM PROPOSAL FOR 4G DOWNLINKS

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Abstract. In this paper we describe an OFDM based 4G downlink for a wide area coverage and high mobility system. User data are multiplexed and OFDM modulated such that the user with the best predicted channel conditions are always using the channel. This user employs the linear modulation scheme that maximizes the spectral efficiency. We show that the system obtains a sector capacity that is significantly better than current 3G systems. Various combinations of OFDM and CDMA are also discussed and it is concluded that it is difficult to motivate the significantly increased complexity of such schemes. Moreover, we also doubt that these combinations can increase spectral efficiency when predicted channel information is utilized at the transmitter.

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 scheme. 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 that 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 [6].

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 time-frequency bins of given bandwidth and duration. These resources are shared among K active terminals.

During each slot, each terminal predicts the signal to interference and noise ratio (SINR) for all bins, with a prediction horizon which is larger than the time delay of the transmission control loop. All 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. 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 the predicted slot, the modulation formats used are those which were suggested by the appointed users.

The bin size 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 and a carrier frequency of 1900 MHz (Doppler 174 Hz), we here select a bin size of 0.667 ms times 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.

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

Thus, each time-frequency bin carries 120 symbols, with 6 symbols of length 111 μs on each of the 20 10 kHz 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 8 uncoded modulation formats: BPSK, 4-QAM, 8-QAM, 16-QAM, 32-QAM 64-QAM, 128-QAM, and 256-QAM. This adaptive modulation system is optimized and evaluated in [6]. It is designed to maximize the spectral efficiency for each user for constant transmit power, by balancing the throughput against the loss due to erroneous packets. Variable transmit power provides only minor improvements [4] and would require a large amount of feedback.

Prediction of the whole channel with a given horizon can be performed either in the time-domain or in the frequency-domain. The best known power predictor performance on measured broadband data is obtained with the unbiased quadratic power predictor presented in [7]. Prediction over 2 ms seems attainable at 1900 MHz also for users travelling at 100 km/h for this predictor.

A more detailed description of the proposed system can be found in [2].

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 [6]. The SINR limits for selecting the appropriate M-QAM format have been optimized to maximize the number of bits that arrives in bins which are declared correctly received by the CRC check. 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 all the modulation formats, weighted by the probabilities that those particular formats will be utilized, and also by the corresponding frame acceptance rates. This raw spectral

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[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.

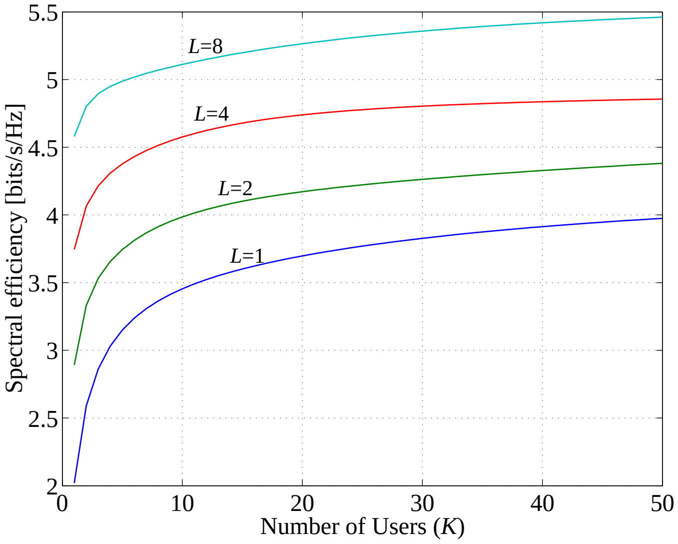

Figure 1. Payload spectral efficiency at SINR 16 dB per receiver antenna, when using adaptive multiplexing and modulation with Lth order MRC diversity in the mobile and Kth order of selection diversity between the users. Degradation due to channel variation within a bin, prediction errors, link layer overhead and frequency reuse is not taken into account.

efficiency 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.

This somewhat ideal sector capacity is evaluated numerically in Fig. 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 Fig. 1 is small for vehicle speeds below 120 km/h [6]. With very few users, a loss of slightly more than 10 % might appear while with 20 users the loss is less than 3 % for an average SNR of 16 dB. 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.

Imperfect channel predictions will also slightly reduce the spectral efficiency. In

[8] it is shown that this results in approximately 10 % degradation of spectral efficiency at an average SNR of 16 dB when all channels have to be predicted 1/3 wavelength ahead (corresponding to 2 ms at a velocity of 100 km/h at 1900 MHz). The loss is smaller for lower velocities. At the link layer, there will be some degradation in spectral efficiency due to CRC bits and sequency numbers. This loss is expected to be between 3 % (for 20 users) and 7 % (for one user). The overall system capacity also must take frequency reuse into account. Preliminary studies show that a frequency reuse of 1.73 is possible in a fully loaded system [2]. Thus in total, the numbers in Fig. 1 should be multiplied by 0.41 for one user and 0.5 for 20 users to obtain a more practical sector capacity for high vehicle speeds and system loads.

4. ON SPREADING AND OFDM IN THE DOWNLINK

Above we outlined a downlink proposal that utilizes uncoded adaptive OFDM. Among other alternative solutions, several researchers have proposed 4G downlinks based on different combinations of OFDM and CDMA. Here we discuss some of the more common spread 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. Unfortunately, MC-CDMA is also often used as a name for the whole family of spread OFDM schemes.

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]

The systems are illustrated in Fig. 2 for the case of 4 chips per bit, 4 subcarriers and no interleaving of chips. When chips are interleaved, the situation becomes more involved. MC-CDMA is still spreading over frequency but the chips for a particular bit are now further apart in frequency such that the fading correlation between them is further reduced. MC-DSCDMA is still spreading over time but the chips corresponding to one bit is again further apart in time. TFL-CDMA probably only makes sense without interleaving since it is especially designed to reduce correlation between users' signals. In the figure we for completeness also include ordinary unspread OFDM.

The performance of the spread schemes depends both on the diversity order that can be obtained with the scheme (which limits the single user performance) and the amount of multiuser interference that is influencing the decision. These factors are quite different in the case of chip-interleaving or no chip-interleaving.

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

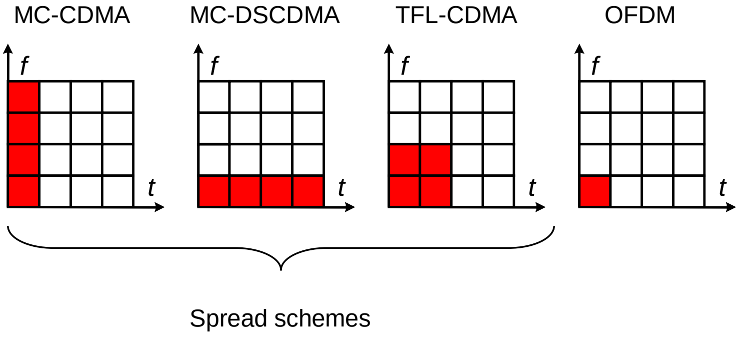

Figure 2. Various combinations of CDMA and OFDM transmission with 4 chips per bit. The red/dark areas represent the time-frequency resources used for each transmitted bit when no chip-interleaving is used. In the spread schemes, several users share these resources.

Without chip-interleaving, the diversity order depends on the frequency/time selectivity of the channel and the outer channel coding, while the multiuser interference (MUI) depends only on the selectivity of the channel (assuming ortogonal codes are used at the transmitter). The impact of selective fading on these different systems are quite different. The diversity order and the MUI of MC-CDMA depend on the coherence bandwidth of the channel. When the coherence bandwidth is large compared to the signalling bandwidth, the spreading does not contribute to the diversity order and the MUI is low. On the contrary, a small coherence bandwidth leads to large diversity orders (maximum N) but also large MUI. In MC-DSCDMA it is the coherence time that influences the diversity order and amount of MUI in the same way. 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 one coherence bandwidth times one coherence time for systems with large spreading and large channel variation. Thus, the spread schemes will perform very similar to pure OFDM when the channel variation is low in frequency and/or time and/or the signalling bandwidth is low.

However in many practical systems, the spread schemes will result in significant MUI and also reasonably large diversity gains. The MUI is smaller for TFL-CDMA than for the other two schemes, but the diversity order is also smaller for TFL-CDMA. With pure OFDM, outer channel coding must be used to obtain diversity, but this scheme is free from multiuser interference. From [9] and [10], the conclusion is that in most cases the coded pure OFDM scheme has a performance advantage when the same outer code is used in all systems. With very few users or very efficient multiuser detectors, the spread schemes may performance slightly better than the pure OFDM scheme but at the expense of either much lower spectral efficiency (few users) or much higher complexity.

With chip-interleaving in the spread systems, the diversity order due to spreading increases and can be made to approach N if a long delay due to interleaving is acceptable. On the other hand, the amount of MUI also significantly increases since the spreading codes becomes random in the receiver due to the uncorrelated (with long interleavers) fading on the different chips in a bit. Thus, multiuser detection is necessary leading to much more complex receivers. In [11] it is concluded that the spread schemes with outer channel coding has some performance improvement compared to coded pure OFDM in single cell systems. If this is the case also in cellular system with more than one cell, seems to still be an open question.

Another problem with spread OFDM schemes, besides the large receiver complexity with multiuser detectors, is that it is an open question how to efficiency use adaptive modulation with them. It is straight forward when no interleaving is used and the channel variation is small in time and/or frequency. Then each bit is transmitted on a constant channel and the same principles as with pure OFDM can be used. In this case, there is however no performance advantage of the spread schemes and thus no reason to use them. With chip-interleaving and/or high variation on the channel, different chips for a given symbol will see different channel gains which means that adaptive modulation becomes more difficult to employ. As far as we know, there is no good current solution on how to employ adaptive modulation when the channel variation of each bit is large. Thus, we conclude that in systems like the one we propose, where channel state information is available at the transmitter, coded pure OFDM is the more attractive choice and also the one with the best known performance. In systems that do not utilize channel state information in the transmitter, we still find it very difficult to motivate all the additional receiver complexity of spread schemes based on the quite limited performance gains that are available. Overall, we believe a simpler system is obtained by utilizing a more powerful outer channel code in the pure OFDM system. This will increase the complexity of the receiver too, but not at all in the same way as the increased complexity due to multiuser detection. So in summary, we believe that pure OFDM has a better tradeoff between performance and complexity on downlinks in almost all cases. For the uplink, the conclusion might be different since the uplink is asynchronous, but this is not the scope of this paper.

5. SUMMARY AND CONCLUSIONS

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 of about 2 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 sacrifice some capacity to improve quality of service and fairness. An issue that seems to be difficult though is to find proper criteria for optimizing the scheduler since such a criteria should depend on the business models that operators will use.

We also discuss some combinations of CDMA and OFDM. Our conclusion is that pure OFDM has a better tradeoff between performance and complexity on downlinks. In systems with channel state information available in the transmitter, it also has much higher spectral efficiency.

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