ON INTER-CELL INTERFERENCE IN OFDMA WIRELESS SYSTEMS

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ABSTRACT

Orthogonal Frequency Division Multiple Access (OFDMA) is a multiple access technique that is starting to be examined as an alternative to Code Division Multiple Access (CDMA) for cellular mobile systems. Until recently, OFDMA had received little attention for multicellular applications and as a consequence of this, few results are available on the impact of interference on OFDMA communications. In this paper, we study the behaviour of an OFDMA system with respect to the inter-cell interference. We show that due to the heterogeneous nature of the interference, interference estimation combined with soft-input channel decoders can be used to improve the performance of the system. We show through realistic simulations that OFDMA can cope with inter-cell interference even without estimating it. Moreover we evaluate the performance gains obtained for different interference estimation techniques and show that a low complexity algorithm can be used to achieve gains of up to 2 dB.

1. INTRODUCTION

Using OFDMA in an interference-limited environment is relatively new [1], as until recently OFDMA was mostly used in non-cellular applications which were resource-limited [2, 3]. It is therefore desirable to obtain a better knowledge of how OFDMA systems perform in the presence of interference. In CDMA, the interference experienced by a user is homogeneous over time as long as no new users are admitted into or leave the system. It is due to cross-correlation between the spreading codes and can be considered as noise. The interference we experience in an OFDMA system is quite different from that of a CDMA system. There is no intra-cell interference as users remain orthogonal even through multipath channel (allocation patterns must be chosen to respectv the orthogonality). However, when users from different cells are present on the same sub-carrier during a given OFDM symbol interval, QPSK or QAM modulated signals superpose with unknown fading gains. Indeed, not only do we not know the symbols and fading gains of the interfering users, we are also uncertain as to which time-frequency units the interfering users are present on. Trying to estimate all of these parameters would mean a prohibitively high computational cost.

Soft-input channel decoders such as turbodecoders operate on soft-valued reliability metrics, such as log-likelihood ratios (LLR). It has been shown in [4] that adjusting the decision metrics based on perfect knowledge of the instantaneous SIR results in considerable performance improvements in terms of Bit Error Rates (BER) and Block Error Rates (BLER). The goal of the present paper is to propose an interference estimation method for such a system in order to adjust the likelihood metrics that are fed to the channel decoder.

2. SYSTEM DESCRIPTION

2.1 Overview

We examine the downlink of a multicellular OFDMA system. In order to produce results which are as relevant as possible for real-world applications, the current study is based on the OFDMA system defined by the "OFDM Study Item" [5] of the 3GPP TSG-RAN working group 1 aiming at evaluating the feasibility and benefits of introducing OFDM to UTRAN for High Speed Downlink Packet Access-like services [6].

The frequency reuse factor is of one, meaning that all cells in the network use the same frequency band. If we consider the users of a given cell, they will receive both the desired signal and interference from neighbouring cells in the same frequency band.

We assume that in each cell, a base station serves up to 15 users. The data to be transmitted to each user is coded, interleaved and passed to a mapping unit which uses either QPSK or 16-QAM modulation. The traffic for the different users is then multiplexed using a time-frequency mapping that is detailed in section 2.2. The multiplexed traffic then undergoes OFDM modulation.

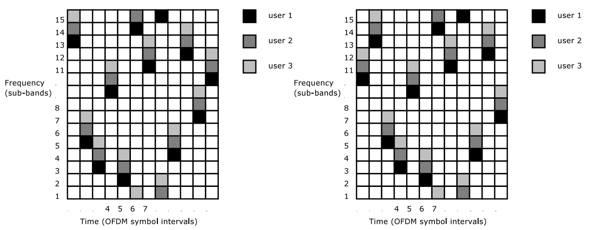
2.2 Frames and user traffic multiplexing

The basic time interval we consider in the present study is a 2 ms frame, which corresponds to 12 OFDM symbols. This duration is often referred to as a Transmission Time Interval (TTI). The OFDM frequency band is divided into 15 sub-bands, that is to say blocks of consecutive sub-carriers. One such sub-band during one OFDM symbol interval is referred to as an *OFDM unit*. User traffic is multiplexed by allocating one OFDM unit to each active user at each symbol interval. The patterns used to multiplex the traffic of different users within a given cell need to be orthogonal in order to avoid intra-cell interference. To allow full frequency reuse without resource planning, the time-frequency mappings should also minimise inter-cell interference.

The time-frequency (T-F) mapping that is used is based on a truncated Costas sequence of length 15 [7]. Costas arrays are $n \times n$ arrays consisting of dots and blanks with exactly one dot in each row and column.

For a given cell and TTI, the allocation patterns for the different users are obtained as a cyclic frequency shift of the basic allocation pattern. The frequency shift is an integer number of sub-bands. Different sets of T-F allocation patterns can be obtained through a cyclic time shift of an integer number of OFDM symbol intervals. To illustrate this, two sets of time-frequency allocation patterns are represented in Figure 1. The right-hand set is obtained by shifting the left-hand set by one OFDM symbol duration.

Every TTI, each cell selects a set of allocation patterns at



(a) allocation pattern 1 (b) allocation pattern 2

FIG. 1 – 2 sets of time-frequency allocation patterns

random, which corresponds to drawing a random time-shift. There are 12 possible sets of T-F allocation patterns, each of which contains 15 allocation patterns.

3. METRICS ADJUSTMENT

3.1 LLRs on flat fading channels with AWGN

Let us consider the case where a signal is transmitted using antipodal signalling over a flat fading channel with AWGN. The received signal can be expressed as a function of the transmitted signal *x*, the channel coefficient *h* and the noise *n* which is a gaussian random variable with variance σ^2 as

$$r = hx + n, \quad x \in \left\{+\sqrt{E_b}, -\sqrt{E_b}\right\}$$

If we furthermore consider equal *a priori* probabilities for the two possible signals $+\sqrt{E_b}$ and $-\sqrt{E_b}$, using the fact that *n* is a gaussian random variable, the log-likelihood ratio can written as

$$L(x \mid r) = 2\frac{\sqrt{E_b}}{\sigma^2}\Re\left(h^* r\right) \tag{1}$$

Equation (1) is interesting as it illustrates the fact that knowledge of the signal to noise ratio is needed in order to compute the log-likelihood ratio. It also shows that the signal to noise ratio $\frac{\sqrt{E_b}}{2\sigma^2}$ appears as a multiplicative term in the LLR.

3.2 Adjusting LLRs to interference

In a multicellular environment, it is no longer reasonable to suppose that the interference is gaussian and white. Deriving an exact expression of the LLR for a given sub-band and time slot would require knowledge of the number of interferers present and their respective phases and amplitudes. Such detailed information is not usually available, but we assume that the total interference power can be obtained by some means.

Let us denote LLR_{in} the metrics output by the demodulator based on formula (1). These metrics are not the actual log-likelihood ratio as they only take into account the estimate of the noise level that was given to the demodulator. In order for the channel decoder to produce better decisions, we should feed it metrics which we will denote LLR_{out} which are closer to the true LLR. If we denote *N* the noise power and *I* the interference power, our goal is to identify a function *f* such that

$$LLR_{out} = f\left(LLR_{in}, I, N\right)$$

is a better estimation of the log-likelihood ratio. A simple LLR weighting method is to consider that the interference will have an impact which is similar to the gaussian noise, and hence use

$$LLR_{out} = LLR_{in}\frac{N}{I+N} \tag{2}$$

Another possible method still under investigation would be to use a mapping of (SIR,SNR) to an equivalent SNR in terms of Bit Error Rates (BER). The BER is calculated for uncoded transmissions over an AWGN channel in the presence of interference for different (SIR,SNR) points. For each one of these points, we look up the SNR level for a noise-only situation which yields the same BER. If we call N_{eq} the mapping function thus constructed, the LLR are adjusted as

$$LLR_{out} = LLR_{in}\frac{N}{N_{eq}\left(I,N\right)} \tag{3}$$

4. INTERFERENCE ESTIMATION METHODS

4.1 Averaged ideal estimation

To obtain a fair upper bound with respect to our realistic interference estimation algorithms (for which we determine only one single SIR value per sub-band), we simulated an averaged ideal interference estimation where the exact powers of both the noise and the inter-cell interference are averaged per sub-band.

4.2 Interferer location

The first practical interference estimation method that was examined relies on the fact that in order to avoid creating excessive interference in the neighbouring cells, a cell will not operate at full load. As a consequence of this, in certain time-frequency (T-F) units the cell of interest does not transmit and we have only interference. We will refer to these T-F units as the *observable T-F units*. In this section, it is assumed that the cell of interest is synchronised in time and frequency with the interfering cells.

Estimating in which T-F units the interferers are present can be viewed as block-decoding a repetition code with a certain number of erasures, namely the T-F units where our cell of interest is present. This is not strictly true as we actually have a superposition of several interfering cells, but a certain amount of information can possibly still be recovered by analysing the power levels in the *observable T-F units*.

We try to detect iteratively the set of allocation patterns, the number of active users and a power measurement for the strongest interfering cell. The motivation for constructing an iterative algorithm as opposed to one that detects all the interferers in one pass is that the sets of T-F allocation patterns are not orthogonal to each other. This means that a given observation of the interference-only units cannot be decomposed into a unique superposition of interfering pattern sets, cell loads and powers.

The algorithm is initialised with the knowledge of the allocation set and number of users for the cell of interest. From this it determines which time-frequency units are *observable*

T-F units. Each iteration of the algorithm can be summarised as follows :

1. For each possible user u of each available allocation pattern set s, compute the average power $P(s,u)$ in the *observable T-F units* where the user would have transmitted.
2. From the $P(s,u)$ metrics determine the allocation set and number of users of the strongest interfering cell.
3. Estimate the power contribution of the detected cell and subtract its contribution from the powers in the *observable T-F units*.

From the detected metrics, the algorithm produces an estimate of the total interference power in the T-F units where the cell of interest is active.

4.3 Demapping and remapping

Another estimation technique that was examined is to calculate the difference between the received signal and the closest constellation point multiplied by the estimate of the channel. This is achieved by demapping the received signal, taking a hard decision and remapping the estimated symbol. In that section we no more assume that interfering cells are synchronized with the cell of interest.

For a given time t let x_t denote the constellation point that was transmitted on a given sub-carrier by the cell of interest, h_t the corresponding channel coefficient and i_t the total interference for at time t. The received signal r_t can be written as

$$r_t = h_t x_t + i_t$$

If we call $\hat{x}_t$ the estimated mapped symbol and $\hat{h}_t$ the estimate of the channel coefficient, our estimate of the total interference for the considered sub-carrier is

$$\hat{i}_t = r_t - \hat{h}_t \hat{x}_t$$

The estimated mapped symbol $\hat{x}_t$ is the constellation point that minimises $\left\| r_t - \hat{h}_t \hat{x}_t \right\|$. As x_t is one of the constellation points, we have the following relationship

$$\left\| r_t - \hat{h}_t \hat{x}_t \right\| \leq \left\| r_t - \hat{h}_t x_t \right\|$$

In the case where $\hat{h}_t = h_t$, that is when our estimate of the channel is correct, the above relationship becomes

$$\left\| \hat{i}_t \right\| \leq \| i_t \|$$

This means that if we have a perfect estimate of the channel, the estimate of the interference will always have a power that is lower or equal to the actual interference power. This is not necessarily a problem as we are more concerned about the relative interference powers for different parts of the signal than about the actual value of the interference power.

5. SIMULATION RESULTS

We evaluated the performance of the different interference estimation and LLR weighting methods using link-level Monte Carlo simulations. The simulator consists of one useful cell, 2 interfering cells and additional thermal noise. This multicell environment is an extension of the work presented in [4], where only one interfering cell was considered. Both the useful and the interfering signals travel over independent occurrences of the ITU Vehicular A (30km/h velocity) channel model.

The Signal to Interference Ratio (SIR) and Signal to Noise Ratio (SNR) values are controlled by a combining block, which sums the useful signal, the interfering signals and the gaussian noise. The combining block is also able to introduce a random time and/or frequency shift between the signal of the cell of interest and the interfering cells.

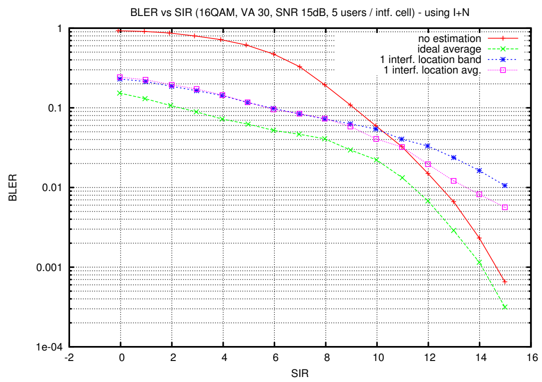


FIG. 2 – BLER for 5 users/interf cell : interferer location

The link-level parameters of the system are those described as the parameter set 2 in [5]. They are summarised in the following table. BLER are computed on blocks of a TTI length.

Parameter	Value
Carrier frequency	2GHz
FFT size	1024
Modulated carriers	705
Guard interval	64
OFDM bandwidth	4.495MHz
Turbocoder	UMTS-like, max 6 iterations

TAB. 1 – OFDM parameters set

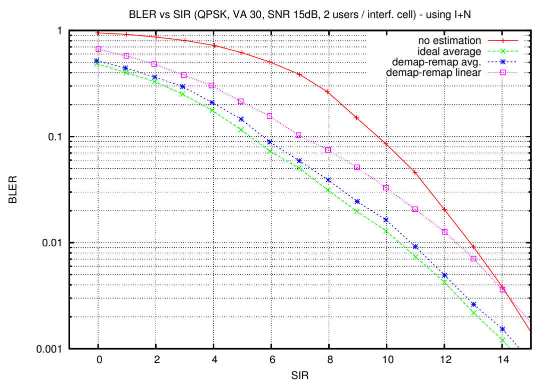


FIG. 3 – BLER for 2 users/interf cell : filtered demap-remap

Fig. 2 shows the performance of the interference location method. This method provides substantial gain as long as inter-cell interference predominates on gaussian noise. Its performance degrades at higher SIR because of a lower interference to noise power ratio[1]. Results from the mapping-demapping method are given by Fig. 3 and 4. As the interference experienced on adjacent sub-carriers remains strongly correlated, it is therefore reasonable to perform filtering of the interference estimates per sub-bands. One filtering we experimented with is a linear interpolation on the interference power estimates. We compared it to simple averaging.

For all configurations examined, using the band-averaged demapping-remapping interference estimate leads to significant performance gains over no estimation. In all of the configurations, the performance when weighting the LLRs with the band-averaged estimate tracks the performance of band-averaged ideal estimation with a near constant offset. This offset is of approximately 0.5dB, except for 16-QAM at 2 users per interfering cell, in which case it is closer to 1dB. The following table summarises the performance gain of band-averaged demapping-remapping over no estimation for a BLER of 10^{-2} in the different configurations.

users per interfering cell	QPSK	16-QAM
2 users	2.1 dB	1.9 dB
5 users	1.1 dB	0.9 dB
8 users	0.7 dB	0.6 dB

TAB. 2 – Performance gains

A slightly surprising result is that the polynomial interpolation of order one yields a performance which is less than that of the averaging. One possible explanation is that the interference estimate resulting from the demapping-remapping operation is very noisy so that increasing the order of the interpolation does not smooth this estimate enough. From these

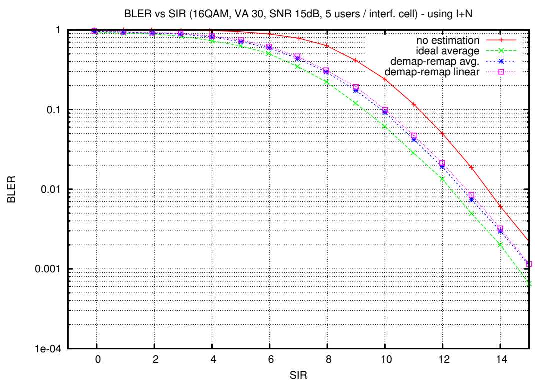


FIG. 4 – BLER for 5 users/interf cell : filtered demap-remap

results, we can say that weighting the LLRs passed to the channel decoder using the demapping-remapping estimation method followed by averaging for each sub-band is a very interesting means of increasing the system's performance. Not only does it yield performance gains regardless of the type of modulation, the load of the interfering cells and the SIR level, but it does so at the cost of very little computational complexity.

[1]in our simulations the power of the gaussian noise is constant and set 15 dB below the useful signal

6. CONCLUSION

From the presented results, it appears clearly that OFDMA is a multiple access technique that is robust to multicellular interference. Furthermore, since the inter-cell interference that is experienced in an OFDMA system is not homogeneous, it is possible to reduce its impact by estimating the time-frequency distribution of the interference.

It is usually assumed that when dealing with interference it is best to average it out over the modulation symbols ; this is the behaviour of CDMA. In OFDMA, the interference is averaged out at the block level, but the interference is still heterogeneous at the modulation symbol level, which can be exploited to improve the system performance. This gain was assessed in practical situations since we designed a low complexity interference estimation algorithm and validated its performance by means of realistic simulations. Namely, provided some sub-band filtering is applied, the demapping-remapping interference estimation method provides an estimate of the interference which can be used to weight the LLRs passed to the channel decoder to achieve substantial performance gains with little computational complexity.

This work could lead to further investigations. Indeed, filtering on the sub-bands of each OFDM symbol is logical if the cell of interest and the interfering cells are synchronised both in time and in frequency. However, when time synchronisation is not assumed, this is no longer true and applying filtering on a per sub-band basis becomes arbitrary. Eventually, from this work, OFDMA appears worth being considered and further investigated as a multiple access for mobile cellular applications, besides its use in nomadic environments as e.g. WiFi.

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