REUSE WITHIN A CELL - INTERFERENCE REJECTION OR MULTIUSER DETECTION?

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Abstract - We investigate the use of an antenna array at the receiver in FDMA/TDMA systems, to let several users share one communication channel within a cell. A decision feedback equalizer which simultaneously detects all incoming signals (multiuser detection) is compared to a set of decision feedback equalizers, each detecting one signal and rejecting the remaining as interference. We also introduce the existence of a zero-forcing solution to the equalization problem as an indicator of near-far resistance of different detector structures. Simulations indicate that multiuser detection in general provides better performance than interference rejection. We have applied the proposed algorithms to experimental measurements from a DCS-1800 antenna array testbed. The results from these experiments confirm that reuse within a cell is indeed possible using an eight-element array antenna at the receiver.

I. INTRODUCTION

In a cellular communication system, multi-element antennas, also known as *antenna arrays*, can be used at the receiver to increase the capacity. It may even be possible to employ *reuse within a cell*, i.e. to let several users share each channel in one cell. In this paper, we illustrate, compare and explore two ways of using an antenna array at the receiver to accomplish channel reuse within a cell:

1. Detect data from one user at a time while treating the other users as interference. In the following, this approach will be denoted *interference rejection* or *interference cancellation* [1, 2].
2. Detect the data from several of all users simultaneously. This will be called *multiuser detection* [3].

As will become evident in the following sections, the performance of (nonlinear) multiuser detectors is mostly superior to that of interference cancellers, for two reasons:

1. They can suppress interference more efficiently than non-linear interference cancellers.
2. The channel estimation is improved, which leads to more precise tuning of the detector.

We will illustrate the influence of these two factors by comparing two types of *decision feedback equalizers (DFE:s)* in FDMA/TDMA systems:

1. The DFE presented in [2], which rejects interference.
2. The DFE of [4], which detects all signals simultaneously.

II. CHANNEL MODELS

The channel models upon which we base the design of the detectors are assumed to be linear, time-invariant and sampled at the symbol rate. We consider a case with M transmitters and N receivers[1]. In uplink transmission, the M transmitters are different mobiles in the cell, while the N receivers are located at the base station. In the downlink, we assume that a separate message is transmitted from each of M antenna elements at the base station. Each mobile is equipped with N receivers, which are used to detect one or all of the messages. In both links, we thus have M transmitters and N receivers. Assuming that $s_j(k)$ is the symbol sequence sent from transmitter j, while $x_i(k)$ is the signal at receiver i and $v_i(k)$ represents the additive noise, define

$$s(k) \triangleq \begin{pmatrix} s_1(k) & s_2(k) & \dots & s_M(k) \end{pmatrix}^T \quad (1a)$$

$$x(k) \triangleq \begin{pmatrix} x_1(k) & x_2(k) & \dots & x_N(k) \end{pmatrix}^T \quad (1b)$$

$$v(k) \triangleq \begin{pmatrix} v_1(k) & v_2(k) & \dots & v_N(k) \end{pmatrix}^T . \quad (1c)$$

We also denote the scalar channel from transmitter j to receiver i as $H_{ij}(z^{-1})$ and define the polynomial matrix

$$\boldsymbol{H}(z^{-1}) \triangleq \begin{pmatrix} H_{11}(z^{-1}) & \dots & H_{1M}(z^{-1}) \\ \vdots & \ddots & \vdots \\ H_{N1}(z^{-1}) & \dots & H_{NM}(z^{-1}) \end{pmatrix} . \quad (2)$$

Using (1a), (1b), (1c) and (2), we can now express the signal received at the antenna array by the MIMO model

$$\begin{aligned} x(k) &= \boldsymbol{H}(z^{-1})s(k) + v(k) & (3a) \\ &= \mathbf{H}_0 s(k) + \dots + \mathbf{H}_L s(k-L) + v(k) . & (3b) \end{aligned}$$

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[1] The receivers can represent multiple antennas or polarization diversity branches. The equivalent number of receivers can be effectively doubled for real-valued signal constellations since real and imaginary parts of received baseband signals then provide two measurements for each symbol to be detected. Fractionally spaced sampling can also increase the equivalent number of receivers.

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The multiuser detector is based on the model (3a). In (3b), L represents the maximum order of all scalar channels. The vector $v(k)$ of noise samples is characterized by the matrix-valued covariance function

$$\psi_{k-m} \triangleq E[v(k)v^H(m)] \tag{4}$$

and can be both spatially and temporally colored. If we explicitly model the signal from only one of the users, we have to handle signals from the remaining users as interference. Assuming signal number 1 to be of interest, we then define a disturbance vector $V(k)$ as the sum of all co-channel interference and noise;

$$V(k) = \sum_{n=2}^{M} \boldsymbol{H}_n(z^{-1})s_n(k) + v(k) \tag{5}$$

where $\boldsymbol{H}_n(z^{-1})$ is column n in (2). The interference $V(k)$ is characterized by its matrix valued covariance function

$$\bar{\psi}_{k-m} \triangleq E[V(k)V^H(m)] \ . \tag{6}$$

The interference rejection design is based on the model

$$x(k) = \boldsymbol{H}_1(z^{-1})s_1(k) + V(k) \ . \tag{7}$$

Remark 1. If we only model one of the signals explicitly, estimation of the matrix-valued covariance function of $V(k)$ is vital. This becomes a major problem, since direct estimation of $\bar{\psi}_m$ will provide poor accuracy for the short training sequences typically present in cellular systems.

III. THE MULTIVARIABLE DFE

3.1. The equalizer structure

A multivariable DFE with a transversal feedforward filter and a transversal feedback filter

$$\begin{aligned} \hat{s}(k-\ell|k) &= \boldsymbol{S}(z^{-1})x(k) - \boldsymbol{Q}(z^{-1})\tilde{s}(k-\ell-1) \\ \tilde{s}(k-\ell) &= \mathrm{f}(\hat{s}(k-\ell|k)) \end{aligned} \tag{8}$$

will be used. The output $x(k)$ of the array is used as input to the equalizer and $\tilde{s}(k-\ell-1)$ are the decisions previously made by the equalizer. The soft estimate $\hat{s}(k-\ell|k)$ is passed through the decision non-linearity $\mathrm{f}(\cdot)$ to produce the hard estimate $\tilde{s}(k-\ell)$. The feedforward filter $\boldsymbol{S}$ is of order n_s, whereas the feedback filter $\boldsymbol{Q}$ is of order n_Q. In general, (8) represents a MIMO DFE, which will be used for multiuser detection. With $\hat{s}$ scalar, we obtain a MISO DFE, to be used for interference rejection. A set of M MISO DFE's can be represended by (8), with $\boldsymbol{Q}$ being *diagonal*. The use of FIR filters in (8) and of model-based (indirect) design of the equalizer is motivated in [5]. We adopt the common assumption that all previous decisions affecting the current symbol estimate are *correct*, i.e. that

$$\tilde{s}(k-\ell-n) = s(k-\ell-n) \quad n = 1,\dots,n_Q+1 \ . \tag{9}$$

The coefficients of $\boldsymbol{S}$ and $\boldsymbol{Q}$ can be adjusted to obtain zero forcing or minimum mean square error (MMSE) designs.

3.2. Zero-forcing and MMSE designs

A multiuser zero-forcing (ZF) equalizer can be defined [1] as a filter which eliminates both the residual intersymbol interference *and* co-channel interference:

Definition 1 *Consider the channel model* (3b) *and a multivariable equalizer which forms the estimate* $\hat{s}(k-\ell|k)$ *of a transmitted symbol vector* $s(k-\ell)$. *If*

$$\hat{s}(k-\ell|k) = s(k-\ell) + \varepsilon(k) \tag{10}$$

where $\varepsilon(k)$ *is uncorrelated with all transmitted symbol vectors* $s(m)$ $\forall\, m$, *then the equalizer is said to be zero-forcing.*

By substituting (3a) and (9) into (8), the zero-forcing condition (10) implies:

$$\boldsymbol{S}(z^{-1})\boldsymbol{H}(z^{-1})s(k) - \boldsymbol{Q}(z^{-1})s(k-\ell-1) = s(k-\ell).$$

A DFE will thus be zero-forcing if and only if $\boldsymbol{S}$ and $\boldsymbol{Q}$ constitute a solution to the *Diophantine equation*

$$\boldsymbol{S}(z^{-1})\boldsymbol{H}(z^{-1}) - z^{-\ell-1}\boldsymbol{Q}(z^{-1}) = z^{-\ell}\mathbf{I}_M \ . \tag{11}$$

The coefficients of an MMSE equalizer are determined to minimize

$$J = E[||s(k-\ell) - \hat{s}(k-\ell|k)||^2] \tag{12}$$

where the expectation is taken over the signal vector $s(k)$ in (1a) and the noise vector $v(k)$ in (1c) (MIMO case) or $V(k)$ in (5) (MISO case). Assuming (9), the design equations for the multivariable MMSE DFE can be obtained from two coupled Diophantine equations, which are transformed into a linear system of equations [5]. In the following, we mainly utilize the MMSE criterion.

3.3. Near-far resistance, well-posedness and zero-forcing solutions

An MMSE DFE optimally balances suppression of intersymbol interference and co-channel interference against noise amplification. When the power of the interfering users is large, rejection of these strong signals is of paramount importance, whereas suppression of the noise is less important. This situation has been studied extensively for CDMA multiuser detectors, in which case the ability to cope with strong interferers is called *near-far resistance* [7].

We may then ask under what conditions are MIMO and MISO MMSE DFE:s near-far resistant? To investigate this question, we let the noise covariance ψ_n tend to zero in (4) and in (6). If all intersymbol and co-channel interference can be removed, then the MMSE equalizer will reduce to a ZF equalizer, and the estimation error will vanish. In this case, perfect equalization is possible, for *any* power of the interfering users. If no ZF equalizer exists, all intersymbol and co-channel interference cannot be removed, so the estimation error will not vanish.

We can therefore use the existence of a ZF DFE as an indication of near-far resistance for the MMSE MIMO DFE or the MMSE MISO DFE. In more general terms, the existence of a zero-forcing solution also indicates that the equalization problem is well-posed in the sense that it can provide a useful solution: Good performance can be guaranteed, for sufficiently low noise levels.

Equalizers which fulfill the zero-forcing condition (11) exists, under mild conditions. In the MIMO case for M users, they exist if and only if [6]

Every common right divisor of $\boldsymbol{H}(z^{-1})$ *and* $z^{-\ell-1}\mathbf{I}_M$ *is also a right divisor of* $z^{-\ell}\mathbf{I}_M$. (13)

Theorem 1 below specifies the filter degrees required. We will consider the generic case when the channels to any antenna element have no common factors. Also, there is no propagation delay in the channel models, i.e. no column in $\mathbf{H}_0$ consists of zeros only. For the general case and a proof, see [5].

Theorem 1 *Consider the MIMO channel model* (3b) *with* M *sources and* N *sensors with* $M \leq N$ *and assume a zero-forcing solution to exist. A generically necessary condition for the existence of a zero-forcing MIMO DFE* (8) *with decision delay* ℓ *and feedforward filter degree* n_s *is then that*

$$n_s \geq \frac{M(\ell+1)}{N} - 1 . \tag{14}$$

The condition

$$n_s \geq \frac{(M-1)L+\ell+1}{N+1-M} - 1 \tag{15}$$

is generically necessary for the existence of a set of M *MISO DFE:s with decision delay* ℓ *and feedforward filter degrees* n_s.

IV. MONTE CARLO SIMULATIONS

The performance of the MIMO DFE is compared by simulation with the performance of the MISO DFE. The MIMO DFE performs multiuser detection on all the signals, whereas the MISO DFE only detects one of the signals. In both DFE:s, the smoothing lag and feedforward filter lengths equal the length of the channel, $\ell = ns = L$.

In our simulation scenario, one, two, three or four BPSK modulated signals impinge on an antenna array with four antenna elements. Each signal is passing through a frequency selective, three-tap Rayleigh fading channel and the taps of the channels fade independently. The channels, of order $L = 2$, are time-invariant over the duration of a TDMA data frame. The channels from different transmitters to a given receiver are independent, and so are the channels from any given transmitter to different receivers.[2] All signals have the same average power and are received in the presence of additive Gaussian noise, which is both spatially and temporally white.

The performance of the algorithms will be addressed as a function of the average SNR per bit [8]

$$\bar{\gamma}_b = \frac{1}{N}\frac{E[|H^0_{ij}|^2 + |H^1_{ij}|^2 + |H^2_{ij}|^2]E[|s_j(k)|^2]}{E[|v_i(k)|^2]} . \tag{16}$$

We assume that $\bar{\gamma}_b$ is equal at different antenna elements and thus independent of i. We also assume that $\bar{\gamma}_b$ is the same for all users and hence independent of j.

4.1. Known channel coefficients and noise covariances

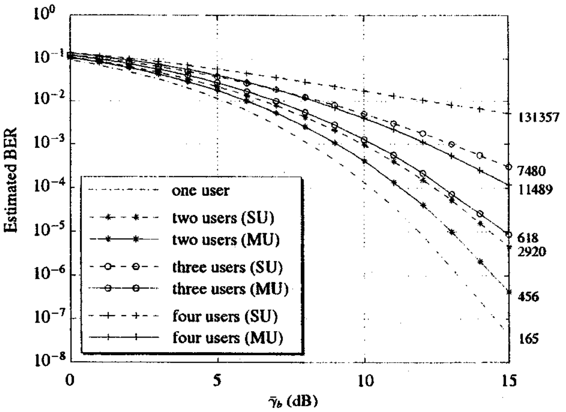

Figure 1: Comparison of the MIMO DFE (MU) and the MISO DFE (SU) for known channels. The numbers to the right of the graph are the number of errors used to estimate the BER for the average SNR per bit $\bar{\gamma}_b$=15 dB.

Fig. 1 shows the estimated BER as a function of the average SNR per bit, when all channel coefficients are exactly

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[2] These assumptions may not always be valid. However, successful multiuser detection does not require uncorrelated channels to different receivers (uncorrelated antennas). See e.g. [5] for a discussion of how antenna correlation affects the performance.

known. With four users, the performance of the MIMO DFE at $\bar{\gamma}_b^j = 15$ dB is around 6 dB better than the performance of the MISO DFE. This difference arises from the fact that the MISO DFE uses up all its degrees of freedom to cancel the interference from the other users. This task is easier for the MIMO DFE since its feedback filter takes care of some of the interference suppression. For fewer users, the difference between the two approaches is smaller. For example, in the case of three users the gain is approximately 3 dB and for two users around 1 dB.

4.2. Estimated channel coefficients

To demonstrate how the MIMO DFE works in a more realistic case, channel estimation is introduced. The data is transmitted in bursts, with a structure similar to that of GSM: A training sequence of 26 symbols is located in the middle of each burst. Together with data symbols, tail symbols and control symbols, this results in a total burst length of 148 symbols. The channel estimation is performed using the off-line least squares method, and the spatial color of the noise is estimated from the residuals of the channel identification. The temporal color of the noise is neglected due to the limited amount of data. Apart from this, the simulation conditions are the same as in Subsection 4.1. The results are indicated in Fig. 2.

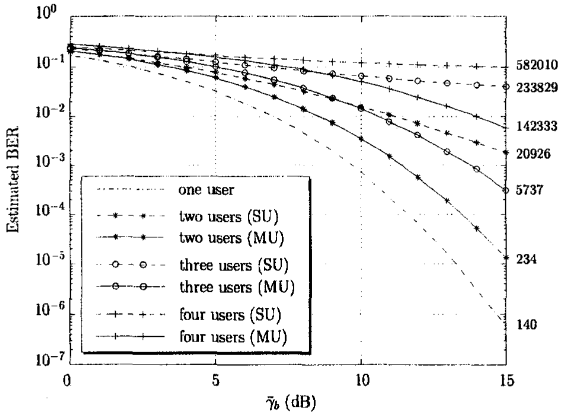

Figure 2: Comparison of the MIMO DFE (MU) and the MISO DFE (SU) for estimated channels.

When we compare Figs. 1 and 2, we see that the difference between the MIMO DFE and the MISO DFE is greater when the channels have to be estimated. The inability to estimate and subsequently use the temporal color of the interference leads to a larger performance degradation for interference rejection. Again, the difference in performance is larger when more users are active in the system. For cases with BER $< 10\%$, the BER can be reduced significantly by using a multi-pass "bootstrap" algorithm [9], where decisioned data are used to improve estimates of the channel and noise parameters.

V. APPLICATION ON MEASURED DATA

The simulations in Section IV. indicate that reuse within a cell is indeed possible. But will it work in practice? To investigate this we will apply the methods described in Section III. to a set of uplink measurements.

5.1. The measurements

The measurements were performed on a testbed constructed by Ericsson Radio Systems AB and Ericsson Microwave Systems AB [10]. The testbed implements the air interface of a DCS-1800 base station. The array consists of four antenna elements, each having two polarization diversity branches, resulting in eight antenna outputs. The measurements were performed in Kista, a suburb of Stockholm, Sweden.

A single mobile mounted on a van transmitted a sequence of data. Two sets of baseband measurements were collected, sampled and recorded. The two sets of measurements were added to represent a situation when two mobile users share the same channel. The algorithms used for the simulations in Section IV. were then applied to the data recorded at the array antenna. The BER was evaluated as a function of the average carrier-to-noise ratio. This quantity cannot be directly measured, but was estimated indirectly.

5.2. Results

The frame structure in DCS-1800 is identical to the one described in Subsection 4.2. In this case, five tap channels are estimated, and $n_s = \ell = L = 4$ is used. The MMSE MIMO DFE and two MMSE MISO DFE:s were used to detect the signals from the two users. In both cases, the bootstrap algorithm described in [9] was utilized to improve the channel estimation. The results are shown in Fig. 3.

The results from the experiments on the measurements from the array antenna are not surprising. For the lightly loaded system with $N = 8$ and $M = 2$, the performance of a MIMO DFE should be only slightly better than the performance of two MISO DFE:s. The investigated scenario constitutes a very difficult detection problem: The channels are in fact flat fading and all intersymbol interference is in this experiment caused by the GMSK modulation. Furthermore, the two mobiles travel exactly the same measurement route, so they have little angular separation. Still, reuse within a cell is possible.

VI. DISCUSSION AND CONCLUSIONS

In our investigation of receiver algorithms designed to accomplish channel reuse within cells, MIMO DFE:s which work as multiuser detectors have been compared to the use

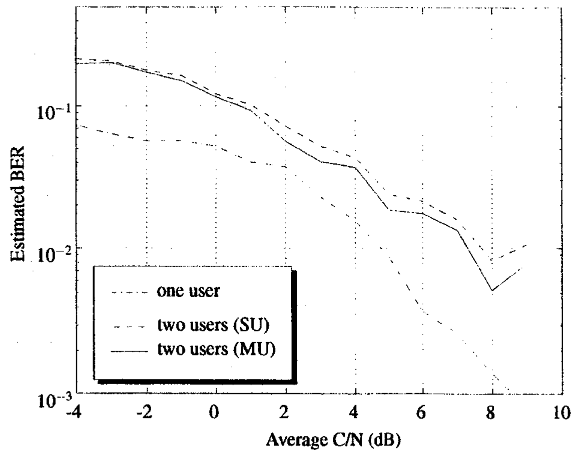

Figure 3: Comparison of the MIMO DFE (MU) and the MISO DFE (SU) applied to measurements from a DCS-1800 testbed. The antenna array had eight outputs and two users were transmitting simultaneously.

of interference rejection, implemented by MISO DFE:s. In summary, simulations indicate that channel reuse within a cell is indeed a viable option, with multiuser detection providing superior performance. We have tested the algorithms on experimental measurements from a DCS-1800 testbed. For the investigated scenario, reuse within a cell is possible using an eight-element antenna array.

Differences in performance between multiuser detection and interference rejection are partly due to the detector *structures*: A multiuser (MIMO) DFE utilizes feedback from previously estimated symbols from *all* users, while the interference rejecting (MISO) DFE performs decision feedback from the user of interest only. The difference also results from the preconditions for *channel estimation*: In the multiuser case, input-output transfer functions can be estimated. For interference rejection, the co-channel interference constitutes colored noise. The multivariate noise models estimated from short data records will have poor accuracy. Estimation of the temporal noise color is problematic even when using a multi-pass (bootstrap) algorithm, if the number of sensors N is large.

Both multiuser detectors and interference rejecting MISO DFE:s can be made near-far resistant. However, the conditions for this, as indicated by the existence of a zero-forcing solution, are somewhat more restrictive for interference rejection.

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