Diversity techniques and spatial preprocessing for existing GSM mobile terminals

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Abstract— **This paper studies the performance improvement by diversity combining at a GSM mobile station (MS). In order to get a low-cost solution, we assume three antennas and separate space and time processing. We use realistic channel models with different angular power spectras for each delay tap. The considered antenna combining schemes range from selection combing (SC) over equal-gain combining (EGC) to optimum combining for frequency selective channels (OC-FS). The temporal processing is done by a conventional GSM receiver with MLSE detection. With OC-FS the SNIR improvement is typically 10dB. SC and EGC show much less improvement.**

I. INTRODUCTION

In recent years, GSM terminals have become smaller and easier to operate. However, the transmission quality (raw BER) achievable with them has not improved. For high-end mobile applications, improvement of the BER independent of the network operator is of interest. One of the most promising ways to decrease the raw BER is the use of smart antennas.

While smart antennas in general, and their application to BS antennas in particular, have received enormous interest in the past years, their application to MSs have remained on the sidelines of research. Of course, the general priciples, as elucidated e.g. in [1], [2], [3], hold also for the MS, but the constraints are quite different. Optimality of the chosen algorithm is less important than simplicity and the possibility to reuse as much of current handset technology as possible. For this reason, separate spatial and temporal processing is desirable. Thus, the combination of the signals from the diversity antennas can be seen as a preprocessing step, whose output is the input of a conventional (off-the-shelf) GSM receiver. While the spatial processing is well-known for the flat-fading channel [6], it is less clear how it should be done in a frequency-selective channel.

An additional requirement for the algorithms is that they work well in different environments, including vehicular at high speeds as specified in the GSM standard. Thus algorithms that rely on the channel knowledge from a previous burst [4] cannot be applied. As most GSM systems, especially in urban environments, are interference limited, so that algorithms that are designed for noise limited channels [5] will also not perform adequately.

The purpose of the current paper is thus to compare different signal combining methods, and discuss the transmission quality as well as the hardware effort for the different techniques. Realistic mobile radio channels are used for the simulations. Especially, the DOA distributions at the MS, which are quite different from those at the BS, are properly taken into account.

The paper is organized the following way: in Sec. II, we discuss the different combining methods and give a brief mathematical description. Section III details the channel model and the simulation configuration in general. Section IV discusses the results, especially the raw bit error probability that the various algorithms can achieve in different environments. In the conclusions, we discuss the practical applicability of the various methods for actual implementation in future GSM terminals.

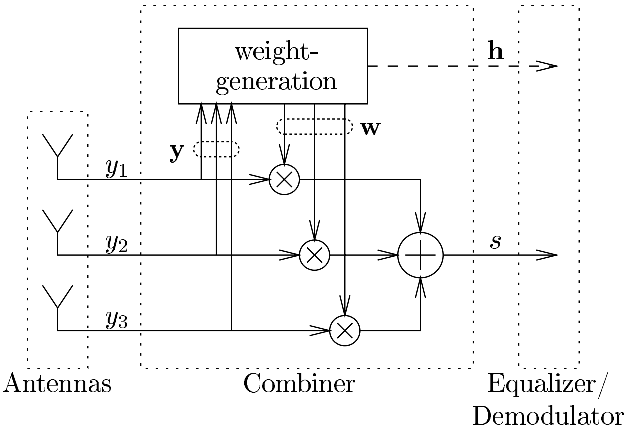

Fig. 1. Combiner structure

II. Combining algorithms

In order to allow a simple receiver structure, we consider space-only combining; temporal equalisation/demodulation is done *after* combining in a separate block. This block is identical to a single-antenna state of the art receiver and will thus be treated only briefly in Sec. III. In case of Optimum Combining for frequency selective channels [7] the dashed line in Fig. 1 is the estimate for the channel response **h.**

Using matrix notation the combined signal **s** can be written as

$$\mathbf{s} = \mathbf{w}^{\mathbf{T}}\mathbf{Y}. \tag{1}$$

$\mathbf{w}^{\mathbf{T}}$ is the transposed complex weighting vector. **Y** is the sampled receive signal which was transmitted over a frequency selective fading channel and has the following structure:

$$\mathbf{Y} = \begin{pmatrix} \mathbf{y_1(t_0)} & \mathbf{y_1(t_1)} & \cdots \\ \mathbf{y_2(t_0)} & \mathbf{y_2(t_1)} & \cdots \\ \mathbf{y_3(t_0)} & \mathbf{y_2(t_1)} & \cdots \end{pmatrix} \tag{2}$$

Y resp. $\mathbf{y(t)}$ can be represented as the addition of the desired signal, the interferers, and uncorrelated noise (spatially and temporally white) [7]:

$$\mathbf{y(t)} = \sum_{\mathbf{n}=-\infty}^{\infty} \mathbf{x_n h(t-nT)} + \sum_{\mathbf{i=1}}^{\mathbf{I}} \sum_{\mathbf{n}=-\infty}^{\infty} \mathbf{u_{n,i} h_i(t-nT)} + \mathbf{n(t)} \tag{3}$$

or in matrix notation:

$$\mathbf{Y} = \mathbf{HX} + \sum_{\mathbf{i=1}}^{\mathbf{I}} \mathbf{H_i U_i} + \mathbf{N} \tag{4}$$

X is a Toeplitz matrix containing the transmit sequence (**U** has the same structure but contains the interferers' data):

$$\mathbf{X} = \begin{pmatrix} x_1 & x_2 & \cdots & x_N \\ x_0 & x_1 & \cdots & x_{N-1} \\ \vdots & \vdots & \ddots & \vdots \\ x_{2-L} & x_{3-L} & \cdots & x_{N-L+1} \end{pmatrix} \tag{5}$$

H denotes the channel response (length L) for all elements and is structured in the same way as **Y**. In case of a flat fading channel the channel responses **H** and $\mathbf{H_i}$ reduce to vectors **h** and $\mathbf{h_i}$ (equivalent to the steering vectors in [6]).

For combining we compare five different algorithms derived from the three basic schemes Selection Combining (SC), Equal Gain Combining (EGC) and Optimum Combining (OC). The changes we made are intended to simplify hardware implementation e. g. by elemination of unwanted additional receivers for each antenna branch.

A. Selection Combining, based on SNIR

This very simple scheme uses SNIR measurements on each antenna branch to determine which antenna to use. Since the combining could be done by switches, the weighting vector becomes:

$$\mathbf{w}_{\mathrm{SC,SNIR}} = \begin{cases} \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} & \text{if } \mathrm{SNIR}_1 = \mathrm{SNIR}_{max} \\ \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} & \text{if } \mathrm{SNIR}_2 = \mathrm{SNIR}_{max} \\ \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} & \text{if } \mathrm{SNIR}_3 = \mathrm{SNIR}_{max} \end{cases}, \tag{6}$$

where $\mathrm{SNIR}_{\mathrm{max}} = \max(\mathrm{SNIR}_1, \mathrm{SNIR}_2, \mathrm{SNIR}_3)$ denotes the best SNIR of all three branches. Since the decision is based on SNIR, demodulation is required for each branch.

B. Selection Combining, based on RF power

To overcome the problem of multiple receive-trains, the selection can also be based on RF power. The performance loss is compensated by the ease of implementation

$$\mathbf{w}_{\mathrm{SC,P_{HF}}} = \begin{cases} \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} & \text{if } P_1 = P_{max} \\ \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} & \text{if } P_2 = P_{max} \\ \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} & \text{if } P_3 = P_{max} \end{cases}, \tag{7}$$

where $P_{max} = \max(P_1, P_2, P_3)$ denotes the maximum RF power of all receive signals.

C. Equal Gain Combining, based on RF signal

This combining scheme performs a simple phase shifting before adding up all three branches. To achieve best performance, the phases φ_n should be chosen so that SNIR is maximised after combining. A more simple approch is to quantize the phase shifts and maximise the RF amplitude after adding. This allows to do the combining at RF so that only one receive-train is needed but a performance loss has to be accepted.

$$\mathbf{w}_{\mathrm{EGC}} = \left[\begin{array}{ccc} 1 & e^{j\varphi_2} & e^{j\varphi_3} \end{array} \right] \tag{8}$$

D. Optimum Combining for flat fading channels (OC-FF)

The weights for the optimum tradeoff between enhancment of desired signal and supression of interfering signals (= maximum SNIR) can be gained by projection of the desired signals steering vector $\mathbf{h}$ on the interferer and noise covariance matrix $\mathbf{R_{nn}}$ [6]:

$$\mathbf{w}_{\mathrm{OC,flat}} = \mathbf{R_{nn}^{-1}h}^*, \tag{9}$$

where $*$ denotes the complex conjugate. Since this formula is derived for flat fading channels, it will lead to suboptimal results in case of frequency selective fading.

E. Optimum Combing for frequency selective channels (OC-FS)

To get better performance in frequency selective fading channels, we try to get a *combined* estimate for the weight vector $\mathbf{w}$ and the channel response $\mathbf{h}$ for optimizing SNIR after combining[1] [7]. This is done by solving a generalized eigenvector problem and leads – for a white training sequence – to:

$$\begin{aligned} \mathbf{h}_{\mathrm{OC,FSel}} &= \mathbf{q_{min}^*} & (10)\\ \mathbf{w}_{\mathrm{OC,FSel}} &= \left(\mathbf{R_{YY}^{-1}R_{YX}q_{min}}\right)^*, & (11) \end{aligned}$$

where $\mathbf{q_{min}}$ denotes the eigenvector associated to the minimum eigenvalue of $\mathbf{R_{XX} - R_{XY}R_{YY}^{-1}R_{YX}}$. $\mathbf{R_{XX} = XX^H/N}$ is the transmitted signal covariance matrix, $\mathbf{R_{XY}}$ and $\mathbf{R_{YY}}$ are defined similarly. Solving the eigenvector problem can be simplified by using Partial Cholesky Factorization [7].

III. CHANNEL MODELS AND SIMULATION APPROACH

A. Channel model

For the simulation procedure, realistic channel models are required. The well-known COST207 models are not directly applicable, because they specify only the power delay profile and the Doppler spectrum, but not the directions-of-arrival; note that the DOAs cannot be computed uniquely from the Doppler spectrum. The channel models must contain both azimuth and elevation angle distribution; this is especially important for mobile stations in urban cells. Furthermore, since we consider interference-limited situations, we have to consider the DOAs not only of the users but also of the interferers. Due to the propagation environment, DOAs of users and interferers will usually be correlated.

The channel model underlying our simulations is a combination of two modeling methods:

(i) the GSCM modeling approach [8], [10]: in this approach, the probability density function of the scatterer location is identified, and for the actual simulation, the scatterers are chosen at random, and the signals arriving at the diversity antennas are computed by summing up the contributions from the single scatterers. Since the physical scatterers are identical for the contributions from the various relevant base stations (desired and interfering), the correlation in the DOA spectra can be taken into account in a very simple way.

(ii) the STC model [11]: in this model, the pdf of the angular delay power spectrum is prescribed, and the instantaneous realizations are chosen at random. It is important that each delay tap can have a different angular power spectrum, so that the spatial structure of the delayed echoes can be taken into account correctly.

These modeling methods are combined the following way: The GSCM is used to compute average delay power spectra and the correlation between the signals from user and interferers. Input parameters of the GSCM, e.g. the number and location of scatterer clusters are taken from the COST259 spatial channel model [9] and results of a recent measurement campaign [13]. The STC model is finally employed to create instantaneous realizations from these spectra.

Specifially, the following environments are analyzed:

(i) flat fading channel, noise limited: this is a test

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[1] The four combining algortihms above do not estimate h. This is done by a subsequent receiver/equalizer.

case to work out some basic properties of the combining algorithms.

(ii) line of sight channel, interference limited (LOS): another test case, and an approximation for some rural environments.

(iii) flat fading, interference limited (FF): a good approximation for some urban environments.

(iv) generalized cross country (CC): inclusion of a far scatterer that works both for the desired and the interfering signal.

(v) generalized urban microcell (UMI): includes the wave guiding effect that occurs both for desired and interfering signal.

(vi) generalized urban macrocell (UMA): includes both waveguiding and far scatterers.

B. *Simulation Environment*

To simulate the BER we transmit baseband GMSK-modulated GSM bursts over the channels described above. We assume synchronisation within $[-T/2, T/2]$ for the receiver that can be achieved by evaluating the GSM synchronization burst. The receiver is based on a structure of [12] with further complexity reductions like omission of the whitened matched filter. The structure is very close to a commercially used GSM receiver.

IV. RESULTS

As a first test, we analyze the performance of the commercial receiver and compare it to an idealized one. The degradation is on the order of 2dB in a flat fading channel with noise. The major drawback of the commercial receiver is its limited ability to combat intersymbol interference. For the generalized cross country, the receiver gives an error floor of about 10^{-3}. This effect could be mitigated by using a more complicated, and thus also more expensive, receiver.

Figures 2–7 show the results of the BER in the six environments. Three antennas were used, and possible correlations between the antenna signals were taken into account. The relative performance of the various combining methods can be commented the following way:

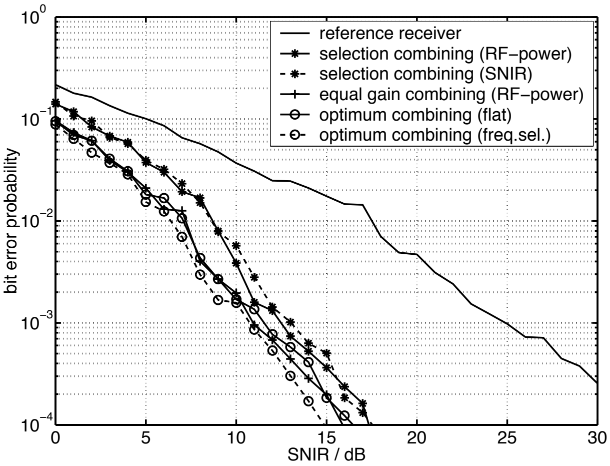

Fig. 2. FF (pure noise)

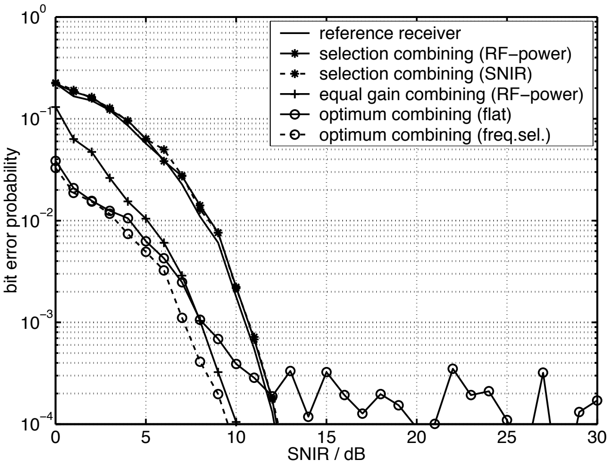

Fig. 3. LOS (two interferer plus noise)

selection combining: RSSI-driven selection combining is the most simple combining method, requiring modifications of the receiver only in the RF-part. For the test cases (channels (i)–(iii)), improvements are quite significant, namely 5–15dB in the region of interest. A similar (though slightly worse) performance can be observed in the generalized urban microcell, which shows a rather low delay spread. For the generalized urban macrocell and the generalized cross country, however, the performance is *much* worse. The selection combining suffers from the same ISI-problems as the standard (commercial) receiver and thus exhibits an error floor.

SNIR-based selection combining showed no significant improvement compared to RSSI-driven selection combining. This rather astonishing result is due mainly to difficulties in estimating the actual SNIR. For a "genie-aided" combining strategies that knows the true SNIR at all receiver antennas, better performance could be achieved.

Also equal gain combining with a finite number of combining phases gives a performance that is very

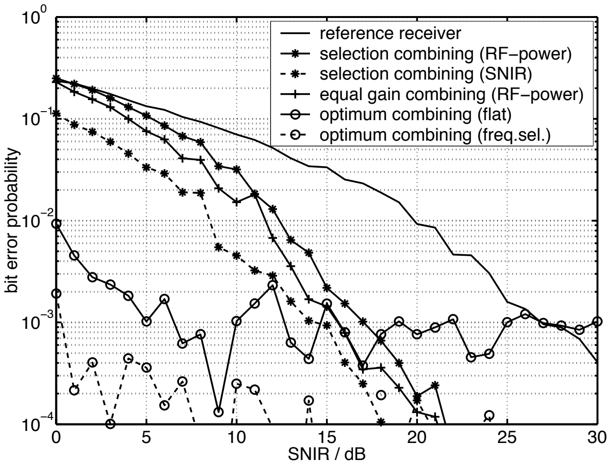

Fig. 4. FF (interferer only)

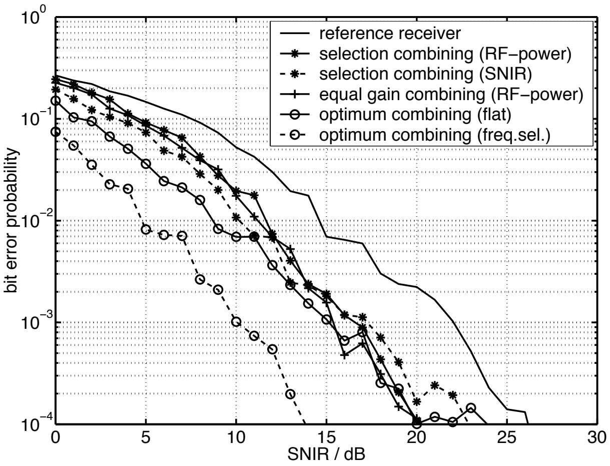

Fig. 6. UMI (two interferer plus noise)

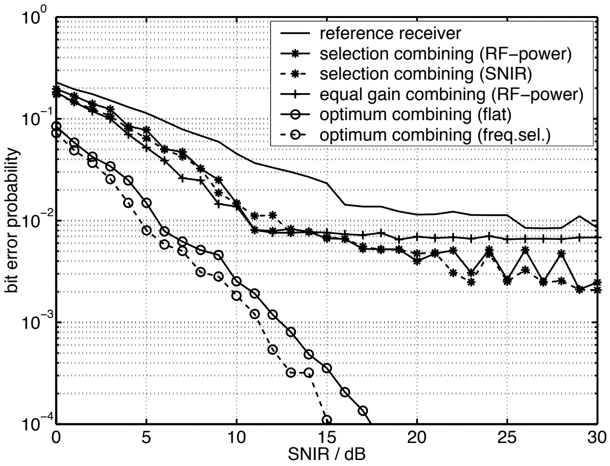

Fig. 5. CC (two interferer plus noise)

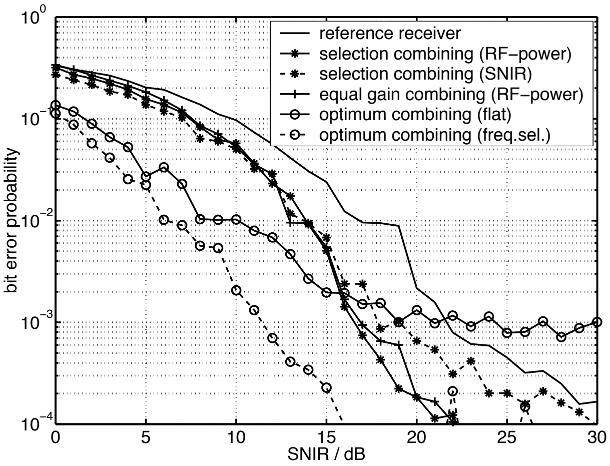

Fig. 7. UMA (two interferer plus noise)

similar to the RSSI-driven selection combining. Considering the small implementation effort of the RSSI-driven selection combining we find it the best of the "simple" combining methods.

optimum combining: optimum combining for flat-fading channels (OC-FF) gives quite good results, but great care has to be taken in the implementation. Realizations that have been shown equivalent under ideal circumstances can perform quite differently in an actual GSM system. A further problem in the implementation of the OC-FF is the determination of the steering vector. For a flat-fading channel, the choice of the optimum weights is unique. For frequency-selective channels, we would have to assign different weights for each delay tap . This is inherently not possible in the OC-FF approach so we have to choose the weights in a quasi-optimum way.

This problem does not occur in the optimum combining for frequency-selective channels (OC-FS), since the antenna weights are chosen in such a way that the SNIR (*after* equalization) is optimized. Figs. 2–7 show that, in all cases, OC-FS give the best results, with improvements (compared to the single-antenna receiver) ranging from 10 to 20dB. OC-FF shows similar performance in noisy flat fading channels, but is considerably worse in interference-limited flat fading channels because of GSM system and receiver restrictions. In environments with street canyons (waveguiding effect), OC-FF is also significantly worse than OC-FS.

V. Conclusions

We have analyzed various combining methodes for diversity signals at the mobile station. We included a commercial receiver structure very similar to what is used in a commercial GSM device. For the mobile radio channel, we used models that include all important propagation effects, including angular power spectra that vary with delay time, waveguiding effects in street canyons, and far scatterer clusters that are effective for both desired and interfering signal. We showed that in an interference-limited environment, as is usually the case for GSM, combining strategies based on the RF signal properties (i.e. RSSI-driven selection combining or equal-gain combining) do not perform well. An optimum combining strategy designed for frequency-selective channels (OC-FS) gives the lowest BER in all practically important cases.

The use of adaptive antennas thus seems an excellent method for obtaining low BERs and good speech transmission quality in GSM terminals.

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