

TYPE-BASED DETECTION IN MACRO-DIVERSITY RECEPTION FOR MOBILE RADIO SIGNALS

Lin Yue and Don H. Johnson

Computer & Information Technology Institute
Department of Electrical & Computer Engineering
Rice University
Houston, Texas 77005-1892

ABSTRACT

Type-based receivers assume no *a priori* channel model, and were previously shown to be effective in direct-sequence spread spectrum communications. In this paper, we investigate the macro-diversity combining of multiple type-based receivers in single-mobile-user reception (BPSK). We present a method for the exact calculation of the bit error rate of type-based receivers in this scenario. Maximal ratio combining of type-based receivers gives near optimal performance in Gaussian noise and better performance than combining matched filter outputs in Laplacian noise. The performance gain achieved by diversity reception is significant regardless of noise statistics, especially in the presence of frequency non-selective Rayleigh fading.

1. INTRODUCTION

Type-based detection is discussed and its asymptotic optimality is proved by Gutman [1]. For digital communication systems using direct-sequence signaling, type-based receivers are quite effective [2]. Without any assumptions about channel variations, type-based receivers yield near optimal performance with reasonable amounts of training data. This adaptability is highly desirable in the wireless environment, where accurate channel modeling can be difficult.

In wireless systems, communication performance suffers from channel fading, including fast multipath fading over short distances and long-term variation and propagation loss over long distances. Diversity reception is one of the most powerful techniques to combat fading. Macro-diversity reception is to combine the receptions of a particular mobile radio signal at multiple base stations. Different combining schemes are proposed and studied in IS-95, [3], and [4]. Among them, maximal ratio combining (MRC) of received signals from each base station sets the performance limit for linear micro-diversity schemes.

In this paper, we study macro-diversity reception with multiple type-based receivers. MRC scheme is performed on the output of each type-based receiver. We present a method for the exact calculation of the

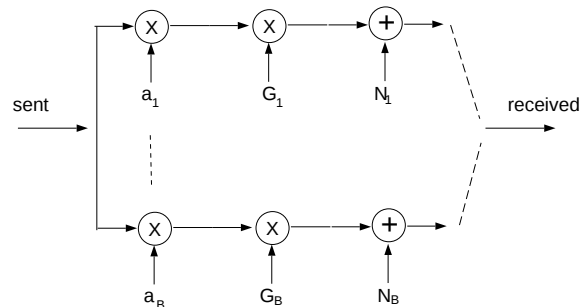


Figure 1. Channel model. The number of branches B equals the number of base stations involved in the reception. The Rayleigh random process a_i accounts for multipath fading; G_i accounts for the long-term variation and propagation loss. N_i is the channel noise.

bit error rate (BER) of type-based receivers for this scenario. This calculation gives a more concrete performance result than the *exponential error rate* in type-based detection theory [1], and it can replace high-complexity simulations for error analysis at high signal-to-noise ratio (SNR). We compare the performance of MRC of type-based receivers with that of matched filters in both Gaussian and Laplacian additive channel noise, and demonstrate the effectiveness of type-based receivers in macro-diversity reception.

In addition to the soft handoff situation where this technique can be applied, the diversity of sufficiently spaced antennas at a single base station can be exploited as well.

2. CHANNEL MODEL

The channel model is depicted in Fig. 1. Each base station involved in the reception of a particular signal forms a branch of the channel. The received signals at each branch are assumed to fade independently since base stations are separated far apart. For each branch, the multipath fading is assumed to be slow and frequency non-selective, with one resolvable component governed by a white Rayleigh fading random process¹

¹A more general correlated Nakagami fading process is simulated by solving stochastic differential equations [5]. Type-based receivers yield similar performance independent of the fading statistic.

a . The dynamics of the fading process is assumed to be changing on a time scale longer than the bit symbol interval. Long-term variations determine the availability of the branch to macro-diversity reception; their effects are assumed to be a multiplicative constant G . Additive i. i. d. noise with zero mean is present in each branch. Note that the optimal receiver must know about the exact channel model, while the type-based receiver doesn't need to know or assume any model.

3. TYPE-BASED RECEIVER

In information theory terms, a *type* is the histogram estimate of a discrete probability function [6]. Type-based detection theory for empirical classification was developed by Gutman [1], and is summarized as follows.

Given training sequences $\mathbf{t}_i$ (length N) from H_i , $i = 0, 1$ respectively, and a test sequence $\mathbf{x}$ (length n) from one of the two hypotheses, the type-based detector forms the types $q_{\mathbf{x}}(\cdot)$ and $q_{\mathbf{t}_i}(\cdot)$,

$$q_{\mathbf{x}}(x) = \frac{1}{n} \sum_{j=1}^n I(x = \mathbf{x}_j),$$

$$q_{\mathbf{t}_i}(x) = \frac{1}{N} \sum_{j=1}^N I(x = \mathbf{t}_{i,j}),$$

where $x \in A$, a finite alphabet. $I(x = y) = 1$ when $x = y$, and 0 otherwise. It then forms the types of $\mathbf{y}_i \equiv (\mathbf{x}, \mathbf{t}_i)$, the concatenation of the test sequence with the training sequence from H_i ,

$$q_{\mathbf{y}_i}(x) = \frac{Nq_{\mathbf{t}_i}(x) + nq_{\mathbf{x}}(x)}{N + n}.$$

When no rejection is allowed in binary-hypothesis testing, the detector calculates the "Gutman statistic",

$$h_i = \frac{N + n}{n} H(q_{\mathbf{y}_i}) - H(q_{\mathbf{x}}) - \frac{N}{n} H(q_{\mathbf{t}_i}) \quad (1)$$

and chooses smallest. Here, $H(\cdot)$ is the entropy computed from the type.

Gutman proved that a type-based detector is asymptotically optimal in the sense that the error probability decays exponentially at the optimal rate when both training and test sequences are long enough. However, the absolute value of the error probability, thus the absolute performance of a type-based receiver, is quite difficult to obtain in general due to the non-linear processing involved. For the following communications setup, we present a method to calculate the probability of error exactly.

3.1. Single Base Station Reception

Assume that direct-sequence spread spectrum and ideally BPSK are used in the CDMA system. For a user whose spreading code is c_l , $l = 0 \dots L - 1$, where L is the number of chips per bit, the bit detection problem at the receiver is

$$H_0 : \quad r_l = s_l^0 + n_l$$

$$H_1 : \quad r_l = s_l^1 + n_l, \quad l = 0 \dots L - 1.$$

where $s_l^i = (-1)^{(c_l + i)} A \cdot a \cdot G$, $i = 0, 1$, and n_l is the zero-mean noise with variance $N_0/2$. Here, a takes on the

value of one realization of a Rayleigh random process at the time the bit to be detected is transmitted over the channel. In our simulations, a changes from bit to bit.

In applying type-based detection theory to digital communication problem, we quantize the received analog signal into a finite-sized alphabet after sampling the received signal once per chip and before forming types. Details of the receiver implementation and some simulation results can be found in [2].

The method for the exact calculation of Pe of a type-based receiver in known noise is illustrated in Fig. 2. Perfect training is assumed, so that the type mimics the true distribution. As will be discussed later, the amount of training needed is acceptable for this assumption to hold.

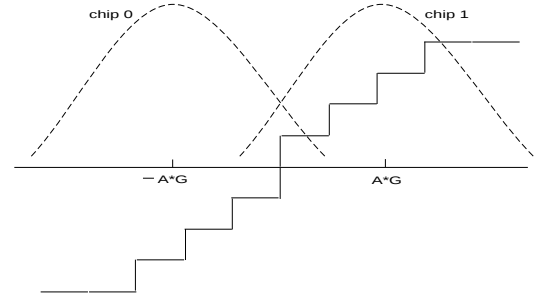


Figure 2. Exact calculation of the probability of error Pe of a type-based receiver when no fading is present ($a = 1$). For a fixed 3-bit quantizer, training types are obtained from the preambles, and are determined by the code of the user, the length of the training sequence, and the noise distribution; The calculation of the test type is explained in the text.

Assuming equally likely hypotheses, the probability of error is

$$\text{Pe} = \sum_{i=1}^{\binom{L+M-1}{M-1}} \Pr\{q_{\mathbf{x}}\} I(h_1 < h_0)$$

where $\binom{n}{k} \equiv n!/(k!(n-k)!)$, M is the number of quantization levels, and h_i , $i = 0, 1$ are computed as in Eqn. 1,

$$\Pr\{q_{\mathbf{x}} = (q_1, q_2, \dots, q_M)\}$$

$$= \prod_{j=1}^M \Pr\{q_{\mathbf{x},j} = q_j | q_{\mathbf{x},1} = q_1, \dots, q_{\mathbf{x},j-1} = q_{j-1}\}$$

Each of the conditional probability in this product is binomially distributed, assuming independent chips. The event of a chip falling into a particular bin is a Bernoulli random variable, with p given by the probability of the observation falling in the bin interval. When we know the noise, we know p . Its advantage over Monte-Carlo simulations is prominent, in terms of both accuracy and complexity, when the BER of interest resides in the large SNR region. It can be easily extended to the

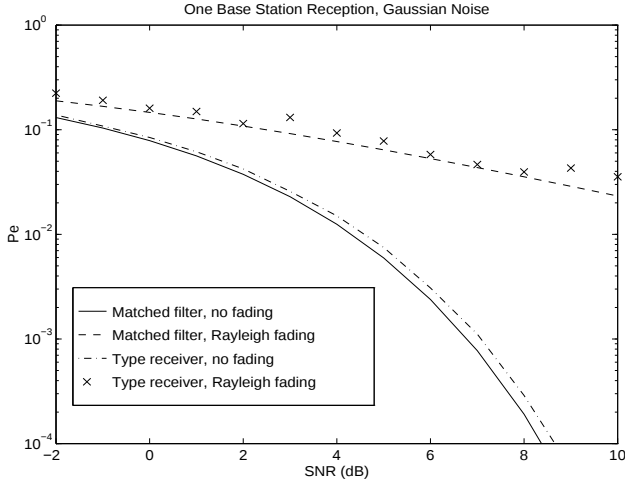


Figure 3. Single branch reception in Gaussian noise, where the matched filter is optimal. The type-based receiver gives close to optimal performance with reasonable amount of training data (32-bit preamble, with $L = 8$). A fixed 3-bit uniform quantizer is used. The channel noise has unit variance; $E[a^2] = 1$ for the Rayleigh fading. $\text{SNR} \equiv E_b/N_0 = E[a^2](A \cdot G)^2 L/N_0$.

error analysis of type-based receivers in multiple base station reception.

The performance² of the type-based receiver and the matched filter are compared in Fig. 3 in Gaussian noise. When no fading is present, the performance of the type receiver tracks that of the matched filter closely. In frequency non-selective Rayleigh fading, the performance of both receivers degrades significantly. But the type-based receiver still yields near optimal performance.

It is well known that, for a given SNR in Gaussian noise, the performance of the matched filter receiver is independent of the spreading factor L . The performance of the type receiver, however, depends on L . Using the error analysis method we presented, we can show easily that the type-based receiver operates equivalently to a matched filter when $L = 1$ in that it achieves the optimal BER $Q(\sqrt{2\text{SNR}})$ in Gaussian noise.

3.2. Multiple Base Station Reception

When more than one base station receive a common user signal, MRC of “soft” decisions³ from each branch

²For simplicity, we assume there is no interference among users in this study. In the situation where users have orthogonal codes, we have a lower bound on the receiver performance when multipath fading is present.

³Diversity combining of certain “hard” decisions from each branch is studied in [4] for Gaussian noise. The performance loss is several dB in SNR compared with the combining of “soft” decisions – matched filter outputs and SNR per bit.

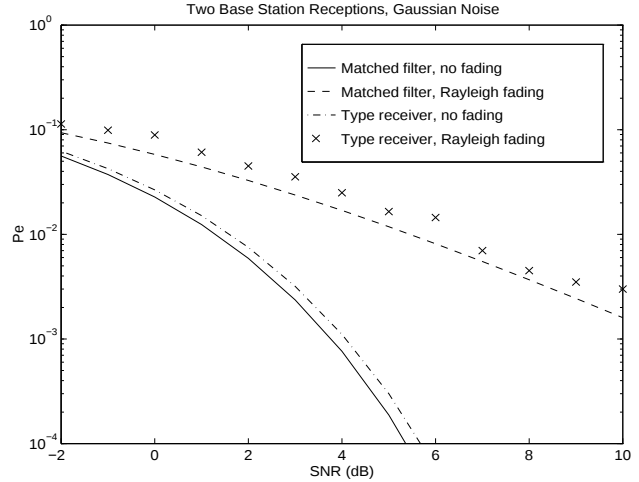


Figure 4. Macro-diversity reception with MRC of soft decisions in Gaussian noise. Parameters are the same as in Fig. 3 except for $B = 2$. Type-based receivers perform well without assuming any channel model.

can be performed to combat multipath fading effectively. The combined SNR equals the summation of SNRs at each branch (e.g. in [7]). The soft decisions we use are matched filter outputs for the matched filter receiver, and Gutman statistics for the type-based receiver at each branch respectively. The combiner of Gutman statistics of multi-branch receivers computes

$$h_i = \sum_{b=1}^B h_{b,i} \sqrt{\text{SNR}_b}, \quad i = 0, 1$$

and chooses smallest, where B is the number of base stations, and $h_{b,i}$ is the statistic obtained at single base station b as in Eqn. 1.

The performance of macro-diversity reception by MRC is shown in Fig. 4 for a two base station example. As in the single base station reception, the type receiver tracks the optimal performance closely. Comparing with Fig. 3, we can see the significant SNR gain achieved by diversity combining. The role of diversity combining in combating fading is much clearer in the small SNR region. For SNRs in the range of -2dB to 2dB , the BER of diversity reception of two base stations *with* Rayleigh fading is smaller than that of single branch reception *without* fading. This is true for both the matched filter receiver and the type-based receiver. Channel conditions being the same, the absolute gain in SNR is directly related to the number of base stations B involved in the reception. The gain for the matched filter is $10\log_{10} B$ dB when no fading is present; calculations show similar gains for the type-based receiver.

For a type-based receiver to perform well, the received signal must lie in as small amplitude level range as possible from chip to chip. This concentration depends on the noise distribution for the single branch

reception of a BPSK signal. For the multi-branch reception, in addition to the noise, combining multiple receptions of a common user signal tends to spread out the amplitude levels. For example, if the long-term fading is different in each branch, the received signals at each branch have different mean amplitude values. Quantization of the MRC of these receptions results in a more uniform type under *both* hypotheses, thus causing performance degradation at the receiver. By making decisions at each branch separately, we eliminate the ambiguous amplitude problem, thus the MRC of Gutman statistics (“soft” decisions) performs better than that of received signals.

We compared the performances of the MRC of the two kinds of “soft” information from each branch – statistics vs signals. The performance loss for combining signals is about 0.5dB even when the branches have the same long-term fading. In addition, since all the information used in combining must be transmitted to some switching center, transmitting statistics is more advantageous than transmitting signals to save the bandwidth. Note that for a matched filter receiver, the MRC of received signals is the same as that of detector outputs at each branch because of the linearity of both the detector and the combiner.

As shown in Figs. 3 and 4, the performance curves are obtained in Gaussian noise, where the matched filter is optimal; the type receiver is suboptimal, without assuming any channel model. In Laplacian noise, however, the type receiver yields much better performance than the matched filter⁴. See Fig. 5. Notice that the performance of the type-based receiver remains relatively unchanged in Laplacian noise and Gaussian noise. We also have found that there is tradeoff between bandwidth and performance for the type-based receiver in Laplacian noise – a larger spreading factor L results in smaller BER for a fixed SNR.

4. CONCLUSIONS

We further studied some properties of the type-based receiver and presented a method for the exact calculation of its performance when noise distribution is known. For macro-diversity reception, the type-based receiver performs reasonably well in both Gaussian and Laplacian noise. Its performance is robust to the noise distribution since no channel model is assumed. The SNR gain achieved by macro-diversity reception with multiple type-based receivers is significant. Furthermore, maximal ratio combining of soft decisions based on statistics instead of received signals gives smaller BER in addition to saving bandwidth.

⁴In Laplacian noise, the sign detector is “locally” (small SNR) optimal. Further results show that the type-based receiver tracks the performance of the sign detector “locally” and outperforms it in large SNR region. Refer to [2] for a single branch example.

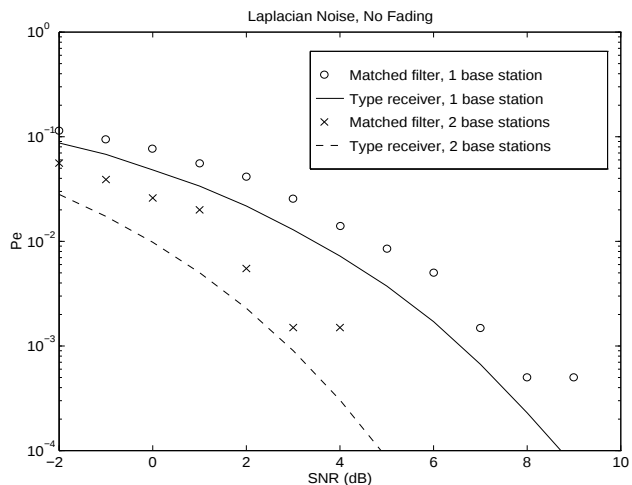


Figure 5. In Laplacian channel noise, with no fading. For either one base station reception or two base stations reception, the type-based receiver outperforms the matched filter. The type-based receiver is independent of the noise distribution.

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