

SUCCESSIVE INTERFERENCE CANCELLATION WITH POWER CONTROL IN IMPULSIVE CHANNEL

Aykut Hocanın and Hakan Delic

Signal and Image Processing Laboratory (BUSIM)
Department of Electrical and Electronics Engineering
Boğaziçi University
Bebek 80815 Istanbul, Turkey
{hocanin, delic}@boun.edu.tr

ABSTRACT

Robust detection is employed in a DS/CDMA system in which the noise process contains outliers. The bit error probability expressions are derived under a Gaussian mixture model. It is observed that the designed robust receiver performs better than the conventional matched filter in impulsive noise environment. The robust correlator is then employed in a successive interference cancellation (SIC) setting. The bit error rate studies indicate that the proposed robust SIC provides superior performance to the conventional one.

1. INTRODUCTION

Direct sequence code division multiple access (DS/CDMA) has captured attention as the future's mobile communications technology in the last decade of the century. Despite the capacity, diversity, soft hand-off, etc. advantages DS/CDMA offers, certain performance-limiting challenges still occupy much of researchers' time. Of these, multiple access interference (MAI) created by other users in a cell is perhaps the primary one. One approach to combat MAI involves multiuser detection, which leads to higher capacity by allowing the sharing of multiuser information [3]. In contrast, conventional single-user detection disregards the existence of other users.

A practical multiuser design with manageable complexity is the successive interference cancellation (SIC) scheme [4]. The basic principle of SIC is to estimate and then subtract each user's contribution to the MAI of the designated user iteratively. However, in the event of data estimation errors, the interference by the corresponding user is not eliminated by the proper amount. Thus, inaccurate or inappropriate noise model assumptions cause significant degradation of the SIC performance.

In this paper, we first consider robust single-user detection in a spread spectrum channel corrupted by MAI and additive white noise that contains occasional outliers. The robust correlator is then deployed in a successive interference cancellation setting, where perfect power control is ensured. In the presence of impulsive noise, conventional SIC is expected to collapse due to the poor performance of matched filtering. We show that a robustified SIC outperforms both cancellation based on linear correlation and robust single-user detection.

2. THE DS/CDMA SIGNAL

Consider the received signal $r(t)$, where user 0 produces the desired signal, and all users employ coherent BPSK.

$$r(t) = \sqrt{2P_0}c_0(t - \tau_0)b_0(t - \tau_0)\cos(\omega_c t + \phi_0) + \sum_{m=0}^{N-1} \eta_K^m(t) + n(t). \quad (1)$$

The multiple access interference generated by the m th chip is

$$\eta_K^m(t) = \sum_{k=1}^{K-1} \sqrt{2P_k}c_k^m p_{T_c}(t - mT_c - \tau_k)b_k(t - \tau_k) \times \cos(\omega_c t + \phi_k)$$

where P_k , b_k , $c_k^m \in \{-1, +1\}$ are the received power, bit sequence (at rate R_b) and the m th chip of the k th user's pseudo-noise (PN) sequence (at rate R_c), respectively. The noise process is denoted by $n(t)$. There are a total of K active users in the system. The uniform random variables τ_k and ϕ_k respectively denote the time delay and phase of the k th user. The bits and chips are rectangular pulses of duration T_b and T_c , respectively, and p_{T_c} is the chip pulse waveform. We

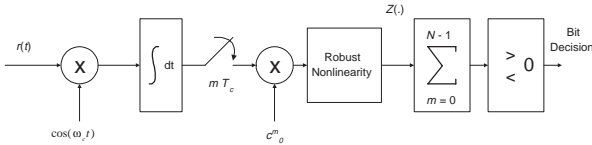


Figure 1: The robust single-user correlator receiver for user 0.

assume that all spreading sequences are known. Without loss of generality, it will be assumed that $\tau_0 = 0$. Ambient noise and MAI are statistically independent. The joint distribution of $\eta_K^m(t)$ and $n(t)$ determine the nature of the detector that has to be employed in the receiver. So far in literature, it has been assumed that $n(t)$ is white Gaussian. In this paper, we consider the environment to contain impulsive elements so that $n(t)$ is still white, but no longer Gaussian.

3. ROBUST SINGLE-USER DETECTION

Suppose that $n(t)$ is a stationary and memoryless noise process. Nominally, $n(t)$ is zero-mean white Gaussian with variance $N_0/2$. However, occasional outliers may occur due to atmospheric disturbances, etc. This can be modeled by Huber's mixture model [2] described by the following two classes of distributions over the m th chip period:

$$\mathcal{F}_0 = \{f(x): f(x) = (1 - \epsilon_0)f_{0,\eta_K^m}(x) + \epsilon_0 f_{h,\eta_K^m}(x)\},$$

$$\mathcal{F}_1 = \{f(x): f(x) = (1 - \epsilon_1)f_{1,\eta_K^m}(x) + \epsilon_1 f_{h,\eta_K^m}(x)\},$$

$\forall x \in \mathcal{R}$ and $h(x) \in \mathcal{H}$, where \mathcal{R} is the real line, and \mathcal{H} is the class of all one-dimensional density functions on \mathcal{R} . The nominal probability density functions (pdfs) $f_{1,\eta_K^m}(x)$ and $f_{0,\eta_K^m}(x)$ generate the data alternatives +1 and -1, respectively, in the presence of MAI. The joint pdf f_{h,η_K^m} covers the impulsive noise ($h(x)$) and MAI. Thus, the data are corrupted by outliers that are generated by the density $h(x)$ with frequency $\epsilon_0 \in (0, 1)$ and $\epsilon_1 \in (0, 1)$ for classes \mathcal{F}_0 and \mathcal{F}_1 , respectively.

The receiver structure is depicted in Fig. 1, in which a robust correlator is used where each chip is passed through an appropriate nonlinearity and the N chips comprising a bit are summed and forwarded to the decision device. The nonlinear processor is designed for protection against unfavorable conditions by eliminating the extreme amplitudes that occur impulsively.

In accordance with the system in Fig. 1, over one chip duration, the persistent interference component is η_K^m , described in equation (1). Invoking the Gaussian approximation, η_K^m is normal-distributed with zero

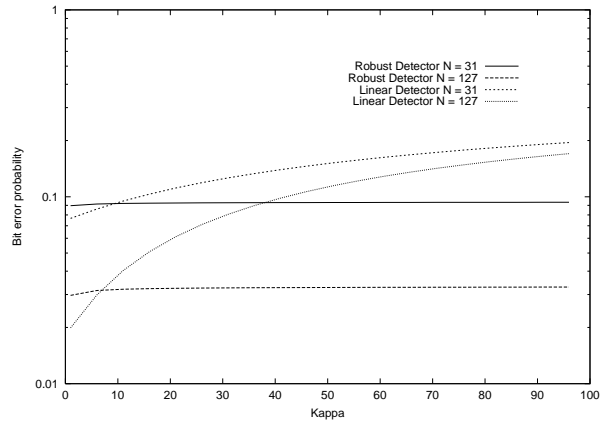


Figure 2: Bit error probability of the robust single-user correlator receiver and the matched filter against κ for $K = 20$, $R_b = 9600$ bps, $E_b/N_0 = 5$ dB and $\epsilon = 0.2$.

mean and variance $\sigma_\eta^2 = (T_c^2/6) \sum_{k=1}^{K-1} P_k$, for sufficiently long PN code sequences and large K [1]. The nominal noise variance is $\sigma_n^2 \approx N_0 T_c/4$ for $\omega_c \gg 2/T_c$ [5]. Then, $r(t)$ is normal-distributed with mean $\mu = \pm \sqrt{P_0/2} T_c$ (contribution from the desired user), and variance $\sigma^2 = \sigma_\eta^2 + \sigma_n^2 = (T_c^2/6) \sum_{k=1}^{K-1} P_k + (N_0 T_c/4)$.

The robust nonlinearity has the following form:

$$z(x) = \begin{cases} d & \text{for } x \leq -d, \\ x & \text{for } -d < x < d, \\ d & \text{for } x \geq d, \end{cases}$$

where the threshold d is such that the average probability of error is minimized. With $\mathbf{x} = \{x_0, \dots, x_{N-1}\}$. The robust decision rule is

$$\delta^*(\mathbf{x}) = \begin{cases} +1 & \text{if } \frac{1}{N} \sum_{m=0}^{N-1} z(x_m) \geq 0, \\ -1 & \text{if } \frac{1}{N} \sum_{m=0}^{N-1} z(x_m) < 0, \end{cases}$$

due to the equiprobable antipodal signaling in spread spectrum systems.

In the sequel, we shall suppose that $h(x) = g(x)$ is Gaussian with zero-mean and variance $\kappa \sigma_n^2$, where $\kappa \geq 1$. The outliers are generated by a Gaussian pdf with heavier tails (larger variance). Thus, $\kappa = 1$ corresponds to the case where the noise distribution is strictly Gaussian and does not contain impulsive elements.

Define $k = d/\sigma$, $\rho = \mu/\sigma$, $k_{og} = d/\sigma_{og}$ and $k_\eta = d/\sigma_\eta$. Then, letting $\Phi(x)$ denote the cumulative distribution function of the zero-mean, unit-variance normal random variable, the average probability of error for a given value of κ is [1]

$$P_e^f(\kappa) = \Phi\left(-N \frac{m_f}{v_f}\right), \quad (2)$$

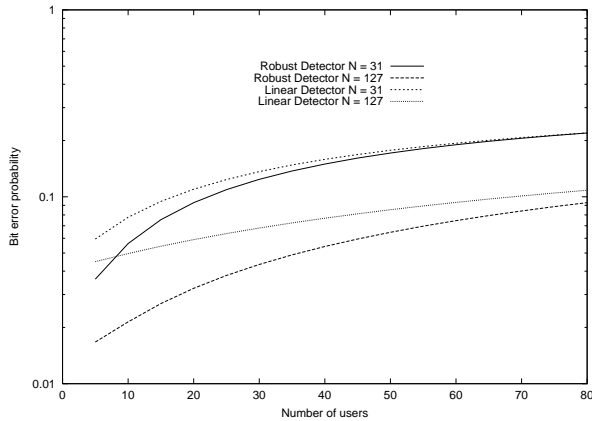


Figure 3: Bit error probability of the robust single-user receiver and the matched filter against the number of active users ($R_b = 9600$ bps, $E_b/N_0 = 5$ dB, $\epsilon = 0.2$).

where

$$\begin{aligned}
m_f &= E\{z(X)|f\} = (1 - \epsilon)m_{f_1}, \\
m_{f_1} &= \sigma\{\mu + [k - \mu]\Phi(k - \rho) - [k + \mu]\Phi(k + \rho) \\
&\quad + \sigma[\phi(k - \rho) - \phi(k + \rho)]\}, \\
v_f^2 &= \text{var}\{z(X)|f\} = (1 - \epsilon)^2 v_{f_1}^2 + \epsilon^2 v_g^2 + \epsilon(1 - \epsilon)v_\eta^2, \\
v_{f_1}^2 &= \sigma^3\{1 + \rho^2 + [k^2\sigma^{-1} - \rho^2 - 1][\Phi(k + \rho) + \Phi(k - \rho)] \\
&\quad + [k - \rho]\phi(k + \rho) + [k + \rho]\phi(k - \rho) - m_{f_1}^2\sigma^{-3}\}, \\
v_g^2 &= \sigma_{og}^3\{1 + 2[k_{og}^2\sigma_{og}^{-1} - 1]\Phi(k_{og}) + 2k_{og}\phi(k_{og})\}, \\
v_\eta^2 &= \sigma_\eta^3\{1 + 2[k_\eta^2\sigma_\eta^{-1} - 1]\Phi(k_\eta) + 2k_\eta\phi(k_\eta)\},
\end{aligned}$$

and $\phi(x)$ is the pdf of the zero-mean, unit-variance normal random variable.

The average probability of error for the matched filter is as in equation (2) with the following substitutions for m_f and v_f^2 :

$$\begin{aligned}
m_f &= E\{X|f\} = (1 - \epsilon)\mu \\
v_f^2 &= (1 - \epsilon)^2(\sigma_n^2 + \sigma_\eta^2) + 2\epsilon(1 - \epsilon)\sigma_\eta^2 + \epsilon^2(\kappa\sigma_n^2 + \sigma_\eta^2).
\end{aligned}$$

The bit error probability expressions for the robust receiver and the matched filter are evaluated via equation (2) for $R_b = 9600$ bps, $E_b/N_0 = 5$ dB and $\epsilon = 0.2$. The processing gain values of $N = 127$ and $N = 31$, with the respective optimal thresholds of $d = -0.00036$ and $d = -0.00086$, are considered. For 20 active users, Fig. 2 indicates that the matched filter with $N = 31$ ($N = 127$) performs slightly better

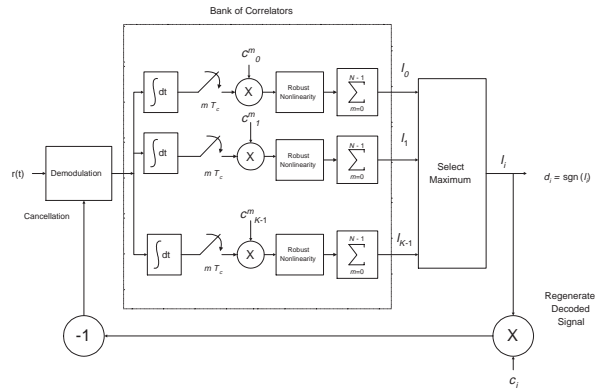


Figure 4: SIC with robust correlation.

when the noise process is near-Gaussian for $\kappa \leq 10$ ($\kappa \leq 7$). However, the robust structure offers significant gains when impulsive elements begin to dominate. In fact, $P_e^f(\kappa) \approx 3.3 \times 10^{-2}$ for the robust single-user detector when $N = 127$ and $\kappa > 10$. The margin of improvement becomes larger with increased N . Once the trimming threshold d is set, it does not matter how large the outlier amplitudes are, and hence we have the bit error probability independent of κ .

Fig. 3 shows that for relatively few users, the impulsive noise is the predominant disturbance rather than MAI. However, when the number of active users exceeds 40, the advantages of offered by the robust receiver begin to disappear, unless the higher processing gain is employed.

4. SUCCESSIVE INTERFERENCE CANCELLATION

The interfering signals are cancelled in descending order of signal power since the removal of the strongest users is the easiest and has the most favorable effect on MAI reduction. Some of the disadvantages include the additional delay and processing complexity required for the ranking of users at each stage.

In this paper, we introduce the robust version of the simple SIC scheme [4] as shown in Fig. 4. It is assumed that the signature sequences of all the users are known but the energies of the individual users are not. At each stage, the robust nonlinearity effectively clips out the impulsive components induced by the outlier noise process, and the selector picks out the strongest user based on the output of the bank of correlators. The information bit of the corresponding user is determined next. The transmitted signal of the decoded user is regenerated and subtracted from the received signal. The

procedure is repeated until the weakest user is decoded. Notice that if the correlator output is not accurate (due to extreme outliers), the regenerated signal magnitude that is subtracted from the MAI term may be much larger than the actual data pulse amplitude. Thus, the estimator performance is of paramount importance in SIC, and the linear correlation is bound to produce catastrophic outcome in non-Gaussian channels.

In Figures 5 and 6, the performance of the SIC scheme with the robust and linear correlators is shown under ideal power control. The simulations are run at $E_b/N_0 = 5$ dB and $N = 31$. The performance of the single-user detectors, which do not contain any cancellation, are also included in the figures for reference. For a given bit error rate (BER) of 1×10^{-3} and $\kappa = 20$, approximately 4 users can be maintained in the robust single-user system whereas this is increased to 7 and 8 users for the simple and robust SIC systems, respectively. When the channel is severely impulsive ($\kappa = 80$), the simple SIC can support 6 users while the robust systems' capacity remain the same. The results indicate a considerable increase in SIC capacity when the robust correlator is employed. The difference in performance is larger when the system has low customer load, i.e., when the impulsive noise dominates MAI. It is worthwhile to note in Fig. 6 that the robust single-user detector works at least as good as the conventional SIC for more than 10 users when $\kappa = 80$.

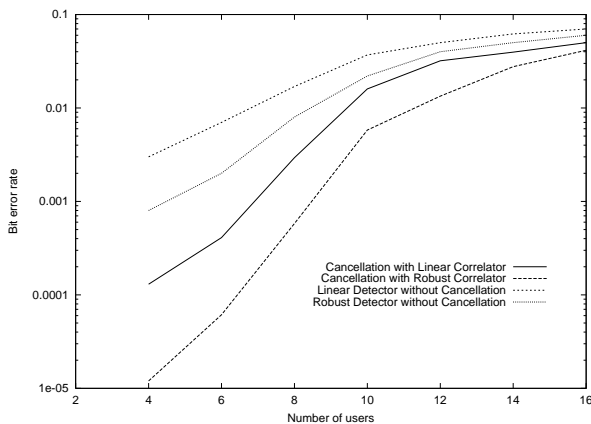


Figure 5: BER performance of SIC with robust and linear correlators under ideal power control ($\kappa = 20$, $E_b/N_0 = 5$ dB).

5. CONCLUSION

A robust detector that reduces the impact of impulsive noise by eliminating the extreme amplitudes is devel-

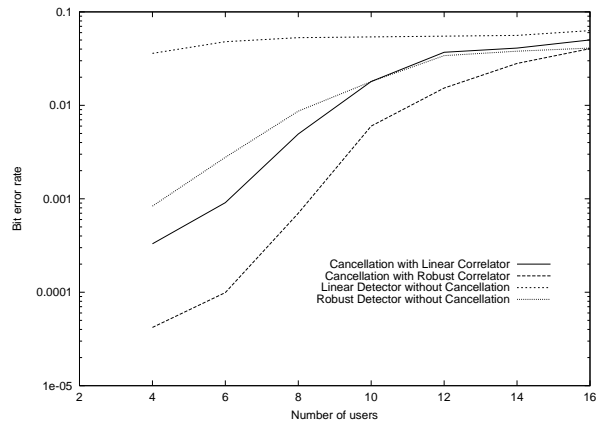


Figure 6: BER performance of SIC with robust and linear correlators under ideal power control ($\kappa = 80$, $E_b/N_0 = 5$ dB).

oped for DS/CDMA. The bit error probability expressions are obtained under a Gaussian mixture assumption. The robust detector is shown to have superior performance to conventional matched filtering. The robust correlator is then deployed in a SIC setting, and its performance is compared to that of the simple SIC scheme. The bit error rate performance of the robust SIC is considerably higher, especially when there are few active users in the system.

The introduction of asynchronism does not change the cancellation algorithm. However, for the ranking of the users, the bits which must be compared in computing the correlations must be determined [4].

While it is demonstrated that robust SIC with perfect power control has much to offer when the channel is impulsive, more significant performance gain is expected if users are heard with unequal received power.

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