Successive Interference Cancellation Using Robust Correlation

Aykut Hocanın
Department of Electrical and Electronics Engineering
Eastern Mediterranean University, Gazimağusa, Mersin 10, Turkey
(aykut.hocanin@emu.edu.tr)

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

***Abstract*— A robust successive interference cancellation (SIC) receiver is designed to work in an impulsive noise environment. The channel includes additive noise which may contain impulsive elements that affect the ranking and detection of each user. The traditional SIC scheme uses linear correlation and its performance deteriorates in non-Gaussian noise. In the proposed receiver, a robust nonlinearity is introduced which effectively clips out the outliers. Parameter estimation is carried out using the output of a bank of robust correlators and the receiver effectively cancels interferences in the order of received signal powers. The results indicate that the proposed robust SIC receiver provides superior performance to the conventional one in terms of bit error rate. The improvement in performance persists for asynchronous reception, as well as power imbalance among users.**

I. INTRODUCTION

In a mobile communication scenario, the transmitters move relative to the receiver and the energies of the received signals are neither equal nor constant. In this situation, the conventional detector often fails to demodulate signals of weak users (near/far effect). One way to combat this problem is to use fast and effective power control. Another approach is to use multi-user detection, which reduces the effect of multiple access interference (MAI) of strong users on weak users. Unlike the conventional detector, which disregards the existence of other users, multi-user detection allows the sharing of multi-user information and has the potential of reducing the near/far effects and combating MAI.

Fundamental research has shown that huge capacity gains can be obtained using optimal designs, at the expense of very high complexity [7], [11]. This has led to the search of practical designs which achieve a part of this potential with manageable complexity [4], [2]. In most multi-user schemes, where the users' signals are detected collectively, the parallel interference cancellation turns out to have a very complex structure [9]. An alternative to the parallel cancellation is the low-complexity successive interference cancellation (SIC) [1], [10]. The basic principle is to estimate each user's contribution to the MAI inflicted on the user to be decoded and then to eliminate MAI iteratively. The user signals are cancelled in descending order of signal power since it is easiest to decode the strongest users. In addition, the removal of the strongest user has the most favorable effect on MAI reduction. Some of the disadvantages are the additional delay induced and the processing complexity required for the ranking of users at each stage. Since different users experience varying amounts of interference in the beginning and at the end of the cancellation process, they experience different bit error rates, which is another disadvantage.

In this paper, we analyze the SIC scheme in which user interferences are cancelled in the order of received powers. The additive noise in the channel may contain impulsive elements that affect the ranking and detection of each user. Therefore, the ranking is obtained from robust correlations of the received signal with each user's chip sequence [3]. It is assumed that phase information is available at the receiver and the amplitude estimation is performed by using the output of the correlators. In order the improve the performance of SIC in impulsive channels, robust correlation is computed at each stage [5]. It is shown in [3] that single-user robust detection offers superior performance over the conventional matched filter in impulsive channels. We demonstrate that the single-user advantages of robust detection carry over to the multi-user SIC setting.

II. THE DS/CDMA SIGNAL AND RECEIVER

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

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

where MAI at the mth chip period is given by

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

$P_k,\ b_k,\ c_k^m \in \{-1,\ +1\}$ are the received power, bit sequence (at rate R_b) and spreading sequence (at rate R_c) of the kth user

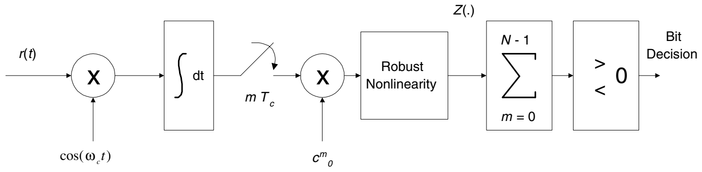

Fig. 1. Robust single-user correlator receiver for user 0.

respectively. There are a total of K active users in the system. τ_k and ϕ_k denote the time delay and phase of the kth user, which are assumed to be tracked accurately. 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 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 performance of the receivers. It has been assumed that $n(t)$ is white Gaussian, and the Gaussian approximation has been utilized to model $\sum_m \eta_K^m(t)$.

In this paper, we consider the environment to contain impulsive elements so that $n(t)$ is still white but no longer Gaussian. In the single-user robust correlator receiver [3] which is shown in Figure 1, each chip is passed through a robust nonlinearity and the N chips comprising a bit are summed and forwarded to the decision device. The robust nonlinearity has the following form:

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

The negative threshold d is determined in such a way that the resulting bit error rate is minimized [3]. 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 and man-made noise. This can be modelled by the Huber's mixture model [6] described by the following two classes of distributions over the mth chip period:

$$\begin{aligned} \mathcal{F}_0 = \{f(x) :\, f(x) = \quad & (1-\epsilon_0) f_{0,\eta_K^m}(x) \\ & + \epsilon_0 f_{h,\eta_K^m}(x), \forall x \in \mathcal{R},\, h \in \mathcal{H}\} \\ \mathcal{F}_1 = \{f(x) :\, f(x) = \quad & (1-\epsilon_1) f_{1,\eta_K^m}(x) \\ & + \epsilon_1 f_{h,\eta_K^m}(x), \forall x \in \mathcal{R},\, h \in \mathcal{H}\} \end{aligned}$$

where $f_{1,\eta_K^m}(x)$ and $f_{0,\eta_K^m}(x)$ stand for the nominal processes that generate the data alternatives $+1$ and -1, respectively, in the presence of MAI. Assuming that the Gaussian approximation applies to the MAI term in equation (1), f_{0,η_K^m} and f_{1,η_K^m} are both normal distributed. 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. ϵ_0 and ϵ_1 denote the a priori probability of departure from the nominal Gaussian assumption for the respective bit types. The density f_{h,η_K^m} is the joint density of $h(x)$ and η_K^m and is in general non-Gaussian [3]. $\mathcal{R}$ is the real line, and $\mathcal{H}$ is the class of all one-dimensional density functions on $\mathcal{R}$. In the sequel, we shall use Middleton's Class A model [8] to describe the impulsive noise. The noise model consists of infinitely expanding Gaussian density functions with different variances and identical means. In our noise model we will keep the first two terms of the expansion so that the noise is a mixture of two Gaussian densities with zero means. The outliers are generated by a Gaussian pdf with heavier tails (variance $\kappa\sigma_n^2$, where $\kappa \geq 1$). Thus, $\kappa = 1$ corresponds to the case where the noise distribution is strictly Gaussian and does not contain impulsive elements.

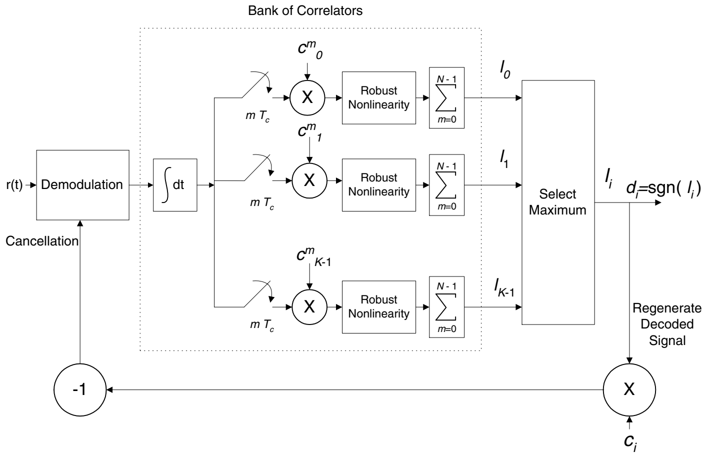

Fig. 2. Robust SIC receiver structure.

III. SYSTEM DESCRIPTION

We consider a synchronous DS/CDMA system with K active users. The bit duration T_b is equal to processing gain (N) times the chip duration T_c and A_k is the amplitude of the kth user. The BPSK received signal is

$$r(t) = \sum_{k=0}^{K-1} A_k c_k(t-\tau_k) b_k(t-\tau_k) \cos(\omega_c t + \phi_k) + n(t). \quad (3)$$

It is assumed that the signature sequences of all the users are known but the energies of the individual users are not. Figure 2 shows the overall structure of the robust SIC which employs robust correlation. At each stage, the selector determines the strongest user by using the output of the bank of correlators. The information bit of the ith user (d_i), is then determined by comparing the decision variable l_i with the threshold (zero due to equiprobable antipodal signaling). The robust nonlinearity effectively clips out the outlier noise process. The transmitted signal of the ith user is regenerated and subtracted from the received signal. The process is repeated until the weakest user is decoded. After $i-1$ cancellations, the decision variable for user i (Figure 2) is given by

$$l_i = \frac{1}{2} A_i b_i + \frac{1}{2} W_i \quad (4)$$

where

$$\begin{aligned} W_i \quad = \quad & \sum_{k=i+1}^{K} A_k U_{k,i}(\tau_{k,i}, \phi_{k,i}) + n_i \\ & - \sum_{s=1}^{i-1} W_{s-1} U_{s-1,s}(\tau_{s-1,s}, \phi_{s-1,s}). \quad (5) \end{aligned}$$

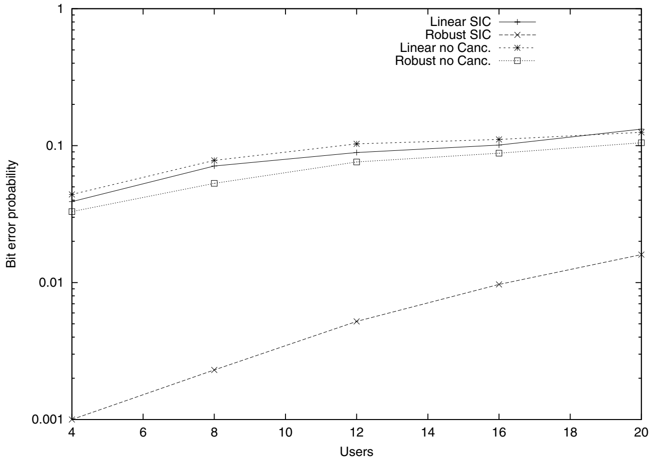

Fig. 3. BER performance of the robust and linear SIC schemes, ideal power control, synchronous ($E_b/N_0 = 5$ dB, $\epsilon = 0.2$, $\kappa = 10$, $N = 31$).

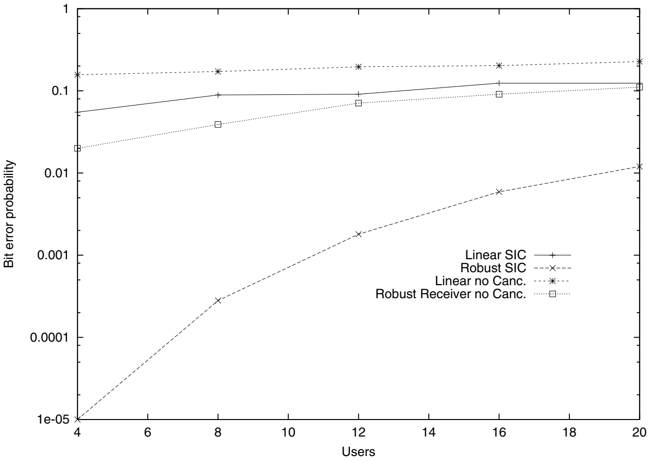

Fig. 4. BER performance of the robust and linear SIC schemes, ideal power control, synchronous ($E_b/N_0 = 5$ dB, $\epsilon = 0.2$, κ=100, $N = 31$).

The first term is the MAI of the uncancelled users, the second term is due to ambient noise and the third term is the cumulative noise due to imperfect cancellation [9]. The robust correlation term is

$$U_{k,i}(\tau_{k,i},\phi_{k,i}) = \frac{1}{T_b}\left[\int_0^{T_b} z\left[c_k(t-\tau_{k,i})c_i(t)\right]dt\right] \times \cos(\phi_k-\phi_i). \qquad (6)$$

IV. PERFORMANCE IN IMPULSIVE CHANNEL

Computer simulations were performed in order to evaluate the performance of the proposed robust SIC detector. In the noise model, κ will determine the intensity and ϵ the frequency of the impulsive noise [3]. In Figures 3 and 4, 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. The results indicate a considerable increase in SIC bit error rate performance 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. 4 that the robust single-user detector works better than the conventional SIC for the range of 4 to 20 users. (for both $\kappa = 10$ and $\kappa = 100$).

In Figures 5 and 6, we consider the case of power imbalance among users. Each interfering user has a signal power level 5 dB stronger than the desired user signal [4]. Even when the impulsive strength of the channel is low ($\kappa = 10$), the performance of the robust cancellation receiver is higher than that of the linear cancellation receiver for a range of user loads. When the number of users is 4, the bit error rate for linear SIC is 0.035 whereas it is equal to 1.5×10^{-4} for the robust SIC receiver. The interference cancellation relieves the performance loss due to power imbalance and the robust receiver effectively clips out extreme amplitudes and provides low bit error rates. This is more notable when the user load is low. The conventional SIC receiver, on the other hand, uses linear correlations to rank the users and decode them iteratively and is susceptible to errors due to impulsive noise. Compared with the ideal power control case (Figure 3), it is evident that the performance of both the single-user linear and robust receivers suffer from power imbalance. However, the successive interference cancellation schemes are efficient in reducing the near-far effects. In Figure 6, the performance of the cancellation schemes are shown in a severely impulsive channel. It is interesting to note that compared with the case where the noise is less impulsive ($\kappa = 10$), there is a slight improvement in the performance of the cancellation schemes. Severely impulsive noise leads to large signal power fluctuations at the receiver which can be utilized to reduce the errors in the ranking of the users.

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 [9]. Bits are grouped into a cancellation frame and after an entire frame is received, the correlations of each user's bits are averaged over the entire frame. The ranking of the users for cancellation is obtained from these average correlations. Figures 7 and 8 indicate the degradation in performance as a result of asynchronism. The simulations are performed where each user experiences a uniformly-distributed delay in the range of $[0, T_c]$. Correlations, which are averaged over a cancellation frame are used to rank the users to determine the order of the cancellations. The effect of MAI which result from asynchronous reception, as well as the effect of impulsive noise are reduced by the robust cancellation which outperforms the linear cancellation scheme for a range of user loads. The successive interference cancellation receivers, show a slight improvement in performance. Asynchronous reception leads to MAI due to the cross-correlations among different users' codes. Hence, the near-far resistance of successive interference cancellation scheme is substantially degraded by timing errors [1], [12]. In addition to the loss of performance due to cross-correlations, the interference cancellation receivers suffer from inaccurate cancellations. The robust SIC scheme benefits from the fluctuations at the correlator outputs due to partial correlations and the effective removal of the outlier components.

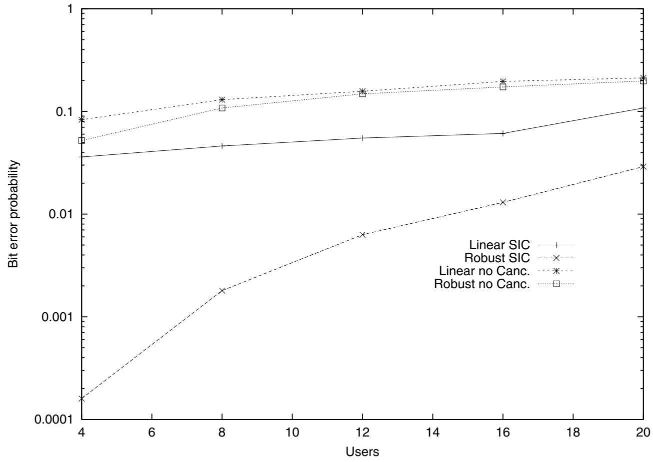

Fig. 5. BER performance of the robust and linear SIC schemes, 5 dB power imbalance, synchronous ($E_b/N_0 = 5$ dB, $\epsilon = 0.2$, $\kappa = 10$, $N = 31$).

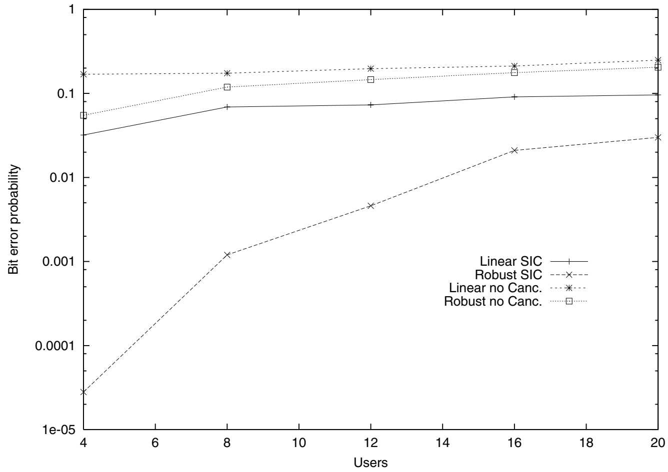

Fig. 6. BER performance of the robust and linear SIC schemes, 5 dB power imbalance, synchronous ($E_b/N_0 = 5$ dB, $\epsilon = 0.2$, $\kappa = 100$, $N = 31$).

V. CONCLUSIONS

In this paper, the details of a robust successive interference cancellation (SIC) detector which is designed to work in an impulsive noise environment is given. The detector computes robust correlations and effectively cancels interferences in the order of received signal powers. The performance of the proposed detector is evaluated for asynchronous reception and power imbalance among users. The results indicate that the proposed robust SIC detector provides superior performance to the conventional one in terms of bit error rate. The improvement in performance is more pronounced for asynchronous reception and when the users have varying power levels.

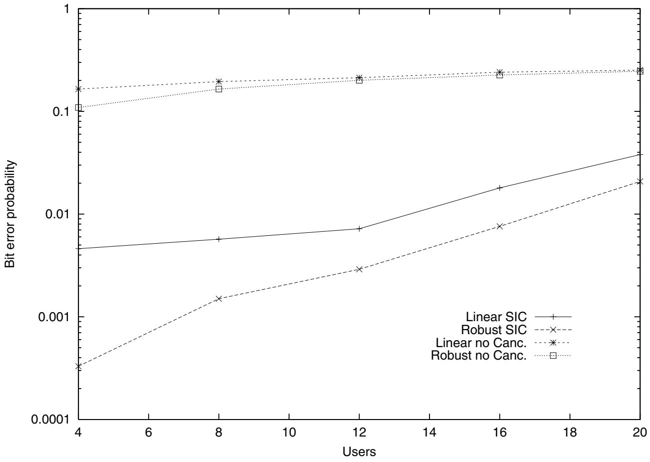

Fig. 7. BER performance of the robust and linear SIC schemes, ideal power control, asynchronous ($E_b/N_0 = 5$ dB, $\epsilon = 0.2$, $\kappa = 10$, $N = 31$).

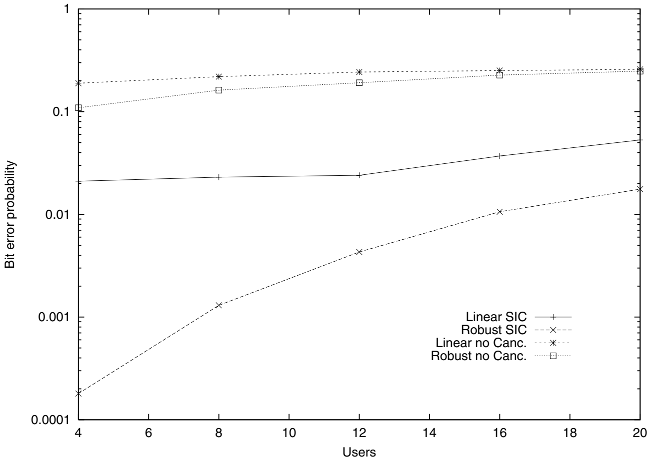

Fig. 8. BER performance of the robust and linear SIC schemes, ideal power control, asynchronous ($E_b/N_0 = 5$ dB, $\epsilon = 0.2$, $\kappa = 100$, $N = 31$).

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