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Multiuser Detection for Time Synchronous ARGOS Signals

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Abstract

Multiuser detection has recently been a big challenge in the increase of the performance for a satellite communication system. In the previous studies on systems such as CDMA, researchers have derived general mathematical expressions to describe the system model. However, when it comes to specific system such as ARGOS system, solutions based on general expressions may no longer be valid and thus new mathematical derivations could be formulated.

In this paper, we propose a new mathematical model for synchronous multiuser communication in ARGOS system and we analyse the performance of the optimum multiuser detector and some sub optimum techniques such as conventional, decorrelator, Minimum Mean Square Error, and successive interference cancellation detectors.

I. Introduction

ARGOS is a worldwide location and data collection system dedicated for studying and protecting the environment. ARGOS platforms [2] transmit messages that are received by 850 km polar orbits satellites. Collected data are then relayed to ARGOS processing centers to compute the results and distribute them to users.

One of the main issues in the current ARGOS system is the multi access interference (MAI) caused by the overlap of many high correlated signals received at different times with different powers. In addition, due to the relative motion between satellites and platforms, the transmitted signals are affected by random carriers frequencies which belong in the 80 KHz band [401.61 MHz 401.69 MHz] specified for ARGOS system [3]. Hence the transmitted signals are not received in separate bandwidths but instead in overlapping bandwidths.

One proposed approach to mitigate the MAI is to implement a radio receiver that can extract the interference and allow for the successful decoding of multiple signals. This topic falls under multiuser detection (MUD) [9].

Over the last decade, studies on CDMA have demonstrated that the maximum likelihood detection (MLD) has the best bit error rate performance compared with other sub optimum

detectors such as conventional detector, decorrelator, linear minimum mean square error (MMSE) and successive interference cancellation (SIC) techniques [1], [6] due to the gain obtained by the MLD in terms of degradation, however MLD is too complicated to be implemented in practice because its complexity is exponential in the number of users.

The novelty of this paper is to investigate optimum and sub optimum multiuser detection techniques in terms of performance and complexity that can be suitable for our detection problem. We focus our attention on symbol synchronous signals with different carrier frequencies, where the symbols of all users coincide at the receiver [8]. Although this assumption is hard to be achieved in practice, its study is necessary by allowing us to have some appreciation of the main issues in the simplest case.

The bit error rate (BER) probability for each user is one of the performance measure in our communication system. However, in multiuser detection problems, the measure of interest is the degradation [10], which is the ratio between the effective signal to noise ratio (SNR) and the actual SNR. The effective SNR denotes the required value to achieve the same probability of error in the absence of interfering users, and the actual SNR is the received energy of the user divided by the power spectral density of the Additive White Gaussian Noise (AWGN).

The rest of the paper is organised as follows. In section II, the system model as well as the mathematical derivations are presented. Several MUD techniques are presented in section III. In section IV, simulation results of the proposed MUD techniques for AWGN channel are presented. Finally, the conclusions are given in section V.

II. System Model

We consider for simplicity a synchronous system with K users, and BPSK modulation in an AWGN channel. We assume also a perfect estimation of signal amplitudes and frequencies at the receiver. The base band received signal in the complex domain can be written as [11]:

$$r(t) = \sum_{k=1}^K \sum_{n=0}^{M-1} A_k \cdot b_k[n] \cdot h(t-nT) \cdot \exp(2\pi i f_k t) + w(t) \quad (1)$$

Where

- K is the number of users.
- M is the number of symbols per user message.

- A_k is the received amplitude of the k^{th} user.
- $b_k[n] \in \{-1, +1\}$ is the symbol emitted by the k^{th} user over the n -th interval.
- $h(t)$ is the unit energy signal square waveform over one symbol interval $[0, T]$ with $\bar{h}(t)$ the complex conjugate.
- T is the period symbol.
- f_k is the carrier received frequency of the k^{th} user channel due to Doppler effect.
- $w(t)$ is AWGN with zero mean and power spectral density $N_0/2$.
- i denoting the complex number with $i^2 = -1$.

The output of the matched filter to the signature waveform of the u^{th} user and sampled at $t = jT$ is given by [11]:

$$y_u[j] = \int_{jT}^{(j+1)T} r(t) \exp(2\pi i f_u t) \bar{h}(t-jT) dt$$

$$y_u[j] = A_u b_u[j] \rho_{(u,u)}(j) + \sum_{k=u(K+1)}^K A_k b_k[j] \rho_{(u,k)}(j) + w_u[j] \quad (3)$$

where $\rho_{(u,k)}(j)$ denotes the time dependent cross correlation of the signature waveforms of the u^{th} and k^{th} users, and $w_u[j]$ the noise at the output of the u^{th} matched filter at $t = jT$.

$$\rho_{(u,k)}(j) = \int_{jT}^{(j+1)T} h(t-jT) \bar{h}(t-jT) \exp(2\pi i (f_k - f_u) t) dt$$

$$\rho_{(u,k)}(j) = \exp(\pi i (f_k - f_u) T (1 + 2j)) \text{sinc}((f_k - f_u) T) \quad (4)$$

$$w_u[j] = \int_{jT}^{(j+1)T} w(t) \exp(2\pi i f_u t) \bar{h}(t-jT) dt \quad (4-b)$$

We notice that (3) is the result of three terms: the useful signal, the multiuser interference from other users, and the additive white Gaussian noise. The term of multiuser interference depends of the time dependent cross correlation matrix and the amplitude of the other received users.

The outputs of the matched filters can be expressed in vector form as [7]:

$$Y(j) = R(j) A b(j) + w(j) \quad (5)$$

where $R(j)$ is the normalized cross-correlation matrix of the signature waveforms at the instant time jT , $R_{u,k}(j) = \rho_{(u,k)}(j)$ and its diagonal entries are the energies per bit equal to unity, $Y(j) = (y_1[j], \dots, y_K[j])^T$, $b(j) = (b_1[j], \dots, b_K[j])^T$ and $w(j)$ is a zero-mean Gaussian K -vector with covariance equal to $\sigma^2 R$ where σ denotes the standard variation of the AWGN.

III. Multiuser Detection Strategies

We first introduce the optimal detector based on the MLD criterion, and then sub optimum techniques such as: the conventional detector, the decorrelator, the linear MMSE detector and the SIC detector [4].

For each technique, we present the criterion chosen for the selection of the received bits as the advantages and the drawbacks for each method.

1. Optimum detector

The optimum multiuser detector attempts to estimate the simultaneous users signals in an MLD sense. Therefore, the optimal detector selects the vector $\hat{b}(j)$ from all the possibles values of $b(j)$ that minimizes the following expression [11]:

$$\| Y(j) - R(j) A \hat{b}(j) \|^2$$

This is equivalent to find $\hat{b}(j)$ at instant jT that maximizes the metric value [9]:

$$\Omega(\hat{b}(j)) = \Re[2 \hat{b}(j)^T A Y(j) - \hat{b}(j)^T A R(j) A \hat{b}(j)] \quad (6)$$

Where $\Re(x)$ is the real component of x .

Hence, the optimum receiver consists of K -user matched filter followed by a detector based on exhaustive research that calculates at each time the metrics for all the 2^K possible transmitted bit vectors and select the one that maximize the metric value.

The optimum detector offers the best performance in terms of bit error rate with a complexity that grows exponentially in the number of users.

2. Conventional detector

The conventional detector is an easy way for making decisions; the multiuser interference is ignored and supposed as an additive noise to the AWGN channel.

The receiver selects the symbol $\hat{b}_u[j]$ that minimizes the following expression [9]:

$$\| y_u[j] - A_u \hat{b}_u[j] \|^2 \quad (7)$$

It consists of K -user matched filter followed by detector thresholds.

The conventional detector represents the optimal detector in the case of absence of any interference term, the case when we have orthogonal signals.

Note that in case of high correlated signals, this detector became inefficient and thus induces the lost of the small signal in the presence of a bigger interference signal

3. Decorrelating detector

In the absence of any background noise, the decorrelator recovers the transmitted bits without multiuser interference.

The decorrelating detector consists of multiplying (5) by the inverse correlation matrix $R^{-1}(j)$ at each instant $t = jT$ [10].

$$\hat{b}(j) = \text{sign} [R^{-1}(j) Y(j)] = \text{sign} [A b(j) + R^{-1}(j) n(j)] \quad (8)$$

Note that each component of the previous vector is free from any interference from other users and the only source of

interference is the background noise. The decorrelating detector is the maximum likelihood solution in the absence of any background noise without the necessity of knowledge about the received amplitudes. The main disadvantage is the computation required to calculate the real time inverse correlation matrix $R^{-1}(j)$ giving that $R(j)$ is non singular matrix.

4. Linear MMSE Multiuser detection

When all the interferers are weak, decorrelator detector may have worst bit error rate than the conventional detector. Minimum mean square error (MMSE) chooses a $K \times K$ matrix $M(j)$ that minimizes the following expression [9], [10]:

$$E[b(j) - M(j)Y(j)]^2 \quad (9)$$

Where the expectation is with respect to the vector of transmitted bits $b(j)$ and the noise vector $n(j)$ which has a zero mean and covariance matrix equal to $\sigma^2 R$.

The linear MMSE detector replaces the transformation $R^{-1}(j)$ of the decorrelating detector by the following matrix $M(j)$ [9]:

$$M(j) = [R(j) + \sigma^2 A^{-2}]^{-1} \quad (10)$$

We note that it is no more necessary to have $R(j)$ non singular matrix since the matrix $\sigma^2 A^{-2}$ is always diagonal positive and knowledge of the received amplitudes is necessary. Note also that the dependence of the MMSE detector on the received amplitudes is through the signal to noise ratio defined by A_k^2 / N_0 . Therefore, as the noise level vanishes, the MMSE approaches the decorrelating detector and (10) approaches $R^{-1}(j)$. As σ increases, (10) becomes a diagonal matrix and the MMSE approaches the conventional detector. The main disadvantage of the MMSE detector is the need for channel estimation for the knowledge of the noise standard deviation.

5. Successive Interference Cancellation (SIC)

The SIC technique is based on the following idea: data of the strongest user with a conventional detector is detected, then that detected signal can be remodulated at the receiver and subtracted from the received waveform [1], [6]. The process can then be repeated with the resulting waveform which contains no trace of the signal due to the stronger user already modulated. Thus, it is necessary to demodulate the users in the order of decreasing received powers.

$$A_1 < A_2 < A_3 \dots A_1 < A_{I+1} < \dots < A_K$$

When making a decision for the k^{th} user, we assume that the decisions of users $k+1, k+2, \dots K$ are correct and therefore [9]:

$$\hat{b}_u[j] = \text{sign}(y_u[j] - \sum_{k=u+1}^K A_k \cdot \hat{b}_k[j] \cdot \rho_{(u,k)}(j)) \quad (11)$$

We notice that any error in the estimation of the received amplitudes and frequencies propagate into noise for the next cancellations [3], [5].

IV. Simulation Results

In this section, we evaluate the performance of the MUD techniques using computer simulations. In all our simulations, we consider a bit synchronous system with $K = 2$ users separated by a frequency shift Δf equals to the difference of the carriers frequencies between the two signals. We assume a BPSK modulation with a bit rate $R_b = 400$ bps. Throughout this paper, we assume also that the received amplitudes A_k and the frequencies increments f_k are known at the receiver.

We begin by presenting a comparison between the optimal detection algorithm and the sub optimum algorithms: the conventional detector, the decorrelator, the linear MMSE detector and the ordered -SIC detector.

The amount of MAI is characterized by the signal to interference ratio (SIR) P_i/P_{in} where P_i denotes the power of the signal of interest and P_{in} denotes the power of the interfering signal. The performance of the MUD and IC techniques has been studied in term of the bit error rate and also in term of degradation of the E_b/N_0 ratio, where E_b denotes the mean energy transmitted per bit of the signal of interest and N_0 denotes the variance of the AWGN.

The E_b/N_0 required to achieve a bit error rate (BER) of 10^{-3} in the presence of MAI is compared with the one required in the AWGN channel. The degradation curves of the E_b/N_0 ratio are plotted for each implemented technique as function of SIR, and for several values of the frequency shift Δf .

We begin by considering Figs. 1, 2 and 3, where we present a comparison between our MLD detection algorithm and the sub optimum detections algorithms.

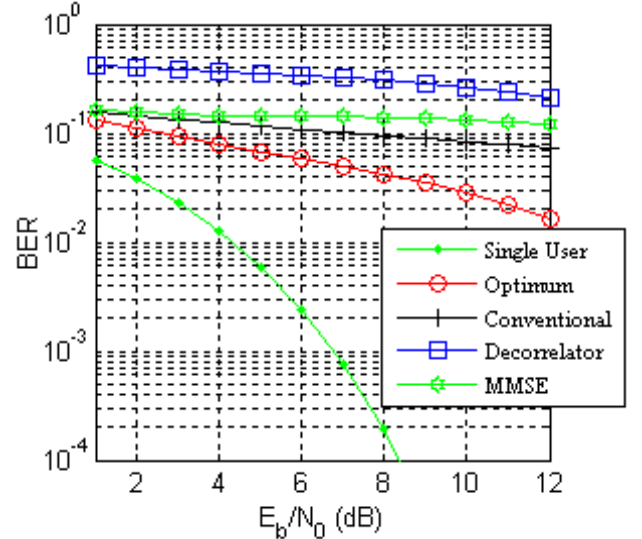


Figure 1 Bit Error Probability for $\Delta f/R_b = 0.125$, SIR = 0 dB, Synchronous transmission over AWGN channel.

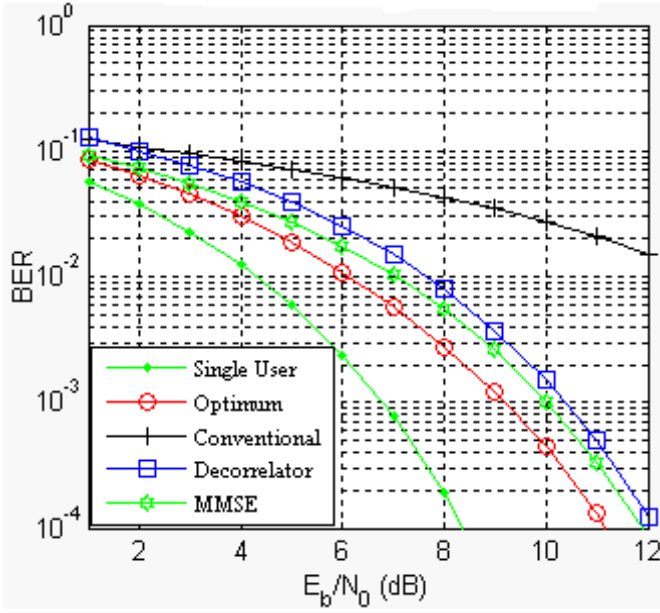


Figure 2 Bit Error Probability for $\Delta f/R_b = 0.375$, $SIR = 0$ dB, Synchronous transmission over AWGN channel.

A close observation of these figures shows that the MLD achieves the best performance in term of bit error rate compared with the other sub optimum multiuser detectors. A close observation of these figures also indicates that as we increase the ratio $\Delta f/R_b$, the proposed algorithm's performance approaches that of the single user detection (4).

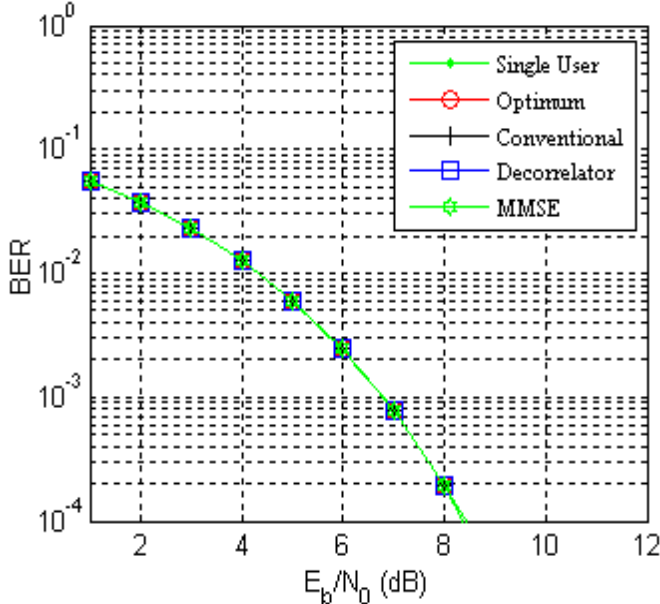


Figure 3 Bit Error Probability for $\Delta f/R_b = 0.5$, $SIR = 0$ dB, Synchronous transmission over AWGN channel.

In Figure 3, we show that for a specific value of $\Delta f/R_b = 0.5$, we have ideal performance for all the detectors due to the presence of orthogonal signals (4) (the real part of the cross correlation coefficients are zeros).

Another important factor in the MUD studies that should be considered, in addition to the BER performance, it is the degradation in terms of E_b/N_0 (dB) for a specific bit error rate. The following figures show the degradations plots as a function of SIR for different values of $\Delta f/R_b$ at a specific bit error rate of 10^{-3} .

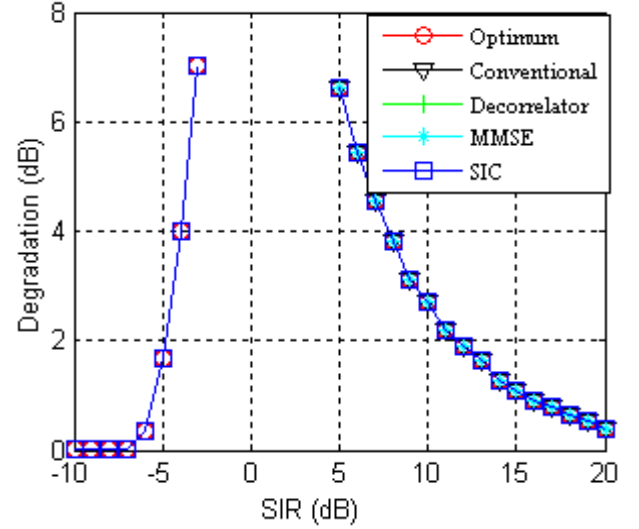


Figure 4 The degradation in dB as a function of SIR for $\Delta f/R_b = 0$ and $BER = 10^{-3}$ over AWG channel.

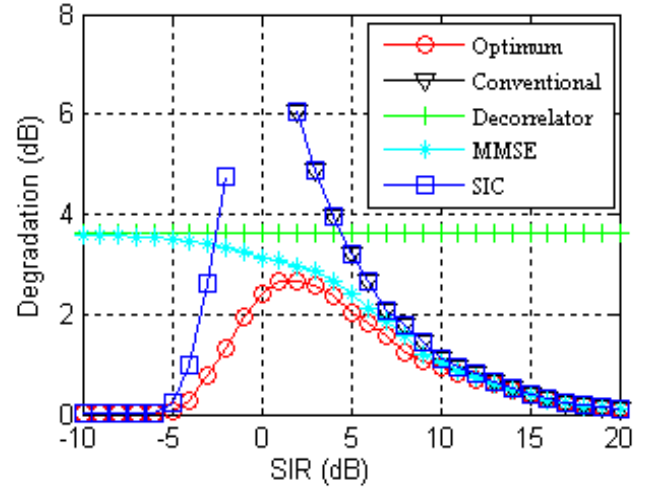


Figure 5 The degradation in dB as a function of SIR for $\Delta f/R_b = 0.375$ and $BER = 10^{-3}$ over AWG channel.

It is shown in our simulations that the MLD gave us the smaller degradation in term of E_b/N_0 with respect to the ideal performance and it works especially in the region where the interfering signal is high or small. We note also a lost of performance in the region where the signals have similar amplitudes. However, the computational complexity with the exhaustive MLD algorithm grows exponentially in the numbers of users and we have to evaluate 2^K metric values in

order to detect one symbol vector composed of all the users (6).

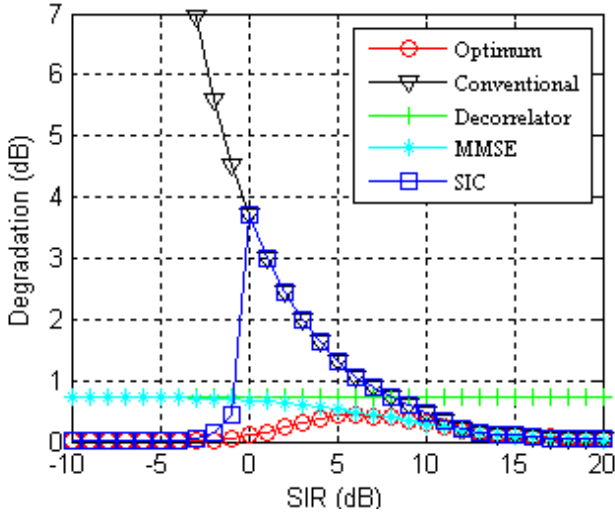


Figure 6 The degradation in dB as a function of SIR for $\Delta f/R_b = 0.625$ and $BER = 10^{-3}$ over AWG channel.

For the decorrelator, it is shown that the degradation for fixed values of $\Delta f/R_b$ and BER is constant and does not depend on the amplitudes of the interfering signal (8). This detector is inefficient for small values of $\Delta f/R_b$. The small values of $\Delta f/R_b$ induced high coefficient correlation (4) of the matrix $R^{-1}(j)$. Therefore the term $R^{-1}(j) n(j)$ will act as an amplified noise (8).

The MMSE linear detector can be seen as a compromise solution that takes into account the importance of each interfering signal and the background noise. Both the conventional receiver and the decorrelator are limiting cases of the MMSE linear detector. However, we note the useless of the MMSE detector in the region where the interest signal is the one with the smallest amplitude ($SIR < 0$).

The simulations show that the SIC performance is very much dependent on the value of SIR. When the difference between the two received signals is small, the global performance is relatively poor because of the high level of interference in the large signal [5]. The errors made in the the large signal detection propagate to the small signal because an incorrect subtraction results in an increase of the large signal interference in the detection of the small signal [4]. Thus, errors in the large signal are correlated with the detection in the small signal. For the large signal, any increase of SIR represents an additional improvement of the performance due to the reduction of the interference. When the error probability for the large signal is sufficiently low, the small signal performance is mainly influenced by the background noise [4].

In figure 6, we see that for a value of $\Delta f/R_b = 0.625$, we can reach a maximum degradation of 0.6 dB for the MLD detection for any value of SIR.

V. Conclusion

In this paper, MUD techniques for the ARGOS system have been presented. The MUD techniques consider both the output of the matched filters and the time dependent cross correlation of the signature waveforms. The performance of the proposed scheme are consistent with the ones that can be obtained with CDMA signals. The performance of the optimum algorithm is compared with different sub optimum multiuser detectors.

One major assumption made in this work is the perfect estimation of signal amplitudes and frequencies at the receiver. In a practical implementation, perfect estimates are difficult to achieve. More research is needed to quantify the performance change under imperfect estimates of amplitudes and frequencies.

Future work could also be extended for other more general situations such as asynchronous transmission.

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