Semi-Blind Impulse Radio – All Win, Limited Complexity UWB System

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***Abstract*—Semi blind impulse radio (IR) is a low complexity receiver, which improves performance by employing prior knowledge of the pulse transmission times of all other users. In this paper we investigate the optimization of the operation of a semi-blind IR system as a multiuser, multiple-access system. We show that optimal semi-blind IR has significant performance improvement over a code division multiple access (CDMA) system. This performance increase is measured by the achievable rate region, and it is shown that using semi-blind IR, the rate of at least one of the users can be made higher, without decreasing the rate of any user.**

***Index Terms*—Impulse Radio (IR), Ultra-Wideband (UWB).**

I. Introduction

Ultra Wideband (UWB) systems spread their transmissions over a very large spectrum, which allows them to share the spectrum with other wideband and narrowband systems. This property, together with the FCC approval for unlicensed use of UWB devices, has attracted much attention to UWB systems both in the industry and in the academy. The main applications considered are short-range communication at very high data rates, and applications that include high precision positioning.

One technique for UWB is Impulse Radio (IR), which spreads its transmission power in the spectrum by transmitting short pulses in a non-continuous manner. The use of non-continuous transmission allows reducing the complexity of the system receivers and transmitters. The pulse timing is determined by a pseudo-random time hopping (TH) sequence, and the data is modulated on each pulse.

IR systems are expected to work in a multiple access scenario in which many users transmit information at the same time, using the same spectrum. In order to achieve good performance in this scenario, the use of multi-user detection algorithms (MUD) [1] were suggested for receiving IR signals [2]. However, these MUD receivers have very high complexity, which prevents their use in practical systems.

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Therefore a typical IR receiver [3] applies only a match filter (MF) to detect the transmitted data. This receiver first performs a synchronization stage, in which it acquires the required user transmission time and TH sequence, followed by a correlation of the received signal with the pulse shape and information detection. This receiver, though optimal for a single user in an additive white Gaussian channel (AWGN), can perform very poorly in a multiple users scenario [4],[5]. The performance of IR systems employing MF are often compared to the performance of code division multiple access systems (CDMA) employing the same (single user MF) receiver [3],[4]. However, the non-continuous nature of the IR transmission enables a degree of freedom that can be used in an appropriate receiver, which does not exist in CDMA. An IR receiver which takes advantage on the impulsive nature of the transmission is termed semi-blind receiver.

The semi-blind receiver is an intermediate solution – in terms of complexity and performance - between the MUD and the MF receivers. The semi-blind receiver is defined in [6], but types of semi-blind receivers were used in IR even before (e.g., [7]). The semi-blind receiver applies the synchronization stage on all of the users in the system, acquiring their transmission time and TH sequences. However, this receiver aims to detect information only from a single, desired user, while ignoring the information of all other users, and considering them as noise. This receiver is much simpler then any MUD receiver because it only performs the first essential step that any MUD receiver must use - the synchronization on all users. On the other side, the knowledge of the other users transmission times and TH sequences allows the receiver to perform much better then the MF receiver [6].

The performance of a single link semi-blind IR system depends on the average signal to noise ratio (SNR), the interference distribution, and the transmission probability (the percentage of the time that the transmitter use). It was shown in [6] that the performance of such semi-blind system increases as the transmission probability increases. In the same time, it was shown that increasing the transmission probability causes performance degradation to other, nearby IR systems. Therefore, it is interesting to check the tradeoffs between the performance of different users in a multiuser semi-blind IR system.

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So far, published works analyzed only the performance of a single link semi-blind IR system. In this paper we analyze, for the first time, the overall system performance and the system optimization for multiple users.

We consider a system of semi-blind IR transmitters and receivers, in which the pulse transmission probability and the average transmission power can be determined separately for each user. In this paper we analyze the optimization of the system throughput in terms of the achievable rates region, i.e. the set of rate vectors that are achievable under the system constraints, where R_i is the rate of information transmitted by the i^{th} user, and N is the number of users.

This paper is organized as follows: Section II presents the system model, while section III defines the optimization problem, and section IV presents some optimization results. Concluding remarks are given in section V.

II. System Model

We analyze a system with N users; all transmit data to a single receiver. In order to simplify the discussion, we assume that all transmissions are symbol synchronized, and analyze the transmission and reception of a single symbol. Our system employs unsynchronized random time hopping, i.e., at each symbol time, a pulse can be transmitted with a known probability, and the transmission of pulse in one symbol is independent of the transmission at another symbol and independent of the transmissions of other transmitters. The transmitted signal model of the i^{th} user for a single symbol can be written as:

$$s_i = d_i g_i, \quad i = 1, \ldots, N, \tag{1}$$

where d_i is a binary random variable that determines whether a pulse is transmitted or not at the analyzed symbol. $d_i = 1$ with probability p_i (the pulse transmission probability), and $d_i = 0$ with probability $1 - p_i$. The information is conveyed through the random variable g_i, which is a Gaussian random variable with zero mean and variance given by the instantaneous pulse power, e_i. The average transmission power of the i^{th} user is $E_i = p_i e_i$.

The received signal is given by:

$$r = \sum_{k=1}^{N} d_i g_i + n, \tag{2}$$

where n is an additive, white Gaussian noise channel (AWGN) of normalized variance 1.

As defined previously, the semi-blind IR receiver utilizes N separate receivers. Each receiver decodes the information of a single user while treating all other users as noise. However, being semi-blind, the receiver knows at any time the instantaneous power generated by all other (interfering) users. The system constraints are given by a maximal average transmission power for each user ($E_i \le E_{i_{MAX}}$, $i = 1, ..., N$). In a practical system, this constraint includes both the maximal power available at the transmitter, and the channel attenuation.

Each user transmits information at a rate R_i, and we wish to analyze the achievable rates region. The rate of each of the users is bounded by the mutual information:

$$R_i < I(g_i; r \mid d_1, ..., d_N). \tag{3}$$

Since the receiver knows which of the interfering users is transmitting, the instantaneous interference can be considered as a Gaussian random variable with known variance, and therefore the mutual information can be expressed by expectation over the well-known Gaussian channel capacity [8]:

$$I_i = I(g_i; r \mid d_1, ..., d_N) = p_i E\left\{ \log\left(1 + \frac{e_i}{1 + \sum_{k \ne i} d_k e_k}\right)\right\}. \tag{4}$$

In this paper we do not discuss the system coding scheme, but rather assume that it nearly achieves the mutual information bound, though (4) represents the achievable user rates ($R_i \approx I_i$).

The state of the system is defined by the pair $(\mathbf{p}, \mathbf{E})$, where $\mathbf{p} = [p_1, ..., p_N]^T$ is the transmission probabilities vector and $\mathbf{E} = [E_1, ..., E_N]^T$ is the average powers vector. In the rest of the paper we will discuss the choice of this vectors such that the system performance is optimized.

Using terms from vector optimization theory, we would always want to work on a ***Pareto optimal*** system state [9]. A system state $(\mathbf{p}^*, \mathbf{E}^*)$ is called ***Pareto optimal*** if there exists no other state $(\mathbf{p}, \mathbf{E})$ such that

$$R_i(\mathbf{p}, \mathbf{E}) \ge R_i(\mathbf{p}^*, \mathbf{E}^*), \tag{5}$$

for all i, with at least one of them with strict inequality. If a system state is not Pareto optimal, then clearly there is another state that has at least one higher rate, without degrading any of the rates, and we always prefer such a state. The set of Pareto optimal system states constitute the boundary of the achievable rate region.

III. System Optimization

A vector-optimization problem is a quite complicated one and its solution has no direct approach. One popular method is the weighted sum optimization [10]. In this approach we try to optimize the single valued function:

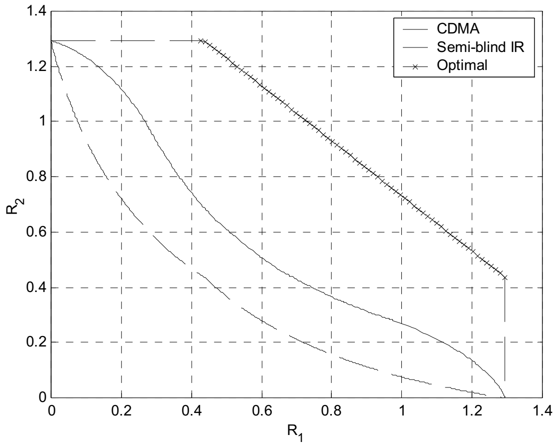

Fig. 1. Achievable rate region of CDMA and semi-blind IR systems, compared to the optimal region. Maximal power of each user achieves SNR=5.

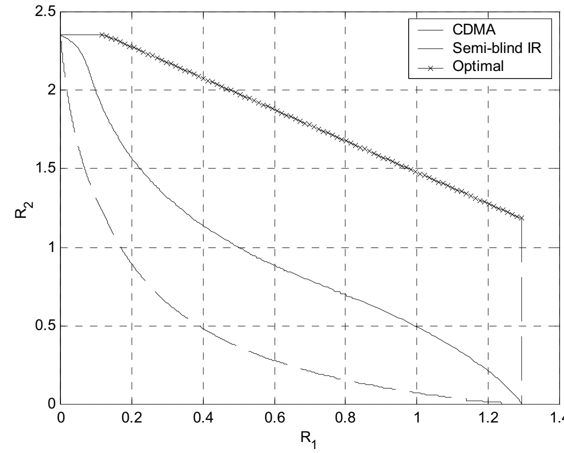

Fig. 2. Achievable rate region of CDMA and semi-blind IR systems, compared to the optimal region. Maximal user powers achieves SNR$_1$=5, SNR$_2$=25.

$$\max_{\mathbf{p},\mathbf{E}} R_T = \max_{\mathbf{p},\mathbf{E}} \sum_{i=1}^{N} \mu_i R_i(\mathbf{p},\mathbf{E}), \tag{6}$$

where $\mu_i \geq 0$ (with at least one component being strictly positive) are the optimization weights. For our case, any system state $(\mathbf{p},\mathbf{E})$, which solves this single valued optimization problem, is a Pareto optimal state of the vector optimization problem [10].

Solving the optimization problems for many values of $\boldsymbol{\mu} = [\mu_1,...,\mu_N]^T$, will eventually produce a good approximation of at least part of the Pareto optimal states set (and therefore the achievable rate region).

The single valued optimization problem is solved numerically using the partial derivatives:

$$\frac{\partial R_T}{\partial p_k} = \sum_{i=1}^{N} \mu_i \frac{\partial R_i}{\partial p_k} \tag{7}$$

$$\frac{\partial R_T}{\partial e_k} = \sum_{i=1}^{N} \mu_i \frac{\partial R_i}{\partial e_k}, \tag{8}$$

where: for $i = k$:

$$\frac{\partial R_k}{\partial p_k} = E\left\{\log\left(1 + \frac{e_k}{1 + \sum_{j \neq k} d_j e_j}\right)\right\} \tag{9}$$

$$\frac{\partial R_k}{\partial e_k} = p_k E\left\{\frac{1}{1 + e_K + \sum_{j \neq i} d_j e_j}\right\}, \tag{10}$$

and for $i \neq k$:

$$\frac{\partial R_i}{\partial p_k} = -p_i E\left\{\log\left(1 + \frac{e_i}{1 + \sum_{j \neq i,k} d_j e_j}\right) - \log\left(1 + \frac{e_i}{1 + \sum_{j \neq i,k} d_j e_j + e_k}\right)\right\} \tag{11}$$

$$\frac{\partial R_i}{\partial e_k} = -p_i p_k E\left\{\frac{1}{1 + \sum_{j \neq i,k} d_j e_j + e_i} - \frac{1}{1 + \sum_{j \neq i,k} d_j e_j + e_i + e_k}\right\}. \tag{12}$$

IV. RESULTS

In this section we present the results of numerical optimization of the semi-blind IR system. These results are compared to the results for a CDMA system (which can be conveniently derived from the same equation, by setting all the transmission probabilities to $p_i = 1$). Both systems are compared to the well-known optimal (MUD) achievable rate region [8].

Since the CDMA system performance are expressed in the same equation by setting $p_i = 1$ ($i = 1,...,N$), clearly its performance cannot be better than that of the semi-blind IR system. The reason is that the semi-blind IR system is optimized over all transmission probabilities and powers, while the CDMA system is optimized only over the possible user powers.

In order to quantify the difference between the systems performance we investigate the simple case of two equal power users. Fig 1 displays the achievable rate region of the semi blind IR system, compared to that of the CDMA system and to the optimal region. The achievable rate region was calculated numerically by a grid search over all parameters. It can be seen that although the semi-blind IR system does not achieve the optimal rate region, its performance is much better than that of the CDMA system.

Note that in the CDMA system the tradeoff between the user rates is controlled only through power control. Therefore, the maximal power of both users is used only at the center point of the graph, in which both user rates are equal. Indeed, at this point the CDMA system performance is closer to that of the semi-blind IR system. In all other points in the graph, the CDMA system uses only part of the available power (with power control), while the semi-blind IR system uses all available user powers (controlling the tradeoff between user rates by the transmission probabilities). This power advantage of the semi-blind IR system gives it an additional advantage, and increases the performance gap between the semi-blind IR and CDMA systems.

The better use of system power is demonstrated even better in Fig. 2, in which the second user power is 5 times the power of the first user. In most points of the graph, the CDMA system power control eliminates this additional power. On the other hand, the semi-blind IR system uses the excess power to reduce the second user transmission probability, though allowing the first user to achieve higher rates.

Interestingly, in all of our simulations we see that all Pareto optimal points (system states that are on the achievable rate region bound) use the maximal allowed average power of all users. We propose a conjecture that the semi-blind IR system can use any additional power (to any of the users) to increase system performance. I.e., the additional power is used to increase the rate of at least one user without degradation to any of the users.

V. Conclusion

In this paper we study the system optimization of a semi-blind IR system. We showed that the semi-blind IR system performance are significantly better than that of the CDMA system, while the system complexity is still much smaller than the complexity of a MUD system. The optimization over 2xN degrees of freedom (transmission probabilities and user powers) allows the system to reach much higher rates than the conventional optimization of users power only (N degrees of freedom).

We conjectured that any increase in power of any of the users will improve system performance in the sense that at least one user will be better off, without performance degradation to any of the other users. This property is very desirable in a communication system, and if correct, will demonstrate a significant advantage of the semi-blind IR receiver over the CDMA.

In this paper we introduced the system optimization problem and started to analyze it. Further research is required to test our conjecture that any user in a semi-blind IR system can only gain from power increase of any other user. Further research also includes study of the performance over a non-line-of-sight (NLOS) channel, and the performance optimization of independent links.

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