BLIND DETECTION FOR BLOCK CODED INTERLEAVED DIVISION MULTIPLE ACCESS

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ABSTRACT

In decentralized communication schemes such as ad-hoc networks, a major challenge concerns the synchronization and detection of users sending information simultaneously. Classical synchronisation techniques based on training sequences decrease dramatically the spectral efficiency and are rarely applicable in non-cooperative settings. In this contribution, we propose an efficient technique for blind detection in the context of block coded Interleaved Division Multiple Access (IDMA). Interestingly, without any additional dimension (space, time or frequency), the users can be fully separated when using low rate LDPC codes with the same interleavers (which is a new feature compared to classical IDMA schemes). Results, in the context of additive White Gaussian Noise (AWGN) and Rayleigh flat fading channels, demonstrate the potential of the method in the multi-user setting.

1. INTRODUCTION

Ad-hoc networks [1] are a new wireless frontier for mobile communications. Unlike traditional mobile networks, ad-hoc networks do not rely on any fixed infrastructure. In this decentralized mode, one main challenge is to design efficient access scheme and protocols able to separate the users. The non-cooperative setting of the transmissions (transmitters send information independently from each others) make classical techniques such as Time Division Multiple Access (TDMA) less appealing. In the same vein, Frequency Division Multiple Access (FDMA) requires some dedicated frequency bands which is quite frequency resource demanding. Techniques based on spreading, which have advantages in terms of diversity against fading, are spectrally inefficient. Indeed, information theoretic considerations [2] show that the optimal trade-off spreading versus coding is achieved when the entire bandwidth expansion is devoted to coding. This had led several authors [3, 4, 5] to propose a new Multiple Access Scheme nick-named Interleaved Division Multiple Access in which the users are separated without spreading.

The idea is to use different interleavers as the only mean for user separation. The scheme is a special case of coded CDMA in which bandwidth expansion is entirely performed by low-rate coding. In fact, the interleaving index sequences can be regarded as multiple access codes and the performance of IDMA has been demonstrated to achieve the same advantages as CDMA in terms of diversity against fading.

Although appealing, in non-centralized networks such as ad-hoc networks, the problem of user detection using IDMA is a non trivial issue. Indeed, users are not synchronized and the receiving node need to determine the interleavers of the different active users in order to decode the information after proper synchronization.

In this contribution, we propose an efficient blind technique for block coded Interleaved Multiple Access. The technique is well suited for the ad-hoc scenario in which users are not synchronized and is an extension of [6, 7, 8] to the multi-user scenario. Contrarily to [3], we suppose that users have the **same interleaver**. The separation is in this case done by virtual different interleavers due to the de-synchronization of the different users. The algorithm determines blindly the synchronization mismatch of the strongest user in the context of Rayleigh flat fading channels (the interleaver is supposed to be known as it is the same for all users). Once the most powerful user is detected, the procedure is done successively for the following users and successive interference cancellation is performed to retrieve the data. Interestingly, simulations results demonstrate the applicability of the method to the multi-user scenario and show that in a Rayleigh flat fading environment, the probability of being synchronized to the most powerful user is more than 0.75 in the case of 16 users and code rate $\frac{1}{16}$ (with a block size of 20 codewords).

2. MODEL AND CAPACITY CONSIDERATIONS

Let us denote by $y(nT)$ the received signal at a given node at time instant nT:

$$y(nT) = \sum_{k=1}^{M} h_k x_k(nT - t_k) + w(nT) \qquad (1)$$

where $\{x_k(nT)\}$ corresponds to the BPSK sequence of the interleaved coded sequence sent by the user k and t_k is the delay of user k. h_k is the flat fading channel of user k supposed constant during a certain number of coded blocks (block fading model) whereas w is an additive white gaussian channel with zero mean and variance σ^2. The goal is to detect all the users blindly. In this respect, we focus, without loss of generality, on the strongest user (denoted M) and rewrite equation (1) as :

$$y(nT) = h_M x_M(nT - t_M) + \xi_M(nT) \qquad (2)$$

where

$$\xi_M(nT) = \sum_{j=1}^{M-1} h_j x_j(nT - t_j) + w(nT) \qquad (3)$$

At the first step, $\xi_M(nT)$ is modeled as White Gaussian additive Noise. Once the synchronization algorithm is applied (in other words t_M is deduced), information x_M is decoded and retrieved from equation (2).The procedure is then applied successively to all the other users.

2.1. Information Theoretic Considerations

Let us focus on the case of two users and show as in [9] that the technique achieves the capacity region. The instantaneous capacity, assuming Gaussian signaling, is given by:

$$C = \log_2(1 + \frac{\mid h_1 \mid^2 + \mid h_2 \mid^2}{\sigma^2})$$

In the case of successive interference cancellation, the capacity of the first and second user are respectively given by (supposing that the rates are known at the transmitter and that the first user is the strongest user):

$$C_1 = \log_2(1 + \frac{\mid h_1 \mid^2}{\mid h_2 \mid^2 + \sigma^2})$$

and

$$C_2 = \log_2(1 + \frac{\mid h_2 \mid^2}{\sigma^2})$$

One can easily show that:

$$C = C_1 + C_2$$

which demonstrates the usefulness and optimality of a successive interference cancellation approach. In practical situations, the users do not know the exact rate of transmission. In this case, assuming the channel is constant within several blocks, the receiving node can signal to the different users (with a very small over-head) the adequate rates.

3. JOINT BLIND INTERLEAVER DETECTION AND SYNCHRONIZATION

In this section, we describe the principles of the blind interleaver detection and synchronization algorithm. We focus on the case of a single user (in our context, this corresponds to the strongest user i.e the user having the strongest instantaneous power) in the presence of noise (the noise corresponds to the multi-user interference due to the other active users as well as the background noise). For simplicity, we first describe the binary additive channel and then the Rayleigh fading case.

3.1. Binary additive channel

3.1.1. Some generalities

Before going further, let us first provide some useful properties of block channel codes. A block encoder is defined by a full-rank generator matrix G that transforms each block of n_b information bits into n_c encoded bits ($n_b < n_c$). Representing the i^{th} information block and the i^{th} encoded block by vectors b_i and x_i, we have: $x_i = b_i G$. x_i is called a codeword. The ratio $R = n_b/n_c$ is called the code rate. The $n_r = n_c - n_b$ redundant bits are computed as the sum modulo 2 of some information bits. Let us denote by r the received codeword:

$$r = m_c \oplus e$$

where m_c is the codeword, e an error vector of length n_c and $\oplus$ stands for the sum modulo 2. From this observation, the receiver should be able to restore the n_b information bits. The optimal decoding from binary data consists in finding the code word that minimizes the Hamming distance to the observation r.

For each generator matrix G corresponds a parity check matrix H of size $n_r n_c$ such that $GH^T = 0$. The decoding principle consists in computing the syndrome $s(r)$ of the observation:

$$s(r) = rH^T = m_i GH^T \oplus eH^T = eH^T.$$

And for each syndrome, we can associate an error word privileging the low weight error word.

3.1.2. Frame synchronization

In usual communication schemes, the system implicitly assumes that the receiver knows the beginning of the code words. Unfortunately, this assumption is to optimistic for ad-hoc networks. Let us denote by $\mathbf{X}$ the received sequence of $\mathbf{Z}$. Because of the propagation channel, $\mathbf{X}$ is a delayed replica of $\mathbf{Z}$ (by t_0 bits corresponding to the propagation delay) that has been passed through a binary symmetric channel. Let us denote p_e the error probability of the channel. Without loss of generality, we assume that the restitution delay t_0 is smaller than the size n_c of a codeword. The goal of frame synchronization is to estimate t_0.

The blind frame synchronization works as follows: The low redundancy code is used to synchronize. Indeed, if one considers a noise free channel, when we are synchronised, all syndromes computed from blocks of size n_c are equal to zero. This is mostly not the case when we are not synchronized. The synchronisation method is based on this obvious observation. Let H_d be an extracted sequence of size Kn_c from the received sequence (with n_c the size of a codeword).

$$\begin{aligned} H_d \;=\; & \Big[\underbrace{x(d), \ldots, x(d+n_c-1)}_{B_1}, x(d+n_c), \ldots, \\ & \underbrace{x(d+(K-1)n_c), \ldots, x(d+Kn_c-1)}_{B_K}\Big]^T . \end{aligned}$$

H_d can be divided into K blocks $(B_i)_{k=1,\ldots,K}$ of size n_c. When $d = t_0$, H_d has exactly K complete codewords. From H_d, we compute a vector of syndromes S_d of size Kn_r (with n_r the number of redundant bits in the codeword).

$$\begin{aligned} S_d &= [S_d^{(1)}, \ldots, S_d^{(K)}]^T \\ &= [S_d(1), \ldots, S_d(Kn_r)]^T \end{aligned}$$

where $S_d^{(i)}$ is the syndrome computed from the block B_i of H_d and $S_d(k)$ is the k^{th} element of S_d.

Figure 1 represents three different sequences of H_d : for $d = 0$, $d = 1$ and $d = t_0$ where the size of H_d is fixed to $K = 3$ and t_0 represents the synchronized position. From S_d, we define $\phi(d)$ as the number of elements equal to zero in the vector S_d:

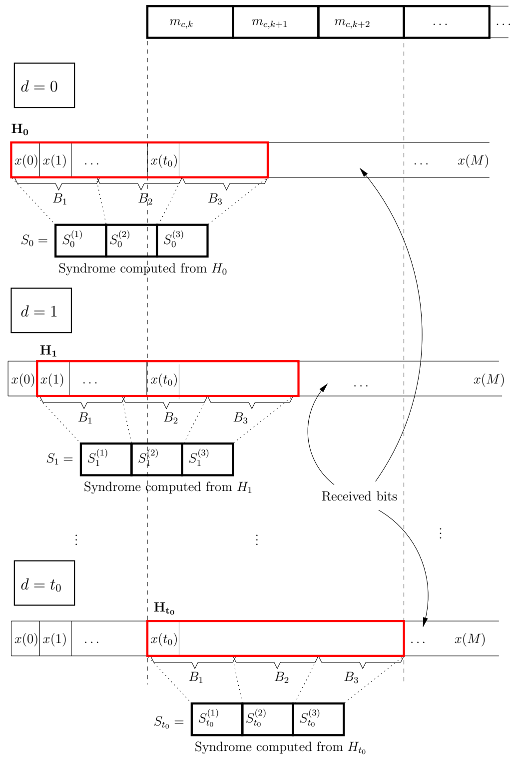

Fig. 1. Blind synchronization principle

$$\phi(d) = \sum_{k=1}^{K(n_r)} S_d(k).$$

The synchronized position is then estimated as the value that minimizes ϕ

$$\hat{t}_0 = \text{ArgMin}_{d=0,\ldots,n_c-1} \phi(d).$$

3.2. Rayleigh fading case

In the following, we adapt the previous algorithm to the Rayleigh fading context and consider the soft value of the syndrome : An element of the syndrome is obtained by the sum of bits and therefore we can compute the LLR of this element using the following approximation [10] : Let us define by

$L(u_i)$ the LLR of the i^{th} bit of the sum:

$$L(u_i) = \frac{2h_M}{\sigma_M^2}\tilde{x}_i \tag{4}$$

with σ_M^2 the variance of $\xi_M(nT)$ (see eq. (2)) and $\tilde{x}(i)$ the received sampled corresponding to the bit u_i. Then the LLR of the sum of L bits can be approximated by:

$$L(S_d(k)) = (-1)^{L+1}\left(\prod_{j=1}^{L}\text{sign}(L(u_j))\right)\beta \tag{5}$$

with :

$$\beta = \min_{j=1,\dots,L}|L(u_j)|.$$

The synchronization position is the one that minimizes:

$$\hat{t}_0 = \text{ArgMin}_{d=0,\dots,n_c-1}\phi_L(d).$$

with

$$\phi_L(d) = \sum_{k=1}^{K(n_r)} L(S_d(k)).$$

It is imporant to note that we only need to estimate $\phi_L(d)$ up to a multiplicative factor which means that we only need to estimate $L(S_d(k))$ up to a multiplicative factor. As we consider a block fading channel, h_M and σ_M^2 are constant over one block and we have:

$$\beta = |\frac{2h_M}{\sigma_M^2}|\min_{j=1,\dots,L}|\tilde{x}_j| \tag{6}$$

Assuming that L is even (we need this assumption only if h_M can be negative), we have :

$$\prod_{j=1}^{L}\text{sign}(\tilde{x}_j) = \prod_{j=1}^{L}\text{sign}(L(u_j)) \tag{7}$$

Using (6) and (7), we obtain an estimate $\hat{L}_d(k)$ of $L(S_d(k))$ up to a multiplicative factor :

$$\hat{L}_d(k) = (-1)^{L+1}\left(\prod_{j=1}^{L}\text{sign}(\tilde{x}_j)\right)\min_{j=1,\dots,L}|\tilde{x}_j|.$$

Thus, we do not need to know h_M and σ_M^2 to estimate t_0: in other word no channel state information is needed to synchronize to most powerful user.

4. PERFORMANCE RESULTS

In [7], it is shown that the synchronization technique in the single user setting is particularly well suited for LDPC codes and shows very convincing performance even for low SNR. In this section, we illustrate the performance of our blind frame synchronization method in the multi-user setting as well as its adaptation to the Rayleigh fading case. The following case is considered: The information bits of each user are coded by the same LDPC having 4 ones on each line of its parity check matrix. The length of a codeword is equal to 256 and the code rate is equal to $\frac{1}{16}$. The system has a maximum of 16 users. All users have the same pseudo random interleaver. A Rayleigh fading channel is considered (i.e. $h_k \sim \mathcal{N}(0,1)$). The probability of correct synchronization of the most powerful is assessed user using Monte Carlo Trials. For each trial, the bits, the interleaver, the delay between the users and the fading coefficients of the channel are randomly chosen. 1000 realizations were run. First of all we consider a noiseless transmission. Figure 2 gives the performance of synchronisation versus the load of the system for different sizes of the synchronization window. In this particular case, a noise free transmission has been considered. As the number of users in the system increases, the performance decreases. However, if one increases the size of the synchronization window, the performance of the synchronization algorithm increases. Indeed with 16 users, the probability of correct synchronization is 72% for a synchronization windows of 20 codewords.

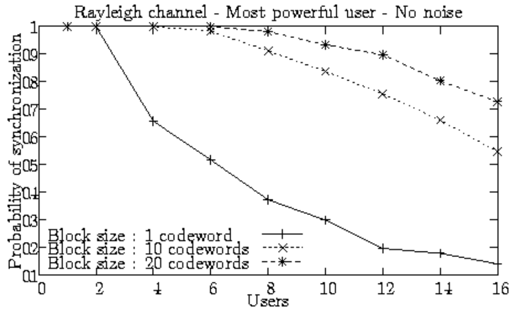

Fig. 2. Probability of synchronization of the strongest user versus the number of users in the system-Rayleigh case

Figure 3 presents the same results but for different SNR values and for a synchronization window of 10 codewords. The need of having a longer synchronization window above 20 codewords is important. In figure 4, the case of an Additive White

Gaussian Noise channel has been considered (all users have the same power). Interestingly, the performance are rather pessimistic with respect to the Rayleigh fading case. In fact, differences in the power values of the users can increase the performance of the system. Similar conclusions have already drawn also in the CDMA setting [11] and show that power control is mainly a drawback as far as system capacity is concerned.

5. CONCLUSION

In this contribution, an efficient blind detection algorithm has been provided to separate users blindly in Rayleigh fading channels. Remarkably, without the use of any additional dimensions (such as space, time or frequency), multi-user communications for ad-hoc networks can be established thanks to the delays of the different users. Extensions of the algorithm to the case of frequency selective fading channels are still under investigation.

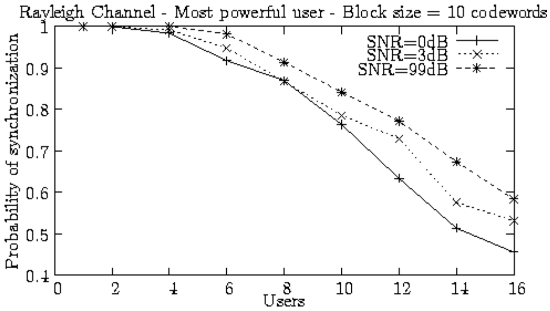

Fig. 3. Probability of synchronization of the strongest user versus the number of users in the system for several SNR values- Size of the synchronization window equal 10 codewords-Rayleigh case

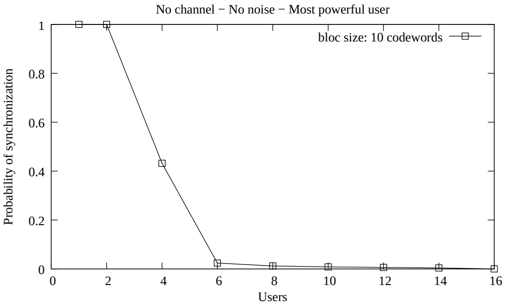

Fig. 4. Probability of synchronization of the strongest user versus the number of users in the system for several SNR values- Size of the synchronization window equal 10 codewords-AWGN case

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