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Multi-Delay Biorthogonal Coded/Balanced TR-UWB Receiver for WPAN Based on Hadamard Matrix

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Abstract

Impulse radio ultra wideband (IR-UWB) communication is becoming an important technology for future Wireless Personal Area Networks (WPANs). One of the critical challenges in IR-UWB system design is the inter-pulse interference (IPI). A Transmit-reference (TR) receiver is proposed to completely remove the IPI especially at low input frame energy-to-noise-ratio (E_f/N_o) values. This receiver is based on the using of a modified version of Hadamard matrix to yield a biorthogonal coded words instead of orthogonal ones. On the other hand, from the complexity view, the proposed TR receiver in this paper has high complexity as compared with the balanced coded orthogonal TR receiver proposed recently but it outperforms it.

Keywords: Impulse radio, Ultra wideband, inter-pulse interference, Hadamard matrix, biorthogonal.

مستلم متعدد التاخير متوازن ذو الحزمة العريضة جدا (UWB) لتطبيقات شبكات WPAN اعتمادا على مصفوفة هادمارد

الخلاصة

يعتبر الـ Impulse Radio (IR) – ذو حزمة الاتساع العريضة جدا Ultra-Wideband (UWB) نظام تكنولوجي لاسلكي والذي يعتمد على ارسال نبضات ضيقة جدا. لذا، يُعتَبرُ نظام IR-UWB مستقبل شبكات الشخصية اللاسلكية WPAN . من اهم التحديات في نظام Impulse Radio (IR) هو التداخلُ بين النبضات IPI .

في هذا البحث تم اقتراح مستلم ارسال اشارة مصدر TR لإزالة التداخلُ بين النبضات بالكامل خصوصاً في طاقةِ الإطارِ المنخفضةِ نسبةِ للضوضاء (E_f /N_o). يستند هذا المستلم على فكرة إستعمال نسخة مُعَدَّلة مِنْ مصفوفةِ Hadamard لإنْتاجِ مصفوفة biorthogonal مشفرة الرموز بدلاً مِنْ واحدةِ متعامدةِ. من الناحية الأخرى، ومِنْ وجهةِ نظر تعقيد النظامَ ، فان المستلم المُقتَرَح TR يملكُ تعقيدُ عاليُ نسبيا مُقارنة مَع TR المتعامد المشقر المتوازن الذي إقترحَ مؤخراً لكنَّه يبدي نتائج أفضل منه.

1. Introduction

Ultra-Wideband (UWB) impulse radio systems transmit data by modulation of sub-nanosecond pulses. These narrow pulses are distorted by the channel, but often can resolve many distinct propagation paths (multipath) because of their fine time resolution capability. However, a Rake receiver that implements tens or even hundreds of correlation operations may be required to take full advantage of the available signal energy.

Transmit-reference (TR) schemes are considered as realistic candidates for impulse-based ultra-wideband (UWB) communication systems. Due to the narrow pulses employed in such systems, many

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multipath components can be resolved, and it is not efficient to estimate all of them. TR schemes sidestep channel estimation by transmitting a reference signal which undergoes the same distortion by the channel as the data signal. This provides an (unfortunately) noisy template [1, 2].

One of the key challenges for impulse radio is the construction of low-cost receivers that work well in multipath environments. Optimum performance is obtained by a coherent rake receiver that has enough fingers to receive all resolvable multipath components (MPCs). However, the number of MPCs can be on the order of tens or even hundreds in typical indoor environments. Though simplified rake structures have been proposed, channel estimation, multipath tracking, and multipath combining contribute to the overall complexity of coherent rake receivers. For these reasons, TR receivers have drawn significant attention in recent years. TR encodes the data in the phase difference of the two pulses of a pulse pair. The first pulse in that pair does not carry information, but serves as a reference pulse; the second pulse is modulated by the data and is referred to as the data pulse. The two pulses are separated by a fixed delay. It can be easily shown that the receiver can demodulate this signal by simply multiplying the received signal with a delayed version of itself. Such receivers are thus exceedingly simple, but they show considerably worse performance than coherent Rake receivers [3].

Many literatures studied and focused on the IPI cancellation or mitigation using TR receivers with all its types.

In [4], the authors proposed *M*-ary orthogonal coded/balanced TR system in which the inter-frame interference (IFI) can be avoided because the frame time can be prolonged due to *M*-ary signaling as far as the required data rate is achieved. Based on this signaling approach, the IPI has been mitigated by using a pair of *balanced* matched filters, which subtracts out the overlap portion between multipath delayed pulses. The effective suppression of the IPI has been validated through the theoretical analysis and simulations in dense multipath. It has been shown that the use of proposed balanced TR can result in significant data rate increases even at a lower transmit power; compared to conventional TR. This receiver is largely suffered from time jitter even for small time values. Also, it's too complex in terms the number of matched filters used. In [5], the authors proposed balanced transmitted reference (TR) system for ultra-wideband (UWB) communications. The proposed TR system is capable of properly eliminating the inter-pulse interference (IPI) between the reference and data pulses in multipath environments, with a low system complexity. In fact, it should be noted that the suboptimal receiver does not completely eliminate the IPI because of the non-linear cross-correlation performed prior to the IPI cancellation. In [6], the authors introduced *M*-ary orthogonal coded/balanced TR system in which the inter-frame interference can be avoided because the frame time can be prolonged due to *M*-ary signaling as far as the required data rate is achieved. Based on this signaling approach, the inter-pulse interference has been overcome jointly by using *balanced* matched filters, which subtract out the overlapping portion between multipath-delayed tail of the reference pulse and subsequent information-bearing data pulse. It has been shown that the proposed TR system in this paper can result in significant data rate increases even at a lower transmit power; compared to conventional TR. They also address the receiver complexity issues and present two suboptimal receiver structures. It is demonstrated that the suboptimal receivers still outperform conventional TR, with lower complexity than the optimal receiver. Finally, they are used to compare the performances of the proposed TR system with that of conventional TR system in the presence of timing jitter and it is clear that, even when a large amount of timing jitter occurs, their proposed TR system with the suboptimal receiver still outperforms conventional TR. Again, it should be noted that the suboptimal receiver does not completely eliminate the IPI because of the non-linear cross-correlation performed prior to the IPI cancellation.

2. The Proposed TR Receiver based on Hadamard matrix

The data rate of the conventional TR system, in general is limited by the multipath delay spread T_{mds}, because the inter-pulse distance T_d should be greater than T_{mds}, so that the interference between the reference and data pulses should not be incurred in a frame. To mitigate this inter-pulse interference (IPI) and boost the TR system's achievable information rate, a new signaling scheme has been proposed.

In this section, an IR-UWB-TR receiver based on Hadamard matrix namely N-ary Biorthogonal Coded/Balanced TR schemes has been proposed, for increasing the information rate and improving the detection performance.

In such transceivers, sending all the rows of Hadamard matrix H_n for N-ary signaling is impossible, due to the following reasons:-

1. The complexity of the receiver is growing as a factor of 2^{Ns}, where N_s is the number of frames per symbol, i.e., it is impractical.
2. By examining H_n, we notice that the first row could not be used for IPI canceling, because it contains (+1s').
3. H_n is orthogonal, in symbolic notations [7] :

$$\sum_{k=1}^{N_s} v_{i,k}.v_{j,k} = \begin{cases} 0 & for \quad i \neq j \\ 1 & for \quad i = j \end{cases}$$

For these reasons, we must modifying H_n in such away that decreasing the receiver complexity and the number of N_s, while increasing the BER in certain level, also increasing the bit rate. Therefore, we can use the multi-delay (MD) technique to completely perform the IPI cancellation.

In the proposed receiver, the modified Hadamard matrix should be constructed firstly, and then the transceiver system according to the new generating matrix will be designed.

Any Hadamard matrix H_n with dimension $(N \times N)$ can be constructed as follows [7]:

$$H_n = \begin{bmatrix} H_{n-1} & H_{n-1} \\ H_{n-1} & \overline{H_{n-1}} \end{bmatrix}$$

H_n is orthogonal and have four quarters, each equator is biorthogonal. In symbolic notations this could be written as:

$$\sum_{k=1}^{N_s} v_{i,k}.v_{j,k} = \begin{cases} 1 & for \quad i=j \\ -1 & for \quad i=1, j=(N/2)-1 \\ 0 & Otherwhere \end{cases}$$

Hence we have:

$$H_n = \begin{bmatrix} v_{11} & v_{12} & \mathbf{K} & v_{1n} \\ v_{21} & v_{22} & \mathbf{O} & \mathrm{M} \\ \mathrm{M} & \mathrm{M} & \mathbf{O} & \mathrm{M} \\ v_{n1} & v_{n2} & \mathbf{K} & v_{nn} \end{bmatrix}$$

H_n can be divided into four quarters, as:

$$\mathrm{H}_n = \begin{bmatrix} \mathrm{Q}_1 & \mathrm{Q}_2 \\ \mathrm{Q}_3 & \mathrm{Q}_4 \end{bmatrix}$$

For symbolic notation simplicity, and without lose of generality, the first quarter Q_1 could be written as:

$$Q_1 = H_{n-1} = \begin{bmatrix} v_{11} & \mathbf{K} & v_{1,n/2} \\ \mathrm{M} & \mathbf{O} & \mathrm{M} \\ v_{n/2,1} & \mathbf{K} & v_{n/2,n/2} \end{bmatrix}$$

with dimension (N/2 x N/2)

The features of Q_1 are as follows:

1. The elements of the first row of Q_1 are all (1s). So, Q_1 could not be used for IPI cancellation because the numbers of +1 and -1 in each row (code vector) should be equal; i.e., half of the elements are +1 and the others are -1.
2. Q_1 is orthogonal matrix. As will be seen later, the orthogonal matrix has worse effect in case of sending N-ary signaling.

Therefore, Q_1 must be modified to overcome the above two points by inverting the first half elements of the first row, as follows:

$$Q_1^* = \begin{bmatrix} \overline{v_{11}} & \mathbf{K} & \overline{v_{1,n/4}} & v_{1,n/4+1} & \mathbf{K} & v_{1,n/2} \\ v_{21} & \mathbf{O} & \mathbf{O} & \mathbf{O} & \mathbf{O} & \mathrm{M} \\ \mathrm{M} & \mathbf{O} & \mathbf{O} & \mathbf{O} & \mathbf{O} & \mathrm{M} \\ v_{n/2,1} & \mathbf{K} & \mathbf{K} & \mathbf{K} & \mathbf{K} & v_{n/2,n/2} \end{bmatrix}$$

Up to now, Q_1^* is completely biorthogonal matrix and it is appropriate for IPI cancellation. It is clear that the first row and row (Ns/2-1) is biorthogonal and cause a wrong detection in the receiver, so, Q_1^* again should be modified in a certain way and via incorporating a multi delay units to distinguish between the N-ary symbols. The following steps show how could the above tasks are done:

1. Given Q_1^* in the following form:

$$Q_1^* = \begin{bmatrix} u_{11} & \mathbf{K} & u_{1,n/2} \\ \mathrm{M} & \mathbf{O} & \mathrm{M} \\ u_{n/2,1} & \mathbf{K} & u_{n/2,n/2} \end{bmatrix}$$

2. Delete the rows from (N/4+1) to (N/2).
3. Replace the deleted rows with the inverting of the first (N/4) rows as:

   $row(i+N/4) = \overline{row(i)}$

   for i=1,2, ………, N/4
4. The new matrix Q_1^{**} is given by:

$$Q_1^{**} = \begin{bmatrix} u_{11} & \mathbf{KKK} & u_{1,n/2} \\ \mathrm{M} & \mathbf{O} & \mathrm{M} \\ u_{n/4,1} & \mathbf{KKK} & u_{n/4,n/2} \\ \overline{u_{11}} & \mathbf{KKK} & \overline{u_{1,n/2}} \\ \mathrm{M} & \mathbf{O} & \mathrm{M} \\ \overline{u_{n/4,1}} & \mathbf{KKK} & \overline{u_{n/4,n/2}} \end{bmatrix}$$

5. Now, the first (N/4) rows of Q_1^{**} are pure orthogonal and so the second (N/4), but they are biorthogonal. To distinguish between them it's enough to assign *only two different delays*, D_1 and D_2 for the first and the second groups respectively.

$$Q_1^{***}=\left[\begin{array}{ccc|c} u_{11} & \cdots & u_{1,n/2} & D_1 \\ \vdots & \ddots & \vdots & \vdots \\ u_{n/4,1} & \cdots & u_{n/4,n/2} & D_1 \\ \overline{u_{11}} & \cdots & \overline{u_{1,n/2}} & D_2 \\ \vdots & \ddots & \vdots & \vdots \\ \overline{u_{n/4,1}} & \cdots & \overline{u_{n/4,n/2}} & D_2 \end{array}\right]$$

Finally, to construct the N-ary signals, duplicate Q_1^{***} with *only two newly different delays*, say D_3 and D_4 to yield (N x N/2+1) matrix, we called it "Generating Matrix" (GM)

$$GM=\left[\begin{array}{ccc|c} u_{11} & \cdots & u_{1,n/2} & D_1 \\ \vdots & \ddots & \vdots & \vdots \\ u_{n/4,1} & \cdots & u_{n/4,n/2} & D_1 \\ \overline{u_{11}} & \cdots & \overline{u_{1,n/2}} & D_2 \\ \vdots & \ddots & \vdots & \vdots \\ \overline{u_{n/4,1}} & \cdots & \overline{u_{n/4,n/2}} & D_2 \\ u_{11} & \cdots & u_{1,n/2} & D_3 \\ \vdots & \ddots & \vdots & \vdots \\ u_{n/4,1} & \cdots & u_{n/4,n/2} & D_3 \\ \overline{u_{11}} & \cdots & \overline{u_{1,n/2}} & D_4 \\ \vdots & \ddots & \vdots & \vdots \\ \overline{u_{n/4,1}} & \cdots & \overline{u_{n/4,n/2}} & D_4 \end{array}\right]$$

The Multi-Delay Biorthogonal Coded/Balanced TR-UWB receiver is shown in Figure (1) based on GM. Hence, the estimated symbol $\hat{S}$ is depending on the output of the decision device which in turn is depending on the largest quantity of the results of the integrator blocks.

3. Simulation Results

In this section, simulation results that compare the performance of the proposed receiver with that in [5] are obtained. The bit error rate (BER) curves are simulated for the IEEE 802.15.3a CM3 and without loss of generality indoor channel which is non line-of-sight (NLOS) channel between 4 and 10 meters. Moreover, the channel is assumed static over one TR frame. The total energy of the channel is normalized by to 1. 75 channel realizations of CM3 are randomly selected and for each channel realization, the total number of time bins, equivalent to the delay spread T_m, is chosen to be 100, i.e., to collect enough pulse energy as well as not to accumulate much noise power. The channel is truncated so as to ture most of the signal energy nearly more than 96% of the total channel energy.

The received pulse is assumed to be the second-order derivative of Gaussian pulse of width 0.5 ns. T_c = 0.5 ns is select, sampling frequency = 100 GHz, bin duration = 0.5 ns, and shaping factor for the pulse = 0.15 ns.

First, figure (2) shows the results of the proposed receiver for N_s = 2, 4, 8, and 16. Obviously, the BER is decreased with increasing N_s. For low E_f/N_o, the cross-over is also observe to occur due to the high-order modulation, which is more sensitive to the noisy channel.

Second, the receiver proposed in [5] is evaluated for N_s = 4, 8, and 16. In each N_s, many N-ary signaling is tested to show the performance of the receiver in that work. As shown in figures (3, 4, and 5), the degradation in the receiver performance with higher

N-ary because the suboptimal receiver does not completely eliminate the IPI

Now, the comparison between the proposed receiver and that in [5] has been done for N_s = 4, 8, and 16. Based on the results in figures (3, 4, and 5), the best BER in each N_s is chosen and compare it with that of the proposed receiver. The results in figures (6, 7, and 8), show that in all cases the proposed receiver is largely outperforming the receiver in [5].

Conclusions

In this paper, TR-TH-MD receiver for UWB WPAN short range indoor channel has been proposed. The proposed receiver is based on a modified version of Hadamard matrix. In this proposed receiver, the IPI is completely removed by using biorthogonal codes which are generated by a modified Hadamard matrix. Besides, a very large bit rates are obtained due to the sending of N-ary symbols.

The performance results presented in the previous section for the proposed receiver show that the Multi-Delay Biorthogonal Coded/Balanced TR-UWB receiver that is Based on Hadamard Matrix outperforms the receiver proposed in [6] in terms of achieving low bit error rates (BERs) values in all cases.

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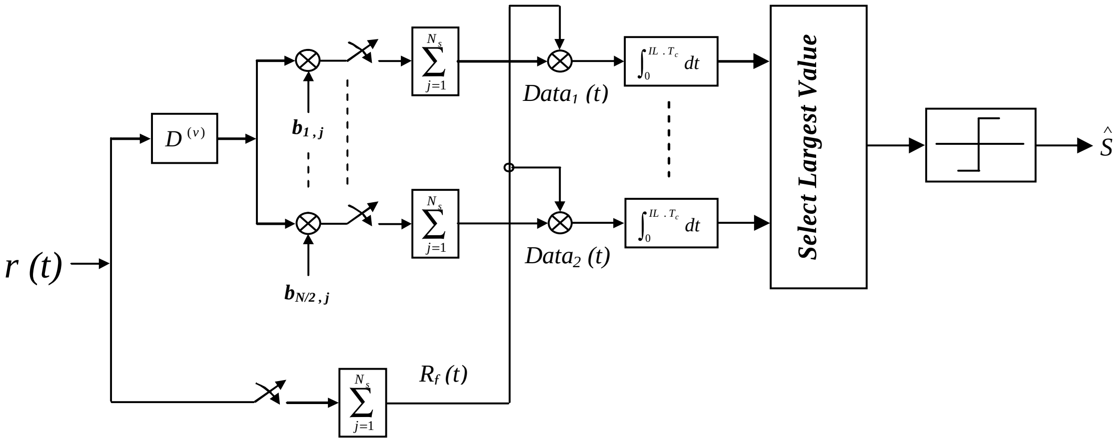

Figure (1) The proposed Multi-Delay Biorthogonal Coded/Balanced TR-UWB Receiver

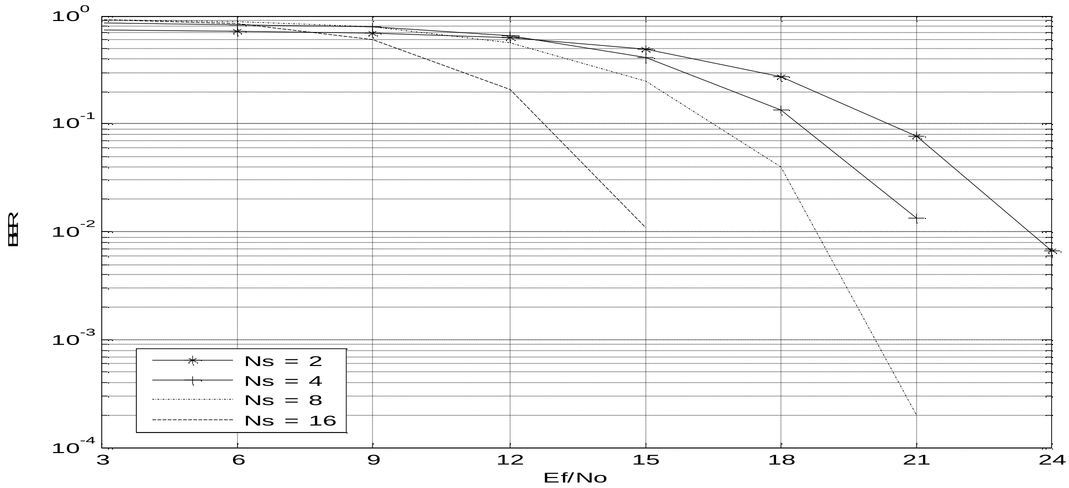

Figure (2) The BER for the proposed receiver

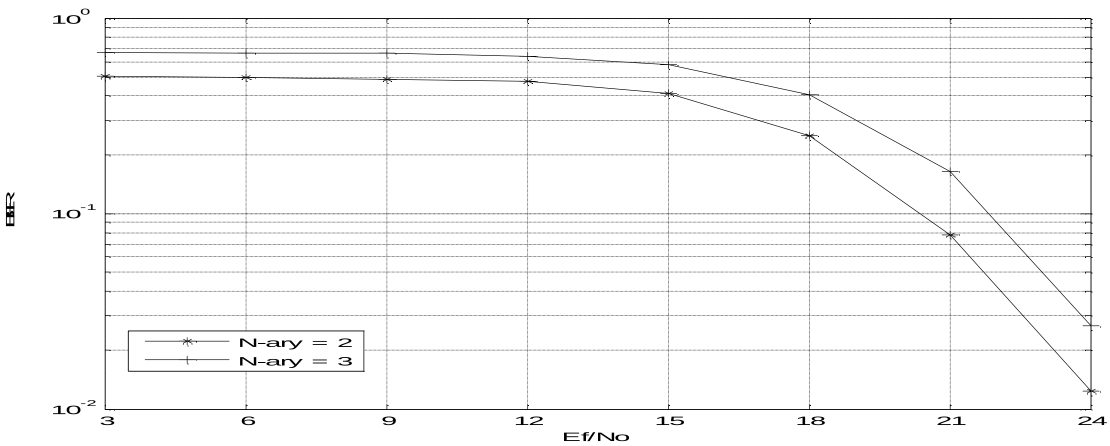

Figure (3) The BER for the receiver in [5] for N_s = 4

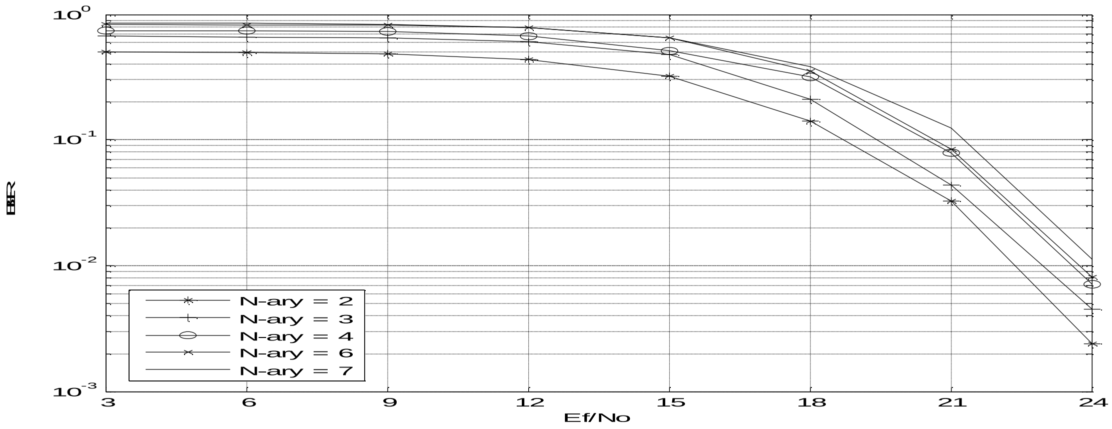

Figure (4) The BER for the receiver in [5] for $N_s = 8$

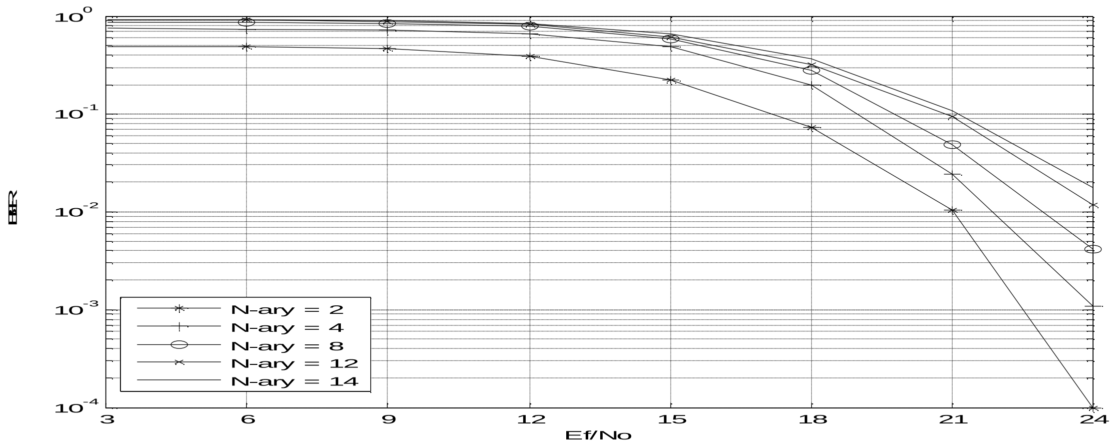

Figure (5) The BER for the receiver in [5] for $N_s = 16$

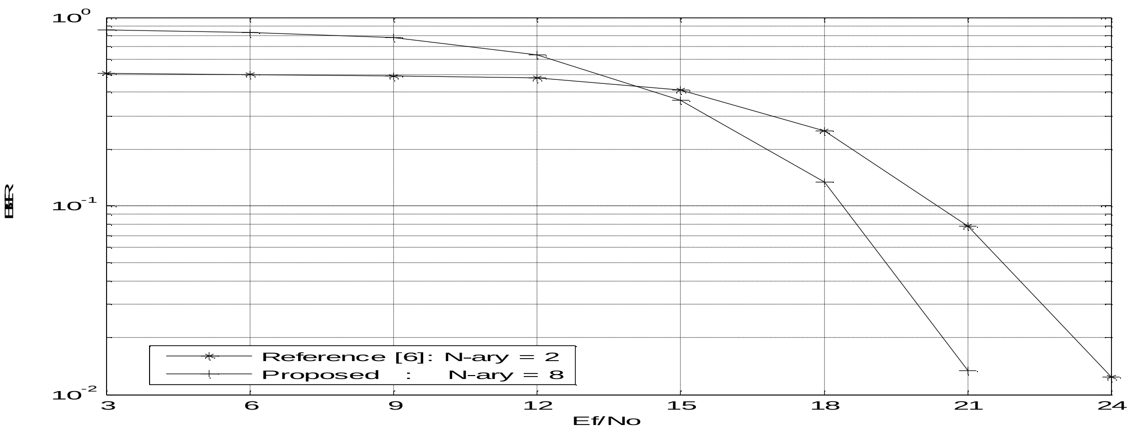

Figure (6) The BER for $N_s = 4$

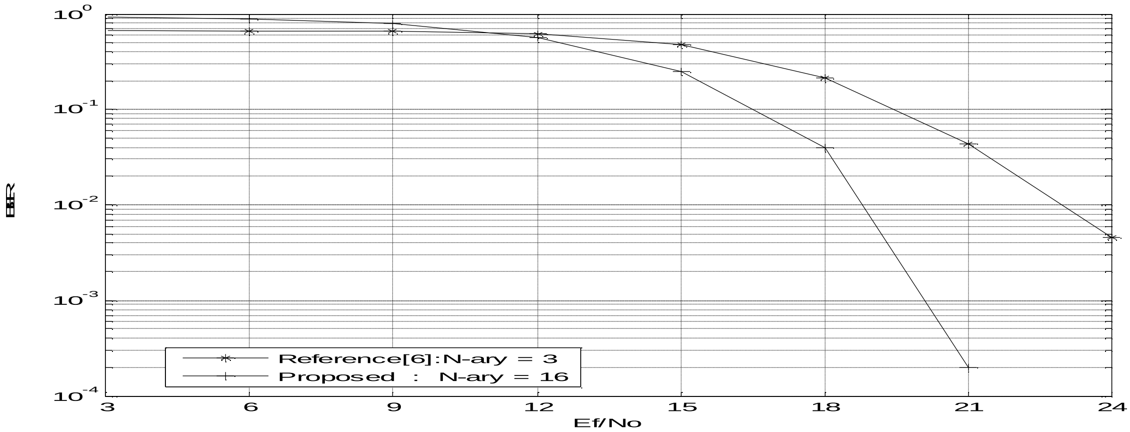

Figure (7) The BER for $N_s = 8$

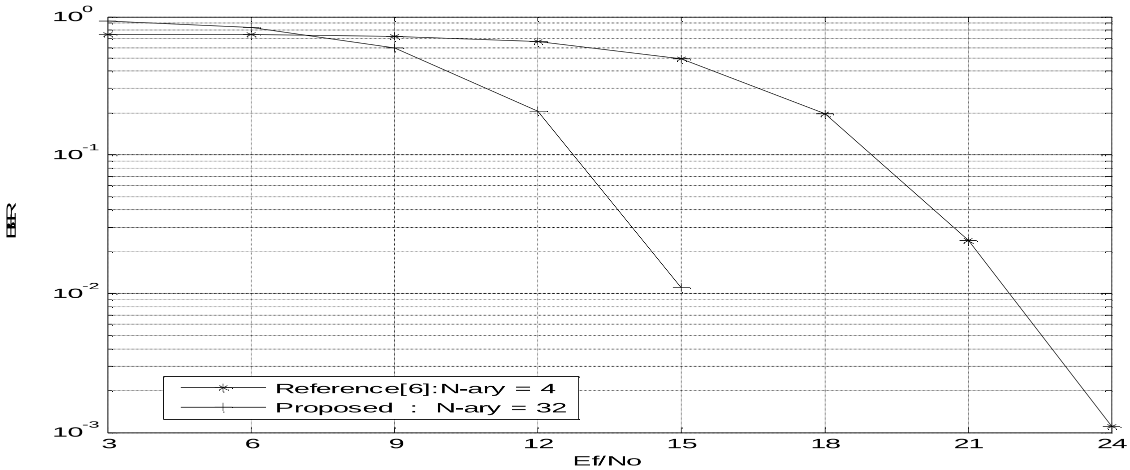

Figure (8) The BER for $N_s = 16$