Zero-Forcing Relay Power Allocation for TDBC-Based Bidirectional Relay Networks

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***Abstract*—Although the amplify-and-forward (AF) relaying is an effective and simple technique for cooperative communication networks, it introduces a noise enhancement problem. This problem occurs when the effects of interference and the multipath fades are amplified during the transmission from the source to the relay. AF is usually used with the multiple access broadcast (MABC) protocol which is a two phases transmission (2P) analog network coding (ANC) protocol for the half-duplex (HD) communication mode. However, MABC is not designed to utilize the direct link (DL) signal no matter how strong it is. To utilize the DL signal, a three transmission phases protocol known as time-division broadcast protocol (TDBC) was proposed at which both end nodes transmit their message at consecutive time slots and the relay nodes broadcasts a combined signal at the 3^{rd} time slot. To deal with the noise enhancement problem and improve the system performance, this paper proposes a zero-forcing based relay power allocation (ZF-RPA) scheme to be used with TDBC protocol, where the noise enhancement is mitigated by introducing adaptive ZF gains at the relay node that inverses the channels effects between sources and relay when the signal is constructed to be transmitted at the third phase of the TDBC. Analytical results of the ZF-RPA scheme is compared to the traditional variable-gain (VG-RPA) scheme under the same nodes power allocation. Simulation results show that the ZF-RPA is superior for all channel qualities in terms of the outage probability compared to the traditional VG-RPA. The total system sum rate comparison reveals that the ZF-RPA scheme could outperform the VG-RPA scheme as long as the channel qualities of the relay-transceiver links are less than certain threshold. This paper also clarifies that it is effective to select either ZF or VG-RPA according to the channel qualities and it can be implemented with VHDL by introducing an adaptive control unit (ACU).**

***Keywords*—TDBC, Bidirectional, Amplify-and-forward, Relay Power Allocation, Analog Network Coding, Zero-Forcing.**

I. INTRODUCTION

Relay-based cooperative communication (CC) networks have attracted great attention recently as one of the key technologies for the current and the next generations of wireless communications. The principle idea behind such research interest is to assist the communication process between transceivers nodes by introducing one or more intermediate nodes known as relay nodes. Many benefits are expected such as increasing the reliability of the communication process, extending the network coverage, reducing the transmit power of the transceivers nodes, and saving energy consumption which leads to great benefits such as environmental protection and cost reduction [1]. By using CC trend, multiple relay nodes equipped with single antenna can cooperate to exploit the spatial diversity offered by multiple-input multiple output (MIMO) by creating a virtual MIMO system or a virtual antenna array [2]. The Long Term Evolution Release 10, LTE-Advanced, [3] adapted the use of relaying as a key feature in the LTE system.

Many relaying protocols have been investigated such as decode-and-forward (DF), amplify-and-forward (AF), compress-and-forward (CF), and estimate-and-forward (EF) [2, 4]. However, most of the research attention is mainly focused on the AF and DF protocols respectively and to the best of our knowledge AF is the first protocol that has been demonstrated in practical system as it is built on the Universal Software Radio Peripheral ”USRP” [5].

Most of the practical relay based networks consider half-duplex (HD) operation which leads to a spectral loss since they require four time slots to relay messages between two transceivers. Ahlswade in his seminal paper [6] first proposed two-way relaying (TWR) with the help of network coding to overcome this spectral loss such as Physical Layer Network Coding (PLNC) [7] or Analog Network Coding (ANC) [7–9]. This scheme allows the relay node to broadcast messages from different sources by combining them. It also improves the spectral efficiency of two-way transmissions by reducing the required time slots from four to only two time slots [8] or three time slots [9] according to the used protocol.

TWR usually uses the multiple access broadcast (MABC) protocol [10] which needs two phases (2P) to complete the message exchange. At the 1^{st} phase, the two transceivers transmit their signals to the relay nodes simultaneously. At the 2^{nd} phase, the relay broadcasts the combined signal back to both nodes which then use self-interference cancelation technique to cancel the effect of its own signal and recover the required message. In the HD operation, both end nodes can not carry out the transmission and reception at the same time. As a result of this constraint, the MABC protocol could not utilize the direct link (DL) to improve the system performance.

On the other hand, the time-division broadcast (TDBC) protocol [10, 11] is a TWR protocol at which the messages exchange is performed in three transmission phases (3P). The two end nodes transmit consecutively while the relay

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nodes broadcasts a combined signal to both two nodes at the 3^{rd} phase. The TDBC technique offers a reduced spectral efficiency compared to the MABC technique. However, such a comparison ignores other factors such as the increased level of interference at the relay nodes in MABC. TDBC technique also offers a higher degree of freedom by allowing end nodes to obtain usable extra overheard information about the other user message during the phase in which the node is not transmitting to the relay unlike MABC protocol. TDBC can offer the possibility to achieve higher interference cancelation and quality of services (QoS) than those in MABC by utilizing the DL signal received by each end node from the other one.

Relay power allocation (RPA) is the process of combining the received signals at the 1^{st} and 2^{nd} phases of the TDBC protocol. The traditional variable-gain relay power allocation (VG-RPA) is a conventional way in TDBC, where both received signals are added together and then multiplied by a normalization factor [10]. In [12], two predefined weight factors (α_a, α_b), known as power allocation numbers, are used to produce a weighted combined signal for broadcasting at the 3^{rd} time slots to achieve either a minimum sum bit-error-rate (BER) or maximum sum rate. According to [12], it is required to feedback the two relay power allocation numbers to both transceiver nodes which represents an overhead to the system. On the other hand, zero forcing (ZF) gains is introduced in [13] for one-way relaying scheme and its extension is given for two-way MABC relaying in [14].

This paper proposed an intuitive zero-forcing relay power allocation (ZF-RPA) scheme for (3P) TDBC protocol based on the concept of using adaptive ZF gains, where the two signals are added after multiplying each one by the inverse of the channel characteristics between the node and the relay in similar way to the ZF equalizer to mitigate the channel effects. In the proposed ZF-RPA scheme, there is no need to feedback the relay power allocations numbers to both transceiver nodes. The concept of ZF-RPA is introduced to the the (3P) TDBC protocol that enables the transceivers to utilize the DL signal, while the MABC protocol is considered in [14]. The traditional VG-RPA scheme is analyzed and compared with the proposed ZF-RPA scheme using the same power allocation for all nodes to guarantee a fair comparison. Comparison is based on the total system throughput and the capacity outage probability. The proposed ZF-RPA can be used with more complex scenarios. In [15], the ZF-RPA is used for energy-efficient power allocation and single relay selection in TWR with multiple parallel relay nodes.

The rest of this paper is organized as follows: Section II describes the system models for the AF TWR network using TDBC protocol, followed by the analysis of the VG-RPA and ZF-RPA schemes in Sec. III. Section IV is for simulation parameters and results and finally Sec.V shows the conclusion.

II. System Model

In this paper, a two-way relay network is considered where two single antenna end nodes, S_1 and S_2, are exchanging messages through a single relay node (R) as shown in Fig.1.

Assume P_{s_1} , P_{s_2}, and P_r are the powers of the signals transmitted from S_1, S_2, and R respectively. It is assumed that

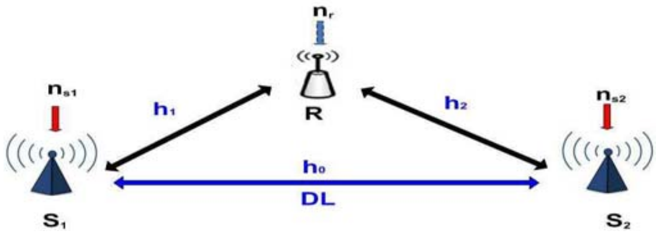


Fig. 1: Cooperative two-way relay network.

all the channels are reciprocal and modeled as Rayleigh flat-fading and time-invariant over three phases transmission where the channel coherent time is much larger than the transmission period. Assume the channels between the transceiver S_i and the relay node is modeled as $h_i \sim C\mathcal{N}(0, d_i^{-v})$ which denotes a circularly symmetric complex gaussian distribution with zero mean, d_i^{-v} variance, v is the path loss exponent, and i =1, 2. We also assume that h_0 is the DL channel coefficient.

We consider an AF protocol which employs ANC with TDBC at which the DL signal could be used to improve the performance. In TDBC protocol, the message exchange is completed in three time phases: the end node S_1 transmits a symbol x_{s_1} with transmit power P_{s_1} in the 1^{st} phase, the end user S_2 transmits a symbol x_{s_2} with transmit power P_{s_2} in the 2^{nd} phase, and the relay R broadcasts a combination of both signals received at the 1^{st} and 2^{nd} phases with transmit power, P_r, in the 3^{rd} phase. The received signals at the relay node in the 1^{st} and 2^{nd} phases are given respectively by:

$$y_{rs_1} = h_1\sqrt{P_{s_1}}\,x_{s_1} + n_r,\ y_{rs_2} = h_2\sqrt{P_{s_2}}\,x_{s_2} + n_r \qquad (1)$$

where n_r is the additive white Gaussian noise (AWGN) at the relay node at both phases with zero-mean and σ^2 variance as shown in Fig.1. At the 3^{rd} phase of the TDBC protocol, the relay broadcast a combined signal back to both transceivers which is generated by linearly combining the two received signals in (1) using a RPA techniques. The details of the RPA techniques are explained in the next section.

III. Relay Power Allocation Techniques for TDBC Protocol

The relay power allocation is the process at which the two received signals at the 1^{st} and 2^{nd} phases are combined to produce the signal to be broadcasted back to both transceivers. In the next two subsections, we will describe the mathematical models of the system using the traditional VG-RPA and the proposed ZF-RPA for TDBC protocol.

A. Variable-Gain Relay Power Allocation

In traditional VG-RPA [9, 16], the two received signals, y_{rs_1} and y_{rs_2} , are added and multiplied by a certain gain G_{vg}, which normalizes the relay transmitted power to the constant value P_r. The relay combined signal is given by:

$$y_{vg} = y_{rs_1} + y_{rs_2} = h_1\sqrt{P_{s_1}}x_{s_1} + h_2\sqrt{P_{s_2}}x_{s_2} + 2\,n_r \qquad (2)$$

The relay combined signal is then multiplied by the normalization factor in (3) and broadcasted back to the two transceivers.

The two received signals at S_1 and S_2 are given respectively by (4) and (5).

$$G_{vg} = \sqrt{\frac{P_r}{(P_{s_1}\,|h_1|^2 + P_{s_2}\,|h_2|^2 + 2\,\sigma^2)}} \tag{3}$$

$$Y_{s_1} \;=\; h_1\, y_{rx} \;+\; n_{s_1} \;=\; h_1\, G_{vg}\, y_{vg} \;+\; n_{s_1} \tag{4}$$

$$Y_{s_2} \;=\; h_2\, y_{rx} \;+\; n_{s_2} \;=\; h_2\, G_{vg}\, y_{vg} \;+\; n_{s_2} \tag{5}$$

where y_{rx} is the relay broadcasted signal, and n_{s_i} is the AWGN noise at two transceivers as shown in Fig.1. Assume without losing generality that n_{s_i} is a zero-mean and variance is the same as the relay noise n_r for simplicity.

Due to the TDBC protocol, the received DL signals at both transceivers S_1 and S_2 at the 2^{nd} and 1^{st} phases are respectively given by:

$$Y_{DL_1} = h_o\sqrt{P_{s_2}}x_{s_2} + n_{s_1},\; Y_{DL_2} = h_o\sqrt{P_{s_1}}x_{s_1} + n_{s_2} \tag{6}$$

where n_{S_1} and n_{S_2} are AWGN at S_1 and S_2. Using a self-interference cancelation technique, each transceiver eliminates its own signal from (4) and (5). Assume that the maximal ratio combining (MRC) is used to combine the DL signal and relay signals. Thus, the total signal-to-noise power ratios (SNRs) at S_1, SNR_{21}, and at S_2, SNR_{12}, are given respectively as:

$$SNR_{21} = \frac{P_{s_2}|h_o|^2}{\sigma^2} + \frac{P_{s_2}\,|h_1|^2\,G_{vg}^2\,|h_2|^2}{\sigma^2\,(1 +\, 2\,|h_1|^2\,G_{vg}^2)} \tag{7}$$

$$SNR_{12} = \frac{P_{s_1}|h_o|^2}{\sigma^2} + \frac{P_{s_1}\,|h_2|^2\,G_{vg}^2\,|h_1|^2}{\sigma^2\,(1 +\, 2\,|h_2|^2\,G_{vg}^2)} \tag{8}$$

where the 1^{st} and 2^{nd} terms in the right sides show the SNR of the received signal component at the destination through to the DL and relay broadcast, respectively. The data rates per unit bandwidth (in bps/Hz) from S_2 to S_1 and from S_1 to S_2 are respectively given by Shannon formula as:

$$R_{21} = \frac{1}{3}\log_2(1+SNR_{21}),\;\; R_{12} = \frac{1}{3}\log_2(1+SNR_{12}) \tag{9}$$

where the pre-log factor $\frac{1}{3}$ is a direct result of using three time slots for information exchange. When the DL is not available, i.e. $P_{s_i}|h_o|^2 \ll \sigma^2$, the DL terms in (7) and (8) are removed.

B. Proposed Zero-Forcing Relay Power Allocation

The concept of using ZF gains for AF relaying was introduced in [13] to investigate an intutive adaptive amplification factor to counteract the effects of the multipath-fading channel in one-way AF protocol. The work in [13] is extended for two-way MABC protocol in [14] which improves the system sum rate of the two-way relay network with ANC. In this paper, a ZF relay power allocation scheme for TDBC protocol is proposed based on the ZF gain concepts by using two parameters to linearly combine the two received signals at the first and the second phases of TDBC protocol.

Fig. 2 shows the proposed ZF-RPA module in the relay node where its operation is divided into 7 steps. The relay node receives the signal transmitted from S_1 at the 1^{st} phase then multiplies it by the first ZF gain (α_1) at step 2. At step 3 which is done at the 2^{nd} phase of the transmission process, the relay node receives the transmitted signal from S_2 and then multiplies it by the second ZF gain (α_2) at step 4. At steps 5 and 6, the relay adds the two signals from steps 2 and 4, and then multiplies it by a normalization factor, G_{zf}, to fix the relay average transmit power at P_r which is broadcasted to both end nodes at step 7 during the 3^{rd} phase of the transmission process.

$$G_{zf} = \sqrt{\frac{P_r}{(P_{s_1} + P_{s_2} + \sigma^2\,(\frac{1}{|h_1|^2} + \frac{1}{|h_2|^2})}} \tag{10}$$

In the ZF-RPA, instead of the combined signal in (2), the two received signals are combined as follow:

$$\begin{aligned} y_{zf} &= \alpha_1\, y_{rs_1} + \alpha_2\, y_{rs_2} \\ &= \sqrt{P_{s_1}}\, x_{s_1} + \sqrt{P_{s_2}} x_{s_2} + n_r(\frac{1}{h_1} + \frac{1}{h_2}) \end{aligned} \tag{11}$$

where $\alpha_1 = \frac{1}{h_1}$ and $\alpha_2 = \frac{1}{h_2}$ are the ZF adaptive gains used for the linear combining process at the relay based on the channels coefficients to mitigate the effect of the interference and the multipath fading in the two-way TDBC relaying. The signal $G_{zf}\, y_{zf}$ is then broadcasted back to both transceiver nodes as shown in Fig. 2.

Using the same procedures as in previous sub-section, the SNRs ratio at S_1 and S_2 due the direct link and the relay broadcasted signal are given respectively as:

$$SNR_{21} = \frac{P_{s_2}\,|h_o|^2}{\sigma^2} + \frac{P_{s_2}\,|h_1|^2 G_{zf}^2}{\sigma^2(1 + |h_1|^2\,G_{zf}^2)} \tag{12}$$

$$SNR_{12} = \frac{P_{s_1}\,|h_o|^2}{\sigma^2} + \frac{P_{s_1}\,|h_2|^2\,G_{zf}^2}{\sigma^2(1 +\; |h_2|^2\,G_{zf}^2)} \tag{13}$$

IV. SIMULATION RESULTS AND ANALYSIS

In this work, Monte-carlo simulations are provided to highlight the performance of the proposed ZF-RPA technique in comparison with the traditional VG-RPA for TDBC protocol. The channels are modeled as Clarke's flat fading model for a non-zero Doppler spread and are time-invariant over three phases transmission, where 6 plane waves are transmitted in random directions. Each plane wave have constant amplitude and take random initial phase distributed from 0 to 2π. Doppler frequency of each plane wave is distributed from $+f_D$ to $-f_D$, where f_D denotes the maximum Doppler frequency. The normalized doppler frequency $f_D\,T_s$ is assumed to be 10^{-4} in

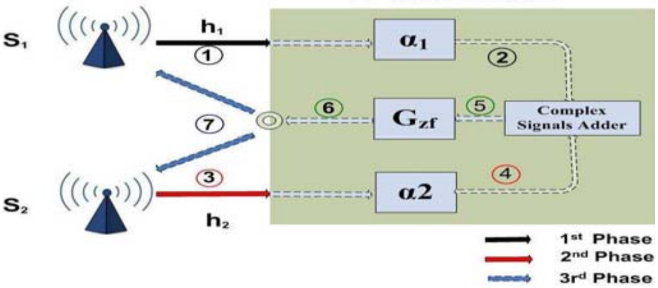
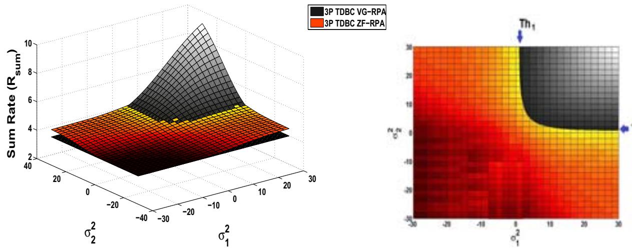


Fig. 2: Block Diagram of ZF-RPA Module with TDBC protocol.



(a) Side view. (b) Top view.

Fig. 3: Sum rate versus channel qualities in ZF-RPA and VG-RPA , where σ_1^2, and σ_2^2 denote the RT links qualities.

TABLE I: Qualities threshold values of the RT links in dB

σ_o^2	**-25**	**-20**	**-15**	**-10**	**-5**	**0**	**5**	**10**	**15**	**20**
Th_1	2	2	**1.6**	1.6	1.3	1	1	0.7	0.6	0.4
Th_2	2	**2**	1.6	1.6	1.3	1	1	0.7	0.6	0.4

the simulation, where T_s denotes symbol duration of 10^{-6} in the simulation. The resulting complex channels vectors (h_o, h_1, and h_2) are gaussian random variables with zero-mean and finite variances of (σ_o^2, σ_1^2, and σ_2^2) respectively where $\sigma_i^2 = E(|h_i|^2)$, and $i \in \{o, 1, 2\}$ which represent the channels qualities of the DL, $S_1 - R$, and $S_2 - R$ links respectively [11, 17]. The noise variances at end nodes and the relay are assumed to be the same and the path loss exponent is 2. In this paper, the system sum rate and the capacity outage probability are used as comparison metrics under the same power allocation of all nodes. The system sum rate represent the total system throughput, R_{sum}, in bps/Hz which is the summation of R_{12} and R_{21}.

Suppose that the TWR system supports sum rate R_{th} bps/Hz. The system is called in outage when sum rate is less than this threshold value (R_{th}). The outage probability is given by:

$$P_{out} = Pr(R_{sum} < R_{th}) \tag{14}$$

In Fig.3, the total system sum rate, R_{Sum}, is compared for the two RPA techniques for different qualities of the two RT links (σ_1^2, σ_2^2) at a constant value of the DL channel quality ($\sigma_o^2 = 0\,dB$). Figs.3.(a) and (b) show 3D figures (side and top views) of sum-rate as functions of channel qualities σ_1^2 and σ_2^2, respectively. It is clarified that there is a trade-off between the ZF-RPA and VG-RPA schemes according to the channel qualities of the RT links. For high channel qualities of the RT links, the VG-RPA scheme is the throughput-optimal scheme. On the other hand, if the channel quality of one or both of the RT links decreases below certain threshold values (Th_1, Th_2), the ZF-RPA scheme is the throughput-optimal scheme.

Table I shows the threshold values of Th_1 and Th_2 for different values of σ_o^2, where Th_1 and Th_2 change according to σ_o^2. This result indicates that decreasing σ_o^2 means increasing the area where the ZF-RPA can outperform the VG-RPA and vice versa.

Fig.4 shows the capacity outage probability for both VG-RPA and ZF-RPA schemes for different values of DL channel

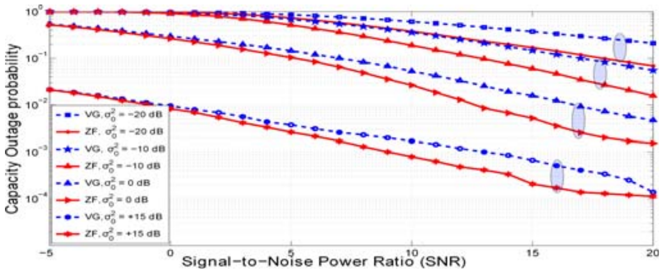


Fig. 4: Capacity outage probability for VG-PRA and the proposed ZF-PRA in case of $R_{th} = 1bps/Hz$.

qualities at constant value of the relay-transceiver links ($\sigma_1^2 = \sigma_2^2 = -20\,dB$) and $R_{th} = 1\,bps/Hz$. It is shown that as the DL quality improves, the outage probability of both schemes improves. Fig.4 also shows that the ZF-RPA scheme has a better outage probability than the VG-RPA for any values of σ_0^2 due to the ZF gains that invert the channels effects.

V. VHDL Implementation for adaptive replay power allocation using adaptive control unit

In the recent years, FPGA are being popularly used for signal processing and wireless application due to its high speed, lower power dissipation compared to digital signal processors (DSPs), and the possibility of reconfiguration. To the best of our knowledge, the TDBC with three phases transmission was not implemented on FPGA before. The results in section IV implies that the proposed scheme can be straightforwardly extended to an adaptive RPA that selects an throughput-optimal solution (i.e., either ZF-RPA or VG-RPA) according to channel qualities. This section clarifies the early results for a VHDL implementation of the proposed adaptive scheme is presented by introducing the design of an adaptive control unit (ACU) that performs the adaptive selection process. The ACU compares the real-time values of the three channels qualities stored in a read-only-memory (ROM) as shown in Table I which is inside the ACU .

The ACU is used to enable either the VG or the ZF-RPA units for creating an adaptive scheme. The ACU internal structure as shown in Fig. 5 is divided into two main units, the 1^{st} is a read-only-memory (ROM) that is used to store the two threshold values (Th_1 and Th_2) of the relay-transceivers links qualities, and the 2^{nd} is a fixed-point comparator module

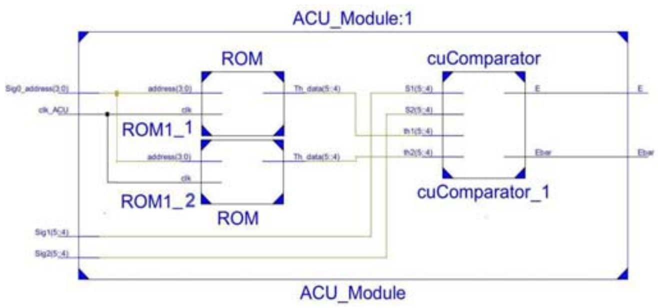


Fig. 5: RTL schematic of the ACU.

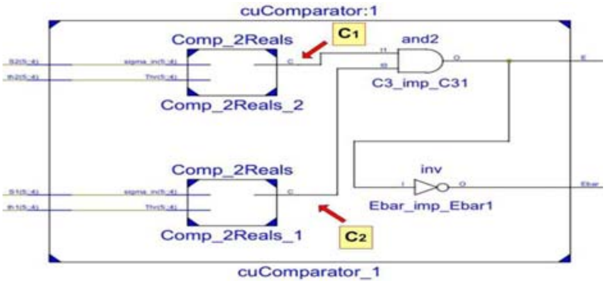


Fig. 6: RTL Schematic of the Fixed-Point Comparator.

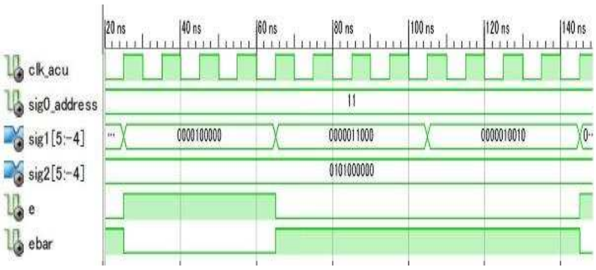


Fig. 7: ISim testbench waveforms.

(cuComparator) shown in Fig. 6 which is responsible of comparing the real-time values of the relay-transceivers links qualities with the stored thresholds corresponding to the real-time value of the DL channel quality. The ACU restores the two threshold values corresponding to the real-time value of DL channel quality, then the fixed-point comparator compares two sets of fixed-point numbers (σ_1^2, Th_1 and σ_2^2, Th_2) which represent the real-time values of the relay-transceiver links and the stored threshold values. Fig. 6 shows the internal RTL schematic of the fixed-point comparator module where both C_1 and C_2 are logic 1 when $\sigma_1^2 \geq Th_1$ and $\sigma_2^2 \geq Th_2$ respectively. To enable the VG-RPA unit, both C_1 and C_2 must be logic 1. If either one of them is not logic 1, the ZF-RPA unit is enabled. The ACU behavior is tested using "Isim" tool embedded with ISE Design Suit 14.5 by Xilinx® where the target family is Spartan3E and the target device is (xc3s500e-4fg320).

Table II shows the synthesis report summary with device utilization and clock report while the test bench waveforms are shown in Fig. 7. Fig. 7 shows that either output (E) or output (Ebar) is enabled, i.e. logic 1, to enable either VG-RPA unit or ZF-RPA unit.

TABLE II: Synthesis Report Summary.

Target family		Target Device		
Spartan3E		xc3s500e-4fg320		
Device Utilization Summary				
	Used	Available	Utilization	
Number of LUT	24	9,312	1%	
Number of occupied Slices	12	4,656	1%	
Number of BUFGMUXs	1	24	4%	
Number of bonded IOBs	27	232	11%	
IOB Flip Flops	4			
Clock Report				
Clock Net	Routed	Fanout	Net Skew (ns)	Delay (ns)
clk_ACU_BUFGP	ROUTED	4	0.002000	0.172000

VI. Conclusion

In this paper, we investigated a ZF-RPA technique to mitigate the multipath and channels effects in TDBC protocol for TWR channel with two transceivers and single relay node. The proposed ZF-RPA scheme is compared to VG-RPA scheme for different channel qualities of the DL and the relay-transceivers links. Simulation results clarified that the ZF-RPA is superior for all channel qualities in terms of the outage probability compared to the traditional VG-RPA. The total system sum rate comparison reveals that the ZF-RPA scheme could outperforms the VG-RPA scheme according to the channel qualities of the relay-transceiver links. For high channel qualities of the relay-transceiver links, the VG-RPA scheme is the throughput-optimal scheme. If the channel quality of one or both of the relay-transceiver links decreases below the given thresholds values, the ZF-RPA is the throughput-optimal scheme. This paper also clarified that early results for hardware implementation of an adaptive RPA scheme is presented by introducing an adaptive control unit design using VHDL.

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