Md. Mirazur RAHMAN*[1], Md. Shafiul ALAM[2], Shahrul ISLAM[2], Md. Arif Abdulla SAMY[3], Nafee Al ISLAM[2]

Department of Electrical and Electronic Engineering, Primeasia University (1)
Department of Electrical and Electronic Engineering, Northern University Bangladesh (2)
Department of Electrical and Electronic Engineering, American Internatunal University Bangladesh (3)

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Cooperative MIMO OFDM system based on Amplify and Forward Relay: Evaluation of ZF-SIC and MMSE-SIC equalization

Abstract. *In the world of wireless communication, cooperative communication is a modern and unprecedented approach which enables wireless nodes to transfer the information in a cooperative manner and finally to reach the destination without least possible deterioration. Orthogonal frequency division multiplexing (OFDM) can provide high data rate and better performance and a combination of OFDM and cooperative communication may push a wireless network forward to its next generation with enhanced reliability and efficiency. In this work, we develop a mathematical model for cooperative multiple input multiple output (MIMO) OFDM system. Results are achieved in the study to evaluate and compare bit error rate (BER) for different detection schemes. Based on the results it can be mentioned that the performance of cooperative MIMO-OFDM with space time block code (STBC) under amplify and forward (AF) relay for the MMSE-SIC detection scheme was found very satisfactory with improved signal to noise ratio (SNR).*

Streszczenie. *W artykule przedstawiono model matematyczny kooperacyjnej komunikacji bezprzewodowej wiele wejść, wiele wyjść (MIMO) z multipleksingiem i ortogonalnym podziałem częstotliwości (OFDM). Określono współczynnik BER (bit error rate) dla różnych metod detekcji. Najlepsze parametry otrzymano dla systemu STBC (space time block code).* ***Kooperacyjny system komunikacji bezprzewodowej MIMO OFDM bazujący na układzie Forward Relay: ocena ekwalizacji ZF-SIC i MMSE-SIC***

Keyword: Cooperative communication; Orthogonal frequency division multiplexing; Amplify and forward; Minimum mean square error - successive interference cancellation and Zero forcing - successive interference cancellation.
Słowa kluczowe: komunikacja kooperacyjna, komunikacja bezprzewodowa, system MIMO

Introduction

When it comes to connectivity, people cannot think of wire now a days. Despite untethered connection to the wireless network, multipath fading is a major issue for data transmission. MIMO system is a combination of multiple antennas (both transmitter and receiver), where each user will experience enhanced bit-rate in communication [1]. Cooperative Communication is a useful technique to mitigate channel fading by exploiting diversity gain through inter relay cooperation [2]. Most importantly the technology requires low power in the transmission end and provides improved spatial diversity gain [3].

Various relay strategies for Cooperative diversity have been reported in numerous studies namely amplify and forward (AF), incremental relaying (IR), decode and forward (DF), coded cooperation (CC), selection relaying (SR) and compress and forward (CF) [4, 7]. The simplest one among them is the fixed relaying scheme where the relay node continuously forwards received information [8], whereas, in selective relaying, the relay node keeps dormant unless the channel surpasses a definite margin [9]. Again, in incremental relaying relay node only responds to a request made from receiving end [10]. The performance of two popular relaying protocols AF and DF has been a matter of debate in the recent past. In one numerical study [11] multi-hop relaying in AF gives better outage probability and BER (bit error rate) than DF protocol. Another analysis [12] for encoded BPSK systems shows that multiple relaying in DF gives about half of the diversity of that in AF relaying. The simulation study shows that cooperative OFDM system assisted by AF relaying protocol provides better BER than other schemes (FRC, SNRC and ESNRC) under BPSK digital modulation [13]. S. Vorkoeper *et al.* examined a distributed Interleave-Division-Multiplexing Space-Time Coding (dIDM-STC) and cooperative Orthogonal Frequency Division Multiplexing (cOFDM) in terms of performance under the decode-and-forward relay network [14]. [15] and [16] proposed a distributed space time coding scheme for a cooperative system. In these works, it was shown that the destination receives different columns of space time coding matrix from several nodes simultaneously. D. Sreedhar *et al.* worked on cooperative space-frequency block-coded OFDM (SFBC-OFDM) networks with amplify-and-forward (AF) and decode-and-forward (DF) protocols at the relays which is prone to inter-symbol interference (ISI) and inter-carrier interference (ICI). However, a practical algorithm is proposed by them that can alleviate both ISI and ICI [17]. N. S. Kumar *et al.* has compared between successive interference cancellation (SIC) based detectors and linear detectors. It was found that in any receiver, adding SIC with MMSE or ZF showed better results concerning BER compared to a receiver without adding SIC [13].

An analytical model for cooperative MIMO-OFDM has been established in this paper with including the radical concept of space time block coding (STBC) under a single amplify-forward (AF) relay. At the end of the study, performance of the system for zero forcing – successive interference cancellation (ZF-SIC) and minimum mean square error – successive interference cancellation (MMSE-SIC) has been investigated based on the retrieved audio and image signals upon their transmissions. Bit error rate (BER) is the basis of performance analysis for both audio and image signals [18].

System Model

Fig. 1 is a demonstration of a cooperative MIMO-OFDM wireless two users' communication system provided with a single relay. Both the users can exchange their messages among them while swapping the roles of a relay and a source between them at different times. In the first digital data part, the audio or image data are channel coded where a simple ½ rated convolution encoder is used. This is performed to reduce error in data, once the system is simulated. In the following step, the data are interleaved before being digitally modulated where BPSK is performed. STBC rearranges the digitally modulated data and sends to the antennas. While original and negative second conjugate data are transmitted to one antenna, another antenna receives conjugate original and second data [19].

OFDM is performed at each antenna sections where data are sent through serial to parallel conversion section and followed by inverse fast Fourier transform (IFFT) section. IFFT converts the data into time domain signal before a cyclic prefix is added. Finally, before transmitting to the antenna, processed data are again converted from parallel to serial. Both antennas send the symbols concurrently to receiving section.

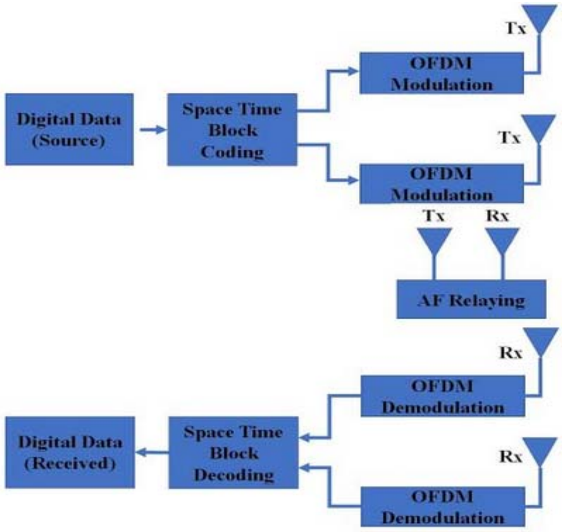

Fig. 1: Block diagram of a Cooperative MIMO-OFDM system incorporated with an STBC and a single AF relay

Receiving end receives data in two phases: phase-I and phase-II. Phase-I refers to the direct link between the source and destination and the relay, whereas, phase-II is the indirect link between the relay and the target. Cooperative relay amplifies the signal and forwards it to the destination. The signal then travels through OFDM demodulator and a digital demodulator. The message subsequently deinterleaved and channel decoded before it is received in the original form of audio or image formats.

Theoretical Analysis of Single Relay

After extracting from image/audio signals the binary data stream is fed as input data to the convolution encoder. We assume the length of this binary data stream, d. is $L_{d,}$ where d_i is the elements: $d_i \in \{0, 1\}$ where *i* =0,1,2,3…. L_d which is made doubled (2 $L_{d,}$) after adding a redundant binary bit after channel encoding. This data is digitally modulated using BPSK scheme which was rearranged using STBC [20, 21]. Here, data are arranged for the first and second antennas as, $S_k^{Tx1} = [S_0, (-S_1)^*, S_2, (-S_3)^* \dots\dots\dots (-S_{K-1})^*]$ and $S_k^{Tx1} = [S_1, (S_0)^*, S_3, (S_2)^* \dots\dots\dots S_{K-1}]$ respectively. 1024 symbols are processed through OFDM after serial to parallel conversion was performed where K=1024. The inverse fast Fourier transform (IFFT) is used in the OFDM block to convert the signal into time domain which is defined as,

$$S^{Tx}(n) = \sum_{k=0}^{N_C-1} S_k^{Tx} e^{j(\frac{2\pi}{N_C})kn} \quad (1)$$

where, the number of subcarriers is denoted by $N_{C,}$ and Tx stands as the transmission identifier. From 0 to N_C-1 are the integers indicated by n and k and j is the complex number. The followings are the equations after time domain discrete signal $S(n)$ is added with the cyclic prefix of length N_{CP} at the end,

$$S^{Tx}(m) = \sum_{k=0}^{N_C+N_{Cp}-1} S_k^{Tx} e^{j(\frac{2\pi}{N_C+N_{CP}})kn} = \sum_{k=0}^{N-1} S_k^{Tx} e^{j(\frac{2\pi}{N})kn} \quad (2)$$

where $m = n + N_{CP}$.and $N = N_C + N_{CP}$.

After passing through a discrete-time baseband channel, for Phase I, the source-destination and the source-relay signals are received as,

$$r_{s,d}(m) = \sqrt{P_s}\{S^{Tx}(m) \cdot h_{s,d}(m) + w_d^1(m)\} \quad (3)$$

$$r_{s,r}(m) = \sqrt{P_s}\{S^{Tx}(m) \cdot h_{s,r}(m) + w_r(m)\} \quad (4)$$

where $h(m)$ is the response after passing through a discrete-time baseband channel and $w(m)$ is the added additive white Gaussian noise (AWGN). Here, $r_{s,d}(m)$ refers to the source-destination signals whereas $r_{s,r}(m)$ stands for the source-relay received signals in Phase I. P_s is denoted as the transmission power of the source. Under amplify-forward (AF) scheme, the source sends signal to relay which is amplified and forwarded to the destination regardless the quality of the link between source and relay.

A linear precoder matrix $(M_s \times M_r)K$ is employed by the relay in Phase II on the source to relay signal vector $r_{s,r}(m)$ which is defined by [22, 23, 24],

$$\kappa = \sqrt{\frac{1}{tr(H_{s,r}^H H_{s,r}(\sigma_r^2 I_{M_r} + \frac{P_S}{M_S} H_{s,r}^H H_{s,r}) H_{r,d} H_{r,d}^H}} H_{s,r}^H H_{r,d}^H \quad (5)$$

where, σ_r^2 variance of noise at the relay, M_s and M_r are no. of relay receiving antenna and transmitting antenna at source respectively. Also, $H_{s,r}$ and $H_{r,d}$ are the channel matrices for the source to relay, and relay to destination respectively. Hence, the transmitted signal from the relay can be expressed as

$$s_r(m) = \kappa \cdot r_{s,r}(m) \quad (6)$$

which is further received at the destination in the form of,

$$\begin{aligned} r_{r,d}(m) &= \left[\sqrt{P_r P_s} \mathrm{K} s^{Tx}(m) h_{s,r}(m)\right] h_{r,d}(m) \\ &\quad + \left[\sqrt{P_r} \mathrm{K} w_r(m)\right] h_{r,d}(m) + w_d^2(m) \\ &= \left[\sqrt{P_r P_s} \mathrm{K} s^{Tx}(m) h_{s,r}(m)\right] h_{r,d}(m) + \widetilde{w}_d^2 \end{aligned} \quad (7)$$

where, the power of the relayed signal is P_r, and $w_d^2(m)$, $w_r(m)$ are the AWGN at destination and relay respectively. Also $\widetilde{w}_d^2$ denotes the effective noise in Phase II. Summing up the received signals at the destination for both phases gives,

$$r_{d-combined}(m) = \left[\sqrt{P_r P_s} \mathrm{K} s^{Tx}(m) h_{s,r_i}(m)\right] h_{r_i,d}(m) + \widetilde{w}_d^2 + \sqrt{P_s}\{s^{Tx}(m) h_{s,d}(m)\} + w_d^2(m) \quad (8)$$

which can be expressed in matrix form as follows:

$$\begin{aligned} r_{d-combined}(m) &= \begin{bmatrix} r_{s,d}(m) \\ r_{r,d}(m) \end{bmatrix} \\ &= \sqrt{P_s} \begin{bmatrix} h_{s,d}(m) \\ \sqrt{P_r} h_{r,d}(m) \mathrm{K} h_{s,r}(m) \end{bmatrix} s^{Tx}(m) \\ &\quad + \begin{bmatrix} w_d^1(m) \\ \widetilde{w}_d^2(m) \end{bmatrix} \\ &= \sqrt{P_s}\{s^{Tx}(m) H(m)\} + w(m) \end{aligned} \quad (9)$$

where, $H(m) = \begin{bmatrix} h_{s,d}(m) \\ \sqrt{P_r} h_{r,d}(m) \mathrm{K} h_{s,r}(m) \end{bmatrix}$ is the effective channel between source and destination, and $w(m) = \begin{bmatrix} w_d^1(m) \\ \widetilde{w}_d^2(m) \end{bmatrix}$ is the effective noise.

Finally, the signal is detected as $r_d(n)$ after performing channel equalization and removal of cyclic prefixing. In the following step, fast Fourier transform (FFT) is performed with FFT size $N = N_C + N_{CP}$ on the detected signal and, we obtain the output,

$$Y_{FFT}(k) = \frac{1}{N} \sum_{n=0}^{N-1} r_d(n) e^{-j(\frac{2\pi}{N})kn} \quad (10)$$

ZF-SIC Detection

The following is the equation for the signal received $Y(k)$, where N_0 and H have been assumed as AWGN for the transmitted signal and channel matrix, respectively.

$$Y(k) = HS_l^{Tx} + N_0 \tag{11}$$

After factorizing the H by Q (unitary matrix) and R (upper triangular matrix) we find as follows [25, 26],

$$H = QR = Q\begin{bmatrix} r_{1,1} & r_{1,2} \\ 0 & r_{2,2} \end{bmatrix} \tag{12}$$

Additionally, the product of the received signal, $Y(k)$, and Q^H gives,

$$S = Q^H Y(k) = RS_l^{Tx} + Q^H N_0 \tag{13}$$

Here, $Q^H N_0$ refers to zero-mean complex Gaussian random vector [27], where, $Q^H N_0$ and N_0 are statistically of equivalent properties. Therefore, (13) can be rewritten as,

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} r_{1,1} & r_{1,2} \\ 0 & r_{2,2} \end{bmatrix}\begin{bmatrix} S_{l_1} \\ S_{l_2} \end{bmatrix} + \begin{bmatrix} N_{0_1} \\ N_{0_2} \end{bmatrix} \tag{14}$$

After neglecting the noise term from the previous equations, the detected signals (S_{l_1} and S_{l_2}) as desired can be written as

$$\hat{S}_{l_1} = \frac{\{S_1 - r_{1,2}(S_2/r_{2,2})\}}{r_{1,1}}, \text{ and } \hat{S}_{l_2} = \frac{S_2}{r_{2,2}} \tag{15}$$

MMSE-SIC Detection

In this case, according to [25, 26], the received signal, channel matrix, and noise can be expressed as extended versions respectively as

$$H_{ex} = \left[H^T \sqrt{\frac{N_0}{E_s}} I\right]^T, Y_{ex}(k) = [Y(k)^T \quad 0^T], \text{ and}$$

$$N_{0ex} = \left[N_0^T - \sqrt{\frac{N_0}{E_s}} S_l^T\right]^T \tag{16}$$

where, $\frac{N_0}{E_s} = \frac{1}{SNR}$ and I is the identity matrix.

After undergoing QR factorization, H_{ex} (extended version) is expressed as

$$H_{ex} = Q_{ex}.R_{ex} \tag{17}$$

Q_{ex} and R_{ex} are the extended versions of Q and R respectively. After replacing every term in Equation (13) with extended versions, we find,

$$S_{ex} = Q_{ex}^H.Y_{ex}(k) = R_{ex}.S_l^{Tx} + {Q_{ex}}^H N_{0_{ex}} \tag{18}$$

After neglecting the noise term ${Q_{ex}}^H N_{0_{ex}}$ from the previous equations (18), the detected signals ($\hat{S}_{l_1}$ and $\hat{S}_{l_2}$) as desired can be written as

$$\widehat{S}_{l_1} = \frac{\{S_{ex_1} - r_{ex_{1,2}}(S_{ex_2}/r_{ex_{2,2}})\}}{r_{ex_{1,1}}}, \text{ and } \widehat{S}_{l_2} = \frac{s_{ex_2}}{r_{ex_{2,2}}} \tag{19}$$

Results and Discussion

In this part, the BER for both audio signal and color image have been investigated by analyzing the simulated results. Simulation was done in MATLAB. The channel coding was set to be 1/2 -rated convolution encoder, whereas, BPSK was used as the digital modulation scheme. The size of the FFT/IFFT was 1024 symbols, and CP has been set as 103 symbols.

Graphical illustrations presented in Fig. 2 demonstrate the system performance under various digital modulations and ZF-SIC and MMSE-SIC channel equalization schemes. The system shows satisfactory performance with BPSK digital modulation in MMSE-SIC signal detection technique.

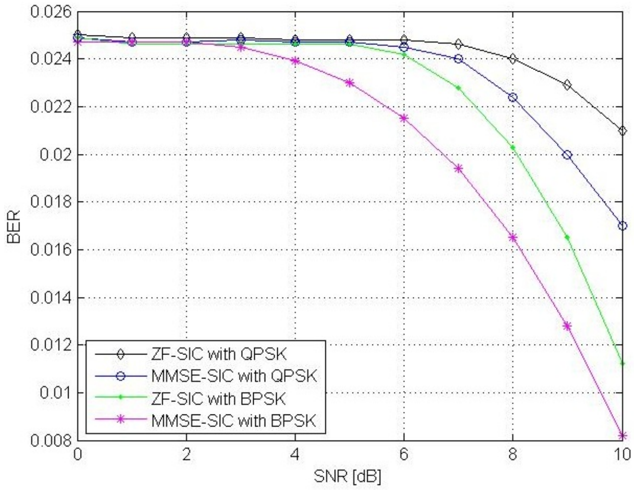

Fig. 2: Comparison in terms of BER between ZF-SIC and MMSE-SIC based detection schemes with BPSK and QPSK for a convolutionally encoded single relayed Cooperative MIMO OFDM system

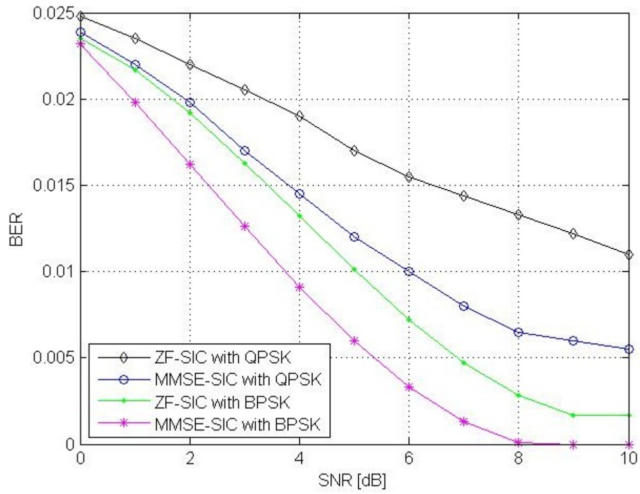

Fig. 3: Comparison in terms of BER between ZF-SIC and MMSE-SIC based detection schemes with BPSK and QPSK for a convolutionally encoded single relayed STBC based Cooperative MIMO OFDM system

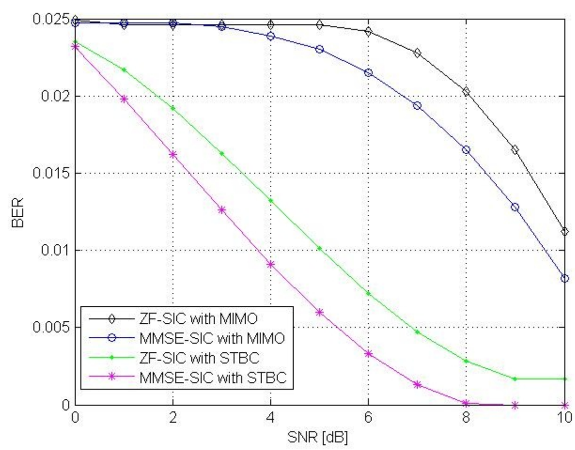

Fig. 4: System performance comparison under STBC, Spatial multiplexing, ZF-SIC and MMSE-SIC channel equalization schemes.

In Fig. 3, it is observed that a significant gap exists between BER performances of the simulated system in case of BPSK as compared to other digital modulations. The STBC based single relayed MIMO Cooperative OFDM wireless communication system shows most reliable and acceptable system performance in BPSK and MMSE-SIC schemes.

In Fig. 4, we have compared the performance of Cooperative MIMO-OFDM system under STBC and spatial multiplexing schemes. Both STBC and spatial multiplexing schemes have been examined for ZF-SIC and MMSE-SIC channel equalization schemes. At the SNR value of 6 dB, the observed value of BER for ZF-SIC detection scheme for the spatially multiplexed MIMO-OFDM system is 0.0242 whereas it is as less as 0.0072 for a STBC based system. This refers a clear improvement of SNR by 5.26 dB. In contrast, the BER values were found as 0.0215 and 0.0033 for MMSE-SIC scheme for the cases of spatial multiplexed and STBC based respectively, which indicates the improvement of 8.13 dB. The graph illustrates that the receiver equipped with MMSE-SIC is superior to that with ZF-SIC in terms performance. Additionally, it can also be noted that the system performs better when encoded with STBC compared to a spatially multiplexed MIMO-OFDM system.

The overall BER performance for the transmitted image for ZF-SIC (spatial multiplexing and STBC) and MMSE-SIC (spatial multiplexing and STBC) is shown in Table 1.

Table 1: Comparison between number of error and BER between ZF-SIC and MMSE-SIC detection for image transmission

Scheme	Number of Error	BER
ZF-SIC with MIMO (Spatial multiplexing)	37	1.6728×10^{-4}
MMSE-SIC with MIMO (Spatial multiplexing)	5	2.2606×10^{-5}
ZF-SIC with STBC	2	9.0422×10^{-6}
MMSE-SIC with STBC	0	0

The SNR value is assumed of 6 dB as typical for investigating the transmitted and received images and the observed result is found to be quite satisfactory upon retrieval in the case of MMSE-SIC scheme based on STBC as shown in Fig. 5. Satisfactory result is found for the transmitted audio signal also as seen in Fig. 6 at the SNR value of 5 dB.

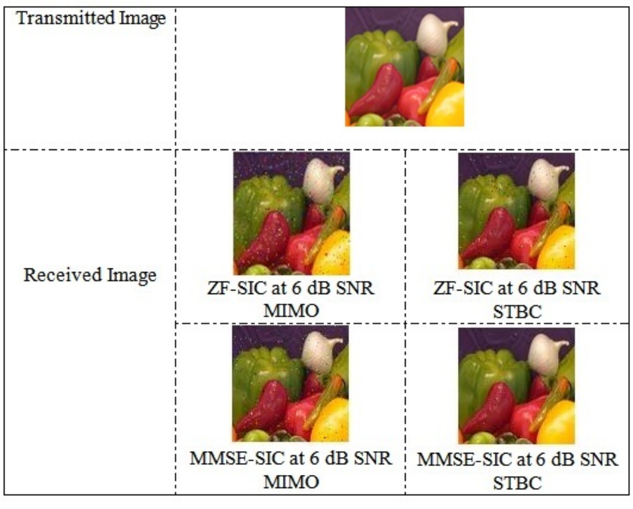

Fig. 5: ZF-SIC and MMSE-SIC: Transmitted vs. Received Images

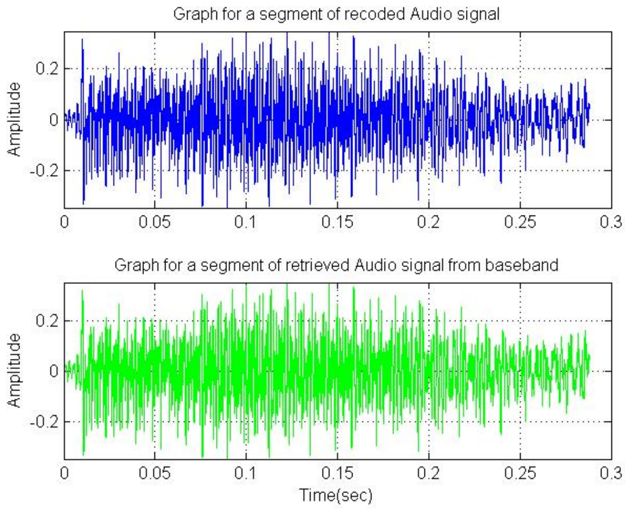

Fig. 6: The transmitted (above) vs. retrieved (below) audio signals after implementing MMSE-SIC based on STBC at the SNR value of 5 dB

Conclusion

In this paper, a cooperative MIMO-OFDM system incorporated with STBC based on amplifying and forward Relay has been derived theoretically. Performances for both ZF-SIC and MMSE-SIC schemes for signal detection have been compared and found that the later scheme provided better result during the implementation of BPSK as the digital modulation technique in the system. However, during retrieval, the audio and image data at the destination both methods have demonstrated similar performances. Hence, a lossless recovery of a transmitted image and audio signal is achievable by the proposed method of using a relay station while the power of the transmitted signals is at a lower level.

Authors: *Md Mirazur Rahman, Department of EEE, Primeasia University, Banani, Dhaka, E-mail: mrzmist@gmail.com. Md. Shafiul Alam, Department of EEE, Northern University Bangladesh, E-mail: gmshafiul@gmail.com. Shahrul Islam, Department of EEE, Northern University Bangladesh, E-mail: shahrulsohan@gmail.com. Md. Arif Abdulla Samy, Department of EEE, American International University Bangladesh, E-mail: arif.samy@aiub.edu. Nafee Al Islam, Department of EEE, Northern University Bangladesh, E-mail: seiumiut@gmail.com.*

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