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# Evaluation of different 4x4 Coded MIMO System

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**Abstract**

In this paper 4x4 coded MIMO-OFDM systems with two different code rate OSTBC (1/2 and 3/4) and different types of QAM as a baseband modulation have been studied, and compared with a 4x2 coded MIMO system. The system has been evaluated over a multipath flat-fading and frequency-selective fading, assuming channels with non line of sight (NLOS). Three different Doppler frequencies (5, 50 and 100 Hz) have been used to study the systems in different channel situations. The results shows that increasing the number of antennas at the receiver side reduce the effect of the Doppler shift, because increasing the number of antennas means increasing the number of channels, and transmitting the symbols through these channels in different times. OSTBC with two different code rate (R=1/2 and 3/4) have been used with 4 transmitting antennas, and OSTBC with R= 1/2 gives a better results than the one with R= 3/4, because when R=3/4 three symbols are send during 4 time slots, but when R=1/2 just two symbols are send during four time slots. That is beside sending multi-copies of each symbol in different time and different space.

## Introduction

The most important need for a MIMO-OFDM system is that with the development of wireless data and multimedia applications, the demand on transmission rate and QoS assurance of wireless communication system is correspondingly rising which could not be served by MIMO or OFDM systems separately. MIMO-OFDM, technique can be used in wireless communication systems to achieve gigabit transmission *[1]*.

In *[2]*, a brief overview of WiMAX technology and MIMO-OFDM system have been described and it also discussed the simplest Space time block code (STBC) known as Alamouti Space Time Code. The research approach is a literary survey to have theoretical understanding of the MIMO-OFDM system and WiMAX. In *[3]*, both block-type pilot and comb-type arrangements in both SISO and MIMO OFDM based systems have been compared, and the estimators used to estimate the channel. In *[4]*, Space Time Frequency coded communication system using diversity schemes like MIMO and Multiple Input Single Output (MISO) simulated, and compared the performances of these schemes over a fading channel having inherent noise. In

*[5]*, the BER performance analyzed under Rayleigh fading channel conditions of MIMO-OFDM in presence of AWGN (Additive White Gaussian Noise), for different number of transmitters and users, and they performed different path gains system by simulating the MIMO-OFDM using MATLAB program, and their simulation results show that the increase in sub-carriers increases the effects of multipath fading.
Also, many works have depicted MIMO-OFDM with different number of antennas *[6-8]*.
In this work the channel model that has been used for proposed systems is with Rayleigh distribution by assuming the absence of Line of Sight (LOS) path.
Many physical factors influencing the characteristics of the fading experienced by the transmitter such as the multipath propagation, mobility of the reflecting objects and scatterers, and the relative motion between the transmitter and the receiver.

The objective of this work is to study and evaluate the MIMO-STC-OFDM with different code rate and antennas, in order to combat the effect of the fading in wireless channels.

## MIMO-STC-OFDM Models

### A. *4x2 MIMO-STC-OFDM simulated model*:

Two types of OSTBC matrix with different code rate have been used in the system with four transmitting antennas, as shown below:

**a) The OSTBC code matrix with R=1/2:**

An OSTBC with code rate (R) equal half has been used to transmit two symbols per block as shown in the following code matrix:

$$\mathbf{S} = \begin{bmatrix} s_1 & s_2 & 0 & 0 \\ -s_2^* & s_1^* & 0 & 0 \\ 0 & 0 & s_1 & s_2 \\ 0 & 0 & -s_2^* & s_1^* \end{bmatrix} \qquad (1)$$

The transmitted space-time code and the channels for this 4x2 system are shown in *Figure (1)*.

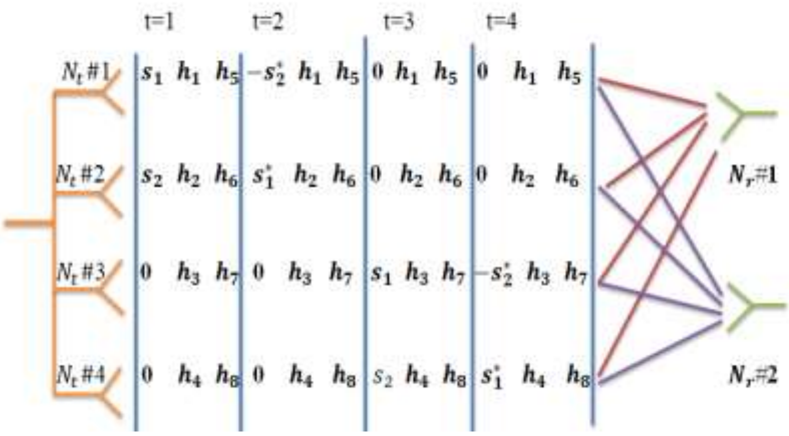



Figure (1): Transmission model for 4-$N_t$ and 2-$N_r$ antennas, with R=1/2.

- **Transmitter 1:**

The transmitting sequence of the first transmitting antenna is:
$x_1$ =[$s_1$ $-s_2^*$ 0 0] : these four blocks are transmitted along the training sequence called (Xteven1), which is used for channel estimation.
Xteven1 = [xt1 0 0 0 . . . xt1 0 0 0 0 0 0 0 xt11 . . . . 0 0 0 xt11].
$x_{11}$ = [Xteven1 $x_1$].
A Guard Bands is added as below:
$z_1$=[0 0 0 0 0 .......0], 28 zeros
$z_2$=[0 0 0 0 .... ..0], 27 zeros

$x_4$ = [$z_1 x_{11}$ $z_2$].

- **Transmitter 2:**

The block code transmitting by second antenna is: $x_2$ =[$s_2$ $s_1^*$ 0 0], these four blocks are transmitted along the training sequence called (Xtodd1).

Xtodd1 = [0 xt2 0 0 . . . 0 xt2 0 0 0 0 0 xt22 0 . . . 0 0 xt22 0].

$x_{22}$ = [Xtodd1 $x_2$].

In the same way as for transmitter 1 guard band is added for each transmitter and 256-IFFT is applied, CP is added, and passed through parallel to serial convertor.

- **Transmitter 3:**

The block code transmitting by the third antenna is:

$x_3$ =[0 0 $s_1$ $-s_2^*$], these four blocks are transmitted along the training sequence called (Xteven2).

Xteven2 = [0 0 xt3 0 . . . 0 0 xt3 0 0 0 xt33 0 0 . . . 0 xt33 0 0].

$x_{33}$ = [Xteven2 $x_3$].

Then same procedure applied as in the previous transmitters.

256-IFFT is applied, cyclic prefix (CP) is added, and finally the three columns are converted to serial sequence to be transmitted by antenna 1.

- **Transmitter 4:**

The block code transmitting by the forth antenna is:

$x_4$ =[0 0 $s_2$ $s_1^*$], these four blocks are transmitted along the training sequence called (Xtodd2).

Xtodd2 = [0 0 0 xt4. . . 0 0 0 xt4 0 xt44 0 0 0 . . . 0 0 0 xt44].

$x_{44}$ = [Xtodd2 $x_4$].

Then same procedure applied as in the previous transmitters.

Where xt1, xt11, xt2, xt22, xt3, xt33, xt4, and xt44 are training symbols and equal random ±1, and used for channel estimation.

And $s_1$ and $s_2$ are modulated symbols and some of their values are shown in Appendix A.

**At the receiver:**

- **Receiver 1**:

At time:

t = 1 $r_1 = s_1 h_1 + s_2 h_2 + n_1$ (2)

t = 2 $r_2 = -s_2^* h_1 + s_1^* h_2 + n_2$ (3)

t = 3 $r_3 = s_1 h_3 + s_2 h_4 + n_3$ (4)

t = 4 $r_4 = -s_2^* h_3 + s_1^* h_4 + n_4$ (5)

Where, $h_1$ is the path gain between the first transmitting antenna and the first receiving antenna, $h_2$ is the path gain between the second transmitting antenna and the first receiving antenna, $h_3$ is the path gain between the third transmitting antenna and the first receiving antenna, and so on.

- **Receiver 2:**

At time:

t = 1 $r_5 = s_1 h_5 + s_2 h_6 + n_1$ (6)

t = 2 $r_6 = -s_2^* h_5 + s_1^* h_6 + n_2$ (7)

t = 3 $r_7 = s_1 h_7 + s_2 h_8 + n_3$ (8)

t = 4 $r_8 = -s_2^* h_7 + s_1^* h_8 + n_4$ (9)

$\tilde{s_1} = r_1 h_1^* + r_2^* h_2 + r_3 h_3^* + r_4^* h_4 + r_5 h_5^* + r_6^* h_6 + r_7 h_7^* + r_8^* h_8$ (10)

$\tilde{s_2} = r_1 h_2^* - r_2^* h_1 + r_3 h_4^* - r_4^* h_3 + r_5 h_6^* - r_6^* h_5 + r_7 h_8^* - r_8^* h_7$ (11)

**b) The OSTBC code matrix with R=3/4:**

An OSTBC with code rate (R) equal (3/4) has been used to transmit 3 symbols per block as shown in the following code matrix:

$$S = \begin{bmatrix} s_1 & s_2 & s_3 & 0 \\ -s_2^* & s_1^* & 0 & s_3 \\ s_3^* & 0 & -s_1^* & s_2 \\ 0 & s_3^* & -s_2^* & -s_1 \end{bmatrix} \qquad (12)$$

The transmitted symbols and the channels for this 4x2 system are shown in *Figure (2)*.

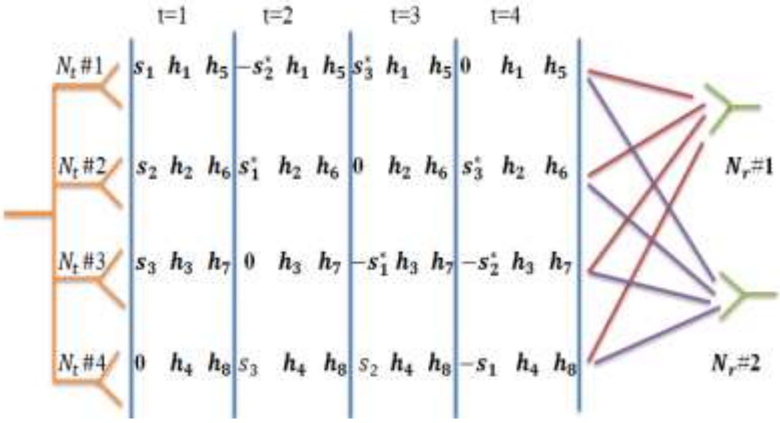



Figure (2): Transmission model for 4-$N_t$ and 2-$N_r$ antennas, with R=3/4.

The transmitting block symbols are:

$x_1 = [s_1 \quad -s_2^* \quad s_3^* \quad 0]$

$x_2 = [s_2 \quad s_1^* \quad 0 \quad s_3^*]$

$x_3 = [s_3 \quad 0 \quad -s_1^* \quad -s_2^*]$

$x_4 = [0 \quad s_3 \quad s_2 \quad -s_1]$

And then, the same steps have been used here as explained for transmitter 1 in the previous systems.

- **Receiver 1:**

At time:

t = 1 $r_1 = s_1 h_1 + s_2 h_2 + s_3 h_3 + n_1$ (13)

t = 2 $r_2 = -s_2^* h_1 + s_1^* h_2 + s_3 h_4 + n_2$ (14)

t = 3 $r_3 = s_3^* h_1 - s_1^* h_3 + s_2 h_4 + n_3$ (15)

t = 4 $r_4 = s_3^* h_2 - s_2^* h_3 - s_1 h_4 + n_4$ (16)

- **Receiver 2:**

At time:

t= 1 $r_5 = s_1 h_5 + s_2 h_6 + s_3 h_7 + n_1$ (17)

t = 2 $r_6 = -s_2^* h_5 + s_1^* h_6 + s_3 h_8 + n_2$ (18)

t = 3 $r_7 = s_3^* h_5 - s_1^* h_7 + s_2 h_8 + n_3$ (19)

t = 4 $r_8 = s_3^* h_6 - s_2^* h_7 - s_1 h_8 + n_4$ (20)

From the above equations the estimation of the three transmitted symbols ($s_1 s_2 \, s_3$ ) could be found.

$\widetilde{s_1} = r_1 h_1^* + r_2^* h_2 - r_3^* h_3 - r_4 h_4^* + r_5 h_5^* + r_6^* h_6 - r_7^* h_7 - r_8 h_8^*$ (21)

$\widetilde{s_2} = r_1 h_2^* - r_2^* h_1 + r_3 h_4^* - r_4^* h_3 + r_5 h_6^* - r_6^* h_5 + r_7 h_8^* - r_8^* h_7$ (22)

$\widetilde{s_3} = r_1 h_3^* + r_2 h_4^* + r_3^* h_1 + r_4^* h_2 + r_5 h_7^* + r_6 h_8^* + r_7^* h_5 + r_8^* h_6$ (23)

The details of the three estimated signals ($\widetilde{s_1}, \widetilde{s_2}$, and $\widetilde{s_3}$) are shown in Appendix B.

**B.** ***4x4 MIMO-STC-OFDM simulated model*****:**

Two type of STBC code matrix have been used with this four transmitting antennas and four receiving antennas system:

**a) The OSTBC code matrix with R=1/2:**

$$S = \begin{bmatrix} s_1 & s_2 & 0 & 0 \\ -s_2^* & s_1^* & 0 & 0 \\ 0 & 0 & s_1 & s_2 \\ 0 & 0 & -s_2^* & s_1^* \end{bmatrix}$$

The transmitted symbols and the channels are shown in *Figure (3).*

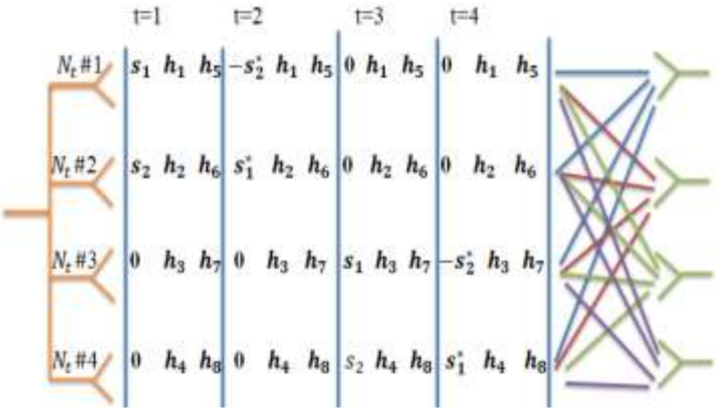



Figure (3): Transmission model for 4-$N_t$ and 4-$N_r$ antennas with R=1/2.

The four transmitters are the same as explained in 4x2 model.

**At the Receiver:**

Four receivers are used, and each receiver is the same as in 4x2 model.

- **Receiver 1:**

At time:

t = 1 $r_1 = s_1 h_1 + s_2 h_2 + n_1$ (24)

t = 2 $r_2 = -s_2^* h_1 + s_1^* h_2 + n_2$ (25)

t = 3 $r_3 = s_1 h_3 + s_2 h_4 + n_3$ (26)

t = 4 $r_4 = -s_2^* h_3 + s_1^* h_4 + n_4$ (27)

- **Receiver 2:**

At time:

t = 1 $r_5 = s_1 h_5 + s_2 h_6 + n_1$ (28)

t = 2 $r_6 = -s_2^* h_5 + s_1^* h_6 + n_2$ (29)

t = 3 $r_7 = s_1 h_7 + s_2 h_8 + n_3$ (30)

t = 4 $r_8 = -s_2^* h_7 + s_1^* h_8 + n_4$ (31)

- **Receiver 3:**

At time:

t = 1 $r_9 = s_1 h_9 + s_2 h_{10} + n_1$ (32)

t = 2 $r_{10} = -s_2^* h_9 + s_1^* h_{10} + n_2$ (33)

t = 3 $r_{11} = s_1 h_{11} + s_2 h_{12} + n_3$ (34)

t = 4 $r_{12} = -s_2^* h_{11} + s_1^* h_{12} + n_4$ (35)

- **Receiver 4:**

t = 1 $r_{13} = s_1 h_{13} + s_2 h_{14} + n_1$ (36)

t = 2 $r_{14} = -s_2^* h_{13} + s_1^* h_{14} + n_2$ (37)

t = 3 $r_{15} = s_1 h_{15} + s_2 h_{16} + n_3$ (38)

t = 4 $r_{16}=-s_2^*h_{15}+s_1^*h_{16}+n_4$ (39)

From the above equations, the estimated $(s_1, s_2)$ could be found [9-10]:

$\tilde{s_1}=s_1(|h_1|^2+|h_2|^2+|h_3|^2+|h_4|^2+|h_5|^2+|h_6|^2+|h_7|^2+|h_8|^2+|h_9|^2+|h_{10}|^2+|h_{11}|^2+|h_{12}|^2+|h_{13}|^2+|h_{14}|^2+|h_{15}|^2+|h_{16}|^2)+n_5+n_6+n_7+n_8+n_9+n_{10}+n_{11}+n_{12}+n_{13}+n_{14}+n_{15}+n_{16}+n_{17}+n_{18}+n_{19}+n_{20}$ (40)

$\tilde{s_2}=s_2h_2h_2^*-n_5+s_2h_1^*h_1-n_6+s_2h_4h_4^*+n_7+s_2h_3^*h_3-n_8+s_2h_6h_6^*+n_9+s_2h_5^*h_5-n_{10}+s_2h_8h_8^*+n_{11}+s_2h_7^*h_7-n_{12}+s_2h_{10}h_{10}^*+n_{13}+s_2h_9^*h_9-n_{14}+s_2h_{12}h_{12}^*+n_{15}+s_2h_{11}^*h_{11}-n_{16}+s_2h_{14}h_{14}^*+n_{17}+s_2h_{13}^*h_{13}-n_{18}+s_2h_{16}h_{16}^*+n_{19}+s_2h_{15}^*h_{15}-n_{20}$

$=s_2(|h_1|^2+|h_2|^2+|h_3|^2+|h_4|^2+|h_5|^2+|h_6|^2+|h_7|^2+|h_8|^2+|h_9|^2+|h_{10}|^2+|h_{11}|^2+|h_{12}|^2+|h_{13}|^2+|h_{14}|^2+|h_{15}|^2+|h_{16}|^2)-n_5-n_6+n_7-n_8+n_9-n_{10}+n_{11}-n_{12}+n_{13}-n_{14}+n_{15}-n_{16}+n_{17}-n_{18}+n_{19}-n_{20}$ (41)

### b) The OSTBC code matrix with R=3/4:

The 4x4 and 4x2 systems with the same OSTBC code rate have the same transmitter system. The channels and the transmitted symbols through each path in different time slots are shown in *Figure (4)*.

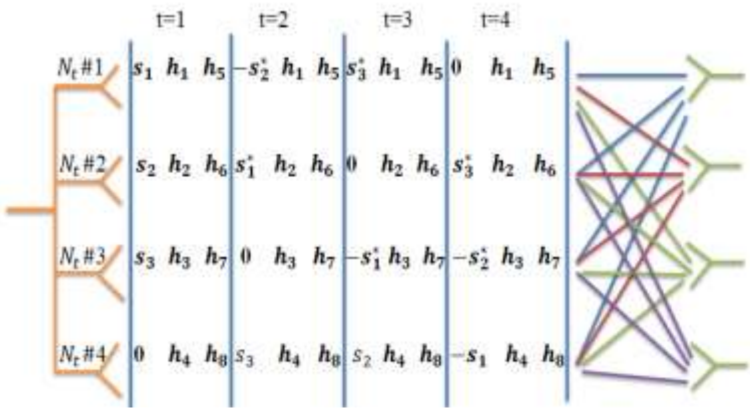



Figure (4): Transmission model for 4-$N_t$ and 4-$N_r$ antennas, with R=3/4.

The OSTBC code matrix is as below:

$$\mathbf{S} = \begin{bmatrix} s_1 & s_2 & s_3 & 0 \\ -s_2^* & s_1^* & 0 & s_3 \\ s_3^* & 0 & -s_1^* & s_2 \\ 0 & s_3^* & -s_2^* & -s_1 \end{bmatrix}$$

- **Receiver 1:**

For the four time slots (t=1 to 4), the received signals ($r_1$, $r_2$, $r_3$, and $r_4$) are:

t = 1 $r_1=s_1h_1+s_2h_2+s_3h_3+n_1$ (42)

t = 2 $r_2=-s_2^*h_1+s_1^*h_2+s_3h_4+n_2$ (43)

t = 3 $r_3=s_3^*h_1-s_1^*h_3+s_2h_4+n_3$ (44)

t = 4 $r_4=s_3^*h_2-s_2^*h_3-s_1h_4+n_4$ (45)

- **Receiver 2:**

For the four time slots (t=1 to 4), the received signals ($r_5$, $r_6$, $r_7$, and $r_8$) are:

t = 1 $r_5=s_1h_5+s_2h_6+s_3h_7+n_1$ (46)

t = 2 $r_6=-s_2^*h_5+s_1^*h_6+s_3h_8+n_2$ (47)

t = 3 $r_7=s_3^*h_5-s_1^*h_7+s_2h_8+n_3$ (48)

t = 4 $r_8=s_3^*h_6-s_2^*h_7-s_1h_8+n_4$ (49)

- **Receiver 3:**

For the four time slots (t=1 to 4), the received signals ($r_9$, $r_{10}$, $r_{11}$, and $r_{12}$) are:

t = 1 $r_9=s_1h_9+s_2h_{10}+s_3h_{11}+n_1$ (50)

t = 2 $r_{10}=-s_2^*h_9+s_1^*h_{10}+s_3h_{12}+n_2$ (51)
t = 3 $r_{11}=s_3^*h_9-s_1^*h_{11}+s_2h_{12}+n_3$ (52)
t= 4 $r_{12}=s_3^*h_{12}-s_2^*h_{11}-s_1h_{12}+n_4$ (53)

- **Receiver 4:**

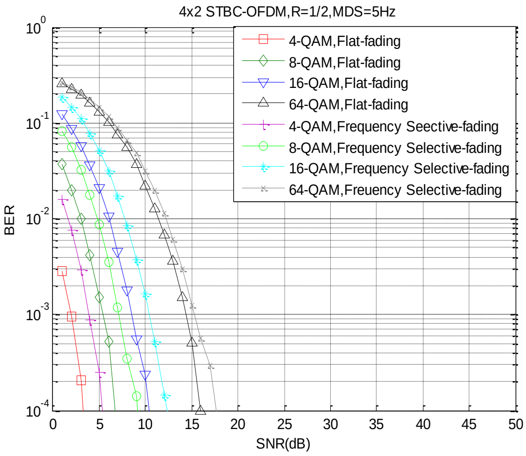
For the four time slots (t=1 to 4), the received signals ($r_{13}$, $r_{14}$, $r_{15}$, and $r_{16}$) are:
t= 1 $r_{13}=s_1h_{13}+s_2h_{14}+s_3h_{15}+n_1$ (54)
t= 2 $r_{14}=-s_2^*h_{13}+s_1^*h_{14}+s_3h_{16}+n_2$ (55)
t= 3 $r_{15}=s_3^*h_{13}-s_1^*h_{15}+s_2h_{16}+n_3$ (56)
t= 4 $r_{16}=s_3^*h_{14}-s_2^*h_{15}-s_1h_{16}+n_4$ (57)
From the above equations the estimations of ( $s_1s_2s_3$ ) are:
$\tilde{s_1}=r_1h_1^*+r_2^*h_2-r_3^*h_3-r_4h_4^*+r_5h_5^*+r_6^*h_6-r_7^*h_7-r_8h_8^*+r_9h_9^*+r_{10}^*h_{10}-r_{11}^*h_{11}-r_{12}h_{12}^*+r_{13}h_{13}^*+r_{14}^*h_{14}$
$-r_{15}^*h_{15}-r_{16}h_{16}^*$ (58)
$\tilde{s_2}=r_1h_2^*-r_2^*h_1+r_3h_4^*-r_4^*h_3+r_5h_6^*-r_6^*h_5+r_7h_8^*-r_8^*h_7+r_9h_{10}^*-r_{10}^*h_9+r_{11}-h_{12}^*-r_{12}^*h_{11}+r_{13}h_{14}^*-r_{14}^*h_{13}$
$+r_{15}h_{16}^*-r_{16}^*h_{15}$ (59)
$\tilde{s_3}=r_1h_3^*+r_2h_4^*+r_3^*h_1+r_4^*h_2+r_5h_7^*+r_6h_8^*+r_7^*h_5+r_8^*h_6+r_9h_{11}^*+r_{10}h_{12}^*+r_{11}^*h_9+r_{12}^*h_{10}+r_{13}h_{15}^*+r_{14}h_{16}^*+$
$r_{15}^*h_{13}+r_{16}^*h_{14}$ (60)

**The Results**

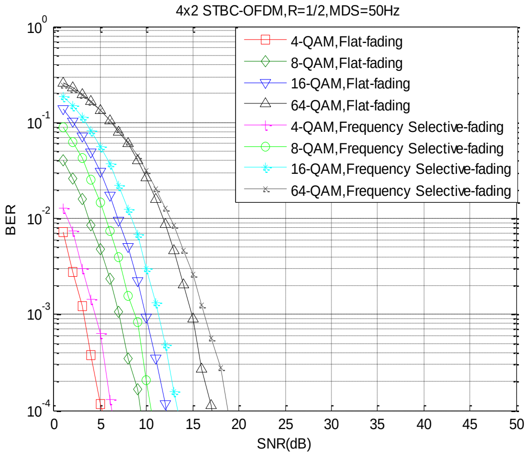
The performance of 4x2 MIMO-STC-OFDM with code rate (R=1/2) for different types of QAM modulation, and different Doppler frequencies, using flat and multipath frequency-selective channel, are shown in *Figures (5-7)*, and the simulation results of 4x2 MIMO-STC-OFDM with R=3/4, are shown in *Figures (8-10)*.
Simulation results of 4x4 MIMO-STC-OFDM with R=1/2, are shown in *Figures (11-13)*, and simulation results of 4x4 MIMO-STC-OFDM with R=3/4 are shown in *Figures (14-16)*.
All the results have been summarized in Tables (1-3), and from these results could be seen that:
Increasing the number of receiving antennas improves the system performance, from Table (1) the results of 4x2 model could be compared with the 4x4 model for same code rate; then it could be seen that for *flat fading* channel, 4-QAM *modulation* and *R*=1/2, when the system is with 2 receiving antennas only, S/N ratio of 3.16 dB is needed to reach a BER with $10^{-4}$.
But for 4x4 model BER is always zero for 4-QAM. Another comparison could be made, for 64-QAM and R=1/2, the S/N ratio needed for BER= $10^{-4}$ is 15.95 dB for the 4x2 model, and 10.74 dB for the 4x4 model. In the same way a comparison could be made for the results in Table (2 and 3) and the improvement could be noticed.
OSTBC used with 4 transmitting antennas and with code rate 1/2 gives a better results than OSTBC with code rate 3/4, because when R=3/4 three symbols are send during 4 time slots, but when R=1/2 just two symbols are send during four time slots. That is beside sending multi-copies of each symbol in different time and different space.

For the 4x4 model, using 64-QAM as a baseband modulation and frequency-selective fading channel, with R=1/2; when MDS= 5 Hz, the S/N ratio needed to reach BER=$10^{-4}$ is12 dB. When MDS increased to 50 Hz, the S/N needed to reach same BER is 13.9 dB, and for MDS=100 Hz the S/N ratio should be 14.53 dB to make the BER= $10^{-4}$. That is mean increasing the receiver speed ten times needs just extra 1.9 dB, and 2.53 dB for increasing the speed 20 times.

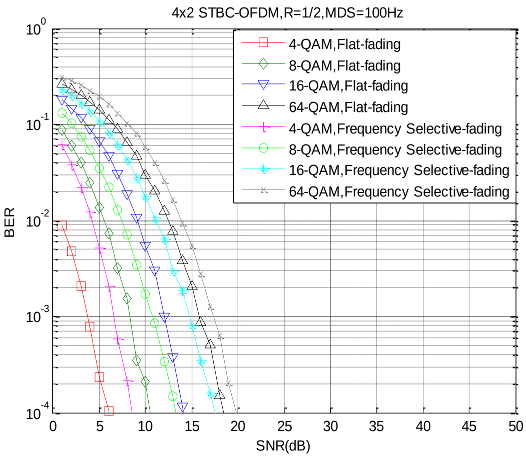
The results shows that increasing the number of antennas at the receiver side reduce the effect of the Doppler shift, because increasing the number of antennas means increasing the number of channels, and transmitting the symbols through these channels in different times.



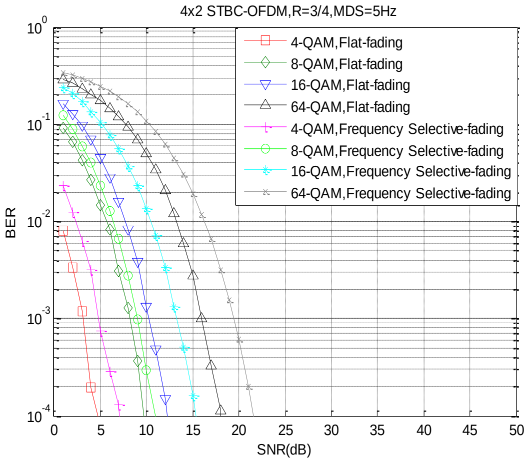

Figure(5): Performance of 4x2 MIMO-STC-OFDM, with R=1/2, (MDS=5Hz).



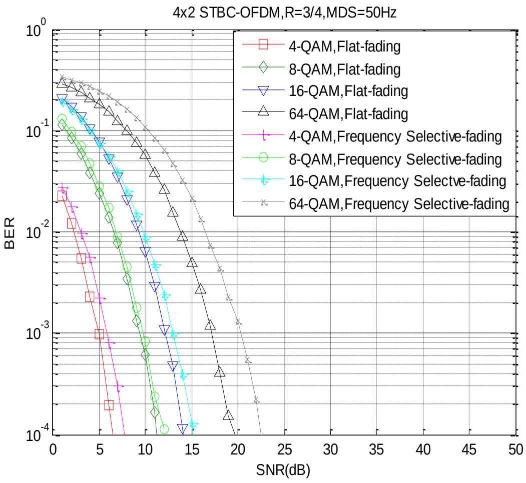

Figure(6): Performance of 4x2 MIMO-STC-OFDM, with R=1/2, (MDS=50Hz).



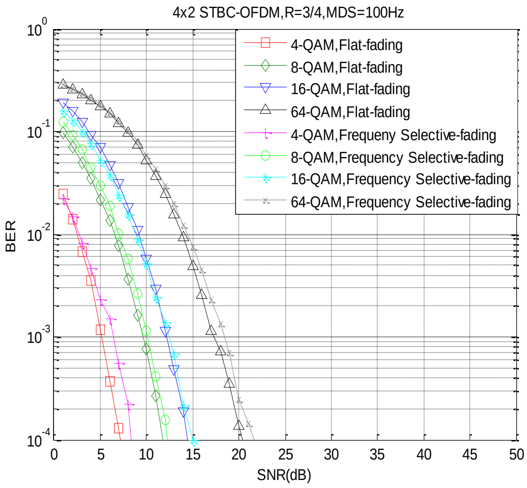

Figure(7): Performance of 4x2 MIMO-STC-OFDM, with R=1/2, (MDS=100Hz).



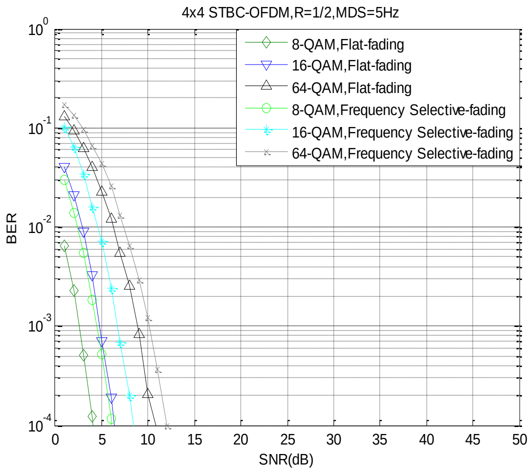

Figure(8): Performance of 4x2 MIMO-STC-OFDM, with R=3/4, (MDS=5Hz).



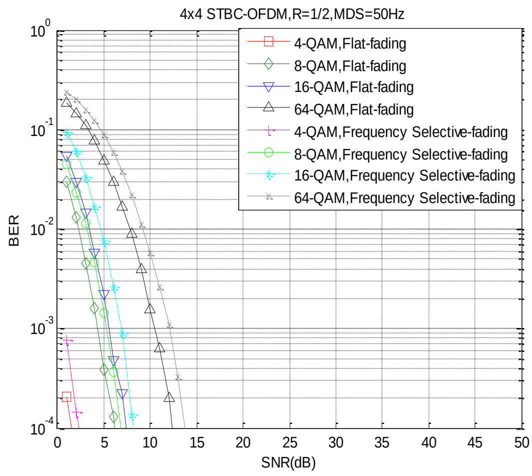

Figure(9): Performance of 4x2 MIMO-STC-OFDM, with R=3/4, (MDS=50Hz).



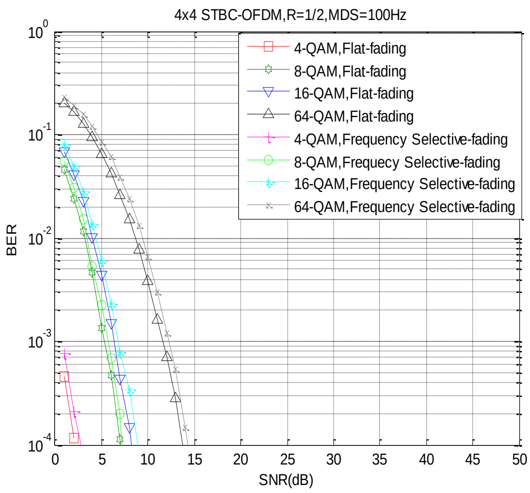

Figure(10): Performance of 4x2 MIMO-STC-OFDM, with R=3/4 (MDS=100Hz).



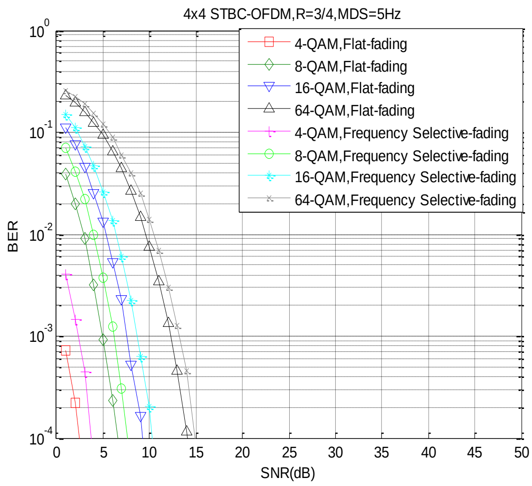

Figure(11): Performance of 4x4 MIMO-STC-OFDM, with R=1/2, (MDS=5Hz).



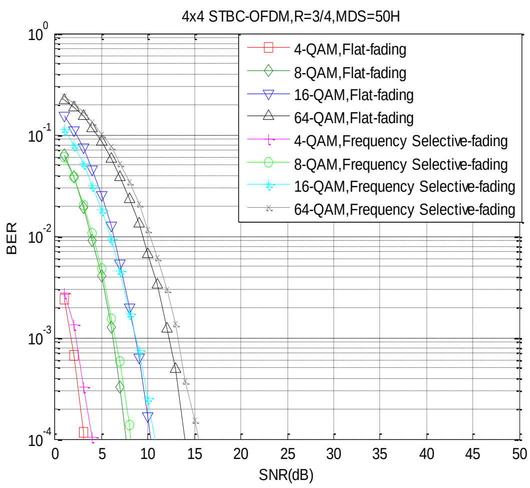

Figure(12): Performance of 4x4 MIMO-STC-OFDM, with R=1/2, (MDS=50Hz).



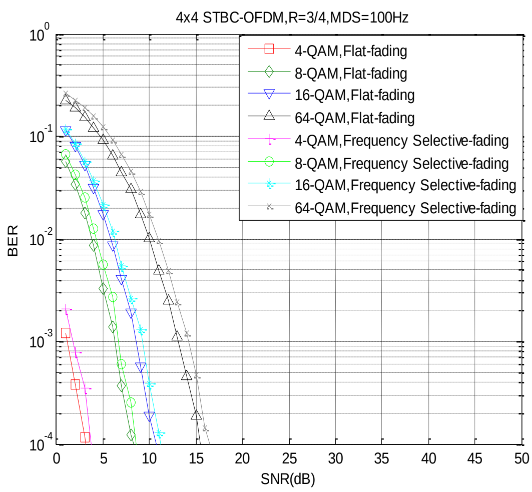

Figure(13): Performance of 4x4 MIMO-STC-OFDM, with R=1/2, (MDS=100Hz).




Figure(14): Performance of 4x4 MIMO-STC-OFDM, with R=3/4, (MDS=5Hz).




Figure(15): Performance of 4x4 MIMO-STC-OFDM, with R=3/4, (MDS=50Hz).




Figure(16): Performance of 4x4 MIMO-STC-OFDM, with R=3/4, (MDS=100Hz).

Table (1): Comparison between the various systems, $f_d$=5Hz.

| **BER=$10^{-4}$ MDS=5Hz** | **Flat Fading** | **SNR (dB)** | **Frequency Selective Fading** | **SNR (dB)** |
|---|---|---|---|---|
| **4x2 system R=1/2** | 4-QAM | 3.16 | 4-QAM | 5.21 |
| | 8-QAM | 6.63 | 8-QAM | 9.16 |
| | 16-QAM | 10.43 | 16-QAM | 12.32 |
| | 64-QAM | 15.95 | 64-QAM | 17.96 |
| **4x2 system R=3/4** | 4-QAM | 4.74 | 4-QAM | 7.11 |
| | 8-QAM | 9.79 | 8-QAM | 11.06 |
| | 16-QAM | 12.32 | 16-QAM | 15.48 |
| | 64-QAM | 18.0 | 64-QAM | 21.64 |
| **4x4 system R=1/2** | 4-QAM | -- | 4-QAM | -- |
| | 8-QAM | 4.10 | 8-QAM | 6.0 |
| | 16-QAM | 6.32 | 16-QAM | 8.53 |
| | 64-QAM | 10.74 | 64-QAM | 12.0 |
| **4x4 system R=3/4** | 4-QAM | 2.52 | 4-QAM | 3.79 |
| | 8-QAM | 6.63 | 8-QAM | 7.74 |
| | 16-QAM | 9.32 | 16-QAM | 10.42 |
| | 64-QAM | 14.22 | 64-QAM | 15.0 |

Table (2): Comparison between the various models, $f_d$=50Hz.

| **BER=$10^{-4}$ MDS= 50Hz** | **Flat Fading** | **SNR (dB)** | **Frequency-Selective Fading** | **SNR (dB)** |
|---|---|---|---|---|
| **4x2 system R=1/2** | 4-QAM | 5.37 | 4-QAM | 6.32 |
| | 8-QAM | 9.48 | 8-QAM | 10.58 |
| | 16-QAM | 12.32 | 16-QAM | 13.58 |
| | 64-QAM | 17.0 | 64-QAM | 18.96 |
| **4x2 system R=3/4** | 4-QAM | 6.63 | 4-QAM | 7.9 |
| | 8-QAM | 11.06 | 8-QAM | 12.32 |
| | 16-QAM | 14.22 | 16-QAM | 15.0 |
| | 64-QAM | 19.75 | 64-QAM | 22.59 |
| **4x4 system R=1/2** | 4-QAM | 1.58 | 4-QAM | 2.52 |
| | 8-QAM | 6.0 | 8-QAM | 6.95 |
| | 16-QAM | 7.58 | 16-QAM | 8.21 |
| | 64-QAM | 12.32 | 64-QAM | 13.90 |
| **4x4 system R=3/4** | 4-QAM | 3.16 | 4-QAM | 4.10 |
| | 8-QAM | 7.74 | 8-QAM | 8.21 |
| | 16-QAM | 10.42 | 16-QAM | 11.06 |
| | 64-QAM | 14.0 | 64-QAM | 15.48 |

Table (3): Comparison between the various models, $f_d$=100Hz.

| **BER=$10^{-4}$ MDS= 100Hz** | **Flat Fading** | **SNR (dB)** | **Frequency-Selective Fading** | **SNR (dB)** |
|---|---|---|---|---|
| **4x2 system R=1/2** | 4-QAM | 6.0 | 4-QAM | 8.53 |
| | 8-QAM | 10.74 | 8-QAM | 13.27 |
| | 16-QAM | 14.22 | 16-QAM | 17.69 |
| | 64-QAM | 18.48 | 64-QAM | 19.9 |
| **4x2 system R=3/4** | 4-QAM | 7.26 | 4-QAM | 8.21 |
| | 8-QAM | 11.85 | 8-QAM | 12.32 |
| | 16-QAM | 14.53 | 16-QAM | 15.0 |
| | 64-QAM | 20.54 | 64-QAM | 21.80 |
| **4x4 system R=1/2** | 4-QAM | 2.21 | 4-QAM | 2.84 |
| | 8-QAM | 7.11 | 8-QAM | 7.26 |
| | 16-QAM | 8.21 | 16-QAM | 8.84 |
| | 64-QAM | 13.90 | 64-QAM | 14.53 |
| **4x4 system R=3/4** | 4-QAM | 3.16 | 4-QAM | 3.79 |
| | 8-QAM | 8.37 | 8-QAM | 8.53 |
| | 16-QAM | 10.90 | 16-QAM | 11.37 |
| | 64-QAM | 15.48 | 64-QAM | 16.59 |

## Conclusions

The performance comparisons of bit error rate (BER) for the different MIMO-STC-OFDM models have been presented.
All the models have been studied and evaluated for four types of QAM (4-QAM, 8-QAM, 16-QAM, and 64-QAM) as a baseband modulation, and three values of Doppler Frequency (MDS) has been used which are (5, 50, and100) Hz.
As a result, the following can be concluded:

1) Increasing the number of receiving antennas also gives some improvement. That is because of using receiver diversity beside the transmitter diversity.
2) OSTBC with code rate R=1/2 gives much better results than the one with 3/4, because of transmitting only two symbols during a one block (4 time slots) beside transmitting a multi-copied of each symbol in different time and space (channel).
3) The proposed system is so far insensitive to Doppler frequency, especially the 4x4 with R=1/2, which means the system could be used for non-static channel.

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## Appendix A

*Some* $s_1$ and $s_1$ values are:
For 8-QAM:
1+*i* , 1-*i*, -1+*i*, -1-*i*, -3-*i*, 3+*i*, 3-*i*, -3+*i*.
For 16-QAM:
1+*i* , 1-*i*, -1+*i*,  -1-*i*,  3+*i*, 3-*i*, -3+*i*, 3+3*i*, 3-3*i*.
For 64-QAM:
1+*i* , 1-*i*, -1+*i*,  -1-*i*,  3+*i*, 3-*i*, -3+*i*, 3+3*i*, 3-3*i*, , -5+*i*, 5+5*i*, 5-7*i*, , -7+7*i*, 3-5*i*, 3-7*i*.

## Appendix B

$\tilde{s_1}$=$(s_1h_1$+$s_2h_2$+$s_3h_3$+$n_1)h_1^*$+$(-s_2^*h_1 + s_1^*h_2 + s_3h_4 + n_2)^*h_2$-$(s_3^*h_1 - s_1^*h_3 + s_2h_4 + n_3)^*h_3$-$(s_3^*h_2$-$s_2^*h_3$-$s_1h_4$+$n_4)h_4^*$+$(s_1h_5$+$s_2h_6$+$s_3h_7$+$n_1\,)h_5^*$+$(-s_2^*h_5 + s_1^*h_6 + s_3h_8 + n_2)^*h_6$-$(s_3^*h_5 - s_1^*h_7 + s_2h_8 + n_3)^*h_7$-$(s_3^*h_6$-$s_2^*h_7$-$s_1h_8$+$n_4)h_8^*$
=$s_1h_1h_1^*$+$s_2h_2h_1^*$+$s_3h_3h_1^*$+$n_1h_1^*$-$s_2h_1^*h_2$+$s_1h_2^*h_2$+$s_3^*h_4^*h_2$+$n_2^*h_2$-$s_3h_1^*h_3$+$s_1h_3^*h_3$-$s_2^*h_4^*$ $h_3$-$n_3^*h_3$-$s_3^*h_2h_4^*$+$s_2^*h_3h_4^*$+$s_1h_4h_4^*$-$n_4h_4^*$+$s_1h_5h_5^*$+$s_2h_6h_5^*$+$s_3h_7h_5^*$+$n_1h_5^*s_2$-$h_5^*h_6$+$s_1h_6^*h_6$+$s_3^*h_8^*h_6$+$n_2^*h_6$-$s_3h_5^*h_7$+$s_1h_7^*h_7$-$s_2^*h_8^*h_7$-$n_3^*h_7$-$s_3^*h_6h_8^*$+$s_2^*h_7h_8^*$+$s_1h_8h_8^*$-$n_4h_8^*$
=$s_1h_1h_1^*$+$n_1h_1^*$+$s_1h_2^*h_2$+$n_2^*h_2$+$s_1h_3^*h_3$-$n_3^*h_3$+$s_1h_4h_4^*$-$n_4h_4^*$+$s_1h_5h_5^*$+$n_1h_5^*$+$s_1h_6^*h_6$+$n_2^*$ $h_6$+$s_1h_7^*h_7$-$n_3^*h_7$+$s_1h_8h_8^*$-$n_4h_8^*$
$n_5$=$n_1h_1^*$, $n_6$=$n_2^*h_2$, $n_7$=$n_3^*h_3$, $n_8$=$n_4h_4^*$, $n_9$=$n_1\,h_5^*$, $n_{10}$= $n_2^*h_6$, $n_{11}$=$n_3^*h_7$, $n_{12}$=$n_4h_8^*$
$\tilde{s_1}$=$s_1(|h_1|^2$+$|h_2|^2$+$|h_3|^2$+$|h_4|^2$+$|h_5|^2$+$|h_6|^2$+$|h_7|^2$+ $|h_8|^2)$+$n_5$+$n_6$-$n_7$-$n_8$+$n_9$+$n_{10}$-$n_{11}$- $n_{12}$ …………. ($B_1$)
$\tilde{s_2}$=$(s_1h_1$+$s_2h_2$+$s_3h_3$+$n_1)h_2^*$-$(-s_2^*h_1 + s_1^*h_2 + s_3h_4 + n_2)^*h_1$+$(s_3^*h_1$-$s_1^*h_3$+$s_2h_4$+$n_3)h_4^*$ -$(s_3^*h_2 - s_2^*h_3 - s_1h_4 + n_4)^*h_3$+$(s_1h_5$+$s_2h_6$+$s_3h_7$+$n_1)h_6^*$-$(-s_2^*h_5 +\ s_1^*h_6 + s_3h_8 + n_2)^*h_5$+$(s_3^*h_5$-$s_1^*h_7$+$s_2h_8$+$n_3)h_8^*$-$(s_3^*h_6 - s_2^*h_7 - s_1h_8 + n_4)^*h_7$
=$s_1h_1h_2^*$+$s_2h_2h_2^*$+$s_3h_3h_2^*$+$n_1h_2^*$+$s_2h_1^*h_1$-$s_1h_2^*h_1$-$s_3^*h_4^*h_1$-$n_2^*h_1$+$s_3^*h_1h_4^*$-$s_1^*h_3h_4^*$+$s_2h_4$ $h_4^*$+$n_3h_4^*$-$s_3h_2^*h_3$+$s_2h_3^*h_3$+$s_1^*h_4^*h_3$-$n_4^*h_3$+$s_1h_5h_6^*$+$s_2h_6h_6^*$+$s_3h_7h_6^*$+$n_1h_6^*$+$s_2h_5^*h_5$-$s_1$ $h_6^*h_5$-$s_3^*h_8^*h_5$-$n_2^*h_5$+$s_3^*h_5h_8^*$-$s_1^*h_7h_8^*$+$s_2h_8h_8^*$+$n_3h_8^*$-$s_3h_6^*h_7$+$s_2h_7^*h_7$+$s_1^*h_8^*h_7$-$n_4^*h_7$
=$s_2h_2h_2^*$+$n_1h_2^*$+$s_2h_1^*h_1$-$n_2^*h_1$+$s_2h_4h_4^*$+$n_3h_4^*$+$s_2h_3^*h_3$-$n_4^*h_3$+$s_2h_6h_6^*$+$n_1h_6^*$ +$s_2h_5^*h_5$ -$n_2^*h_5$+$s_2h_8h_8^*$+$n_3h_8^*$+$s_2h_7^*h_7$-$n_4^*h_7$
$n_{13}$=$n_1h_2^*$, $n_{14}$=$n_2^*h_1$, $n_{15}$=$n_3h_4^*$, $n_{16}$=$n_4^*h_3$, $n_{17}$=$n_1h_6^*$, $n_{18}$=$n_2^*h_5$, $n_{19}$=$n_3h_8^*$, $n_{20}$=$n_4^*h_7$

$\widetilde{s_2}$=$s_2(|h_1|^2$+$|h_2|^2$+$|h_3|^2$+$|h_4|^2$+$|h_5|^2$+$|h_6|^2$+ $|h_7|^2$+$|h_8|^2)$+$n_{13}$-$n_{14}$+$n_{15}$-
$n_{16}$+$n_{17}$-$n_{18}$+$n_{19}$-$n_{20}$ ………….. (B$_2$)
$\widetilde{s_3}$=$(s_1h_1$+$s_2h_2$+$s_3h_3$+$n_1)h_3^*$+$(-s_2^*h_1$+$s_1^*h_2$+$s_3h_4$+$n_2)h_4^*$+$(s_3^*h_1 - s_1^*h_3 + s_2h_4 + n_3)^*h_1$+$(s_3^*h_2 - s_2^*h_3 -$
$s_1h_4 + n_4)^*h_2$+$(s_1h_5$+$s_2h_6$+$s_3h_7$+$n_1)h_7^*$+$(-s_2^*h_5$+$s_1^*h_6$
+$s_3h_8$+$n_2)h_8^*$+$(s_3^*h_5 - s_1^*h_7 + s_2h_8 + n_3)^*h_5$+$(s_3^*h_6 - s_2^*h_7 - s_1h_8 + n_4)^*h_6$
=$s_1h_1h_3^*$+$s_2h_2h_3^*$+$s_3h_3h_3^*$+$n_1h_3^*$-$s_2^*h_1h_4^*$+$s_1^*h_2h_4^*$+$s_3h_4h_4^*$+$n_2h_4^*$+$s_3h_1^*h_1$-$s_1h_3^*h_1$+
$s_2^*h_4^*h_1$+$n_3^*h_1$+$s_3h_2^*h_2$-$s_2h_3^*h_2$-$s_1^*s_4^*h_2$+$n_4^*h_2$+$s_1h_5h_7^*$+$s_2h_6h_7^*$+$s_3h_7h_7^*$+$n_1h_7^*$−$s_2^*$
$h_5h_8^*$+ $s_1^*h_6h_8^*$+$s_3h_8h_8^*$+$n_2h_8^*$+$s_3h_5^*h_5$-$s_1h_7^*h_5$+$s_2^*h_8^*h_5$+$n_3^*h_5$+$s_3h_6^*h_6$-$s_2h_7^*h_6$-$s_1^*$
$h_8^*h_6$+$n_4^*h_6$=$s_3h_3h_3^*$+$n_1h_3^*$+$s_3h_4h_4^*$+$n_2h_4^*$+$s_3h_1^*h_1$+$n_3^*h_1$+$s_3h_2^*h_2$+$n_4^*h_2$+$s_3h_7h_7^*$+
$n_1h_7^*$+$s_3h_8h_8^*$+$n_2h_8^*$+$s_3h_5^*h_5$+$n_3^*h_5$+$s_3h_6^*h_6$+$n_4^*h_6$
$n_{21}$=$n_1h_3^*$, $n_{22}$=$n_2h_4^*$, $n_{23}$=$n_3^*h_1$, $n_{24}$=$n_4^*h_2$, $n_{25}$=$n_1h_7^*$, $n_{26}$=$n_2h_8^*$, $n_{27}$=$n_3^*h_5$, $n_{28}$=$n_4^*h_6$
$\widetilde{s_3}$=$s_3(|h_1|^2$+$|h_2|^2$+$|h_3|^2$+$|h_4|^2$+$|h_5|^2$+$|h_6|^2$+$|h_7|^2$+$|h_8|^2)$+$n_{21}$+$n_{22}$+$n_{23}$+$n_{24}$+$n_{25}$+$n_{26}$+$n_{27}$+$n_{28}$ …… (B$_3$)