Analysis of Channel Estimation Techniques in MIMO-OFDM System

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Abstract: The reception of the higher data rates, the better utilization of available bandwidth, and the reliable communication demand a better technology for the end users. The modern wireless MIMO-OFDM system is the answer for such a technology. In order to achieve these benefits, the channels of MIMO-OFDM system have to be estimated for getting the accurate channel state information. For channel estimation, different techniques like Pilot, Blind and Decision Directed based estimation techniques, are used. But the channel estimation with Pilot Symbols is selected for the purpose of analysis for this research paper. Methodology used for the analysis is such that different parameters are initialized first, and then processed on MATLAB. When the transmitter sends the data streams, it gets distorted on its way to the receiver due physical properties of the channel. Pilot symbol based channel estimation techniques like LS and MMSE are used to estimate the channel with the help of BER and SNR functions. These functions are affected by the Pilot Symbols and the Channel Taps. As the size of Pilot Symbols or Channel Taps is increased, the BER is also increased or decreased, respectively. So, it can be concluded that estimation of channels in MIMO-OFDM system is of utmost importance for effective performance of the system.

Keywords: *MIMO, OFDM, Channel Estimation, Pilot Symbols LS, MMSE,*

1. Introduction

Keeping in view the variety of wireless broadband services, the demand has increased for a technology which is capable of transmission of higher data rates, being robust against the multi path fading, and being efficient in the utilization of available bandwidth. The answer for the demand of such a technology lies in the modern wireless MIMO-OFDM system.

The multiple receiving and transmitting antennas help a MIMO system to transmit parallel data streams, and to exploit the diversity for increasing the system capacity. And for the bandwidth efficiency, it uses spatial multiplexing feature [1]. OFDM system also increases system capacity and spectral efficiency by dividing the available bandwidth into many narrowband, low-rate, frequency-non-selective subcarriers. These subcarriers are overlapping but orthogonal to each other. This property of orthogonality helps an OFDM system to avoid interference between the subcarriers [2].

Channel estimation in MIMO-OFDM system is important because when the system transmits signals, it gets distorted, delayed, and attenuated due to the physical properties of the channel [3]. To mitigate these effects, following CE techniques are used.

Pilot based CE technique uses the pilot symbols for the CE. These pilot symbols utilize already scarce bandwidth. Whereas, the Blind CE technique avoids the pilot symbols. Rather it is done with the exploitation of redundancy introduced by the cyclic prefixes. This estimation technique suffers from the computational complexities, and it is for the time invariant channels. So, it cannot be applied for the cellular systems whose channels are time variant. In order to avoid this defect, the Decision Directed channel estimation technique has been used in MIMO-OFDM system. It utilizes both the pilots and the hidden information of transmitted symbols while estimating the channel.

2. Related Work

A MIMO system has multiple transceiver antennas for delivering parallel data streams. It easily exploits transceiver diversity for increasing the system capacity. Besides, it also increases the available bandwidth efficiency because of spatial multiplexing feature therein.

An OFDM system also increases the system capacity and spectral efficiency [4]. An OFDM system does so by dividing the available bandwidth into many narrowband, low-rate, frequency-non-selective subcarriers. These subcarriers are overlapping but orthogonal to each other. This property of orthogonality in OFDM system helps to avoid the interference in different subcarriers. Despite many advantages, an OFDM system suffers from the problems of Peak-to-Average Power Ratio (PAPR), and Inter-Carrier Interference (ICI) due to frequency offset [5].

When MIMO system is combined with OFDM system, i-e a MIMO-OFDM system, the system capacity and spectral efficiency is very much increased as compared to other systems [6].

When the transmitter transmits any signal in MIMO-OFDM system, it gets distorted, delayed, and attenuated due to the

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physical properties of channel it travels through to reach the receiver. Consequently, there is a need of estimating the channel in order to reduce these undesired effects and to accurately demodulate and decode the signal at the receiver end [7]. For that, following CE techniques are used.

In Pilot based channel estimation technique, the pilot or training symbols at the particular position are sent along with the data symbols [8]. These pilot symbols are then used to estimate the CSI-Channel State Information- corresponding to its position. Whereas, the CSI corresponding to data symbols position is obtained with the help of interpolation [9].

There are two types of the pilot based channel estimation, i-e Block type and Comb type. In Block type channel estimation, all subcarriers are used as pilot symbols in a specific period. In Comb type channel estimation, a part of each subcarrier is reserved for pilot symbol for all period of time [10].

The Block or Comb type channel estimations can be performed by using either Least Square (LS) or Minimum Mean Square Error (MMSE) algorithms [11]. As the statistics of channel are not used in LS, the complexity level is very low, but its performance is not satisfactory. While, the statistics of channel in MMSE are taken into account, the complexity level is very high, but its performance is very good [12].

One drawback in overall Pilot based estimation technique is that due to presence of pilot symbols, it brings about wastages in already scarce bandwidth [13].

Because of the wastage of bandwidth in Pilot based estimation technique, there has been need of such a technique which avoids the presence of Pilot symbols in channel estimation [14]. This defect of inserting pilot symbols in estimation has been resolved with the help of Blind channel estimation technique. In blind channel estimation technique, instead of using pilot symbols, the channel estimation is done with the exploitation of redundancy introduced by the cyclic prefixes [15]. The information hidden in the cyclic prefixes is taken into account by estimating a small part of autocorrelation matrix of the received signal vector. Blind channel estimation is done with the help of subspace decomposition algorithm [16].

Blind channel estimation has some disadvantages i-e computational complexity due to long data requirement for estimation, and channel to be time-invariant [17]. Besides, Blind channel estimation technique cannot be applied to time-varying channel which is hallmark of mobile communication systems.

But the time-varying channels in mobile communication can easily be accommodated in Decision Directed channel estimation technique. It utilizes both the pilot symbols and the hidden information of transmitted symbols while estimating the channel [18]. Besides, it uses a recursive filter for providing the feedback information at the output of symbol demodulator [19]. In this way, we get the symbol to symbol information for the channel estimation with reduced complexity [20]. DDE suffers from error propagation and from significant SNR loss on higher velocities [21].

3. Methodology

The fundamental steps taken in the modeling and simulations of the channel estimations in a wireless communication system are described as under:
For running the simulations, a transmitter, channel and a receiver are required. The BER and the MSE, as a function of SNR, are used for the purpose of analysis. BER and SNR are plotted on two dimensional graphs on MATLAB. Table 1 shows the initialization parameters used in simulations.

Table 1: Parameter Specifications

Parameters	**Specification**
OFDM symbols	500
length of OFDM symbols	80
Constellation Order	2
Pilot Symbols	2, 4, 8
Cyclic Prefix length	4
Channel Length or Taps	2, 4
SNR	0 to 40 dB
Modulation Scheme	QAM

3.1 Initialization

Initialization of the parameters is very first step towards the simulation. It can be seen in table 1 that different parameters have been initialized. Value of SNR has been set from 0 to 40 dB. Whereas, Pilot symbols have been initialized at 2, 4, and 8. Similarly, initialization values of channel taps have been set at 2 and 4. Further, the values of cyclic prefix, OFDM symbol length, Number of OFDM symbols have also been initialized. MIMO transmitters (2x2) have been employed in these simulations.

3.2 Transmitter

After initialization, the data bits are generated at transmitter. These data bits are sent to the transmitter for modulation. After modulation, the conversion of these data bits from serial to parallel is performed. After that insertion of pilot symbols to the streams is done so that estimation can be performed. Then IFFT performs a procedure to convert that streams to time domain, so that these bits can be easily transmitted further towards to receiver. Before sending these bits on the wireless channel, the cyclic prefixes are added to the streams and are converted to serial streams from parallel streams.

3.4 Channel

It is assumed that the channel is multipath fading channel, as multiple-input and multiple-output is employed. In this MIMO system, two transmitting and two receiving antennas have been employed. As there are multiple antennas, data streams arrive from different paths. Hence there is destructive interference in the data streams [22]. To resolve this problem, OFDM multiplexing is used. Besides destructive interference, channel also gets white Gaussian noise. It is described in the next paragraph.

3.5 Additive White Gaussian Noise (AWGN)

As the signal is transmitted on the wireless channel a noise is added to that signal. That noise is called Additive White Gaussian Noise (AWGN). AWGN is produced as a vector of random numbers with zero mean and variance one [23]. After that data streams reach at receiver end.

3.6 Receiver

All the operations that are performed at transmitter end are reversed at the receiver end. Whatever is done with data streams at the transmitter is reversed at the receiver [24]. For example, data is demodulated; data is converted to the frequency domain; data is converted from parallel to serial form; cyclic prefixes are removed, etc. The received data streams at this stage become noisy. To remove the noise in the data, the channel has to be estimated. How the channel is estimated is explained in the next session.

3.7 Channel Estimation

When data streams reach at the receiver end it is distorted due to the multipath fading and the noise in the channel. The channel has to be estimated for the sake of getting the exact information sent from the transmitter to the receiver. In order to do that channel estimates have to be obtained at each subcarrier. In general, the channel can be estimated with pilot symbols sent with data symbols to the receiver. Further, different interpolation method can be employed to estimate the data symbols. We have used MATLAB 'spline' functions for the data symbol estimation.

Different implementation aspects like performance, computational complexity, etc must be considered for the different techniques which are used for the estimation. Pilot based channel estimation has been selected for this thesis. The Least-Square (LS) and Minimum-Mean-Square-Error (MMSE) estimation techniques are generally employed when we use pilot symbols. These are described as follows:
Pilot symbols for N subcarriers, which are orthogonal to each other, can be represented by following diagonal matrix [25]:

$$X = \begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & 0 & \cdots & X[N-1] \end{bmatrix}$$

Where X[k] pilot symbol at the kth subcarrier with $E\{ X[k] \} = 0$ and $\mathrm{Var}\{ X[k] \} = \sigma^2_x$, k = 0,1, 2, …., N-1. As the all subcarriers are orthogonal, the X is given by diagonal matrix. If the channel gain is H[k] for each subcarrier k, the received signal Y[k] is given by:

$$\begin{bmatrix} Y[0] \\ Y[1] \\ \vdots \\ Y[N-1] \end{bmatrix} = \begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & 0 & \cdots & X[N-1] \end{bmatrix} \begin{bmatrix} H[0] \\ H[1] \\ \vdots \\ H[N-1] \end{bmatrix} + \begin{bmatrix} Z[0] \\ Z[1] \\ \vdots \\ Z[N-1] \end{bmatrix}$$

$$Y = XH + Z \quad (1)$$

Where H is the channel vector and Z is the noise vector. In the following discussion, let $\hat{H}$ *denote the estimate of H.*

3.7.1 *LS Channel Estimation*

Channel estimate $\hat{H}$ *is found by Least Square channel estimation by reducing the following cost function [26].*

$$J(\hat{H}) = \|Y - X\hat{H}\|^2$$
$$= (Y - X\hat{H})^H (Y - X\hat{H})$$
$$= Y^H Y - Y^H X\hat{H} - \hat{H}^H X^H Y + \hat{H}^H X^H X\hat{H}$$

By taking the derivative of the function with respect to $\hat{H}$ *to zero:*

$$\frac{\partial J(\hat{H})}{\partial \hat{H}} = -2(X^H Y)^* + 2(X^H X\hat{H})^* = 0$$

We get $X^H X\hat{H} = X^H Y$, *this gives the solution to the LS channel estimation as*

$$\hat{H}_{LS} = (X^H X)^{-1} X^H Y = X^{-1} Y \quad (2)$$

If each component of LS channel estimate $\hat{H}_{LS}$ *can be denoted by* $\hat{H}_{LS}[k]$, *where k = 1, 2 … N-1, then the LS channel estimate of each subcarrier can be written as,*

$$\hat{H}_{LS}[k] = \frac{Y[k]}{X[k]} \quad (3)$$

The Mean Square Error (MSE) of the LS channel estimate is given as

$$MSE_{LS} = E\{(H - \hat{H}_{LS})^H (H - H_{LS})\}$$
$$= E\{(H - X^{-1}Y)^H (H - X^{-1}Y)\}$$
$$= E\{(X^{-1}Z)^H (X^{-1}Z)\}$$

$$= E \{Z^H (XX^H)^{-1} Z\}$$

$$MSE_{LS} = \frac{\sigma_z^2}{\sigma_x^2} \quad (4)$$

From above equation of MSE_{LS}, which is inversely proportional to SNR ($\frac{\sigma_x^2}{\sigma_z^2}$), it is implied that noise enhancement may be subjected on it.

3.7.2 Minimum Mean Square Error Channel Estimation

For reducing the MSE in the channel, MMSE uses the second order statistics. The auto covariance of the channel impulse response (R_{gg}) and the transfer function (R_{HH}) are known to the receiver [27]. These second order statistics increase the MMSE's computational complexity.

$$R_{HH} = E\{\vec{H}\vec{H}^H\} = E\left\{\left(F\vec{g}\right)\left(F\vec{g}\right)^H\right\} = F R_{gg} F^H$$

$$R_{gY} = E\{\vec{g}\,\vec{Y}^H\} = E\left\{\vec{g}\left(XF\vec{g} + \vec{N}\right)^H\right\} = R_{gg} F^H X^H$$

$$R_{YY} = E\{\vec{Y}\vec{Y}^H\} = XFR_{gg}F^H X^H + \delta_N^2 I_N$$

Channel Estimates $\vec{H}$ of MMSE estimator are given by:

$$\vec{H}_{MMSE} = R\, F_{gY}\, R_{YY}^{-1}\vec{Y}$$

$$= F\left\{\left(F^H X^H\right)^{-1} R_{gg}^{-1}\,\delta_N^2 + XF\right\}^{-1}\vec{Y}$$

$$= F\, R_{gg}\left\{\left(F^H X^H X F\right)^{-1} R_{gg}^{-1}\,\delta_N^2 + R_{gg}\right\} F^{-1} H_{LS}$$

$$\vec{H}_{MMSE} = R_{HH}\left\{\delta_N^2\left(X X^H\right)^{-1} + R_{HH}\right\}^{-1} H_{LS} \quad (5)$$

4. Results and Discussions

4.1 Effect of Pilot Symbols on Channel Estimations

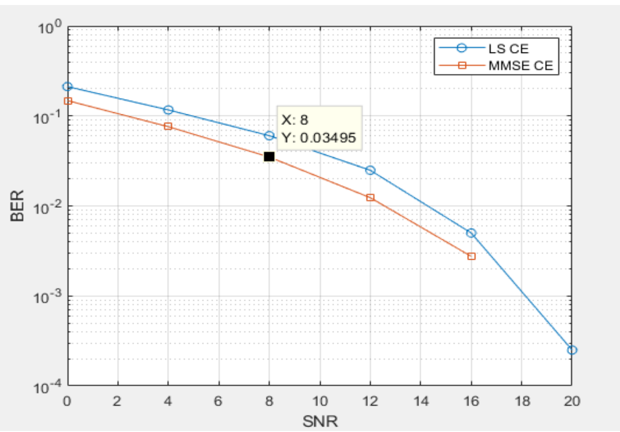

Figure 1: Channel Estimations with Pilot Symbols=2

Table 2: Channel Estimations with Pilot Symbols=2

Using pilot Symbols=2						
LS CE	SNR	0	4	8	12	16
MMSE CE		0	4	8	12	16
LS CE	BER	0.212	0.1166	0.0603	0.0249	0.005
MMSE CE		0.1481	0.0759	0.0349	0.0123	0.0027

Figure 1 shows the value of BER of the LS and MMSE channel estimations. From the figure 1, it may be noted that the BER of the LS and of the MMSE channel estimations decreases as the SNR of these channel estimations increases. For example, as shown in table 2, at SNR value 0, the BER value of the LS and MMSE remains at 0.212 and 0.1481 respectively. But at SNR value 4, the BER value of the LS and MMSE channel decreases to 0.1166 and 0.0759 respectively. The more we increase the SNR value, the more BER value decreases. Moreover, the channel estimation in MMSE outperforms the channel estimation in LS.

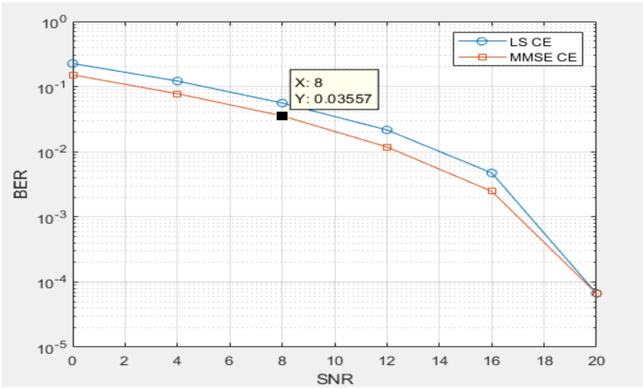

Figure 2: Channel Estimations with Pilot Symbols=4

Table 3: Channel Estimations with Pilot Symbols=4

Using pilot Symbols=4						
LS CE	SNR	0	4	8	12	16
MMSE CE		0	4	8	12	16
LS CE	BER	0.226	0.1218	0.0559	0.0216	0.004
MMSE CE		0.1514	0.0777	0.0355	0.0118	0.0024

Figure 2 shows the value of BER of the LS and MMSE channel estimations. From the figure 2, it can be seen that the BER of the LS and of the MMSE channel estimations decreases as the SNR of these channel estimations increases. For example, as shown in table 3, at SNR value 0, the BER value of the LS and MMSE remains at 0.226 and 0.1514 respectively. But at SNR value 4, the BER value of the LS and MMSE channel decreases to 0.1218 and 0.0777 respectively. The more we increase the SNR value, the more BER value decreases. Moreover, the channel estimation in MMSE outperforms the channel estimation in LS.

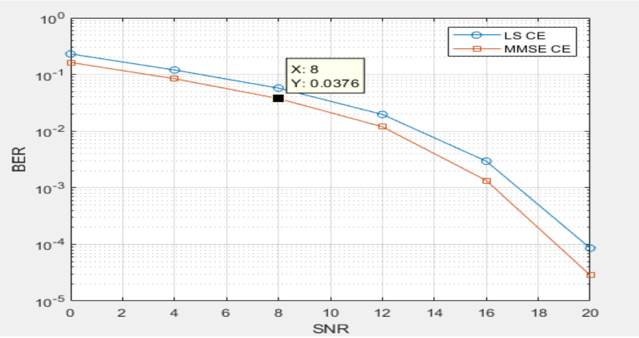

Figure 3: The Channel Estimations with Pilot Symbols=8

Table 4: The Estimations with Pilot Symbols=8

Using pilot Symbols=8						
LS CE	**SNR**	0	4	8	12	16
MMSE CE		0	4	8	12	16
LS CE	**BER**	0.2305	0.1199	0.0574	0.0196	0.0029
MMSE CE		0.1629	0.0841	0.0376	0.0119	0.0013

Figure 3 shows the value of BER of the LS and MMSE channel estimations. From the figure 3, it can be seen that the BER of the LS and of the MMSE channel estimations decreases as the SNR of these channel estimations increases. For example, as shown in table 4, at SNR value 0, the BER value of the LS and MMSE remains at 0.2305 and 0.1629 respectively. But at SNR value 4, the BER value of the LS and MMSE channel decreases to 0.1199 and 0.0841 respectively. The more we increase the SNR value, the more BER value decreases. Moreover, the channel estimation in MMSE outperforms the channel estimation in LS. This must be noted that as the number of Pilot Symbols increases, the value of BER of the LS and MMSE channel estimators also increases. Accordingly, the SNR value of these estimators decreases. Consequently, the efficiency of the channel estimators has suffered. The MMSE channel estimator's performance with regards to channel estimation is way better than the LS channel estimator. But the MMSE channel estimator suffers from more computational complexity than the LS channel estimator.

4.2 Effect of Channel Taps on Channel Estimations

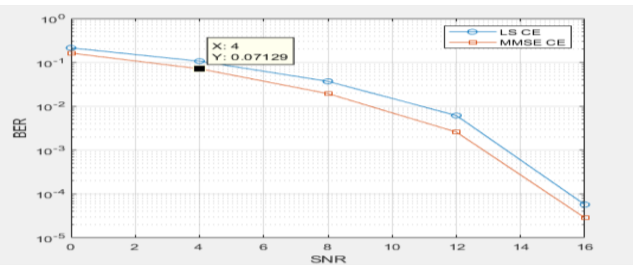

Figure 4: The Channel Estimations with Pilot Symbols=8 and Channel Taps=2

Table 5: The Channel Estimations with Pilot Symbols=8 and Channel Taps=2

Using pilot Symbols=8 and Channel Taps=2						
LS CE	**SNR**	0	4	8	12	16
MMSE CE		0	4	8	12	16
LS CE	**BER**	0.2192	0.1062	0.0368	0.0061	5.71E-05
MMSE CE		0.1624	0.0712	0.0193	0.0025	2.86E-05

Figure 4 shows the value of BER of the LS and MMSE channel estimations on different channel taps. From the figure 4, it can be seen that the BER of the LS and of the MMSE channel estimations decreases as the Channel Taps of these channel estimations increase. For example, as shown in table 5, by using value of Channel Taps 2, at SNR value 0, the BER value of the LS and MMSE remains at 0.2192 and 0.1624 respectively. But at SNR value 4, the BER value of the LS and MMSE channel decreases to 0.1062 and 0.0712 respectively. Keeping the value of Channel Taps at 2, the more we increase the SNR value, the more BER value decreases. Further, let's see, in the following figure, what happens when the Channel Taps are increased.

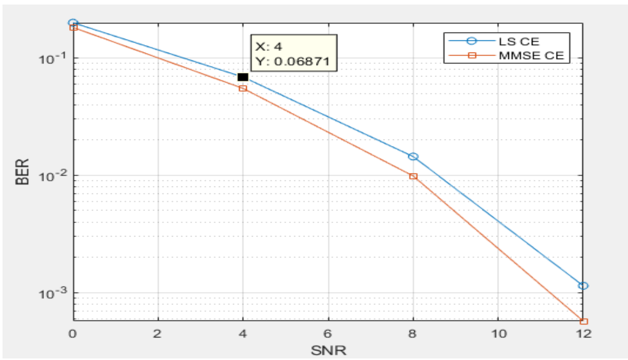

Figure 5: The Channel Estimations with Pilot Symbols=8 and Channel Taps=4

Table 6: The Channel Estimations with Pilot Symbols=8 and Channel Taps=4

Using pilot Symbols=8 and Channel Taps=4						
LS CE	**SNR**	0	4	8	12	16
MMSE CE		0	4	8	12	16
LS CE	**BER**	0.1995	0.0687	0.0144	0.0011	0
MMSE CE		0.1821	0.0549	0.0098	0.0005	0

Figure 5 shows the value of BER of the LS and MMSE channel estimations on different Channel Taps. From the figure 5, it can be seen that the BER of the LS and of the MMSE channel estimations decreases as the Channel Taps of these channel estimations increase. For example, as shown in table 6, by using value of Channel Taps 4, at SNR value 0, the BER value of the LS and MMSE remains at 0.1995 and 0.1821 respectively. But at SNR value 4, the BER value of the

LS and MMSE channel decreases to 0.0687 and 0.0549 respectively. Keeping the value of Channel Taps at 4, the more we increase the SNR value, the more BER value decreases.

4.3 MIMO Capacities of Various Channels

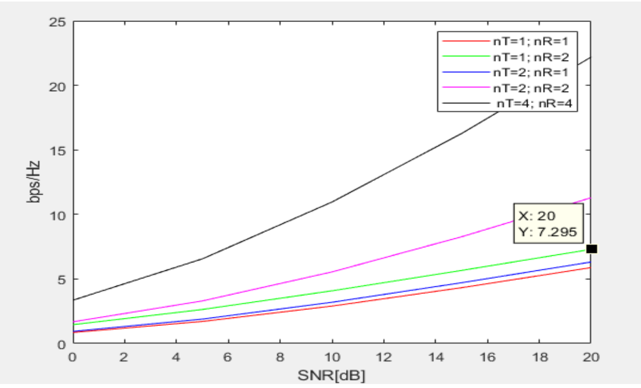

Figure 6: MIMO capacities of channels with different Antennas

Table 7: MIMO capacities of channels with different Antennas

MIMO Channel Capacities					
SNR	0	5	10	15	20
1T_1R--bps/Hz	0.9	1.84	3.13	4.64	5.88
1T_2R--bps/Hz	1.44	2.61	4.06	5.64	7.29
2T_1R--bps/Hz	0.8	1.83	2.99	4.33	6.25
2T_2R--bps/Hz	1.68	3.3	5.54	8.26	11.29
4T_4R--bps/Hz	3.35	6.56	10.96	16.27	22.19

The Multiple-Input and Multiple-Output (MIMO) is a technique for increasing the channel capacity without sending extra signal power or utilizing the extra bandwidth. As compared to single receive and transmit antennas, the multiple transmit and receive antennas increase the system capacity by the factor of minimum number of antennas. The channel capacity is directly related to the number of antennas that are used in a system. For increasing the system capacity, different multiple antenna techniques are used. Precoding or Beamforming is one such technique. In Beamforming same data stream, with appropriate phase and gain, is transmitted from each transmit antennas. At the receiver, the data streams from these antennas are constructively added up for increasing the capacity of the system. Similarly, spatial multiplexing is another technique for improving the system capacity. This technique is used to divide the main signal stream into different smaller data streams. All these different data streams are sent through different transmitting antennas on the same frequency channel. Further, there is another technique i-e Diversity Coding which is also used to increase the system capacity. In Diversity Coding technique, the same streams which are coded with space timing coding are sent from the different transmit antennas.

From the figure 6 it can be seen that the capacity system increases when the number of antennas also increases. For example, as shown in table 7, at SNR value 0, the capacity of single transmitting and receiving antenna remains at 0.9 bps/Hz. Referring to the table 6, at SNR value 0, with one transmitting antenna and two receiving antennas, capacity increases from 0.9 bps/Hz to 1.44 bps/Hz. There is a significant increase in the system capacity when the four transmitting and four receiving antennas are used. At SNR value 0, and with four transmitting and receiving antennas, the system capacity reaches to 3.35 bps/Hz. Similarly, when the SNR value is increased, the system capacity is also improved. Referring to the table 6, at SNR value 20, with four transmitting and receiving antennas, capacity increases from 5.88 bps/Hz to 22.19 bps/Hz, as compared to single antennas.

5. Conclusion

MIMO-OFDM systems are believed to the best systems for increasing the channel capacity, for reliable wireless communication, and for the better utilization of available bandwidth. In order to get these benefits of MIMO-OFDM system, the channels must be estimated first. Channel estimation can be done by LS and MMSE techniques. LS and MMSE estimators use pilot symbols for channel estimation. From results it can be concluded that, the performance of MMSE channel estimator is way better than LS estimator. Whereas, LS estimator is simple to implement, but MMSE estimator suffers from computational complexity. Further, from the results it can be concluded that the size of pilot symbols and the channel taps do affect the performance of estimation techniques. The greater the size of the pilot symbols, the worse the efficiency of the system. Similarly, the greater the channel taps or length, better the performance. So, it can be concluded that estimation of channels in MIMO-OFDM system is of utmost importance for effective performance of the system.

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