

All-Digital Self-Interference Cancellation Technique for MIMO Full-Duplex Systems

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ABSTRACT

In this paper, the MIMO full-duplex system is proposed to remove self-interference signal using modified DFT based channel estimation technique. In SISO full-duplex systems only single transceiver can transmit data on either side simultaneously whereas in MIMO full-duplex systems multiple transceivers can transmit data simultaneously from both sides. During MIMO full-duplex transmission self-interference and circuit impairments may occur, to avoid such noises digital cancellation technique is used which is a lowest complexity self-interference cancellation technique in all full-duplex systems. In this technique receiver auxiliary chain and its copy circuit called ordinary receiver chain is used to cancel out the both self-interference and its circuit impairments. Noise added during wireless channel is suppressed by using passive suppression technique and Gaussian noise, phase noise and quantization noise is eliminated by the active cancellation technique. So, combination of active cancellation and passive suppression techniques are used to eliminate the circuit impairments. The proposed channel estimation technique is used to cancel out the self-interference produced at the output of both auxiliary and ordinary receiver chains. By using digital self-interference cancellation technique the amount of self-interference cancelled is 37dBm higher than the receiver noise floor. The achievable rate and throughput of MIMO full-duplex system is 28 bits/sec/Hz and 1049.04 Mbps respectively which is very large when compared to MIMO half-duplex, SISO full-duplex and SISO half-duplex systems.

General Terms

QAM, OFDM, Modified DFT based channel estimation, Digital cancellation.

Keywords

Full-duplex system, Digital self-interference, MIMO, Channel capacity, Throughput, Spectral efficiency

1. INTRODUCTION

The exponential evolution in mobile data traffic demands a spectrum and power efficient wireless transceiver which is capable to keep up this growth. To meet this demand, the solution was using high amount of spatial streams, efficient modulation schemes like 16 QAM, enhanced channel codes etc. But, there is one essential feature of wireless transceivers which was not seen anywhere is duplexity. Full-duplex wireless devices use the same frequency band for simultaneous transmission and reception. Recently, this concept has gained much attraction in the research

community, since the capacity [10] of a wireless link might be doubled with respect to half-duplex systems.

The main constraint impacting full-duplex transmissions [5] is managing the strong self-interference signal which transmits and receives the signal simultaneously by using the same transceiver. For a full-duplex system to reach its greater spectral efficiency, the distorted signal is to be significantly blocked to the receiver reference noise floor. Self-interference cancellation technique is categorized into two types: passive suppression and active cancellation techniques. In passive suppression technique [4], the self-interfered signal is blocked before it passed through receiver circuitry. In case of active cancellation technique [7], the unwanted signals are removed by using digital cancellation technique [1], [2]. Before the signal entered into the receiver section nonlinearity is reduced by using the RF-power amplifier whose output signal is linear for most of the input signal and phase noise [3] is reduced by using PLL circuit.

The remaining of the paper is planned as follows: Design of MIMO full duplex system is discussed in section II. Section III deals with the experimental results and analysis of the proposed MIMO full duplex system. Section IV deals with the calculation of the system parameters called achievable rate, channel capacity, throughput and spectral capacity of the proposed MIMO full duplex system. Finally, Section V derives the conclusion.

2. SYSTEM MODEL

The complete system prototypical of proposed MIMO full-duplex system [6] architecture is displayed in fig 1. The system prototypical consists of both ordinary and auxiliary receiver chains which are used to cancel out the self-interference signal. At the transmitter side, both information signals X_1 and X_2 are modulated and converted into time domain signals using OFDM. The time domain signal is then filtered using LPF, amplified using PA and power divided signals are transmitted through the transmitting antennas. The amount of divided signal is then given to both auxiliary and ordinary chains equally. The auxiliary and ordinary receiver chains are frequency converted and share the same PLL to reduce phase noises.

The output of both auxiliary and the ordinary receiver chains are given to proposed channel estimator to eliminate noise for large extent. Now, the estimated channel is multiplied with the auxiliary receiver output signal and then subtracted from the ordinary received signal to obtain interference-less signal. The output of the digital cancellation signal is QAM demodulated to get original signals Y_1 and Y_2 .

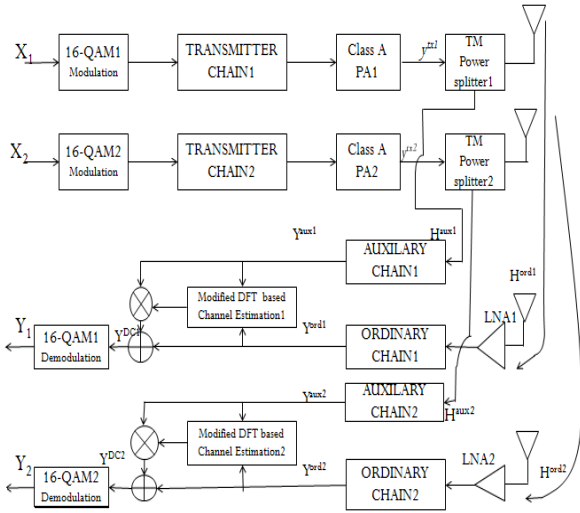


Fig 1: Complete block diagram of the proposed MIMO full duplex system

2.1 QAM

In QAM single carrier which is generated by a local oscillator circuit is divided equally into two paths, one path is delayed by 90 degrees called quadrature phase component and another path is a direct path called in phase component. Both are amplitude modulated and added together in a summing circuit to get information on both amplitude and phase of the transmitted carrier.

2.2 Transmitter Chain

The transmitter chain consists of OFDM, DAC, mixer along with PLL and filter. OFDM transmits huge amount of digital time domain non-overlapping narrow band subcarriers which are closely placed to each other's. Orthogonality between subcarriers is achieved by using IFFT at the transmitter side and FFT at the receiver side respectively [8]. IFFT converts digital frequency domain signals into digital time domain signals for base band wireless applications and FFT is used to convert digital time domain signals into digital frequency domain signals to make analysis easy. The one fourth length of IFFT is appended at the starting of the previous symbol called cyclic prefix or guard interval to lessen ISI between present and previous symbols during multipath propagation. DAC converts digital signal into an analog signal for base band wireless applications.

2.3 Power Amplifier

Power amplifier is an important module in modern wireless communication systems to increase the signal strength before it is processed through the wireless channel. The point at which output power is decreased at certain input level is called 1-dB Compression Point [12]. The power amplifier input and output relation diagram is displayed in below fig 2.

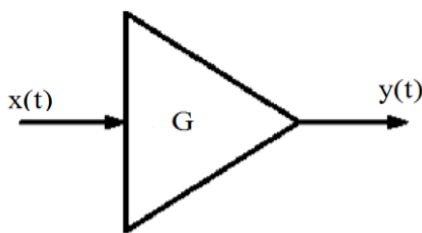


Fig 2: power amplifier input and output relation diagram

The system equation of linear power amplifier is taken as

$$y(t) = \beta_1 x(t) \quad (1)$$

Due to the effect of non-linearity the overall equation of the RF power amplifiers is generalized as

$$y(t) = \beta_1 x(t) + \beta_3 x(t)^3 \quad (2)$$

When a sinusoidal signal is applied to the input signal then the equation (2) can be taken as

$$y(t) = \beta_1 x(t) + \frac{3}{4} \beta_3 x(t) A^2 \quad (3)$$

2.4 Power Splitter

Power splitter splits single input signal into the two equal signals. The direction of power flow is normal to the plane containing both E and H components.

$$P_z = \frac{1}{2} |\vec{E}_x \times \vec{H}_y| \quad (4)$$

In Transverse Magnetic (TM) case Magnetic vector (H_x or H_y) is normal to the direction of propagation while Electric vector has both normal and parallel components (E_{zx} or E_{zy}). So, under PML condition the reflection quotient (R_p) is zero when it interface normal to either x-axis or y-axis. When a plane wave propagating along y-axis, PML medium absorbs both H_y and E_{zx} components [13] and allows H_x and E_{zy} components. When a plane wave propagating along x-axis, PML medium absorbs both H_x and E_{zy} components and allows H_y and E_{zx} components.

2.5 Wireless Channel

Rayleigh fading [9] prototypical is mainly convenient in the circumstances where the signal is dispersed between the transmitter and receiver, which means signal spreads in multipath broadcasts. The real and imaginary parts of the response are demonstrated by

$$r(t) = x(t) + j y(t) \quad (5)$$

The signal is randomly attenuated and shifted in phase are expressed as

$$R(t) = \sqrt{(x(t))^2 + y(t)^2} \quad (6)$$

$$R(\varphi) = \angle (x(t) + j y(t)) \quad (7)$$

2.6 LNA

LNA is used to strengthen the received RF signal from the wireless channel to an acceptable level and minimizing the noise added to it. The noise is minimized and signal strength is increased by using the stability analysis [11] and matched network selection. The 'BJT AT-31011' has better stability on the required frequency range of 2.4 GHz. By using two port network concept input reflection coefficient, output reflection coefficient and power available at the output of LNA have been calculated.

2.7 Proposed Modified-DFT Based Channel Estimation Technique

The LS estimation is the modest channel estimation technique based on the parallel Gaussian channel model in frequency domain. Since the LS channel estimation technique [14] does not use any channel information its performance is not up to acceptable level. So, the proposed modified LS channel estimation technique called modified DFT-based channel

estimation technique has been used because of low-computational complexity.

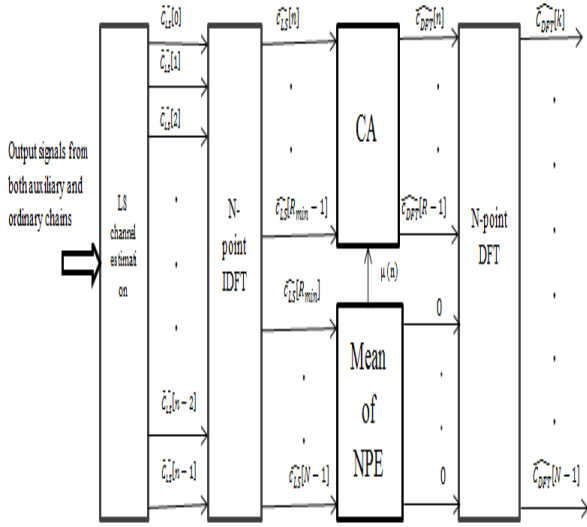


Fig 3: Block diagram of modified DFT-based channel estimation

The LS channel output signal has both original signal and noise signal. According to DFT-based channel estimation technique it takes the output values up to the length of the CIR R whose length is less than the length of the guard interval and the remaining signal except length of the CIR is taken as zeros because it has noise only components. This technique also does not give the proper information but better than LS channel estimation. Now, the proposed modified DFT-based channel estimation technique displayed in above fig 3 consists of Channel Aggregator (CA) and mean of Noise Power Estimator (NPE) gives the proper channel information. The noise components which are directly taken zeros in the previous technique have some amount of information. So, that noise components are averaged and added to the CA to improve the signal information.

The mean of NPE first average all the time domain NPE noise-only existing part and added to the CA. The expression for NPE is given by

$$\sigma_{noise}^2(n) = \frac{1}{N-R_{min}} \sum_{n=R_{min}}^{N-1} |\widehat{c}_{LS}[n]|^2 \quad (8)$$

Now, the mean of NPE is expressed as

$$\mu(n) = \frac{1}{N-R_{min}} \sum_{n=R_{min}}^{N-1} (\sigma_{noise}^2(n)) \quad (9)$$

Where,

$$\mu(n) = \text{mean of NPE}$$

The discrete Mean Square Error (MSE) of modified DFT-based channel estimation technique of n^{th} subcarrier is expressed as

$$MSE_{prop}[n] = \frac{(R_{min}+1)^2 \gamma^*}{(K-2)^3} \left(\frac{S}{N}\right) \quad (10)$$

Where,

$$R_{min} = \text{minimum value among the lengths of CIR}$$

The MSE value is depends on the length of the CIR. If the length of the CIR is maximum (R_{max}) then the maximum MSE is obtained. So, in the proposed modified-DFT based channel

estimation technique minimum CIR (R_{max}) length is taken to obtain the least MSE value.

3. EXPERIMENTAL RESULTS and ANALYSIS

The QAM output signal has a complex constellation points ($I + jQ$) which are normally organized in a square set-up with equal vertical and horizontal spacing between them. Each point in a 16 QAM has separate amplitude and phase information (for example the point 0000 in a 16 QAM has amplitude value 0.9 volts and phase value -135 degrees and so on for all other 15 points). In OFDM, IFFT is used to convert digital frequency domain samples into digital time domain samples which is having 1000 symbols with each symbol of 64 bits (52 subcarriers+12 pilot carriers). So, 64 IFFT is used for this conversion process. Each symbol among 1000 symbols is separated by 1ms and every symbol has 64 bits that each bit is separated by 15ms. So, overall each bit from total of 1000 symbols is separated by $15\mu s$. As each bit is separated by some seconds all the bits are non-overlap to each other. So, by using IFFT in OFDM all the bits are transmitted orthogonally. The end of the OFDM symbol is copied into the guard interval and this guard interval is transmitted followed by OFDM symbol. So, 25% at the end of a present symbol is copied and appended at the starting of that symbol itself to eliminate the inter symbol interference from the earlier symbol. Therefore 16 bits are added at the starting of each IFFT output to get total of 80 bits per symbol.

Basically, a filter can be used to reject all unwanted signal components and pass only those signals which are to be allowed for the further processing. The output of the transmitter chain signal is a weak signal, for base band wireless applications strong signal strength should be necessary because it will travel for long distances during wireless transmissions. So, PA strengthens the weak signal from 67dBm to 122dBm with 50% efficiency and 55dB gain. The PS splits output of the PA 122dBm into two equal signals of 122dBm each. By using PML concept [15] the loss less power dividing is possible that is input 122dBm is purely obtained at the output. The Rayleigh fading attenuates nearly 67dBm power from 122dBm to get 54dBm power because of the multipath distortion. AWGN is simply adds uniformly distributed white Gaussian noise to the output of Rayleigh fading which gives the signal to noise ratio 12dB.

The signal strength of LNA is increased from 54dBm to 67dBm which is nearly equal to the output signal of the transmitter chain and the SNR is increased to 21dB which much better than the wireless channel. The maximum available gain of LNA is 53dB. ARC output directly taken from PS which is a wired communication, but ORC output is taken from wireless channel. Due to attenuation losses in wireless channel ORC amplitude value is very small when compared to ARC. It has very low quantization noise nearly equal to zero because of high number of bits (80000). The time domain samples are converted into frequency domain samples for analysis of complete system. LS channel estimation is very easy technique to implement but it has no perfect channel information. So, proposed modified DFT based channel estimation is used to improve channel information. The MSE value for LS channel estimation technique is very large because it does not have any channel information. So, MSE is decreased to a satisfactory level by using the DFT based channel estimation technique which divides the maximum length of channel taps by output of LS channel estimator. Now, by using proposed modified DFT

based channel estimation technique MSE value is decreased by a large extent as displayed in the below fig 4.

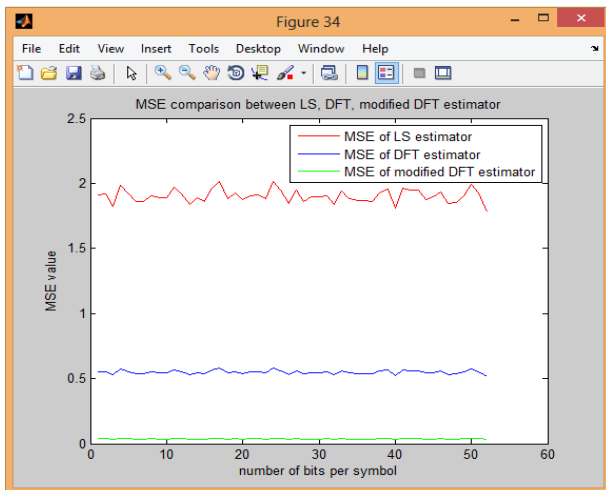


Fig 4: MSE comparison between LS, DFT and Modified DFT channel estimators

The noise floor has -90 dBm self-interference signal which is taken as reference signal. By using the digital cancellation technique the SISO self-interference cancellation signal is -87 dBm which is a 3 dBm above the noise floor. Now, the obtained proposed MIMO self-interference cancellation signal is -53 dBm which is a 57 dBm above the noise floor. The proposed technique is 54 dBm above the previous SISO full duplex system technique.

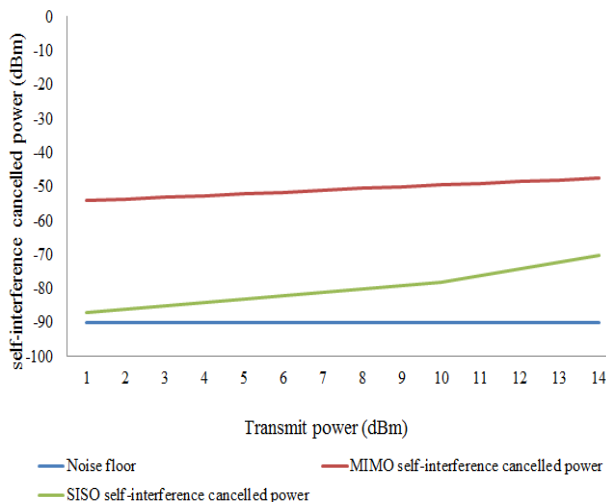


Fig 5: self-interference cancellation comparison between noise floor, MIMO system and SISO system

The SNR of the channel is very low that is 8 dB when compared to the LNA and channel estimation due to attenuation and phase losses by the rayleigh fading. So, by using the matched network circuits and S-parameter model the reduced signal is increased to required value and its signal to noise ratio is increased to 14 dB. By using proposed modified DFT based channel estimation technique the SNR is increased to 20 dB which is high value when compared to channel and LNA outputs.

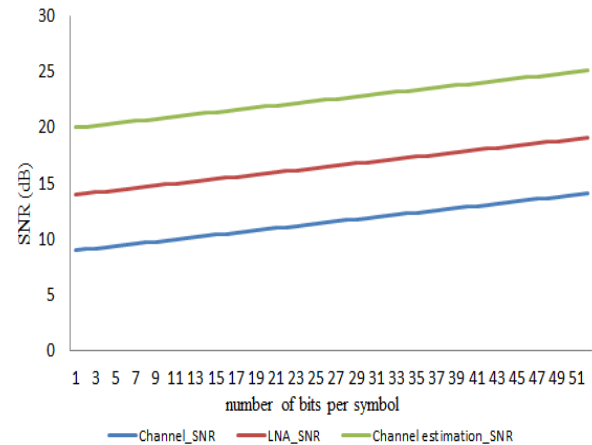


Fig 6: SNR comparison between channel, LNA and channel estimation

4. CALCULATIONS of SYSTEM PARAMETERS

4.1 Calculation of Achievable Rate

The obtained achievable rate for the MIMO full duplex system is 28 bits/sec/Hz which is higher than MIMO half-duplex system 14 bits/sec/Hz, SISO full duplex system 10 bit/sec/Hz and SISO full duplex system 5 bit/sec/Hz as displayed in the below fig 7.

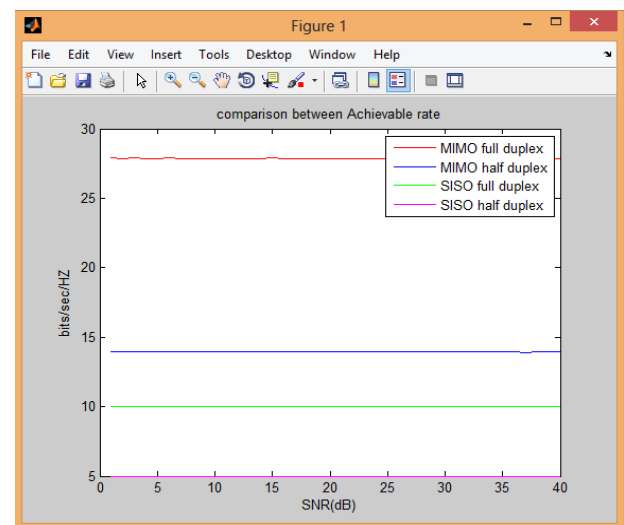


Fig 7: Achievable rate comparison between MIMO full duplex, MIMO half duplex, SISO full duplex and SISO half duplex systems

4.2 Calculation of Channel Capacity

The obtained channel capacity for the MIMO full duplex system is 560000000 bits/sec (534.05 Mbps) which is higher speed than MIMO half-duplex system 280000000 bits/sec (267.02 Mbps), SISO full duplex system 200000000 bit/sec (190.73 Mbps) and SISO half-duplex system 100000000 bit/sec (95.36 Mbps) as displayed in the below fig 8.

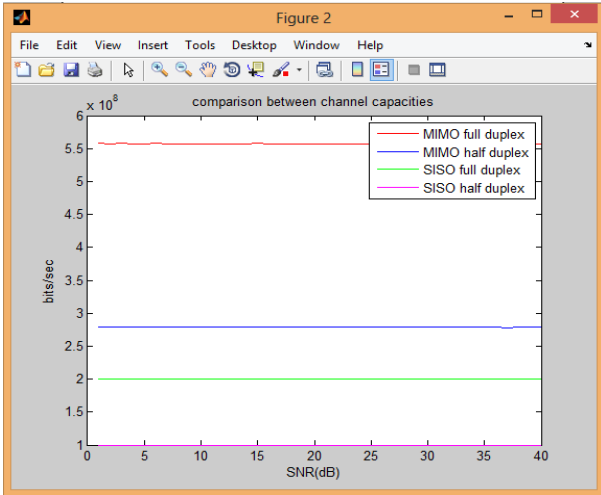


Fig 8: Channel capacity comparison between MIMO full duplex, MIMO half duplex, SISO full duplex and SISO half duplex systems

4.3 Output of Throughput

The obtained throughput for the MIMO full duplex system is 170000000 bits/sec (162.12 Mbps) which is higher speed than MIMO half-duplex system 120000000 bits/sec (81.06 Mbps), SISO full duplex system 200000000 bit/sec (19.07 Mbps) and SISO half-duplex system 10000000 bit/sec (9.53 Mbps) as displayed in below fig 9.

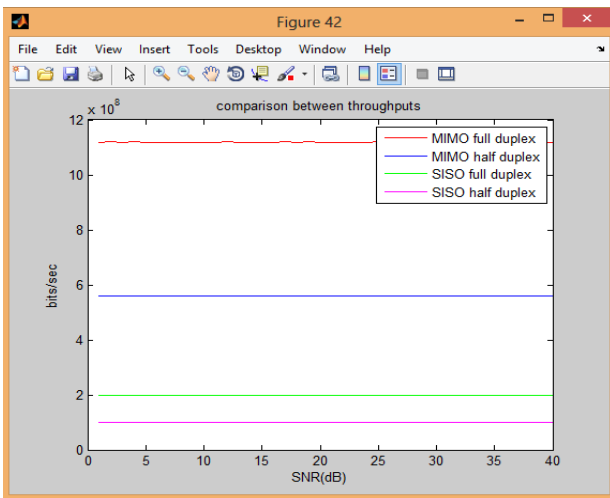


Fig 9: Throughput comparison between MIMO full duplex, MIMO half duplex, SISO full duplex and SISO half duplex systems

4.4 Output of Spectral Efficiency

The obtained spectral efficiency for the MIMO full duplex system is 82% which is higher efficiency than SISO full duplex system 76% as displayed in the below fig 10.

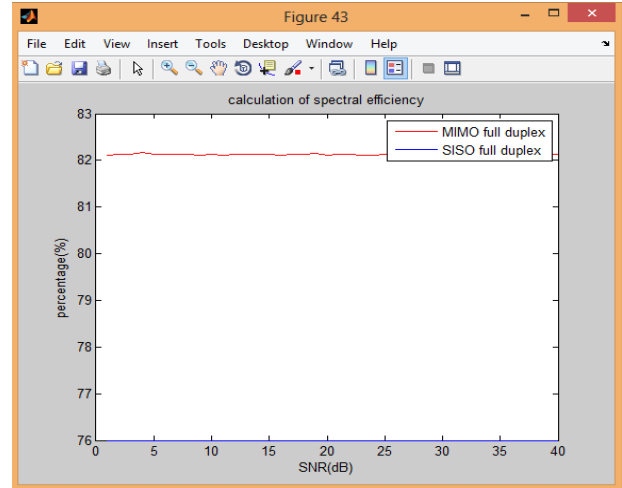


Fig 10: spectral efficiency comparison between MIMO full duplex, MIMO half duplex, SISO full duplex and SISO half duplex systems

The channel capacity and throughput of MIMO full duplex system is large when compared to MIMO half duplex, SISO full duplex and SISO half duplex systems. So, MIMO full duplex system delivers high data rate when compared to other systems as displayed in the below table 1.

Table 1. Achievable rate, channel capacity and throughput comparison between MIMO full duplex, MIMO half duplex, SISO full duplex and SISO half duplex systems

Type of system	SNR (dB)	Achievable rate (bits/sec/Hz)	Channel capacity (Mbps)	Throughput (Mbps)
MIMO full duplex system (proposed method)	40	28	534.05	1049.04
MIMO half-duplex system	40	14	267.02	524.50
SISO full duplex system	40	10	190.73	190.73
SISO half-duplex system	40	5	95.36	95.36

5. CONCLUSION

The designed MIMO full-duplex system uses QAM for information carried out in both amplitude and phase of the transmitter carrier. By using OFDM technique the symbols created by the QAM travels orthogonally along the wireless channel and digital domain signal is converted into analog domain signal for wireless base band applications. PA in the transmitter side strengthens the signal to a large extent and splits the strengthened signal equally into wired and wireless channels. When the signal passes through wireless channel its strength decreases and noise added due to the Rayleigh fading and AWGN.

LNA in the receiver section increases the signal strength to a required value and converts into the digital signal for digital applications. The receiver section consists of auxiliary chain and its copy circuit called ordinary chain is given to channel estimation which reduces the noise to an optimized value. By using proposed modified DFT based channel estimation technique the amount of self-interference cancelled is 57dBm higher than the receiver floor. The achievable rate and

throughput of MIMO full duplex system is 28 bits/sec/Hz and 1049.04 Mbps respectively which is very large when compared to MIMO half duplex , SISO full duplex and SISO half duplex systems.

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