DESIGN OF RF CANCELLATION FOR 5G FULL-DUPLEX MIMO SYSTEMS

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Abstract

The imagination vision of for our the future of wireless communications is for the a better quality of service, higher data rates, and decreased latency, all of which is an importantform the focus of the fifth generation (5G) technologies. Thus, the prime concept of is a full-duplex single-channel (FDSC) for multiple input, multiple output (MIMO) systems which can provide double throughput and higher spectral efficiency. The design and simulation results of the FDSC communication for MIMO systems are the methods to for transmitting and receive receiving at the same time on the same frequency. The main challenge of full-duplex communication systems are the resulting self-interference and mutual-interference signals. In this paper, we propose a novel technique for the interference cancellation using a pre-defined RF radio frequency circuit network in the analog cancellation part. Our simulation results show that the proposed technique can improve the performance of the transmitting and receiving systems depending on the decrease of the interference powers.

Keywords: MIMO systems, self-interference, mutual-interference, full-duplex communication

Introduction

In the near future, the concept of full-duplex (FD) communications are has the potential and promising technology for the fifth generation (5G) of wireless communication systems as well as the multiple-input, multiple-output (MIMO) systems (Albreem M . A. M., *et al*., 2015; Gupta and Jha, 2015; Zhang X., *et al*., 2015a). It The concept has been accepted as the key idea of the designed 5G technology in order to increase demand for higher data rates, more users, and real-time. Thus, the approach of FD wireless communication approaches is to increase the data rates, high spectral efficiency, and double throughput, and to have a larger network capacity. Moreover, the FD wireless transmission is typically implemented using both time division multiplexing (TDD) and frequency division multiplexing (FDD). The simultaneous transmitting and receiving operate at the same time and on the same frequency band (Zhang Z., *et al*., 2016; Alves H., *et al*., 2015), the so- called the full-duplex single-channel (FDSC). The challenge of this concept is the strong interference signals generated from transmitter to receiver

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at the same side. The interference signal is happened happens that because of the signal leakage between transmitting and receiving at the same antenna, so called as the self-interference signal. The literatures proposes many techniques in order to suppress self-interference. The radio frequency (RF) interference cancellations are is proposed in the literatures (Bharadia and Katti, 2014; Zhang Z., *et al*., 2015b; Choi J. I., *et al*., 2010; Liempd V., *et al*., 2014). In (Bharadia and Katti, (2014), authors have cancelled the self-interference by using an RF cancellation circuit, whose the complexity of which scales linearly with the number of antennas, and this complexity is as close to the optimum as possible. In (Choi J. I., *et al*., (2010), this literature presentsproposed using an antenna cancellation technique which uses 2 transmitting antennas and 1 receiving antenna. For a wavelength λ, the 2 transmission antennas are placed at distances d and d+$\frac{\lambda}{2}$ from the receive receiving antenna. Offsetting the 2 transmitters by half a wavelength causes their signals to add destructively and cancel one another.

The FDSC MIMO system is one of the most interesting technologies for 5G wireless communications. This is because the system is able to transmit and receive simultaneously within a single channel. Moreover, the problem of interference signals are happened happens due to multiple transmitting and receiving antennas. The interference signals are happenedoccur between antennas both the transmitting and receiving antennas, so which is called as mutual-interference. This problem is not considered by in all the techniques in the literatures. The interference signals are is the a combination of both the self-interference and mutual-interference signals. The past previous techniques considers only self-interference. The analog cancellation is proposed using the elimination of the self-interference signal. The main keys of the interference cancellation are the amplifier and phase shifter techniques. Many works in the literatures neglect the real power (Lioliou P., *et al*., 2010; Suraweera H. A., *et al*., 2013; Sung Y., *et al*., 2012; Darsena D., *et al*., 2015).

In this paper, the design of the RF cancellation for a 5G FDSC 2×2 2x2 MIMO system has beenis presented. The design of the analog cancellation is pre-known as for the interference signals. This design uses the a combination of a modified hybrid coupler and a phase shifter. The modified hybrid coupler is designed from the different phase between mutual-interference and self-interference. As a result, it is that the success of the interference signal cancellation by using the novel technique is proposed. The results show that the proposed technique is not only to suppresses the interference but also to improves the system's performance capacity.

Problem Formulation

In this section, the authors explain the basic challenges in building an FD full-duplex radio. However, the authors consider the full-duplexFD wireless communication operating on the same frequency and at the same time. The proposed FDSC MIMO system can transmit and receive simultaneously, which so the self-interference and mutual-interference signals are the main problem of for communication. Hence, the main key success is to eliminate the self-interference and mutual-interference signals as much as possible.

Full-Duplex Single-Channel MIMO Systems

As shown in Figure 1, our design is a single channel 2×2 2××2 MIMO systems (i.e. the MIMO system employs the multiple antennas to transmit and receive on the same frequency and at the same time). Each antenna is connected with to a circulator (CR) to transmit and receive signals simultaneously. However, the imperfection of the circulator allows the transmitting signal to leak into the receiving path, so calledwhich is self-interference. A single antenna is connected to a circulator at the 2nd port, which provides limited isolation between the 1st port and the 3rd port, as shown in Figure 1. The transmitted signal is fed through the 1st port, which routes it to the antenna connected to the 2nd port, while the received signal from the antenna is passed toto the 3rd port through the 2nd port. A circulator cannot isolate the 1st port and 3rd port completely. So, the transmitted signal leaks (self-interference) from the 1st port to the 3rd port and causes interference to the received signal.

The problem of the MIMO system is the effect of mutual coupling. The mMutual coupling describes the energy absorbed by one 1 antenna's receiver when another nearby antenna is operating. The mMutual coupling (Shi H., *et al*., 2012) is typically undesirable because the energy that should be radiated away is absorbed by a nearby antenna. Similarly, energy that could have been captured by 1 antenna is instead absorbed by a nearby antenna. Hence, mutual coupling reduces the antennas' efficiency and the performances of the antennas in both the transmit and receive modes. The problem of mutual coupling is called as mutual-interference and is shown in Figure 1. Furthermore, the problem of mutual-interference cannot be neglected because the power of mutual-interference is stronger than self-interference. Thus, the main challenge of a 2x22×2 FDSC MIMO system is to cancel both the self-interference and mutual-interference signals.

System Model

In this section, the theoretical model of the MIMO system is proposed with m transmitting antennas and n receiving antennas. Let x be the desired signal, and H is the channel between the transmitting and receiving antennas. The received signal, y, can be written as

$$y = H * x + n \quad (1)$$

where (*) denotes the convolution operator. The FDSC system uses a single antenna for the transmitting and receiving paths. The proposed system has the strong self-interference and mutual-interference signals at the receiving antenna. The received signal can be written as

$$y = H * x + H_I * s + n \quad (2)$$

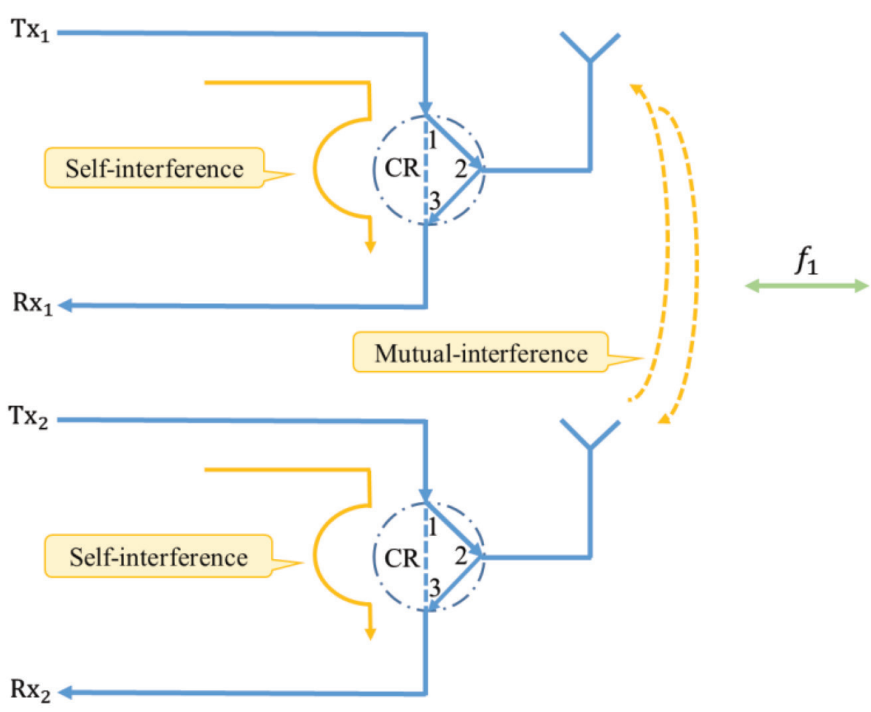

Figure 1. The 2×22x2 FDSC MIMO system with both self-interference and mutual-interference signals

where H_I is the interference channel for both self-interference and mutual-interference, and sis the transmitted signal. The interference channels are the combination of both self-interference and mutual-interference channels, and H_I is given by

$$H_I * s = H_{SI} * s + H_{MI} * s \quad (3)$$

where H_{SI} denotes the self-interference channel., and H_{MI} denotes the mutual-interference channel. The interference signal can be estimated by subtracting with the known transmitted signal which in the defined channel is shown by $\widetilde{H_I}$. The received signal after the estimation of the interference channel, $\tilde{y} = \widetilde{H_I} * s$, can be written as

$$y - \tilde{y} = H * x + H_I * s - \widetilde{H_I} * s + n \quad (4)$$

The challenges of FDSC communication for MIMO systems are to cancel the power levels of self-interference and mutual-interference at the receiving antennas. Therefore, we proposed to a design for the interference cancellation technique. We have designed the analog cancellation part.

Design for Interference Cancellation

In this section, we describe the design of the analog cancellation technique. Our design is a single antenna system (i.e. the same antenna is used to simultaneously transmit and receive at the same time and on the same frequency). The novelty of our work lies in the design and implementation of the RF cancellation, as well as their performance.

Modified hybrid Hybrid couplerCoupler

This section describes the design of a 90° hybrid coupler, by which the inputting signal of each input ports are is sent to each output ports. The 90° hybrid coupler have has phase shifts and an amplitude balance. The 90° hybrid coupler is called a branch line couplers by using transmission lines. In (Nachouane H., *et al*., (2014); and Zhou C., *et al*., (2014), in the design of microstrip transmission lines, the signal at output ports are is attenuated by three 3 decibels and has a 90° phase difference for of the each lines. Each of the transmission lines have has a length depending on the center frequency. Hence, this paper presents to a design of an FDSC communication for 2××22×2 MIMO systems, as shown in Figure 2. We designed a modified hybrid coupler by designingin which the green lines denote the first antenna and the red lines denote the second antenna; that the 3rd and 4th ports are represented the input of the modified hybrid coupler and the 5th and 6th ports are represented the output of the modified hybrid coupler. In the first antenna, the 3rd port is the reference signal for self-interference and the 4th port is the reference signal for mutual-interference that it is the effect of the mutual-interference signal of the first antenna. In the second antenna, the 4th port is the reference signal for the self-interference signal and the 3rd port is the reference signal for the mutual-interference that it is the effect of the mutual-interference signal of the second antenna. So, we can find the coefficient of the modified hybrid coupler and phase of modified hybrid coupler. The modified hybrid coupler is proposed to for the difference phase between the self-interference and mutual-interference signals, as described in the following section.

Design of the analog Analog Cancellation

The novel technique is describes on the design and implementation of the analog cancellation. We know that the advantages of this communication systems are the amplitude and phase of the self-interference and mutual-interference signals from the measurement results. It The system can be designed and developed the system in order to reduce the power levels of the interference signals. The design of the circuit considers the phase and amplitude of the signals using the analog cancellation technique for the circulator leakage and mutual coupling between the antennas. To cancel the interference signals, it includes the attenuators, modified hybrid coupler, and phase shifters. Thus, we propose a technique to cancel the self-interference and mutual-interference signals by using the modified hybrid coupler and phase shifter, as shown in Figure 2. The green lines is are the signals at the first antenna and the red lines is are the signals at the second antenna. The signals of the 1st port can be written as

$$x_1^i = A_1 e^{-j(\omega t+\emptyset_1)} \tag{5}$$

where A_1 is the amplitude of the 1[st] port and $\emptyset_1$ is the phase of the 1[st] port at the i^{th} antenna. The signals of the 2[nd] port is are denoted by $x_2^i = A_2 e^{-j(\omega t+\emptyset_2)}$. The x_1^i signal is transmitted to the coupler, which is separated into 2 ways. The principal power of the x_1^i signal goes through the antenna and the residual in the 3[rd] port is the input of the modified hybrid coupler. From the diagram of the first antenna, the signal in the 3[rd] port is the reference signal for the self-interference signal and the signal in the 4[th] port is the reference for the mutual-interference. Then, the combination of the reference signals of self-interference and mutual-interference at the first antenna can be written as

$$x_{cm1}^i = \frac{1}{\sqrt{2}}(\alpha_{c_{11}}\alpha_{cm_1}A_1 e^{-j(\omega t+\emptyset_1+\emptyset_{c_{11}}+\emptyset_{cm_1})} + \alpha_{c_{21}}\alpha_{cm_2}A_2 e^{-j(\omega t+\emptyset_2+\emptyset_{c_{21}}+\emptyset_{cm_2})}) \tag{6}$$

where $\alpha_{c_{11}}$ and $\alpha_{c_{21}}$ denote the attenuation coefficients of the 3[rd] and 4[th] ports, respectively, $\emptyset_{c_{11}}$ and $\emptyset_{c_{21}}$ denote the phases of the 3[rd] and 4[th] ports, respectively, α_{cm_1} and α_{cm_2} denote the attenuation coefficients of the received signals at the first and second antennas, respectively, and $\emptyset_{cm_1}$ and $\emptyset_{cm_2}$ denote the phases of the received signals at the first and second antennas, respectively. The signal of the 7[th] port is transmitted into the circulator. The signal leakage is happened happens because of the imperfection of the circulator. This leakage is named ascalled the self-interference signal, which can be written as

$$x_{L1}^i = (1-\alpha_{c_{11}})\alpha_L A_1 e^{-j(\omega t+\emptyset_1+\emptyset_{c_{12}}+\emptyset_L)} + (1-\alpha_{c_{21}})\alpha_t\alpha_{mc}\alpha_t A_2 e^{-j(\omega t+\emptyset_2+\emptyset_{c_{22}}+\emptyset_t+\emptyset_{mc}+\emptyset_t)} \tag{7}$$

where α_L and $\emptyset_L$ denote the attenuation coefficient and phase of the signal leakage from the circulator, respectively., α_t and $\emptyset_t$ denote the attenuation coefficient and phase of the coaxial cable, respectively., and α_{mc} and $\emptyset_{mc}$ denote the attenuation coefficient and phase of the mutual-interference signals, respectively. The main concept of analog interference cancellation is the a suitable design of the modified hybrid coupler and phase shifters by the phase of the 5[th] port and the phase of the 9[th] port difference π. The amplitude of both signals should be approximately the same level. As shown in Equation (8), the received signal R_{11}^i must be equal to the desired receiving signal y_3^i. The interference signals are perfectly suppressed, and $x_{cm1}^i = -x_{L1}^i$ can be written as

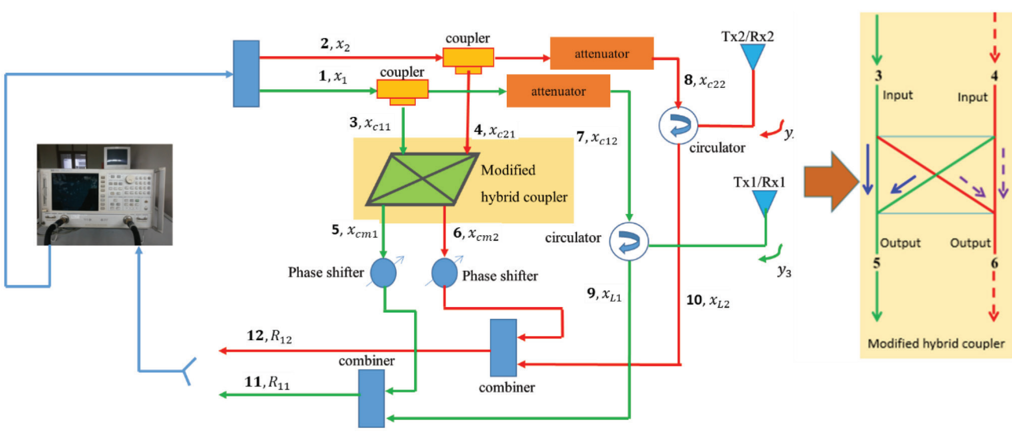

Figure 2. The block diagram of the analog interference cancellation part

$$R_{11}^{i} = y_3^{i} + x_{cm1}^{i} + x_{L1}^{i} \tag{8}$$

So, the attenuation coefficients and phase shifts are matched, and x_{L1}^{i} can be rewritten as

$$\left(1 - \alpha_{c_{11}}\right)\alpha_L A_1 e^{-j\left(\omega t + \emptyset_1 + \emptyset_{c_{12}} + \emptyset_L\right)} = -\frac{1}{\sqrt{2}}\alpha_{c_{11}}\alpha_{cm_1}A_1 e^{-j\left(\omega t + \emptyset_1 + \emptyset_{c_{11}} + \emptyset_{cm_1}\right)} \tag{9}$$

and

$$\left(1 - \alpha_{c_{21}}\right)\alpha_t \alpha_{mc}\alpha_t A_2 e^{-j\left(\omega t + \emptyset_2 + \emptyset_{c_{22}} + \emptyset_t + \emptyset_{mc} + \emptyset_t\right)} = -\frac{1}{\sqrt{2}}\alpha_{c_{21}}\alpha_{cm_2}A_2 e^{-j\left(\omega t + \emptyset_2 + \emptyset_{c_{21}} + \emptyset_{cm_2}\right)} \tag{10}$$

Therefore, the self-interference and mutual-interference cancellations are that the design for the modified hybrid coupler based on Equations (9) and (10).

When considering the second antenna, the principal power of the x_2^{i} signal goes through the antenna and the residual in the 4th port is the input of the modified hybrid coupler. From the diagram of the second antenna, the signals in the 4th and 3rd ports are the reference signals for the self-interference and mutual-interference, respectively. The combination of the reference signals of self-interference and mutual-interference at the second antenna (x_{cm2}^{i}) are the same as that of the reference signals at the first antenna $\left(x_{cm1}^{i}\right)$, as defined in Equation (6).

Next, the signal leakage of the circulator at the 8th port can be written as

$$x_{L2}^{i} = \left(1 - \alpha_{c_{21}}\right)\alpha_L A_2 e^{-j\left(\omega t + \emptyset_2 + \emptyset_{c_{22}} + \emptyset_L\right)} + \left(1 - \alpha_{c_{11}}\right)\alpha_t \alpha_{mc}\alpha_t A_1 e^{-j\left(\omega t + \emptyset_1 + \emptyset_{c_{12}} + \emptyset_t + \emptyset_{mc} + \emptyset_t\right)} \tag{11}$$

As shown in Equation (12), the received signal R_{12}^{i} must be equal to the desired receiving signal y_4^{i}. The interference signals are perfectly suppressed, and $x_{cm2}^{i} = -x_{L2}^{i}$ can be written as

$$R_{12}^{i} = y_4^{i} + x_{cm2}^{i} + x_{L2}^{i} \tag{12}$$

So, the attenuation coefficients and phase shifts are matched, and $x_{cm2}^{i} = x_{L2}^{i}$ can be rewritten as

$$\left(1 - \alpha_{c_{21}}\right)\alpha_L A_2 e^{-j\left(\omega t + \emptyset_2 + \emptyset_{c_{22}} + \emptyset_L\right)} = -\frac{1}{\sqrt{2}}\alpha_{c_{21}}\alpha_{cm_2}A_2 e^{-j\left(\omega t + \emptyset_2 + \emptyset_{c_{21}} + \emptyset_{cm_2}\right)} \tag{13}$$

and

$$\left(1 - \alpha_{c_{11}}\right)\alpha_t \alpha_{mc}\alpha_t A_1 e^{-j\left(\omega t + \emptyset_1 + \emptyset_{c_{12}} + \emptyset_t + \emptyset_{mc} + \emptyset_t\right)} = -\frac{1}{\sqrt{2}}\alpha_{c_{11}}\alpha_{cm_1}A_1 e^{-j\left(\omega t + \emptyset_1 + \emptyset_{c_{11}} + \emptyset_{cm_1}\right)} \tag{14}$$

Finally, this proposed method is that the amplitude and phase of the self-interference and mutual-interference signals can be calculated from only from measurement. Figure 3 shows t he measurement of the FDSC 2x22×2 MIMO system by using the analog cancellation technique. For the measured self-interference signal, the 1st port of the network analyzer connects with the power splitter. The signal is sent from the 1st to the 3rd ports of the circulator. For the measured mutual-interference signal, the 1 antenna receives a signal from another antenna. The modified hybrid coupler and phase shifter are the reference signals which are designed to reduce the power levels of the interference signals. Thus, the values of the amplitude and phase of the interference signals will not be changed because all the positions are determined. Hence, the proposed circuit can cancel interferences very well.

Results and Discussion

Channel Capacity

In this section, the interference channels are pre-known from the signal leakage and the effect between the antennas (mutual coupling). This is the average of the capacity in bits per second per Hertz (bps/Hz). Hence, the a uniform transmitting power is assumed for each antenna, $\left(E\{\boldsymbol{x}\boldsymbol{x}^{\boldsymbol{H}}\} = \frac{P_o}{N_s}\boldsymbol{I}_x\right)$. The capacity of the FDSC 2x22×2 MIMO system can be written by Equation (15)

$$C = \log_2 det\left[\boldsymbol{I} + \frac{P_o}{N_s}\boldsymbol{H}_{\boldsymbol{I}}\boldsymbol{H}_{\boldsymbol{I}}^{\boldsymbol{H}} \times \left(\boldsymbol{\sigma}_{\boldsymbol{I}}^{2}\boldsymbol{H}_{\boldsymbol{I}}^{'}\boldsymbol{H}_{\boldsymbol{I}}^{'\boldsymbol{H}} + \boldsymbol{\sigma}_{\boldsymbol{d}}^{2}\boldsymbol{I}\right)^{-1}\right] \tag{15}$$

where P_o denotes the maximum received power, and N_s denotes the power of the interference signals. Figure 4 shows the performance of the capacity by considering 3 cases. In the first case, there is are no the self-interference and mutual-interference signals in the system, so which is called as without interference. The second case is that where the analog cancellation is proposed on for the FDSC 2x22×2 MIMO system (by using the modified hybrid coupler and phase shifters technique) for the self-interference and mutual-interference signals. In the last case, we have not used any cancellation technique to eliminate the self-interference and mutual-interference signals, so there will be interference.

The simulation of MATLAB programming can be described as follows. The source and destination are assigned with 2 transmitting and 2 receiving antennas; $x = s = 2$. The interference channel H_I is the combination of both the self-interference as well asand the mutual-interference channels, H_{SI} and H_{MI}. Figure 4 shows the channels' capacity versus the signal-to-noise

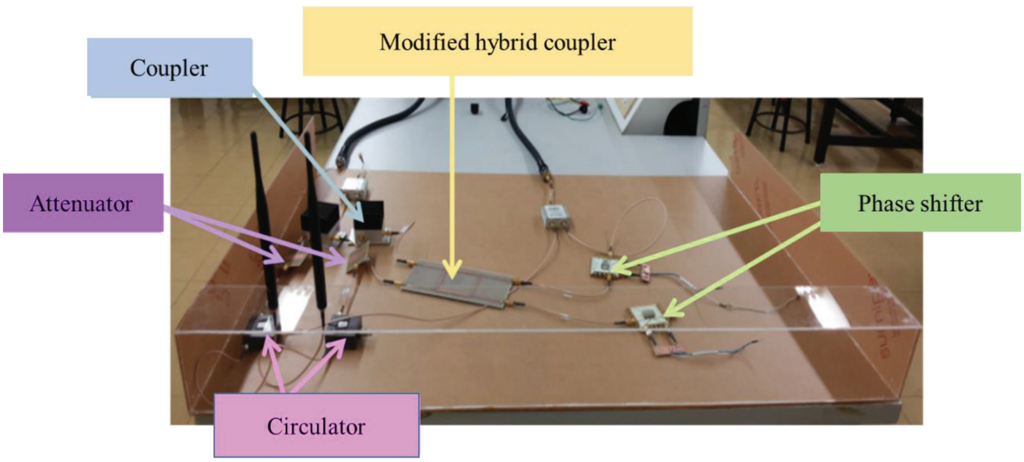

Figure 3. The measurement of the FDSC 2x22×2 MIMO systems on using the analog cancellation technique

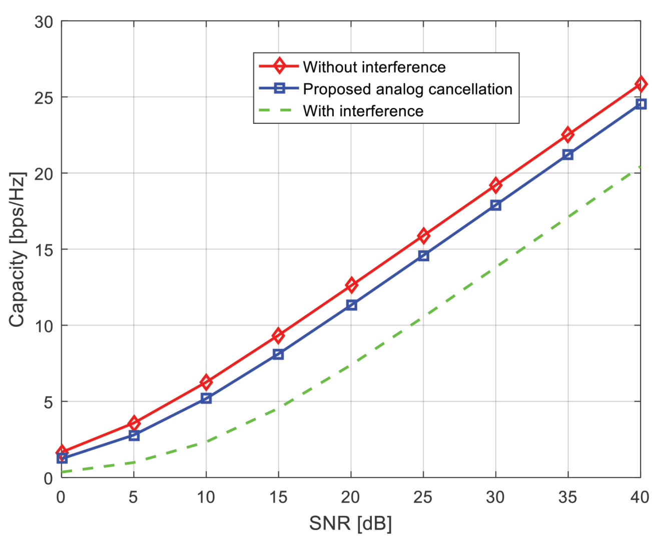

Figure 4. Capacity versus SNR for the 2×22x2 MIMO system

ratio (SNR) with the FDSC 2x22×2 MIMO system. As seen in Figure 4, the proposed technique lies between with and without the interference cancellation. The capacity of the proposed technique is about 3.907 bps/Hz (at SNR = 20 dB) higher than the system with interference signals.

Performance of FDSC 2×2 C 2×2 MIMO System

In this paper, the design digital cancellation employs the Sspace-Ttime Bblock Ccoding (STBC) technique to eliminate the residue of the self-interference and mutual-interference signals after the analog cancellation with the known transmitted signals. All signals are sent to the decoder in order to check the error rate. As shown in Table 1, when the distance between the transmitter and receiver is 35 cm., then the conventional 1-way 2×2 MIMO givesone 1-way 2x22×2 MIMO gives a a bit error rate (BER) of 0.2267., Wwhereas the proposed 2×2 2x22×2 MIMO system (full-duplexFD) gives a BER of 0.2494 by using the self-interference and mutual-interference cancellation techniques. In the last case, we have not used any cancellation techniques for the 2×2 2x22×2 MIMO system, (full-duplexFD) so it increases the error rate and itwhich comes out to be a BER of 0.6688. Thus, the self-interference and mutual-interference signals have not happened occurred with the conventional one 1-way 2×22x22×2 MIMO system so it has a lower bit errorBER. The Eexperimental result shows that the proposed technique can improve the BER performance better than the system without any cancellations for farther distances. The FDSC 2×22x22×2 MIMO system without any cancellations provides the maximum error rate. It means that the proposed technique can eliminate both the self-interference and mutual-interference signals and improves the performance of the system by decreasing the BER.

Conclusions

The Aanalog cancellation technique is proposed using a modified hybrid coupler and phase shifters. In this paper, wWe designed the model of the FDSC 2×2 2x22×2 MIMO system. In this paper, We proposed the method of analog cancellation for the self-interference and mutual-interference cancellations. The performance of proposed technique can cancel the interference signals using pre-known interference signals which are affected by signal leakage and mutual coupling between antennas. The simulation results show that the self-interference and mutual-interference are eliminated with the proposed analog cancellation. This elimination can be achieved in the FDSC 2×2 2x22×2 MIMO system which as can be illustrated with the more greater capacity.

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Table 1. The measured BER versus the distance for the FDSC 2x22×2 MIMO system

Distance (cm)	Bit Error Rate		
	2×x2 2×2 MIMO, 1-way	FDSC 2×x2 2×2 MIMO, analog and digital cancellations	FDSC 2×x2 2×2 MIMO, without any cancellations
35	0.2267	0.2494	0.6688
50	0.2316	0.2493	0.7409
90	0.2449	0.2513	0.7489

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