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Balanced RF-circuit based self-interference cancellation for full duplex communications

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ABSTRACT

Self-interference cancellation in the analog domain is critical to achieve full duplex wireless communications. However, the capability of analog self-interference cancellation is not fully explored. To this end, a new approach of analog self-interference cancellation is developed in this paper. More specifically, a balanced RF frond-end circuit is designed to allow a signal to propagate through symmetrical paths such that: (1) transmit signals taking different paths to arrive at the receiver can be cancelled; (2) receive signals from different paths are simply added at the receiver. As a result, self-interference is gracefully cancelled without impacting the normal operation of transmission and reception. Furthermore, this new approach includes several distinct features. First, it can achieve high analog self-interference cancellation. Implementation and experiments are conducted to validate the new approach, and experimental results show that it can achieve more than 65 dB of self-interference cancellation over 5 MHz bandwidth and 52 dB cancellation over 100 MHz bandwidth with a flat frequency response. Second, the new approach can be easily integrated with existing analog self-interference cancellation schemes to deliver much higher self-interference cancellation. Third, it can be easily extended to MIMO communications in a scalable way. Experiments show that our proposed antenna cancellation schemes are sufficient to achieve the goal of analog self-interference cancellation for MIMO communications.

1. Introduction

Full duplex wireless communications bring many benefits to the network. A full duplex radio can theoretically double link throughput and improve the spectrum efficiency. Full duplex communications can resolve the hidden terminal issue and can also improve the fairness of channel allocation in AP-based networks [1]. In [2], full duplex communications are used in cognitive radios to enable simultaneous transmission and sensing. Many other applications of full duplex communications are presented in [3], including opportunistic spectrum use, real time packet error notification, and so on.

It has been a challenging issue to design a radio to achieve full duplex communications. The key reason for the challenge is the extremely strong self-interference caused by the transmitting signal to the received signal. In a full duplex radio, the interference signal received from its own transmitter is millions to billions of times stronger (i.e., 60–90 dB) than the target signal, so it is extremely challenging to suppress the self-interference to the noise floor. For example, in WiFi the noise floor for a radio is about −90 dBm; considering a transmit power of 20 dBm, it is necessary to cancel nearly 110 dB self-interference to achieve full duplex communications.

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The cancellation of self-interference can be conducted in both analog and digital domains. However, analog self-interference cancellation needs to achieve sufficient performance, as explained in the following example. The dynamic range (DR) of ADC is determined by the number of bits n according to $DR(\text{dB}) = 6.02 * n + 1.76$ dB [4]. In practice we need 2 bits margin. Thus, a 12-bit ADC allows 62 dB dynamic range of the self-interference signal. Considering the requirement of 110 dB self-interference cancellation, the analog self-interference cancellation needs to be as high as 48 dB. In a WiFi system, 7 dB margin is needed to combat OFDM peak to average power ratio (PAPR) [5]. As a result, analog cancellation must provide more than 55 dB of self-interference cancellation for a full duplex WiFi radio. Otherwise, the remaining interference cannot be processed in the digital domain.

In fact, when analog self-interference cancellation is insufficient, there exists another problem: non-linear self-interference appears in the digital domain [6]. Traditional digital cancellation scheme [7,8] is not competent. Additional process [6] is needed to fulfill non-linear digital cancellation. As a result, analog cancellation of self-interference plays a critical role in achieving full duplex wireless communications. So far, several research papers [1,6,9–14] have presented some implementations of a full duplex radio. The analog self-interference cancellation approaches demonstrated in these papers include separation (i.e., path loss) between transmit antenna and receive antenna, antenna cancellation through antenna placement, circulator isolation, and dynamic cancellation through a fine-tuning circuit. However, the cancellation capability in analog domain are not fully explored in these papers. For example, before a dynamic cancellation circuit is applied, existing schemes only depend on path loss [1,9,10,13], antenna cancellation [11], or circulator isolation [6,12] to conduct analog cancellation. Thus, the dynamic cancellation circuit is expected to deliver a high level of self-interference cancellation, which makes the circuit design complicated. Moreover, such a dynamic cancellation circuit is hard to be extended to MIMO communications, because each receive antenna needs to cancel the interference from all the other transmit antennas in full duplex MIMO communications; in this case, the dynamic cancellation circuits for MIMO become too complicated for practical implementation.

In this paper, we focus on improving cancellation capability before dynamic cancellation circuits. More specifically, a novel RF front-end design is designed to explore the capability of analog cancellation. The key idea is that a balanced RF circuit is designed so that a signal to be transmitted takes symmetrical paths but with a phase difference of 180 degrees to arrive at the antennas. As a result, self-interference of the transmitted signal is cancelled. Due to the feature of the balanced RF circuit, the novel RF front-end design is called Balanced Cancellation (BC) [15] in this paper.

Compared with existing schemes of analog interference cancellation, the BC design contains a few distinct features. (1) For many applications requiring small bandwidth (e.g, a few MHz), the BC design can achieve sufficient analog self-interference cancellation by itself; our experimental results show that it can achieve 65–70 dB cancellation over 5 MHz bandwidth. (2) The degree of symmetry in the BC circuit can be fine tuned to achieve graceful performance within a much wider bandwidth; our experimental results show that 52 dB cancellation over 100 MHz bandwidth can be achieved with a flat frequency response. (3) It can be easily integrated with existing full duplex radios to deliver much higher self-interference cancellation; combined with a dynamic cancellation circuit, it can significantly increase the level of self-interference cancellation and maintain the stability of cancellation in the analog domain. (4) The BC design can be easily extended to MIMO communications. In this paper, several novel antenna cancellation schemes are proposed to work with the BC design for scalable full duplex MIMO communications. These antenna cancellation schemes can provide more than 25 dB cancellation without bandwidth limitation. Combined with path loss of 40 dB, this level of cancellation (i.e., 65 dB) is sufficient to satisfy the goal of analog self-interference cancellation. Consequently, the BC design can easily be applied to full duplex MIMO communications in a scalable way.

The rest of the paper is organized as follows. In Section 2, the problems of self-interference cancellation for a full duplex radio and full duplex MIMO communications are studied. The novel BC design is developed in Section 3. System integration of the BC design is briefly explained in Section 4. Its extension to MIMO communications is proposed in Section 5. Performance results are presented in Section 6. Limitations and promising features of the BC design are discussed in Section 7, and the paper is concluded in Section 8.

2. Self-interference: components and existing cancellation schemes

The self-interference in full duplex communications consists of several components. The first one is the transmit signal itself. Due to wireless propagation, this signal experiences different attenuations and delays in the environment and the RF front-end circuit. This component is the strongest in the self-interference, but it is a linear component of the original signal. The second component includes the harmonics of the transmit signal [6], i.e., it consists of the higher order term (such as x^3, x^5) of the original signal x. This part is a non-linear component and the second strongest. The last component is the transmit noise, which includes the noise created by active device such as power amplifier and phase noise in local oscillators [16]. These noises are independent and have no correlation with the transmit signal.

To achieve full duplex wireless communications, it is obvious that all components of self-interference need to be cancelled as much as possible. However, several rules must be followed by analog self-interference cancellation: (1) cancellation in the analog domain must be sufficient to avoid saturating ADC; (2) to reduce the complexity of digital cancellation, the non-linear component of self-interference must be cancelled as much as possible in the analog domain; and (3) an RF circuit for self-interference cancellation cannot bring additional noise to radio. Thus, the capability of analog self-interference cancellation must be fully explored. However, none of existing schemes has fully achieved this goal yet.

We first look into a few designs for single-input–single-output (SISO) full duplex radios. In [13], a cancellation signal is created by another transmit radio according to the channel status and is added to the receive chain for cancellation. The extra transmit radio creates extra transmit noise and non-linear interference that cannot be cancelled in the digital domain [16]. If path loss is not utilized, this design can only achieve at most 35 dB cancellation considering both analog cancellation and digital cancellation. Thus, long distance between transmit antenna and receive antenna is required to meet the cancellation goal, which makes the design impractical.

In [1], the Balun copies an inverse signal of the transmit signal and then feeds it to receive chain through a dynamic tuning device QHx220 according to the channel status. This design can cancel a certain amount of non-linear interference and transmit noise, because the cancellation signal is a copy of self-interference. There exist two drawbacks in this design. First, the tuning device is an active device, which further brings non-linear interference and noise. Second, the reflected signal by the transmit antenna is ignored. In practice, the antenna cannot emit all power to space, i.e. some power is reflected back. The reflected signal also enters the receive chain through the Balun and degrades the cancellation. As a result, the Balun cancellation can only achieve 20 dB cancellation at high transmit powers (20 dBm) in practical experiments. This design also depends on the path loss to provide enough cancellation in the analog domain.

The RF front-end design in [6] includes two parts. One is circulator, and the other is a dynamic cancellation circuit. The circulator can separate transmit and receive signals, so it enables simultaneous transmission and reception with a single antenna. In a perfect circulator, signals can only flow in a specific way, e.g., signals can only flow from port 1 to port 2 or from port 2 to port 3. However, practical circulator exists leakage in reverse flow. In addition, there is also a strong self-interference from antenna reflection, so the actual isolation performance of the circulator is limited by the stronger self-interference: *circulator leakage* or *antenna reflection*. In [6], the overall isolation from the circulator is 15 dB isolation, so the antenna reflection must be as low as -15 dB, which means a high performance antenna is selected to work with the circulator. In the dynamic cancellation circuit, a copy of the original signal is created and fine-tuned to create a cancelling signal, which is then fed into the receive chain for cancellation. The dynamic cancellation circuit can provide another 45 dB cancellation.

For MIMO communications, self-interference cancellation in the analog domain is much more challenging. In a MIMO system, each receive antenna must cancel the interference from all other transmit antennas. Most existing schemes for SISO cannot be easily extended to MIMO communications. For example, the design in [13] needs an extra radio that brings non-linear interference and noise, so it is hard to be extended to MIMO. For the design in [1] or [6], if it is simply extended to MIMO with N antennas, then the number of dynamic cancellation circuits has to be increased by N^2. Besides, at least N^2 algorithms have to executed simultaneously to fine tune the circuits, which is too complicated to implement in practice.

So far two mechanisms [17–19] has been proposed to achieve full duplex MIMO communications. In [17,18], a so-called two-level antenna cancellation scheme through antenna placement is proposed, which provides about 45 dB cancellation in an open environment. Combined with path loss, it makes full duplex MIMO come true. However, the antenna cancellation scheme in [17,18] needs a large number of antennas, e.g. it requires 12 antennas to achieve a 3×3 MIMO and antenna placement is inflexible, e.g. the transmit antennas and receive antennas must be placed on each other's perpendicular bisector, which makes it unscalable for practical implementation. In [19], it propose a improved mechanism based on [6] to achieve a 3×3 MIMO communications in practical. Some cascade dynamic cancellation circuits are utilized to cancel the cross antenna self-interference. Thus, the algorithm complexity can be reduced to be linear. However, the complexity is still very high and it is hard to achieve scalable MIMO communications, since there exist too many attenuators which are needed to be fine-tuned simultaneously in limited time.

As we can see from the above designs, before a dynamic cancellation circuit, only path loss, circulator isolation, or antenna placement is employed. Thus, the overall performance of self-interference cancellation heavily depends on a dynamic cancellation circuit. For MIMO systems, either the dynamic cancellation circuit becomes too complicated or antenna placement becomes infeasible. Thus, in all existing schemes, the capability of analog self-interference cancellation is not fully explored. In this paper, we focus on a BC design to explore the cancellation capability before dynamic cancellation circuit. With such a circuit, we can not only improve the cancellation in analog domain, but also highly reduce the complexity in MIMO extension. In the next section, such an RF circuit is developed.

3. RF front-end design

3.1. The RF circuit for balanced cancellation

The structure of the novel RF circuit is depicted in Fig. 1. A transmit signal is first split into two signals with equal power but a phase difference of 180 degrees. The two signals then pass through circulators and then emit to the air via port 2 of circulators. With the help of the circulator, one antenna can transmit and receive simultaneously. Thus, two antennas are used in our design. In the receive chain, a power combiner is used to add the signals from port 3 of both circulators. Due to the balanced design from the transmit chain to the receive chain, the self-interference (i.e., the signal leaked from the transmit chain to the receive chain) can be gracefully cancelled. Thus, our design of the novel RF circuit is called balanced cancellation (BC) design in this paper.

There exist three types of self-interference in the BC design. The first type comes from the circulator leakage

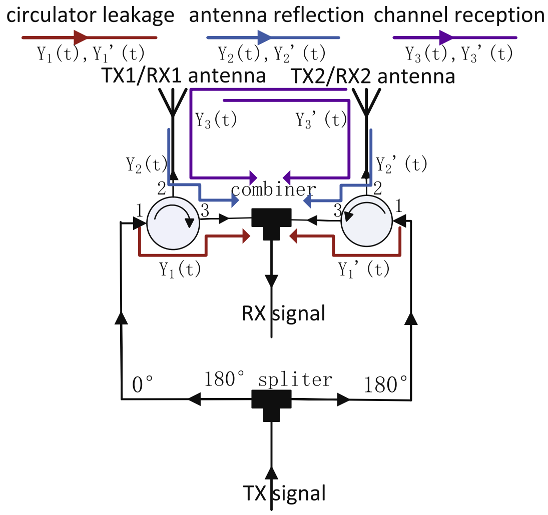


Fig. 1. Balanced cancellation (BC) design.

from port 1 to port 3, which depends on the circulator performance. The second type is from the antenna reflection determined by the antenna performance. The last type is the signal received by one antenna from the other antenna. For example, the RX1 antenna will receive the signal from the TX2 antenna as shown in Fig. 1. Since the BC design is symmetric, there are actually six major components of self-interference, as shown in Fig. 1. Other types of interference may exist, but they are much weaker than the major ones and are thus neglected.

Self-interference cancellation via our BC design is analyzed as follows. Assuming the original signal is $x(t)$, when it gets through the 180 degree power spliter, it is divided into two parts: $x(t)/\sqrt{2}$ and $-x(t)/\sqrt{2}$. The receive chain gets six components of self-interference:

$$Y_1(t) = h_1 e^{-j\theta_1} x(t)/\sqrt{2}, \quad (1)$$

$$Y'_1(t) = -h'_1 e^{-j\theta'_1} x(t)/\sqrt{2}, \quad (2)$$

$$Y_2(t) = h_2 e^{-j\theta_2} x(t)/\sqrt{2}, \quad (3)$$

$$Y'_2(t) = -h'_2 e^{-j\theta'_2} x(t)/\sqrt{2}, \quad (4)$$

$$Y_3(t) = h_3 e^{-j\theta_3} x(t)/\sqrt{2}, \quad (5)$$

$$Y'_3(t) = -h'_3 e^{-j\theta'_3} x(t)/\sqrt{2}, \quad (6)$$

where $Y_1(t)$ and $Y'_1(t)$ are the interference from the circulator leakage, h_1 and h'_1 are the attenuations of the signal in the circulator, and θ_1 and θ'_1 are the phase shift. $Y_2(t)$ and $Y'_2(t)$ are the interference from antenna reflection, h_2 and h'_2 are amplitude loss of the transmitting signal as reflected by the antenna, and θ_2 and θ'_2 are the phase shift. $Y_3(t)$ ($Y'_3(t)$) is the self-interference received from antenna TX2 (TX1), h_3 and h'_3 are attenuations by the channel, and θ_3 and θ'_3 are the phase shift. The six components of self-interference are added by the power combiner, and then the final received signal at the receive chain is

$$Y(t) = Y_1(t) + Y'_1(t) + Y_2(t) + Y'_2(t) + Y_3(t) + Y'_3(t). \quad (7)$$

Since the structure of the BC design is symmetric, so if two antennas and two circulators are perfectly the same and the channel is symmetric, i.e.,

$$\begin{cases} h_1 = h'_1 \\ \theta_1 = \theta'_1 \\ h_2 = h'_2 \\ \theta_2 = \theta'_2 \\ h_3 = h'_3 \\ \theta_3 = \theta'_3 \end{cases}, \quad (8)$$

then we get

$$Y(t) = 0, \quad (9)$$

which means all major interference components are cancelled. The key idea of the BC design is to use a symmetric RF circuit to create a copy of the self-interference with inverse phase for cancellation. In fact, practical antennas and circulators are not perfectly the same, so self-interferences cannot be cancelled completely.

3.2. Impact of circuit unbalance on cancellation performance

The performance of self-interference cancellation of the BC design depends on balance in the symmetric signal paths. However, the signal paths may not be balanced, even though they have symmetric design. The unbalance is due to a few factors: (1) the antennas on the two symmetrical paths do not have the same property of reflection; (2) the two circulators have different isolation and phase shift; and (3) the power splitter and the power combiner are not perfect. The impact of circuit unbalance to the performance of self-interference cancellation is analyzed below.

In the BC design there exist three types of self-interference. If all types of self-interference are considered, according to Appendix, the power of the total received signal is

$$P = P' + P'', \quad (10)$$

where

$$P' = \left\{ \sum_{i=1}^{3} A_i^2 (1 - 2\alpha_i cos\theta_i + \alpha_i^2) \right\} x^2(t), \quad (11)$$

$$P'' = \left\{ \sum_{m=1}^{2} \sum_{n=2, n\neq m}^{3} 2A_m A_n [cos(\phi_m - \phi_n) - \alpha_m cos(\phi_m - \phi_n + \theta_m) - \alpha_n cos(\phi_m - \phi_n - \theta_n) + \alpha_m \alpha_n cos(\phi_m - \phi_n + \theta_m - \theta_n)] \right\} x^2(t), \quad (12)$$

where A_i and $\phi_i (i = 1, 2, 3)$ represents the amplitudes of the three types of self-interference (i.e., circulator leakage signal, antenna reflected signal, and signal received the other antenna) and the phase shifts on one side of the BC design, respectively, $\alpha_i (i = 1, 2, 3)$ is the amplitude ratio, and $\theta_i (i = 1, 2, 3)$ denotes the phase offset of the symmetric components of self-interference. Thus, the power of the total received interference consists of two parts (P' and P''). P' shows three residual powers that come independently from three types of self-interference. P'' reflects the residual powers due to cross-interactions among different types of self-interference. Taking practical implementation on a printed circuit board (PCB) as an example, the total residual power from these two components is illustrated below.

In PCB implementation, the isolation of the circulator can easily achieve 20 dB [20]. Thus, $A_1 = 0.1$. Moreover, it is not difficult to ensure two antennas have low antenna reflection. As in [6], the antenna reflection is assumed to be 15 dB, i.e., $A_2 = 0.1778$. The path loss between two antennas is assume to be 30 dB, i.e., $A_3 = 0.0316$.

The unbalance between two components of the circulator leakage self-interference is caused by inconsistency in two circulators and unbalance in the power splitter and the power combiner. The unbalance between two components of the antenna reflected self-interference is due to inconsistency between two antennas and unbalance in the power splitter and the power combiner. For the two components of the received self-interference from each other antenna, their unbalance is caused by inconsistency of channel condition as well as unbalance between the power splitter and the power combiner. In PCB implementation, two antennas can be made with consistent performance. Similarly, it is not difficult to have two surface-mounted circulators with consistent performance. Thus, the unbalance in amplitude and phase in three types of interference is mainly determined by the unbalance in the power splitter and the power combiner. Usually, the unbalance of a power combiner can reach 0.01 dB in amplitude and 0.5 degree in phase [21]. The two-way 180-degree power spliter can achieve the same performance as the power combiner. As a result, it is reasonable to assume that the unbalance of all types of self-interference is 0.03 dB in amplitude and 0.5 degree in phase, i.e., $\alpha_i = 0.03, \theta_i = 0.5, i = 1, 2, 3$.

With the above parameters, we can get 53 dB cancellation in P' based on Eq. (11). P'' is also related to the phase shift of each type of self-interference. If we assume $\phi_1 = 0\pi, \phi_2 = \pi$ and $\phi_3 = 0.2\pi$, the entire cancellation considering both P' and P'' can reach 64 dB. The increased cancellation is due to the negative value from P''. However, P'' can be positive. For example, if $\phi_1 = 0\pi, \phi_2 = 0.5\pi$ and $\phi_3 = 0.2\pi$, then the entire cancellation drops to 51 dB. This result shows an interesting hint to improve cancellation performance of the BC design: amplitude unbalance and phase offset in all types of self-interference need to be minimized, but the phase shifts of these self-interference signals also need to be fine-tuned. When two types of the residual self-interference after cancellation have inverse phase, they can further be added to cancel each other. If the BC design can achieve 0.01 dB unbalance in amplitude and 0.2 degree in phase, and $\phi_1 = 0\pi, \phi_2 = \pi$ and $\phi_3 = 0.2\pi$, then the BC design can achieve 73 dB cancellation.

The above analysis illustrates the feasibility of our BC design. In Section 6, a balanced RF circuit built based on discrete RF components also shows that more than 55 dB self-interference cancellation can be achieved across a bandwidth of 80 MHz.

4. System integration

In this section, we discuss how the BC design can be integrated with other full duplex technologies. For example, when much higher self-interference cancellation is needed in the analog domain, a possible solution is to integrate the BC design with a dynamic cancellation circuit. Moreover, since self-interference cannot be cancelled completely in analog domain, digital cancellation is necessary to achieve a full duplex radio.

4.1. Integrated with dynamic cancellation circuit

One advantage of the BC design is that it can be easily integrated with a dynamic cancellation circuit. So far there exit several dynamic cancellation schemes [1,6,12]. A dynamic cancellation circuit can be added in the BC design before the 180 degree power splitter in the transmit chain and after the power combiner in the receive chain, as shown in Fig. 2.

The dynamic cancellation circuit draws transmit signal from the transmit chain and adjusts the amplitude and phase of this signal according to the feedback of the self-interference. It then combines this signal with the received self-interference signal in the receive chain for cancellation. One important issue is that the dynamic cancellation circuit must consist of passive devices to prevent the spectrum leakage, which will be discussed in Section 6.2.2.

The BC design and the dynamic cancellation circuit can provide mutual benefits. Firstly, the amount of analog cancellation and the cancellation stability can be improved, which can eliminate the non-linear self-interference cancellation in digital domain to reduce the complexity of digital cancellation. Secondly, the complexity of the dynamic cancellation circuit can be decreased, because the BC design can provide higher cancellation. In [6], the circulator only provides 15 dB cancellation, so the dynamic circuit must provide 45 dB cancellation, which leads to a

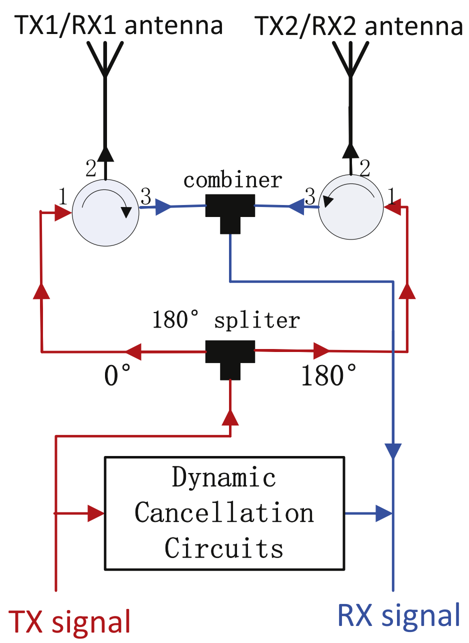


Fig. 2. Integrating the BC design with dynamic cancellation circuits to achieve higher analog cancellation.

complicated dynamic cancellation circuit that needs 16 attenuators and 16 delay lines. If the BC design is used, the number of circulators and delay lines can be significantly decreased.

4.2. Digital cancellation

The analog cancellation cannot cancel the interference completely. The remaining self-interference can be cancelled in digital domain. To evaluate our BC design as a whole system for full duplex radios, we also implement digital cancellation in this paper and the results will be reported in Section 6.

The received signal of the linear interference can be described as:

$$\mathbf{y}[n] = \mathbf{H}\mathbf{x}[n] + \mathbf{w}[n], \tag{13}$$

where $\mathbf{x}[n]$ is the original transmit signal, $\mathbf{w}[n]$ represents the noise, and $\mathbf{H}$ represents the attenuations and delays. To cancel linear self-interference, $\mathbf{H}$ needs to be estimated. Schemes such as least square (LS), minimum mean squared error (MMSE), or maximum likelihood (ML) can be employed. In this paper, we use LS because of its simplicity. The above scheme is effective for cancelling linear self-interference. However, if the analog cancellation is not sufficient, non-linear self-interference cancellation [6] is needed in the digital domain.

5. MIMO extension

Another advantage of the BC design is that it can be extended to scalable MIMO communications. To achieve this goal, we leverage the BC design to propose two novel antenna cancellation schemes for MIMO communications.

5.1. Antenna cancellation of existing schemes

Antenna cancellation makes use of antenna placement in the space for cancellation. Usually, two or more transmit antennas are placed to form null points and the receive antenna is placed at these null points to achieve cancellation. So far, a few antenna placement schemes [11,17] are proposed for self-interference cancellation. In this paper, we propose two novel antenna placement schemes to support the BC design for MIMO communications. To illustrate the advantages of our schemes, the limitations of existing antenna cancellation schemes for MIMO are first discussed.

As shown in Fig. 3(a), three antennas are used for cancellation in [11]: two transmit antennas and one receive antenna. The two transmit antennas send the same signals with different power. The receive antenna is placed in between two transmit antennas, with a distance of d to one transmit antenna and a distance of $d + \lambda/2$ to the other, where λ is the wavelength of the transmitting signal. Thus, the two transmit signals reach at the receive antenna with inverse phase. After fine tuning of the transmit power, the two receive signals will have the same amplitude at the receive antenna, which suppresses receive signals. This method depends on the wavelength λ, so it can only achieve 30 dB cancellation with a bandwidth of 5 MHz. It is not enough in many applications, like WiFi. On the other hand, this antenna cancellation method cannot be extended to MIMO. The other antenna cancellation scheme in [17] uses two transmit antennas to send the inverse phase signals. The two receive antennas place symmetrically at the perpendicular bisector of the transmit antennas to achieve a so called two-level antenna cancellation, as shown in Fig. 3(b). This antenna placement method does not depend on the wavelength for cancellation, so the bandwidth is not limited theoretically. However, MIDU uses phase shifter to generate the inverse phase signals, which makes the deign still limited by the bandwidth. If more transmit antennas and receive antennas are placed at each perpendicular bisector, this method can be extended to full duplex MIMO communications. The antenna placement, however, is not flexible and the size of the system is large. On the other hand, in this method antennas can only transmit or receive, which leads to too many antennas for MIMO extension, e.g. a 3×3 MIMO needs 12 antennas. Finally, the performance degrades dramatically in multi-path environment.

5.2. Antenna cancellation based on the BC design

In the BC design, each antenna pair is capable of both transmission and reception. Based on this feature, we develop an approach of novel antenna cancellation. With this approach, our BC design can be extended to full duplex MIMO system in a scalable way. Two schemes are designed: one is starlike model and the other is parallel model [22]. A 3×3 MIMO is shown in Fig. 4 for these two models.

5.2.1. Starlike model

In this model, the antenna placement only demands the middle points of all the BC designs intersect at one point, as shown in Fig. 4(a). The distance between two antennas of each BC design can be different. For example, AA' can be unequal to BB'. The angel between each BC design can also be different, such as $\angle\alpha \neq \angle\beta$. It should be noted that more BC designs can be added into the model, so this method enables scalable full duplex MIMO communications.

The BC design can cancel self-interference by itself. How BC designs cancel interference between each other is explained below. Consider an example of how BC design A cancels the interference from BC design B. The antenna A receives two signals from antenna B and B' respectively. The two signals reach antenna A through different paths but cannot cancel each other. Assuming the transmitting signal of BC design B is $x(t)$, so the signals from antenna B and B' are $x(t)/\sqrt{2}$ and $-x(t)/\sqrt{2}$. We denote the receive signals at antenna A as $Y_1(t)$ and $Y_2(t)$:

$$Y_1(t) = h_1 e^{j\phi_1} x(t)/\sqrt{2}, \tag{14}$$

$$Y_2(t) = -h_2 e^{j\phi_2} x(t)/\sqrt{2}, \tag{15}$$

where h_1 and h_2 are the channel attenuations, and ϕ_1 and ϕ_2 are the phase delays. The antenna A' can also receive two signals (i.e., $Y_3(t)$ and $Y_4(t)$) from antenna B and B' and they are given as

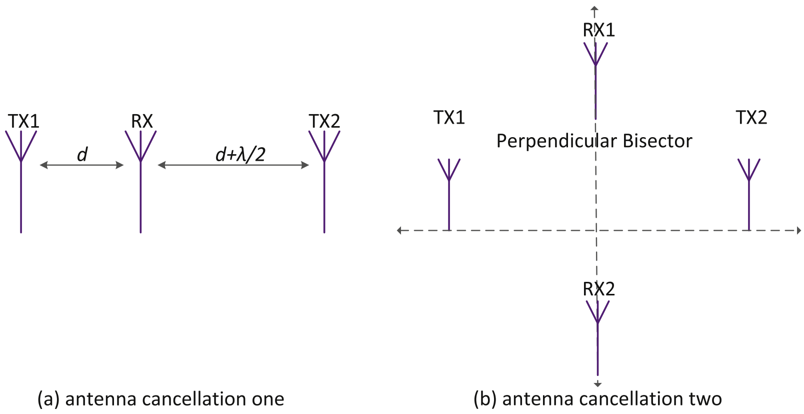


Fig. 3. Antenna cancellation: (a) the scheme in [11]; (b) the scheme in [17].

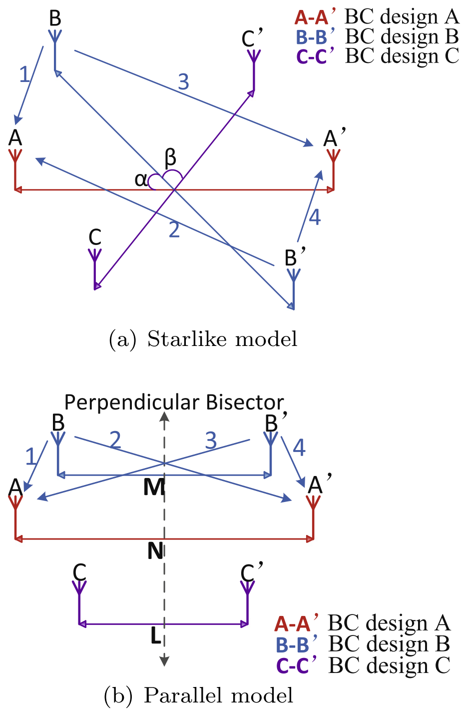


Fig. 4. MIMO extension of the BC design: (a) the starlike model of 3×3 MIMO, where the middle points of three BC designs intersect at one point; (b) the parallel model of 3×3 MIMO, where the perpendicular bisectors of all the BC designs overlap.

$$Y_3(t) = h_3 e^{j\phi_3} x(t)/\sqrt{2}, \quad (16)$$

$$Y_4(t) = -h_4 e^{j\phi_4} x(t)/\sqrt{2}, \quad (17)$$

where h_3 and h_4 are the channel attenuations, and ϕ_3 and ϕ_4 are the phase delays. Finally, BC design A combines all the received signals to get an aggregated signal $Y(t)$ as

$$Y(t) = Y_1(t) + Y_2(t) + Y_3(t) + Y_4(t). \quad (18)$$

From the symmetric structure we know that $AB = A'B'$ and $AB' = A'B$. Signals through symmetric paths are assumed to get the same attenuations and delays. This has been confirmed in [17], where a static channel with short distance shows high symmetry and stability over time. Thus, we get the following equations

$$\begin{cases} h_1 = h_3 \\ \phi_1 = \phi_3 \\ h_2 = h_4 \\ \phi_2 = \phi_4 \end{cases}, \quad (19)$$

as a result, we get

$$Y(t) = 0. \quad (20)$$

This means the interference from BC design B and BC design C can be cancelled in BC design A. As a result, BC design A can cancel the interference from both itself and all other BC designs. The same cancellation can be applied to BC design B and C, so the entire system can achieve effective self-interference cancellation for MIMO communications.

Since the antenna placement is not perfect in practice, the four signals at a BC design may not cancel each other completely. In Section 6, we will show that antenna cancellation can achieve 25–30 dB. Combining antenna cancellation with path loss (20 cm separation can get about 40 dB suppression at 2.4 GHz), the total cancellation can be more than 60 dB, which meets the goal of analog self-cancellation.

5.2.2. Parallel model

In this model, the antenna placement only demands the perpendicular bisectors of all BC designs overlap. A 3×3 MIMO based on the parallel model is shown in Fig. 4(b). The distance between antennas of each BC design can be different, such as $AA' \neq BB'$. The distance between each BC design can also be different, such as $MN \neq NL$ in Fig. 4(b), which enables the parallel model scalable.

Analysis on cancellation performance can be conducted in the same way as that for the starlike model. Each BC design receives four interference signals from other BC designs but the four signals cancel each other because of the symmetric structure. As a result, the entire system can meet the cancellation target in the analog domain.

5.2.3. The comparison of the two proposed models

The two antenna placement schemes are equal theoretically. However, the parallel model is easier to be implemented for engineering use. Thus, the parallel model can achieve higher cancellation in practical, which is shown in Section 6.2.4.

5.2.4. The merits of our antenna cancellation for MIMO

Compared to MIDU [17,18], the BC design has the following merits for MIMO. (1) We do not use phase shifter in the BC design as shown in Fig. 1. Our antenna cancellation methods also have nothing to do with frequency. Thus, there are no bandwidth limitation in our design as compared to MIDU. (2) We enable an antenna to simultaneously transmit and receive. Thus, only a half number of antennas are needed in our design. As shown in Fig. 4, only 6 antennas are needed for a 3×3 MIMO in both starlike model and parallel model. However, MIDU need 12 antennas to achieve this target. Thus, the space we needed is also smaller. (3) The antenna placement is more flexible in our deign. The transmit antennas and receive antennas can only be placed at each perpendicular bisector as shown in Fig. 3(b). We remove this antenna placement restriction in our design.

Overall, combining antenna cancellation and path loss in our design can provide enough interference cancellation in the analog domain, so the MIMO extension eliminates the demand of dynamic cancellation circuits for cross antenna interference cancellation, which is the bottleneck for scalable full duplex MIMO communications.

6. Performance evaluation

6.1. Experiment setup

The BC design in Fig. 1 has been implemented. Its performance is measured via a network analyzer. The testing frequencies are in a range of 1.9–2.0 GHz which is the frequency range of our RF devices. As shown in Fig. 5, the implemented BC design is measured in an indoor environment. Since the indoor environment is characterized by the multi-path effect, it provides a stress test to our design. We have also implemented digital cancellation of linear self-interference on USRP [23] platform. Furthermore, the performance of antenna cancellation for MIMO extension of our BC design is measured through experiments.

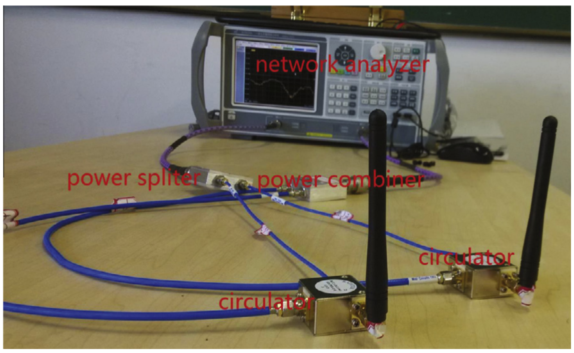


Fig. 5. The implemented BC design and testing equipment.

6.2. Experimental results

6.2.1. Isolation by circulator

In our experiment, the circulator isolation [24] from port 1 to port 3 is 20 dB lower than the transmitting signal. The transmit antenna and the receive antenna are separated by 12 cm, which provides about 24 dB and 29 dB suppression at 2.0 GHz and 2.4 GHz, respectively. Thus, the interference from the wireless channel is more than 20 dB lower than the transmit signal. The antenna reflection is about 5 dB lower than the transmit signal, which means the antennas in our experiment has low performance. As a result, the performance of the circulator is actually bottlenecked by the antenna, and the maximum isolation by the circulator is only 5 dB. To get 55 dB cancellation (for example), the symmetric structure of our BC design must provide 50 dB cancellation.

6.2.2. Cancellation by BC design

First, we use a transmit power of 0 dBm to test the performance of our BC design. The bandwidth is 100 MHz between 1.9 GHz and 2.0 GHz. In this case, we find that the BC design can provide about 55 dB cancellation over 80 MHz bandwidth, including a higher cancellation of about 60 dB over about 50 MHz bandwidth, as shown in Fig. 6(a). This result meets the cancellation requirement in the analog domain for full duplex communications. Next, we increase the transmit power to 10 dBm to study its impact to cancellation. As shown in Fig. 6(b), the BC design can still provide about 55 dB analog cancellation over about 80 MHz bandwidth. Comparing results in Fig. 6(a) and (b), we find some differences at various frequencies and also strong variations when the cancellation is more than 60 dB. These differences and variations are caused by the channel variation, which is explained in Section 7.1.

As we can see from Fig. 6, if we consider a narrow bandwidth (e.g., 5 MHz), the cancellation can be more than 65 dB. Such a high cancellation indicates the BC design itself is enough for analog cancellation. However, if we want to utilize the BC design only to provide more than 60 dB cancellation over a wide bandwidth (e.g., 60 MHz), the frequency response is not flat and a small variation of the environment can lead to dramatic change of frequency response, which distorts the received signal and leaves a challenge for dynamic cancellation circuit and digital cancellation. To resolve this issue, we need to reduce the requirement on the symmetry (i.e. decrease the sensitivity to the symmetry), which leads to lower cancellation but flat and stable frequency response. As shown in Fig. 7, if the BC design only provides 55 dB cancellation, we get a flat frequency response over about 60 MHz bandwidth. In some systems, the demand for bandwidth is higher. For example, a 802.11ac radio may need a bandwidth of 80 MHz or more. In this case, we can further decrease the degree of the symmetry in our BC design to meet the higher requirement of the bandwidth. A result of about 52 dB cancellation over 100 MHz bandwidth with flat

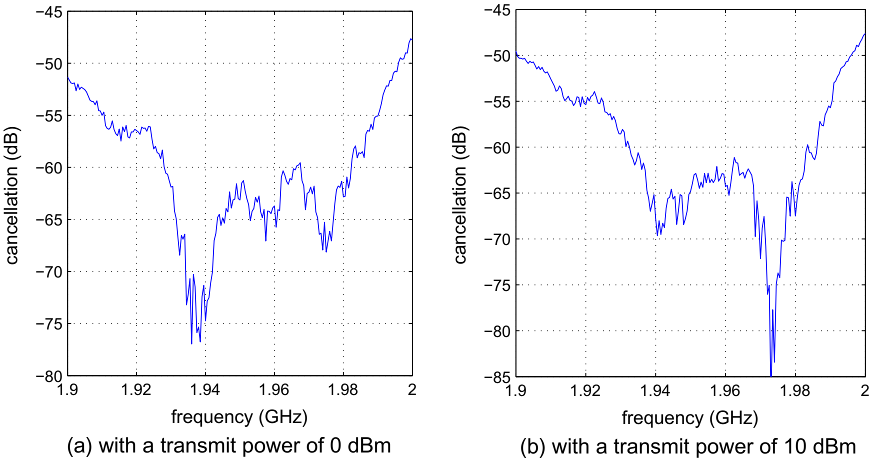


Fig. 6. The results of analog cancellation achieved by the BC design: (a) with a transmit power of 0 dBm; (b) with a transmit power of 10 dBm.

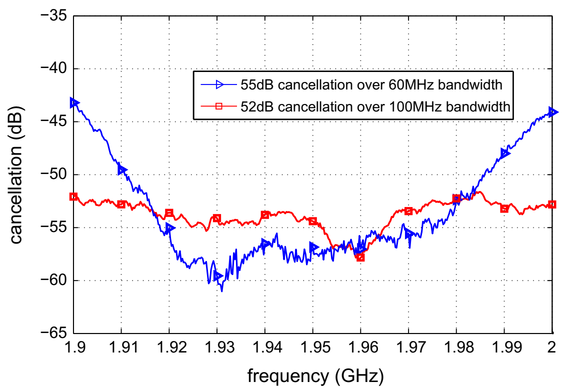


Fig. 7. The cancellation results with flat frequency response.

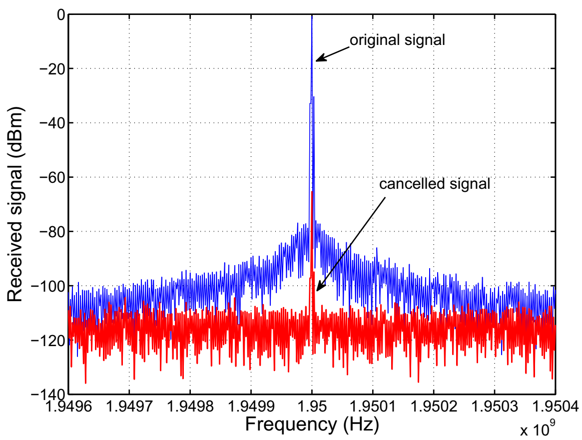


Fig. 8. Spectrum leakage of BC design.

frequency response is presented in Fig. 7. We notice that the person conducting the experiment has almost no influence on cancellation performance in this case. However, 52 dB does not meet the cancellation requirement in the analog domain. Thus, in this case the BC design must be integrated with a dynamic cancellation circuit to achieve higher analog cancellation.

The spectrum leakage of the BC design is also evaluated. The Balun cancellation in [1] leads to interference leakage in adjacent spectrum [12] since it uses active device QHx220. However, all components of the BC design are passive, so there is almost no spectrum leakage as that in [12]. The experiment result is shown in Fig. 8. We send a signal at 1.95 GHz with the power of 0dBm. As we can see, there exists some spectrum leakage in the original signal. However, no spectrum leakage exists after self-interference cancellation. The reason is that the leaked signals are also cancelled by BC design.

An additional experiment is conducted to measure the performance of the BC design under the interference from another radio. We only use on radio to send the interference signal, because it is sufficient to study the impact of interference on the performance of BC design. The experiment is conducted as follows. We first transmit a signal of 20 MHz bandwidth with the power of 0dBm at the transmitter of the BC design. Then we send an interference signal by another radio. In order to see the influence to BC design, the bandwidth of the interference signal is set to 40 MHz. The results of experiment are shown in Fig. 9, where the cancellation result is indicated by a line with “square” marks and the received original signal is depicted by a line with “triangle” marks. Considering the signals outside the central 20 MHz, the interference signal is not cancelled. However, for the signals within the central 20 MHz, the self-interference signal is very close to the signal level when interference does not exist. Thus, the performance of self-interference cancellation is not influenced by the interference from another radio. The reason for the above results is simple: the interference from the third radio does not change the behaviour of BC design.

6.2.3. Digital cancellation

WiFi signals are considered in this experiment. Integrated with our BC deign, we implement digital interference cancellation on USRP for different modulations,

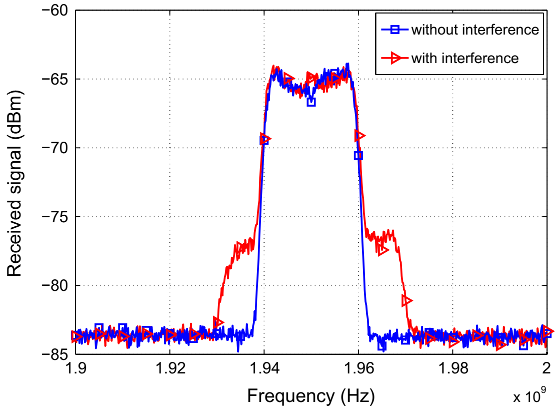


Fig. 9. Performance with the interference from another radio.

from BPSK to 64QAM. For each modulation we test for 100 times and get the average. The cancellation results are shown in Fig. 10. As we can see, digital cancellation can provide about 30 dB cancellation for the linear self-interference. The digital cancellation results are almost consistent from QPSK to 64QAM. Only the BPSK case has 2 dB higher cancellation. Limited by our computer capability, we conduct this experiment in 2 MHz bandwidth. In [6], however, a digital cancellation results of 50 dB cancellation of both liner and nonlinear cancellation over 20 MHz bandwidth are achieved by WARP radios.

As shown in Fig. 6, the analog cancellation from the BC design is more than 62 dB over 20 MHz. Thus, the BC design and digital cancellation can achieve a total cancellation of 90 dB. It still lacks 20 dB cancellation to achieve full duplex communications for WiFi. This additional cancellation can be achieved via non-linear self-interference cancellation in the digital domain [6] or integrating our BC design with a dynamic cancellation circuit. However, there is no need to have both non-linear self-interference cancellation in the digital domain and the dynamic cancellation circuit in the analog domain. This features the advantage of our BC design.

6.2.4. Antenna cancellation for MIMO

As for a full duplex MIMO system, the interference between antennas has to be suppressed for more than 55 dB for each receive chain before ADC. In our antenna cancellation experiments, we first use two transmit antennas and one receive antenna. The transmit antennas are placed at A and A' and receive antenna is placed at B as shown in Fig. 4. The receive antenna has a distance of 17 cm to the nearer transmit antenna, in other words $AB = 17$ cm, and we get about 35 dB cancellation as shown in Fig. 11, which is higher than the attenuation when the distance between one transmit antenna and one receive antenna is 20 cm. The reason is that, with two transmit antennas, there exist some positions at which the receive signals are weaker than the case with one transmit antenna [11].

We then add another receive antenna B' for the starlike model and the parallel model respectively as shown in Fig. 4 and measure antenna cancellation results. As shown in Fig. 11, antenna cancellation provides about 25–30 dB cancellation. Thus, combined with the path loss, the total analog cancellation is more than 60 dB, which meets the cancellation requirement in the analog domain. On the other hand, our antenna cancellation is not limited by bandwidth. It can provide effective cancellation over 100 MHz bandwidth as shown in Fig. 11.

The path loss and antenna cancellation can provide enough analog cancellation for each receive chain, so the dynamic cancellation circuits are not needed for MIMO extension. This feature avoids the bottleneck of the MIMO extension. However, to make the entire full duplex radio work, nonlinear self-interference cancellation is still needed for high bandwidth applications.

So far the best full duplex radio is designed in [6]. It can achieve about 60 dB flat cancellation over more than 80 MHz bandwidth in the analog domain. However, it needs a complicated dynamic cancellation circuit and a dynamic fine-tuning algorithm to support the cancellation circuit. Compared to the design in [6], the cancellation result of BC design is a little lower but the system structure is much simpler. In the BC design, we do not need a dynamic cancellation circuit or fine-tuning algorithm. Because of this feature, BC design can be easily extended to MIMO communications. On the other hand, the BC

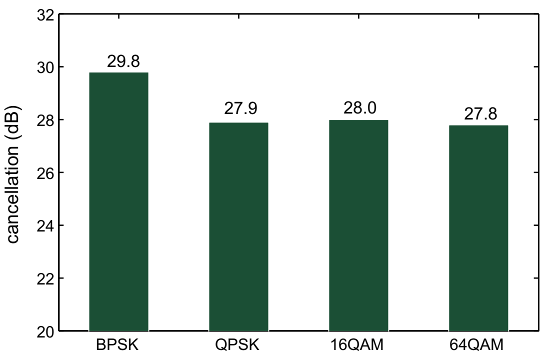


Fig. 10. Performance of digital cancellation.

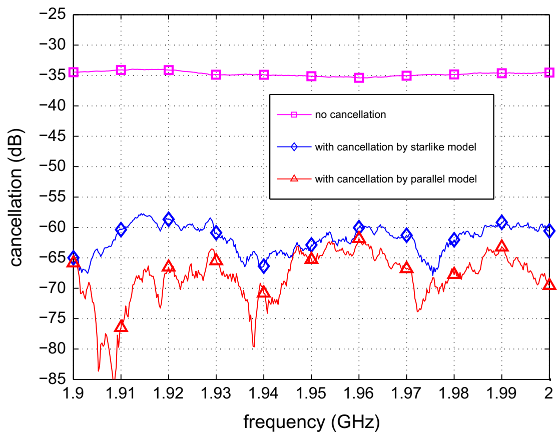


Fig. 11. The antenna cancellation results.

design is focused on the RF front-end part before a dynamic cancellation circuit is applied. Thus, it can be integrated with the design in [6] to achieve higher analog cancellation. Thus, the BC design is complementary to the design in [6].

7. Discussion

The BC design provides sufficient cancellation in the analog domain and makes a solid step towards to full duplex MIMO. However, limitations exist in the BC design, which demands future research.

7.1. Influence of channel variations

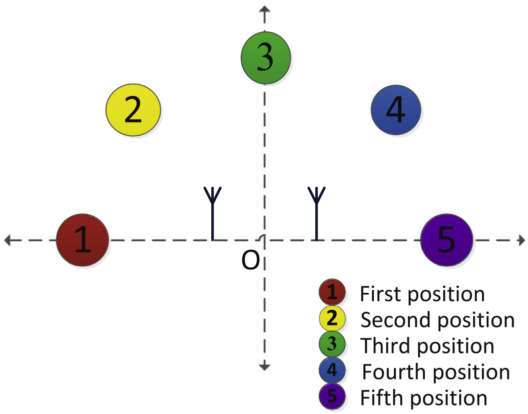
It is assumed that the channel is symmetric in the BC design. However, in a practical indoor environment, the channel cannot be perfectly symmetric. We conduct an experiment to observe the influence by channel variations. We use a cylinder metal box with a height of 20 cm and a radius of 5 cm as an obstacle and place it at different positions with a distance of about 30 cm to the middle point O in Fig. 12(a). The measured cancellation results are shown in Fig. 12(b). As we can see, the result with the obstacle at the third position is almost consistent with that with no obstacle because the obstacle at this position makes little influence to the symmetric channel. The obstacle at the other positions causes about 5–10 dB fluctuations in cancellation. Such influence exists when the obstacle is near the antennas. When the obstacle is placed 1 m away from the antenna, there is nearly no influence to cancellation.

We notice the similar effect of the channel variation caused by the movement of a person in the lab. When a person moves at a distance of about 2 m away from the antennas, the cancellation of the BC design does not change. However, if the person move within 1 m from the antennas, about 10 dB and 5 dB fluctuations are measured for the BC design cancellation and antenna cancellation, respectively.

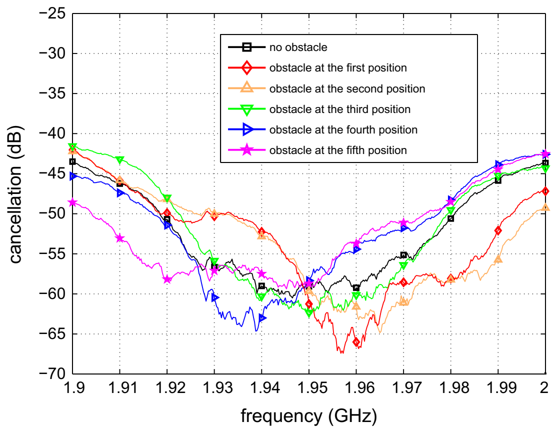
As a result, the best application scenario for the BC design without a dynamic cancellation circuit is an open outdoor environment, like the outdoor WiFi system. However, the BC design can be easily integrated with an existing dynamic cancellation circuit to resist the channel variation and thus becomes applicable in the indoor environment.

7.2. Improvement of cancellation

In our experiment, the BC design is built based on a discrete component circuit. If the BC design is implemented on the PCB with surface-mounted RF devices, then the symmetry can be highly improved. Reducing the antenna reflection is another effective option to improve the cancellation. In our experiment, the antenna reflection is about -5 dB of the transmit signal. If we reduce the antenna reflection to -15 dB like that in [1,6], then the BC design can achieve additional 10 dB analog cancellation under the same symmetric structure.



(a) The positions of the obstacles



(b) The effects by the obstacles

Fig. 12. Channel symmetry influenced by obstacle: (a) the positions of the obstacles; (b) the cancellation results with the obstacle.

7.3. Null points

In the BC design, two antennas are used to transmit inverse signals, which results in a radiation pattern that is different from that of a transmitter with only one antenna. Particularly, the BC design results in null positions in space. In fact, two transmit antennas may cause a weaker received signal no matter whether they transmit the same or inverse signals.[1] When two transmit antennas send the same signals, the signal add destructively at positions where the distances to the two transmit antennas are d and $d + (2n+1)\lambda/2, (n = 0, 1, 2\cdots)$. These positions are on the hyperbola as shown in Fig. 13(a). When the two transmit antennas send inverse signals, the null positions may not only exist on the hyperbola where the distance from two antennas differ by $n\lambda, (n = 1, 2, 3\cdots)$, but also on the perpendicular bisector as shown in Fig. 13(b). Since the powers of the two received signals are different at the hyperbola, the received signals at these positions may not cancel each other completely. However, at the perpendicular bisector, the powers of the two signals are nearly the same,

[1] Here we assume each antenna is omnidirectional.

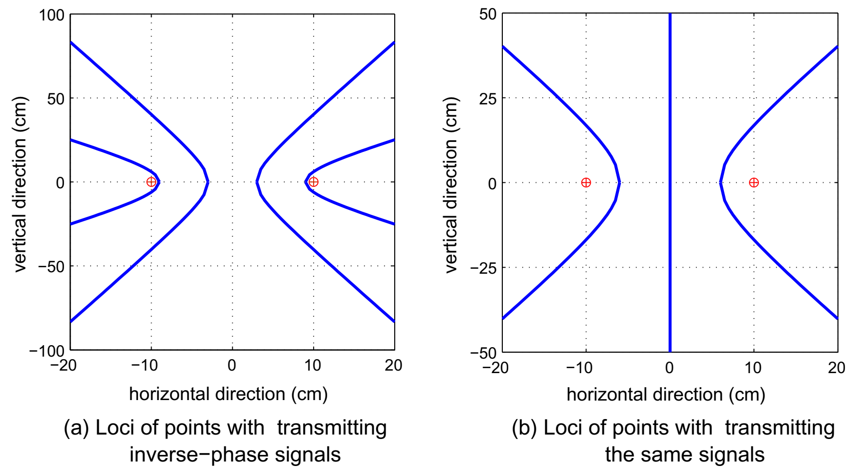


Fig. 13. Loci of points where two received signals have inverse phases (the circles indicate the antenna locations): (a) two antennas transmit the same signals; (b) two antennas transmit inverse-phase signals.

which form null positions. Thus, we need to look into two questions: (1) do null positions affect communications practically? (2) Can null positions be used to achieve antenna cancellation for MIMO communications? They are discussed below.

In [18,17], the effect of null positions is measured and the conclusion is that null positions exist only in the near field. In the far flied (3 m away) there are almost no null positions because of the channel independence and multi-path effect. We also conduct a similar experiment to measure null positions of our BC design. We first use only one transmit antenna with the transmit power of −16 dBm and measure the received signal power for 40 points at a distance of 1 m away from the transmit antenna in the near field. We then use two antennas sending inverse signals and repeat the experiment with the same transmit power, which means the power of each transmitting antenna is −19 dBm. The received signal power from single-antenna experiment is used as a reference to check if the received signal from the two-antenna experiment is nullified. The results of received signal power of these two experiments are shown in Fig. 14. We find that the null points only appear at the perpendicular bisector (indicated by 90 degree and 270 degree in Fig. 14), where the received signal power in two-antenna experiment is about 15 dB lower than that in the single-antenna experiment. However, when the position is a little deviated from the perpendicular bisector, the received signal power increased dramatically to the level of the single-antenna experiment. For all other points, the signal powers only differ by about 5 dB. The above results prove that our BC design is not restricted by the null-point issue in practice.

It is impractical to leverage null positions for antenna cancellation in full duplex MIMO. If we use the hyperbola positions for antenna cancellation, there exist three problems. The first one is to change the transmit power of the two antenna as in [11] so that the two received signals can be nulled at hyperbola positions. However, the transmit power of the two antennas is the same in the BC design. The second problem is that the hyperbola positions change with frequency. For example, the hyperbola positions of 5 GHz signals is different from that of 2.4 GHz signals. Thus, null positions are not adaptive to different channels. In other words, when a communication channel is changed, antenna cancellation may become ineffective, unless antenna positions are adjusted accordingly. The

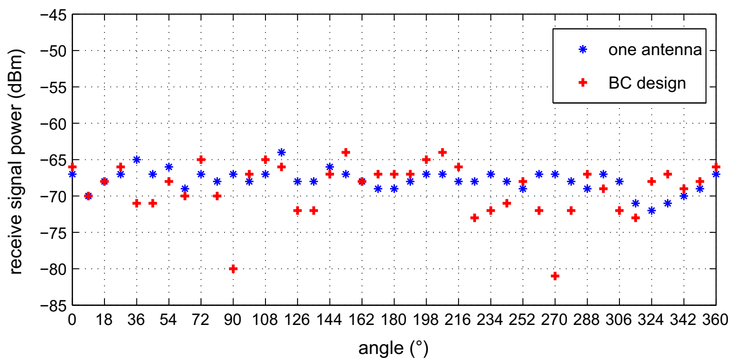


Fig. 14. The effect of null positions in the BC design at a distance of 1 m away from the antennas.

third problem is that hyperbola positions are not symmetric, i.e, even if we place the second BC design at the hyperbola positions of the first BC design, the first BC design is not necessarily at the hyperbola positions of the second BC design. If we use perpendicular bisector positions for antenna cancellation, the above problems in hyperbola positions do not exist. However, we can only achieve 2×2 MIMO communications. This limited setup can be considered as a special case of our proposed MIMO extension.

8. Conclusion

In this paper, a novel balanced RF circuit was developed for self-interference cancellation in the analog domain. Furthermore, the BC design was extended to achieve scalable full duplex MIMO communications. Experiments validated the distinct features of the BC design: (1) for applications demanding a few MHz bandwidth, the BC design and linear digital cancellation are sufficient to achieve enough self-interference for a full duplex radio; (2) for applications with wide bandwith, the BC design needs additional support by either a digital cancellation circuit or non-linear digital cancellation, but not both; and (3) extension of the BC design to MIMO is scalable and achieves sufficient analog cancellation. Moreover, design and analysis in this paper showed that the BC design can be easily integrated with a dynamic cancellation circuit and can also simplify the dynamic cancellation circuit in full duplex MIMO.

In the future work, we will implement the BC design in a PCB. Moreover, a dynamic cancellation circuit will be implemented together with the BC design on a full duplex radio.

Acknowledgment

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Appendix A

There are three types of self-interference in the BC design. Considering the first component of each type of self-interference, let $A_1x(t)e^{j\phi_1}, A_2x(t)e^{j\phi_2}$ and $A_3x(t)e^{j\phi_3}$ denote self-interference from circulator leakage, antenna reflection, and the signal received from the other antenna, respectively. The other component is denoted by $A'_1x(t)e^{j\phi'_1}, A'_2x(t)e^{j\phi'_2}$ and $A'_3x(t)e^{j\phi'_3}$, respectively. A_i and $A'_i(i=1,2,3)$ are the amplitudes of these signals, and ϕ_i and $\phi'_3(i=1,2,3)$ are the phase shifts. Let $\alpha_i = A'_i/A_i(i=1,2,3)$ to represent the amplitude ratios and $\theta_i = \phi'_i - \phi_i - \pi(i=1,2,3)$ to represent the phase offsets of the symmetric components of the self-interference. Thus, the received signal of the six components is

$$\begin{aligned} y(t) &= A_1x(t)e^{j\phi_1} + A_2x(t)e^{j\phi_2} + A_3x(t)e^{j\phi_3} + A'_1x(t)e^{j\phi'_1} \\ &\quad + A'_2x(t)e^{j\phi'_2} + A'_3x(t)e^{j\phi'_3} \\ &= \sum_{i=1}^{3} A_ix(t)e^{j\phi_i}(1-\alpha_ie^{j\theta_i}) \end{aligned} \tag{21}$$

The power of the received signal is given by $y(t)\overline{y(t)}$, where $\overline{y(t)}$ is the complex conjugate of the signal $y(t)$. Thus, the power of the received signal becomes

$$\begin{aligned} P &= \sum_{i=1}^{3} A_ix(t)e^{j\phi_i}(1-\alpha_ie^{j\theta_i}) * \sum_{i=1}^{3} A_ix(t)e^{-j\phi_i}(1-\alpha_ie^{-j\theta_i}) \\ &= \left\{ \sum_{i=1}^{3} A_i^2(1-2\alpha_i cos\theta_i + \alpha_i^2) \right. \\ &\quad + \sum_{m=1}^{3}\sum_{n=1,n\neq m}^{3} A_mA_ne^{j(\phi_m-\phi_n)}(1-\alpha_me^{j\theta_m} - \alpha_ne^{-j\theta_n} \\ &\quad \left. + \alpha_m\alpha_ne^{j(\theta_m-\theta_n)}) \right\} x^2(t) = P' + P'', \end{aligned} \tag{22}$$

where

$$P' = \left\{ \sum_{i=1}^{3} A_i^2(1-2\alpha_i cos\theta_i + \alpha_i^2) \right\} x^2(t), \tag{23}$$

$$\begin{aligned} P'' &= \left\{ \sum_{m=1}^{3}\sum_{n=1,n\neq m}^{3} A_mA_ne^{j(\phi_m-\phi_n)}(1-\alpha_me^{j\theta_m} - \alpha_ne^{-j\theta_n} \right. \\ &\quad \left. + \alpha_m\alpha_ne^{j(\theta_m-\theta_n)}) \right\} x^2(t) \\ &= \left\{ \sum_{m=1}^{2}\sum_{n=2,n\neq m}^{3} 2A_mA_n[cos(\phi_m-\phi_n) - \alpha_m cos(\phi_m-\phi_n+\theta_m) \right. \\ &\quad \left. - \alpha_n cos(\phi_m-\phi_n-\theta_n) + \alpha_m\alpha_n cos(\phi_m-\phi_n+\theta_m-\theta_n)] \right\} x^2(t). \end{aligned} \tag{24}$$

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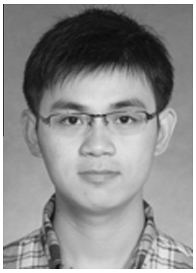

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