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Review

Self-Interference Cancellation: A Comprehensive Review from Circuits and Fields Perspectives

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Abstract: Increased demand for higher spectrum efficiency, especially in the space-limited chip, base station, and vehicle environments, has spawned the development of full-duplex communications, which enable the transmitting and receiving to occur simultaneously at the same frequency. The key challenge in this full-duplex communication paradigm is to reduce the self-interference as much as possible, ideally, down to the noise floor. This paper provides a comprehensive review of the self-interference cancellation (SIC) techniques for co-located communication systems from a circuits and fields perspective. The self-interference occurs when the transmitting antenna and the receiving antenna are co-located, which significantly degrade the system performance of the receiver, in terms of the receiver desensitization, signal masking, or even damage of hardwares. By introducing the SIC techniques, the self-interference can be suppressed and the weak desired signal from the remote transmitter can be recovered. This, therefore, enables the full-duplex communications to come into the picture. The SIC techniques are classified into two main categories: the traditional circuit-domain SICs and the novel field-domain SICs, according to the method of how to rebuild and subtract the self-interference signal. In this review paper, the field-domain SIC method is systematically summarized for the first time, including the theoretical analysis and the application remarks. Some typical SIC approaches are presented and the future works are outlooked.

Keywords: interference cancellation; self-interference; full-duplex communications

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1. Introduction

With the rapid growth of the modern wireless communication systems and the Internet-of-Things technologies, wireless devices become pervasive nowadays [1]. In many space-limited platforms, such as chips, base stations, and vehicles, the demand to achieve higher spectrum efficiency and data rates has spawned the development of integrated transceivers, which enable the transmitting and the receiving in a co-located system [1–4]. Full-duplex communication, as a promising approach, provides a novel paradigm to improve spectrum efficiency by opening up the possibility to transmit and receive signals within the same frequency band and time slot, and even in a space-limited environment [5–8].

The key challenge of full-duplex communications is to reduce the self-interference as much as possible, ideally, down to the noise floor. In a full-duplex transceiver, the high-power transmitted signal propagates into the local receiver through a direct path between the transmitting and receiving antennas, and the reflection multi-paths created by the transmit signal scattering off nearby objects [9]. These transmitted signals combine and modulate at the radio frequency (RF) front-end of the local receiver and become a self-interference that is overwhelmingly stronger than the signal of interest (SoI) from the remote transmitter. The strong self-interference would interfere or even saturate the receiving chain, and thus needs to be suppressed at the RF front-end before the analog-to-digital converter (ADC) quantization process [10].

As can be seen from the above introduction, the investigation of the self-interference suppression methods is extremely important to realize the full-duplex integrated transceivers. Numerous self-interference suppression techniques have been reported in the literature, from the simplest isolation to the complex adaptive cancellation [11–14]. The aim of passive suppression approaches is to attenuate the self-interference by separating the transmitting and receiving antennas in the way of antenna directionality, orthogonal polarization, or simplest spatial isolation [15,16]. Another way is to use a circulator to share one antenna for both transmitting and receiving [17,18]. Isolators, such as the parasitic elements, metamaterial inspired isolators, and electromagnetic bandgap structures, have also been studied in previous research [19–22]. These passive approaches can be easily realized, but the isolation performance is normally limited, especially when the interference channel varies in time. In addition to the passive methods, the active methods have also received much attention. One of them is the transmit beamforming approach, which is widely used to boost the system performance, including mitigating the self-interference [23].

Among all the self-interference suppression approaches, self-interference cancellation (SIC) is a promising and effective technique to realize the full-duplex communications [24]. The basic principle of SIC is to rebuild a copy of the RF self-interference signal by some dedicated methods. The rebuilt signal will be subsequently used to subtract from the receiving signal, which combines both the SoI and the self-interference at the front-end of the receiver to suppress the strong self-interference signal. According to different division standard, the SIC methods can be classified into different categories. Whether the SIC can be adaptively adjusted with the varying of the environment is used to allocate the SIC to the active way or the passive way. In addition to this, SIC can be divided to the field-domain SIC (FDSIC) and the circuit-domain SIC (CDSIC), from the perspective of the signal processing domain, since the self-interference signal can be rebuilt in the field domain, or the circuit domain. The CDSIC can be further classified as the analog SIC, the digital SIC, and the analog–digital hybrid SIC.

Analog SIC in the circuit domain is the most popular approach; it attempts to generate a reference signal that is a replica of the self-interference by using the analog circuits. Digital SIC is implemented after the ADC, where the residual self-interference is estimated and subtracted from the received digital signal sample. The FDSIC can be easily implemented but suffers the drawback of a relatively low interference cancellation ratio (ICR). Different SIC methods should be adopted according to realistic situations. Normally, no single method of cancellation is sufficient to remove the effect of the self-interference thoroughly, and a combination of them is sometimes required.

A review paper on SIC techniques exists in the literature [25]. However, it only focuses on the SIC in the circuit domain. A review of the noise cancelling technique can be found in [26], which reviews the development of the noise cancellation the voltage or current domains, after frequency downconversion to baseband. However, the field domain cancellation technique is not highlighted. The wideband transmitting–receiving coupling reduction methods in propagation domain are reviewed in [27]. However, the circuit domain approaches are not included. This paper, for the first time, gives a comprehensive review of the SIC from the perspective of both the circuit domain and field domain. The phenomenon and effects of the self-interference in a co-located integrated communication system are at first reviewed, followed by the discussion of the conventional CDSIC techniques in analog, digital, and hybrid methods. FDSIC, which has never been summarized to the best knowledge of the authors, is then analyzed. It is similar with the CDSIC in terms of the operating theory. However, one difference is that the FDSIC has its unique design strategy and, thus, brings benefits of low-cost, low complexity, etc., compared with the conventional CDSIC. FDSIC is therefore suitable for many scenarios in which simple structured SIC devices are needed.

The rest of the article is organized as follows: the phenomenon and effects of the self-interference are introduced in Section 2. The classification of the SIC techniques is given in Section 3. The CDSIC, including the analog ways and digital ways are analyzed in Section 4, prior to the discussion of the FDSIC in Section 5. The comparison of the different SIC approaches are shown in Section 6. Finally, concluding remarks and future research outlooks are drawn in Section 7.

2. Phenomenon and Effects of Self-Interference

Interference is a phenomenon where received unwanted signals disturb the performance of a communication system. The growing trend of multiple operators sharing a common site has led to a serious interference issue. A collocated scenario of an integrated transceiver that contains high-power transmitters and a victim receiver is illustrated in Figure 1. A receiving antenna is mounted close to a number of transmitting antennas and in most commercial sites the transmitting antennas carry a number of transmit channels. These transmitted signals combine together at the RF front-end of the local receiver and form a self-interference that is much stronger than the SoI from a remote transmitter. The victim receiver therefore receives high-power jamming signals and these cause a number of distortions.

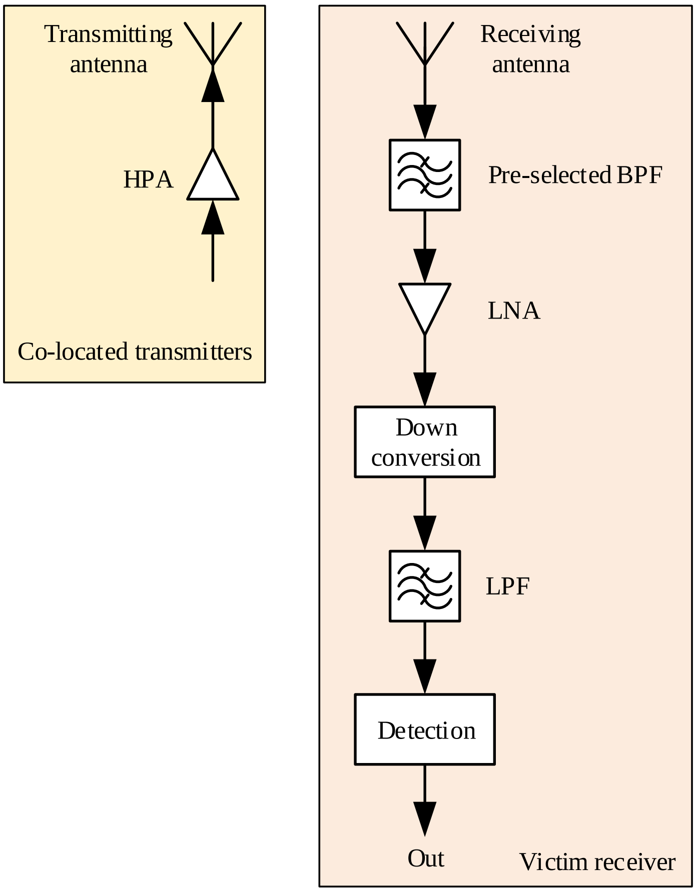


Figure 1. A co-located communication system that includes multiple transmitters and a victim receiver.

Firstly, consider blocking and desensitization. The desensitization is caused when the interference is large enough to affect the quiescent value and the low-noise amplifier (LNA) or the mixer in the receiver. The blocking occurs when the receiver circuits are forced into saturation by the high-power interference signals, regardless of their carrier frequencies [28].

Secondly, consider the radiated distortions from the co-located transmitters. They are generated when a high-powered signal from one transmitter radiates into a second transmitter. The signals mix together in the non-linear output stage of the high-power amplifier (HPA). The unwanted third-order intermodulation products can interfere with nearby receivers operating in their frequencies.

Thirdly, consider the intermodulation (IM) distortion, which is generated within the front-end circuits of the victim receiver. The large transmit signals from the co-located transmitters combine at the victim receiver, and thus form IM distortions. This becomes serious when it falls directly on the SoI frequency band. The LNA is most susceptible to the interference signals.

The distortion generated with in the receiver is well studied and modeled by the receiver's third-order intercept point. It can easily affect the active devices, such as the LNA or mixer, especially when it falls in the SoI channel. Blocking does not require interference transmitters to operate at specific frequencies, but can be caused by just one high-power transmitter. In order to mitigate the interference signal, and protect the receiver from performance degrading or even damaging, the SIC methods should thus be introduced.

3. Classification of the SIC Techniques

The operating mechanism of the SIC techniques is illustrated in Figure 2. The core concept of the SIC technique is to cancel the self-interference signal by rebuilding a copy of the reference self-interference signal. Based on different methods of how to rebuild and subtract the copy of the self-interference signal, the SIC can be classified to the circuit domain approach or the field domain approach. The distinction of the CDSIC and the FDSIC is shown in Figure 3. The CDSIC rebuilds the copy of the self-interference signals via analog circuits or digital circuits. The FDSIC rebuilds the self-interference signals in the field domain and cancels the self-interference at the antenna terminal. By introducing the control methods to the FDSIC, the adaptive SIC can be realized. The classification of the SIC techniques is summarized in Figure 4.

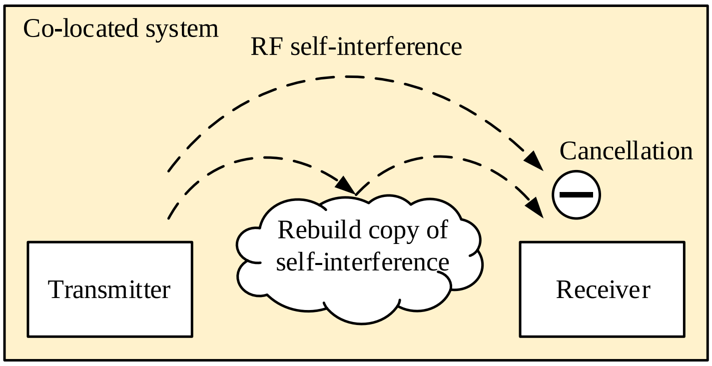
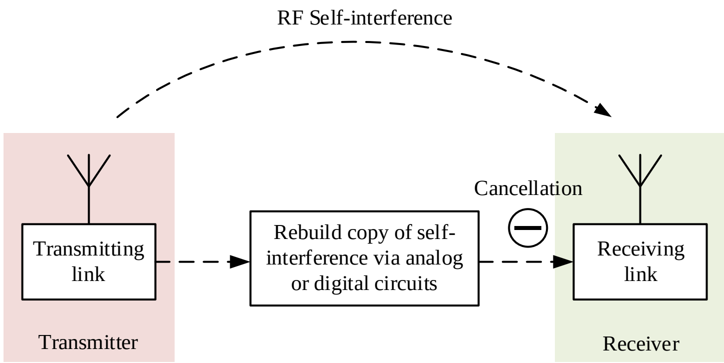
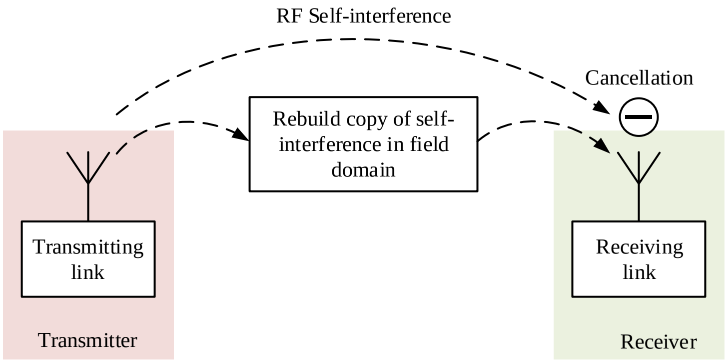


Figure 2. Operation mechanism of the SIC techniques.



(a) Circuit domain SIC

Figure 3. *Cont.*



(b) Field domain SIC

Figure 3. Distinction between the circuit- and field-domain SIC.

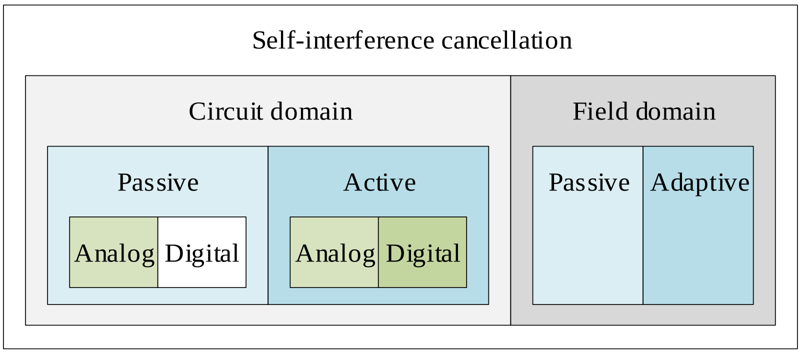


Figure 4. Classification of the SIC techniques.

4. SIC via Analog and Digital Circuits

4.1. Analog SIC

Among all the SIC methods, the analog SIC has been widely recognized as one of the most effective schemes published, since it is particularly critical to prevent the ADC from becoming saturated [29–31]. A typical analog self-interference cancellation system (SICS) is illustrated in Figure 5 [30]. The transmitted signal at the input of the transmitting antenna is sampled and used as the reference signal. The reference signal is delayed and multiplied by the amplified and looped-back residual self-interference with a vector modulator. The product of the residual self-interference signal and the delayed reference self-interference signal is then filtered with a pair of low-pass filters (LPFs) to update the complex weighting coefficient, which, in turn, modifies the delayed reference signal at the vector modulator. The synthesized cancellation signal is obtained by combining the output signal of the SICS and the received signal of the receiving antenna. After cancellation, the residual self-interference is amplified by the LNA.

The presented single-tap topology shown in Figure 5 is suitable for narrow band interference cancellation. It has been shown that cancellation techniques using a single-tap structure can only operate over narrow instantaneous bandwidths and inherently cannot address reflection paths from the environment [32]. In order to achieve wideband interference cancellation, the multitap configuration should be included to mimic the realistic interference channel, which considers the multi-path effects [8,33,34]. The multitap design in [34] passes the coupled RF-transmitted signal through a more complicated circuit that consists of 16 parallel fixed lines of different delays and tunable attenuators to reconstruct the multipath self-interference signal. However, this method dramatically increases the complexities in hardware design and requires sophisticated algorithms for attenuation tuning instead of more general gradient descent approaches [8]. Other different aspects of the analog SIC have been studied by many other researchers, in terms of the matching strategy [35], the performance bound [29,36,37], and the SIC performance under complex circumstances, i.e., the Doppler effects, the channel fading effects, and the nonlinear distortion effects [38,39]. All these studies from various perspectives form a relatively mature research framework of the analog SIC compared with the digital and hybrid approaches.

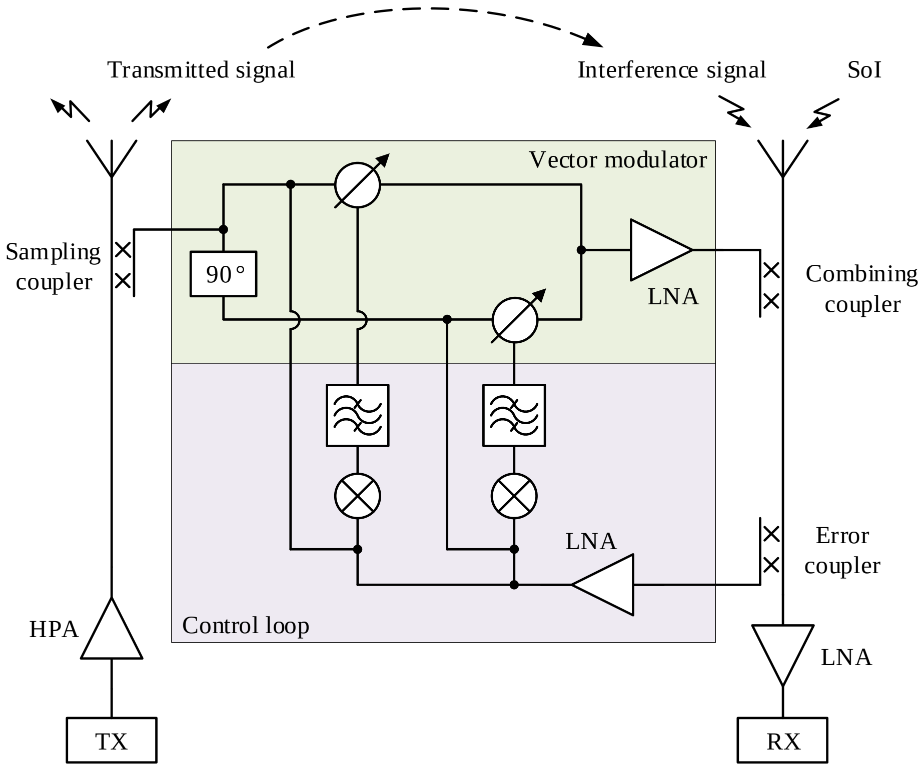


Figure 5. A typical analog SIC topology.

4.2. Digital SIC

The cancellation that occurs in the digital domain after the received signal has been quantized by an ADC is called the digital-domain SIC. Examples of full-duplex systems where digital-domain SIC has been implemented are presented in [40,41]. A typical digital-domain SIC is shown in Figure 6 [42]. Both the sampled reference self-interference signal and the received signal of the receiver are downconverted to digital signal by using the ADC and the downconverter. An equivalent discrete-time coupling channel is estimated to rebuild a digital self-interference signal. Then, the rebuilt self-interference signal will be subtracted from the digital received signal.

Given that the cancellation process is performed in the digital domain, digital SIC techniques are some of the least complex among all active cancellation techniques [43,44]. The digital-domain SIC is carried out after ADC, and many highly efficient digital signal processing algorithms can be utilized, which brings more degrees of freedom to the SICS design. However, as mentioned above, when the interference power is too large to saturate the front-end of the receiver, the interference cancellation performance of the digital-domain SIC will decrease significantly [45]. The analog SIC can solve this problem. However, the suppression performance of the analog SIC is normally subjected to the accuracy of the delay unit and attenuator of the vector modulator. As a result, the digital-domain SIC is commonly implemented together with the analog-domain SIC, i.e., the strong self-interference is at first suppressed by the analog SIC, and the residue self-interference is then cancelled by the digital SIC [14,46,47], see Figure 7.

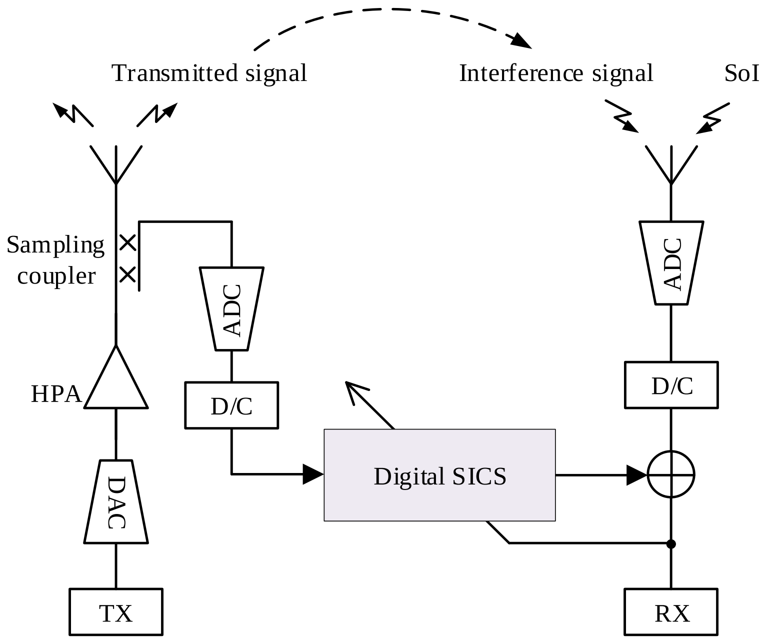


Figure 6. A typical digital SIC topology.

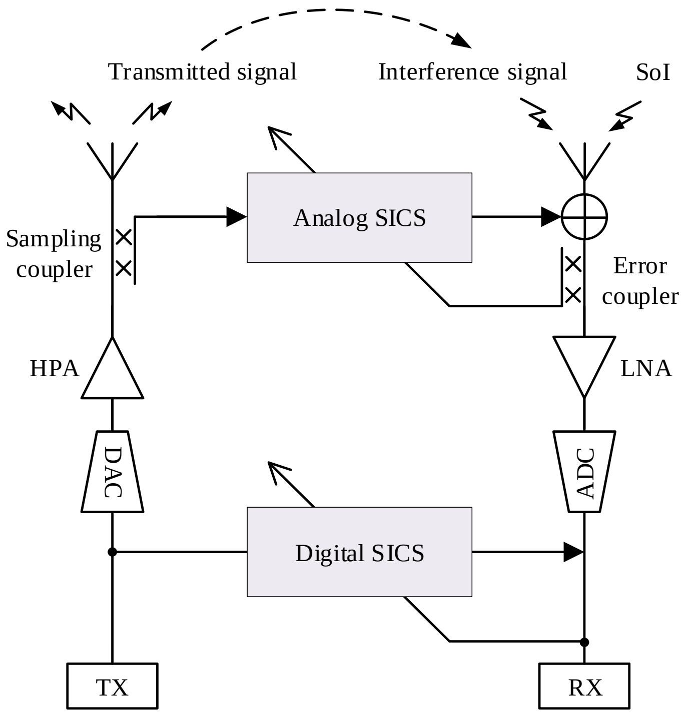


Figure 7. A two-stage SIC topology that contains both the analog SIC and digital SIC.

4.3. Analog–Digital Hybrid SIC

As discussed above, the analog SIC is able to suppress the high-power SI, while the digital SIC allows a more complex adaptive algorithm. It is quite a consequential idea to combine the advantage of both methods. The analog–digital hybrid SIC is thus proposed. This approach is performed by building a digital copy of the self-interference signal from the baseband-transmitted signal and then transmitting the digital copy through an auxiliary analog transmit chain to reconstruct the RF self-interference signal [48–52]. In this approach, a finite impulse response filter is implemented in the digital domain to characterize the self-interference propagation channel to generate a reconstructed self-interference signal of multipath components.

A typical analog–digital hybrid configuration is shown in Figure 8 [51]. The high speed ADCs are utilized to directly sample the self-interference signal and the error feedback signal. The control loop is, therefore, realized in the digital domain, and then connected to the analog vector modulator by the digital-to-analog converters (DACs). The adaptive control algorithm of the SIC can, thus, be implemented in the digital circuits, which enables a more efficient, more complex, and high-performance algorithm.

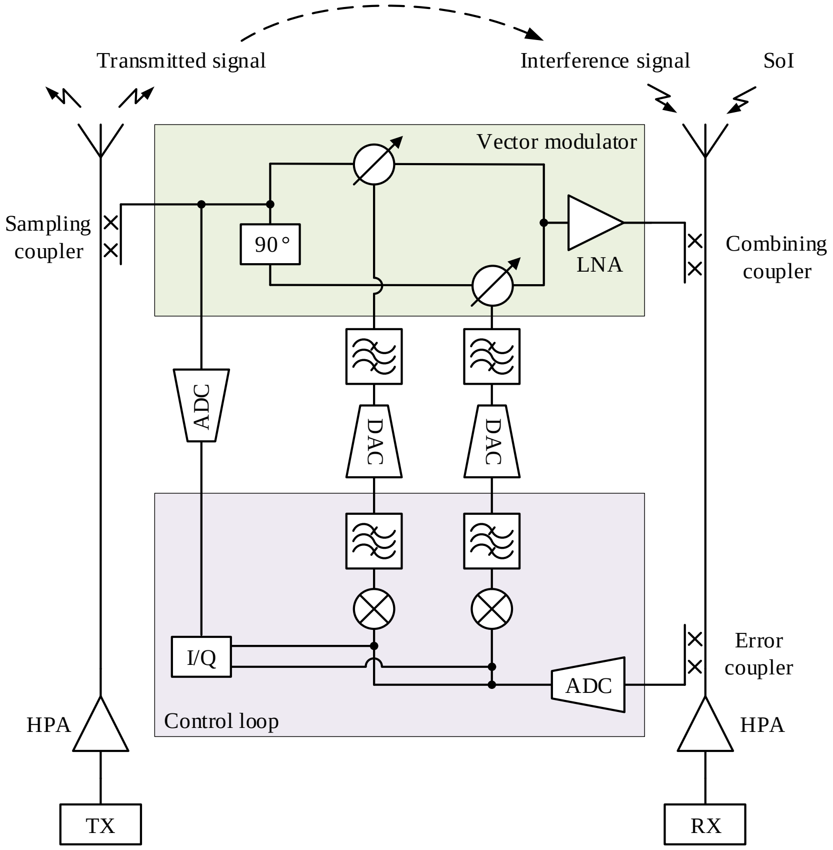


Figure 8. A typical analog–digital hybrid SIC topology.

4.4. Passive SIC

If the SIC can be adaptively adjusted to optimize the ICR in a time-varying environment, it is defined as the active SIC. Otherwise, it is featured as the passive SIC, which is also useful for many scenarios [53]. From the circuit perspective, the passive SIC is based on the use of passive circuits or components, e.g., resistor, capacitor, inductor, circulator etc. [54–56], and active passive SIC always contains active components [29,30,51]. Similar to the adaptive SIC, passive SIC techniques extract the reference signal from the transmitter, and cancel the interference signal at the receiver. The signal modulation can be implemented by the analog resonant circuits. The main difference is that the control circuit is omitted in the passive SIC, which will tremendously decrease the complexity of the SICS. Thus, this method is suitable for a situation in which the coupling path between the transmitter and receiver is (quasi) static. Note that the passive SIC so far is not realized in the digital domain.

4.5. Features of the Circuit-Domain SIC

As we can see from the above analysis, for all the CDSIC techniques, including both the active and passive SICs, extracting the reference self-interference signal from the transmitter is mandatory. This will inevitably decrease the transmitting power and, thus, degrade the transmitter performance. In the case that the coupling between the transmitting and receiving antenna is very strong, the loss of the transmitting power will be significant, because a high-power reference signal is needed to cancel the strong interference signal. On the other hand, since the CDSIC is realized by circuits, it can be integrated with the transceiver, and thus, the shielding can be easily implemented. As a result, the radiation patterns of the transmitting and receiving antenna will not be affected.

5. SIC in Fields Domain

5.1. Operating Mechanism of the FDSIC

Most of the previous SICS is realized in the circuit domain through analog or digital approaches. The advantage of this method is that a high ICR can be obtained. However, the CDSIC is complex and costly, since many basic components are mandatory, such as the sampling coupler, the vector modulator, and the combining coupler. Compared with the CDSIC, the FDSIC normally has a simpler structure [57–59].

The operating mechanism of the FDSIC is illustrated in Figure 9. The current excited in the transmitting antenna is described by I. Through the direct coupling path, a current αI is induced on the receiving antenna, where α is the coupling coefficient. By adding a FDSIC system, a new situation is generated, the coupling situation of which can be worked out to the first order. A current $\beta_1 I$ is now also induced in the FDSIC system, generating in its turn an induced current $\beta_1\beta_2 I$ in the receiving antenna, where β_1 is the coupling coefficient between the transmitting antenna and the FDSIC system, and β_2 is the coupling coefficient between the FDSIC system and the receiving antenna. The total induced current in the receiving antenna is $\alpha I + \beta_1\beta_2 I$. When the FDSIC system is properly designed, the FDSIC system creates reverse coupling, meaning that the total induced current approaches zero:

$$\alpha I + \beta_1\beta_2 I = 0 \tag{1}$$

The self-interference is cancelled in the field domain like this. In essence, the FDSIC system is designed with a scatterer, which can generate rich scattering characteristics to rebuild the copy of the SI.

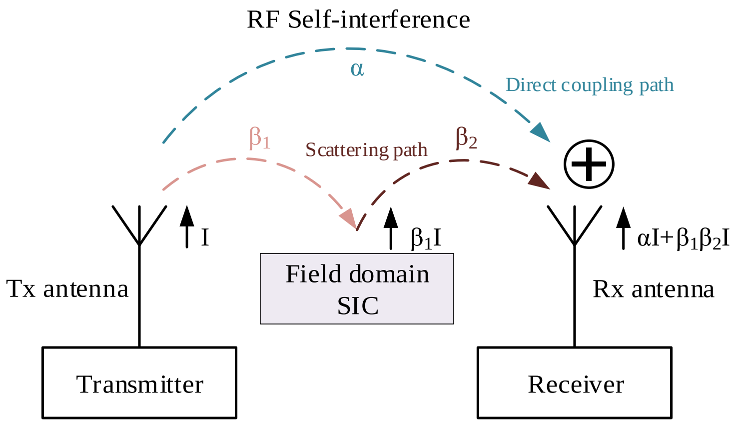


Figure 9. Operation mechanism of the FDSIC.

5.2. Features of the FDSIC

Compared with the CDSIC, the FDSIC is relatively simple, since some components that are necessary in the CDSIC can be omitted. The reference signal is extracted from the radiation of the transmitting antenna directly in the space, while the interference signal is cancelled at the receiving antenna terminal. In this way, the sampling coupler and the combining coupler are not needed, which greatly decreases the complexity of the SICS. Different from the CDSIC, the transmitting power will not be decreased when the FDSIC system is utilized, since the radiated power of the transmitter is "captured" by the FDSIC system in the space.

The drawback of the FDSIC is the distortion of the radiation patterns. When introducing a FDSIC system between the transmitting antenna and the receiving antenna in the space, the SIC is inherently coupled with the transmitting and receiving antenna, and thus affects the radiation patterns. However, through careful design, this effect can be miniaturized and will not impact the system performance. An example is shown in Figures 10 and 11 [58]. The coupling is suppressed, while the radiation patterns are slightly affected when the SIC isolator is introduced. The ICR of [58] is limited compared with many CDSIC [29,30,51], since it is a great challenge to rebuild a perfect copy of the self-interference signals via the simple scatterer.

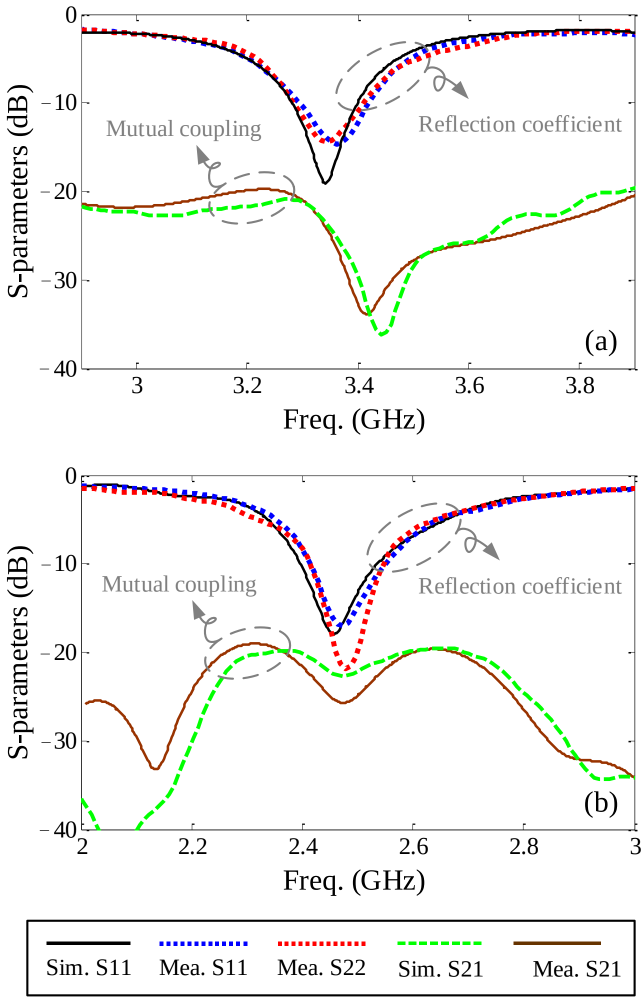


Figure 10. S-parameter performance of a field-domain SICS [58]. (**a**) State 1, (**b**) State 2. The dashed lines indicate the measurement results, the solid lines indicate the simulation results.

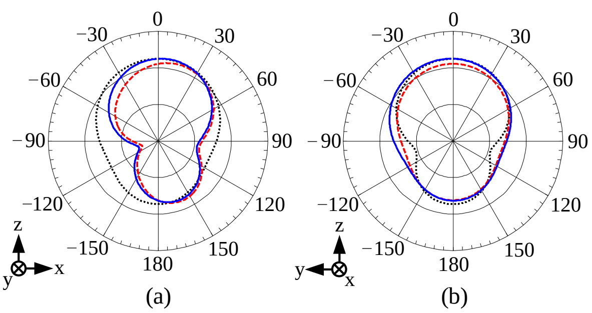


Figure 11. *Cont.*

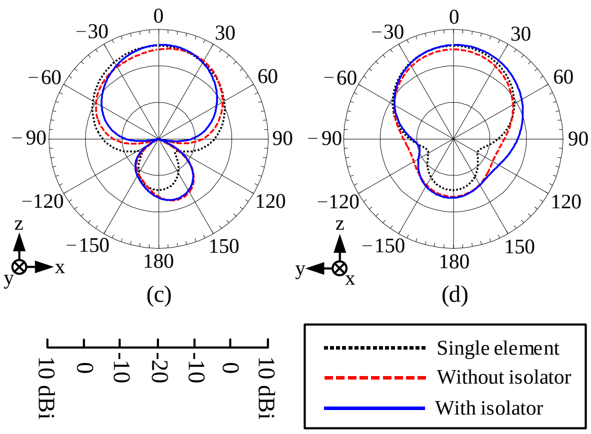


Figure 11. Radiation patterns of a field-domain SICS [58]. (**a**) State 1, xz plane, (**b**) State 1, yz plane, (**c**) State 2, xz plane, (**d**) State 2, yz plane.

6. Comparison of the Circuit- and Field-Domain SIC

The key performances of some typical SIC systems in the circuit domain and field domain are compared in Table 1. The characteristics of the CDSIC and the FDSIC are summarized in Table 2. In terms of the transmitting power, the CDSIC will result in a high power loss, while the FDSIC does not have the power loss theoretically, since the transmitting power of transmitting system will be sampled by the CDSIC, see Figure 12. However, the radiation patterns of the transmitting and receiving antenna will be affected to some extent when introducing the FDSIC system. This problem will not happen for the CDSIC. Note that the CDSIC will affect the received SoI and the noise floor. The typical receiving system and the receiving system containing an SIC are presented in Figure 13a,b, respectively. In the latter case, the receiving signal is delivered to the combining coupler via the cables. Then, the combined signal, which contains the reference signal and the receiving signal, is sent to the receiver via the error coupler and an LNA. The receiving transmission link of the SoI contains the receiving antenna, the cables, the combining coupler, the error coupler, the LNA and the receiver. This will inevitably increase the noise figure of the receiving system [60]. Given that the combining coupler and the error coupler are inserted in the receiving transmission link, the SoI will also be attenuated.

Table 1. Key performance comparison of typical circuit and field-domain SIC.

Ref	Category	Complexity	ICR	Bandwidth
[29]	CDSIC-analog	High	30–40 dB	narrow
[30]	CDSIC-analog	High	60–80 dB	narrow
[32]	CDSIC-analog	High	ca. 30 dB	narrow
[35]	CDSIC-analog	High	ca. 30 dB	wide
[43]	CDSIC-digital	High	25–60 dB	narrow
[46]	CDSIC-hybrid	High	30–40 dB	wide
[53]	CDSIC-passive	Low	12 dB	narrow
[56]	CDSIC-passive	Low	60 dB	narrow
[58]	FDSIC-passive	Low	ca. 8 dB	narrow
[59]	FDSIC-active	High	40 dB	narrow

Table 2. Comparison of the circuit domain SIC and the field-domain SIC.

		Transmitting Power Loss	Attenuation of the SoI	Effect on the Noise Figure	Radiation Pattern
Circuit domain	Analog	Yes	Yes	Yes	No effect
	Digital	Yes	Yes	Yes	No effect
Field domain	-	No loss	No attenuation	No effect	Distortion

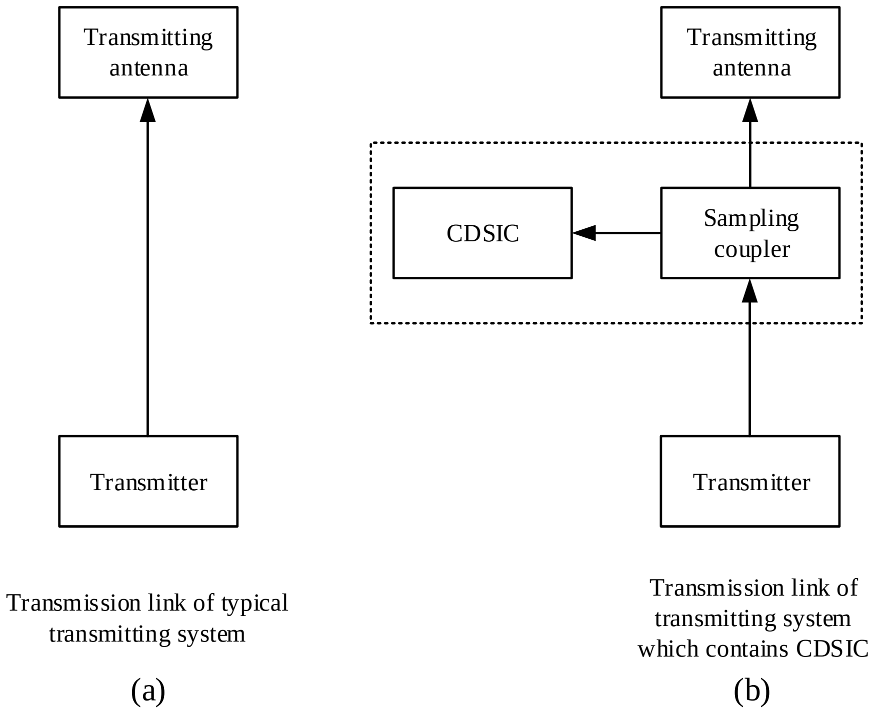


Figure 12. Typical transmitting system and transmitting system containing a CDSIC.

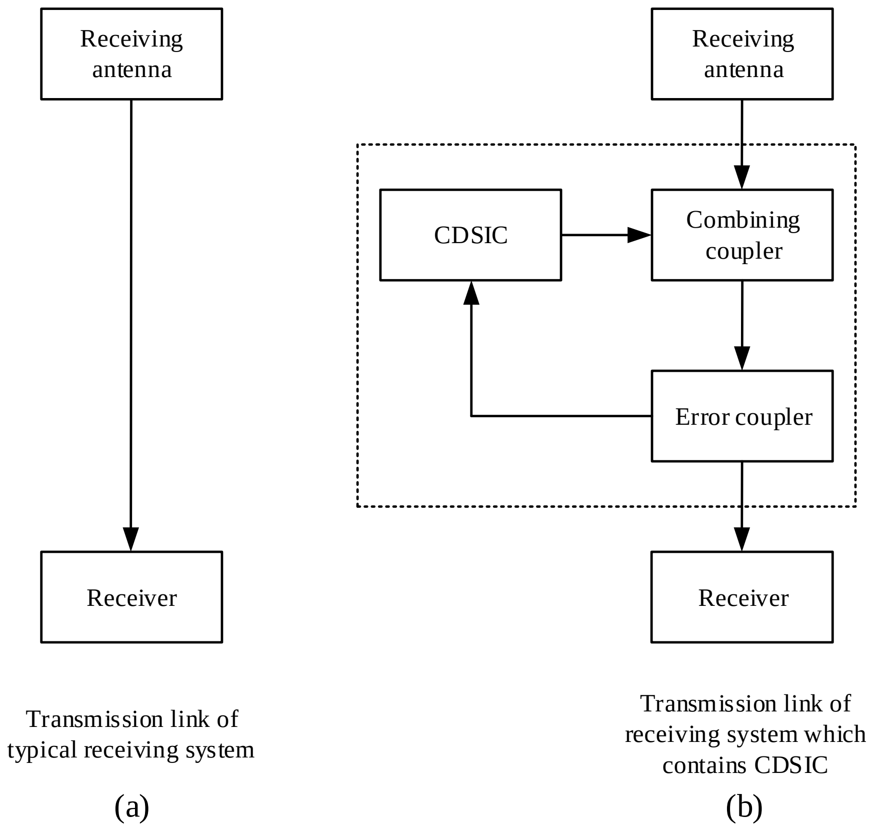


Figure 13. Typical receiving system and receiving system containing a CDSIC.

Summarily, compared with the CDSIC, FDSIC has a relatively low complexity and smaller effects on the receiving system. However, CDSIC normally has a high ICR, since it is easier to precisely reconstruct the self-interference via circuits.

7. Conclusions

7.1. Concluding Remarks

A comprehensive review of the SIC technology for integrated transceivers from circuits and fields perspective is presented in this paper. It has been shown that the performance of the receivers will degrade due to blocking or distortion when the co-located transmitters exist. In order to protect the receiver and improve the system performance, SIC techniques are required. According to the methods of how to rebuild and subtract the copy of the self-interference signal, the SIC can be classified as a CDSIC or a FDSIC. The former can be further divided to the analog SIC and the digital SIC. The CDSIC and the FDSIC have the same basic operating mechanism, however, the design strategies and implementation approaches are different. In real applications, the implementation of the SIC methods depends on the specific scenarios and the targeted requirements. The analog way is particularly critical to prevent the ADC from becoming saturated. However, implementing SIC in the analog domain is normally challenging and highly complex, so the analog CDSIC is normally chosen when the self-interference is strong and a high ICR is required. In contrast to the analog CDSIC, the digital CDSIC deals with the self-interference signals in the digital domain, after the self-interference signal has been quantized by an ADC. The digital CDSIC technique has a lower complexity compared with the analog approach, and many high-performance SIC algorithms can be easily implemented. However, this method is always limited by the hardware performance. To reduce the self-interference power below the noise floor, the dual-stage interference cancellation, which combines both the analog and digital CDSIC, is commonly used. A high ICR can be obtained if the strong self-interference is at first suppressed by the analog canceller, and the residual interference is then cancelled by the digital canceller. However, obviously, this kind of cancellation is very complicated. The FDSIC has a much simpler structure than the CDSIC, since the sampling coupler is on the transmitter side, and the combining coupling on the receiver side can be omitted. What is more, the power of the transmitting signal and the received SoI will not be attenuated when implementing the FDSIC. Although the radiation pattern will be affected, the FDSIC is suitable for the application scenarios in which the cost and complexity are strictly limited.

7.2. Future Outlooks

As a promising technique, artificial intelligence (AI) receives much attention at present, and plays a very important role for both signal processing and electromagnetic designs [61]. It also holds great potential for the future of SIC design in terms of two aspects: (1) AI-based high-performance algorithm for SIC signal processing [62] and (2) automatic AI-driven design for SIC topologies [58]. For the first aspect, more effective models for the digital canceller with fewer parameters and low-complexity optimization algorithms are needed, which will trigger the application of the AI approaches. For the second aspect, it is an advantageous idea to propose a generic SIC method for diverse configurations serving complex applications, without requiring extensive experience from the designers. The AI-driven design automation is quite promising for this scenario, especially for the design of the FDSIC system. Beyond that, the idea of combining the AI concept and the SIC techniques can be stretched to more applications, such as the reference-less SIC.

This paper provides a broad overview of the SIC techniques from the perspective of the circuit domain and field domain, and paves a way for the future explosive research.

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Abbreviations

ADC	analog-to-digital converter
AI	artificial intelligence
CDSIC	circuit-domain self-interference cancellation
DAC	digital-to-analog converter
FDSIC	field-domain self-interference cancellation
HPA	high power amplifier
ICR	interference cancellation ratio
IM	intermodulation
LNA	low noise amplifier
LPF	low pass filters
SIC	self-interference cancellation
SICS	self-interference cancellation system
SoI	signal of interest
RF	radio frequency

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