ISSN: 0067-2904

Self-Interference Cancellation Techniques for In-Band Full-Duplex Wireless Communication Systems: A Review

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Received: 21/9/2022 Accepted: 17/12/2022 Published: 30/10/2023

Abstract

In-Band Full-Duplex (IBFD) systems have the capability of simultaneously transmitting and receiving signals through the channel and require the same resources as half-duplex systems. Unfortunately, IBFD systems have self-interference (SI) issues that prevent the system from gaining double throughput with respect to half-duplex systems. Therefore, the IBFD system will be more reliable if SI is mitigated more. This contribution will look at SI cancellation in wireless radio and underwater acoustic systems. The reviewed documents cover all types of SI cancellations, including passive, analog, and digital cancellations. In a practical full-duplex system, the SI cancellation for all domains must cancel the SI below the receiver noise floor.

Keywords; Self-interference; In-Band Full-duplex; Wireless communication; Analog cancellation; Digital cancellation; Underwater acoustic.

تقنيات إلغاء التداخل الذاتي لأنظمة الاتصالات اللاسلكية ثنائية الاتجاه داخل النطاق – مراجعة

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الخلاصه

تتمتع أنظمة الازدواج ثنائية الاتجاه داخل النطاق (IBFD) بالقدرة على إرسال واستقبال إشارات متزامنة عبر القناة ، وتتطلب نفس الموارد مثل الأنظمة أحادية الاتجاه. لسوء الحظ ، تحتوي أنظمة IBFD على مشكلة التداخل الذاتي (SI) والتي تمنع النظام من الحصول على إنتاجية مضاعفة فيما يتعلق بأنظمة Half-Duplex. لذلك ، سيكون نظام IBFD أكثر موثوقية ، إذا تم تخفيف التدخل الذاتي أكثر. الهدف من هذه المساهمة هو مراجعة إلغاء SI في كل من الراديو اللاسلكي والأنظمة الصوتية تحت الماء. تغطي المستندات التي تمت مراجعتها جميع أنواع عمليات الإلغاء في نظام SI بما في ذلك الإلغاء السلبي والتناظري والرقمي. في نظام الازدواج الكامل العملي ، يجب أن يؤدي إلغاء SI لجميع المجالات إلى إلغاء SI إلى ما دون مستوى ضوضاء المستقبِل.

1. Introduction

Traditional wireless radio systems use half-duplex radios to transmit and receive signals by turning off either the transmitter or the receiver at each instant. During the signal transmission, the transmitter is on while the receiver is off; after the signal is transmitted, the transmitter turns off, and the receiver listens to the environment to gather the signal. About two decades ago, Goldsmith [1] asserted that interference does not let radio systems transmit and receive simultaneously.

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However, nowadays, there are hundreds of articles that refuse this claim, and many practical systems have developed since. The keyword in all full-duplex systems is SI cancellation. The SI is due to receiving the transmitted signal by the receiver while both the transmitter and the receiver are on, as shown in Figure 1. Therefore, the source of SI is the near-transmitted signal, which has the advantage known as the nature of interference; hence, with prior knowledge of interference, researchers attempt to mitigate the SI.

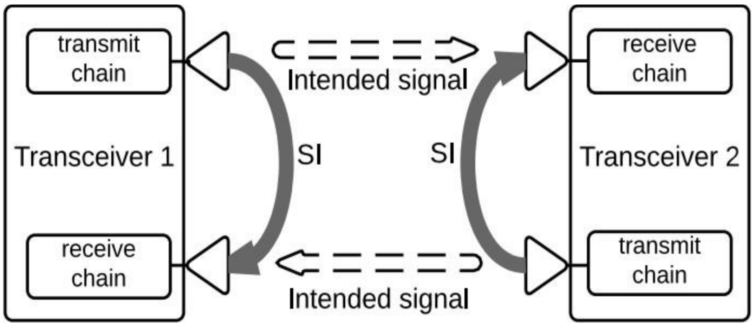


Figure 1: An example of a Full-Duplex wireless radio system [4].

By successfully removing the SI in In-Band Full-Duplex (IBFD) wireless radio systems, the system can achieve up to double the gain performance in terms of throughput with the same bandwidth usage as a half-duplex system. Accordingly, the topic of SI cancellation is much more interesting in its theory than in its practical implementation.

It is worth noting that while the IBFD methods use the same channel to transmit and receive data, the gain in capacity or throughput is practically not doubled. This is because the implemented system always suffers from interference and noise. As a result, canceling interference is an interesting and important domain for researchers. However, the main source of interference is the near transmitting signal, at which the transmitter has much power but the receiver has been attenuated during the path taken. The power of the transmitting signal is 50-100 dB higher than the receiving signal [1]. The SI signal should be successfully reduced to the level of the noise floor. That means the SI signal should be reduced before the Analog to Digital Converter (ADC) to prevent the signal of interest from being lost at the ADC and achieve a signal-to-noise ratio (SNR) level roughly equivalent to that of the Half Duplex (HD) mode.

This has brought to light the need for a good SI cancellation (SIC) mechanism. As a result, the suppression of SI for the practical system is done by three subsystems, including passive suppression, analog cancellation, and digital cancellation. Passive SI cancellation is the result of the physical or electrical separation between the transmitter and the receiver, so the transmitted signal has lower penetration than the received signal. The physically separated transmitter and receiver are not enough to suppress the SI level so that it is lower than the noise level. After the passive cancellation stage has been implemented, the active cancellation methods should be used to cancel the residual SI signal. This goal is achievable through digital and analog cancellation. An analog signal is fed to the ADC to be converted to digital samples. since an ADC has dynamic range limitations. If the input signal has a powerful SI, the ADC may quantize away the weak received signal, which makes it impossible to recover the received signal in this case. Hence, attenuation of the SI on the analog signal before digitalization would be a must.

While analog cancellations not only cancel the SI in the direct path but also reduce SI power in the reflective path, SI generally comes from two paths. One is the “direct path,” which refers to the direct interference between the transmitter (TX) and receiver (RX) chains, and the other is caused by the near surroundings, namely the “reflected path” [3].

In the following, the methods for SI cancellation will be reviewed, which have a practical view on IBFD wireless radio and underwater acoustic systems. The first section is allocated to wireless radio SI cancellation, and its subsections present passive, analog, and digital SI suppression, respectively. The next section, subsequently, reviews the methodology of SI suppression for the underwater acoustic system in order of passive, analog, and digital parts.

2. SI Cancellation for Full-Duplex Wireless Radio Communication Systems

A domain of wireless radio communication that draws many researchers’ attention is FD operation. “FD” in a communication system means simultaneously sending and receiving a radio signal at the same frequency. Since decoding a signal with very low power while transmitting was practically impossible, it became a challenge for researchers. For the first time, [6] presented a method for concurrent transmission and reception of the signal on 802.15.4 radio. They suggested using an antenna cancellation to cancel the SI. The usage of SI cancellation has been studied in various communication systems, such as device-to-device (D2D) relay communication [7] and [8], wireless local area networks (WLAN) [9] and [10], a cellular network [11] and [12], and self-backhauling systems [13]. Increasing spectral efficiency and extending wireless coverage are important in wireless radio communication. In-Band Full-Duplex (IBFD) has drawn much attention from researchers who seek spectral efficiency and wireless coverage. However, simultaneous transmitting and receiving on the same frequency leads to the presence of large SI restrictions on the realization of IBFD. To overcome SI cancellation, some systems have been invented, which could be classified as analog cancellation, digital cancellation, filtering, or a machine learning approach. The filtering subclasses include adaptive filtering, Kalman filtering, and kernel filtering.

2.1. Passive SI Cancellation

The primary approach to canceling the SI is passive cancellation. Passive cancellation is a defined method that attenuates SI by separating the transmitters and receivers. In this approach, the interference signal will not be combined with the received signal at high power. However, due to imperfect implementation and some limitations on isolating the transmitters and receivers, there is always leakage of interference into the received signal. Antenna separation, antenna cancellation, directional isolation, cross-polarization, absorptive shielding, and transmit beamforming have all been proposed to achieve this [3].

2.2.Analog SI cancellation

In this subsection, the analog cancellation of SI will be considered. Employing analog cancellation can be reduced to two subclasses of SI: linear components and nonlinear components.

An analog SI canceller is a circuit that outputs a delayed, phase-shifted, and attenuated version of the transmitted signal. The change in delay, phase, and amplitude of the SI is due to the imperfection of the RF front-end at both the transmitter and receiver.

The base of analog cancellation is the known transmitted signal. The analog cancellation typically causes some delay and phase shift on an attenuated transmitted signal to adapt with SI. The high-performance method should reconstruct SI accurately. Following that, the reconstructed SI is subtracted from the tainted received signal. Since the analog cancellation knows the transmitted signal, the SI can be obtained by an accurate channel estimation method. A straight way to estimate the delay and amplitude of transmitting the signal to be adapted to SI is the Weiner filter. Hence, the performance of analog cancellation by this method depends on the algorithm used for delay estimation, the adjustment of parameters, and the delay range in the SI channel [14].

Fundamentally, by creating a reference signal, which is a replica of the transmitted signal with modifications on delay, phase, and amplitude, and combining it with the received signal, the signal-to-noise interference ratio can be increased. Although this SI cancellation is not enough for the practical system, it is mandatory. The proof of a system with reference signal cancellation is explained in [14].

Either analog cancellation implemented in the RF or the baseband stage or a perfect reference signal can sufficiently increase the SINR. Fundamentally, three steps are needed to implement analog cancellation to remove linear SI components, as follows:

2.2.1. Estimating the inverse of SI signal

The inverse of phase can achieve the inverse of the signal by estimating the inverse of the SI signal on a defined bandwidth. However, this defined bandwidth restricts the capacity of the cancellation. Simply put, perfect cancellation requires perfect signal inversion and a signal frequency close to the center frequency. As the signal moves further away from the center frequency, the phase offset of two versions from the transmit antennas shifts away from perfect inversion, and in this case, the two of them do not cancel completely. To address the mentioned problem, [14] presents balanced/unbalanced (Balun) cancellation circuits that are capable of canceling up to 45 dB, and in combination with digital cancellation, the SINR can be increased by 73 dB. The methods that use phase adjustment to inverse the signal always have the problem of bandwidth limitation. If the inverse of the signal comes without phase changing, there will not be any limits on bandwidth; also, the satisfaction of SI cancellation requires inverting a signal.

The Balun transform has these features and is a common element in audio and video circuits as well as RF. It is explained in [14] that increasing the signal bandwidth causes reduced cancellation performance in both phase adjustment and balun inversion of a signal. However, the reduced performance in the upper bandwidths of Balun is much lower than phase adjustment methods. Moreover, in [14], a method for self-cancellation for channel changes has been developed. This method requires precise programmable delays with a resolution as accurate as 10 picoseconds to exactly match the delay experienced by the SI from the TX to the RX antenna [3]. The authors of [3] created a method for estimating interference signals in the analog domain that was based on a different perspective of cancellation circuits and treated the cancellation problem as sampling and interpolation. They designed a circuit that took a small copy of the transmitting signal as input and passed the copied signal through lines of changeable delays and adjustable attenuation. At the final stage, all output lines integrate together and are subtracted from the received signal at the receiver. This work has the benefit that it does not need high-resolution programmable delays.

[17] theoretically demonstrated that line of sight (LOS) is the most important factor in receiving signals. The LOS SI is the propagated signal from the transmitter directly to the receiver without any obstacle between them. However, the non-line-of-sight components are due to multipath propagation. Also, it is proved in [17] that LOS SI has no path attenuation. This work uses a dual-channel circuit to estimate the LOS SI.

2.2.2. Tune delay and attenuation

Tune delay and attenuation are used for analog cancellation; the estimation of delay and attenuation of the SI signal has to be essential to reconstructing the inverse of the SI signal based on the estimated delay and attenuation. To do so, knowing the information of the channel is necessary, as introduced in [18, 19] for channel estimation. The channel state can be estimated in the baseband, including the channel of the transmitter and receiver chains and the SI channel. However, by equalizing the received signal using the feedback of the transmitted signal to the received signal of the channel, the overall channel state can be estimated [18]. Furthermore, to tune the delay and phase shift, one can use an adaptive filter such as the one introduced in [20, 21]. Reference [21] addresses channel estimation by using an auxiliary transmission channel.

2.2.3. Combine the SI with its inverse

The last step for analog cancellation is to combine the SI with its inverse to mitigate interference. However, it does not remove all interference, as further techniques are required to remove residual SI. An analog SI cancellation has been presented in [22] based on digital processing. An analog signal is converted to a digital signal by a zero-intermediate-frequency ADC and DAC chip, and the cancellation procedure is done in the digital domain. All the reconstruction procedures, including amplitude attenuation, phase shift, and time delay, are in the digital domain.

Adaptive filtering is used for SI cancellation, where it tries to minimize the SI and reconstructed signal to be subtracted from the received signal. At the same time, adaptive filtering can be used in analog and digital cancellation types. The base of the digital adaptive filter is digital signal processing to compute the weighting coefficient of the adaptive filter to minimize the error of SI cancellation. Some studies on the digital adaptive filter are found in [20-24]. This type of adaptive analog filter is presented in [25-27]. There are several ways to create adaptive digital filters to cancel SI. One approach is to up-convert a digitally designed signal via an auxiliary transmit channel. Another approach is to use a digital FIR filter and many taps to model the linear channel rather than a reference signal that can be coupled into the receiver [20].

An ideal analog integrator is much more expensive and usually not practical. An alternative to the ideal integrator for analog weighting coefficient for an adaptive filter is the first-order low-pass filter (LPF), which is a completely analog LMS loop called the

ALMS loop [28].

The ALMS loop architecture was introduced in [28], as shown in Figure 2. The work in [28] developed a single carrier system, while a multi-carrier system was presented in [29]. In [30], the analysis of frequency response and accuracy on SI cancellation is discussed. The study [31] examined performance using practical considerations such as in-phase and quadratic modulation and demodulation, as well as their imbalance. All these works were made by [32] as a prototype of SI cancellation using an ALMS loop. Furthermore, the ALMS loop has the potential for SI cancellation in MIMO systems rather than just SISO systems [25].

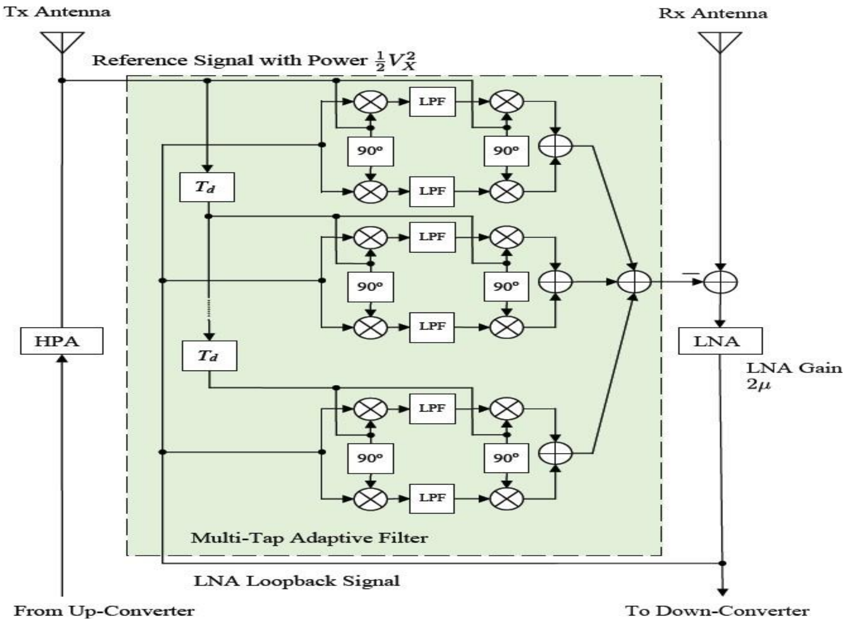


Figure 2: The schematic of ALMS loop [25].

There are some important topics in the ALMS loop that remain unsolved and are fundamental for a practical IBFD system. One could be investigated to consider noise resilience, which is because of nonlinear components such as modulators and demodulators. Furthermore, some noise will be added to the ALMS loop while processing the weighting coefficient since the integration of feedback from the error signal and the transmitted signal may cause noise. Although most of the power of SI is canceled by the ALMS loop, further research on the propagation path and the digital domain is necessary to force the power below the noise level.

Recently, 5G systems have been introduced, and studies in this field are growing fast. Anew study on full-duplex 5G systems has been introduced in [33]. This work introduced an analog SI cancellation in 5G systems for wide band operation, which was inherited from 5G systems. The work theoretically demonstrated that proper tap delay was critical for valid wide band systems and experimentally suggested the proper tap delay for a prototype system. The paper [34] proposed an analog SI cancellation method and prototype based on superheterodyne architecture. They experimentally indicated that it could cancel 35 dB of SI. To compare the ALMS loop to various RF adaptive filter structures, we looked at the data in Table 1. The ALMS loop, in contrast to other adaptive filters, needs fewer additional modules while generating adequate SIC to meet the demands of the RF domain.

Table 1: Comparison between adaptive filters and ALMS loop in analog SI cancellation [25].

Criteria	[20, 23]	[24]	[35]	[26, 27]	ALMS loop [28, 29, 30, 31, 32, 36, 37]

No DSP involvement											✓		✓				
No additional Tx chain		✓									✓		✓				
No DAC or ADC											✓		✓				
No channel state information (CSI) requirement		✓			✓						✓		✓				
No additional down-converter					✓							✓					
Sufficient SIC demonstrated				✓		✓						✓					

2.3. *Digital SI cancellation*

Due to the imperfection of passive and analog SI cancellation on the RF side, there is a residual SI after digitalizing the signal at the ADC's output. Hence, to suppress residual SI, the digital-based method is used. Basically, digital cancellation subtracts the estimate of the SI signal by estimating channel information from the received signal. However, digital cancellation should consider removing SI from passive and analog cancellation parts. The linear and nonlinear components of residual SI are the two major components. The linear one is easy to encounter; however, the nonlinear component appears due to the nonlinear distortion caused by analog circuits, and it is not easy to cancel. Such nonlinear distortion is caused by the QHx220. Accordingly, routine methods to remove linear components are a group of least squares and minimum mean square error-based methods. After the analog cancellation stage, there is a residual SI signal that still impacts the signal of interest detection, so it should be suppressed in the digital stage after the ADC to reach the noise floor. Many methods are used to cancel the residual SI signal in the digital stage, including linear digital, nonlinear digital, combining linear and nonlinear, the Kalman filter, and neural methods.

2.3.1. *Linear Digital SI Cancellation*

Obviously, in the case of a total fixed received power, increasing analog cancellation on the RF side of the receiver reduces the amount of suppression SI required on the digital side. Reference [38] surveyed the impact of RF and digital cancellation on overall SI cancellation, theoretically. It is demonstrated that better SI cancellation for full-duplex communication systems can be obtained by canceling the majority of the SI in analog devices rather than after digitalizing the received signal. However, there are some restrictions on the capability of RF cancellation circuits, so the need for digital cancellation is crucial in full-duplex systems, as the capability of digital cancellation increases with the received signal power [38].

The linear digital SI cancellation consists of the cancellation of the SI channel response on the received signal. Hence, the estimation of the channel in full-duplex systems is based on linear digital SI mitigation. There are three popular iterative algorithms to estimate SI channels, including Least Mean Square (LMS), Normalized Least Mean Square (NLMS), and Recursive Least Square (RLS). Considering the baseband digital signal before the power amplifier at the transmitter side, x_n, the impulse response of the channel is h_n, and the estimation of the channel impulse response is h'_n. The fading channel, such as Rician or Rayleigh, should be considered because there is a multipath between the transmitter and the receiver [39], as indicated in figure 3.

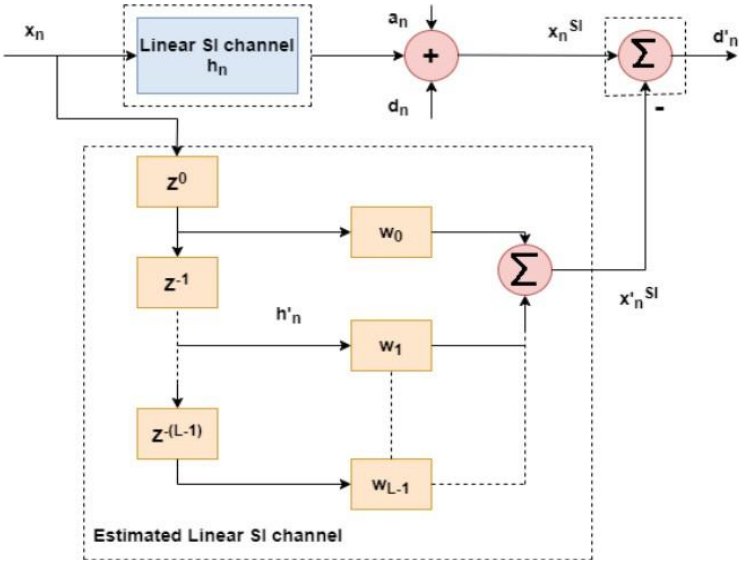


Figure 3: The illustration of linear channel SI estimation in digital SI cancellation [39].

1. Recursive Least Square, the weights calculation of the RLS adaptive filter, has a different approach with respect to LMS and NLMS. The weights of the RLS method also require the calculation of an autocorrelation matrix and its inverse matrix, which adds complexity. The benefit of more complexity in RLS with respect to LMS and NLMS is excellent performance. This presents the trade-off between RLS and LMS on performance and complexity [39].

2.3.2. *Nonlinear Digital SI Cancellation*

Since radio-frequency RF power amplifiers have the potential to generate out-of-band distortion, which is a nonlinear portion of undesired interference and might not be canceled with analog cancellation, digital SI cancellation can challenge this, and a practical full-duplex system should prevent the power amplifier from saturating with a high-power level. The digital SI cancellation makes full-duplex system implementation more realistic, as illustrated in Figure 4.

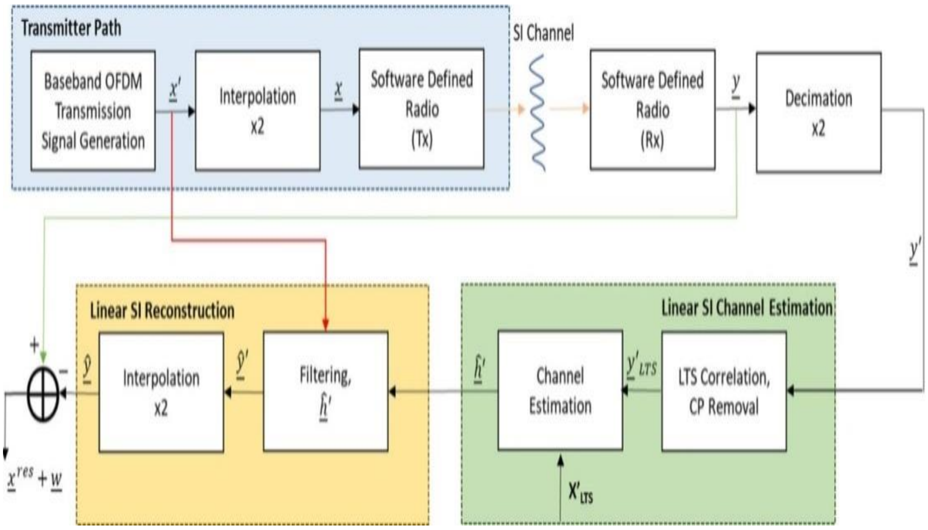


Figure 4: The overall schematic of nonlinear digital cancellation, including channel estimation and so then SI reconstruction [41].

The mitigation approaches for the nonlinear part of SI on the digital side can be subclassified into *memory* and *memoryless* models. The memoryless models work on instant time and assume the distortion is just from the instantaneous origin [40].

Although the most effective technique is the memory model, the foundation of all memory models is the Volterra series [40]. Table 2 demonstrates the comparison of nonlinear digital SI cancellation techniques.

Table 2: Comparison of nonlinear digital SI cancellation

Year	Reference	Contribution	complexity	Assumption
2019	[41]	proposed a nonlinear digital cancellation based on memory polynomial	Low	single antenna FD radio on software defined radio integrated with a slot pitch antenna
2020	[43]	comparison between nonlinear least square and least mean square based digital SI cancellation	High	single antenna IBFD
2015	[44]	novel adaptive nonlinear SI canceller		tracking the time-varying SI coupling channel
2020	[45]	cancel the SI iteratively by estimating the source of SI in three stages: 1- estimate the coefficients of IQ imbalance 2-channel estimation, 3- power amplifier gains	High	apply post distortion to the received signal
2021	[46]	proposed a novel Digital cancellation based on Wiener model	High	used CMOS integration as a transceiver

2.3.3. Integrated Linear and Nonlinear Digital SI Cancellation

So far, linear and nonlinear SI cancellation have been investigated [47]. The linear SI cancellation addresses the estimation of linear channel properties, while the nonlinear SI cancellation stands for nonlinear transceiver circuits. A well-done study [47] simulated the surveyed digital SI cancellation on the same setup, which was a WARP v3 SDR and a single antenna for the transceiver. The aim of linear and nonlinear integration is to fully mitigate SI cancellation at the baseband. In these systems, the baseband transmitted signal is fed to both linear and nonlinear methods to estimate the SI signal, as shown in Figure 5.

In addition to linear, nonlinear, and integrated linear and nonlinear digital SI cancellation, the study [48] addresses the denoising of residual SI after digital SI cancellation using wavelet denoising. Assuming the desired signal is known, wavelet denoising can improve the SINR a bit more by removing the residual SI, which is below the noise level.

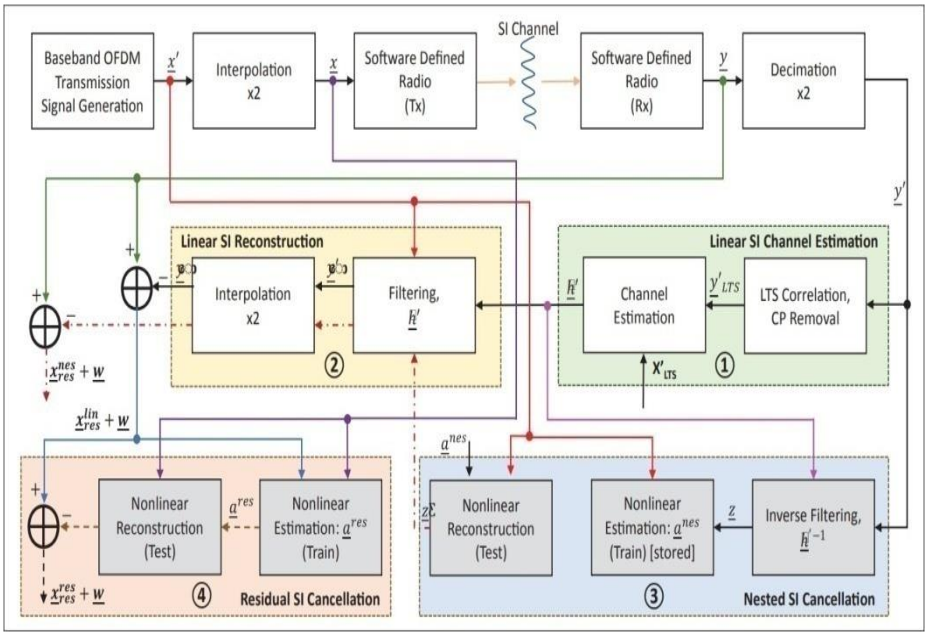


Figure 5: Illustration of integrated linear and nonlinear digital SI cancellation [47].

2.3.4. *Kalman filter Digital SI Cancellation*

As aforementioned, there is a residual SI in the digital domain of the receiver after the ADC circuit. to search for a signal of interest rather than linear, nonlinear, and integrated linear. The nonlinear signal can use an adaptive filter such as the Kalman filter to mitigate residual SI. The idea of the Kalman filter for the SI challenge came from acoustic echo control. The control of acoustic echo and an end-to-end full-duplex system have similarities in many aspects. Adaptive filtering based on the Kalman filter was proposed by [49]. Generally, the Kalman filter has two main parts: prediction and updated measurements. In the first part, the Kalman filter predicts the next value of state space as the next instant of time, and in the latter part, it updates the predicted value with the measured value at each instant of time.

Hence, the Kalman filter on the problem of SI cancellation can predict a canceled signal based on the previously received signal and update it with the signal of interest, which is known on the digital side. This loop challenges the residual SI after passive and analog cancellation. The adaptive Kalman filter with SI cancellation has some advantages. The conventional model of linear and nonlinear SI channels, the Hammerstein parallel model, has much more unknowns in the nonlinear model. It can also cover instant channel changes and track changes in signal strength [49]. The study [49] addressed the state space of linear and nonlinear coefficients of SI channels based on first-order Markov models. The authors of [50] extended the work in [49] and covered the channel correlation, the noise of the transmitter, and the receiver imperfection noise. They challenged the SI cancellation by Kalman filtering.

Furthermore, the study [51] was conducted using the same approach as [49] by extending the usage of the Kalman filter to an "Extended Kalman Filter," which proposed a full-duplex system. Preferentially, the Extended Kalman filter is used for nonlinear systems to cover the nonlinear problem of the Kalman filter. Because the major transceiver channel SI is nonlinear, the expected SI cancellation performance should be improved. It is a procedure that says that more performance leads to more complexity, and it is obvious that the Extended Kalman Filter has more complexity than the Kalman Filter. Reference

[52] proposed an overall full-duplex communication system that used a Kalman filter in digital SI cancellation. Since the ADC has limits on the range of amplitude, it might remove some samples of the signal of interest because of residual SI after analog cancellation. Hence, the study [53] addressed the estimation of removed samples using a fixed-lag Kalman filter.

2.3.5. *Neural Network and Machine Learning based Digital SI Cancellation*

Nonlinear SI cancellation is hard to compromise, and the polynomial can mitigate the IQ imbalance and PA nonlinearities properly; however, it is complex to implement. [54] introduced nonlinear digital SI cancellation based on neural networks for the first time, achieving polynomial modeling accuracy with 36% less complexity.A typical neural network consists of input, hidden, and output layers, as shown in Figure 6. The figure has six input neurons as six input data, five neurons in one hidden layer, which is a hyperparameter that should be set, and two output neurons as two output data. Simply, neural networks get an input, multiply it by weights in hidden layers, add bias, and do this again in the output layer; the result should be the expected value. There are some methods to calculate the error between the output and ideal output of a neural network, such as mean square error (MSE) and mean absolute error (MAE). The neural network propagates this error back to the layers to correct the weights and biases of each neuron. Actually, the neural network estimates the nonlinear parameter of the received signal, and by inputting the transmitted signal to the neural network, the output will be the estimated SI. In [54], we introduced the design of neural network-based SI cancellation integrated with linear SI cancellation. Also, they implemented the suggested design in [55] on a Virtex-7 FPGA and concluded that the throughput increased by 96% more than the polynomial model. They showed that the polynomial model needed two times more DSP slices than the neural network canceller. On throughput criteria, the ASIC result was comparable to the FPGA.

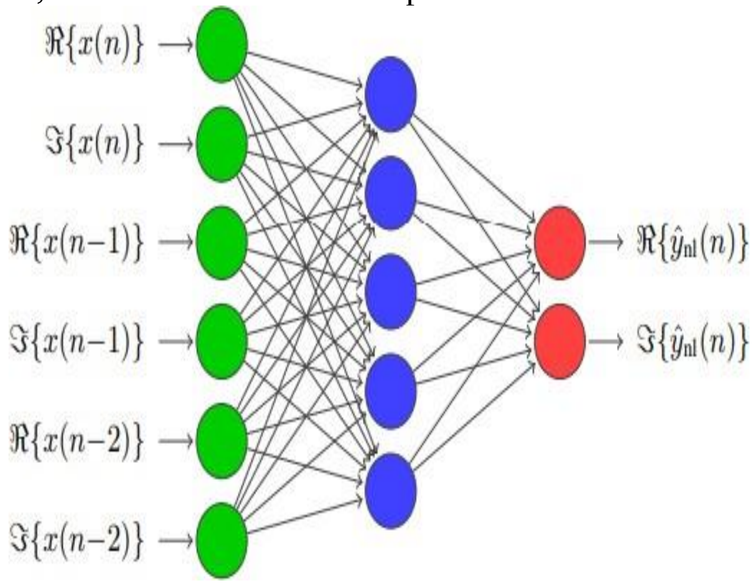


Figure 6: The schematic of simple Neural Network based SI cancellation [54].

In [56], they continued the neural network-based SI cancellation, while [55] introduced a more detailed version of the neural network SI cancellation system. They indicated the impact of the number of layers and neurons in each layer and suggested optimized numbers. Table 3 demonstrates a comparison of neural network digital SI cancellation techniques.

Machine learning and neural networks can also be used in RF/analog cancellation. In analog cancellation, the canceller tries to estimate the SI based on the tuned amplitude and delays of the transmitted signal. However, the studies [57] and [58] addressed this issue by suggesting a neural network design. The work [57] performed a comprehensive research study on the design and implementation of neural network cancellation on the RF side.

As studied in [64], the nonlinear part of SI can be modeled in optimization problems and solved using a support vector machine (SVM) solution. The SVM acts as adaptive filtering and does not need a model of interference. Furthermore, there are more methods in which there is no need to model nonlinear SI, such as the kernel filter [65, 66].

Table 3: Comparison of neural network digital SI cancellation

Year	Authors	Contribution	Complexity	Assumption
2020	Elsayed et al. [59]	model SI signal by ladder-wise grid structure and moving window grid structure as two separate Neural Network	Low	proposed a Neural Network with a partial connection of layers (not fully connected)
	Kurzo et al. [56]	implementation of Neural Network digital SI cancellation on FPGA and ASIC	Low	Virtex-7 XC7VX485 FPGA
	Li et al. [60]	consider the radar jammer similar to SI in IBFD systems and propose a neural network-based method	Low	LFM in 10 30 MHz and random for BPSK
2019	Guo et al. [61]	train a deep neural network and implement it on USRP DSP	High	
	Kristensen et al. [62]	trained deep neural network (3 layers) based on ADAM optimizer	Low	10MHz bandwidth
2018	Balatsoukas-Stimming [54]	introduced simple SI cancellation based on Neural Networks and compared the result with a polynomial model	Low	used Titan Xp GPU for training
2021	Zhou et al. [63]	proposed a Neural Network which gets both transmitted signal (related to signal of interest) and received signal as input	High	fiber radio access

As a summary, RF wireless communication systems require increased spectral efficiency and extended wireless coverage. IBFD has drawn much attention from researchers who seek spectral efficiency and wireless coverage. However, simultaneous transmitting and receiving on the same frequency leads to the presence of large SI restrictions on the realization of IBFD. To overcome SI cancellation, some systems have been invented, which could be classified as analog cancellation, digital cancellation, filtering, or a machine learning approach. The filtering subclasses include adaptive filtering, Kalman filtering, and kernel filtering, as indicated in figure 7.

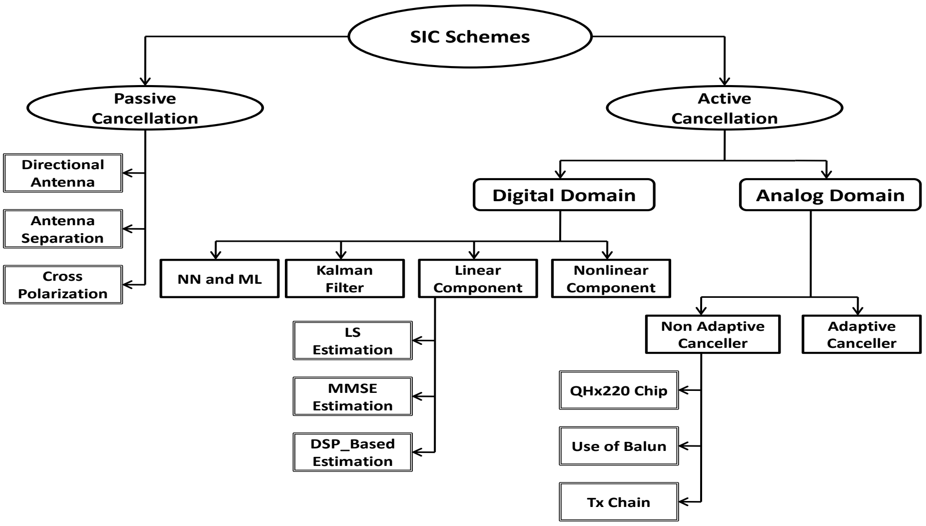


Figure 7: The schematic of the SIC in RF IBFD communication system

3. SI Cancellation in Full-Duplex Underwater Acoustic System

Communication in an underwater environment is extremely challenging because of complex situations such as propagation loss and scattering issues. Acoustic communication is the most practical technique in underwater communication because of the low attenuation of sound in water over long distances, despite the fact that acoustic propagation speed is much slower than radio signal speed [84].

Likewise, wireless radio communication systems, such as the full-duplex Underwater Acoustic (UWA) systems, suffer from SI, while it is traditional to use the same methods of SIcancellation in wireless radio systems to mitigate the interference in UWA. The aim of this sectionis to introduce the UWA SI and the methods of reducing its power to enable the detection of the signal of interest from a far node. However, the low signal frequency in full-duplex UWA has the advantage of high-resolution ADCs. This means that the system can prevent ADC saturation while passing more SI power, and the major cancellation can be made on the digital side.

However, in addition to the SI issue of FD in UWA systems, the application of OFDM in UWA is a critical issue because of the increasing error rate in the small offset of uplink signals and the effect on SI cancellation. Due to theDoppler shift resolution and OFDM symbol duration having an inverse relationship, the studyof Doppler shift compensation is a necessary consideration for practical UWA systems, as done by [85] and [86]. In [87], the channel estimation for OFDM-based systems was addressed, which utilized the DFT for better performance.

The major contributions to dealing with SI cancellation are the same as for full-duplex wireless radio systems. Moreover, the SI cancellation of full-duplex UWA systems can be categorized, as can full-duplexwireless radio systems, into passive, analog, and digital SI cancellation. Hence, the same topics will be discussed for the UWA SI cancellation.

The practical UWA system is based on a much lower carrier frequency in comparison to wireless systems. Such systems are capable of going up to 100 dB SI because of the high rate of ADC (up to 24) [88]. Also, the impairment of hardware can be removed in the digital domain. The hydrophones are equipped with a pre-amplifier to avoid SNR loss due to long cables [89]. Pre-amplifier response is linear within a specific voltage, and beyond that, it is nonlinear [90]. Furthermore, the transducer has a nonlinear response except for small values of amplitude. Hence, the digital cancellation should be capable of removing the interference due to multipath channels (i.e., near-end and far-end path channels) as shown in Figure 8. The devices' nonlinearity includes the PA and transducer. Another consideration for a realistic full-duplex UWA system is the fast time-varying feature of the channel. On the other hand, the Kalman filter, which was developed in the last century, proved to be very capable of adapting to the nature of the problem, and it can be used to solve the problem of the fast varying-time channel. The schematic of the three types of SI cancellation, including the passive, analog, and digital stages, is displayed in Figure 9.

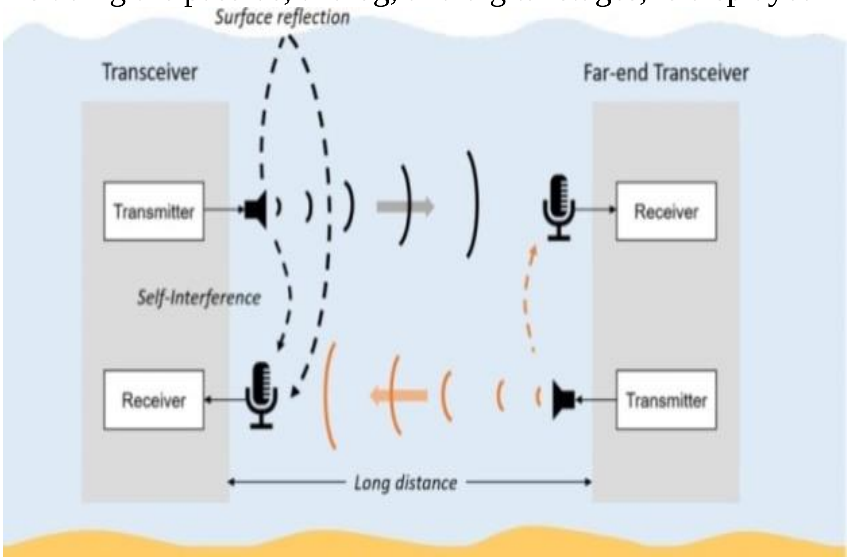


Figure 8: The schematic of the full-duplex underwater acoustic system. Both transmitting and receiving signals are done at specified bandwidths at the same time [88].

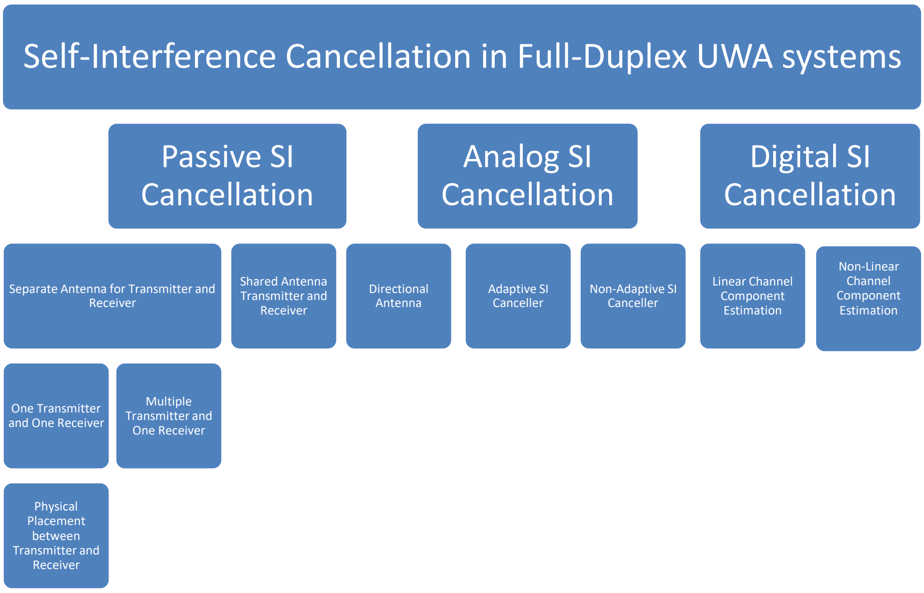


Figure 9: The schematic of three types SI cancellation in UWA systems.

3.1. Challenges of SI Cancellation in UWA

Inherently, the interference in UWA systems includes two types:

1. SI

2. Self-multipath interference (interference due to reflection of the sea surface and seafloor).The receiver input signal due to the SI and the multipath interference is:

$$r(t) = \sum_{i=0}^{\infty} x(t-\tau_i) * h_i(t) + s(t) + z(t) \quad (1)$$

where x(t) is the transmitted signal from the transducer, τ_i is the delay for i-th multipath link. $h_i(t)$ represents the complete response of the channel, including the amplifier nonlinearity, transducer response and medium effects of i-th interference link, $s(t)$ is the signal of interest and $z(t)$ is the measurement noise. The first term of equation (8) can be interpreted as the sum of self-loop and self-multipath. The SI signal is $x(t-\tau_0) * h_0(t)$ and the multipath interference signals is $x(t-\tau_i) * h_i(t), i \geq 1$. There are some challenges with IBFD in UWA systems that do not belong to wireless radio systems, such as high power reflected signals and significant delay from received interference. A good representation model of path loss for reflected interference is given by the following relation [91].

$$\mathrm{A(d,f) = (d/d_0)^{\mu} a(f)^{d-d_0}} \quad (2)$$

where f is the carrier frequency of the transmitted signal, d is the distance of the transmission signal, $\mathrm{d_0}$ is the origin of distance (the transmitter or the receiver location), is the path loss exponent (usually considered $\mu = 2$), and the important parameter a(f) is the absorption coefficient (the frequency should be the order of 103 (Hz) while it can be retrieved by Thorp’s formula [91].

$$10\log\ \mathrm{a(f)} = 0.11\frac{\mathrm{f^2}}{1+\mathrm{f^2}} + 44\frac{\mathrm{f^2}}{4100+\mathrm{f^2}} + 2.75 * 10^{-1}\mathrm{f^2} + 0.003 \quad (3)$$

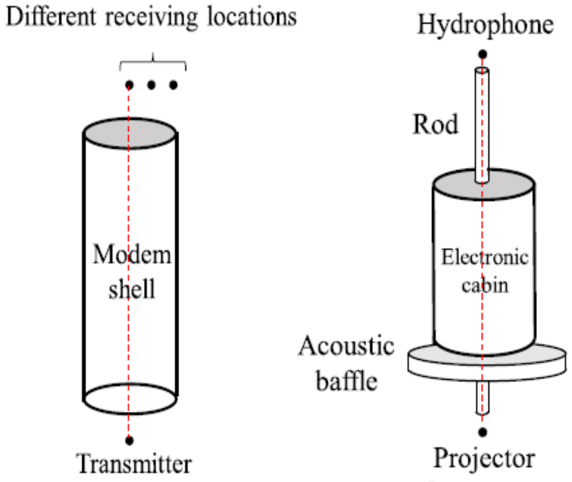
where the a(f) is in dB/Km for f in KHz. Although the issue of multipath in the deep ocean has less effect on performance than in shallow water, there are other types of issues in underwater full-duplex communication systems. The most important challenge is the order of delay due to the speed of sound. Because the speed of sound is very slow with respect to the frequency sampling of the acoustic signal, the delay of SI is of a very high order of magnitude and is so hard to estimate in the light of hardware restrictions. This problem does not belong to the IBFD wireless radio systems because of the high speed of light. Additionally, the distance of the antenna is in the order of meters, which needs more interference suppression. The interference may not be just SI, and white thermal noise may be the non-white noise added. Furthermore, some existing methods in the RF channel are not practically efficient, such as [6]. Research [6] suggests that the sum of two acoustic signals with π phase difference can mitigate the interference. However, this method was very sensitive to bandwidth, and UWA systems have wide bandwidth.

3.2. Passive SI Cancellation in UWA

Access to higher throughput for the UWA system can be gained via a full-duplex system. Similar to wireless radio communication systems, in UWA systems, the acoustic wave emitted by the transducer is received by the hydrophone because of its near-end location. So, those methods preventing leakage from the transducer to the hydrophone will cause much less SI and require less effort in analog and digital domain SI cancellation. Passive SI cancellation can be made using a secondary transducer to mitigate the SI in the received signal [92]. The secondary transducer is just used to emit the acoustic signal directly to the hydrophone, where the transmitted signal can be removed. However, there are some channel considerations that cause non-complete SI cancellation. Research [89] studied the effect of acoustic-shell coupling in communication modems on the performance of SI cancellation through the estimation of SI in a short-range channel. Moreover, an electrically separating antenna will help absorb less signal from the transmitter. The electrical separation can be gained via the phase shift of a specific signal through different elementsof the antenna [93].

In UWA systems, because the transmitter and the receiver are physically separated, the SI will be attenuated by path loss from the transducer to the hydrophone. However, one can use more than two antennas to cancel the SI. Obviously, more distance between antennas leads to more loss of SNR in the direct path of the signal to the receiver, while multiple antennas can estimate the interference more accurately [15] [81]. An effective technique in UWA systems is to use acoustic shell coupling, as addressed in [89]. It has been shown in [89] that the sound pressure level at the center of the modem shell (the direct path from the transmitter to the receiver) is higher compared to other positions. Also, more SI cancellation will be gained by changing the receiver position (Figure 10.a). Another configuration is used in [94], in which an acoustic baffle is placed between the hydrophone and projector (Figure 10. b).

The most important difference between passive SI cancellation in wireless radio communication and UWA systems is that UWA systems cannot use a circulator to mitigate the SI. In addition, adding two transmitted signals is not practical because of the wideband nature of acoustic signals. To reduce the interference level, the study in [95] suggested nullifying the transmitter, where the signal propagates in all directions but not in the direction of the receiver. In [96], a new SI channel model is investigated based on a variable-directional FD modem that plays a circuit role in the SI cancellation process in the underwater environment.



(a) (b)

Figure 10: a) modem configuration for FD UWA systems suggested in [89], b) suggested in[94].

3.3. Analog SI Cancellation in UWA

The problem of SI leading to ADC at saturation points is also an issue in UWA systems, where SI cancellation is necessary to prevent ADC from reaching saturation. Similar to wireless radio systems, the most popular approach in research is adaptive filtering estimation for SI such as LMS and NLMS. The NLMS method adaptively estimates the amplitude and delays the phase of the reference signal with prior knowledge of the transmitted signal, as described in [97]. The methods performed before the ADC in the analog part are categorized as "analog SI cancellation." In [98], the SI channel model of UWA systems is proposed, which helps to improve the estimate of the SI signal in the analog part. In [99], we discussed the effects of the sea's depth on the channel modeling and showed experimental results with linear frequency modulation, which led to more resolution signaling.

Generally, the analog cancellation of SI in UWA systems is the same as in wireless radio communication systems. However, many methods of wireless radio communications were inherited from UWA. The basic idea of analog cancellation is to estimate the inverse signal of SI and add it to the received signal to completely remove it.

3.4. Digital SI Cancellation in UWA

Similarly to full-duplex wireless radio systems, the major residual SI on the digital side of UWA systems is due to power amplifier nonlinearity. The Volterra series [100] and Volterra series-based extension are major suggested works for digital SI cancellation. These methods require much complexity to estimate the nonlinearity of the channel, and the study [101] suggested using the power amplifier output as a reference signal [101] [102]. In this case, the nonlinear PA distortion is incorporated with the reference signal, and linear digital SI cancellation has more effect. In [101], we also addressed the sampling frequency effect on digital SI cancellation and proved that proper sampling results in a much better SI cancellation. The system is evaluated based on the experimental results in a shallow lake, which showed that it can cancel 56 dB of SI at its maximum. The digital cancellation of SI was based on a recursive least-squares adaptive filter.

As mentioned, the aim of digital SI cancellation is to estimate the channel property to reconstruct the SI and remove it from the received signal. The primary studies just considered the Gaussian noise in an intended signal using the least squares method [81], in which the performance will be reduced in a non-Gaussian environment. However, more studies addressed channel estimation with more robust methods such as maximum likelihood (ML) and its extension [103]. The extensions of ML include non-parametric maximum likelihood (NPML) [104], natural-gradient non-parametric maximum likelihood (NG-NPML) [105], and the proposed method in [103]. Reference [103] used a stochastic gradient of the cost function to iteratively estimate the channel and achieved better performance in the convergence rate.

The digital SI cancellation will be done after ADC and in baseband. The methods of RLS, LMS, and NLMS used to mitigate the SI in wireless radio systems are also effective here and used in some cases [101] [103] [106]. In UWA, the channel is a time-varying feature due to surface reflection, and the RLS family methods do not cancel the SI experimentally. However, the Kalman filter with prior channel information has better performance in time-varying channels. The method SRLS-P proposed in [106] showed better experimental results compared to the classical RLS methods in the time-varying channel.

The estimation of nonlinear channel distortion was investigated in [107]. Also, the over-parameterization RLS (OPRLS) algorithm within sparse constraints was proposed. Research [102] reported digital SI cancellation based on an RLS adaptive filter applied iteratively with dichotomous coordinate descent (DCD) in an indoor water tank. Moreover, an adaptive equalization algorithm for mitigation of nonlinear distortion of the hydrophone pre-amplifier was presented in [106].

The way-mark model presented in [108] simulated the end-to-end UWA system while the transmitter and receiver were moving and considered the channel impulse response in time-varying variation. This model was used in some studies to represent the result of mitigated SI in UWA, such as [92].

4. Conclusion

In this document, a comprehensive survey on the issues for IBFD both in wireless radio communication and UWA systems is conducted. As mentioned, the main issue with IBFD systems is the SI system. However, in UWA systems, multipath interference is also a challenge. Three stages are defined for SI cancellation, which are passive, analog, and digital cancellation. The passive SI cancellation is done by antenna manipulation such as multitransmitter, directional transmitting, and others. The analog SI cancellation will be done after passive SI cancellation in the RF domain. The main purpose of analog cancellation isto estimate the inverse signal of interference based on the transmitted signal and add it to the received signal to mitigate the SI. However, because of nonlinear components in channel and device responses, there is residual interference that should be canceled in the digital baseband domain. Digital SI cancellation is helpful for the mitigation of residual interference and is based on channel estimation properties. If the nonlinear properties of device responses, such as PA and I/Q impairments, belong to channel estimation in digital SI cancellation, then more interference can be removed. However, the nonlinearchannel estimation is not a straightforward task, specifically in the UWA system, since the channel is fast and time-varying. Therefore, it needs more work to estimate the fast time-varying channel; however, some researchers addressed thisissue by using the Kalman filter. The Kalman filter is not a unique solution because of its merit inmany tasks, so it can help speed up the follow-up of the channel response.

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