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A Survey of Self-Interference Management Techniques for Single Frequency Full Duplex Systems

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ABSTRACT This paper presents a comprehensive survey of the literature on self-interference management schemes required to achieve a single frequency full duplex (FD) communication in wireless communication networks. A single frequency FD system often referred to as in-band FD system has emerged as an interesting solution for the next generation mobile networks, where the scarcity of available radio spectrum is an important issue. Although studies on the mitigation of self-interference have been documented in the literature, this is the first holistic attempt at presenting not just the various techniques available for handling self-interference that arises when an FD device is enabled, as a survey, but it also discusses other system impairments that significantly affect the self-interference management of the system, and not only in terrestrial systems, but also on satellite communication systems. The survey provides a taxonomy of self-interference management schemes and shows by means of comparisons the strengths and limitations of various self-interference management schemes. It also quantifies the amount of self-interference cancellation required for different access schemes from the first generation to the candidate fifth generation of mobile cellular systems. Importantly, the survey summarizes the lessons learnt, identifies and presents open research questions and key research areas for the future. This paper is intended to be a guide and take off point for further work on self-interference management in order to achieve FD transmission in mobile networks, including heterogeneous cellular networks, which is undeniably the network of the future wireless systems.

INDEX TERMS 5G, active interference cancellation, full duplex, passive interference mitigation, remote radio heads, self-interference cancellation.

I. INTRODUCTION

The sustained advancement in the digital world economy and the evolution of the mobile cellular and wireless networks has led to increased global mobile traffic [1]–[3]. With the proliferation of smart devices (e.g., smart phones, tablet computers, and Internet of Things (IoT) devices) and the race for 5G at an advanced stage, capacity issues on wireless communication systems needs to be addressed [4]. A promising emergent technology in this regard is the in-band Full Duplex (FD) system which is capable of potentially doubling the capacity or Spectral Efficiency (SE) of the current wireless communication systems. FD operation entails enabling wireless terminals to transmit and receive signals at the same time over the same frequency band. Enabling FD operation in a wireless network involves the radios operating in FD mode. In this mode, Self-Interference (SI) will occur. SI here refers to the receive antennas capturing the interfering signals from their own transmit antennas as well as receiving the interference, noise and useful signals from other radios. Fig. 1 depicts a single cell FD base station (BS) serving two HD user equipment (UE), with both operating on same frequency - one on the downlink (DL) designated as UE1 and the other on the uplink (UL) designated as UE2. The SI leaking from the transmit path to the receive path as well as the UL to DL interference constitute nuisance to the users. The SI can be several millions stronger than the desired signal due to the short distance between transmit and receive antennas at the BS [5]–[7].

Managing interference in current half duplex (HD) wireless networks is already a significant issue which becomes

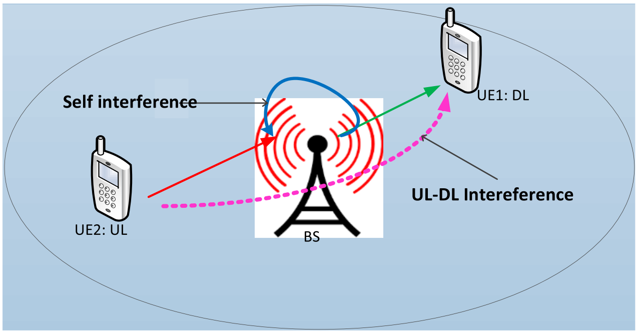

FIGURE 1. **Full duplex enabled BS showing effects of self-interference.**

more pronounced and challenging heterogeneous cellular deployment scenarios that involve multi-source and multi-destination channels. Enabling FD operation in wireless communication networks will make this problem even more critically important due to SI.

Communication can either be simplex or duplex. A **simplex** communication is simply a one-way communication. Conversely, a **duplex** communication involves connected parties capable of communicating with one another in both forward and reverse directions [8], [9]. Duplex systems are presented in two forms: **HD communication** and **FD communication**. Depending on capabilities and configurations, a Mobile Terminal (MT) – used interchangeably with UE - is capable of either HD or FD operation in some frequency bands [9]. Conventionally, most currently deployed communication terminals operate in HD mode, separating the transmission and reception in either frequency or time domain [10], [11]. HD is a bidirectional transmission based on two orthogonal channels typically using time (i.e., Time Division Duplex (TDD)) or frequency (i.e., Frequency Division Duplex (FDD)) dimensions, to provide separation between transmit and receive signals [11], [12]. This therefore means available communication resources are not efficiently utilized leading to loss and inefficiency in spectrum usage.

As service demand profiles evolve over the wireless networks, there is increased need to provide a far more efficient and reliable mobile communication typified by higher data rates and SE than is presently obtainable with HD systems. A possibility for efficient spectrum management is developing a technique capable of enabling Simultaneous Transmission and Reception (STR) of radio signals on the same frequency and time resources [13]. This is called FD communication. In literature, this concurrent transmission and reception using same frequency is also referred to as in-band full duplexing [14]–[18]. FD is defined in [19] as "*the ability of a wireless terminal to transmit and receive simultaneously over non-orthogonal channels which could potentially double the available spectrum and subsequently increase the data rates*."

Beyond potentially doubling the SE of current HD wireless communication systems; FD offers more flexibility in spectrum usage. It is capable of improving security of data during transmission and also able to reduce the air interface latency and delays. In addition, FD systems are capable of solving end-to-end delays in wireless networks [11] as well as the hidden node problems [3], [6]. The implementation of Medium Access Control (MAC) allows each node to transmit simultaneously meaning the system is designed not to permit hidden nodes. With instantaneous retransmission without intermittent stoppages for either the transmission duration or the reception duration, latency is improved. FD can improve ad-hoc, mesh and relay networks and could enable the introduction of novel, flexible and efficient channel access mechanisms. However, achieving these potentials of FD is only possible if the threat posed by the catastrophic effects of SI is adequately managed. For improved performance over other current HD technologies which also have potential for huge capacity increases such as Multiple Input Multiple Output (MIMO) techniques, SI needs to be mitigated at least to the noise floor or reasonably close to it [15], [20].

Several solutions for SI management[1] have been proposed and discussed in literature. Whereas some of these hinged on the domain the mitigation takes place, others are more about the mechanism employed. Current SI management techniques involve passive methods followed by active analogue and active digital mitigation schemes. The active analogue schemes mainly eliminate SI by signals inversion using extra hardware in generating the cancellation signals. The active digital schemes are promising but linear distortion and noise coupled with high complexities make the digital cancellation costly. For this reasons, in addition to comprehensively examining current SI mitigation schemes, the paper shall identify some open research questions and future research directions in areas it believes require further evaluation and research in a bid to realising a feasible, practical, cost-effective SI management scheme that could enable FD for the future wireless communication systems.

A number of FD-related projects have been launched geared at realising the next generation of wireless communication systems. These include: Adaptive, Heterogeneous, Incentive-Compatible, Localized and Secure Networking (AGILENET) [21] and Full-Duplex Radios for Local Access (DUPLO) [22]. AGILENET was set up mainly to coordinate research in the field of Cognitive Radio Networking (CRN). It benefited from some of the standardisation work done by 5th Generation Non-Orthogonal Waveforms for Asynchronous Signaling (5GNOW) and Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society (METIS) [21]. The programme concerned its work particularly with FD operation and extended the state-of-the-art in spectrum utilisation. DUPLO project is involved with research on FD systems. The project focuses on the new

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[1] It is almost impossible to completely cancel self-interference, but for the sake of this survey, we shall be using self-interference cancellation and self-interference mitigation or management interchangeably to mean the same thing.

TABLE 1. List of acronyms and definitions.

Acronyms	Definition
ADC	Analogue-to-Digital Converter
AMPS	Advanced Mobile Phone Service
AGILENET	Adaptive, Heterogeneous, Incentive-Compatible, Localized and Secure Networking
BDMA	Beam Division Multiple Access
BS	Base Station
CDMA	Code Division Multiple Access
CM	Common Mode
CRN	Cognitive Radio Networking
CSI	Channel State Information
CW	Continuous Wave
DAC	Digital-to-Analogue Converter
dB	Decibel
dBm	Decibel-metre
DL	Downlink
DM	Differential Mode
DSC	Digital Self-Interference Canceller
DSP	Digital Signal Processing
DUPLO	Full duplex Radios for Local Access
DVB-S2	Digital Video Broadcasting – Satellite - Second Generation
D2D	Device-to-Device
EBD	Electrical Balance Duplexer
EDGE	Enhanced Data Rate for GSM Evolution
EVDO	Evolution-Data Optimised
EVM	Error Vector Magnitude
FBMC	Filter Bank Multi-Carrier
FD	Full Duplex
FDD	Frequency Division Duplexing
FDBM	Full Duplex Block Markov
FDMA	Frequency Division Multiple Access
FDMH	Full Duplex Multi-Hop
FDR	Full Duplex Relay
GEO	Geosynchronous Equatorial Orbit
GW	Gateway
GPRS	General Packet Radio Service
GSM	Global Systems for Mobile Communications
HD	Half Duplex
HDR	Half Duplex Relay
HetNets	Heterogeneous Networks
HPA	High Power Amplifier
HSDPA	High speed Downlink Packet Access
HSUPA	High speed Uplink Packet Access
Hz	Hertz
IBFD	In-Band Full Duplex
IEEE	Institute of Electrical and Electronic Engineers
IoT	Internet of Things
I/Q	In-phase Quadrature
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
LOS	Line of Sight
LTE	Long Term Evolution
LTE-A	Long Term Evolution –Advanced
MAC	Medium Access Control
MEO	Medium Earth Orbit
METIS	Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society
MIMO	Multiple-Input Multiple-Output
MMIC	Monolithic Microwave Integrated Circuits
MOP	Minimum Output Power
MP	Memory Polynomial
MT	Mobile Terminal
OFDM	Orthogonal Frequency Division Multiplexing
PLR	Packet Loss Rate
PN	Phase Noise
RF	Radio Frequency
RMS	Root Mean Square
RRA	Radio Resource Allocation
RRM	Radio Resource Management
RX	Receive
SatCom	Satellite Communication
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDR	Software Defined Radio
SE	Spectral Efficiency
SI	Self-Interference
SIC	Successive Interference Cancellation
SISO	Single Input, Single Output
SLNR	Signal Leakage plus Noise Ratio
SNR	Signal-to-Noise-Ratio
SOFDMA	Scalable Orthogonal Frequency Division Multiple Access
STR	Simultaneous Transmission and Reception
SVD	Singular Value Decomposition
TD	Tie Domain
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TRM	Transmit / Receive Module
TX	Transmit
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications Systems
UT	User Terminal
WARP	Wireless Open-Access Research Platform
WCDMA	Wideband Code Division Multiple Access
WIMAX	Worldwide Interoperability for Microwave Access
3GPP	Third Generation Partnership Project
5G	5th Generation
5GNOW	5th Generation Non-Orthogonal Waveforms for Asynchronous Signalling

FD radio transmission paradigm which enables STR on same carrier at the same time and aims at developing new systems and technologies for future networks by introducing the FD radio transmission model mostly focusing on small area radio communication systems and networks such as femto cells, pico cells, metro cells and micro cells.

The contributions of this paper includes the following:

1) Comparison of full duplex self-interference management systems in terms of their potentials and limitations/constraints.
2) The classifications / taxonomy of the self-interference mitigation schemes in two different formats – domain-based and non-domain-based.
3) The state of the art potential of SIC schemes as well as comparison of different self-interference cancellation schemes and their capabilities.
4) The paper also presents the required amount of cancellation needed to enable full duplex in different technologies and access schemes from 1st to 5th generation of wireless communication systems.
5) Discussions of self-interference mitigation schemes for satellite communication systems.
6) Reviewing the plethora of literature available on full duplex systems and self-interference mitigation schemes, the authors gleaned the lessons learnt and appropriately suggested recommendations for researching the subject further.

The rest of the paper is organised as follows:

In Section II the key points of published survey papers relevant to FD and SI mitigation are reviewed and presented. The aim is to highlight what has been studied in literature with regards to different available techniques for SI management. As an outcome of this exploration, it is found that key gap in the available literature is the amount of SI cancellation required (and the corresponding SI mitigation methods) to enable FD for different access schemes (for terrestrial as well as satellite communication). In this Section we also present the trend for SI management in early FD systems.

Section III reviews and presents the different classification of SI mitigation schemes and their capabilities, including mitigation schemes for satellite communication (SatCom). It also discusses the advantages and disadvantages of the schemes.

In section IV, we discuss the effects of transceiver impairments on the SI cancellation abilities of the various SI mitigation schemes as well as model the analogue circuit distortions caused by these impairments.

Section V discusses the SI issues with MIMO systems starting with identifying extra interferences on the systems as a result of FD operations, then progressing to a simple modelling perspective of the multi-antenna systems before calculating and presenting the amount of SI cancellation needed to enable FD operations for various technologies. The section concludes by discussing some MIMO-assisted SI mitigation schemes.

In Section VI, the highlights of the possible challenges of SI mitigation in multi-cell wireless communication systems citing examples with full- duplex relay networks as well as cellular Heterogeneous Networks (HetNets) is presented.

Finally in Section VII is the summary of the lessons leant and subsequently some open research issues and future direction as well as conclusion of the survey are presented.

Notation: Standard notations are employed in this paper. Non-bold variables denote scalars, bold lower case variables represent vectors while bold upper case variables represent matrices. For any general matrix $\mathbf{H}$, $\mathbf{H}^{\dagger}$ refers to the conjugate transpose. $\mathbf{I_{NR}}$ **is the NxR** Identity matrix. Furthermore, we shall use MT, UE and Users interchangeably to refer to mobile devices throughout the paper.

II. RELATED WORK

It is probably correct to say that FD system is a new topic of interest among researchers. However, the principles of full duplexing in wireless communication have been available since the 1940s and have been implemented in a range of communication systems. Currently, there is a rapidly growing and significant literature on in-band SI mitigation reported in various surveys. This section presents some survey work around FD including SI suppression / mitigation as well as SI cancellation in the earlier days of FD systems.

A. RELATED SURVEYS

Some surveys and tutorials have been carried out regarding FD systems, mainly focusing on the array of technologies that have been proposed in literature for in-band FD, the evaluation of the performance capabilities of the FD network, the challenges for implementing FD systems; including SI, FD relay systems, opportunities, applications, as well as the perspective of FD from the physical and MAC layers. The context of SI as a major challenge for enabling FD operation have also been either partially mentioned in these surveys or treated in some reasonable depth. Some of these works are presented below, with their contributions and research topics reviewed and presented in Table II.

Sabharwal *et al.* [10] review the main concepts of in-band FD wireless systems by giving an overview of the historical developments including the research advances in in-band FD wireless systems. They mirror three basic wireless communications topologies which could leverage the opportunities of FD operation. These topologies are the relay topology, the bidirectional topology and the base station topology. Recognising SI as the singular biggest practical impediment to the operation of FD, the survey considers several techniques for SI reduction while also discussing numerous research challenges, such as antenna and circuit design as well as opportunities in the design and analysis of in-band FD wireless systems. Some of the research opportunities the paper identifies include: effective channel modelling of the FD system, optimal resource allocation and optimisation as well as performance limits for the in-band FD wireless network.

Alves *et al.* [23] discuss the importance of FD communications while highlighting the major drawback - SI. SI mitigation techniques which covered antenna design techniques through to digital SI cancellation are provided. The paper further identifies passive techniques, e.g., antenna separation as a technique capable of isolating and shielding the reception from transmission as well as the active techniques, e.g., analogue and digital domain SI suppression techniques capable of SI cancellation in the analogue receive-chain circuitry before the ADC and SI cancellation after the ADC using signal processing schemes, respectively. The performance analysis of FD relay so far carried out as well as assessment of current developments in FD relaying is presented while discussing a couple of promising protocols namely: FD Multi-Hop (FDMH) and FD Block Markov (FDBM), and how they are encoded and decoded. Whereas the former relies on multi-hopping and seen as the simplest protocol, the latter is considered as the best performance achieving FD relaying scheme. It concludes by discussing the importance of FD relaying on 5G networks.

Liu *et al.* [3] examine in-band FD Relaying (FDR) as a promising technology that shall integrate the advantages of FD wireless and relaying technology. The paper identifies interference management, small-size FD device design, security, cross-layer resource management, channel modelling and estimation as some of the many challenges and research issues that need to be addressed before widespread deployment of FDR can be implemented. In addition to the basics and enabling technologies of in-band FDR, the paper also presents SI cancellation in different domains; theoretical information performance analysis incorporating capacity analysis, outage probability and diversity-multiplexing trade off; key design issues including power allocation, antenna selection and challenges of in-band FDR.

TABLE 2. Survey papers that have studied self-interference cancellation for full duplex systems.

Title of paper	Reference	Year	Contributions and Research topics reviewed
In-band Full duplex Wireless: Challenges and Opportunities	[10]	2014	➢ Presented the research advances in FD wireless communications ➢ Mirrors the opportunities presented by FD technology ➢ Discusses the techniques for reducing self-interference ➢ Research challenges and opportunities are discussed
Brief Survey on full-duplex relaying and its applications on 5G	[23]	2015	➢ Notes SI cancellation methods of passive, analogue and digital schemes ➢ Discusses FD relaying protocols such as FDMH and FDBM ➢ Analysis the encoding and decoding processes for the protocols ➢ Presents performance analysis of FD schemes ➢ FD relaying on 5G is presented
In-band Full Duplex Relaying: A Survey, Research Issues and Challenges	[3]	2015	➢ Gives a historical perspective of in-band full duplex relaying ➢ Classifies full-duplex relaying systems ➢ Discusses self-interference cancellation domains ➢ Presents information-theoretic performance analysis of FDR systems ➢ Points out key design issues and challenges of FDR systems
A survey of in-band Full-Duplex Transmission: From the perspective of PHY and MAC layers	[5]	2015	➢ An overview of different in-band FD topologies ➢ Effects of in-band FD on system performance of the FD topologies ➢ Brief highlight of passive SI and active SIC ➢ Presents research challenges of the different FD topologies
Full Duplex Wireless Communications: Challenges, Solutions, and Future Research Directions	[25]	2016	➢ Benefits of FD operations by making performance comparisons of HD and FD modes ➢ In-depth discussion on self-interference cancellation ➢ Presents MAC layer protocol design for FD systems ➢ Implementation, improvement and optimisation issues in FD systems are discussed ➢ Potential future research directions are presented

Kim *et al.* [5] present three topologies for in-band FD transmission which includes bi-directional, relay and cellular topologies. To achieve FD in these topologies they recognise the need for both passive and active forms of SI management. The paper evaluated capacities for FD in the given topologies as well as SI schemes and challenges associated with each topology. In the same vein, the authors also provide comprehensive survey of MAC layer issues related to these three topologies and also present research challenges associated with MAC protocols for the in-band FD systems including the need for the development of advanced MAC protocol for ultra-low latency for 5G networks which needs to be backward compatible with the traditional HD networks.

Amjad *et al.* [24] studied specifically the FD communication in Cognitive Radio Networks (CRNs) – a deviance from the conventional wireless networks – and considered SI mitigation in the CRNs. The paper took a narrow scope and limited its discourse on the architecture, MAC protocols, spectrum sensing and security requirements for FD-CRNs only.

Perhaps [25] is the most comprehensive survey around FD wireless communications. In this paper, the authors review the state of the art on FD communications highlighting the benefits of FD communications; investigate critical techniques for SI cancellation and MAC layer protocols design for FD communications. The paper also investigates the hardware imperfections associated with wireless communications as well as discuss the advantages, disadvantages and design challenges of an FD system including its applications. More important, the authors present analysis of passive SI suppressing schemes that took into cognisance antenna separation, antenna cancellation and directional passive suppression; analogue SI cancellation and digital SI cancellation.

Whereas all these surveys have done a good work on identifying SI as the major drawback to commercial implementation of FD systems, none of them focused solely on discussing the SI management of FD systems and the amount of SI mitigation required to achieve FD communications. We have bridged this gap by calculating and presenting in Table VI the minimum required amount of SI cancellation needed to enable FD for different access schemes from the 1$^{\text{st}}$ to the 5$^{\text{th}}$ generation of wireless communication systems. It is important to note that all the SI mitigation scheme so far studied and presented discuss only terrestrial wireless networks. As a further contribution, we study and present SI mitigation schemes in satellite communication systems. We also present the modelling aspects of SI signals, especially for multi-antenna systems which before now, to the best of our knowledge, are not presented in any of the existing surveys that have studied SI mitigation.

B. SELF-INTERFERENCE MANAGEMENT IN EARLY FULL DUPLEX SYSTEMS

Radio SI cancellation being the most critical enabler for FD radios has been an age long technological challenge whose history transcends over a century [3]. Incidentally, the eventual success of radio SI cancellation may well depend on not only improved hardware technology but also innovative signal processing schemes. From the times, several efforts have been made in trying to cancel SI in an FD system. Though FD has not been widespread until recently due to the devastating effects of SI that a transmitting FD node causes to itself, FD concepts however have been an old paradigm with a reasonably long history. Interestingly, researches in this area include those from radar systems and the traditional telephony systems. FD models date back to the 1940s with the Continuous Wave (CW) radar systems [26], [27], which uses either shared antenna systems (mono-static) or separate (bi-static) antenna system for simultaneous transmission and reception of signals [28]. In a shared antenna architecture, each transmit and receive chain pair share a common antenna whereas in a separate antenna architecture, each transmit-chain as well as each receive-chain uses a dedicated radiating antenna. Transmitter leakage [29], [30] as SI was termed in those days posed the primary challenge to the design of CW radars. Isolation in CW radars of the mid-20th century between the incoming and outgoing signals was achieved through the use of circulators in the mono-static antenna systems by exploiting the nonlinear propagation in magnetic materials [31]. For the bi-static antenna systems, transmitter to receiver (TX-RX) isolation is achieved through antenna based path loss. Due to the slight isolation achieved using these two techniques, keeping SI levels within satisfactory levels meant intensely limiting transmit power and consequently limiting the range of these radars to short-range targets.

Following up to the techniques of the 1940s was an analogue circuit-based SI canceller known as the feed-through nulling aimed at increasing the dynamic range of CW radars [29]. This solution, which was capable of a 60 dB cancellation, came with a very expensive and heavy leakage canceller which made it unfeasible. An improved canceller capable of adapting to varying channel conditions was however proposed in 1990 [20]. This provided further improvement on the mono-static CW radars by reducing the weight of the leakage canceller and consequently reducing the price [29]–[33].

Apart from the CW radars, earliest recorded use of FD in cellular networks was as repeaters in the 1980s for extending cellular coverage [29], [32]–[36]. After then, wireless communications have not implemented much of FD technology until recently when the technology have been used

In relay systems where repeaters receive, amplify and re-transmit signals on the same frequency. Wireless relays are basically used for boosting coverage in difficult terrain where it is not cost effective to deploy wire line backhaul technologies. Just like in the bi-static CW radars, earlier technologies for SI cancellation in relays employed physical separation of transmit and receive transmitters [35]. These passive techniques have recently been taken over by active analogue and digital techniques [14], [37].

More recently, beamforming-based interference nulling techniques [13], [34], [38]–[45], [115] have been made possible by using antenna arrays. Though rich history exists on enabling single frequency wireless communication in relays, there has just been surge in research activities demonstrating the feasibility of enabling FD communications in other wireless and cellular systems recently [6], [16], [37], [42], [43], [46]–[48].

Some demonstrations reported in [16], [21], and [49] using improved SI cancellation schemes have achieved levels sufficient enough for enabling FD in WiFi systems, with few bottlenecks identified. These bottlenecks point to impairments introduced by the transmit radio chain [49]–[55]. Whereas successes have been recorded in some wireless technologies, the SI cancellation so far achieved even with the proposed advanced schemes that take into account the transmit radio chain impairments [7], [11], [46], [56], still fall short of levels required for the practical implementation of FD system in wireless networks.

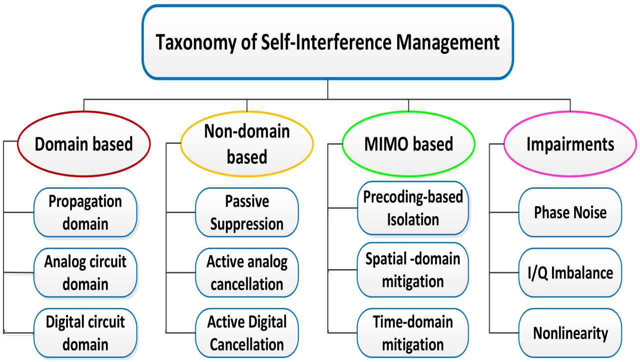

FIGURE 2. Taxonomy of Self-Interference Management.

C. TAXONOMY OF SELF-INTERFERENCE MANAGEMENT IN WIRELESS COMMUNICATION SYSTEMS

All the works done around the implementation of FD systems identify SI mitigation as the key to achieving FD communication. To properly study SI management, we present a taxonomy as shown in Fig. 2. In doing so, we have identified four broad classification regimes as explained below:

1) DOMAIN-BASED CLASSIFICATION

Here consideration is made for the domain under which the cancellation takes place in classifying the techniques. The domains include: propagation domain, analogue-circuit domain as well as digital circuit domain.

2) NON-DOMAIN BASED CLASSIFICATION

Under this category, we consider whether mitigation leads to suppression of SI signals or cancellation. While the former presents schemes collectively referred to as passive suppression schemes, the later considers active cancellation / mitigation schemes. Whereas the active schemes are further sub-grouped under active and digital cancellation, some of the techniques criss-cross the several domains as mention under domain based classification.

3) MIMO-AIDED CLASSIFICATION

With the benefits of MIMO technology in mind, it is imperative to think of enabling FD for MIMO systems. To achieve this, solutions for SI cancellation schemes suitable for the MIMO systems is suggested in literature. These schemes include natural isolation between the transmit and receive antennas of a MIMO system antenna array [15] as well as time-domain cancellation [57] and spatial-domain suppression schemes [58].

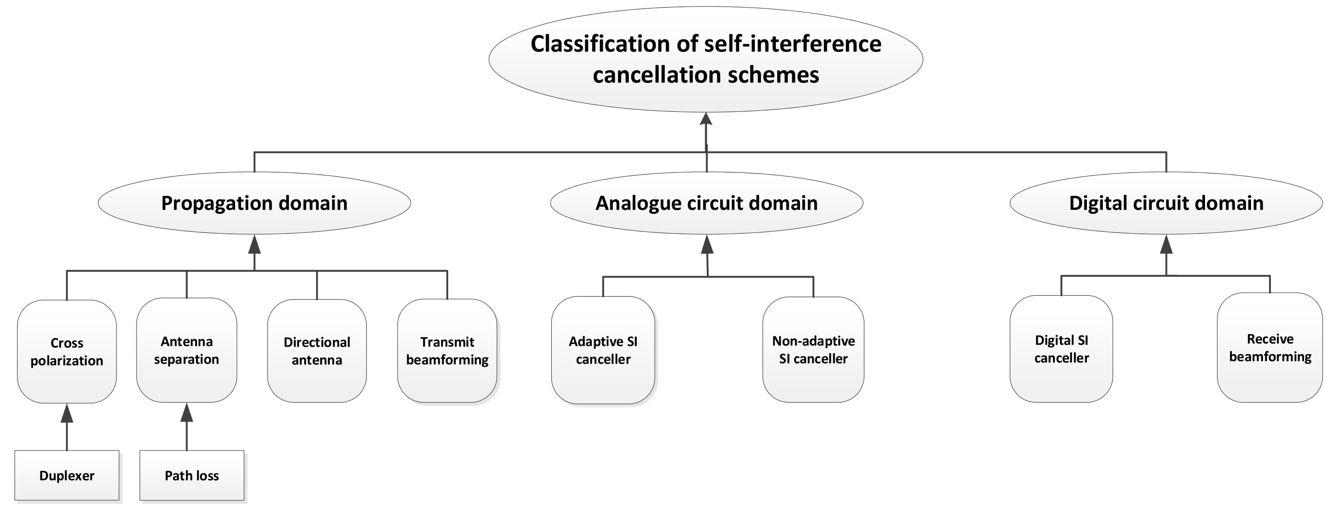

FIGURE 3. Classification of self-interference cancellation schemes.

TABLE 3. Domain-based SIC schemes classification: advantages and disadvantages.

SIC DOMAIN	Advantages	Disadvantages
Propagation Domain [3], [6-7], [65], [14-20]	• SI mitigation due to path loss • Capable of improving power efficiency • More separation results to more SI attenuation • Reduces inter-device interference • Ease of implementation • Capable of high cancellation • Robust in narrowband systems	• Unfeasible for small form-factor devices • Requires large separation distance • Suffers channel degradation
Analogue-Circuit Domain [3], [7], [16], [65], [66]	• Easy implementation • Low complexity compared to digital domain schemes • Compensates for multipath propagation • Enables advanced optimization • Minimises power of residual SI • Improves the useful signal • Suppresses both SI and noise • Adapts to varying Signal to Interference Ratios • Suitable for wideband frequency flat channel • Uses off-the-shelf MIMO radios	• Designed only for flat fading channels • Requires self-interference estimation • Requires CSI at the base station • Channel attenuation impacts performance greatly • High complexity compared to propagation analogue domain schemes • Extra hardware cost
Digital-Circuit Domain [3], [14-20], [34], [65]	• Eliminates residual SI following analogue cancellation • Modulation independent • Has high collision combating capability • Address hidden node issues	• Increases quantization noise • Limited cancellation capability • Might not be required after a good analogue cancellation

4) CHALLENGES POSED BY IMPAIRMENTS ON SI MANAGEMENT

non-idealities, especially on the RF analogue front-end pose a great challenge to the SI cancellation capability of FD systems. The main impairments of concern are the transceiver phase and quantization noise, I/Q imbalance as well as non-linearities [5], [25] which also results in channel estimation errors.

III. SELF-INTERFERENCE CANCELLATION TECHNIQUES

Since FD became a hot research topic in wireless communications, several attempts have been made at SI mitigation. Studies are not lacking in SI management techniques which could be broadly classified using several indices. Whereas some taxonomical classification consider the domain under which SI mitigation is performed, others consider whether SI is passively suppressed or actively cancelled. For the former, we classify the techniques that make use of a combination of propagation domain, analogue circuit domain and digital circuit domain while for the later we consider passive and active cancellation grouping. In Fig. 3 we show the various schemes and how they fit under the domain of cancellation and also present the advantages and disadvantages of SI cancellation under these domains in Table III. Classification for passive and active mitigation schemes are shown in Fig. 4 while a comparison of

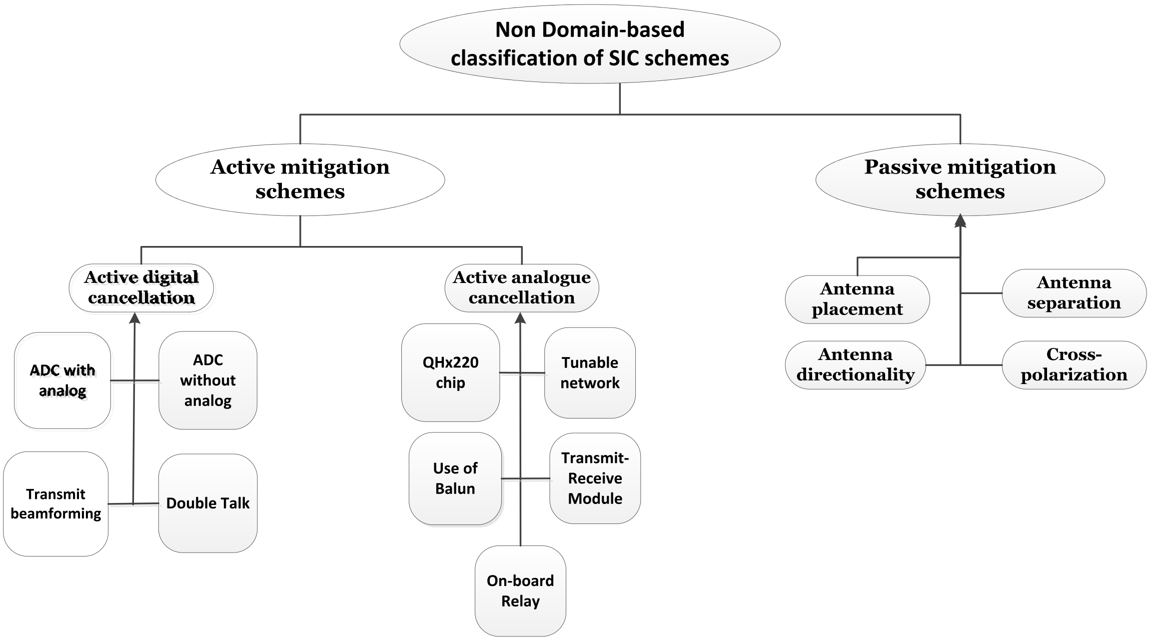

FIGURE 4. Self-interference cancellation schemes.

the performance capabilities of these schemes is presented in Table IV.

A. CLASSIFICATION OF SELF-INTERFERENCE MANAGEMENT SCHEMES BASED ON DOMAIN OF CANCELLATION

1) PROPAGATION DOMAIN SELF-INTERFERENCE MANAGEMENT SCHEMES

Propagation-domain SI cancellation schemes seek to separate the transmit chain and the receive chain using electromagnetic properties. It achieves this by suppressing the SI before it shows up in the receive chain circuitry. It is accomplished mostly by a combination of passive schemes including antenna directionality [18], [36], cross-polarisation [10], [37], [42], [59], path loss resulting from antenna separation [6], [16], [29], [37], [47], [58] and an active scheme in the form of transmit beamforming [3], [10], [60]. The propagation-domain SI suppression suffers from the possible problem of having the desired signals also suppressed in the process of trying to suppress the SI [10]. This is because the SI at the receiver of an FD terminal is usually very high and could easily exceed the capability of the receiver circuitry thus overwhelming it in the process.

2) ANALOGUE CIRCUIT-DOMAIN SELF-INTERFERENCE MANAGEMENT SCHEMES

In the analogue-circuit domain SI cancellation schemes, a copy of the transmitted signal is tapped from the transmitter and subtracted from the receive feed after appropriate delay, phase and gain adjustments have been made. This tapped signal from the transmitter could be described as auxiliary transmit signal whereas the transmitted signal is described as the primary transmit signal. The auxiliary transmit signal is pre-filtered by adding pre-weighting coefficients to the Orthogonal Frequency-Division Multiplexing (OFDM) tones and Radio Frequency (RF) modulated [12] then added to the received signal in the RF domain before the Low Noise Amplifier (LNA) or it can be added in the analogue baseband before the Analogue-to-Digital Converter (ADC). These schemes aim to suppress SI just before the ADC within the analogue-receive chain circuitry by using both adaptive (e.g., Balun) and non-adaptive (e.g., QHx220 chip) SI cancellers. The schemes within the analogue-domain circuitry are however affected by environmental factors such as reflections and refractions which could not be predicted and modelled in the design stage. Again, Channel State Information (CSI) cannot be exploited in the analogue domain making it practically impossible to implement a dynamic scheme in this domain. For these imperfections and challenges obtainable within the analogue circuitry at present, cancellation in digital domain becomes imperative.

3) DIGITAL-DOMAIN SELF-INTERFERENCE MANAGEMENT SCHEMES

Digital-domain SI mitigation takes place after the ADC by means of Digital Signal Processing (DSP) techniques applied on the receive signal. In the digital domain, CSI can be exploited and used in SI cancellation and also in resource allocation for learning and determining, for instance, the appropriate power allocation required across the network resources (time, frequency, bandwidth) [20], [36], [43]. However the ADC limits the dynamic range of the amount of SI that can be mitigated in the digital domain circuitry [10]. The DSP that goes along with digital domain SIC can also be a complex and costly process.

TABLE 4. Comparison of different self-interference cancellation schemes.

Schemes	Techniques		Capability	Pros	Cons	References
Passive Suppression	Antenna directionality		30 dB	Easy to implement Provides directional diversity Suitable in narrowband scenarios	Suffers bandwidth constraints due to large range of wavelengths Not suitable for wideband	[66], [74]
	Antenna placement		47 dB	Robust in narrowband scenarios	Requires 3 antennas; extra cost Suffers severe amplitude mismatch Requires manual tuning and so do not adapt to the environment	[6], [14], [47], [75]
	Antenna separation		30 dB	Uplink and downlink are spatially separated Uses the idea of increasing path loss between TX and RX antennas Ease of implementation	Not applicable to point-to-point scenarios where both nodes are FD enabled Not feasible with small form-factor devices Suffers degradation on individual antennas radiation pattern Can suppress desired signal	[3], [47], [54], [72]
	Cross-polarisation		50 dB	Can be applied to both separate and shared antennas Can be applied to small form-factor devices with duplexers	Unaware of system characteristics Affected by environmental factors	[7], [19], [62], [74]
Active Suppression	Analogue Cancellation	Balun circuit	45 dB	Generates inverted version of the Received signal for cancellation Non-bandwidth limited; non-power limited Adaptive to the environment	Incurs additional non-linearity from the noise cancelling circuit Cancellation is not adequate	[46], [60], [74],
		Electric Balance Duplexer	Highly Frequency dependent	Uses one antenna Suitable for small form-factor devices Tunable over a wide frequency range Not constrained by separation distance	Frequency dependent Requires manual tuning Not very good power handling capability Prone to non-linear IB distortions Limits isolation bandwidth	[78-80]
		QHx220 chip	45 dB	Provides extra RF chain	Non-adaptive to the environment Difficulty in wideband scenarios	[15-16], [32], [74]
	Digital Cancellation	With analogue cancellation	60 dB	Suppresses both SI and noise	Suffers transmitter distortion due to non-ideality of transmitter and receiver components	[7], [14]
		Without analogue cancellation	10 dB	Capable of eliminating residual SI after analogue cancellation	Hardware impairments including I/Q imbalance	[6], [15-16], [37]

B. PASSIVE SUPPRESSION SCHEMES

Passive SI mitigation schemes rely on separating the transmit RF chain from the receive RF chain. There have been proposals for passive cancellation techniques which rely on antenna directivity in combination with physical separation of the antennas, polarisation and use of additional RF absorbing materials [37], [61]. When each of these techniques are employed either as standalone solution or in conjunction with one or two other passive techniques, the primary idea is isolating the transmit RF chain from the receive RF chain as much as is possible. We present below the passive suppression schemes available in literature for SI mitigation.

1) ANTENNA SEPARATION

is the most common technique for achieving SI suppression at antenna level. This technique requires large distances between antennas for sufficient SI suppression. It employs the idea of increasing the pathloss between transmit and receive antennas and exploiting surrounding obstacles (e.g., buildings and shielding plates) in blocking direct paths [3], [62]. This approach has been applied in traditional in-band repeaters [37], [63], [64] to suppress SI by increasing the physical distance of separation between transmit and receive antennas. Antenna separation technique has also been used in some recent test beds [7], [16], [58].

2) ANTENNA PLACEMENT

is a cancellation technique (sometimes classified as analogue-domain scheme [68]) based on antenna placement [6], [9], reported in [6] as antenna cancellation. This technique as reported in literature [5], [7], [68], involves two transmit antennas spaced apart with the receiving antenna placed in between at distances d and $d+\lambda/2$, respectively so that the transmit antennas are able to superimpose a null at the receive antenna (λ is the wavelength of the operational frequency) and hence cancel each other at the receive antenna. The technique uses the fact that the distance between transmit and receive antennas naturally reduces the SI due to signal attenuation. The cancellation is achieved by means of phase offset. In a simple implementation scenario, the transmission signal is split between two transmit antennas sandwiching a receive antenna as described above resulting in destructive

TABLE 5. Reference form factor values for Full duplex devices [68].

Full Duplex Devices	Access Point Type	Form Factor Dimensions
Base Stations	Femto Base Station	236 x 160 x 76 mm
	Pico Base Station	426 x 336 x 128 mm
	TETRA Base Station	55 x 143 x 57 mm
User Equipment	Netbook	285 x 202 x 27.4 mm
	Tablet PC	241.2 x 185.7 x 8.8 mm
	Smart Phone	123.8 x 58.6 x 7.6 mm
	PDA	132 x 66 x 23 mm

and constructive interference patterns over space [6], [11]. Antenna placement suffers bandwidth constraints due to large range of signal wavelength [6], [9]. Employing separate transmit and receive antennas has potential for better SI suppression but this multi-antenna system comes at a cost to the spatial domain which includes degrading the antenna radiation pattern and spoiling the far field coverage. For example, the three antenna architecture of one receive antenna and two transmit antennas with 180 degrees phase shift proposed in [7] causes transmit signals to add constructively while cancelling out the receiver. Again, for this technique to work, the distance between antennas must be large enough in order to achieve an acceptable value of cancellation. This is not always possible, especially given the small form factor of compact radio nature (Table V shows some reference form factor values for some FD devices) of most wireless communication devices such as Smart phones, Netbook, femto cells, etc.

Antenna placement is useful especially for narrowband cases but would suffer SI cancellation performance degradation in cases of wideband signals where null regions of destructive interference is created in the far-field region in effect destroying the far field coverage [5], unless used for larger form-factors where system size constraints may be limited. The technique does not adapt to environment conditions as it requires manual tuning and needs three antennas which represents extra cost for hardware. It could also suffer severe amplitude mismatch between the two transmit antennas. This is because the technique work for antennas optimally positioned only in the line-of-sight (LOS). If antennas are off LOS the reflected signals may not cancel out, thereby limiting the capability of antenna placement. The technique is only capable of 60 dB cancellation [6]. However, pairwise symmetric antenna technique [14] can help overcome the bandwidth constraints inherent in the antenna placement procedure. Pair-wise symmetric antennas theoretically have zero coupling over entire frequency range. This implies that symmetrical transmit and receive antennas can be positioned in such a way that SI is reduced. The cancellation is achieved by means of phase offset, and has been classified by some authors as an active SI cancellation technique.

3) CROSS-POLARISATION

is another passive SI mitigation technique that electromagnetically increases the isolation between transmit and receive antennas [3]. Polarisation of an antenna dictates and determines the direction and sense of the electric field vector radiated by the antenna. Ideally, the energy radiated between two orthogonal polarisations is zero indicating that maximum energy will occur between two antennas if their polarisations are the same but will reduce when there is polarisation mismatch. When the transmit signal of an FD node is horizontally polarised for instance, it can only receive vertically polarized signals with the aim of avoiding interference between the antennas. Cross-polarisation can be applied to both separate antenna systems [69] and shared antenna systems [70]. Shared antenna deployment uses less space. The technique is promising for small form-factor device deployment and is recently gaining prominence following the work of Bhardia *et al.* [7] which have shown the feasibility of deploying shared antenna systems in a Single Input Single Output (SISO) scenario. In this scenario, isolation is achieved within the shared antenna system by the means of duplexers [7], [14], [71]. FD antennas stand to benefit by utilizing orthogonal polarisations in order to increase antenna energy isolation.

However, as effective as the current passive SI management schemes are in mitigating SI resulting from direct paths, it is bedeviled with some problems. Some of these include not being feasible for small-form-factor devices [7], [61], and being adversely limited by environmental factors since the techniques are unaware of the system characteristics and do not take them into account. There is also a possibility of inadvertently suppressing the desired signal while trying to adjust transmit and receive patterns in passive SI mitigation [10], [61]. For instance, some impractical antenna separation distances can actually thin out the desired signals. Similar situation is also possible if the angular separation using antenna directionality is totally out of phase or not implemented correctly.

C. ACTIVE SELF-INTERFERENCE CANCELLATION SCHEMES

Most active cancellation schemes are done in the active analogue circuit-domain as described in Section III-A. Active cancellation techniques use active components and exploit the knowledge of a node's own SI Signal in generating a cancellation signal that can be subtracted from the received signal [26], [61], [70]. The family of active mitigation techniques can be subdivided into active analogue cancellation and active digital cancellation and mixed active analogue / active digital techniques [62]. The active cancellation method employed before the digitization of the received signal is called active analogue cancellation whereas the active cancellation methods employed to cancel the residual SI within the received signal after digitization is called digital cancellation [16], [40], [72]–[74].

1) ACTIVE ANALOGUE CANCELLATION SCHEMES

Analogue cancellation schemes generally cancel SI in the analogue-receive chain / circuitry by subtracting a copy of the predicted SI from the received signal before it enters the digital circuit, just before the ADC. As already stated, the scheme involves mirroring the primary transmit signal and obtaining the auxiliary transmit signal which is pre-weighted and RF modulated before adding it to the receive signal just before the ADC. These schemes can be classified as either adaptive or non-adaptive depending on their abilities to respond to changing effects of the environment [46], [60], and [71].

The adaptive active analogue cancellation techniques dynamically adjust their parameters according to the reflected channel and are able to mitigate both direct-path and reflected SI signals. An example of the adaptive analogue scheme is the use of RF Balun. This scheme uses signal inversion technique for SI mitigation [46]. The mechanism employed by the active analogue cancellation circuitry is for generating a cancellation signal which simply makes use of balanced-to-unbalanced converter to generate the inverse of the SI signal which it uses to cancel the SI. The SI generated by the transmitting node is met with the slightly modified (modified by applying a variable delay and attenuation) inverted SI (auxiliary transmit) signal applied by the means of a noise cancelling integrated circuit. This scheme involves tuning algorithm which controls the gain and delay that the chip applies to input. The Balun cancellation technique is theoretically capable of providing SI cancellation of 45 dB and has no power or bandwidth limitations [6], [65]. However, on the flip side, its capabilities still fall short of the required SI cancellation to enable FD. It also incurs additional nonlinearities from the imperfections inherent with the RF Balun and the noise cancelling circuit.

The non-adaptive schemes are not environment aware. They are sensitive to reflected paths of SI because they are not aware of the changes in the environments [15], [16], [78], [81]. They require manual tuning and use fixed parameters such as gain, delay and phase in predicting SI. An example is the use of the noise canceller chip, QHx220 as depicted in Fig. 5a. QHx220 chip is used to introduce an extra circuit. This circuit generates an extra RF suppressing signal which is subtracted from the receivers' chain a known analogue SI signal from the received signal [65]. The idea in using an extra transmit RF chain is to estimate channel and design an extra inverted RF chain by means of off-the-shelf radios which adds to the transmit signal at the receive chain as shown in Fig. 5b.

The DUPLO project also proposed another non-adaptive active analogue SI cancellation scheme that uses a tunable cancellation network combined with a dual-polarised antenna [62] as depicted in Fig. 6. It has similar working operation to the RF Balun set up. The network is designed to copy a portion of the transmit signal with the in-band impairments using a directional coupler which it adds back to the receive path before the LNA after phase rotation and attenuation. The main advantage of performing the active cancellation close to the antenna ports is that transmitter impairments are maximally included in the cancellation loop, thereby improving the cancellation and reducing the potential of saturating the first receiver components. After the modification and 180 degrees phase-shifting (inversion as in Balun), the addition is achieved by means of an RF combiner. This addition is made before the LNA because the losses added to the network at that stage are very minimal. A result of simulation done with the active cancellation network using discrete components and the dual-polarised antenna shows an SI cancellation of 15 dB over 10 MHz [70], [81].

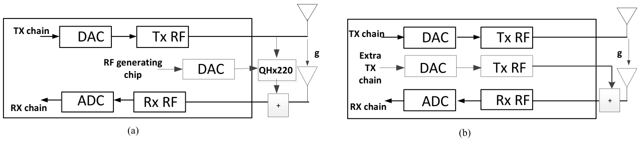

FIGURE 5. The non-adaptive extra RF chain circuitry for SIC [37].

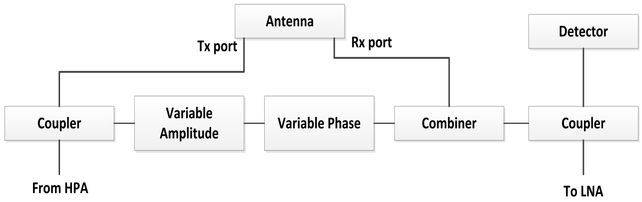

FIGURE 6. Tunable analogue cancellation network with dual-polarized antenna [70].

Furthermore, the tunable cancellation network described above is not so different from the Electrical Balance Duplexer (EBD) [80]. A hybrid transformer-based EBD provides both Differential Mode (DM) and Common Mode (CM) signals at the receiver input. The DM is to provide SI reduction and protect the receiver from CM signals which are capable of causing breakdown of the LNA due to large voltage swing at the input of the LNA. EBD demonstrates the usage of a conventional single-port antenna in achieving FD operations by exploiting the electrical balance in hybrid junctions to provide high TX-RX isolation over wide bandwidth [78]. The concept of EBD is the balancing of the antenna impedance with balanced network impedance at ports of a hybrid junction. An EBD can pass signals between the transmitter and the receiver of the antenna while also providing cancellation of SI originating from the local transmitter at the same frequency. Using multiple antennas as is obtainable with antenna separation and antenna placement introduces null in the antenna beam pattern which in turn degrades coverage. The strength of EBD which is capable of providing up to 60 dB of isolation at 20 MHz bandwidth, 50 dB at 40 MHz and 30 dB at 200 MHz [80] lies in its suitability for implementation in small form-factor devices because of its usage of a single antenna while ensuring good far-field coverage. Unlike antenna separation, the capability of the EBD is not limited by physical separation. It is tunable over wide range of frequencies and can be implemented using integrated circuits. However, the TX-RX isolation can only be obtained when the balancing impedance closely matches the antenna impedance. This limits the isolation bandwidth.

Again, EBD is susceptible to in-band distortions produced by nonlinear components of the duplexer causing difficulties in subsequent SI cancellation in the transceiver.

Similarly, [7] and [16] reported an experiment set up that used Wireless Open-Access Research Platform (WARP) in providing an extra transmit chain which generates an inverted cancellation signal that was subtracted from the receive chain. The primary difference with this scheme and the Balun is that whereas this technique performs SI cancellation by phase offset, the Balun performs SI cancellation by signal inversion. Not so long ago, Stanford university researchers [7], reported impressive results showing FD operations based on a SI cancellation technique that utilises a 10×10 cm Printed Circuit Board (PCB) circulator equipped with several adjustable attenuators, each of varying length capable of introducing varying delays. The design was made to reproduce the antenna mismatch reflection and the circulator leakage. Though there are promising results with the work as reported, especially SI cancellation up to WiFi noise floor of about 110 dB, some other issues with real life application including nearby obstacles are yet unresolved. Moreover, their prototype is frequency dependent and targeted WiFi frequencies in the 2.4 GHz band. It also targets SISO scenarios making the cross talk you get with MIMO systems still an issue of concern and thus open for further investigations. The 10×10 cm prototype board is suitable for mid-sized form-factor devices and the technique might not be applicable to larger cells and very small portable devices.

2) ACTIVE DIGITAL CANCELLATION SCHEMES

Current mitigation schemes presented by the passive and analogue circuit technologies have shown impressive promise. Nonetheless, though they may be able to provide enough SI cancellation for repeaters (relay systems) [3] which only receive-amplify and forward, they do not present sufficient suppression for some other cases and scenarios, for instance cellular networks which need to also decode the receive signals. For this reason, active digital cancellation technologies become handy. It is identified in Literature that Digital SI Canceller (DSC) and transmit beamforming are schemes which could be adopted in digital domain to actively suppress residual SI which might have escaped the passive and analogue circuitry. Digital cancellation makes use of complex and advance DSP techniques in mitigating SI. The DSC estimates the residual SI after passive and analogue cancellation and subtracts this predicted or estimated signal from the received baseband samples in digital domain [15], [16], [37]. In the receive beamforming technique [18], a MIMO scenario is considered in which case SI is suppressed by adaptively adjusting per-antenna weight according to the SI channel condition. Receive beamforming can also be implemented in analogue domain, but is commonly implemented in digital domain owing to complexity and power consumption issues.

Digital cancellation suffers from transmitter distortion due to non-ideality of amplifiers, oscillators, ADCs and DACs. The active digital cancellation techniques would be successful only if an equivalent discrete time baseband model that is able to capture all the distortions of the FD terminals is built. To solve this problem, [7] proposed and experimentally demonstrated a hybrid joint analogue-digital design capable of modelling all linear, nonlinear and transmitter noise distortions and cancelling SI up to the noise floor. Their work is credited with presenting the first realistic demonstration of using a combination of SI mitigation schemes in realising FD. Though the size of the board used for implementing the circulator fits well with BSs for cellular networks, the work was implemented on the 2.4GHz band. Besides, the components of the circuit are frequency dependent, making it unadaptable to varying frequency scenarios. Besides, the targeted scenarios were SISO leaving a huge challenge for implementing the solution on MIMO where cross-talk between antenna elements presents a challenge.

With these challenges in mind, coupled with the complexities of the active cancellation schemes, the expectations are that there is need for further research into more cost effective, less complex solutions capable of modelling not just signals from a single antenna but also the distortions from multiple antennas. We discuss impact of impairments on SI cancellation in the following sections while possibilities for overcoming these challenges, especially for the MIMO scenarios are presented under the section for open research questions and future directions.

D. SELF-INTERFERENCE MITIGATION SCHEMES FOR SATCOM

Historically, Satellite Communication (SatCom) has always served as an effective medium of coverage infrastructure mainly in areas that are not adequately covered by the terrestrial communication infrastructure. Though several technologies have been suggested and implemented to improve spectral efficiency in SatCom such as reducing the guard bands with improved waveforms, however the availability of satellite spectrum has always been a big challenge. Just like cost is of big concern to terrestrial wireless systems, high cost of multiple transponders on-board a satellite fuels the interest in FD for SatCom. If FD is achieved in this environment, it will save money and increase the number of users that can be served within a given RF #band [81]. Achieving this though is still a significant challenge given the large distance and large power transmission required for SatCom. Whereas FD communication has made a significant head way in terrestrial communication, owing to its low power transmissions and short distances, its application to SatCom is still in its early days. The difficulty in implementing an FD system increases with the distance between the radios; the larger the difference between the TX and RX power, the more challenging the problem becomes [83]. In SatCom, the distance of separation between the TX and RX antennas are enormous when compared with terrestrial networks. In the following subsections, we present the techniques for SI mitigation in satellite systems when enabling FD communication.

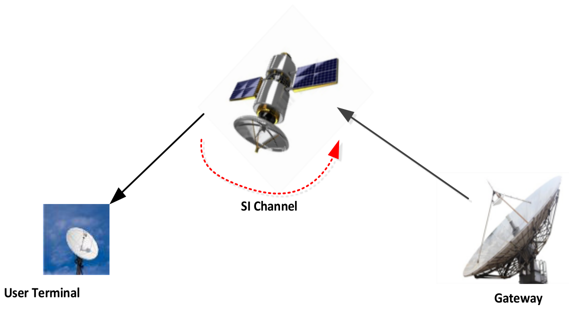

FIGURE 7. SatCom Full-duplex forward path relaying showing SI [84].

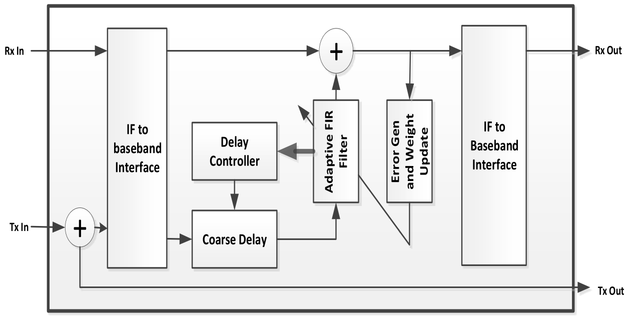

FIGURE 8. Block diagram showing the double talk implementation [82].

1) ON-BOARD FD RELAY SYSTEM

Fig.7 describes a satellite system operating in the FD mode. This technique involves the use of same frequency band on the feeder uplink represented by the Gateway (GW) to Satellite link and the downlink represented by the User Terminal (UT) to satellite link. To access the feasibility of the solution, [84] carried out a rigorous analysis of the impact of SI. In their feasibility work, they demonstrated the use of FD relaying principles on-board the satellite systems, and show, from a technical point of view, that satellite FD communication can be a promising solution for the efficient use of satellite spectrum. First, the authors identified different sources of interference on the on-board relay system to include: high power amplifier (HPA) non-linearities, memory effects and on-board noise components. The SI comprises of the linear and the non-linear terms and is induced by the SI channel; the non-linear components of SI, are due to the transponder characteristic and can be modelled as a non-linear function without memory. The noise component is broken down into the Uplink noise component (which is generated by the transponder and unaffected by the SI), the Downlink and Receiver noise (due to the transponder and the UT), and the Full-Duplexing noise (which arises as a result of the SI). The SI component and transmit noise are mitigated by non-adaptive analogue cancellation by tapping a line from the transmit antenna to the receive antenna.

However, there remains the challenge of accurately estimating the on-board SI channel. Whereas, as earlier mentioned, existing works have discussed the techniques for mitigating these impairments in terrestrial communication via a mix of analogue and digital techniques, for the on-board relay system, only RF cancellation can be implemented. Lack of processing capabilities impede the on-board digital cancellation. Furthermore, on-ground predistortion and equalisation at the GW and UT, respectively, can be introduced to augment the on-board analogue interference mitigation [84], [85].

2) DOUBLE TALK

Double Talk is a kind of an echo canceller for satellite signals [82]. Each end of the link sees a modified ''echo'' of its own transmitted signal in the downlink it receives. Whereas the concept of using echo cancellation in terrestrial networks is simple, to meet the requirements for using it in challenging satellite environments require significant enhancements. These enhancements are required because:

- Non-static frequency offsets are imposed by the uplink and downlink conversions and the frequency translation of the transponder.
- A Doppler shift due to satellite motion is present as the motion of the satellite(specifically for low and medium earth orbit satellites) causes the round trip delay between the earth stations to be time varying.
- Non-Linearities in the RF electronics throughout the processing cause distortion and sometimes introduce interference between carriers.

Each of these effects has to be compensated in the canceller architecture. Collins and Treichler [82] were able to use digital signal processing (DSP) to address the enhancement requirements by utilizing the concept of an echo canceller for satellite signals, and its use to eliminate intentional echoes of signals introduced solely for the purpose of minimising the link bandwidth. Double Talk was originally intended to be modem agnostic and had only IF interfaces. A high level signal processing architecture of Double Talk is shown in Fig. 8, where;

- Rx In denotes the received composite IF downlink signal consisting of both the desired signal from the far end of the link and the (co-channel) echo of the transmitted signal (Tx Out) from the local modem.
- Tx In denotes the IF uplink signal from the local modem.
- Rx Out denotes the IF output signal from DoubleTalk. This is the signal from the far end of the link recovered in Double Talk by cancelling echo of the local uplink signal Tx Out.
- Rx Out is subsequently passed to a suitable modem for demodulation.

The essence of DoubleTalk is quite simple. The local IF uplink signal is digitised, stored in memory, adaptively filtered and subtracted from the received input. An adaptive FIR filter (canceller) using minimum output power (MOP) or least mean square criterion is used to adjust the filter taps to minimise the differences between the local reference and the downlink signals [86], [87]. Because the signal from the far end of the link is presumed uncorrelated with the locally transmitted uplink signal, the MOP criterion is satisfied only when the desired signal from the far end of the link remains after the cancellation process. This is a classic 'noise cancelling' adaptive filtering problem. The performance of this scheme in the lab yielded 28-29 dB cancellation, which is far from the supposed 130 dB [82] required to enable FD operations in the SatCom systems.

3) TRANSMIT / RECEIVE MODULE (TRM)

Bharj *et al.* [88] study a FD, multi-channel TRM for an S-Band SatCom Phased Array system. The multi-channel S-Band TRM has been designed for SatCom on FD mode, and applicable to satellites in Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geo Synchronous Orbit (GEO). The TRM utilises over 90 Monolithic Microwave Integrated Circuits (MMICs) for transmit and receive beamforming and array control and has internal shields in the modules which provide RF isolation with the array providing simultaneous multiple high gain transmit and receive beams within a hemisphere to communicate with satellites during the time they are above the local horizon. The main design components of the TRM, consists of high rejection ceramic diplexers, low noise MMIC amplifiers, 4- Bit transmit and receive digital phase shifters and integrated circuit micro controllers. Included in the design are polarization diversity, RF shielding and design considerations for interfacing with a beamformer, among other things. Whereas this solution could be optimised to offer a reasonable solution for the FD SatComs by building a plug and play device within the SatCom systems capable of a 45 dB cancellation, the drawback is that there is a difference in the transmit and receive frequency bands which are 1.75-2.1 GHz and 2.2-2,3 GHz, respectively. This do not necessarily imply STR on same radio resource. It should be interesting researching more on the possibility of implementing the TRM on same frequency band.

IV. EFFECTS OF TRANSCEIVER IMPAIRMENTS ON SELF-INTERFERENCE MANAGEMENT

It has been suggested in literature that active SI cancellation is capable of ridding the FD system of issues of SI and bringing home the benefits of FD systems. However, several non-ideality issues limit the performance of the SI mitigation. Some of these includes receiver noise, transmitter noise, phase noise, channel estimation errors, dispersion and nonlinearities. As the prospects for the implementation of FD systems increase with improvements in the SI mitigation techniques, it is imperative to understand the dominant nonlinearities within the system and correctly model them. With the increasing complexities of wireless communication systems, nonlinear behaviours are observed in more and more blocks. These nonlinear behaviours as a result of hardware imperfections pose the highest limiting factors to conventional SI mitigation techniques [5]. This is especially true in FD systems where due to strong SI signals, the system nonlinearities pose huge limitations to the cancellation of the SI power. Radio elements in a wireless communication systems are susceptible to RF front-end impairments. These become more obvious with higher-data rate devices such as FD radios both in the RF analogue front-end and digital baseband. For instance, as shown by [89], as a requirement for active cancellation the active analogue canceller needs to mitigate the analogue SI to ensure it meets the Analogue-to-Digital Converter (ADC) sampling requirement. However, the active analogue cancellation performance is often restricted by the non-ideal electronic components, e.g., the tunable attenuator, the phase shifter and associated circuits, which introduce nonlinear distortions to the residual SI signal that enters the receive chain, as the transmit power increases.

To tackle the key challenge of SI in FD systems, suggestions have been made for joint analogue and digital cancellation which take into account the characteristics of the RF analogue imperfections. Whereas it is not strictly accurate to state that the total amount of SI cancellation is directly proportional to the amount of analogue cancellation, it is however correct to say that the amount of digital cancellation achieved has a direct bearing to the amount of analogue cancellation when cascaded [25]. In other words, if the analogue cancellation reduces the system SI to a lesser degree, then digital cancellation is able to cancel the residual SI even more substantially.

In practice, SI consists of multiple components as the transmit signal is corrupted by these different impairments, such as nonlinearity, phase and quantization noise [90]. Some of these by-products are noisy, others are deterministic. The transmit signal, including its by-products, is coupled into the receiver through various paths, e.g., direct crosstalk, TX-RX antenna leakage due to limited isolation, and reflections on nearby objects in the environment. To achieve a receiver sensitivity similar to the conventional HD radios is very challenging, as all SI components should be suppressed to below the receiver noise floor. SI cancellation in the analogue circuit is still limited by a number of impairments which for the sake of this survey, we have classified as: transceiver phase noise [74], quadrature imbalance, and power amplifier nonlinearity [72], [77]. There are however other non-idealities which impact the SI cancellation capabilities in FD systems. These includes: ADC quantization noise [91], carrier and frequency offsets etc. Both the transmitter and the receiver are impacted by impairments with both consisting of nonlinearities and noise components as well as some system level impairments.

A. TRANSCEIVER PHASE NOISE

Sahai *et al.* [74] note that the amount of active analogue cancellation is limited to 35 dB. This is as a result of phase noise in the local oscillator which limits the amount of active cancellation [92]. Phase noise in the transceiver causes the disturbances which ensures the SI and the nulling signals do not cancel out. This claim is further elucidated by the analysis in [15] which demonstrated that the transceiver oscillator phase noise is one of the major bottlenecks limiting the amount of SI cancellation in practical FD systems. In [16], it was analytically established that the capacity gain of FD systems is significantly decreased as phase noise increases / becomes stronger making it clear that for efficient SI cancellation, reduction of transceiver phase noise should be considered seriously. Sahai *et al.* [74] present an analysis of the impact of phase noise on the strength of the residual SI signal on analogue cancellation. In the analogue domain, an imperfect SI channel estimation was considered with the conclusion that the residual SI signal strength consists of the SI-dependent component as well as the phase noise-dependent component in the pre-mixer, post-mixer and the baseband canceller. It could be inferred from their studies that in the presence of high received SI power levels, phase noise will dominate the residual SI after analogue cancellation because the phase noise dependent component scales linearly with the SI power [25].

B. IN-PHASE /QUADRATURE IMBALANCE

A signal from the transmitter is usually received in the receiver as a modulated signal. A modulated signal includes an in-phase component and a quadrature component. There is always an amount of deviation in the proper alignment of the in-phase and quadrature components of the modulated received signal. This deviation may occur in both the amplitude and the phase of the in-phase and quadrature components of the signal. Even though other system impairments such as phase noise and sampling jitter degrades the SI cancellation ability of several techniques [93] describes I/Q imbalance and PA nonlinearities as the most prominent impairments that limit the system performance especially the precision of digital SI cancellation techniques. On the transmitter side in general, I/Q imbalance contributes to the transmitter error vector magnitude (EVM) and also adjacent channel leakage [94]. It represents an additional loopback signal leakage to the receiver path. It is noted in [73], which studied the effect of I/Q imbalance on the FD transceiver, that IQ imbalance causes residual SI even after all the cancellation stages. The discrepancies of I/Q imbalance parameters within two transmission chains causes the generation of imprecise SI signal. This hampers the performance of SI suppression. To study the influence and effects of I/Q imbalance in the performance of SI mitigation in FD devices, and how to mitigate I/Q imbalance in a wireless transceiver, [95] proposed advance pre-equalisation units which are able to handle the I/Q impairments. Though the results of the analysis presented are appreciable, they more than anything, showed the dire effects of the I/Q imbalance to the SI capability of an FD system.

C. TRANSCEIVER AND POWER AMPLIFIER NONLINEARITIES

Generally, RF / analogue impairments cause signals in wireless communication systems to be distorted in different subsystems. These distortions are made up of the linear components as well as the nonlinear components [72]. As [89] notes, the main sources of the system nonlinearities in practical systems are the power amplifier at the transmitter side and the LNA at the receiver side. These pose a significant challenge to the SI cancellation ability of the FD wireless system. According to [7], [89], and [97] the nonlinear distortions in an FD transceiver can be approximated using polynomials. Several works have modelled nonlinearities in an FD device, so we shall not be making any analytical derivations but shall refer to a couple of such modelling.

The output, y of any wireless system nonlinear component can generally be modelled as in [92] as a polynomial function of the input signal as follows:

$$y\left(t\right)=\sum_{p=1}^{P}\beta_p\Gamma(t)^p \tag{1}$$

Where, the first term $\Gamma\left(t\right)$, represents the linear component input, the higher order terms contribute to the spurious nonlinear component. This is consistent with the analysis of [97] which showed that the 2nd and 3rd order terms or receive chain induced nonlinearities are the most significant distortion components with transmit powers above 10 dBm. Furthermore [92] shows that only the odd orders of the polynomial contribute to the in-band distortion. Accordingly, equation (1) can be simplified and written in the digital baseband as:

$$y_q=\sum_{p=1}^{P}\beta_p\Gamma_{\mathrm{q}}\left|\Gamma_{\mathrm{q}}\right|^{p-1} \tag{2}$$

Where, Γ_{q} and y_q are the digital base-band representation of the input and the output of the nonlinear component and P is odd.

To model the nonlinear distortion of the active analogue circuit, the Memory Polynomial (MP) model with even order nonlinear terms is used. The MP model can be described as [98]:

$$y_{AC}\left[n\right]=\sum_{k=0}^{K-1}\sum_{q=0}^{Q-1}w_{kq}x\left[n-q\right]\left|x[n-k]\right|^k \tag{3}$$

where, $y_{AC}[n]$ is the analogue circuit model output, K is the order of nonlinearity, and Q is the depth of memory length.

The multipath SI channel between the transmitter and the receiver can be modelled with a Finite Impulse Response (FIR) filter as [89], [57], [98], [99]:

$$y_{SI}\left[n\right]=\sum_{m=0}^{M-1}h_mx\left[n-m\right] \tag{4}$$

where, $y_{SI}\left[n\right]$ is the SI signal, h_m is the m-th filter coefficient of the equivalent digital FIR representing the channel.

The received signal after the active analogue circuit can be written as:

$$\begin{aligned}
&y_{RA}\left[n\right]\\
&\quad=y_{SI}\left[n\right]-y_{AC}\left[n\right]\\
&\quad=\sum_{m=0}^{M-1}h_mx\left[n-m\right]-\sum_{k=0}^{K-1}\sum_{q=0}^{Q-1}w_{kp}x\left[n-q\right]\left|x[n-k]\right|^k
\end{aligned}$$

$$= \sum_{k=0}^{K-1}\sum_{p=0}^{P-1} \bar{\varpi}_{kp} x\left[n-p\right] \left|x[n-p]\right|^{k} \tag{5}$$

where, $P = \max\{M, Q\}$ is the memory depth of the model after active AC cancellation, $\bar{\varpi}_{0p} = h_p - w_{0p}$ and $\bar{\varpi}_{kp} = -w_{kp}$ for $k > 1$ are the model parameters.

Therefore the overall SI signal model comprising the AC nonlinearity and the multipath SI channel can also be expressed as a MP model.

To mitigate the effects of nonlinearities to SI cancellation, [97] proposes a solution which involves two active SI cancellation stages after passive suppression. An RF cancellation is first performed at the input of the receiver chain by subtracting the transmitted signal from the received signals followed by an additional SI cancellation in the baseband (digital domain) which estimates the SI signal channel and regenerates it based on the estimate. The idea behind this is increasing the precision of the regenerated SI signal, thus increasing the amount of achievable digital SI cancellation when operating with practical nonlinear RF components.

V. SELF-INTERFERENCE MANAGEMENT ISSUES FOR MULTI-ANTENNA SYSTEMS

A. OTHER FORMS OF INTERFERENCE FOR FULL DUPLEX MIMO OPERATION

In addition to the devastating SI, FD introduces other forms of interference within the network. Whereas FD concept is able to improve spectrum efficiency, in a multi-cell scenario, for example, HetNets, multi-access and multi-user interferences are introduced [3]. Apart from SI and the co-channel interference prevalent in HD systems, there are the two major sources of interference introduced to a multi-antenna HetNet due to FD operation namely; UE-UE interference and BS-BS interference.

1) UE-UE INTERFERENCE

this type of interference is prevalent in smaller cells than large cells and depends on the UE locations and their transmission powers. When the UEs have FD capability and share same radio resources, the uplink UEs will interfere with the downlink UEs. To mitigate this type of interference, intelligent scheduling and coordination mechanism are required. The goal of the coordination is to select those UEs for simultaneous transmission such that their rate as well as power allocation would create less interference for each other and extract the capacity gain potential of FD operation [11].

2) BS-BS INTERFERENCE

next generation networks will be driven on the strength of dense networks. As more and more cells are introduced, the more inter-cell interference challenge is introduced. This becomes even more complex with FD capability. For instance, due to simultaneous transmission and reception at the BS, adjacent BS downlink signals would always interfere with the UL signals in the home BS, resulting to BS-BS interference. Techniques to mitigate BS-BS interference are necessary to realize FD BS deployment. Reference [11] with FD enabled at the BS of a cellular network for instance, BS-BS interference becomes an extremely serious issue capable of overwhelming weak UL signals and resulting in serious loss of UL capacity. This makes it imperative that effective SI management scheme should seek to mitigate this source of additional interference.

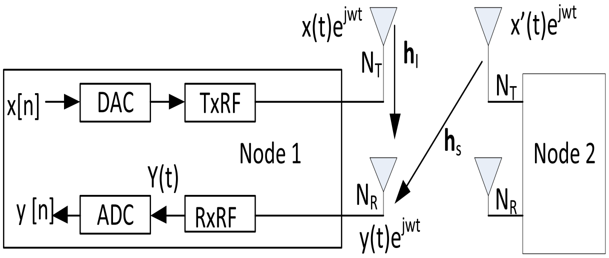

FIGURE 9. Full duplex system model.

B. MODELLING PERSPECTIVE OF SELF-INTERFERENCE FOR MULTI-ANTENNA SYSTEMS

Modelling the SI signal is perhaps the most crucial task of an in-band FD transceiver. Generating an accurate cancellation signal is required both in the RF and digital domains, or else the level of the residual SI will be too high for efficient communication. The general structure of the considered FD transceiver is shown in Fig. 6, where the basic operating principles of the different SI cancellation stages are also shown.

Considering an FD system model as shown in Fig. 9, each node is equipped with N_T transmit antennas and N_R receive antennas, respectively. If $\mathbf{HH}_{\mathrm{s}}$ is the $N_R \times N_T$ matrix of channel gains from the N_T antennas of the j-th node to the N_R antennas of the i-th node$(i \neq j)$, then the SI matrix of the channel gains for the i-th node, $\mathbf{HH}_{\mathrm{I}}$ can be given as: $N_R \times N_T$. If we consider a SISO system, the received signal at node 1 will be given as:

$$\mathbf{y}\left(t\right) = \mathbf{H}_{\mathrm{s}}\mathbf{x}^{'}\left(t\right) + \mathbf{H}_{\mathrm{I}}\mathbf{x}(t) + \mathbf{z}(t) \tag{6}$$

Where, the first term represents the signal of interest, the second term represents the interfering signal and $\mathbf{z}(t)$ is the additive white Gaussian noise at the receiver. After quantisation, the received signal can be rewritten as:

$$\mathbf{y}\left(n\right) = \mathbf{H}_{\mathrm{s}}\mathbf{x}^{'}\left(n\right) + \mathbf{H}_{\mathrm{I}}\mathbf{x}(n) + z(n) \tag{7}$$

If the SI is completely eliminated by using an estimated channel defined by $\Delta\mathrm{H}_{\mathrm{I}}$ in (8), then the received signal at node 1 will be:

$$\begin{aligned} \mathbf{y}\left(n\right) &= \mathbf{H}_{\mathrm{s}}\mathbf{x}^{'}\left(n\right) + \mathbf{z}(n) \\ \Delta\mathbf{H}_{\mathrm{I}} &= \mathbf{H}_{\mathrm{I}} - \mathbf{H}_{\mathrm{I}}{'} \end{aligned} \tag{8}$$

Therefore with active cancellation, equation (6) omitting the discrete function [n] can be rewritten as:

$$\mathbf{y} = \mathbf{H}_{\mathrm{s}}\mathbf{x}^{'} + \left(\mathbf{H}_{\mathrm{I}} - \mathbf{H}_{\mathrm{I}}^{'}\right)\mathbf{x} + \mathbf{z} \tag{9}$$

which is the received analogue signal at node 1 after cancellation. We can therefore define the unwanted residual SI signal at node 1 as:

$$\mathrm{y}_{1\mathrm{res}} \left(\mathbf{H}_{\mathrm{I}} - \mathbf{H}_{\mathrm{I}}^{'} \right) \mathbf{x} + \mathbf{z} \tag{10}$$

Where, $\mathrm{y}_{1\mathrm{res}}$ is the leaked unwanted residual signal from node 1 transmitter and $\mathbf{H}_{\mathrm{I}}^{'}$, is an exact image of the transmit channel.

For a multi-antenna scenario, we model the received signal according to [100] utilising pre-coding and decoding matrices to process the SI in order to mitigate the negative effects of SI. Let $\mathbf{UH}_{\mathrm{i}}$ given as $N_T \times d_i$ and $\mathbf{VH}_{\mathrm{i}}$ given as $N_R \times d_i$ be the pre-coding and decoding matrices for the i-th node respectively, then the signal received at the i-th node can be written as:

$$\mathrm{y}_{\mathrm{i}} = \mathbf{V}_{\mathrm{i}}^{\dagger}\mathbf{H}_{\mathrm{sj}}\mathbf{U}_{\mathrm{j}} + \mathbf{V}_{\mathrm{i}}^{\dagger}\mathbf{H}_{\mathrm{Ii}}\mathbf{U}_{\mathrm{i}}\mathbf{x}_{\mathrm{i}} + \mathbf{V}_{\mathrm{i}}^{\dagger}\mathbf{z}_{i} \tag{11}$$

Where, $\mathbf{x}_{\mathrm{i}}$ $(d_i \times 1)$ is the vector of transmitted signals for the i-th node and $\mathbf{z}_i$ $(d_i \times 1)$ is the noise at the i-th node. Whereas the first term represents the desired signals at the i-th node, the second term represents the SI signals suffered by operating in FD mode. For the i-th node receiver, If we let the covariance matrices of the direct channel representing the desired signals be given by $\mathbf{W}_{i,j}$ and the SI signals be given as $\mathbf{W}_{\mathrm{i,i}}$, then before adding the decoding matrix we can write:

$$\begin{aligned} \mathbf{W}_{\mathrm{i,j}} &= \mathbf{H}_{\mathrm{sj}}\mathbf{U}_{\mathrm{j}}\mathbf{P}_{\mathrm{j}}\mathbf{U}_{\mathrm{j}}^{\dagger}\mathbf{H}_{\mathrm{sj}}^{\dagger} \\ \mathbf{W}_{\mathrm{i,i}} &= \mathbf{H}_{\mathrm{Ii}}\mathbf{U}_{\mathrm{i}}\mathbf{P}_{\mathrm{i}}\mathbf{U}_{\mathrm{i}}^{\dagger}\mathbf{H}_{\mathrm{Ii}}^{\dagger} \end{aligned} \tag{12}$$

Where, $\mathbf{P}_i = \left\{ \mathbf{x}_i\mathbf{x}_i^{\dagger} \right\}$. The achievable rate i-th node assuming unitary decoding matrices will therefore be written as:

$$\mathbf{R}_i = log_2 \left[\left[\mathbf{I}_{\mathrm{NR}} + \left(\Gamma_{\mathrm{i}} + \mathbf{W}_{\mathrm{i,i}}\right)^{-1} \mathbf{W}_{\mathrm{i,j}} \right]\right] \tag{13}$$

where, $\Gamma_{\mathrm{i}} = \left\{ \mathbf{z}_i\mathbf{z}_i^{\dagger} \right\}$.

To be able to solve the above equations and use the achievable rate equations, it is important to correctly model the SI channel. In the SI Pricing approach for SI management, [100] made use of pre-coding and decoding matrices to process the SI in order to minimise its effects. To achieve this, the authors estimated the SI channels while assuming that the forward channels are perfectly known. Again, in presenting advanced SI cancellation in a MIMO system, [97] considered a MIMO FD transceiver model through two active SI cancellation stages in addition to passive schemes. At the input of the receive chain, an RF cancellation, where the transmitted signals is subtracted from the receive signal is performed. A further SI cancellation is performed in the digital domain beyond the actual receive chain. This is achieved by estimating the SI signal and then regenerating it based on the channel estimate. However, for the scope of this survey, we do not intend doing an in-depth modelling of SI channels for an FD-MIMO system.

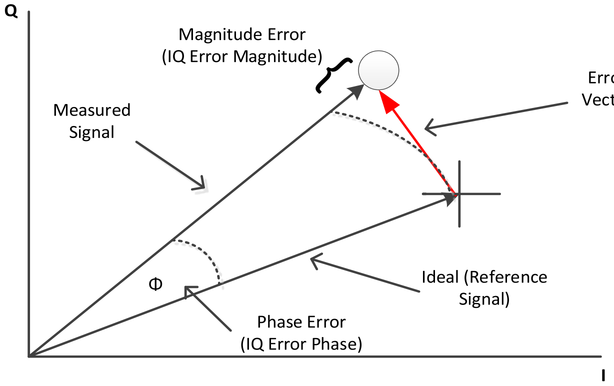

FIGURE 10. Error vector magnitude.

C. AMOUNT OF SELF-INTERFERENCE CANCELLATION REQUIRED FOR FULL DUPLEX OPERATION

The fundamental challenge of full duplexing centers on the isolation of the transmit path from the receive path to a level which ensures that the transmit signal acting as a source of SI does not affect the receivers' sensitivity. Such huge level of required transmit-receive isolation (in the order of 100 dB) [7] is much larger than the isolation level needed even for decoupling of MIMO antenna system. As already mentioned, SI is made up of the linear components, the nonlinear components and the transmitter noise. Choi and Shirani-Mehr [11] describe the SI – the leakage of transmitted signal in to the receive chain - as echo. Without the cancellation of this echo and other echoes that might result as a result of impedance mismatch at the antenna and the reflections from the surrounding obstacles, the desired signals may not be properly decoded at the receiver. A big component of that echo is EVM [68]. EVM (the difference between the error vector and the measured symbol as depicted in Fig. 10 is the Root Mean Square (RMS) magnitude of the error vector between the received constellation points and the corresponding ideal constellation points. Simply put, it is the magnitude of phase difference as a function of time between an ideal reference signal and the measured transmitted signal. EVM represents a single metric / number used to describe the degradation of the transmitted signal due to several transmitter impairments (such as phase noise, I/Q imbalance, amplitude distortion, phase distortion and thermal noise) already discussed [68]. EVM has a great impact on the required amount of SI cancellation and subsequently on FD as EVM at the local transmitter may raise the noise floor at the local receiver thereby lowering the sensitivity of the receiver.

To effectively isolate, the transmit signal from leaking into the receive path, it is important to provide interference cancellation beyond the noise floor. Noise is an ever present factor in wireless communication systems. It deteriorates the receive signal quality and degrades throughput in digital systems [27]. It is known that for a communication system to achieve FD, the radio has to cancel the self-destruct signal that leaks from within its' transmit chain to the receive chain. In other words, for a receiver to detect an RF signal, the power of the receive signal has to be up to the receiver's sensitivity and equal to or more than the noise floor for a good system performance. Noise cancellation has proven to be a herculean task. For instance [101] attempted cancelling noise components in the digital domain, but could not arrive at a good performance level. This is because noise cancellation in the digital domain do not have high enough resolution in the approach employed. The noise floor of a wireless system is the summation of all unwanted signals, including noise and the signals generated within the system. Though the receivers' sensitivity is independent of the transmitter, it is directly proportional to the noise floor.

Given a reference bandwidth B (Hz) and Temperature T_o (K), the noise power can be calculated as

$$N = F\left(KT_o\right)B$$

Then the output noise is given as

$$N_{out} = FKTB \tag{14}$$

Assuming a perfect amplifier, i.e., $F = 1$, and using the above, the output noise power received at the receiver at the room (noise) temperature (290K) is given as −174 dBm/Hz. The in-band receiver noise floor is then calculated as:

$$P_n = -174\left(\frac{dBm}{Hz}\right) + NF\ (dB) + 10\log[B\ (Hz)] \tag{15}$$

where, F is the noise factor defined as the ratio of input SNR to the output SNR, NF is the noise figure, K is the Boltzmann constant (given as $1.38 \times 10^{-23} J/K$), and W is the system bandwidth.

For instance as shown in [7], using the calculation above, assuming a system bandwidth of 80 MHz, a transmit power of 20 dBm and a noise figure of 5 dB, we realise that the noise floor is −90 dBm implying that to enable FD operation in a WiFi system a SI cancellation of $20\ dBm\ (-90\ dBm) = 110\ dB$ is required. Similarly, without loss of generality and ignoring receiver noise figure, we present the SI cancellation required to enable FD operations in several technologies and generations of wireless communications systems in Table VI.

D. MIMO-BASED SELF-INTERFERENCE MANAGEMENT SCHEMES

In an FD MIMO systems, there are several transmit and receive antennas operating simultaneously in a transceiver. In this scenario, the total loopback signal or SI signal coupling to a singular receiver is a summation of all the transmitted signals from the various transmit antennas. Unlike the SISO systems, there are a number of other issues associated with MIMO systems which impacts the capability for SI cancellation techniques in a MIMO setup. These include: antenna coupling, frequency offset, synchronisation error, etc. [25] explores three approaches for improving the SI mitigation capabilities in FD MIMO systems. These includes natural isolation, time-domain cancellation and spatial suppression.

1) PRECODING-BASED ISOLATION

Precoding-based isolation techniques for the FD MIMO systems are implemented by employing signal processing techniques in providing additional isolation of the transmit and the receive chain. This is different from the physical separation discussed under passive suppression. For instance, Anderson *et al.* [33] presents precoding-based antenna isolation techniques using separated transmit and receive antenna arrays for FD MIMO aided relays. This technique was extended further in [102] and [103] where the antennas of an FD aided relay are partitioned to let some of the relay antennas transmit while the others receive. This essentially introduces obstacles in the line-of-sight by either adding a shielding plate or exploiting surrounding structures and buildings [18]. Achieving isolation via precoding has also been achieved by exploiting antenna directionality and making antenna elements orthogonal [18], [33], [102]. A more practical application of precoding in achieving natural isolation has been implemented by using same antenna array with a duplexer for STR. To ensure isolation is achieved, the duplexer is connected to the antenna array which splits the input and the output feeds [104].

2) TIME-DOMAIN MITIGATION

This technique is implemented on the assumption that the FD device is able to estimate its transmitted signal and the loopback signal fairly accurately [18], [25]. To do this it has to have full knowledge of the transmitted signal to be able to replicate a mirror image signal that can be used to cancel out the SI signal. For analog cancellation, Time Domain (TD) cancellation algorithms such as training-based methods can be used in both SISO and MIMO scenarios. The TD methods can be beneficially utilized for loopback signal leakage estimation as well as reliable SI cancellation. Everett *et al.* [105] present a relay recorder with prior knowledge of the interference sequence employing time-orthogonal training in enabling a structured SI cancellation in time domain. The structured SI cancellation technique enables the FD device to estimate the TX-RX signal leakage path using the knowledge of its own transmit signal. Again, for replicating the loopback signal, [106] used time-orthogonal-training-based algorithms. However both training methods are susceptible to system noise and channel estimation errors which in effect degrade the SI performance, especially in FD-MIMO systems [25].

3) SPATIAL-DOMAIN MITIGATION

This technique makes use of the spatial dimensions for receive and transmit filtering thus offering an extra degree of freedom. This is a particularly useful technique for multi-antenna systems where spatial domain could offer multiple antenna systems a whole new range of SI cancellation solutions [107]. SI mitigation in the spatial domain is implemented using several schemes, which for this survey we do not intend to present in great details. Some of these as already

TABLE 6. Amount of Self-Interference that needs to be cancelled to enable full duplex operation.

Generations	Technologies / Access Technology	Channel Bandwidth	Transmit power	Noise power	Required SI cancellation
1G	Advanced Mobile Phone Service (AMPS) (Frequency Division Multiple Access (FDMA))	30 KHz	Up to 60 dBm	-129 dBm	189 dB
2G	Global Systems for Mobile Communications (GSM) (Time Division Multiple Access (TDMA))	200 KHz	36 dBm	-121 dBm	157 dB
	Code Division Multiple Access (CDMA)	1.25 MHz	48 dBm	-113 dBm	161 dB
2.5G	General Packet Radio Service (GPRS)	200 KHz	39 dBm	-121 dBm	160 dB
	Enhanced Data Rate for GSM Evolution (EDGE)	200 KHz		-121 dBm	
3G	Wideband Code Division Multiple Access (WCDMA) / Universal Mobile Telecommunications Systems (UMTS)	5 MHz	43 dBm	-107 dBm	150 dB
	Code Division Multiple Access (CDMA) 2000	1.25 MHz		-113 dBm	156 dB
3.5G	High speed Uplink / Downlink Packet Access (HSUPA / HSDPA)	5 MHz	43 dBm	-107 dBm	150 dB
	Evolution-Data Optimised (EVDO)	1.25 MHz		-113 dBm	156 dB
3.75G	Long Term Evolution (LTE) (Orthogonal / Single Carrier Frequency Division Multiple Access) (OFDMA / SC-FDMA)	20 MHz	46 dBm	-101 dBm	147 dB
	Worldwide Interoperability for Microwave Access (WIMAX) (Scalable Orthogonal Frequency Division Multiple Access (SOFDMA) Fixed WiMAX	10 MHz		-104 dBm	150 dB
4G	Long Term Evolution Advanced (LTE-A) (Orthogonal / Single Carrier Frequency Division Multiple Access) (OFDMA / SC-FDMA)	20 MHz	46 dBm	-101 dBm	147 dB
	Worldwide Interoperability for Microwave Access (WIMAX) (Scalable Orthogonal Frequency Division Multiple Access (SOFDMA) Mobile WiMAX	10 MHz	43 dBm	-104 dBm	150 dB
5G	Beam Division Multiple Access (BDMA) and the non-and-quasi-orthogonal or Filter Bank Multi-Carrier (FBMC) multiple access	60 GHz	20 dBm	-96 dBm	116 dB
	802.11ac - Gigabit Wi-Fi (taunted as 5G Wi-Fi)	20, 40, 80, 160 MHz		-91 dBm	112 dB
	802.11ad - Wireless Gigabit (Microwave Wi-Fi)	2 GHz		-81 dBm	101 dB
	802.11af – White-Fi	5, 10, 20, 40 MHz		-98 dBm	118 dB

discussed in [25], [58], and [102] include:

- Antenna Subset Selection – which involves a joint transmit and receive filter design found by calculating the Frobenius norm for all transmit and receive antenna array combinations and selecting the set with least residual SI strength.
- Null-space projection – in the null space projection the precoding and decoding matrices from the Singular Value Decomposition (SVD) of the SI channel is selected such that the FD MIMO device is able to direct the receive and transmit in different orthogonal subspaces.
- Joint Eigen beam Projection – joint transmit and receive Eigen beam selection is based on the SVD of the loopback signal. This can be achieved by minimising the power of the SI signal by pointing the transmit and receive beams to the minimum Eigen modes of the loopback (SI) channel. This is called optimal Eigen beamforming [25]. Intuitively, the optimal joint beam selection can be solved by testing all the TX-RX array combinations just as with antenna subset selection. This FD assisted multi antenna SI suppression scheme is capable of extending the coverage area and increasing the rate [108].

VI. CHALLENGES OF SELF-INTERFERENCE MANAGEMENT IN MULTI-CELL WIRELESS COMMUNICATION SYSTEM

The SI caused by the coupling of the transceivers' own transmit signal to the receiver while trying to receive signal sent by another equipment in a cellular network has been a key challenge that has made cellular systems largely avoid the use of FD in the past. As is hugely evident in literature, FD systems hold impressive promise for the next generation of cellular networks. The scope and potential applications of FD in cellular systems include: FD relays [44], [108], FD connection in small cells [17], re-use of radio resources with FD transmission, device–to–device (D2D) connection with FD, connection for cellular backhaul with FD, and FD

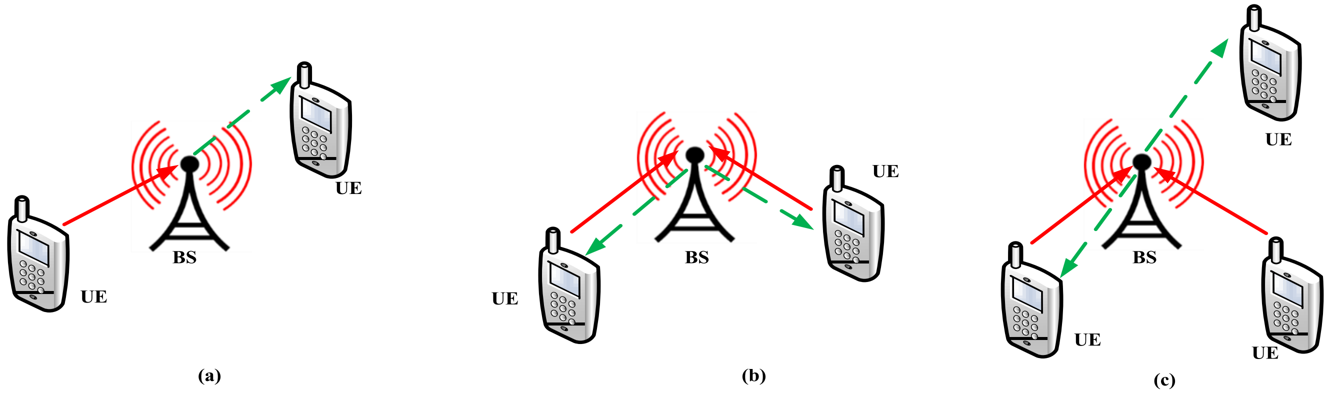

FIGURE 11. Full duplex network deployment scenarios.

transmission in wireless mesh networks. Efforts are currently made on further research for application of FD systems on small cells for cellular networks, ad-hoc and mesh networks and UE relay and wireless cellular backhaul in public safety networks [6], [7], [10], [11], [72]–[74]. This section focuses on relay networks and multi-cell networks which are generally composed of small cells.

A. FD RELAY NETWORKS

Earliest instances of FD systems in cellular networks came in form of relaying, where in-band repeaters as a way of improving coverage and throughput of cellular networks, receive, amplify and re-transmit signals on same frequency [10], [66], [75], [77]. Radio-based FD relay (FDR) is a promising energy and spectral efficient technology for high speed data services [44]. While capable of improving the service quality of users within its service range, it can also improve the link capacity of users within its service range. Most existing works on relays have been done on HD mode. This owes largely to its simplicity of implementation. However, implementing relay systems in HD mode requires extra dedicated resources which leads to inefficiency in radio resources use. Because of its good performance in challenging terrains like tunnels, FD-capable relay system is a prospective component of future FD enabled cellular networks capable of resource conservation in contrast to HD relay systems where additional frequency or time slot is usually dedicated for relay transmissions. The primary challenge for FDR systems remains how to mitigate the strong SI and residual SI, especially in small devices scenario. Several proposals on the implementation of same frequency FDR have been made by the Institute of Electrical and Electronic Engineers (IEEE) and the 3GPP [110], but the implementation still faces strong challenges including form-factor issues, security, channel modelling and estimation, joint radio resource management and SI management.

Traditionally, HD relay (HDR) systems are usually employed in wireless communications. This does not help the issue of spectrum scarcity. In order to improve the offering from relay systems including achieving spectral efficiency benchmarked against the traditional HDR, several relaying schemes have been studied and reported in [66], [77], and [110]. Because the focus of this paper is not on relay systems, we shall only mention these schemes. They include: successive relaying, two-way relaying, buffer-aided relaying, frame-level virtual FD relaying, out-band FD relaying and IBFD relaying.

B. CHALLENGES OF SIC IN A FULL DUPLEX MULTI-CELL NETWORK

Enabling FD in wireless networks will technically be more feasible in HetNets comprising different cell sizes (pico cells, femto cells, metro cells, micro cells and macro cells) and different nodes (relays, remote radio heads, eNodeBs and mobile devices) with different capabilities. Enabling FD in cellular networks can be done under the following different single-tier (we purposely left multi-tier network for simplicity of explanation) network deployment scenarios depicted in Fig. 11. The BS as represented in the diagrams are FD enabled as such have same frequency in both directions.

1) FD ENABLED BS AND HD ENABLED UE

This scenario involves deploying an FD capable BS and HD enabled MTs. In this scenario as shown in Fig. 11(a), the FD BS is able to simultaneously communicate with both the DL and the UL users with the former receiving data from the BS and the later transmitting data to the BS. The challenges of this scenario include: accurately measuring co-channel interference at different nodes and backhauling it to the BS, user-scheduling for maximum gain and effectively managing additional interference caused by leakages from signals transmitted from neighbouring bands.

2) FD ENABLED BS AND FD ENABLED UE

In this scenario shown in Fig. 11(b), both the BS and the UE are FD enabled with the BS expected to constantly establish FD links to scheduled UEs. This scenario holds prospects for a no co-channel interference situation and holds potential for doubling the overall spectral efficiency compared to the traditional HD only systems, since the BS is simultaneously

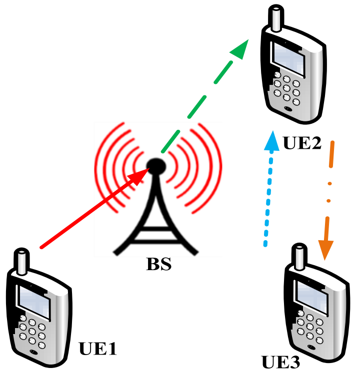

FIGURE 12. A small cell with FD BS and FD D2D UEs.

transmitting and receiving. This could ultimately be the future implementation of FD wireless communication. However SI on the BS and also on the UE threatens to dominate performance. Just like in the scenario described in Fig. 11(a), this scenario induces inter-user interference which is not obtainable with HD only systems. In this case the UL transmission causes interference to the DL reception and in cases of strong inter-user interference in the system even with SI mitigated, this problem can easily erode the gains of FD if not properly mitigated.

3) FD ENABLED BS WITH BOTH FD AND HD ENABLED UES COEXISTING

This scenario has been identified as a futuristic prospect for FD cellular systems where an FD BS serves both FD and HD UEs all coexisting in same cell. As shown in Fig. 11(c), an FD BS serves a mix of users some of which are capable of simultaneous transmit and receive on same radio resources and others operating as traditional HD terminals which could only transmit on an UL frequency and receive on a different DL frequency or use different time slots to accomplish their UL and DL transmissions.

4) FD D2D COMMUNICATION

A D2D communication involves the source and destination devices exchanging data with each other without the involvement of the base station, though could be supported by the base station for link information [111]. The idea behind this scenario is the ability of two users to communicate as FD devices on the unused macro resource if none of their neighbours are using it. As illustrated in Fig. 12, if UE2 and UE3 are FD enabled, they could reuse UE1's UL resources for their FD communication. Also, the D2D performance between them could be improved. A different Radio Resource Allocation (RRA) method could see UE2 reusing its macro DL resources for its transmission to UE3 whereas UE3 uses UE1's macro uplink channel for its transmission to UE2 [7].

VII. LESSONS LEARNT, OPEN RESEARCH ISSUES AND FUTURE DIRECTION

In this section we present the lessons learnt from surveying the different SI management schemes. These then form the basis for the directions and likely challenges for future work for implementing appropriate SI mitigation scheme with less complexities and costs but capable of enabling single frequency FD systems in the mobile wireless networks.

A. LESSONS LEARNT

1) The evolution of future networks tends towards small cells, ad-hoc and mesh networks in a dense environment. A network comprising of small cells having the capability for connecting users to the base station and supporting STR could greatly improve the SE of the system. However, this throws up several other sources of interference apart from SI. One of the things that we have learnt is that there is not a single fully operational system that has incorporated the increased effects of co-channel, multi-cell, and SI due to FD operation.

2) No single method is all sufficient. Work done so far suggests that a hybrid combination of passive suppression and active cancellation could prove more effective for SI management in FD systems. Literature also has it that the effectiveness of digital cancellation has a reliance on analogue cancellation. For instance, with Double Talk technique in SatCom, a cancellation of 30-35 dBm achieved with DSP in the 'back-end' is not enough to enable FD operation. In essence, this must be augmented by careful and ingenious front-end analogue design to provide the requisite extra interference cancellation. Again, none of the solutions seem to have adequately nailed that trade off or equilibrium level that defines a cost effective balance of passive suppression and active cancellation for effective SI management. For efficient Digital SI cancellation, there should be an effective analogue design and cancellation.

3) Sufficient Passive Suppression methods only may be difficult to attain. Especially with small form factor devices, it is difficult achieving a reasonable TX-RX isolation capable of enabling FD functionality.

4) Frequency dependent solutions may not aid digital cancellation schemes especially in MIMO systems. The fact that most RF components are frequency sensitive, designing a one-fits-all solution for frequency varying circuits is a challenge, especially in wideband scenarios.

5) SI cancellation in MIMO systems suffers the inherent problems with MIMO multi antenna issues. MIMO already has the challenges posed by antenna coupling, synchronization error and frequency offset. These challenges becomes even more pronounced in FD-MIMO system making it more difficult for SI management.

6) Transmitter noise induced distortion in an FD receiver is an important factor that impacts the SI cancellation capability of the system. For any efficient cancellation scheme, it is important to model the linear, nonlinear components and understand EVM impact for more efficient antenna design. A good example is the SI mitigation technique in SatCom requiring an on-board relay system. The noise generated by the receiver systems on both the uplink and downlink directions is as equally important as the SI channel.

7) Though there is minimal isolation problem with satellite systems compared to the very formidable isolation issue with the terrestrial systems, the power imbalance in SatCom system is enormous. Whereas studies have demonstrated the possibility of mitigating the SI using the on-board relay system in satellites, to realise FD satellite system, further comprehensive investigation need to be carried out to study the practicality of estimating the on-board SI channel to a high accuracy.

B. SELF-INTERFERENCE MANAGEMENT IN SMALL FORM-FACTOR DEVICES

Most of the state-of-the-art SI mitigation schemes focus on small form-factor devices e.g., as shown in Table VI. For instance, DUPLO project, like many others target small cell scenarios implying that FD transceiver designs must consider small form-factor devices which support integration into commercially viable compact radio devices. Whereas the idea behind this can hardly be faulted, first because most devices operating on wireless communication networks (e.g., smart phones, some relay systems, etc.) are of small sizes and second and importantly because future networks are targeting small cells. Antenna miniaturization (antenna size reduction) suffers extremely limited bandwidth and other technical difficulties due to space and shape constraints. As already noted, relay systems are mostly of a small form-factor size and to be able to enable FD in such systems further research needs to be done. Furthermore, most schemes reported in literature are implemented within the propagation and active analogue-domain spheres. This makes it a challenge having the required space for isolation that could enable FD as well as enough space for the analogue circuits. A possible future direction in addressing miniaturization of the antenna systems could be investigating the possibility of a planar antenna device capable of doing FD both on small form-factor devices but which could also be integrated on larger microwave and, or millimeter-wave solutions.

C. IMPROVING THE HARDWARE CIRCUITRY AND CHANNEL MODELLING

In theory, FD can potentially double the spectral efficiency of a communication system. This is however feasible if the system has infinite dynamic range, perfect channel estimation and is able to perfectly suppress SI signal. This prospect is threatened by hardware limitations including transceiver signal quantisation, I/Q imbalance and nonlinearities. As already pointed out in the work of [7], the analogue 10x10 cm PCB design is capable of cancelling the SI generated in a WiFi network up to the noise floor including the linear, nonlinear and transmitter noise components. However, it only supports SISO scenarios. To introduce this solution to the multi-antenna systems, an analogue chip that is able to cancel distortions across multiple antennas and capable of dynamic adaptation in terms of changing environmental conditions needs to be developed. Carrying out SI mitigation increases both the complexities and cost of FD devices. A SI cancellation solution for MIMO will often require extra analogue circuitry with more power consuming components. It is therefore noteworthy to balance power consumption, and cost against SI management performance when designing the SI cancellation circuitry. Finding that point of balanced tradeoff between SI cancellation and the associated cost of hardware required to accurately deliver improved SI cancellation is a huge challenge. Moreover the strength of digital-domain cancellation relies on the systems' knowledge of the CSI both on the transmitter and the receiver side. Not many studies have done an actual characterization of the SI channel, as most have assumed SI follows Gaussian distribution, Rayleigh distribution or Nakagami–m distribution [3]. It will be interesting besides designing a more efficient circuitry, modelling accurate and effective channels that capture the residual SI, and the distortions introduced in the channel by the transceiver in the mold of the hybrid analogue-digital design proposed in [7] which accurately model all the linear, nonlinear distortions as well as the transmitter noise.

D. IMPLEMENTING SELF-INTERFERENCE CANCELLATION IN FD MIMO SCENARIOS

The simple fact that the capacity of a MIMO system grows linearly with the minimum of the number of transmit or receive antenna without needing extra radio resources shows that the performance of a cellular network can be improved by employing multiple antennas. However, antenna systems in MIMO systems suffer from coupling and synchronization error as well as cross talk when the antenna modules are placed so close to each other. For instance, the work of [7] seems to be holistic in mitigating SI up to the noise floor, albeit for SISO systems. Whereas the general design of the system is not frequency dependent, most of the components used within the analogue circuitry are frequency dependent and can only work well in a given frequency range. The design targeted only SISO scenarios which effectively makes it impractical to enable FD in MIMO scenarios using the technique described. Extending their work to MIMO scenarios, never mind massive MIMO will require a novel design to handle cross talks and other distortions coming from closely arranged MIMO antenna modules and hardware impairments. It is obvious that active cancellation mechanism relies substantially on the precision of cancellation signal. Therefore the hardware impairments such as phase noise and I/Q imbalance limit the cancellation performance. It is therefore imperative that as a future direction the design of a comprehensive model incorporating the different hardware impairments capable of coping with the transmitter noise difficult to compensate for in the baseband [46] is pursued. This in turn will require an accurate mathematical modelling and statistical characterisation of the SI channel to serve as the basis for performance-matrix analysis, e.g., achievable rate, as well as system design. In view of this, a future direction would be investigating the impact of antenna correlation, antenna non-linearity, effects of synchronization error, gain /phase offset, carrier offset, In-phase Quadrature (I/Q) imbalance and other non-idealities within the baseband receiver in enabling FD in MIMO systems.

E. RADIO RESOURCE MANAGEMENT AND MULTI-USER DIVERSITY SCHEMES

FD technology definitely offers extra degree of freedom by allowing the whole spectrum to be used in both forward and reverse transmission direction. This will sure increase the available multiuser diversity in the communication systems. It is important to note that SI may not be fully mitigated when performing resource allocation. Therefore, to fully harvest the increased multiuser diversity and address the SI problem, new multiple access techniques needs to be proposed and evaluated. These should be such capable of supporting different duplexing scenarios such as point-to-point FD and point-to-multipoint FD scenarios. Again, designing radio resource management algorithms that take into account the features of FD are essential to improving the multiple access techniques.

Resource management plays important roles in energy efficiency spectrum efficiency and quality of service provisioning [112]. Since SI is involved in FDR networks, how to dynamically allocate the space-time-frequency resources becomes even more important and challenging than in the traditional wireless networks. Take beamforming for example, while one can electronically steer transmit and receive weight of different antenna elements for the purpose of SI mitigation, this may also unintentionally reduce the power radiated on the desired signals and hence degrade the system performance / service quality. Similar phenomenon exists in other resource allocation processes, such as power allocation, antenna selection and relay node selection. Therefore effective resource management approaches should balance the performance of SI mitigation and other systems measures.

Though it is easy to infer from literature that so much work is being done in designing and implementing FD capable devices and systems, the impact of FD on the capacity and the energy of heterogeneous networks have not be sufficiently analysed. Whereas some work have been done regarding resource management and SI management such as [113] which evaluated FD operations in a small cell cellular scenario by implementing a joint UL and DL beamforming for a single cell and [114], which studied a joint radio resource allocation for the UL and DL in an FD system, there still exists some gaps. For example, while the work of [114] considered a non-cooperative power allocation algorithm, the DUPLO experiment did not consider the multi-user diversity gain that could be derived by appropriate power adjustments and user scheduling. Not only is this approach suboptimal, the paper did not take into account the inter-user interference generated in the system when a user is allowed to increase its power arbitrarily and its impact on the SI cancellation capability of the system. An effective resource management approach which is capable of SI mitigation while deriving the gains of FD without degrading the system performance remains a challenge yet to be resolved. These possibilities could steer a future direction.

F. IMPLEMENTING COST EFFICIENT SPATIAL DOMAIN SOLUTIONS

Separating transmit and receive antennas in space presents a simple SI passive suppression scheme, especially for SISO systems. However, implementing spatial-domain suppression schemes for MIMO systems come with an extra complexity burden capable of limiting the SI mitigation ability of the system. This results from the very complex matrix computations required in this scenario. As a future direction for achieving FD in wireless networks, it is imperative that more cost-efficient spatial domain SI suppression algorithms for MIMO channels have to be designed.

G. INTERFERENCE MANAGEMENT IN HETEROGENEOUS NETWORKS

Future networks with dense heterogeneous cells presents multiple sources of interference in addition to SI which in turn presents a challenge to SI management and makes the implementation of FD more complicated. This situation is made worse in a heterogeneous multi-tier, multi-cell hierarchical structure where as the number of small cells increase, so also are there multiple sources of inter-cell interference, BS-BS interference as well as UE-UE interference in cases where the user terminal is also FD enabled with a reuse factor of one. In this case, radio resource management increasingly becomes complex and challenging. Whereas the prospect for increased SE exists, this will only be obtained using an efficient radio resource management scheme and effective power allocation scheme. Finding this practical balance between system performances against the performance of SI management schemes is an interesting future direction.

VIII. CONCLUSION

This article discusses the state-of-the-art on SI mitigation schemes for enabling single frequency FD networks. The benefits of FD systems over HD systems are huge. FD systems are capable of potentially doubling the spectral efficiency of the network. However, the major challenge hampering the implementation of this technology in practical mobile communication systems is the very destructive effects of signal leakages from the transmit chain to the receive chain. This leakage can be several millions ($>$100 dB) more than the received signal thereby suppressing the desired useful signals. To harness the gains of FD, the SI has to be mitigated and suppressed to or nearly the receiver noise floor. This paper has highlighted the schemes for SI mitigation available in literature by classifying and comparing their pros and cons. The mitigation schemes are either active or passive and the processes take place in any of the following domains: the propagation domain, analogue circuit domain or digital circuit domain. These are also impacted by some transceiver non-idealities. Furthermore, we classified the available schemes for SI mitigation and showed through figures and tables the capabilities, advantages and disadvantages. Whereas a combination of some schemes has shown proven results for cancelling SI up to the noise floor, the challenges facing the implementation of such schemes are also highlighted leading us to identifying some open research issues and proposing future research directions towards realising FD cellular networks. These include: improving the small form-factor solutions, the hybrid analogue-digital solutions, improvement of the analogue circuitry, implementing effective SI mitigation techniques for FD in MIMO scenarios and design of efficient RRM techniques that could aid SI mitigation. Our intention with this survey is to present the mitigation schemes available in literature while highlighting the pending practical challenges for adequately mitigating SI and enabling FD operation in wireless systems. While it is fair to say that there are many SI mitigating schemes already studied and implemented with varying degrees of success, it is also important to note that a lot still needs to be done in order to design a less complex, easily implementable scheme that provides sufficient mitigating capability for enabling FD operations in wireless communication systems.

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