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Special Section on Full-Duplex Transceivers for Future Networks: Theory and Techniques

I. FULL-DUPLEX COMMUNICATIONS

CONVENTIONAL wireless communication systems operate in a half-duplex mode, i.e., current radios cannot transmit and receive at the same time and on the same frequency. Full-duplex wireless operation was generally assumed to be impossible due to the great difference in transmit and receive signal power levels. However, recent advances in antenna, hardware, and signal processing techniques have shown that full-duplex operation is practically feasible. Thanks to novel combinations of antenna, analog, and digital cancellation techniques, self-interference suppression of 80–110 dB can be made possible. The feasibility in building a practical full-duplex radio using off-the-shelf hardware and software-defined radios therefore alleviates many problems in wireless network design.

The full-duplex capability is as important also in wired communications when aiming at realizing cables' two-way capacity to the maximum. In fact, historically, full-duplex capability has already been adopted in digital subscriber line systems/standards in the form of echo cancellation decades before the research on wireless full-duplex systems started. Thus, there is no question about the overall feasibility of full-duplex wired networking, but interesting new research problems and innovation opportunities emerge from developing full-duplex transceiver hardware, signal processing and networking concepts to outperform their half-duplex counterparts optimally in terms of different objectives and under varying design constraints.

A. SELF-INTERFERENCE CANCELLATION IN FULL-DUPLEX SYSTEMS

Self-interference cancellation in radio systems is a challenging problem. The noise-like transmitter leakage seen at the receiver is not static, not least because it changes with the channel effects like fading. It is similar to a radar profile, where there are near-field and far-field effects with constant fluctuation in the delay and amplitude of the reflected signals. Any cancellation system overcoming the self-interference effects should be capable of constantly learning the nonlinear leakage channel with a speed and accuracy to achieve a desired amount of cancellation. The reflections arise from near field as well as far field, requiring a delay profile in estimating the self-interference component. In addition, the cancellation system should introduce minimal or no noise into the receiver chain.

The self-interference cancellation for a full-duplex system is typically implemented in analog and digital domains. Cancellation in the analog domain preserves the dynamic range of analog-to-digital conversion for maximum capability in the digital domain. The key to efficient cancellation of self-interference in the analog domain is the ability to replicate the self-interference responses of the linear multipath components, while the digital cancellation system comprises the estimator and canceler. The digital estimator estimates the self-interference channel to derive and apply cancellation filter taps in analog and digital domain. The digital canceler removes the residual interference left from the analog canceler, which typically includes also non-linear distortion caused by a transmitter high-power amplifier.

One of the most significant hardware limitation and often overlooked when analyzing full-duplex techniques in many research papers is dynamic range. Full-duplex transceivers inherently require significant isolation between the transmit chain and receive chain. Given that both transmit and receive operation is simultaneous in the same frequency, the interference can occur inside the radio, as reflection from near-field and far-field effects. The nearby reflection is of higher power while the farther reflection is of lower power. In effect, the cancellation system should be capable of maintaining the dynamic range to cancel the high-power near-field interference over 100 dB while also being capable of canceling a reflection few 100 ns later. Other hardware issues in a full-duplex transceiver system involve being able to generate sufficient delays and taps to cancel majority reflections in analog and digital domain.

B. MIMO/MMWAVE FULL-DUPLEX COMMUNICATIONS

Self-interference cancellation in a multiple-input multiple-output (MIMO) system presents more challenges with the multi-antenna system. Each transmitter antenna is capable of creating interference to each receive antenna forming a self-interference matrix. Moreover, next-generation communication systems like fifth-generation (5G) cellular and IEEE 802.11ad/ay harness the wide bandwidths available at millimeter wave (mmWave) frequencies (roughly 30–100 GHz) to meet the ever-growing demand for high-rate wireless access. To communicate at mmWave frequencies, systems rely on high beamforming gains afforded by dense antenna arrays—on the order of dozens or hundreds of elements—to overcome high path loss and achieve sufficient link margin.

The combination of analog and digital beamforming—termed "hybrid digital/analog beamforming"—is employed in practical mmWave systems to control and configure these dense antenna arrays with a desirably low number of radio frequency (RF) chains. Hybrid beamforming is an efficient means to achieve high beamforming gains while also supporting spatial multiplexing.

Combining MIMO with mmWave presents interesting opportunities and challenges to achieve good self-interference cancellation to enable full-duplex systems. For mmWave systems, typically the antenna arrays are large ranging from 64 elements to as high as 1024 elements building up a large self-interference matrix. However, given that mmWave experiences significant path loss, this matrix is low rank providing opportunities to optimize the self-interference channel matrix. In addition, from the discussion of beamforming above, self-interference cancellation for mmWave is a combination of digital cancellation, digital beamforming, analog beamforming and analog self-interference cancellation.

C. APPLICATIONS

There are potentially many applications of the full-duplex radio technology. Full-duplex operation has been used in the context of continuous-wave radars of the 1940s and 1950s. In early continuous-wave radars, separate antennas or circulators in the case of shared antenna systems were used to achieve isolation. However, ubiquitous use of full-duplex technology has been hindered up until recently due to the unavailability of advanced self-interference cancellation methods. This unfavorable situation has dramatically changed due to recent breakthrough research in self-interference mitigation, and now several full-duplex applications are being actively considered.

Physical layer security applications are expected to benefit from the ability of full-duplex radios to simultaneously broadcast a jamming signal while receiving the desired signal. Another use case is cognitive radio applications, as full-duplex operation allows a secondary transmitter to sense the environment for primary signals to avoid interference while broadcasting its own signals. In wireless power transfer applications, full-duplex transceivers can be designed to recycle a portion of the RF energy of the self-interference component. Current literature has also studied small-cell full-duplex operation modes with short link distances and reduced transmit powers. These results have verified that under scheduling and power control, full-duplex mode can deliver high spectral efficiencies in highly dense and heterogeneous wireless networks. The use of relaying nodes for outdoor-to-indoor communications and in public safety networks with improved coverage are two other potential applications of full-duplex communication.

In the case of 5G, mmWave spectrum is well-suited as a wireless backhauling solution and full-duplex operation is ideal to deliver integrated access and backhaul services. Moreover, integrated access and backhaul will have a key role to remove some of the challenges inherently associated with fiber optic installations and allow aggressive network densification using street-site deployments in future networks. In addition, several technologies are currently being considered for implementing sixth-generation (6G) networks including intelligent reflective surfaces which operate on the full-duplex principle. Such programmable surfaces are capable of controlling the RF waves to match to the surrounding electromagnetic environment and hence open up a broad range of potential use cases such as directed pencil-beamforming, spatial modulation of received signals, energy harvesting, and promoting wireless security.

Recently, echo cancellation and full-duplex operation were introduced into data over cable service interface specification (DOCSIS). This enables new architectures in cable network systems such as distributed access architecture along with new access schemes like full-duplex, dynamic spectrum split between upstream and downstream, and guard band elimination. Full-duplex communication in DOCSIS and digital subscriber line wired systems provides symmetric data rate and low latency to enable heterogeneous communication architecture that combines wired backhaul network with wireless access.

II. SPECIAL SECTION AIM AND ACCEPTED PAPERS

This special section highlights novel contributions to the theory and practice of echo/self-interference cancellation and full-duplex operation, targeting a broad range of physical and medium access control sublayer issues as well as important applications of full-duplex operation in future wireless and wired network designs. After a rigorous peer review process, we have selected nine papers to be published in this section.

Taghizadeh *et al.* [A5] study the performance degradation of a multiple antenna full-duplex amplify-and-forward relaying system due to imperfect hardware. In particular, the relay transfer function and the mean squared-error performance under the joint impact of additive and multiplicative transmit and receive impairments are analyzed. The authors have also formulated an optimization problem to minimize the communication mean squared-error, which is formulated and solved using the penalty dual-decomposition framework. Numerical examples of the paper verifies the significance of the proposed distortion-aware design and analysis compared with the existing simplified approaches as hardware accuracy degrades.

Chen *et al.* [A9] present a comprehensive overview on the implementation and comparison of various state-of-the-art integrated solutions for full-duplex applications. The survey is the first-of-its-kind with its focus on integrated circuit (IC) implementations of various types of shared-antenna interfaces, such as electrical-balance duplexers and circulators, and cancellers, such as time-domain and frequency-domain approaches, in the radio-frequency and analog baseband domains. Their figures-of-merit for the IC-based shared antenna interfaces and self-interference cancellers capture various design considerations and performance trade-offs including the achievable isolation/cancellation, bandwidth, noise figure degradation, power handling, and power consumption.

Motz *et al.* [A2] propose an optimized digital self-interference cancellation scheme to mitigate the unacceptable performance degradation caused by harmonics induced in a power amplifier. Without efficient mitigation, transmit signal leakage combined with the power amplifier harmonics can create self-interference problems that desensitize receivers in frequency-division and in-band full-duplex operation as well as in carrier aggregation. The proposed approach is based on the derivation of an appropriate interference model and the quantification of interference power levels for a specific power amplifier, and it is characterized by low complexity owing to its target at mitigating solely the dominating components. The capabilities of the approach are demonstrated with simulations and validated on measurement data.

Koc *et al.* [A1] propose a novel angular-based joint hybrid precoding/combining (AB-JHPC) technique for the full-duplex mmWave massive-MIMO systems. In the considered AB-JHPC, the RF-stage is designed using slow time-varying angle-of-departure (AoD) and angle-of-arrival (AoA) information, while the digital baseband (BB)-stage of AB-JHPC is constructed via the reduced-size effective intended channel. In this stage, a novel semi-blind minimum mean square error method is also proposed to suppress the residual self-interference power by using AoD/AoA parameters. As a result, the instantaneous self-interference channel knowledge is not required. Numerical examples show that the AB-JHPC can significantly cancel the self-interference signal and the total amount of self-interference cancellation almost linearly increases via antenna isolation techniques. In addition, compared to its half-duplex counterparts, the full-duplex system can double the achievable rate as the antenna array size increases and the transmit/receive antenna isolation improves.

Kolodziej *et al.* [A4] propose a novel way of using a feed-forward neural network to enhance the tuning of multi-tap adaptive analog RF cancellers. The proposed approach not only provides an accurate estimate of the canceller weights but also leads to the fastest convergence speed. The advantage of the proposed concept was thoroughly demonstrated for various network configurations in terms of both layer and node counts as well as the optimal input data structure and training sample density. The obtained results show that neural networks can be effectively used to enable in-band full-duplex operation in dynamic interference environments, such as 5G wireless networks.

Fouda *et al.* [A8] investigates the application of blind source separation techniques for self-interference cancellation in in-band full-duplex MIMO systems. Experimental results are presented and it is shown that complex independent component analysis outperforms real independent component analysis by 3 dB at the expense of a higher complexity. The proposed approach is carefully compared with existing self-interference cancellation methods. Furthermore, practical challenges such as nonlinearities and complexity constraints are discussed and used as motivation for future work.

Righini *et al.* [A7] explore design, analysis and hardware realization of analog coupling and self-interference cancellation stages to enable broadband 2x2 MIMO power line communication. Various techniques for self-interference mitigation in power line communication systems are described and two front-end circuit structures are proposed and contrasted to perform self-interference cancellation, one based on active cancellation of self-interference in an opamp circuit and another based on magnetic circulators. Furthermore, both systems are evaluated and experimental results on real power line networks are presented.

Nomikos *et al.* [A3] target reliable full-duplex network operation by utilizing hybrid relay selection algorithms which combine buffer-aided successive relaying with delay- and diversity-aware half-duplex algorithms. A hybrid full-duplex delay- and diversity-aware algorithm and a low-complexity distributed version of it are presented in this work. The proposed algorithms offer superior outage and throughput performance while lowering the average delay. Such algorithms can pave the way towards ultra-reliable low-latency communication systems.

Ordoñez *et al.* [A6] build up on minimizing the quantization noise at the ADC which can limit the dynamic range of the self interference estimation and cancellation system. The work in the article proposes using modulo ADCs to reduce the quantization noise in addition to using the conventional techniques such as analog and digital domain interference cancellation. The article presents analysis of the performance benefits of building modulo full duplex transceivers.

APPENDIX: RELATED ARTICLES

[A1] A. Koc and T. Le-Ngoc, “Full-duplex mmwave massive MIMO systems: A joint hybrid precoding/combining and self-interference cancellation design,” *IEEE Open J. Commun. Soc.*, vol. 2, no. 1, pp. 754–774, 2021, doi: 10.1109/OJCOMS.2021.3069672.

[A2] C. Motz, T. Paireder, and M. Huemer, “Low-complex digital cancellation of transmitter harmonics in LTE-A/5G transceivers,” *IEEE Open J. Commun. Soc.*, vol. 2, no. 1, pp. 948–963, 2021, doi: 10.1109/OJCOMS.2021.3073172.

[A3] N. Nomikos, T. Charalambous, N. Pappas, D. Vouyioukas, and R. Wichman, “LoLa4SOR: Leveraging successive transmissions for low-latency buffer-aided opportunistic relay networks,” *IEEE Open J. Commun. Soc.*, vol. 2, no. 1, pp. 1041–1054, 2021, doi: 10.1109/OJCOMS.2021.3077036.

[A4] K. E. Kolodziej, A. U. Cookson, and B. T. Perry, “RF canceller tuning acceleration using neural network machine learning for in-band full-duplex systems,” *IEEE Open J. Commun. Soc.*, vol. 2, no. 1, pp. 1158–1170, 2021, doi: 10.1109/OJCOMS.2021.3080618.

[A5] O. Taghizadeh, S. Stanczak, H. Iimori, and G. T. F. De Abreu, “Full-duplex amplify-and-forward MIMO relaying: Design and performance analysis under erroneous CSI and hardware impairments,” *IEEE Open J. Commun. Soc.*, vol. 2, no. 1, pp. 1249–1266, 2021, doi: 10.1109/OJCOMS.2021.3080239.

[A6] L. G. Ordoñez, P. Ferrand, M. Duarte, M. Guillaud, and G. Yang, “On full-duplex radios with modulo-ADCs,” *IEEE Open J. Commun. Soc.*, vol. 2, no. 1, pp. 1279–1297, 2021, doi: 10.1109/OJCOMS.2021.3085518.

[A7] D. Righini and A. M. Tonello, "MIMO in-band-full-duplex PLC: Design, analysis and first hardware realization of the analog self-interference cancellation stage," *IEEE Open J. Commun. Soc.*, vol. 2, no. 1, pp. 1344–1357, 2021, doi: 10.1109/OJCOMS.2021.3085830.

[A8] M. E. Fouda, C.-A. Shen, and A. E. Eltawil, "Blind source separation for full-duplex systems: Potential and challenges," *IEEE Open J. Commun. Soc.*, vol. 2, no. 1, pp. 1379–1389, 2021, doi: 10.1109/OJCOMS.2021.3086105.

[A9] T. Chen *et al.*, "A survey and quantitative evaluation of integrated circuit-based antenna interfaces and self-interference cancellers for full-duplex," *IEEE Open J. Commun. Soc.*, vol. 2, no. 1, pp. 1753–1776, 2021, doi: 10.1109/OJCOMS.2021.3098476.

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