Digitally-Controlled RF Self-Interference Canceller for Full-Duplex Radios

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***Abstract*—This paper addresses the self-interference (SI) cancellation in a full-duplex radio transceiver. In particular, we focus on shared-antenna based full-duplex transceivers where the self-interference coupling channel is always frequency-selective and can also be strongly time-varying depending on the antenna matching characteristics and reflections from the surroundings. A novel digitally-controlled RF self-interference canceller structure is described, being able to process the signals in a frequency-selective manner as well as track adaptively the time-varying SI features, stemming from the fast digital control loop. A complete demonstrator board is developed, reported and measured, incorporating both the RF processing and the digital control processing. Comprehensive RF measurements are then also carried out and reported at 2.4GHz ISM band, evidencing more than 40dBs of active RF cancellation gain up to 80MHz instantaneous waveform bandwidths. Furthermore, real-time self-adaptive tracking features are successfully demonstrated.**

Keywords—self-interference, active RF cancellation, adaptive filtering, digital control, wideband cancellation, self-adaptive systems, self-healing, RF measurements

I. INTRODUCTION

Bi-directional radio communications between two radio nodes or units is commonly building on the time-division duplexing (TDD) or frequency division duplexing (FDD) principles, where the transmission and reception in an individual device are divided either in time or frequency. In order to boost the flexibility and efficiency of the radio spectrum use, the so-called inband full-duplex radio principle, where the device is transmitting and receiving simultaneously at the same carrier is receiving increasing interest, see, e.g., [1]-[4] and the references therein. This technology is currently under intensive research, at both device and radio network layers.

To realize inband full-duplex radio communications, one of the biggest challenges to solve is the massive self-interference (SI) problem. This is stemming from the concurrent transmission and reception at the same carrier, implying that the strong transmit signal from own transmitter is directly coupling to the own receiver [1], [3]-[7]. As the transmit powers in, e.g., mobile cellular radio systems are in the order of +20dBm (mobile devices) or even close to +50dBm (base stations), while the receiver sensitivity requirements are typically in the order of -90 … -100dBm, overall SI suppression in the order of 110-150dB should basically be achieved. Such massive suppression or isolation numbers thus call for novel solutions and innovations in antenna technologies, RF circuits as well as digital signal processing.

Common approaches to realize elementary isolation between the transmitter and receiver chains is to either adopt separate transmit and receive antennas [4]-[6], or to share the antenna through a circulator [3], [7] or electrical balance duplexer type of circuit [8], [9]. With these approaches, especially in smaller form factor devices, maximum isolation numbers of around 30-40dBs have been reported in the recent literature. On top of this, active RF cancellation where an explicit cancellation signal is injected at low noise amplifier (LNA) input is commonly adopted, as described, e.g., in [3]-[5], [8], [9]. In most works, relatively narrow carrier bandwidths of around 1-20MHz are assumed, and the maximum active RF cancellation numbers are commonly around 30-35dB [4], [5]. Finally, an additional digital SI cancellation stage can be deployed where the remaining SI is then attenuated further [1]-[5], [10]-[12].

In this paper, we report a novel digitally-controlled wideband RF canceller which is able to provide reliable and highly accurate SI cancellation under time-varying SI coupling characteristics and when operating with wideband waveforms

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This work was funded by Intel Corporation, the Academy of Finland (under the project #259915 ”In-band Full-Duplex MIMO Transmission: A Breakthrough to High-Speed Low-Latency Mobile Networks”), the Linz Center of Mechatronics (LCM) in the framework of the Austrian COMET-K2 programme, and by the Internet of Things program of DIGILE (Finnish Strategic Centre for Science, Technology and Innovation in the field of ICT) funded by Tekes.

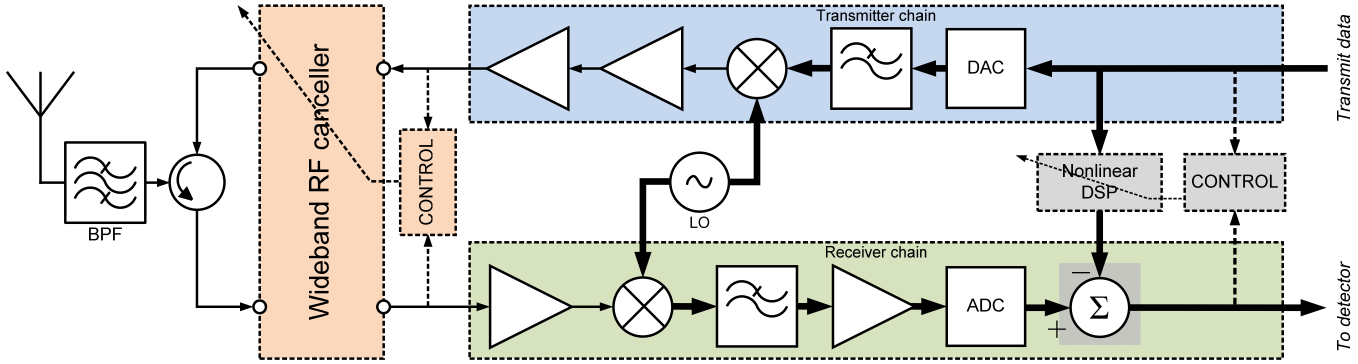


Fig. 1. Illustration of the overall assumed full-duplex device architecture, building on the shared-antenna concept. The main emphasis in this work is on the advanced RF cancellation solutions with digital control.

of the emerging radio systems. The basic structure of the canceller builds on the foundations and fundamental developments in [7], in the form of a multipath RF canceller principle with adjustable amplitudes and phases in each branch, which are taken into use in this work. As a particular contribution, we provide self-tuning type of automatic control solutions where the amplitude and phase characteristics of individual cancellation paths are controlled digitally. This can enable fast adaptation and adjustment to time-varying reflections from the surrounding objects as well as to the changes in the antenna reflections due to, e.g., hand effects in mobile devices. Also a complete demonstration board is implemented and measured at 2.4GHz ISM band, evidencing more than 40dBs of active RF cancellation gain even with 80MHz instantaneous waveform bandwidth.

The rest of the paper is organized as follows. In Section II, we shortly describe the considered overall architecture of the full-duplex radio device. Then, in Section III, the operating principle, structure and associated tuning algorithms of the novel digitally-controlled RF canceller are described. Section IV, in turn, provides a description of the developed overall prototype board implementation while the corresponding RF measurement results are reported in Section V. Conclusions are finally drawn in Section VI.

II. CONSIDERED OVERALL FULL-DUPLEX DEVICE ARCHITECTURE

The considered overall full-duplex device architecture is depicted at a conceptual level in Fig. 1. The widely-adopted direct-conversion radio architecture is here assumed, for both the transmit and the receive chains. As also illustrated in the figure, the TX and RX chains are sharing an antenna, either through a circulator or an electrical balance duplexer (EBD). In such cases, the reflection from the antenna is usually the most dominant SI component, while other SI components then arise due to the reflections from the surrounding objects as well as the direct leakage through the circulator or the EBD.

The active RF cancellation builds on the idea of using the PA output signal as the reference. Alternative ideas using, e.g., an additional or auxiliary transmitter to generate the RF cancellation signal have been proposed in [4], [5]. Using the PA output as the reference signal is generally useful as it can facilitate partial cancellation of the TX chain and power amplifier (PA) imperfections. The digital cancellation, in turn, naturally relies on the original digital TX data as reference, being then filtered linearly or nonlinearity, to create the actual cancellation signal. In general, in both cancellation stages, the most critical factor is fast and reliable calibration and tuning of the canceller parameters and characteristics.

III. DIGITALLY-CONTROLLED WIDEBAND RF CANCELLER

A. *Basic Modeling and Cancellation Principle*

In this sub-section, we provide first the basic SI modeling adopting complex-valued baseband equivalent signals and notations. In general, as discussed already earlier, the transmit signal can couple from TX to RX through multiple paths. Thus, to model such scenario, the SI at RX input, prior to any RF cancellation processing, is here expressed as

$$y(t) = \sum_{n=1}^{N_{SI}} h_{SI,n} x(t - \tau_{SI,n}) + n(t) \qquad (1)$$

where $h_{SI,n}$ and $\tau_{SI,n}$ denote the complex coupling coefficient and delay of the *n*-th SI component. Furthermore, $x(t)$ denotes the baseband equivalent of the PA output while $n(t)$ represents thermal noise.

The actual RF cancellation circuit is then building on a set of N_C parallel cancellation paths, as illustrated at conceptual level in Fig. 2. Each of the paths have different but fixed delays, denoted with $\tau_{C,n}$ for the *n*-th cancellation path, while then allowing for freely adjustable amplitude and phase control. When described again at complex baseband equivalent level, such cancellation processing can be expressed as

$$z(t) = y(t) - \sum_{n=1}^{N_C} w_n x(t - \tau_{C,n}) \qquad (2)$$

where w_n denotes the controllable amplitude and phase change of the *n*-th cancellation path. Notice that in general, the set of delays $\tau_{C,n}$ does not need to be identical or matched to the SI coupling channel delays $\tau_{SI,n}$, since each cancellation path is equipped with both amplitude and phase control, thus enabling accurate regeneration of the SI waveform. Similarly, the number of cancellation paths does not need to be equal to the true number of SI multipath components.

B. Digital Self-Adaptive Control Algorithms

In order to obtain accurate regeneration of the SI waveform, and thus good RF cancellation performance, in unknown and potentially time-varying SI coupling channel characteristics, fast and reliable parameter learning is essential. Instead of separate open-loop type parameter estimation phase, we adopt closed-loop digital tuning of the RF canceller parameters w_n, such that the prevailing instantaneous power at the RF canceller output is minimized. Such closed-loop structure is in general a complicated nonlinear control loop, having both RF signals and digital baseband signals as well as the associated components and data converters involved. As illustrated in Fig. 2, the prevailing SI power is measured through an additional feedback downconverter whose output is digitized. As this signal represents the error signal from the cancellation perspective, we deliberately denote that by $e(t)$, or $e(k)$ in the discrete time domain, in the continuation where *k* refers to the discrete-time index.

In order to facilitate real-time processing with low computing complexity, the simplest approach is to adopt least mean square (LMS) type digital coefficient adaptation in the control loop. This is expressed here for the *n*-th cancellation path with parameter w_n as

$$w_n(k+1) = w_n(k) + \mu x_n^*(k)e(k) \tag{3}$$

where μ refers to the adaptation step-size controlling the learning and tracking rate as well as steady-state variance. Furthermore, $e(k)$ denotes the instantaneous error sample, obtained through the feedback downconverter through a digitization stage while $x_n(k)$ refers to the corresponding digitized sample of the *n*-th path downconverter. When written in terms of the parallel I/Q signals, this boils down to

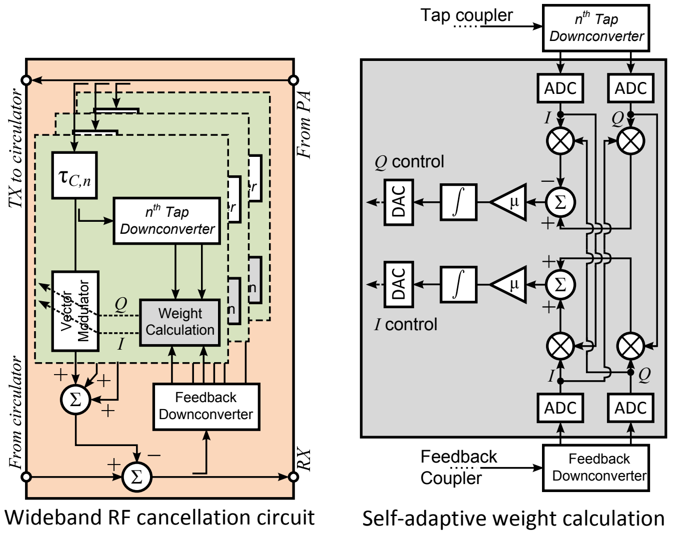
$$\begin{aligned} w_{n,I}(k+1) &= w_{n,I}(k) + \mu\Big(x_{n,I}(k)e_I(k) + x_{n,Q}(k)e_Q(k)\Big) \\ w_{n,Q}(k+1) &= w_{n,Q}(k) + \mu\Big(x_{n,I}(k)e_Q(k) - x_{n,Q}(k)e_I(k)\Big) \end{aligned} \tag{4}$$

This overall processing is depicted in Fig. 2, in terms of the parallel I and Q signals and the associated control voltages.

IV. DEMONSTRATOR BOARD

A. RF Canceller

A three-tap version of the RF canceller was built using off-the-shelf RF components for demonstration purposes. The aim of this design is to demonstrate the overall cancellation performance and proper operation of the control system. Therefore, versatility and functionality of the system was emphasized over detailed optimization of, e.g., the TX and RX chain insertion losses or RF canceller output noise level.



Wideband RF cancellation circuit   Self-adaptive weight calculation

Fig. 2. Left: The overall multi-branch or multi-tap RF cancellation structure incorporating fixed delays together with adjustable vector modulators offering tunable amplitudes and phases per branch. Right: Least-mean square processing based self-adaptive digital control-loop, depicted in terms of the parallel I and Q signals, providing the I and Q control voltages of an individual vector modulator.

To obtain the necessary cancellation signals, the TX signal at the PA output is divided using a 4-way splitter (Minicircuits BP4U). One of the signals is used for the circulator towards the antenna while the remaining three are used as tap inputs. Splitting the TX signal in this way provides enough cancellation power for the tap signals without external amplification. The relative delays of the taps can be adjusted using proper cabling.

A coupler (Anaren XC0900P-10S) is then used to split the signal from each tap. The coupled signal is downconverted to baseband (Maxim Integrated MAX2023) to be digitized for the digital control system. Majority of the power goes to the vector modulators (Hittite HMC631LP3) which adjust the phase and amplitude of the RF signals based on the I and Q control voltages. The outputs of the three vector modulators are then combined (Minicircuits SCN-3-28) to form the total cancellation signal. Finally, the cancellation signal is coupled to the circulator RX port, resulting in a significant reduction of the SI power towards the LNA.

The feedback or error signal for the digital control system is observed after the cancellation point, using a coupler (Anaren XC0900P-10S) and feedback downconverter. As the power level of the feedback signal is typically relatively low, especially from the ADC interface perspective, an LNA (RF Comp HD24089) is used to amplify the feedback signal already prior to the downconversion. The feedback signal is then downconverted into baseband and digitized for the control system processing. The overall RF canceller demonstrator board, excluding the digital control system, is depicted in Fig. 3.

B. Digital Control System

Each tap, alongside with the feedback signal, require two ADC channels to facilitate the digital processing and generation of the I and Q control voltages. For a three-tap canceler, a total of eight channels are thus required. A good dynamic range is also important in order to capture the low power feedback signal accurately. Notice also that the update rule in (4) requires only 4 real multiplications per tap, and thus 12 real multiplications overall, per update cycle. In this demonstrator concept, the downconverted and filtered baseband signals are digitized using TI ADS5295, which is a 12-bit 8-channel ADC platform. The ADC sampling rate is 40 MSPS.

The actual digital algorithm and processing run on a BeMicro CV A9 development board, which utilizes Cyclone V 5CEFA9F23C8 field-programmable gate array (FPGA). The ADC sampling clock is also used as a reference for the FPGA system clock. The algorithm uses two's complement representation but the control values have to be switched to offset binary form to account for the vector modulator control voltage range properly.

The final vector modulator analog control voltages are created using AD5676, a 16-bit 8-channel digital to analog converter (DAC), which is controlled with serial peripheral interface (SPI) running at 40 MHz. A reference voltage of 3V was chosen for the DAC so that the half-scale value corresponds to the null gain of the vector modulator. The update rate for the control voltages in this implementation is 247 kHz.

V. RF MEASUREMENT RESULTS

A. Measurement Setup

To demonstrate and evaluate the performance of the implemented digitally-controlled RF canceller, real-life RF measurements and experiments are performed using the measurement setup shown in Fig. 4. The measurements are carried out using a National Instruments PXIe-5645R vector signal transceiver (VST), which is used both as a transmitter and a receiver, complemented with an external low-cost power amplifier (TI CC2595). The used transmit signal is an LTE waveform with an instantaneous bandwidth of 20, 40 or 80 MHz, centered at 2.46 GHz. The VST output is then connected directly to the used PA which has a gain of 24 dB at the chosen input power levels. The used PA is a commercial low-cost chip intended to be used in low-cost battery-powered devices. This means that the PA produces a significant amount of nonlinear distortion into the SI waveform, especially with the power levels used in these measurements.

Accounting for all the losses incurred by dividing the transmit signal among the different paths, the approximate transmit power at the antenna in these measurements is in the order of +6…+8 dBm. The deployed circulator and the low-cost shared-antenna yield an overall isolation in the order of 20 dB between the transmitter and receiver chains, mostly because of the reflection from the antenna. Then, the desired RX signal and SI are routed back to the RF canceller, which performs the analog cancellation. Finally, the processed signal is routed to the receiver (NI PXIe-5645R) and captured as digital I and Q samples, which are then used process and analyze the results.

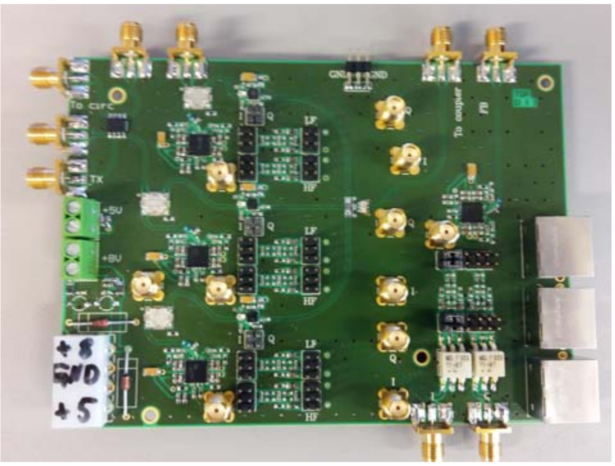


Fig. 3. Developed RF canceller demonstrator board.

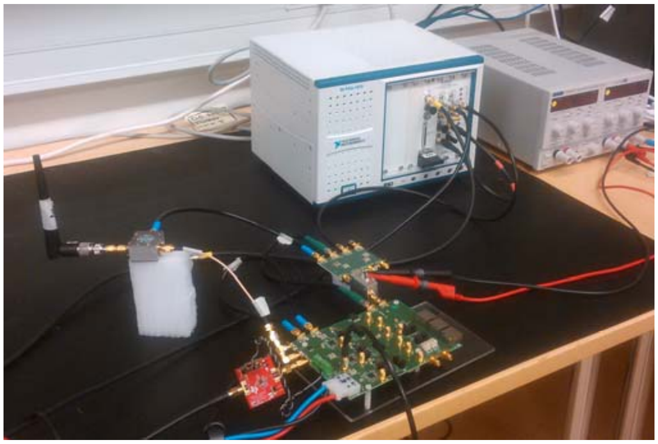


Fig. 4. Overall RF measurement setup.

B. Measurement Results

The RF spectra at different stages of the full-duplex device are shown in Fig. 5. There, the TX signal, signal before the RF canceller, and the cancelled signal are shown for transmission bandwidths of 20, 40 and 80 MHz. As already mentioned, the isolation provided by the antenna and the circulator is in the order of 20 dB, resulting in an SI power of approximately -14 dBm being coupled towards the RX. This is clearly too powerful a signal for any practical radio receiver to handle, and thereby the necessity of analog RF cancellation is obvious.

When observing the 20 MHz case, it can be seen that the RF canceller is capable of attenuating the SI by almost 50 dB, meaning that the overall attenuation for the transmit signal is roughly 70 dB before the receiver chain. This is one of the highest reported analog cancellation figures for a signal of this bandwidth, and it is more than enough to prevent the saturation of the receiver. When the signal bandwidth is further widened, it is evident from Fig. 5 that the RF canceller still provides a high amount of suppression for the SI signal. With the 40 MHz and 80 MHz bandwidths, the amounts of RF cancellation are 45 dB and 41 dB, respectively. Again, these are some of the highest reported RF cancellation performances for bandwidths of this magnitude. Overall, it can be said that the implemented

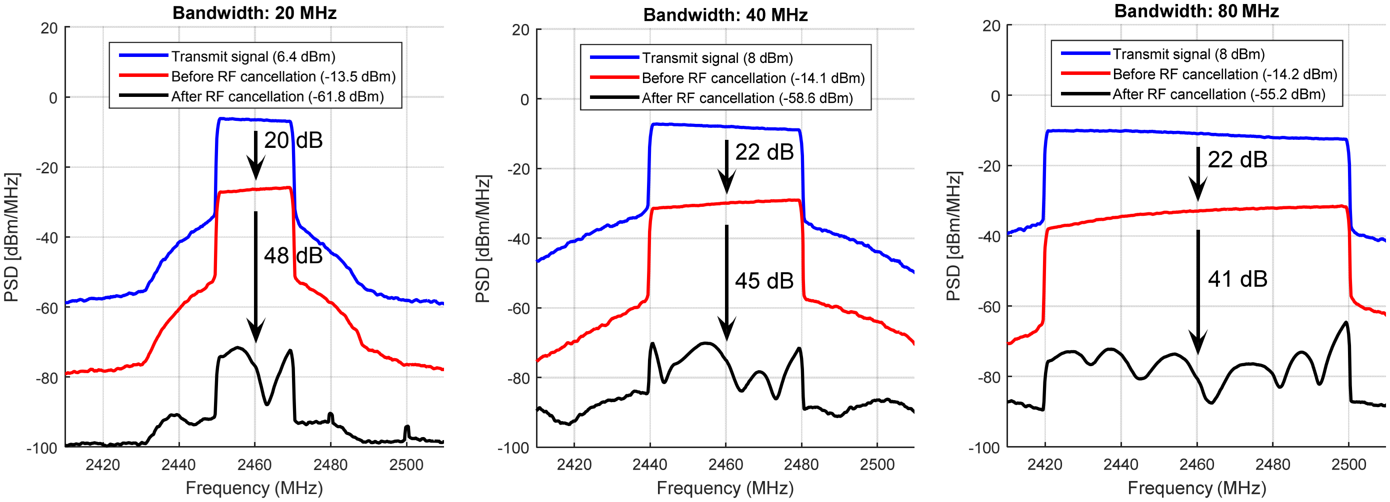


Fig. 5. Measured RF spectra using the developed digitally-controlled RF canceller prototype.

three-tap RF canceller already enables inband full-duplex operation for bandwidths up to 80 MHz.

Next we illustrate the behavior of the control voltages, over time, in Fig. 6. They were first manually set to 1.5V which is the null point of the vector modulators. After that, the developed digital control system is successfully driving the control voltages to stable steady-state values, such that the RF cancellation is maximized, as shown already in Fig. 5. To push and test the control system further, we next impose deliberate changes to the antenna environment and reflections by nearby objects. The ability of the digital control system to react fast to such changes is illustrated through a video available at

- http://www.tut.fi/full-duplex/RFCancDemo4.mp4

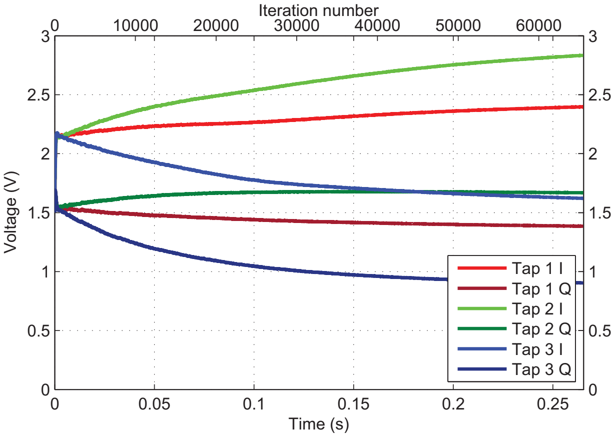


Fig. 6. I/Q control voltages of the vector modulators of taps 1-3 over time.

VI. CONCLUSIONS

In this paper, a novel digitally-controlled RF self-interference canceller was described, where multiple RF branches with tunable amplitudes and phases are adopted. A complete RF demonstrator board was also developed and measured, incorporating a closed-loop self-adaptive digital control system, evidencing that beyond 40dB RF cancellation gain can be obtained even with 80 MHz instantaneous bandwidth and substantially nonlinear PA. This represents state-of-the-art RF self-interference cancellation in full-duplex radios, being empowered with fast and accurate digital computing and digital self-healing control algorithms.

REFERENCES

[1] A. Sabharwal, P. Schniter, D. Guo, D. Bliss, S. Rangarajan, and R. Wichman, “In-band full-duplex wireless: Challenges and opportunities,” *IEEE J. Selected Areas Commun.* vol. 32, no. 10, Oct. 2014.

[2] S. Hong, J. Brand, J. Choi, M. Jain, J. Mehlman, S. Katti, and P. Levis, “Applications of self-interference cancellation in 5G and beyond,” *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 114–121, Feb. 2014.

[3] D. Bharadia, E. McMilin, and S. Katti, “Full duplex radios,” in *Proc. SIGCOMM’*13, Aug. 2013, pp. 375–386.

[4] M. Duarte, C. Dick, and A. Sabharwal, “Experiment-driven characterization of full-duplex wireless systems,” *IEEE Transactions on Wireless Communications*, vol. 11, no. 12, pp. 4296–4307, Dec. 2012.

[5] M. Duarte and A. Sabharwal, “Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results,” in *Proc. 44th Asilomar Conf.Signals, Syst., Computers*, Nov. 2010, pp. 1558–1562.

[6] E. Everett, M. Duarte, C. Dick, and A. Sabharwal, “Empowering full-duplex wireless communication by exploiting directional diversity,” in *Proc. 45th Asilomar Conf. Signals, Syst.Computers*, Nov. 2011, pp. 2002–2006.

[7] Y.-S. Choi and H. Shirani-Mehr, “Simultaneous transmission and reception: Algorithm, design and system level performance,” *IEEE Trans.Wireless Commun.*, vol. 12, no. 12, pp. 5992–6010, Dec. 2013.

[8] L. Laughlin, M.A. Beach, K.A. Morris, and J.L. Haine, "Optimum Single Antenna Full Duplex Using Hybrid Junctions," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 10, Oct. 2014.

[9] B. Debaillie, D.J. van den Broek, C. Lavín, B. van Liempd, E.A.M. Klumperink, C. Palacios, J. Craninckx, B. Nauta, and A. Pärssinen, “Analog/RF Solutions Enabling Compact Full-Duplex Radios,” *IEEE J. Selected Areas Commun.*, vol. 32, no. 10, Oct. 2014.

[10] L. Anttila, D. Korpi, V. Syrjälä, and M. Valkama, “Cancellation of power amplifier induced nonlinear self-interference in full-duplex transceivers,” in *Proc. 47th Asilomar Conference on Signals, Systems and Computers*, Nov. 2013, pp. 1193–1198.

[11] D. Korpi, T. Riihonen, V. Syrjälä, L. Anttila, M. Valkama, and R. Wichman, “Full-duplex transceiver system calculations: Analysis of ADC and linearity challenges,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 7, pp. 3821–3836, Jul. 2014.

[12] D. Korpi, L. Anttila, V. Syrjälä, and M. Valkama, “Widely-linear digital self-interference cancellation in direct-conversion full-duplex transceiver,” *IEEE J. Selected Areas Commun.*, vol. 32, no. 10, Oct. 2014.