# Crosstalk and Self-Interference Cancellation in Full-Duplex Communication Systems

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***Abstract*— This paper provides insights into the ongoing research work of NATO IST-175-RTG that aims to demonstrate the benefits of *full-duplex* radios in military applications. *Full-duplex* radios in general allow to simultaneously transmit and receive RF signals in the same frequency band but require solving technical challenges that are not present in conventional *half-duplex* systems. Mainly this means suppressing the *self-interference* which is caused by the transmitted signal reaching the receiver path. This can result because of, e.g., circulator leakage, antenna mismatch, or reflections from the environment. Several techniques, both digital and analog, have been proposed in literature to cope with such strong interference in the receiver path after the point from which the interference has reached there.**

**However, an additional challenge can arise in transceivers with improper internal isolation such as, e.g., low-cost software-defined radios, where the leaking, or *crosstalk*, takes place inside the radio. In such cases, the analog cancellation cannot be positioned after the leakage point, but must be implemented pre-emptively. This paper quantifies the *crosstalk* for one such *commercial-off-the-self* transceiver plus presents and compares solutions for managing both, the *crosstalk* and the *self-interference* either separately or jointly.**

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***Keywords*— *Crosstalk, Full-Duplex, Self-Interference, Digital and Analog Cancellation***

## I. INTRODUCTION

Over the last decade, the *full-duplex* (FD) technology became more and more attractive for several areas of application. The FD technology allows the simultaneous transmission and reception of *radio frequency* (RF) signals in the same frequency band and at the same time. Consequently, it has the capability to double the spectral efficiency because two functions, transmit and receive, could be performed in parallel without the need for widely used access technologies like *frequency division multiple access* (FDMA) or *time division multiple access* (TDMA). The key scientific challenge in this context is the reduction of the strong *self-interference* that is caused by the transmit signal in the reception path. Typically, the *self-interference* is tens of dBs stronger than the weak *signal-of-interest*.

Research on the topic of *in-band full-duplex* (IBFD) has therefore focused on maximizing the *self-interference cancellation*. First designs in [1] focused on two and three antenna arrangements to improve the isolation for a specific frequency carrier in combination with an analog *self-interference canceller* (SIC). Single antenna FD systems with circulators are addressed by, e.g., [2],[3] and have been combined with a two-stage concept of analog and digital SICs. It has been shown for the ISM frequency band, that the *self-interference* can be reduced to close to the noise floor in many different configurations [5].

While most of these approaches to *full-duplex* systems address classical communication scenarios at typically high carrier frequencies (more than 2 GHz), high spectral bandwidths (typically 0.5 - 80 MHz) and low transmit powers (less than 1 Watt), its benefits and opportunities have also attracted a lot of interest in the military domain. However, military driven scenarios, e.g., jamming and communication, exhibit more challenging design constraints (like lower carrier frequencies in the VUHF band, lower spectral bandwidths in the kHz range, as well as higher transmit powers, e.g., 50 Watts). This requires new scientific solutions for the design of military-ready *full-duplex* systems [4] - [8].

To study the relevance of the FD technology for military applications, a *Research Task Group* (RTG) has been established at NATO. This group aims at developing an experimental setup which is (to the widest possible extent) based on *commercial off-the-shelf* (COTS) components. Like it is common in academia and research institutions, the group selected so-called USRP™ B205mini-i from Ettus Research as low-cost *software defined radios* (SDRs) as transceiver (XCVR) modules. These SDRs are flexible, affordable, easy to use, but unfortunately, this specific model suffers from an internal *crosstalk* from the transmit path to the receive path. This leads to another undesired interference which needs to be compensated on top of the *self-interference* problem that is already known for *full-duplex* systems.

The paper is structured as follows. In Section II we will briefly introduce the NATO group and its aims and objectives. In Section III we will give insights into the experimental setup and the resulting scientific challenges. The evaluation results will be discussed in Section IV. Finally, we will conclude our findings in Section V and we will also provide an outlook on future research topics in Section VI.

## II. Aims and Objectives of IST-175-RTG

The NATO *Science and Technology Organization* (STO) *Collaboration Support Office* (CSO) provides scientists from governmental agencies, academia, research labs, and industry a unique platform to collaborate on emerging technologies that are of interest for NATO nations and partner nations. Within the *Information Systems Technology* (IST) panel of NATO STO CSO, the NATO IST-175 *Research Task Group* (RTG) has been established to study the *full-duplex* technology and its relevance for military applications [8][10].

According to the program of work, the NATO IST-175-RTG at first identified several potential areas of military applications that can benefit from the new emerging technology [10]. These areas were from the *communications* (COM) domain, the *electronic warfare* (EW) domain, and/or both. Secondly, the group selected two of these areas and decided to implement multinational experimental setups for demonstration purposes. The first demonstrator shall illustrate the benefits for bi-directional communications, while the second demonstrator combines spectrum sensing/monitoring with jamming.

The present paper provides insights into the results that have been achieved in the context of the first demonstrator. The details of the multinational experimental setup will be explained in the following Section III.

## III. Experimental Setup And Challenge

Our experimental setup utilizes COTS products as far as possible. This regards, for instance, the SDRs and analog RF components. Due to the focus on low carrier frequencies in the VUHF band in our work, a modular RF design with shielded components and shielded cables is applicable and additionally provides easy modification purposes for design optimizations. Furthermore, SDRs provide a flexible way to convert on the one hand digital baseband signals for transmission (TX) into analog signals and on the other hand received analog signals back to digital baseband. Beside this, SDRs offer a high flexibility for tuning typical parameters, e.g., carrier frequencies, signal bandwidth, transmit power etc., while signal processing takes place in state-of-the-art computer hardware.

In the following we will introduce three experimental setups facing different challenges in this paper:

1. A single cancellation circuit for crosstalk cancellation only (see Fig. 1)
2. Two separate cancellation circuits, one for crosstalk cancellation and one for the classical full-duplex approach (near field & environment, antenna mismatching, circulator leakage) (see Fig. 2)
3. One combined cancellation circuit to face effects for *crosstalk* and *self-interference* together (see Fig. 3)

### A. Overview Experimental System Design

The block diagrams for each of the three experimental setups are depicted in Figs. 1 to 3. The digital domain is implemented in real-time software (C++, Qt) for a computer with audio interface. It includes mainly the waveform's (WF) signal processing as well as a novel *full-duplex* digital cancellation module. As waveform we use a modified version of the NATO *narrowband waveform* (NBWF) according to STANAG 5630 Ed.1 [11]. Our implementation of the NBWF includes physical layer signal processing [12], *Medium Access Control* (MAC) layer processing [13], and application layer processing. The NBWF PHY parameters are chosen as given in [12][14], e.g., 25 kHz N1 mode. The NBWF uses *Time Division Multiple Access* (TDMA) scheme for channel access. However, the TDMA scheme is modified in a way that the *voice slots* allow to communicate in a *full-duplex* manner. Furthermore, a *mixed-excitation linear prediction* (MELP) codec with *push-to-talk* functionality for audio transmissions is implemented. The digital cancellation software uses a linear one-tap model, based on channel estimation algorithms for the typical modulation & coding schemes of NBWF.

After digital processing, the baseband signal of the NBWF mode is transmitted and received via the *Universal Software Radio Peripheral* (USRP™) *Hardware Driver*™ (UHD) interface of the B205mini-i from Ettus Research. The B205mini-i is a classical approach to SDRs and provides an operational frequency range from 70 MHz up to 6 GHz with up to 56 MHz analog bandwidth and *full-duplex* operation capability. Within this work, the instantaneous bandwidth is set to the minimum of 200 kHz, which corresponds to the NBWF 25 kHz mode with an oversampling factor of 8. Additionally, the signal is mixed up to the carrier frequency of 300 MHz. The radio transmitter gain is set to the maximum of 89.75 dB and because of the constant envelop shape of the NBWF a digital scaling factor of 1.0 is applied. Therefore, a round about 16 dBm signal power is reached. The receiver (RX) gain is set to a moderate value of 40 dB, where the

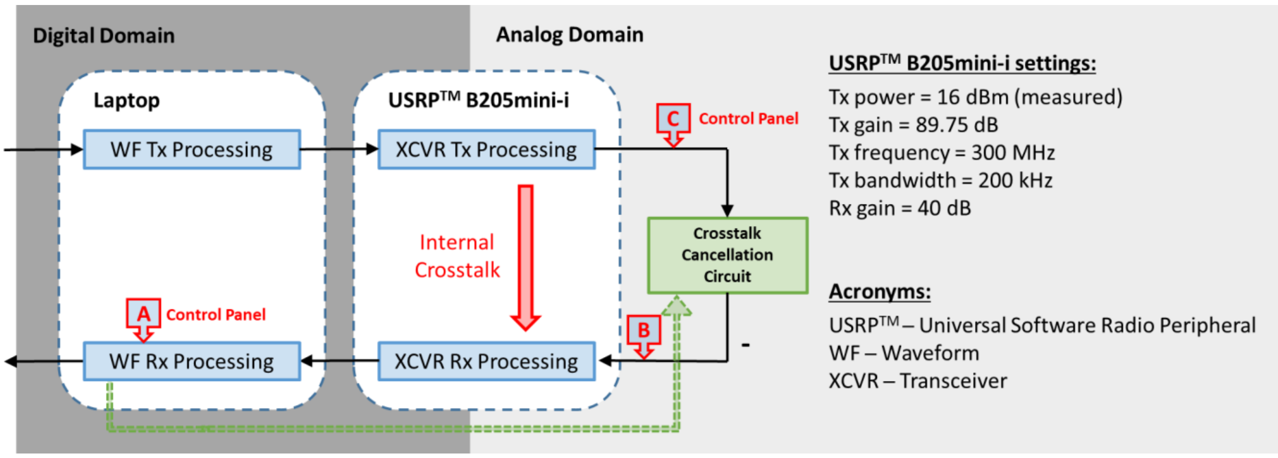


Figure 1: Block diagram of the reduced experimental setup with crosstalk cancellation circuit and USRP™ B205mini-i with provided settings

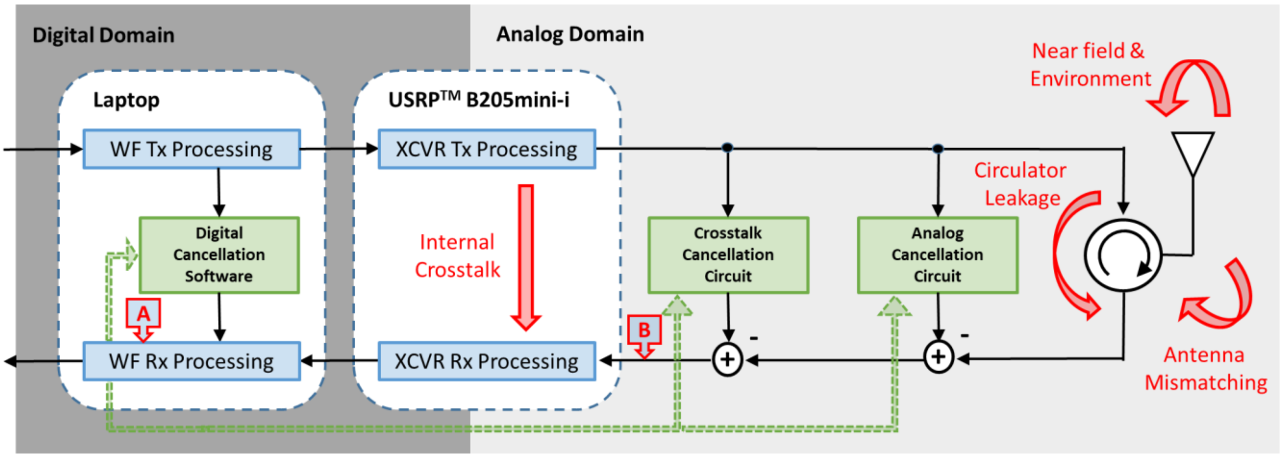


Figure 2: Block diagram of the experimental setup as in Fig. 1 with additional analog cancellation circuit, circulator, and antenna

observed measured noise is kept low, and the receiver sensitivity is still good.

For the use of *full-duplex* or *half-duplex* mode, the B205mini-i is shipped with two SMA-connectors called TRX and RX2. An inner double switch matrix between transmitter and receiver path can be toggled to change the operation mode. In *full-duplex* operation, the RX2 connector is directly connected to the inner receiver path all the time, and the TRX connector is connected to the transmitter path. In *half-duplex* operation only the TRX connector is used, and the double switch is toggling during *half-duplex* operation of the waveform every time when transmission is turned on or off.

Because of this flexible architectural concept of the B205mini-i an unintentional internal *crosstalk* from transmitter path to receiver path has been induced over the isolation path of the switch matrix, when *full-duplex* operation is chosen and furthermore the carrier frequencies for TX and RX are tuned to the same frequency. This introduces *in-band self-interference*, which degrade the receiver's sensitivity, defined by the digital observable noise floor. In this case, signal reception in *full-duplex* operation is limited to the dominant internal *crosstalk* instead of the noise floor observable from the RX2 connector.

## B. *Crosstalk Canceller*

To suppress the dominant internal *crosstalk*, we propose in our experimental setups a novel approach of an outer *crosstalk* cancellation (XTC) circuit. The design of the XT canceller is optimized for a carrier frequency of 300 MHz. The linear network for the XTC circuit is designed in a classical approach known from literature [1][2] with eight different cables with linear increasing cable length. This design results in group delays in steps of 45-degree phase shifts from 45-degree to 360-degree equally distributed around the unity circle of the complex in-phase and quadrature component plain (one wavelength). Beside this, each path has a digital tuneable attenuator from 0 dB to 31.75 dB in 0.25 dB steps. This combination of fixed delay and variable attenuation values provide a flexible way of tuning delay and amplitude of the overall canceller. In an optimal case, the signal after the XTC network matches to a 180-degree phase shifted copy of the internal *crosstalk* of the device, which is then suppressed inside the device. For an optimal working range of the XTC network an additional 15 dB attenuator is placed in the chain.

Finally, a fixed 20 dB attenuator plus limiters are connected to RX2 connector for power overload protection of the USRP™ device. Therefore, in total 35 dB attenuation (plus insertion loss of used RF components) is needed for optimal dynamic working range of the XT canceller to the power level of the internal *crosstalk*.

## C. *Full-Duplex Canceller*

In Fig. 1 the reduced experimental setup with a XTC circuit was presented. In Figs. 2 and 3 the setup is extended

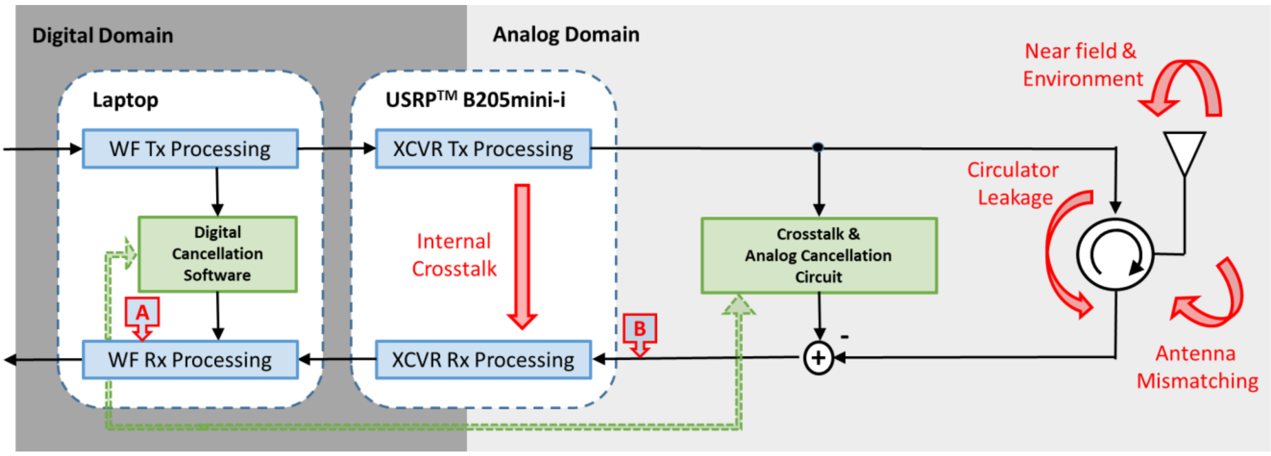


Figure 3: Block diagram of the experimental setup as in Fig. 2 with a single cancellation circuit for the same task

for being used in combination with a classical approach of instantaneous *full-duplex* communication system. For this purpose, in Fig. 2 an additional *analog cancellation* (AC) circuit is introduced for cancelling effects due to the leakage of the circulator, the near field & environmental coupling and finally the mismatching of the antenna. All three effects are compensated by the linear network in the analog domain, to provide optimal *self-interference* cancellation before digitization by the B205mini-i. The AC circuit, the broadband circulator, and broadband antenna are all optimized for a carrier frequency of 300 MHz. The architecture of the network follows the same principle of the crosstalk network except the 15 dB attenuator.

Finally, the AC circuit and XTC circuit are merged in the third experimental setup as depicted in Fig. 3. This setup provides a reference, on how the design may be simplified for practical applications and is therefore being analyzed contrarily to Fig. 2.

### D. Measurement Control panels

Within the block diagram of the experimental setup shown in Figs. 1 to 3, three different control panels A, B, and C for measurement purposes are also illustrated. Control panel A is the most important one, describing the digital spectrum and power level after and before the digital compensation stage in the receiver path. Therefore, it provides measurement information of the *crosstalk* and *self-interference* suppression for the overall system. The measurement is depending on the waveform sensitivity. For moderate signal-to-noise ratios channel estimation information can be provided as feedback from the digital domain to the analog domain. We used an adaptive energy-based trial and error algorithm to tune both, the XTC circuit as well as AC circuit attenuators. Unfortunately, measurements at control panel A cannot provide power levels in dBm due to the digital interface provided by the UHD driver in specific representations of the IQ baseband signal levels. Thus, the control panels B and C are introduced for further measurements in the analog domain with spectrum analyzers.

## IV. Evaluation Of Experimental Setups

After introducing the three different experimental setups in the previous section, we will now present the measurement results in detail. For this, a Rohde & Schwarz ESCI-3 has been used as spectrum analyzer for control panels B and C. Table I provides the parameter details for the measurements.

TABLE I. Parameter Setup For Rohde & Schwarz ESCI-3

| Parameter Infos | Parameter Value |
|---|---|
| Radio Bandwidth (RBW) | 300 kHz |
| Video Bandwidth (VBW) | 300 kHz |
| Mode | Zero Span |
| Carrier Frequency | 300 MHz |
| Ref. Level | Optimized [dBm] |
| Protection Attenuation | 10 dB |
| Pre-Amplifier | Not Used |

The radio and video bandwidths of the spectrum analyzer are set to the closest value of 300 kHz being slightly bigger then the B205mini-i analog bandwidth of 200 kHz. The measurement of absolute power in units of dBm is initialized and measurement data is transferred back over SCPI (*Standard Commands for Programmable Instruments*) to the analysis. For a more precise measurement of the mean power the spectrum analyzer was set to Zero Span Mode (time domain). With the time representation of the recorded amplitudes a calculation of the measured mean power has been performed for several records. Beside this, the TDMA slot structure of the NBWF implementation has been considered, to separate the signal portion from the noise floor. The reference level in dBm as well as the choice of appropriate attenuation values, protection capabilities and preamplifier are optimized for each experimental configuration.

### A. Transmit Power and Transmit Noise Floor (M1)

For the measurement of the transmit power and the transmit noise floor at control panel C of the experimental setup shown in Fig. 1, no cancellation circuit has been considered. Instead, the RX2 connector has been terminated by 50 Ohm. Considering the values for the attenuators, and insertion loss of several RF components the maximum transmit power has been identified at round about 14 to 16 dBm. The transmit noise floor has been measured while the B205mini-i was transmitting baseband signals with representative values of zero amplitude. A transmit noise floor relative to the maximum transmit power has been identified in the range round about -65 to -66 dBm.

TABLE II. Power Range At Different Setup Points (M1, Tx And Rx Measurement)

| Setup Points | Power Range |
|---|---|
| Control Panel C (Measured) | ~ -6 to ~ -4 dBm |
| Insertion Loss (TRX to Control Panel C) Attenuator (Protection) | ~20 dB |
| Estimated Power @ TRX | ~14 to ~16 dBm |
| Insertion Loss (Control Panel B to RX2) Attenuation + Limiters | ~21 dB |
| Transmit Noise Floor @ TRX | -65 to ~ -66 dBm |

### B. Evaluation of Crosstalk Cancellation (M2)

Afterwards the internal *crosstalk* has been quantified by applying the experimental setup of Fig. 1 as it is. For this, control panel A and B have been evaluated at the same time. In a first step, the XTC circuit was deactivated by setting all eight attenuators to the maximum possible value of 31.75 dB. In a next step, the XTC circuit has been optimized to provide maximum *crosstalk* cancellation at control panel A. In all cases the additional digital cancellation was not used.

#### 1) Spectra at Control Panel A (digital)

In Fig. 5 the different spectra of the graphical user interface of the NBWF application at control panel A are shown as reference. On the top left, the *crosstalk* spectrum before cancellation is depicted. There, one can observe the typical NBWF transmission envelope. On the top right, the noise floor of the receiver system is provided. On the bottom left bottom, the spectrum of the residual of the crosstalk after cancellation is presented. On the bottom right, all three previous curves are merged into one figure. Considering the distance between green and blue curves a crosstalk suppression gain of round about 56 dB is provided by the XT canceller. Beside this, comparing the green and black curve brings up round about 70 dB crosstalk component (without the receiver's local oscillator leakage).

TABLE III. POWER RANGE AT DIFFERENT SETUP POINTS (M2, CROSSTALK CIRCUIT)

| Setup Points | Power Range |
|---|---|
| **XTC circuit off** | |
| Control Panel B (Measured) | ~ -69 dBm |
| Estimated Power @ RX2 | ~ -90 dBm |
| Estimated Isolation TRX to RX2 | ~ -104 to ~ -106 dB |
| **XTC circuit optimized @ Control Panel A** | |
| Control Panel B (Measured) | ~ -28 to ~ -26 dBm |
| Estimated Power @ RX2 | ~ -49 to ~ -47 dBm |
| Estimated Crosstalk TRX to RX2 | ~ 61 to ~ 65 dB |

#### *2) Measurements at Control Panel B (analog)*

From the measurement at control panel B, we get the measured values as provided in Table III. Considering 14 to 16 dBm (control panel C in M1) as transmit power as well as -28 to -26 dBm (control panel B in M2) as receiver power and considering 21 dB the insertion loss of the 20 dB attenuator plus limiter (see Table II), an estimated crosstalk of 61 to 65 dB is seen between connector TRX and RX2, respectively. Therefore, the internal *crosstalk* might be higher inside the B205mini-i when additional insertion losses are considered in TX and RX chain before the switching matrix.

#### *3) Link Budget*

Finally, from the given values a *link budget* for the *crosstalk* cancellation can be calculated as shown in Fig. 4. As it can be seen, the maximum transmit power is given by the measured 16 dBm. The crosstalk couples with round about 65 dB to the RX side. Considering a thermal noise floor

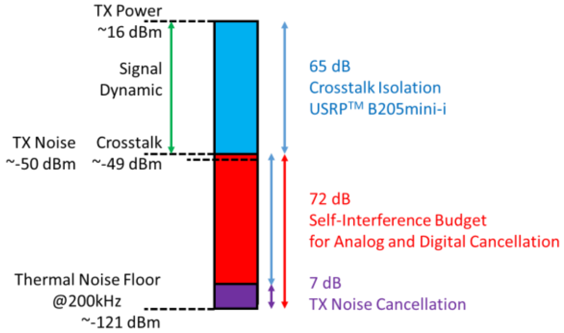


Figure 4: Link budget for crosstalk cancellation

for a signal bandwidth of 200 kHz and a temperature of 300 K, the noise floor is placed at round about -121 dBm. The link budged to completely handle crosstalk is about 72 dB, where it is composed by 65 dB of signal cancellation components and 7 dB of TX noise cancellation.

### *C. Evaluation of Separate Crosstalk Cancellation and Analog Cancellation (M3)*

In the next step an experimental setup as depicted in Fig. 2 has been considered for evaluation. For measurement purposes, in a first step, the *crosstalk* cancellation has been performed, while the AC circuit with all its eight paths has been adjusted to maximum attenuation of 31.75 dB. The XTC circuit has been activated and measurements have been done for control panel A and B. Due to the static nature of *crosstalk*, an optimization at the beginning of the start time of the NBWF application on the B205mini-i is completely enough. When the *crosstalk* is suppressed the AC circuit is activated and optimized during NBWF communication.

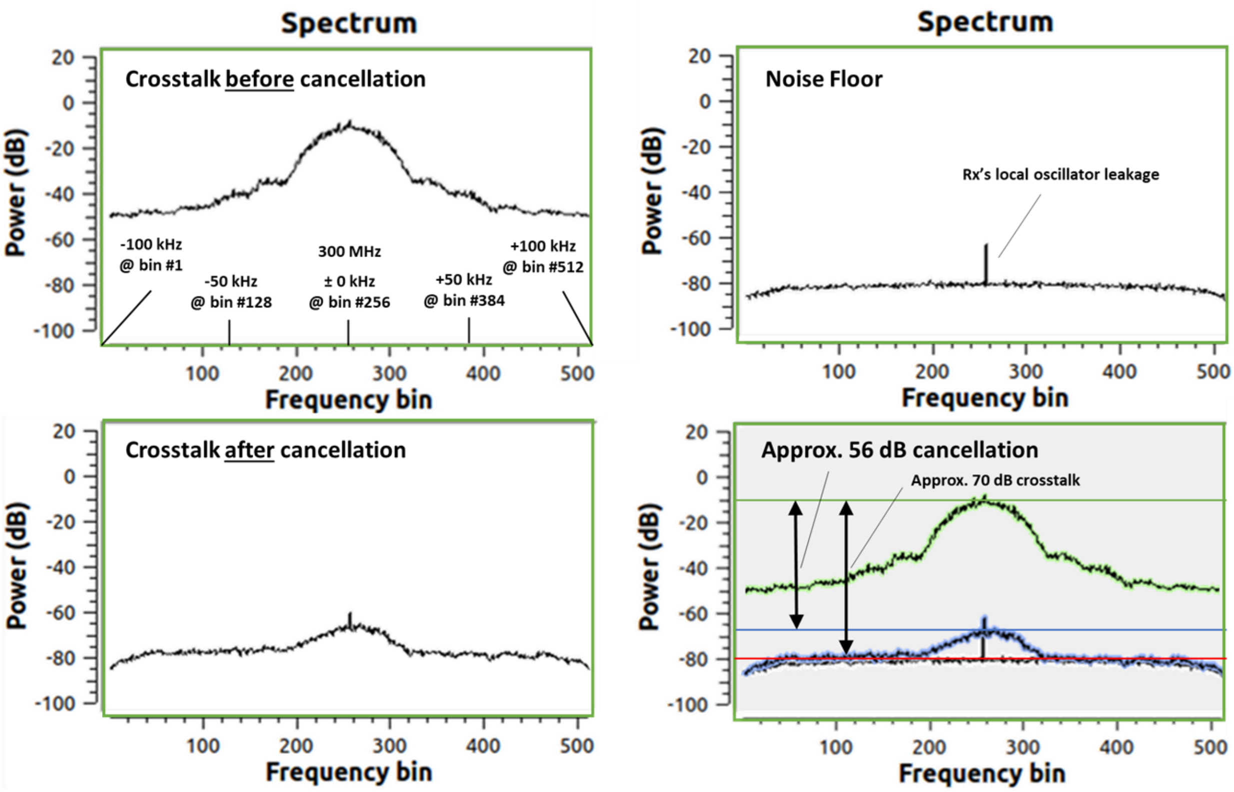


Figure 5: Spectra before crosstalk cancellation (top left), noise floor only (top right), after crosstalk cancellation (bottom left), and all together (bottom right)

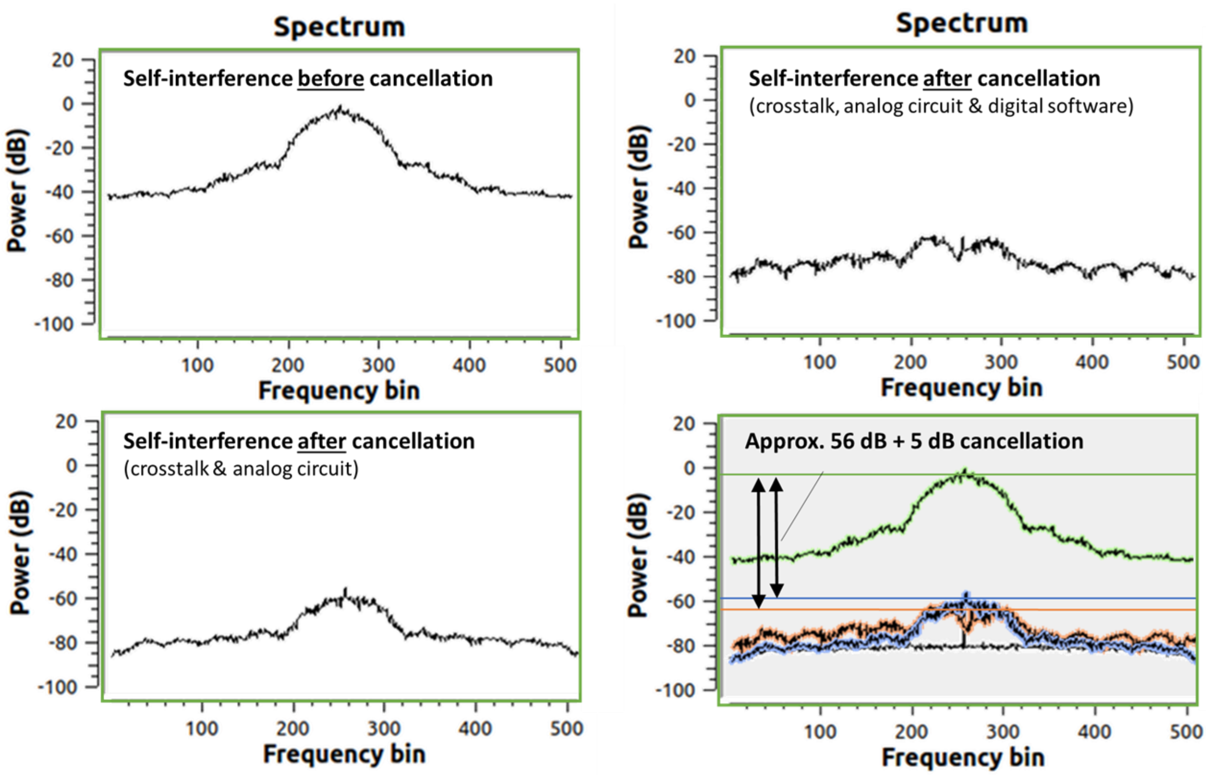


Figure 6: Spectra before self-interference cancellation (top left), after crosstalk, analog and digital self-interference cancellation (top right), after crosstalk and analog self-interference cancellation (bottom left), and all together (bottom right)

*1) Spectra at Control Panel A (digital)*

In Fig. 6 the results of the different spectra are depicted. On the top left, the measured spectrum before *self-interference* and *crosstalk* cancellation is shown. On the top right, the overall suppression based on both, *crosstalk* and analog, circuits plus the digital cancellation are performed. On the bottom left, the spectrum after AC and XTC is provided. The fourth plot on the bottom right shows again the result after merging all these curves into a single plot.

As it can be seen, the two cancellation circuits allow to reduce all sources of interference (*crosstalk*, circulator leakage, antenna mismatch and near field & environment effects) by approx. 56 dB. If the digital cancellation software is also applied, an additional 5 dB of suppression can be achieved. This results in a total performance improvement of 61 dB.

*2) Measurements at Control Panel B (analog)*

The measurement results at control panel B are provided in Table IV. In a first step, again the transmit power has been measured because of the changed experimental setup with separated circuits. With the measured transmit power of -5 dBm and with the given insertion loss from TRX connector to control panel C approx. 18 dBm has been reached. With the additional insertion loss from the TRX connector to the antenna an estimated transmit power at the antenna of 7 dBm is determined. Considering a configuration, where XTC and AC circuits are deactivated, the measured power at control panel B reaches approx. -22 dBm. With the insertion loss from the antenna to control panel B, an estimated received power of the TX signal is determined by approx. -1 dBm. This corresponds to an antenna return loss of approx. 8 dB, which is dominant compared to the circulator leakage of 23 dB. Considering a second configuration, where the XTC circuit is still deactivated and the AC circuit is optimized at control panel B by the measurement equipment, a residual received power of the *self-interference* component is measured with approx. -81 dBm. Considering this, a *self-interference* cancellation of 59 dB has been determined.

TABLE IV. POWER RANGE AT DIFFERENT SETUP POINTS (M3, CROSSTALK CIRCUIT +ANALOG CIRCUIT + CIRCULATOR + ANTENNA)

| Setup Points | Power Range |
|---|---|
| Control Panel C (Measured) | ~ -5 dBm |
| Insertion Loss (TRX to Control Panel C) Splitter + Attenuator (for Protection) | 23 dB |
| Estimated Transmit Power @ TRX | ~18 dBm |
| Insertion Loss (TRX to Antenna) Splitter + Circulator | ~11 dB |
| Estimated Transmit Power @ Antenna | ~7 dBm |
| Insertion Loss (Antenna to Control Panel B) Circulator + Splitter + Combiner | ~21 dB |
| Insertion Loss (Control Panel B to RX2) Attenuation + Limiters | ~21 dB |
| Circulator Isolation | ~23 dB |
| **XTC circuit off, AC circuit off, Antenna Active** | |
| Control Panel B (Measured) | ~ -22 dBm |
| Estimated Received Power @ Antenna | ~ -1 dBm |
| Estimated Return Loss @ Antenna | ~8 dB |
| **XTC circuit off, AC circuit opt. @ B, Antenna Active** | |
| Control Panel B (Measured) | ~ -81 dBm |
| **Analog Self-Interference Cancellation Performance** | |
| Self-Interference Cancellation @ B | ~ 59 dB |

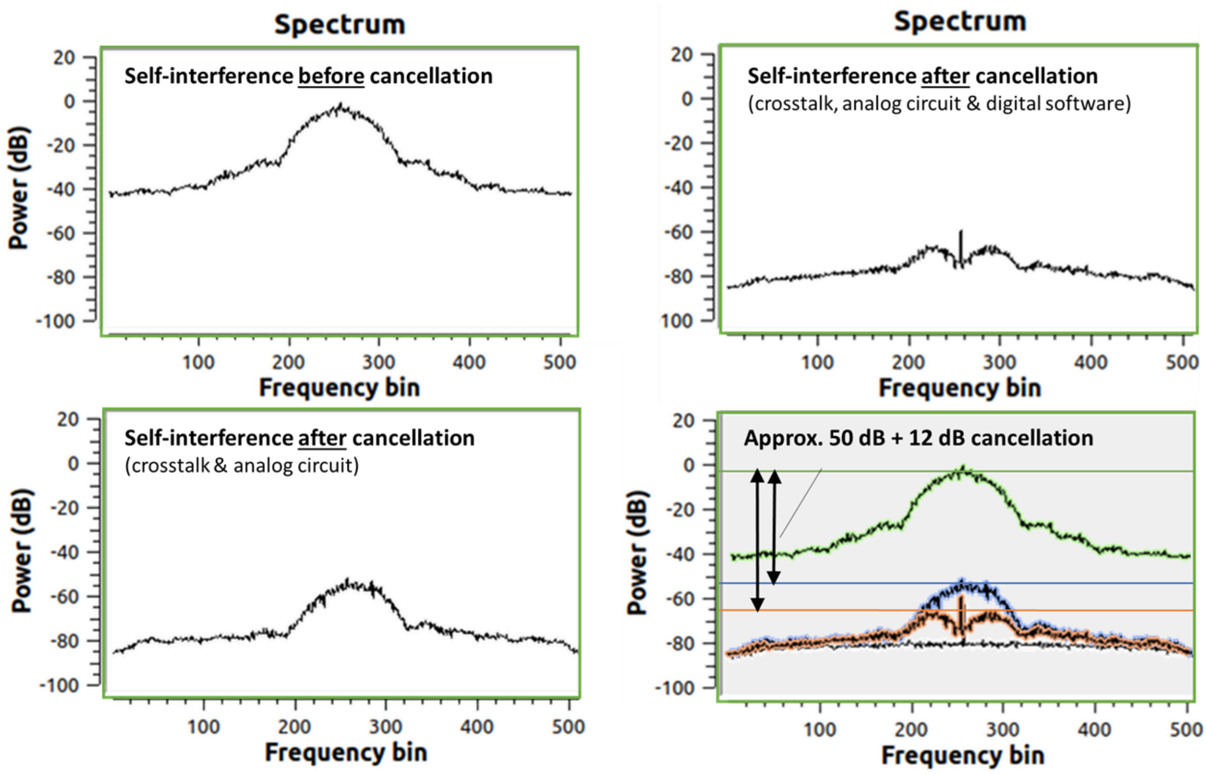


Figure 7: Spectra before self-interference cancellation (top left), after crosstalk, analog and digital self-interference cancellation (top right), after crosstalk and analog self-interference cancellation (bottom left), and all together (bottom right)

*3) Discussion of Results at Control Panels A vs. B*

This estimated value is a bit higher than the observed 56 dB of the spectra in the digital domain. The difference comes from the different configuration and measurement points. For the *self-interference* optimization at control panel B only the AC circuit has been used. The digital feedback is not applicable, because of the internal *crosstalk*. Instead of that, the measurement equipment has been used for feedback and optimization. For the digital domain both the AC and XTC circuits have been applied for optimization. This is done sequentially, e.g., first the XTC circuit optimization (antenna switched off) and afterwards the same for the AC circuit. Note, the other way around is possible, too. Finally, this means that the 59 dB was related to only *self-interference* while 56 dB is related to both, *crosstalk* and *self-interference*. Therefore, it cannot be higher than the *self-interference* alone.

## D. Evaluation of Combined Crosstalk and Analog Cancelation (M4)

While in the previous subsection two separate cancellation circuits have been applied for the *crosstalk* and the typical *self-interferences* of *full-duplex* systems, we finally evaluate the results for a setup in which both circuits are merged into a single one. The corresponding experimental setup is shown in Fig. 3.

*1) Spectra at Control Panel A (digital)*

Fig. 7 shows the result of the spectra, comparable to the previous Fig. 6. As a result, the combined circuit allows to suppress the crosstalk, circulator leakage, antenna mismatch as well as near field & environment effects by approx. 50 dB. Compared to Fig. 6, this is obviously 6 dB less. This loss may result from a mismatch between the working point of the combined network and the internal *crosstalk* component. But the digital cancellation is performing much better and allows to achieve a suppression gain of 12 dB (compared to the 6 dB in Fig. 6). The total suppression gain is with 62 dB nearly the same compared to the previous section. From this perspective the more complex system design with two separated circuits can handle a bit more of the analog cancellation, while the latter design with a merged circuit is simpler and performs nearly the same when digital and analog cancellations are used together.

*2) Measurements at Control Panel B (analog)*

Additionally, the measurement results at control panel B are provided in Table V for the case of using a merged circuit.

TABLE V. POWER RANGE AT DIFFERENT SETUP POINTS (M4, MERGED CIRCUIT + CIRCULATOR + ANTENNA)

| Setup Points | Power Range |
|---|---|
| **Merged Circuit Off, Antenna Active** | |
| Control Panel B (Measured) | ~ -19 dBm |
| **Merged Circuit Optimized @ B, Antenna Active** | |
| Control Panel B (Measured) | ~ -74 dBm |
| **Analog Self-Interference Cancellation Performance** | |
| Self-Interference Cancellation @ B | ~ 55 dB |

When the circuit is off, only the circulator and antenna is active. In this case, the measured power at control panel B is approx. -19 dBm, which matches the strongest component of *self-interference* related to the antenna, e.g., antenna reflection component (antenna mismatch). When the merged circuit is optimized to minimize the residual of *self-interference* at control panel B approx. -74 dBm of power can be measured. Nevertheless, the *crosstalk* is not considered by this optimization, as it cannot be identified from outside the device. Bringing both measured power values together, an analog *self-interference* cancellation of approx. 55 dB can be realized.

*3) Discussion of Results at Control Panels A vs. B*

This is a bit more compared to the results of approx. 50 dB from the observed spectra at control panel A. This can be explained, by the fact, that at control panel A *crosstalk* and *self-interference* are measured and optimized jointly. Consequently, overall analog suppression performance may degrade, because of the dynamic power range of the different effects itself and the position at which the effect takes place. The *crosstalk* is compensated inside the device, while the antenna and circulator effects are suppressed directly before control point B. Furthermore, the tuning coefficients during adaptation are slightly different in both optimization cases. Compared to the optimization related to control panel B the measured power at control panel B for the optimized circuit related to control panel A is higher.

## V. Conclusion

In this paper, we provided insights into the ongoing research work of NATO IST-175-RTG. In particular, we discussed the phenomenon of *crosstalk* within a low-cost SDR which is used in a *full-duplex* system. We presented a novel *crosstalk* cancellation circuit for handling the internal crosstalk in the SDR device before cancelling classical *self-interference* with another analog circuit. The results show promising cancellation of 56 dB, close to the noise floor of the digital received signals, when XTC is optimized in analog domain. Due to the NBWF sensitivity, e.g., synchronization, modulation & coding, further improvements in digital cancellation are limited to the channel estimation based on a successful reception of bursts and to the linear one-tap model being used for cancellation. In combination 56 dB of cancellation can be increased by additional 5 dB of cancellation for the case of two circuits. So, in total 61 dB of cancellation is reached for the complete system.

Finally, we merged both cancellation circuits into a single one. In this case, the maximum analog cancellation is degraded to 50 dB while the digital cancellation is increased to 12 dB. So, in total 62 dB has been reached, which matches the performance of the configuration with two separate circuits. Considering this, the internal *crosstalk* can be completely handled with only one circuit with a light degradation in the analog domain. Nevertheless, in combination with the digital cancellation the overall performance is still the same. The situation may change when amplifiers for higher transmit powers are considered within the communication system. Then, the amplifier will be placed between both circuits on the transmitter path and therefore, the working range of each network will be different.

## VI. Future Work

In the future, we want to improve our experimental setup to higher transmit powers of several watts, which is typical for military applications in the VUHF frequency bands. For this the mentioned amplifiers at transmitter and receiver side need to be included and RF components with higher maximum power are required.

Furthermore, the RF design, which uses a fixed pre attenuator for the XTC circuit, can be optimized to reduce the insertion loss at transmitter and receiver side. This could be done by replacing splitter/combiners with directional couplers with matching coupling factors. Additionally, the protection circuit with at least 20 dB of attenuation needs to be replaced by a special limiter for extreme low power levels. This is important to increase the dynamic range of the receiver system to a better signal to noise ratio. Otherwise, a development of the digital cancellation concept cannot be improved due to the missing dynamic range of the residual after AC and XTC.

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