Full-Duplex Radio – Increasing the Spectral Efficiency for Military Applications

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***Abstract*—This paper summarizes the results of the NATO STO IST Panel's Exploratory Team IST-ET-101. The team studied the *full-duplex radio technology* as an innovative solution to deal with the scarce and congested electromagnetic frequency spectrum, especially in the VHF and UHF bands. This scarcity is in strong contrast to the growing bandwidth requirements generally and particularly in the military domain. The success of future NATO operations relies more than ever on new real-time services going hand in hand with increased data throughputs as well as with robustness against and compatibility with electronic warfare. Therefore, future tactical communication and electronic warfare technologies must aim at exploiting the spectral resources to the maximum while at the same time providing NATO with an advantage in the tactical environment.**

Keywords—full-duplex radio, spectrum scarcity, tactical communications, electronic warfare

I. INTRODUCTION

The electromagnetic frequency spectrum is a limited resource, especially so in the VHF and UHF bands. On the other hand, there are growing requirements with respect to higher bandwidths especially in the military domain. The future of NATO operations does not only rely on real-time services and high data throughput in tactical communication. It is also about robustness against and compatibility with electronic warfare systems. Therefore, using the full spectral capacity is the key for future tactical operations to succeed. The availability of spectral resources should not depend on technological, but on operational circumstances.

In the past 10 years, researchers from different universities such as Stanford University, USA [1], Rice University, USA [2], and Tampere University of Technology, Finland [3][4][5], have demonstrated novel radio designs that are able to work in a real in-band full-duplex mode, i.e., simultaneously transmitting and receiving within the same frequency band. The systems are particularly interesting because they are using existing off-the-shelf software defined radio (SDR) components to perform the real-time signal processing. The full-duplex radio principle is a (r)evolutionary improvement compared to the current use of communication systems and multiple access methods based on time or frequency division multiplexing (TDD/TDMA or FDD/FDMA). As shown in the demonstrated designs in the civilian domain, the full-duplex radio is able to increase the spectral efficiency. However, the applications of the full-duplex radio technology to the military domain have not been investigated in detail so far.

The technical challenge regarding a simultaneous in-band operation is to sufficiently cancel the transmitted signal in the receiver part of the radio where the signal is leaked due to limited isolation between the transmit and receive path. Therefore, the cancellation mechanisms have to be exact since the transmitted signal (self-interference signal) may not only be of high power compared to the receiver noise floor but it also contains linear and non-linear distortions. Typically, the underlying self-interference cancellation system is divided into two cancellation stages, one in the analog radio frequency domain and the other in the digital baseband domain. In military applications, the capabilities of the self-interference cancellation need to be higher than in their civilian counterparts because of the typically lower transmit frequencies, higher transmit powers, and the requirements for better receiver sensitivity.

The underlying technology of full-duplex radio can also be used advantageously in lots of different military applications ranging from tactical communication and cognitive radio to jamming detection. A consistent integration of the real full-duplex technology in widely spread applications can have significant impact on spectral management with respect to the more efficient frequency usage. In addition, the full-duplex radio technology is a promising approach to efficiently combine communication and electronic warfare aspects.

The outline of this paper is as follows: In Section II we will briefly discuss the challenges of as well as the state-of-the-art solutions for the emerging full-duplex technology. Section III provides insights into a first multinational demonstrator proofing that it is in principle feasible to set up a military in-band full-duplex radio transceiver. In Section IV we will give examples for military applications beyond communications which might benefit from the technology in the future.

II. STATE-OF-THE-ART OF FULL-DUPLEX TECHNOLOGY

A. *Classic Approaches to Quasi Full-Duplex Operation*

For many decades, it was considered to be technically impossible to implement radio front ends that can transmit and receive simultaneously on the same frequency channel. The most important, but quite simple reason for this was that the self-interference which is caused by the transmit signal in the reception path is too strong. Typically, this self-interference is significantly stronger than the actually desired received signal. Due to the unbalanced power levels, it was

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This paper is based on NATO IST Panel activity ET-101 "Full Duplex Radio – Increasing the Spectral Efficiency for Military Applications".

considered technically impossible to extract the desired received signal from the mix of signals. The knowledge of the transmit signal did not significantly help at this point because it is generally known only in its pure form, but the various linear and non-linear effects that occur up to the reception path could not be modeled with the high precision needed for sufficient compensation.

However, in order to be able to offer users communication systems with quasi-duplex capabilities (full-duplex), time division (time division duplexing, TDD), frequency division (frequency division duplexing, FDD), or combinations of both have been proposed (see Figure 1). Here, time duplexing means that, although the same frequency channel can be used for transmission and reception, it is used alternately in time. Although the simultaneous transmission and reception is possible in the frequency duplex case, a greater outlay on transmitting and receiving components may become necessary due to the use of two separate frequency channels. It is also obvious in both methods that the highly demanded physical resources (time and frequency spectrum) are not efficiently used bi-directionally, as long as these domains can only be occupied direction-dependently.

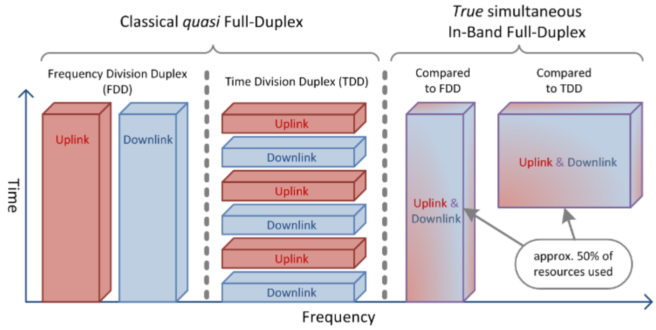


Figure 1: Classical quasi full-duplex operation versus true simultaneous full-duplex operation.

In 2013, results were published by the renowned Stanford University in California, USA [1], which among the first demonstrated that true full-duplex-enabled radio frontends can be realized with today's technologies. This true full-duplex operation leads to a considerable increase (ideally a maximum of doubling) in spectral efficiency over the classical duplex methods. In relayed networks the achievable gains can even be higher.

B. *New Approaches to True Full-Duplex Operation*

Besides that of Stanford University [1], further research works from different universities like Rice University, USA [2], and Tampere University of Technology, Finland [3], have demonstrated in-band full-duplex radio designs that are able to simultaneously transmit and receive within the same frequency band. The general concept, which is in common for all approaches, shall be explained next.

The key idea behind many approaches to *true full-duplex* operation is to find a powerful model or implement reconstruction for the self-interference component in the received signal such that an accurate estimate can be subtracted from the signal of the reception path. For this purpose, at least the dominant negative artefacts which cause the linear and non-linear distortion need to be properly modelled or reproduced.

The main reasons for the intrusion of interfering transmit signal components into the RX path are the non-ideal characteristics of both, the circulator and the connected antenna. The circulator is a non-reciprocal passive RF device that has several inputs/outputs (ports), each of which is intended to transmit unidirectional electromagnetic waves in the direction of rotation. But, due to the limited isolation of real-world circulators, there is some unintended leakage from the transmit path to the receive path (see also Figure 2). In addition, based on the assumption that COTS (commercial off-the-shelf) components are to be used for full-duplex radio frontends, a more or less pronounced mismatch can be anticipated with regard to the antennas used. This leads directly to the partial reflection of the transmit signal into the receive path via the circulator. Likewise, further reflections on the antenna side (e.g. from the near field environment) are coupled into the receive path.

When using IEEE Wi-Fi 802.11 as an example [1], the self-interference components need to be attenuated by approximately 110 dB. Such high attenuation needs to be realized in the analog and/or the digital domain. Both domains have their specific pros and cons. Therefore, a separation into both domains is recommended which typically leads to a *two-staged cancellation approach.*

A first reason for the separation of the cancellation process into different domains (digital baseband and analog carrier frequency) lies in the fact that the TX signal is affected by transmitters' noise-like imperfections. Since the noise that is mainly added and amplified in the transmit chain is inherently a non-deterministic distortion, it must be removed in the analog domain by an appropriately prepared copy of the transmit signal. The digital cancellation (DC) by definition requires a discrete modeling in time and value, and it has neither access to the random noise signal nor to its necessary equivalence in the sampled baseband domain. Thus, it cannot be predicted by an algorithm.

A second reason is given by the technical limits of the components in the RX chain, especially with respect to the input amplitude range of the analog-to-digital converter (ADC). To avoid its saturation and thus non-linear clipping effects, strong self-interference signal components should be cancelled to a certain level before they are fed into the RX path. Furthermore, a second cancellation stage in the digital domain may also be able to handle linear components caused by near field reflections. These ones may be out of range with respect to the practical and physical limitations of an analog cancellation stage that is based on a fixed delay line based analog circuit.

As related in [1] for IEEE Wi-Fi 802.11 as an example, 110 dB of cancellation needs to be achieved. If an ADC with 12 bit resolution is applied in the reception path and if 2 bits serve as a margin, the remaining 10 bits allow the system to provide a dynamic range of approximately 60 dB. If another 10 dB margin is taken into consideration in order to cope with the high peak-to-average-power-ratio (PAPR) of the OFDM-signal then the ADC requires a maximum input power level of -40 dBm. Consequently, a self-interference reduction of 60 dB needs already to be achieved in the analog domain. Thus, in case of a maximum transmit power of 20 dBm (100 mW) as well as a receiver noise level of -90 dBm, approximately 60 dB of cancellation needs to be realized in the analog domain and the remaining 50 dB suppression needs to be realized by digital cancellation.

C. *Key Conlusions from an Assessment of Several State-of-the-Art Prototypes*

The ET-101's assessment of a relevant subset of state-of-the-art prototypes leads to two general observations:

- Firstly, the feasibility of full-duplex operation has been convincingly proven for low-power commercial mobile communication systems in laboratory environments. Laboratory testing has the key advantage of reproducibility of the test results, but it typically suffers from operational relevance because of the idealized environmental conditions (e.g. indoor, limited ranges, no mobility). The state-of-the-art prototypes around the world achieve beyond 100 dB of total self-interference cancellation, even with rather large operating bandwidth (up to 80 MHz).
- Secondly, almost without exceptions, the existing experimental research is limited to the 2.4 GHz industrial, scientific, and medical (ISM) band only.

From these two observations, it follows immediately that in view of future military applications,

- The results need to be confirmed under more realistic conditions, e.g. in field environments for a selection of relevant operational scenarios. Compared to lab tests, field tests can better reflect outdoor conditions like communication ranges, multipath propagation, mobility (i.e., Doppler), and environmental interference. As an intermediate step between lab and field testing, sophisticated high dynamic range channel emulators might be considered;
- Further research is needed to confirm the prospects of full-duplex radios,
  - when operating in the mobile field environment, under e.g. multipath, fading, Doppler conditions.
  - at lower military frequencies, e.g., at HF, VHF, and UHF. Although modulation bandwidth is typically much smaller in military systems at lower carrier frequencies, frequency hopping still requires wideband self-interference cancellation.
  - at higher transmit powers, e.g., at 20 or even 50 Watts, to ensure higher communication ranges.

These conclusions have already motivated ET-101 to start working on a common multinational in-band full-duplex transceiver demonstrator.

III. FIRST INSIGHTS INTO THE INITIAL MULTINATIONAL IN-BAND FULL-DUPLEX TRANSCEIVER DEMONSTRATOR

Solving all the challenges (highlighted above) for utilizing the in-band full-duplex transceiver technology in military applications is beyond the scope of our Exploratory Team. Typically, an Exploratory Team paves the way for a follow-on Research Task Group (RTG) that gets more time and resources to study the topic under consideration. However, in order to prove that such a follow-on RTG is ready to work on solutions, an initial multinational in-band full-duplex transceiver demonstrator with two nodes has already been set up. For this purpose, an implementation of the NATO *Narrowband Waveform* (NBWF) [6], [7] from RMA, Belgium, has been used in an in-band full-duplex transceiver system from FKIE, Germany.

A. *FKIE's In-Band Full-Duplex Transceiver System*

At FKIE, a single-antenna in-band full-duplex radio has been designed that follows the original proposal from Stanford University [1]. That means that the self-interference cancellation is achieved in two stages, one in the digital and the other in the analog domain. Also similar to Stanford's non-military application, FKIE's proprietary OFDM waveform is used that is based on the IEEE 802.11 standard.

The upper part of Figure 2 shows the block diagram of the FKIE setup including the different types of interference (as introduced in Section II.B).

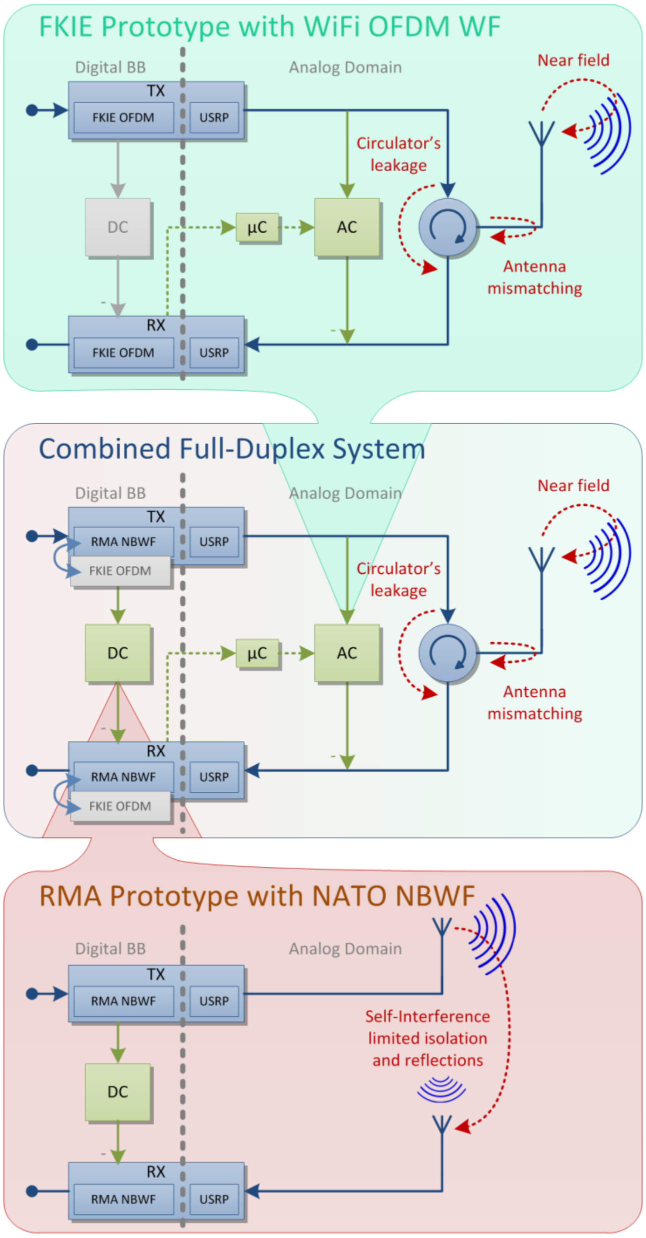


Figure 2: Block diagram of overall in-band full-duplex transceiver system.

The current prototype consists of a testbed with two full-duplex nodes that are able to communicate simultaneously in the same frequency band. The transmitter (TX) and receiver (RX) hardware are realized using USRP B205 mini COTS radio frontends from Ettus Research. The interfaces for the digital cancellation (DC) have already been specified, but the DC's functionality is currently deactivated. Like in Stanford's approach, the analog cancellation (AC) filter boards have been designed for 2.4 GHz Wi-Fi applications, i.e., the physical filter geometries are related to the wave length of $\lambda = 12.5\ cm$ (for a 2.4 GHz center frequency).

The AC board is a linear filter network consisting of eight delay lines, each with digitally adjustable step attenuators (DSAs) and equally distributed delays to handle linearly distorted self-interference components caused by the circulator and antenna. The network allows reconstructing a first estimate of the self-interference signal by a superposed linear combination, based on a tapped copy of the analog TX signal in the RF domain.

The filter coefficients can be configured by changing the attenuation values of the DSAs. With each of them covering a range of 128 attenuation values between 0 dB and 31.75 dB, the network provides $8^{128} \approx 2.7 * 10^8$ combinations or transfer functions, respectively. The attenuators can be set digitally via a serial bus every 2 µs per coefficient's change allowing quick responses on adapting to conditions within the circulator's path.

In order to find the best configuration of attenuation values, different iterative optimization algorithms can be applied. In the current FKIE's setup, they are all based on energy considerations. The default algorithm uses part of the incoming signal to calculate an averaged energy metric, while not separating its own self-interference signal from that (potentially) received from a distant radio. Another more complex algorithm is also able to distinguish signals that are fed into the RX branch that only include the self-interference signal for energy calculation. With the current prototype setup, the system can achieve up to 50 dB of cancellation with a maximum sample rate of 2 MSps in stable conditions.

B. *RMA's NATO Narrowband Waveform Implementation*

At RMA, a demonstrator for the *NATO Narrowband Waveform* (NBWF) [6], [7] has been set up. The block diagram is shown in the lower part of Figure 2.

The NATO NBWF is a modern *Combat Net Radio* (CNR) waveform with networking capabilities that shall serve for achieving interoperability among the NATO partner nations in multinational and combined missions. It offers several transmission modes, which support occupied bandwidths of 25 kHz and 50 kHz, the latter providing data throughput up to 82 kbps. It is supposed to operate primarily in the VHF, but also in the UHF frequency bands. Also in the demonstrator system from RMA, USRP B205 mini COTS radio frontends from Ettus Research are used to convert the waveform from the digital baseband to the actual analog transmit frequencies and vice versa.

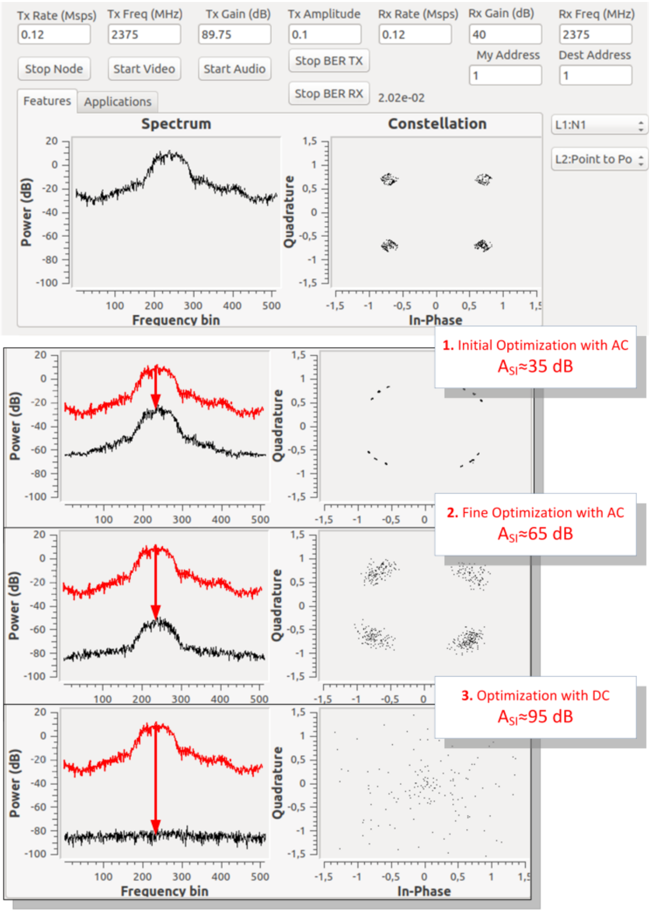
In addition, the demonstrator at RMA includes new digital cancellation software. Exploiting the knowledge of the predefined transmit sequences in the training period (header information) allows estimation of parameters like amplitude, frequency, time and phase offsets (of the self-interference signal).

C. *Combined In-band Full-Duplex Transceiver System*

The combination of both systems is illustrated in the center of Figure 2 yielding the initial version of the multinational in-band full-duplex transceiver system. The components related to the NBWF waveform as well as the DC are taken from RMA's demonstrator, while the overall system setup including the analog cancellation filter, as well as its configuration and control unit, are from FKIE.

The fact that both original setups were based on USRP B205 mini COTS radio frontends eased the integration process. The most challenging aspects were related to the transmit frequency as well as to the configuration and control of the attenuation values of the DSAs. Because FKIE's AC board had been designed for 2.4 GHz Wi-Fi applications, the NATO NBWF had to operate at the same frequency (even though it is intended for the military VHF and UHF bands). In addition, with respect to the configuration and control of the attenuation values, the relevant data for the energy measurements needed to be provided by RMA's implementation of the NATO NBWF.

After having solved the above challenges, the capabilities of the combined in-band full-duplex transceiver system have been demonstrated for a wide variety of applications ranging from bit error rate measurements up to real-time voice communications, using a *Mixed-Excitation Linear Predictive* (MELP) codec.



Tx Rate (Msps): 0.12
Tx Freq (MHz): 2375
Tx Gain (dB): 89.75
Tx Amplitude: 0.1
Rx Rate (Msps): 0.12
Rx Gain (dB): 40
Rx Freq (MHz): 2375
My Address: 1
Dest Address: 1
2.02e-02
L1:N1
L2:Point to Po

Figure 3: Self-interference cancellation performance of the combined full-duplex transceiver system.

The upper part of Figure 3 shows the graphical user interface (GUI) of the modified RMA NBWF software, where TX and RX frequencies are adapted with respect to FKIE's AC board. The waveform is operating in mode N1 with a signal bandwidth of 25 kHz and a modulation index $h = 1/2$. Note that the NBWF is using continuous phase modulation (CPM). Thus, four aggregations in the complex plane are displayed in the software's constellation diagram (when synchronized with the correct sample rate).

The combined system is able to achieve approximately 95 dB of total self-interference cancellation. The lower part of Figure 3 shows the self-interference cancellation in three steps, which are either based on the analog domain or the digital baseband domain. In the case shown, the compensation process is done in absence of an external incoming signal from a second transceiver node, i.e., the spectrum and constellation diagrams are always related to the transceiver's own transmit signal. A first initial optimization of the analog cancellation can reach about 35 dB. A second optimization, with the parameters of the AC's algorithm adapted, leads to approximately 65 dB of cancellation. For this step, the algorithm is configured to focus on the adjacent surroundings of the first optimization result, i.e., the search space is significantly reduced and scanned more granularly. The reason for the AC to reach more than 50 dB of self-interference cancellation (as mentioned in Section III.A) lies in the smaller bandwidth of the NBWF compared to the wideband OFDM waveform. With DC operating, a final overall cancellation of 95 dB is achieved, further improvement limited by the noise floor. This cancellation value is related to the self-interference power lever at the receiver's input. Thus, it does not include the isolation given by the combination of the circulator and the attached antenna. Also considering this additional isolation, of about 13 dB, will lead to a total compensation of almost 110 dB.

Both nodes were able to successfully operate in the simultaneous full-duplex mode, i.e., one direction can be used for a voice MELP service and the other one for a bit error rate (BER) measuring service and vice versa. The latter mentioned BER service is based on the transmission of a pseudo-random binary sequence, which, on the receiver side, is fed into a linear feedback shift register (LFSR) to allow an estimation of the BER, by averaging over counted bit errors within multiple packets.

The results achieved by the ET-101 prove that is feasible in principle to realize in-band full-duplex transceiver systems. This paves the way for a follow-on RTG activity in which the challenges resulting from typical military constraints (e.g. lower transmit frequencies, higher transmit powers) have to be addressed.

IV. EXAMPLES FOR AREAS OF MILITARY APPLICATION BEYOND TACTICAL COMMUNICATIONS

It is worth mentioning that the advantages of the full-duplex transceiver technology may not be limited solely to the increased spectral efficiency of two-way tactical communications. There exists a wide range of potential applications, where the full-duplex transceiver technology can also provide benefits especially in the military domain.

For instance, military full-duplex transceiver systems could allow armed forces to merge electronic warfare into tactical communications and, thus, establish novel combat tactics and techniques. In [5], the various options have been grouped into three main categories:

- information reception with simultaneous electronic attack
- signals intelligence during information transmission
- signals intelligence with simultaneous electronic attack

The first category allows the transmission of jamming signals while receiving data from a communication partner. The intent of the jamming signal can be either, for preventing opponents' receivers from operating, or for neutralizing improvised or radio controlled explosive devices, sensors, or drones. The second category allows activities like spectrum monitoring and signal surveillance during information transmission to be performed. Jamming detection during ones' own transmission is another potential area of application. The third category can be considered as a combination of the preceding two, where communication is not involved.

So far, the ET-101 did not perform an in-depth study of all the various options on how to merge communications with electronic warfare activities. Nevertheless, it is also on the roadmap for the follow-on RTG to go further into the details and to include some exemplary use cases in the multinational demonstration.

V. CONCLUSIONS

The IST-ET-101's analysis of the relevance of the emerging in-band full-duplex transceiver technology for future military applications has shown that it is in principle possible to build such transceivers. However, most findings published so far are not specific for military use cases and sideline constraints such as typical military frequency bands and transmit power. Further research is needed to evaluate and demonstrate the benefits of the in-band full-duplex transceiver technology in the military domains of tactical communications and electronic warfare. In addition, field tests have to be performed to increase the technology readiness level.

The results of IST-ET-101's analysis pave the way for an in-depth follow-on study. Thus, the results motivate the establishment of a Research Task Group on military full-duplex radio technology. Such a follow-on RTG might, for example, work on an extended demonstrator to show the benefits which are achievable in each of the above mentioned groups. For instance, in the spectrally efficient two-way tactical communications, the gain of the "true" full-duplex approach over a classic approach to "quasi" full-duplex operation can be determined.

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