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STO TECHNICAL REPORT **TR-IST-ET-101**

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

(La Radio Full-Duplex)

Report of Exploratory Team IST-ET-101.

Published January 2020

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The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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List of Acronyms

5G	5th Generation Mobile Networks
AC	Analog Cancellation
ADC	Analog-to-Digital Converter
AGC	Automatic Gain Control
AJ	Anti-Jamming
APIs	Application Programming Interfaces
AWGN	Additive White Gaussian Noise
BEL	Belgium
BER	Bit Error Rate
BFT	Blue Force Tracking
C4ISR	Computer Intelligence, Surveillance and Reconnaissance
CaP1	(NATO) Capability Panel 1
CIS	Communications and Information Systems
COP	Common Operational Picture
COTS	Commercial Off-the-Shelf
CPM	Continuous Phase Modulation
CVSD	Continuously-Variable Slope Delta Modulation Algorithm
CW	Continuous Wave
DAC	Digital-to-Analog Converter
dB	Decibel(s)
dBm	Decibel(s) related to 1 mW
DEU	Deutschland (Germany)
DSA	Digitally Adjustable Step Attenuator
EA	Electronic Attack
EFP	Enhanced Forward Presence
EP	Electronic Protection
ES	Electronic Support
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FKIE	Fraunhofer Institute for Communication, Information Processing and Ergonomics
FMN	Federated Mission Networking
FPGA	Field Programmable Gate Array
GHz	Gigahertz
GPP	General Purpose Processor
GUI	Graphical User Interface
HF	High Frequency
IBFD	In-Band Full-Duplex
IEEE	Institute of Electrical and Electronics Engineers
IMD	Intermodulation Distortion
IoT	Internet of Things
IP	Internet Protocol

ISM	Industrial, Scientific, And Medical
IST-ET	Information Systems Technology (Panel) – Exploratory Team
IT	Information Technology
kHz	Kilohertz
kSamples/s	Kilo-Samples per Second
LMA	Levenberg-Marquardt Algorithm
LMS	Least Mean Squares (Algorithm)
LNA	Low Noise Amplifier
LOS Comms CaT	Line Of Sight Communications Capability Team
LPC10e	Linear Predictive Voice-Coder (also known as STANAG-4198 and FS-1015)
LPD	Low Probability of Detection
LPI	Low Probability of Interception
L-REC	Rectangular Shaping Pulses
MAN 802.11 mil	FKIE Military Waveform based on IEEE 802.11
MANET	Mobile Ad Hoc Network
MC	Military Committee
MELP	Mixed-Excitation Linear Predictive Voice-Coder
MELPe	Mixed-Excitation Linear Predictive Voice-Coder Enhanced
MHz	Megahertz
MIMO	Multiple Input Multiple Output
MLE	Maximum-likelihood Estimation
MSamples/s	Mega-Samples per Second
mW	Milliwatts
NATO	North Atlantic Treaty Organization
NBWF	Narrowband Waveform
NC3A	NATO Consultation Command And Control Agency
NJFA	NATO Joint Civil/Military Frequency Agreement
NRF	NATO Response Forces
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio
PCB	Printed Circuit Board
RF	Radio Frequency
RMA	Royal Military Academy
RTG	Research Task Group
RX	Receive
SDR	Software-Defined Radio
SF-STAR	Same Frequency Simultaneous Transmit and Receive
SHF	Super High Frequency
SI	Self-Interference
SIC	Self-Interference Cancellation
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
SOM	Start of Message
SOMs	Start of Message – Short
STANAG	(NATO) Standardization Agreement
STO	Science and Technology Organization

TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TN	Technical Note
TRL	Technology Readiness Levels
TV	Television
TX	Transmit
UDP	User Data Protocol
UHD	USRP Hardware Driver
UHF	Ultra High Frequency
USA	United States of America
USRP	Universal Software Radio Peripheral
VHF	Very High Frequency
VJTF	Very High Readiness Joint Task Force
VST	Vector Signal Transceiver
WF	Waveform
WiFi	Wireless Fidelity (IEEE-802.11 Standard)
WRC	World Radiocommunication Conferences
ZIP	Data Compression Code

IST-ET-101 Membership List

CHAIR

Dr.-Ing. Marc ADRAT
Fraunhofer FKIE
GERMANY
Email: marc.adrat@fkie.fraunhofer.de

MEMBERS

Dr. Mark BOWYER
Airbus Defence & Space Ltd.
UNITED KINGDOM
Email : mark.bowyer@airbus.com

Dr. Ir. Vincent LE NIR
Royal Military Academy
BELGIUM
Email : vincent.lenir@rma.ac.be

Mr. Karel PÄRLIN
Rantelon Ltd.
ESTONIA
Email : karel@rantelon.ee

Ass. Prof. Taneli RIIHONEN
Tampere University
FINLAND
Email : taneli.riihonen@tuni.fi

Col. Prof. Bart SCHEERS
Royal Military Academy
BELGIUM
Email : bart.scheers@rma.ac.be

ADDITIONAL CONTRIBUTORS

Mr. Reinhardt KELLER
Fraunhofer FKIE
GERMANY
Email : reinhardt.keller@fkie.fraunhofer.de

Mr. Steffen WILDEN
Fraunhofer FKIE
GERMANY
Email : steffen.wilden@fkie.fraunhofer.de

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

(STO-TR-IST-ET-101)

Executive Summary

This report summarizes the results of the Exploratory Team IST-ET-101. The team studied the problem of a scarce and contested electromagnetic frequency spectrum, especially in the VHF and UHF bands. This fact 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 and with robustness against and compatibility with electronic warfare. Therefore, future tactical communication and electronic warfare technologies (electronic attack, electronic support, and electronic protection) must aim at using the full spectral capacity while at the same time providing NATO an advantage in the tactical environment. The availability of spectral resources should not depend on technological, but on operational circumstances.

In order to find a powerful solution for the problem the team has analysed the relevance of emerging in-band full-duplex transceiver technology for future military applications in the domains of tactical communications and electronic warfare. In-band full-duplex transceiver technology allows a device to simultaneously transmit and receive radio signals on the same frequency and allows use of a single antenna.

Historically, in-band full-duplex transceivers have been considered to be technically impossible due to the strong self-interference from the transmit path into the reception path of the transceiver. In the past, to avoid this self-interference problem, quasi full-duplex approaches have been proposed which, e.g., either use the same frequency at different times for transmit and receive operations (time division multiplex operation) or use different frequencies at the same time (frequency division multiplex operation). However, these are just means which allow the user to experience a full-duplex operation. Obviously, at the air interface, these quasi full-duplex approaches reduce the spectral efficiency when compared to a true in-band full-duplex transceiver which offers both types of operations at the same time on the same frequency.

The IST-ET-101's analysis of the relevance of the emerging in-band full-duplex transceiver technology for future military applications starts with the provision of relevant background information. To this end, two conflicting trends with respect to frequency spectrum are discussed.

On the one hand, the present and future tactical communication services in NATO-led operations like NATO Response Forces (NRF), Very High Readiness Joint Task Force (VJTF), Enhanced Forward Presence (EFP), and also in NATO initiatives like Federated Mission Networking (FMN) are raising more and more attention for the need for assured communications. Consequently, more military frequency spectrum is required to satisfy the information exchange needs in the wireless tactical communications domain. In addition, the information exchange needs to be protected against electronic warfare threats (e.g., intentional jamming, interception, reconnaissance).

On the other hand, frequency spectrum is a scarce and limited resource which cannot be augmented. This leads to the challenge to use the frequency spectrum as efficiently as possible. Several solutions to cope with the spectrum challenge are briefly discussed. One of them is the emerging in-band full-duplex radio technology.

In the next step of the IST-ET-101's analysis more details about this new technology are provided. In particular, it is highlighted that the intrusion of a self-interference signal in the reception path causes the key challenges for designing full-duplex systems. This self-interference signal needs at first to be modelled properly and secondly, be cancelled from the reception path. Some state-of-the-art approaches which have been proposed from researchers at different universities are briefly discussed. All of them have in common that they use a two-staged approach, one stage in the analog domain and another stage in the digital domain. Exemplary solutions for both stages are briefly discussed within this report.

The 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 a laboratory environment. Laboratory testing has the key advantage of reproducibility of the test results, but it typically suffers from operational relevance because of idealized environmental conditions (e.g., indoor, limited ranges, no mobility). The independent state-of-the-art prototypes around the world achieve beyond 100 dB of total Self-Interference Cancellation (SIC), even with rather large operation 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.

From these two observations it follows immediately that:

- Results need to be confirmed under realistic conditions, e.g., in field environments for a selection of relevant operational scenarios. Compared to laboratory tests, field tests allow to better reflect outdoor conditions like communication ranges, multipath propagation, mobility (Doppler), environmental interferences, etc. As an intermediate step between laboratory 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., 20 or even 50 Watts, to ensure higher communication ranges.

Some potential operational scenarios are also discussed, in particular, examples where the new full-duplex technology can beneficially be used in both military domains, tactical communications and electronic warfare. These examples are categorized in three groups:

- Spectrally efficient two-way tactical communications;
- Tactical communications with electronic warfare; and
- Signal intelligence with simultaneous electronic attack.

Finally, the IST-ET-101 has also provided an initial basic multinational demonstration which proofs that it is in principle feasible to set up a military demonstrator for an in-band full-duplex radio transceiver. For this purpose, an implementation of the NATO Narrowband Waveform (NBWF) of one ET-101 member nation has been used in an in-band full-duplex transceiver system of another ET-101 member nation.

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 side constraints such as typical military frequency bands and transmit powers. Further research is needed to evaluate and demonstrate the benefits of the in-band full-duplex transceiver technology in both military domains, 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 (RTG) 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 group the gain of the "true" full-duplex approach over a classic approach to "quasi" full-duplex operation can be determined.

La Radio Full-Duplex

(STO-TR-IST-ET-101)

Synthèse

Ce rapport résume les résultats de l'équipe exploratoire IST-ET-101. L'équipe a étudié le problème du spectre electromagnétique de fréquences qui est une ressource rare et contestée, particulièrement dans les bandes VHF et UHF. Ce fait entre en contradiction avec les exigences d'augmentation de la bande passante particulièrement dans le domaine militaire. Le succès des opérations de l'OTAN futures compte plus que jamais sur des services temps-réel et des plus grands débits de données incluant de la robustesse contre et de la compatibilité avec du matériel de guerre électronique. Par conséquent, les futures communications tactiques et les technologies de guerre électronique (attaque électronique, support électronique, et protéction électronique) doivent viser à utiliser la totale capacité spectrale tout en donnant à l'OTAN un avantage dans un environement tactique. La disponibilité des ressources spectrales ne doivent pas dépendre des circonstances technologiques, mais plutot opérationelles.

Afin de trouver une solution puissante au problème, l'équipe a analysé la pertinence de la nouvelle technologie d'émetteur-récepteur full-duplex en bande pour les futures applications militaires dans les domaines des communications tactiques et de la guerre électronique. La technologie des émetteurs-récepteurs full-duplex en bande permet à un appareil d'émettre et de recevoir simultanément des signaux radio sur la même fréquence et d'utiliser une seule antenne.

Historiquement, les émetteurs-récepteurs full-duplex en bande ont été jugés techniquement impossibles en raison de la forte auto-interférence de la chaine de transmission dans la chaine de réception. Dans le passé, pour éviter ce problème d'auto-interférence, des approches quasi full-duplex ont été proposées, qui utilisent, par exemple, la même fréquence à des moments différents pour les opérations d'émission et de réception (opération de multiplexage temporel) ou utilisent des fréquences différentes en même temps. (fonctionnement en multiplexage par répartition en fréquence). Cependant, ce ne sont que des moyens détournés permettant à l'utilisateur de faire l'expérience d'un fonctionnement en full-duplex. Évidemment, à l'interface air, ces approches quasi full-duplex réduisent l'efficacité spectrale par rapport à un véritable émetteur-récepteur full-duplex en bande, qui offre les deux types d'opérations au même moment sur la même fréquence.

L'analyse par IST-ET-101 de la pertinence de la nouvelle technologie d'émetteur-récepteur full-duplex en bande pour les futures applications militaires commence par la fourniture d'informations de base pertinentes. À cette fin, deux tendances contradictoires concernant le spectre de fréquences sont discutées.

D'une part, les services de communication tactiques présents et futurs dans des opérations dirigées par l'OTAN telles que NATO Response Forces (NRF), Very High Readiness Joint Task Force (VJTF), Enhanced Forward Presence (EFP), ainsi que dans les initiatives de l'OTAN comme Federated Mission Networking (FMN), attirent de plus en plus l'attention sur la nécessité de communications garanties. Par conséquent, davantage de spectre militaire est nécessaire pour répondre aux besoins en matière d'échange d'informations dans le domaine des communications tactiques sans fil. En outre, l'échange d'informations doit être protégé contre les menaces de guerre électronique (par exemple, brouillage intentionnel, interception, reconnaissance).

D'autre part, le spectre de fréquences est une ressource rare et limitée qui ne peut pas être augmentée. Cela nous oblige à utiliser le spectre de fréquences aussi efficacement que possible. Plusieurs solutions pour faire face au défi du spectre sont brièvement discutées. L’une d’entre elles est la technologie émergente de la radio full-duplex.

Dans la prochaine étape de l’analyse IST-ET-101, davantage de détails sur cette nouvelle technologie sont fournis. En particulier, il est souligné que l’intrusion d’un signal auto-interférant dans la chaine de réception constitue le principal défi de la conception de systèmes en full-duplex. Ce signal d’auto-interférence doit d’abord être modélisé correctement et, d’autre part, être annulé de la chaine de réception. Quelques approches de pointe proposées par des chercheurs de différentes universités sont brièvement présentées. Toutes ont en commun d’utiliser une approche en deux temps, une étape dans le domaine analogique et une autre dans le domaine numérique. Des solutions exemplaires pour les deux étapes sont brièvement présentées dans ce rapport. L’évaluation d’un sous-ensemble pertinent de prototypes à la pointe de la technologie conduit à deux observations générales:

- Premièrement, la faisabilité du fonctionnement en full-duplex a été prouvée de manière convaincante pour les systèmes de communication mobiles commerciaux à faible puissance dans un environnement de laboratoire. Les tests de laboratoire présentent le principal avantage de reproductibilité des résultats de test, mais ils souffrent généralement d’une faible pertinence opérationnelle en raison de conditions environnementales idéalisées (par exemple, à l’intérieur, portées limitées, sans mobilité). Les prototypes indépendants les plus récents dans le monde atteignent plus de 100 dB d’annulation d’auto-interférence totale (SIC), même avec une bande passante de fonctionnement relativement importante (jusqu’à 80 MHz).
- Deuxièmement, presque sans exception, la recherche expérimentale existante est limitée à la bande Industrielle, Scientifique et Médicale (ISM) de 2,4 GHz.

Il découle immédiatement de ces deux observations que :

- Les résultats doivent être confirmés dans des conditions réalistes, par exemple dans des environnements de terrain pour une sélection de scénarios opérationnels pertinents. Comparés aux tests de laboratoire, les tests sur le terrain permettent de mieux refléter les conditions extérieures telles que les distances de communication, la propagation par trajets multiples, la mobilité (Doppler), les interférences environnementales, etc. En tant qu’étape intermédiaire entre les tests de laboratoire et sur le terrain, des émulateurs sophistiqués peuvent être utilisés.
- Des recherches supplémentaires sont nécessaires pour confirmer les perspectives des radios full-duplex :
  - Lors d’un fonctionnement dans un environnement de terrain mobile, par ex. trajets multiples, atténuation, Doppler.
  - À des fréquences militaires inférieures, par exemple en ondes décamétriques, VHF et UHF. Bien que la largeur de bande de modulation soit généralement beaucoup plus petite dans les systèmes militaires à basses fréquences porteuses, le saut de fréquence nécessite toujours une annulation d’auto-interférence à large bande.
  - À des puissances d’émission supérieures, par ex. 20 voire 50 watts, pour assurer des distances de communication plus élevées.

Certains scénarios opérationnels potentiels sont également abordés, en particulier des exemples dans lesquels la nouvelle technologie de full-duplex peut être utilisée de manière avantageuse dans les domaines militaires, des communications tactiques et de la guerre électronique. Ces exemples sont classés en trois groupes :

- Communications tactiques bidirectionnelles à efficacité spectrale;
- Communications tactiques avec du matériel de guerre électronique;
- Intelligence du signal avec attaque électronique simultanée.

Enfin, l'IST-ET-101 a également fourni une première démonstration multinationale de base démontrant qu'il est en principe possible d'installer un démonstrateur militaire pour un émetteur-récepteur radio full-duplex en bande. À cette fin, une implémentation de la Narrowband Waveform (NBWF) de l'OTAN d'un pays membre de l'ET-101 a été utilisée dans un système d'émetteur-récepteur full-duplex en bande d'un autre pays membre de l'ET-101.

CONCLUSIONS ET RECOMMENDATIONS

L'analyse par IST-ET-101 de la pertinence de la nouvelle technologie d'émetteur-récepteur full-duplex en bande pour les applications militaires futures a montré qu'il est en principe possible de construire de tels émetteurs-récepteurs. Cependant, la plupart des conclusions publiées jusqu'à présent ne sont pas spécifiques aux utilisations militaires et aux contraintes secondaires telles que les bandes de fréquences militaires typiques et les puissances d'émission. Des recherches supplémentaires sont nécessaires pour évaluer et démontrer les avantages de la technologie d'émetteur-récepteur full-duplex en bande dans les domaines militaires, des communications tactiques et de la guerre électronique. De plus, des tests sur le terrain doivent être effectués pour augmenter le niveau de préparation de la technologie.

Les résultats de l'analyse d'IST-ET-101 ouvrent la voie à une prochaine étude approfondie. Les résultats ont donc motivé la création d'un groupe de travail sur la technologie de la radio militaire full-duplex. Un tel prochain RTG pourrait, par exemple, travailler sur un démonstrateur étendu pour montrer les avantages réalisables dans chacun des groupes susmentionnés. Par exemple, dans le groupe de communications tactiques bidirectionnelles à l'efficacité spectrale, il est possible de déterminer l'avantage de l'approche « véritable» en full-duplex par rapport à une approche classique du fonctionnement en «quasi» full-duplex.

FULL-DUPLEX RADIO: INCREASING THE SPECTRAL EFFICIENCY FOR MILITARY APPLICATIONS

1.0 INTRODUCTION

1.1 Motivation

The electromagnetic frequency spectrum is a limited resource, especially so in the VHF and UHF bands. This fact 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 and with robustness against and compatibility with electronic warfare. Therefore, future tactical communication and electronic warfare technologies must aim at using the full spectral capacity and providing NATO an advantage in the tactical environment. The availability of spectral resources should not depend on technological, but on operational circumstances.

In the past 10 years, researchers from different universities like Stanford University, USA [1], Rice University, USA [1], and Tampere University of Technology, Finland [3], [4], [5], [6], have demonstrated full-duplex 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. Applications of the full-duplex radio technology to the military domain have not been investigated in detail so far.

The technical challenge regarding the system constellation 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 (RF) domain and the second in digital baseband. In the military domain, the capabilities of the self-interference cancellation need to be higher than in the civilian domain because of the typically lower transmit frequencies, higher transmit powers, and the requirements for a 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 communications and electronic warfare applications.

Please notice that in the literature, full-duplex radios are also commonly called Same Frequency Simultaneous Transmit and Receive (SF-STAR) systems.

1.2 General Objectives

The key objective of this study is to explore the introduction of the full-duplex technology to the military domain. For this purpose, possible applications in tactical communications and in electronic warfare benefiting from the full-duplex principle are investigated. An initial study of the requirements and challenges for implementing full-duplex technologies in military environments is provided.

In particular, the following topics are addressed in this report:

- What is the state-of-the-art of full-duplex technology?
- Which military applications can benefit from using full-duplex technology?
- What are the specific requirements of these military applications influencing the use of full-duplex technology?
- Which challenges and opportunities appear for the integration of full-duplex principles?
- What are the short, middle, and long-term challenges and opportunities of the emerging full-duplex technology?

This study attempts, on one hand, to identify the basic requirements and key challenges and, on the other hand, to explore solutions and technologies. With this, the study aims at paving the way for more detailed experimentations and examinations (e.g., using a multinational technology demonstrator) in a follow-on activity in a Research Task Group.

1.3 Outline of This Report

The outline of the report at hand is as follows:

- Section 2.0 provides background information. In particular, it highlights two conflicting trends with respect to frequency spectrum. On one hand, the present and future NATO tactical communications requirements are asking for more military frequency spectrum to satisfy the information exchange needs in the wireless domain. On the other hand, frequency spectrum is a scarce and limited resource which cannot be augmented. This leads to the challenge to use the frequency spectrum as efficiently as possible. Several solutions to cope with the spectrum challenge are briefly discussed. One of them is the emerging full-duplex radio technology.
- Section 3.0 provides more details about this new technology. In particular, it is shown that the intrusion of a self-interference signal in the reception path causes the key challenges for designing full-duplex systems. First, this self-interference signal needs to be modelled properly and secondly, be eliminated from the reception path. Some state-of-the-art approaches which have been proposed from researchers at different universities are briefly discussed. All of them have in common that they use a two-staged approach, one stage in the analog domain and another stage in the digital domain.
- Section 4.0 gives examples where the new full-duplex technology can beneficially be used in both military domains, communications and electronic warfare.
- Section 5.0 provides insights into a first multinational demonstrator which proves that it is in principle feasible to set up a military in-band full-duplex radio transceiver. For this purpose, an implementation of the NATO Narrowband Waveform (NBWF) from the Royal Military Academy in Brussels, BEL, has been used in an in-band full-duplex transceiver system from Fraunhofer FKIE in Wachtberg, DEU.
- Finally, Section 6.0 provides conclusions from the preceding sections. In particular, it motivates the establishment of a Research Task Group on full-duplex radio technology. The follow-on RTG might, for example, work on a demonstrator to show the gains which are achievable with the “true” full-duplex approach if compared to classic approaches to “quasi” full-duplex operation.

2.0 BACKGROUND INFORMATION

The purpose of this section is to provide background information which shall motivate the application of full-duplex radio technology to communications and/or electronic warfare.

On one hand, the challenges of future tactical communications are briefly summarized. Due to the variety of emerging IT services, the need for sharing information wirelessly as well as the amount of data to be shared increases steadily. At the same time, the wireless communication system must operate in an environment in which it has to cope with manifold electromagnetic threats.

On the other hand, frequency spectrum is a scarce and limited resource. Therefore, an efficient use is essential to provide as many services as possible.

2.1 Tactical Communication Services in NATO-led Operations

In 2012, the NATO Consultation Command and Control Agency (NC3A) published a revised version of the Technical Note (TN) 1246 which describes a “Wireless Communications Architecture (Land): Scenarios, Requirements and Operational Views” [7]. This architecture serves as an outline for future NATO alliance and coalition operations in the land tactical domain. In particular, it contributes to NATO activities in the development of future waveforms and mobile ad hoc networking aiming at coalition interoperability, and their implementation through technologies such as software-defined radio. For instance, the NATO CaP1 Line of Sight Communications Capability Team (LOS Comms CaT) is a team of experts standardizing such future waveforms and mobile ad hoc networking capabilities.

In the TN 1246 several operational scenarios and vignettes were derived and discussed with respect to their information exchange requirements. It turned out that voice communications remains the primary type of service, but the roles of sharing Blue Force Tracking (BFT) information for a Common Operational Picture (COP) as well as for a situational awareness, of targeting information, of providing core services (like chat, Email, photographs, maps), of Functional Services (like data base access and replication), and of video is becoming more and more important.

More recently, a first draft of the Military Committee 640 (MC) on “NATO Minimum Scale of Communications and Information Systems (CIS) Capabilities in the Land Tactical Level” was published. The MC 640 provides a framework for the employment of common NATO Combat Net Radio waveforms. MC 640 gives guidance on how to use common and national waveforms in multinational tactical land environments. It is in particular of relevance for NATO-led operations like:

- NATO Response Force (NRF),
- Very High Readiness Joint Task Force (VJTF), and
- Enhanced Forward Presence (EFP).

Furthermore, for the implementation and operation of land tactical CIS services:

- NATO Federated Mission Networking (FMN) principles shall be applied and followed.

2.1.1 NATO Response Force

The NATO Response Force was established in 2003 as a high readiness force comprising land, air, sea and special forces units capable of being deployed quickly on operations wherever needed. Among other tasks, the primary objectives of NRF are to provide an immediate collective defence response capability, to support crises management and peace keeping operations as well as to perform disaster relief and to protect critical infrastructures.

2.1.2 Very High Readiness Joint Task Force

In 2014, the NATO Allies agreed on enhancing the capabilities of NRF further by establishing a Very High Readiness Joint Task Force which can be deployed within a few days. This evolutionary step became necessary because of the emerging threats at NATO's eastern and southern borders. The VJTF shall be able to be react at the first warnings and indicators of potential threats, i.e., even before an actual crisis appears. With this a further escalation of the threat shall be avoided.

2.1.3 Enhanced Forward Presence

Finally, because of the further developing threat at the eastern border, NATO Allies decided in 2016 to deploy four multinational battle groups in the four NATO nations most at risk, i.e., Estonia, Latvia, Lithuania and Poland. These four battle groups are known as NATO's Enhanced Forward Presence.

2.1.4 Federated Mission Networking

Federated Mission Networking is an initiative to support Command, Control, Communications, Computer Intelligence, Surveillance and Reconnaissance (C4ISR) as well as information sharing and decision making in multinational operations. For this purpose, an interoperable mission network shall be established. The development and standardization of FMN started in 2015 and it follows an incremental approach. The main focus of the initial increments (also called FMN spirals) was on wired networks. Future FMN spirals will also include the specifics of the wireless domain. Typically, the data throughputs in the wireless domain are significantly lower than in the wired domain. In addition, the signal processing algorithms and protocols on the lower layers as well as the actual applications on the higher layers need to be able to cope with unintentional (e.g., noise, propagation loss, multipath propagation) and intentional interferences (e.g., jamming).

Obviously, in all these NATO-led operations and initiatives there is a huge demand for establishing interoperable communication and information networks in order to be able to share all data of the emerging IT services. At the same time, these networks need to be protected against electronic warfare threats.

2.2 Military Frequency Spectrum for Land Mobile Communications

Frequency spectrum is a highly valuable, but limited resource under national sovereignty. In principle, each nation has the right, for its own territory, to decide how to assign specific frequencies to specific services at a specific location and at a specific time. However, for several reasons, e.g., for interoperability matters or for interference avoidance, it is of high importance to harmonize the spectral usage between the different nations. Such a harmonization happens at the World Radiocommunication Conferences (WRC) which takes place roughly every three to four years. The next one will be from October 28th till November 22nd, 2019 in Sharm el-Sheikh, Egypt.

The results of the World Radiocommunication Conferences are also considered in the NATO Joint Civil/Military Frequency Agreement (NJFA), which is a binding document for all NATO nations. From this follows that all NATO nations have to make sure that the military spectrum requirements set by the NJFA are also reflected in the national frequency allocation table.

The NJFA regulates the military access to the radio frequency spectrum in the range of 14 kHz to 100 GHz in peacetime, during exercises, in times of crisis, and in military operations. For this purpose, the NJFA contains tables specifying in different columns the specific frequency band, the service allocations used by military forces, the military requirements/usage, and the conditions of use.

Typical military frequency bands for land tactical mobile communications are:

• 1,6065 – 30 MHz	HF
• 30 – 87,5 MHz	VHF

225 – 450 MHz	UHF (NATO Band I)
610(790) – 960 MHz	UHF (NATO Band II)
1350 – 2000 / 2690 MHz	UHF (NATO Band III and III+)
4400 – 5000 MHz	SHF

However, it is worth mentioning that even if all these bands can theoretically be used for land tactical mobile communications this does not mean that there is an exclusive usage in practise. Typically, the frequency band mentioned above needs to be shared with other military services, like aeronautical radio navigation. In addition, various radio systems in the domain of land tactical mobile communications might be used simultaneously in the same band for coalition use and for several national uses of the coalition partners. In the past, where voice was the main communication means, this situation led to a natural shortage of military frequency spectrum.

Because all the other IT services mentioned in Section 2.1 (e.g., BFT, COP, Targeting Information, Core and Functional Services, Video) are gaining more and more importance in the contexts of NRF, VJTF, EFP, FMN etc., it can already be anticipated that the spectrum scarcity problem will intensify in the future. It is very unlikely that the military domain will get access to extra frequency spectrum to satisfy the increasing needs. Even if frequency spectrum can be freed throughout the modernization process of wireless services (e.g., the digital dividend when switching from analog TV broadcasting to a spectrally efficient full digital approach) the key profiteers can most probably be found in the civil/commercial domain. Typically, they have a strong political support to ensure the provision of wireless broadband services to anybody at any time and everywhere.

2.3 Spectral Efficiency: Challenges and Solutions

In the military domain, on one hand, the demand for transferring information wirelessly is steadily increasing (see Section 2.1). On the other hand, the frequency spectrum which is allocated for military applications is a limited and scarce resource (see Section 2.2). In order to cope with these conflicting trends, sophisticated techniques are required, which lead to an efficient use of the frequency spectrum. Spectral efficiency is typically quantified by the amount of data bits which are transmitted in a certain time period in a given frequency band. Thus, the unit of the spectral efficiency is bits/s/Hz.

To solve the spectrum efficiency issue, several solutions have been proposed in literature. The following list gives some examples but may not be considered as all-encompassing:

- **Data Compression** [8]. Data compression is applied at the application level and aims at reducing the amount of digital data to be transmitted. It is also called source coding. There exist lossless and lossy approaches to data compression. Both are of high relevance for military applications.

  A well-known example for a lossy data compression approach is voice coding. Typically, for a telephone like speech quality 8 kSamples/s quantized to (at least) 8 bit/sample are required, i.e., giving a gross data rate of 64 kbps. Voice codecs like STANAG 4209 CVSD (with 16 kbps), STANAG 4198 LPC10e (with 2.4 kbps), and STANAG 4591 MELPe (with 600 bps up to 2.4 kbps) allow reducing the data rate by factors of 4 (for 16 kbps) up to more than 100 (for 600 bps). However, such high compression factors can only be achieved if a reduced speech quality (intelligibility, clarity, noise freeness, etc.) is tolerated by the user.

  Another example for a lossless data compression approach is, e.g., ZIP coding, which can be applied to any data which contains redundancy.

- **Data Fusion** [9]. Data fusion is also applied at the application level and it aims at integrating the data information from several sources to a single result. Data fusion techniques can be classified into mainly three nonexclusive categories: data association, state estimation, and decision fusion (see Ref. [9]).

In the military domain, data fusion is of high relevance when, for example, several sensors provide information about the same source.

- **Cognitive Radio (Networks)** [10]. Cognitive radio networks try to solve the spectrum shortage issue at the network and medium access layer. For this purpose, they scan the radio environment and try to identify temporally and spatially unused spectrum. Measurements have shown that even if the entire frequency spectrum is assigned to dedicated services, that it is typically not used by the licensee to 100% in time and location. In such situations, a secondary user might take advantage of the free spectrum.

  The relevance of cognitive radios (networks) technology for military applications is currently intensively studied by other Research Tasks Groups like the IST-140 (Cognitive Radio Networks – Efficient Solutions for Routing, Topology Control, Data Transport, and Network Management) and IST-146 (Electromagnetic Environment Situational Awareness for NATO).

- **Efficient/Adaptive Coding and Modulation** [11], [12], [13]. On the physical layer, the digital data bits are transformed into an analog transmission signal, which is appropriate for the transmission over a wireless channel.

  On one hand, channel coding (aka forward error correction) adds redundancy to the signal, which can be exploited by the receiver to detect and/or correct transmission errors. The more redundancy is added, typically the higher the error correcting capabilities can be, but at the same time spectral efficiency gets lost.

  On the other hand, modulation maps one or more consecutive coded bits into a symbol. The more coded bits are mapped into one symbol, the higher the spectral efficiency becomes, but simultaneously the vulnerability against transmission noise typically increases.

  Consequently, the physical layers of most military digital communication systems in service today are designed for an anticipated worst-case scenario. However, in most of the use cases the channel condition is better than anticipated such that spectral efficiency is reduced. Thus, instead of finding only a single trade-off in the design decision, several modes for different channel conditions are designed and always the most suitable mode is chosen by adaptive algorithm.

  Among others, the Exploratory Team IST-ET-096 (Expeditionary 5G Technology) is looking at efficient/adaptive modulation and coding techniques in the context of 5G (fifth generation of mobile communications).

- **Multiple Input/Multiple Output (MIMO) Systems** [14], [15], [16]. Another physical layer approach to increase the spectral efficiency is known as MIMO technology. By using several transmit and receive antennas, benefit can be generated from the spatial separation. If uncorrelated and independent transmission channels between the antennas are assumed, the information theoretic channel capacity can be increased by roughly the minimum number of antenna elements at the transmitter or receiver side.

  The Exploratory Team IST-ET-096 is also looking at MIMO techniques in the context of 5G.

- **Full-Duplex Transceivers** [1]. Last but not least, full-duplex transceivers are also a promising physical layer approach to increase the spectral efficiency. In contrast to cognitive radios, which are searching for temporarily and spatially unused spectrum, full-duplex transceivers transmit their own signals while at the same time receiving a signal from another partner. Even though the own transmit signal interferes with the desired received signal in the reception path of a digital receiver and even if such self-interference is much stronger than the latter one, it has recently been shown from different recognized researchers that a bidirectional communication can still be guaranteed. For this purpose, the self-interference needs to be properly modelled and subtracted from the reception path.

  The role of the ET-101 on “Full-Duplex Radio – Increasing the Spectral Efficiency for Military Applications” is to study this approach in more detail and to assess its relevance for military use.

Before, the full-duplex radio technology will be discussed in more detail in the subsequent sections, it is important to note that the above mentioned approaches for increasing the spectral efficiency of digital communication systems are not mutually exclusive, but can be combined to a wide extent.

2.4 Benefits of Full-Duplex Technology Beyond Increasing the Spectral Efficiency

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

Some examples for such potential applications using the full-duplex transceiver technology for tactical communications and for electronic warfare will be discussed in Section 4.0.

2.4.1 Physical Layer Security

Physical Layer Security exploits asymmetries in channel quality between legitimate users and adversaries, and defines processing steps to guarantee secrecy at the physical layer [17], [18]. The mathematical foundations come from the field of information theoretic security and date back to Shannon's work on "perfect secrecy" in the 1940's and Wyner's work on "weak secrecy" in the 1970's. Two-way schemes use processing steps such as advantage distillation, information reconciliation and privacy amplification. Unlike conventional cryptography, the security achieved at the physical layer holds irrespective no matter how large the adversary's computational power. In recent years, there is much renewed interest in physical layer security due to perceived threat of Quantum Computers to break many established key agreement schemes.

In-Band Full-Duplex (IBFD) radios have intrinsic capabilities to support secure wireless communications [17], [19], [20]. In particular, an IBFD can transmit jamming signal while simultaneously receiving a secret key from another radio, at the same time and same frequency, to prevent an eavesdropper from receiving the same key.

2.4.2 Prevent Hidden Node Problem

Adverse propagation environments not only affect the wireless point-to-point links between tactical units but also impose stringent requirements on the networks, in which those radios operate. Typically, tactical networks have highly time-variant topologies and are expected to work in self-forming, self-healing, infrastructure-less manner without sacrificing data rate, end-to-end delay, nor tactical unit mobility. Developing cognitive algorithms that handle spectrum management, electronic battle tasks, and network topology adjustment for tactical networks has been considered one of the predominant challenges in designing radios for military networks [21]. Initially, Mobile Ad Hoc Networks (MANETs) were conceived for that exact purpose in the military domain and they have since been successfully adopted for use in the commercial domain [22]. In the military domain, MANETs enable opportunistic networks topologies to be created so that the self-forming and self-healing requirements are satisfied.

The most apparent benefit any such network can gain from integrating the full-duplex technology is the improved network throughput which in certain cases can be more than doubled despite the spectral efficiency only increasing by twofold. However, due to the typically asymmetrical data flow, imperfect self-interference cancellation, and increased inter-node interference, the increase in throughput is not always significant. Nevertheless, full-duplex radio technology has the potential to also enhance several other aspects of tactical networks which in turn can increase situational awareness and network security. One of the most notable challenges in MANETs is the hidden node issue that arises when a node is not aware that its intended recipient is already receiving a transmission because that transmission is not reaching the node which intends to transmit, i.e., the transmission is hidden. If the node, which is not aware of the already ongoing transmission also starts transmitting, then the recipient receives mixed signals and ultimately the information becomes corrupt. Consequently, the network throughput decreases as information has to be retransmitted. Through simultaneous reception and transmission, the recipient can, however, transmit a feedback or acknowledgement signal concurrently to receiving information. Therefore, by applying the full-duplex radio technology, the recipient informs any nodes in its range about the ongoing communications and prevents the hidden node issue from occurring as nodes know not to interfere with the ongoing communication [23]. Furthermore, since simultaneous sensing can be performed on a frequency band during transmission, each node can decide whether other nodes have simultaneously started transmitting and thus prevent multiple access collisions, the probability of which is increasing as the number of nodes grows.

2.4.3 Quadruple Capacity Gain in Wireless Networks

With regard to the spectral efficiency, it is one of the most obvious advantages of simultaneous in-band full-duplex radios to approximately double the capacity in a direct point-to-point communication. This is due to the fact that both sides can transmit and receive at the same time and therefore double the data throughput. However, it has been shown in Ref. [24] that in relayed networks the capacity can also be increased by a factor of up to four compared to networks with half-duplex nodes.

3.0 STATE-OF-THE-ART FULL-DUPLEX RADIO TECHNOLOGY

3.1 Classic Approaches to Quasi Full-Duplex Operation

For many decades, it was considered 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 (see Figure 1). Typically, this self-interference is significantly stronger than the actually desired received signal. Due to the unbalanced power strengths it was 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 in its pure form , but the various linear and non-linear effects that occur up to the reception path could not be modelled with such high precision which is needed for a sufficient compensation.

Nevertheless, in order to be able to offer users communication systems with quasi duplex capabilities (full-duplex), time division (time division duplexing, TDD) or frequency division duplexing (frequency division duplexing, FDD) and combinations of both have been proposed (see Figure 2). Here, time-duplex 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-dependent.

In 2013, results were published by the renowned Stanford University in California, USA [7], which for the first time demonstrate 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) of the spectral efficiency over the classical duplex methods. In relayed networks the achievable gains can even be higher as mentioned in Section 2.4.

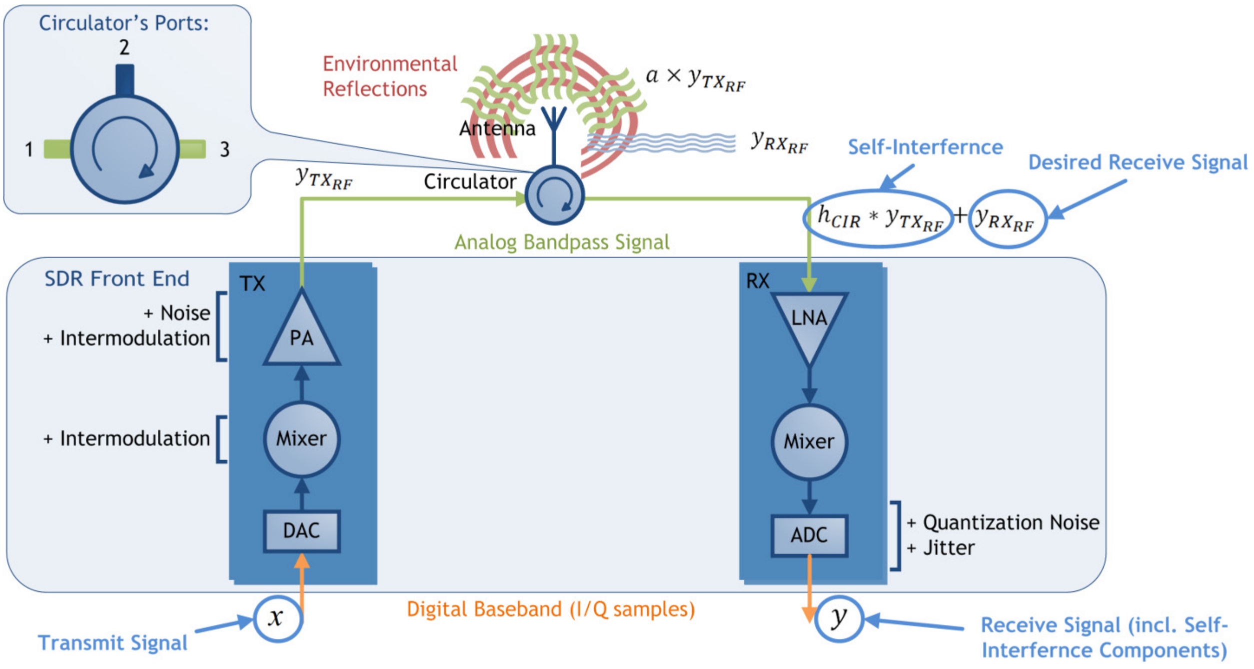


Figure 1: Block Diagram of an SDR Front End.

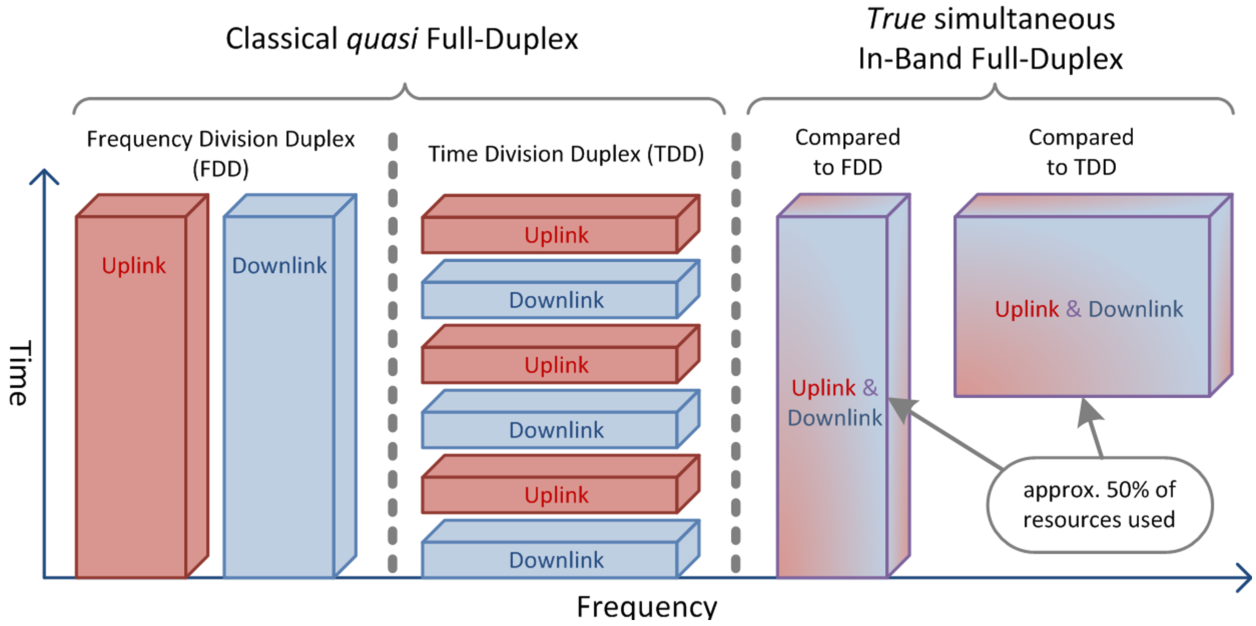


Figure 2: Classical Quasi Full-Duplex Operation Versus
True Simultaneous Full-Duplex Operation.

3.2 New Approaches to True Full-Duplex Operation

In the past 10 years, researchers from different universities like Stanford University, USA [1], Rice University, USA [1], and Tampere University of Technology, Finland [3], [4], [5], [6], have demonstrated full-duplex radio designs that are able to work in a true in-band full-duplex mode, i.e., simultaneously transmitting and receiving within the same frequency band. Before the key principles behind their approaches are briefly reviewed in Sections 3.2.1 to 3.2.4, the general concept which is in common for all approaches shall be explained next.

3.2.1 Common Concept Behind All Approaches to True Full-Duplex Operation

The key idea behind all approaches to true full-duplex operation is to find a powerful model or use a 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 distortions need to be properly modelled or reproduced.

3.2.1.1 Intrusion of Self-Interference into the Reception Path

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.

A circulator (see also Figure 1) 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. For practical application in a full-duplex radio, the scattering parameter S_{31} is of particular importance. It specifies the transmission and thus the blocking effect or isolation between Ports 1 and 3 (see Figure 1), i.e., the direct path between the transmit and receive paths.

Based on the assumption that Commercial Off-The-Shelf (COTS) 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 at Port 2 of the circulator and thus – even with ideal scattering parameters of the circulator – to a leakage of T from the transmit to the receive path. Likewise, further reflections on the antenna side (e.g., from the near field environment) are coupled into the receive path.

3.2.1.2 Using IEEE WiFi 802.11 as an Example

The authors of Ref. [1] provided some link budget considerations for an IEEE WiFi 802.11 application as an example. According to the specification the maximum transmit power is 20 dBm (100 mW). If a receiver noise level of -90 dBm is assumed, then the self-interference component needs to be reduced by approximately 110 dB to ensure the necessary Signal-To-Noise Ratio (SNR) as it would be given by non-full-duplex receivers. Measurements in Ref. [1] have also shown that a typical circulator will already attenuate the signal in isolation direction (S_{31}) by about 15 dB within the desired frequency band, even if this isolation must not be seen as frequency-independent.

Thus, when using IEEE WiFi 802.11 as an example, the self-interference component needs to be attenuated by approx. 110 dB resp. 95 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.

3.2.1.3 Two-Staged Cancellation Approach

A first reason for the separation of the cancellation into different domains (digital baseband and analog carrier frequency) lies in the fact that the TX signal is affected by transmitter noise. 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 by definition requires a discrete modelling 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 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.

Figure 3 shows the example from Ref. [7]. 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 providing a dynamic range of approx. 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 an OFDM-signal like IEEE WiFi 802.11 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.

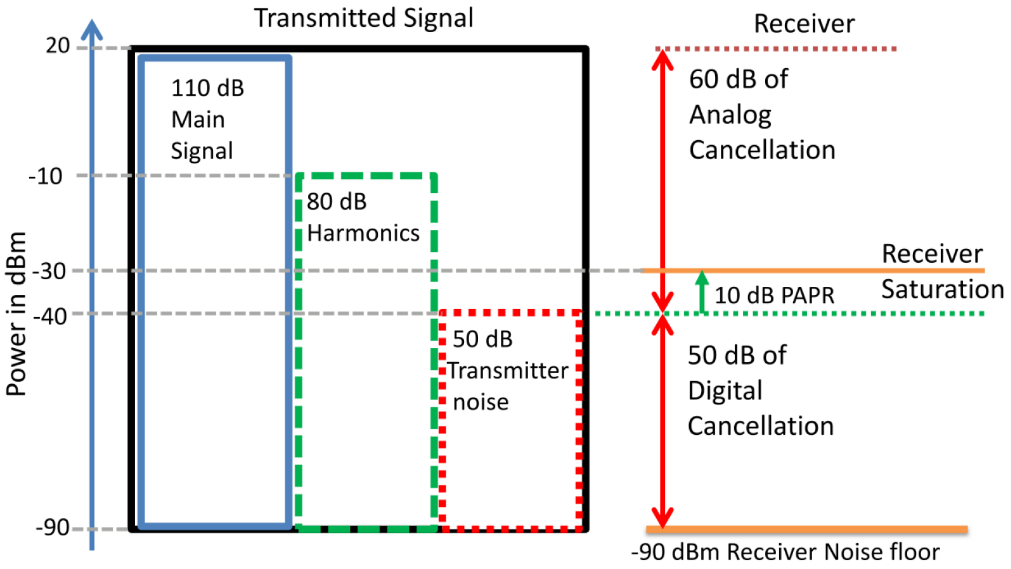


Figure 3: Link Budget Considerations for IEEE WiFi 802.11 (Neglecting the 15 dB Isolation of Typical Circulators).

Again, for many decades it was considered to be impossible to achieve the required attenuation in a real-world application. However, as mentioned before, researchers from different universities have demonstrated that true full-duplex radio designs are possible with COTS radio components. This is remarkable since these commercial components, especially the radio front end, are expected to cause additional and also non-linear distortions that will further increase the challenge of modelling and cancelling a concrete self-interference signal with respect to the digital domain. Besides Intermodulation Distortions (IMDs) coming from non-linear components like the Power Amplifier (PA) in the TX chain of the front end or the mixers, there are also other imperfections to be expected like jitter as well as a limited crosstalk isolation between TX and RX chain regarding the required WiFi power budget.

3.2.2 Stanford University, USA

One widely recognized architecture for a single antenna in-band full-duplex radio has been proposed by the researchers from Stanford University, USA [7]. The architecture is shown in Figure 4. It follows the concept already described in Section 3.2.1, i.e., in order to cope with the self-interference problem, it considers two cancellation stages, one in the analog domain and one in the digital domain.

Similar to Figure 1, the blocks transmitter (TX) and receiver (RX) correspond to the transmission and reception paths of a conventional radio front end with all the relevant components between the digital baseband (T_b and R below the ADC, analog-to-digital converter) and the antenna with the analog transmit or received signal (T or C or R). The signal C represents a copy of the transmission signal T. The linear terms aT and iT correspond in a simplified manner to the self-interference signal which is superimposed on the actually desired received signal R.

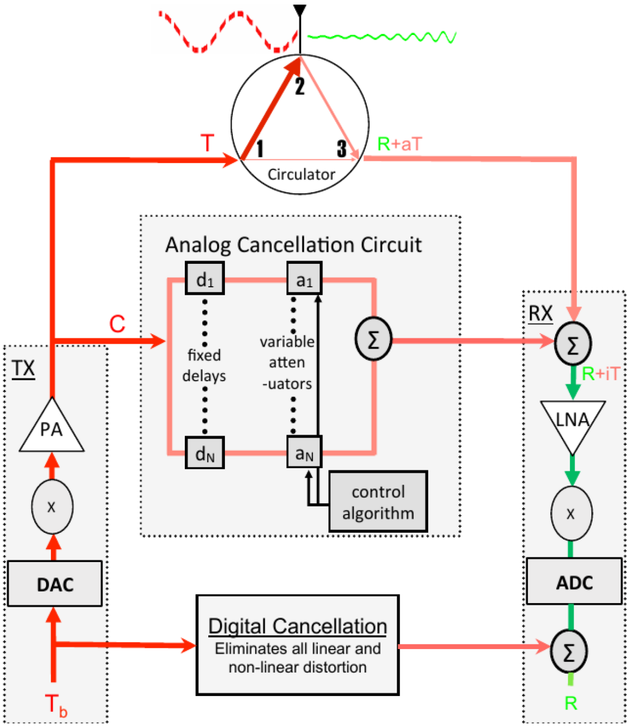


Figure 4: Full-Duplex Radio Architecture Proposed by Stanford University [1].

The factor i weights the residual portion of the self-interference components after the application of an Analog Cancellation Circuit (henceforth Analog Cancellation or AC). The elimination of these remaining interference components iT, more precisely their representation in the digital baseband, is the task of the Digital Cancellation.

3.2.3 Rice University, USA, and Other Prior Designs

In contrast to the Stanford full-duplex architecture mentioned in Section 3.2.2, the design of the Rice University, USA [25] uses an extra transmit chain in addition to the main transmit chain with at least an additional DAC, mixer and PA. This extra chain generates a cancellation signal that is combined with the signal on the receive chain to cancel the self-interference signal. However, besides possible benefits with respect to MIMO applications (as mentioned in Ref. [25]), additional chain components can be seen as modification of the underlying transceiver hardware design. Figure 5 shows the Rice University design in comparison to the architecture given by Stanford University.

Like the original Rice design is based on multiple antennas, there are several other prior designs (Refs. [26], [27]) using at least two antennas, also to realize a sufficient cancellation performance by allowing an increased RX/TX isolation compared to the use of a circulator.

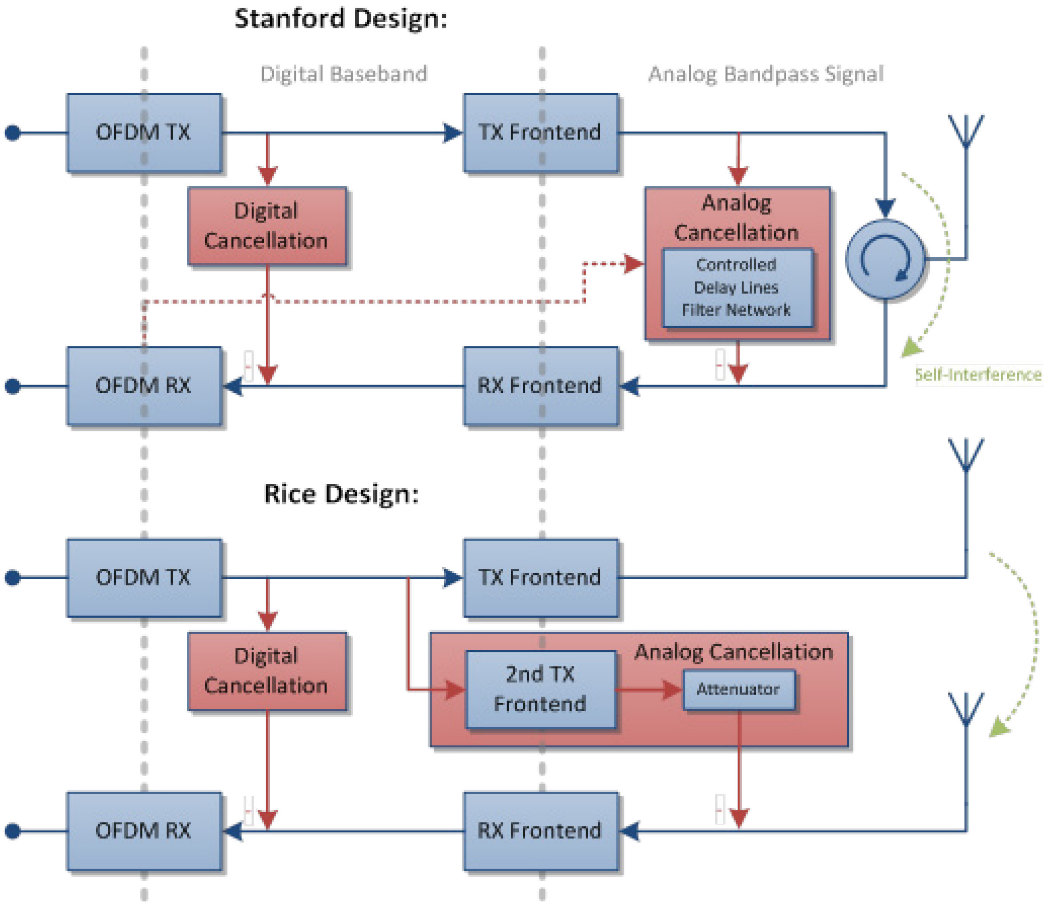


Figure 5: Full-Duplex Radio Designs in Comparison; Top: Stanford University, Bottom: Rice University.

3.2.4 Tampere University, Finland

Similar to the Stanford architecture, a research group from Tampere University, Finland, has performed experiments on a prototype full-duplex radio with two separated cancellation stages, one in the digital and one in the analog domain [28]. The difference lies in the encapsulated real-time implementation of an independent analog RF canceller with the use of an FPGA, where Least Mean Squares (LMS) weight adaptation for the delay lines is fed by received and self-interference signals. As for digital cancellation, their research has paid particular attention to the non-linearity of a transmitter Power Amplifier (PA) and I/Q imbalance. These imperfections require the implementation of non-linear and widely linear channel estimation and SI cancellation algorithms for effective SI suppression, respectively, in contrast to basic linear processing [28]. The non-linear distortion caused by the PA in the transmitter is concluded to be typically the dominating factor. The benchmark results for digital cancellation figures are obtained with offline processing after recording the digital waveform with a high-quality Vector Signal Transceiver (VST) while real-time online version with lower SI suppression can be used for demonstration purposes.

The main technical challenge in non-linear digital cancellation is to model the power amplifier accurately while simultaneously restricting the complexity of processing. The research group from Tampere University has contributed especially on this front [28]. The simplest memoryless non-linear models turn out to be highly ineffective for the problem at hand. Thus, most of solutions in literature utilize a memory polynomial signal model that, however, is not capable of modelling the SI signal accurately with very high-power amplifiers. A Volterra-series-based model, on the other hand, remains accurate also under the more complex distortion waveforms produced by the high-power amplifiers, thereby providing the necessary amount of digital cancellation even with very large transmit powers. However, this comes at the cost of rather high complexity in estimating the model's parameters and non-linear filtering.

3.2.5 Algorithms for Digital and Analog Cancellation

Cancellation stages in the digital and analog domain require appropriate algorithms. Since the self-interference signal is affected by different distortions, both stages will have different requirements for their algorithms.

3.2.5.1 Analog Cancellation

Assuming the Stanford approach, the analog cancellation has to be controlled in a manner so that the delay lines filter network can reconstruct the channel between TX and RX chain, i.e., the circulator's path's transfer function. Therefore, the WiFi OFDM waveform and its training procedure could be used to derivate the necessary channel information during operation. Note that from the network's perspective, the self-interference signal being fed into the receive path is only linearly distorted. With a known filter network, i.e., its measured transfer functions, there might be different ways of solving this optimization problem.

3.2.5.1.1 Closed Form Solution

A closed form solution is based on a linear system to directly solve the least squares problem. The algorithm can benefit from its computation speed and possible accuracy, but it is sensitive to the used model of transfer functions and due to the need of a discretization procedure and other practical issues it has high complexity.

3.2.5.1.2 Iterative Algorithms

In contrast to direct methods, iterative algorithms can have less or even no requirements on an underlying model function since the estimation steps may only be triggered by a feedback metric, e.g., measure of self-interference power. Algorithms to be used vary from Simulated Annealing, Threshold Accepting and Local Search.

3.2.5.2 Digital Cancellation

The main principle behind the digital cancellation stage is the preamble-based channel equalization on the path between TX and RX chain of the SDR-Frontend. In contrast to the circulator's path with regard to the analog cancellation, the self-interference signal is now assumed to be also distorted in a non-linear manner. This is caused by the fact that the signal flow is now also affected by non-linear devices within the TX and RX chains, mainly the PA and mixers. Following the Stanford approach, it shall be sufficient to use an algorithm based on the linear Maximum-Likelihood Estimation (MLE), even if this algorithm has to be modified to also cover the non-linear problem including a model of intermodulation distortions.

As a common representative algorithm for unconstrained non-linear optimization, the Levenberg-Marquardt Algorithm (LMA) could also be chosen to estimate the distortions contained in the self-interference signal.

Both cancellation stages act in different domains each with a representation of the self-interference signal that is affected by different distortions. This is not only related to the above mentioned linearity or non-linearity of the distortions but also to some time constraints. Besides different requirements on the performance in terms of each cancellation stage's convergence time, both stages cover different time durations with regard to linear self-interference components, i.e., signal reflections either caused by the antenna-circulator combination (leakage, mismatching and antenna characteristics) or by near field environment.

3.2.6 Summary of State-of-the-Art Prototypes

In recent years, various full-duplex radio transceiver prototypes or demonstrator implementations for self-interference cancellation have been reported in the literature. As originally summarized by D. Korpi in his doctoral dissertation, Table 1 collects the key specifications and performance figures of the most notable prototype implementations [28]. It should be noted that, unless otherwise mentioned, the total amount of Self-Interference Cancellation (SIC) listed in the table for each prototype includes also the passive suppression, i.e., it is calculated as a difference between the transmit power and the residual self-interference power after all the considered cancellation stages. Moreover, all the SIC figures cannot be compared fairly, because some experiments focus on analog cancellation only and the total amount of SIC would likely be much larger when combined with digital cancellation.

Table 1 leads to two general conclusions.

- Firstly, the feasibility of full-duplex operation has been convincingly proven for low-power commercial mobile communication systems in a laboratory environment. The independent state-of-the-art prototypes around the world achieve beyond 100 dB of total SIC, even with rather large operation bandwidth (up to 80 MHz).
- Secondly, almost without exception, the existing experimental research is limited to the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. Further research is still needed to confirm the prospects of full-duplex radios at lower military frequencies, e.g., at HF, VHF and UHF bands (see Section 2.2). Although modulation bandwidth is typically much smaller in military systems at lower carrier frequencies, frequency hopping still requires wideband self-interference cancellation.

Table 1: The Key Specifications and Performance Figures of Landmark Prototypes for Self-Interference Cancellation, Based on Ref. [28]. The implementations are SISO unless otherwise mentioned.

Prototype	Year	Frequency Band	BW [MHz]	Architecture	Analog Cancellation	Digital Cancellation	SIC [dB]
MIT [29]	2007	370 MHz	0.1	7 × 3 MIMO relay	No	Yes	60
Rice [30], [2]	2010	2.4 GHz	0.625	Two antennas	Yes	Yes	80
Stanford [27]	2010	2.48 GHz	5	Three antennas	Yes	Yes	100
Stanford [26]	2011	2.4 GHz	10	Wired setup	Yes	Yes	73
NYU Poly [31]	2012	915 MHz	7	Shared antenna	Yes	No	59
Rice [32], [33]	2012	2.4 GHz	20	2 × 1 MISO	Yes	Yes	85
Stanford [1]	2013	2.45 GHz	80	Shared antenna	Yes	Yes	110
Rice [34]	2014	2.4 GHz	20	Directional	Yes	Yes	95
Stanford [35]	2014	2.45 GHz	20	3 × 3 MIMO	Yes	Yes	104
Chengdu [36]	2014	2.535 GHz	20	2 × 2 MIMO	Yes	Yes	114
Bristol1 [37]	2015	1.89 GHz	20	Shared antenna	Yes	No	83
FhG HHI [38]	2015	2.4 GHz	20	Shared antenna	Yes	No	54
Irvine [39]	2015	2.5 GHz	10	Reconfigurable	No	Yes	95

Prototype	Year	Frequency Band	BW [MHz]	Architecture	Analog Cancellation	Digital Cancellation	SIC [dB]
Yonsei [40]	2015	2.52 GHz	20	Dual-polarized	Yes	Yes	103
Aalborg [41]	2016	2.4 GHz	80	Two antennas	Yes	Yes	100
MIT [42]	2016	2.45 GHz	20	Shared antenna	Yes	No	78
TCL [43]	2016	2.48 GHz	5	Two antennas	Yes	Yes	70
TUT&Intel [44]	2016	2.46 GHz	80	Shared antenna	Yes	Yes	88
TUT&Aalto [45]	2017	2.56 GHz	80	Compact relay	No	Yes	100
FhG FKIE	2018	2.4 GHz	2*	Shared Antenna	Yes	No	50*

***Note:** The limitation in bandwidth is mainly given by the non-fully-optimized C++ waveform implementation running on a GPP. The value of SIC is given excluding the additional isolation of the used circulator which brings further 23 dB.

4.0 APPLICATION OF FULL-DUPLEX TRANSCEIVERS IN THE MILITARY DOMAIN

4.1 Application to Communications and Electronic Warfare

In the above section, we established the prospects of implementing an individual full-duplex radio transceiver that is suitable for practical usage in the military domain. In this section, we move forward to explaining how to actually employ such devices in the battlefield presuming that we already have some with sufficient self-interference cancellation capabilities at hand. Figure 6 illustrates some of the key applications that can be envisioned and are discussed next. Theoretical work to characterize all potential military applications of the full-duplex radio technology begun in the end of 2016 as related in Refs. [3], [4]. The final outcomes of the Finnish national exploratory team's research in 2017 have been reported in Refs. [5], [6].

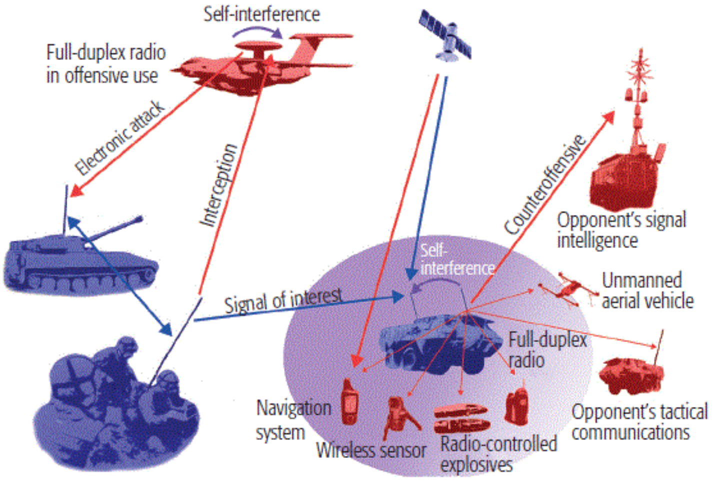


Figure 6: General Overview of the Applications of the Full-Duplex Radio Technology to Tactical Communications and/or Electronic Warfare [5].

The potential applications can be classified as shown in Figure 7. The usage of military full-duplex radios not only facilitates spectrum-efficient two-way information transfer, but they also allow armed forces to merge electronic warfare into tactical communications and, thus, establish novel combat tactics and techniques pertaining to information reception with simultaneous electronic attacks and signals intelligence during information transmission or an electronic attack.

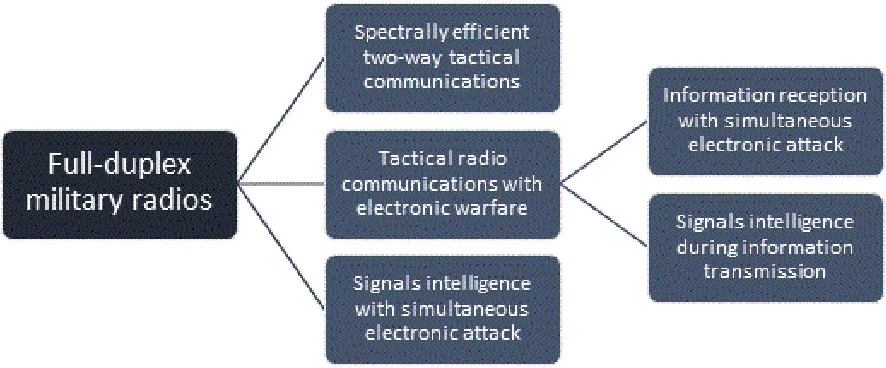


Figure 7: General Classification of the Military Applications of the Full-Duplex Radio Technology.

4.2 Spectrally Efficient Two-Way Tactical Communications

When using full-duplex radio technology for improving the spectral efficiency of tactical communication networking, its purpose is not much different from that of the corresponding technology which was originally developed in the non-military (i.e., civilian/commercial) domain. For example, in ad hoc networking, a cluster head or a gateway node may simultaneously receive information from one node while transmitting information to another one at the same frequency channel. This can yield even doubled spectral efficiency, i.e., data rate per allocated spectrum, which is a significant advantage considering how congested and limited military spectrum allocations are. Conceptually, the cluster head and the gateway can be seen as equivalent to a base station or an access point and a relay station, respectively, so that much of the theory developed for cellular networking can be rather directly transferred to tactical communications.

The main differences in two-way communications between the military and non-military domains arise from the typical frequency bands in use and operation conditions in the battlefield. Firstly, many military communication systems operate at High or Very High Frequency (HF or VHF) bands instead of commercial cellular mobile radio bands. Thus, practical military scenarios are rather different from academic laboratories, where the corresponding technology is already demonstrated to be feasible for non-military use at upper Ultra High Frequency (UHF) bands, usually at the 2.4 GHz Industrial, Scientific and Medical (ISM) radio band. However, this is mainly a transceiver design aspect that does not directly relate to applications. Secondly and perhaps more importantly, the military applications face many challenges that are strange to non-military domain, including the extreme requirements for bandwidth, latency, stability, sensitivity, security, connectivity, reliability, etc. Full-duplex radio technology is not only subject to these challenges, but it can also facilitate their solutions, especially as per bandwidth, latency and topology awareness.

4.3 Tactical Communications with Electronic Warfare

In this category, military full-duplex radios allow combining tactical radio communications with the capability of performing electronic attacks (transmission) or signals intelligence (reception). The radios are either receiving or transmitting communication signals at the same time that they are conducting the non-communication function in the respective transmit or receive direction.

4.3.1 Aspects of Electronic Warfare

Electronic Warfare can be categorized in three main tasks: Electronic Support (ES), Electronic Attack (EA) and Electronic Protection (EP). While ES and EA deal with the communication signals of a potential enemy, EP deals with one's own communication signals.

The purpose of Electronic Support is to get a better understanding of the enemy's communications. Examples for ES measures are Search, Intercept, Direction Finding and Signal Analysis. These measures are commonly considered to be passive measures because they do not have any influence on the signal under consideration and therefore, they cannot be observed by the enemy. The findings of the ES measures can be used in the own decision-making process.

The purpose of Electronic Attack is to have influence on the enemy's communication. Ideally, the EA measures prevent the enemy from exchanging mission critical information, in order to gain information superiority. Examples of EA measures are jamming, deception and neutralization. In contrast to the ES measures, the EA measures are active because they require the emission of signals. Typically, these emissions take aim at the receiving end of the enemy's communication (and not at the transmitter). Due to the radio emissions, the EA measures can be observed by the enemy.

The purpose of Electronic Protection is to make one's own communication more robust against the ES and EA means of the potential enemy. Electronic Protection can be both, passive and active. Examples for passive EP measures are shielding, emission control, directional antennas, hiding, etc. Typically, the passive EP measures aim at reducing the enemy's ES capabilities. Examples for active EP measures are Encryption, Low Probability of Detection (LPD), Low Probability of Interception (LPI) and Anti-Jamming (AJ) means. For instance, direct sequence spread spectrum is a powerful mean for LPD, LPI and AJ. The active EP measures serve the purpose to limit the effectiveness of the enemy's ES and EA measures.

4.3.2 Information Reception with Simultaneous Electronic Attack

In Figure 6, the applications pertaining to this class assume that the Electronic Attack is transmission of a jamming signal, which prevents opponents' receivers from operating in the vicinity while the full-duplex transceiver is capable of simultaneously receiving tactical communication signals from its own team. The enemy receivers to be neutralized this way could be those in improvised or radio-controlled explosive devices, sensors or drones. Jamming or spoofing satellite navigation receivers also falls into this category.

4.3.3 Signals Intelligence During Information Transmission

The full-duplex radio technology allows also incorporating signals intelligence into tactical radios. The devices could perform spectrum monitoring and signal surveillance. Without full-duplex capability, the opponent gets an opportunity to hide its transmissions by making them take place concurrently at the same frequency channel with our own team's tactical communications, because there is no self-interference cancellation to eliminate the masking effect in the conventional case.

4.4 Signals Intelligence with Simultaneous Electronic Attack

In this category, the full-duplex transceiver conducts an Electronic Attack, usually jamming, simultaneously with spectrum monitoring and signals surveillance. A simple example scenario highlights the potential of such applications. Let us assume that one transmits jamming to its opponent in order to decrease the quality of its tactical communication link which obviously also decreases the link quality for interception or locating the transmitter. However, an inadvertent opponent typically tries to compensate for the effect of jamming by simply its increasing transmission power in order to achieve some minimum link quality by which the link quality for interception increases too assuming that self-interference cancellation works well. If controlling the power levels well, it is probable that the signal quality for interception is actually better with jamming than without it despite the residual self-interference. In other words, it may be worthwhile to tolerate self-inflicted performance loss in order to gain back much more from the opponents' countermove.

5.0 DEMONSTRATION OF MILITARY WF INTEGRATED INTO FULL-DUPLEX TESTBED

5.1 Scope

This section shall serve as an introduction of the full-duplex principle into the military domain by demonstrating a prototype system with a military waveform. The resulting demonstrator was set up based on the prior work of the Fraunhofer FKIE on a full-duplex framework including analog cancellation as well as the Belgian RMA who is providing a military waveform with a digital cancellation capability.

5.2 Fraunhofer FKIE Framework

The Fraunhofer FKIE framework (Figure 8) is based on the single-antenna full-duplex radio design as it was originally proposed by Stanford in 2013 [1]. Following the description in Section 3.2.1, the full-duplex capability is achieved with two stages of cancellation, one in the digital and another one in the analog domain. While there have been several simulation-based investigations regarding digital cancellation algorithms, the first focus laid on the realization of an analog cancellation filter network. Thus, a digital cancellation is not yet implemented in the current early state of the point-to-point FKIE demonstration system and should not be covered in this report. However, the current prototype consists of a testbed with two transceivers allowing communicating simultaneously in the same frequency band. The transmitter and receiver hardware are from a USRP B205 mini off-the-shelf radio frontends from Ettus Research. According to Stanford's approach, the analog cancellation filter boards have been designed for 2.4 GHz WiFi applications, i.e., the physical filter geometries are related to the wavelength of $\lambda = 12.5\ cm$ (for a 2.4 GHz center frequency). Similar to Stanford's civil application, a proprietary FKIE OFDM waveform implementation is used that is based on the IEEE 802.11 standard.

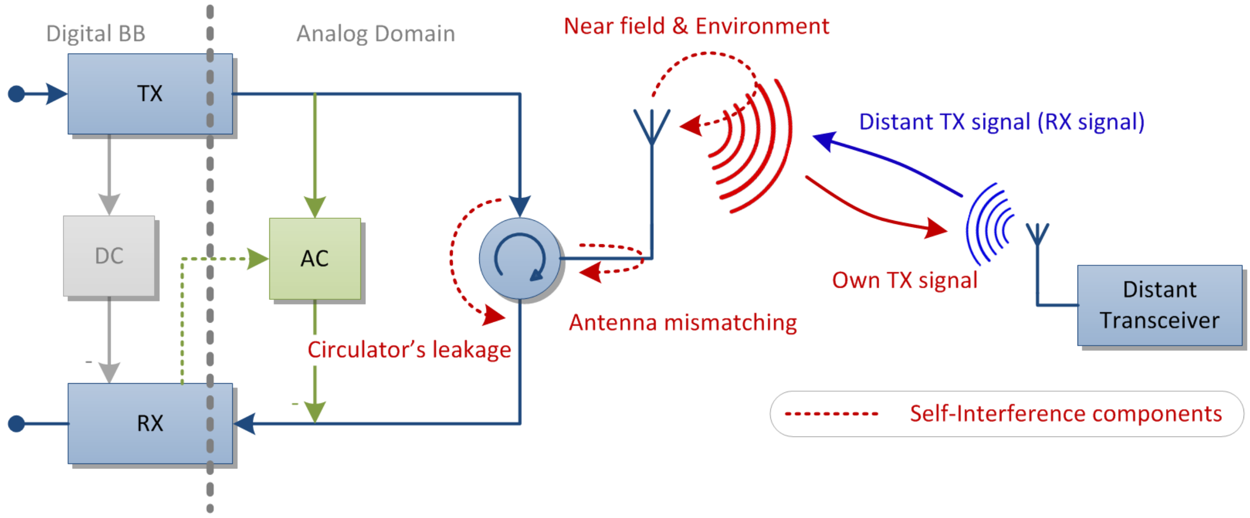


Figure 8: Block Diagram of FKIE Full-Duplex Radio Design.

5.2.1 Analog Cancellation Network

Assuming the single-antenna radio design the main reason for the transmit signal to leak into the receiving path and thus causing self-interference lies in the limited amount of isolation by the circulator. To be more precise, several self-interference components occur by either direct leakage through the isolating path of the circulator or by reflections due to mismatched antenna impedance as well as its near field characteristics. While a digital cancellation may help to estimate and cancel radiated reflections of the TX signal (linear components from the surrounding environment), a first stage of analog cancellation is mandatory to reduce stronger self-interference components caused by the circulator/antenna combination. Otherwise these components would saturate the ADC leading to non-linear clipping effects. Furthermore, a passive analog cancellation filter benefits from its capability to also cancel non-deterministic parts of self-interference components.

The FKIE analog cancellation board is a linear filter network consisting of 8 delay lines, each with Digitally Adjustable Step Attenuators (DSAs) and equally distributed delays to handle linear distorted self-interference components caused by 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. Figure 9 shows the assembled PCBs including the first FKIE prototype of an analog cancellation network.

The filter's coefficients can be configured by changing the attenuation values of the DSAs. With each of them covering a range of 128 attenuation values within a range of 0 dB to 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 coeffiecent's change allowing quick reponses on changing conditions within the circulator's path.

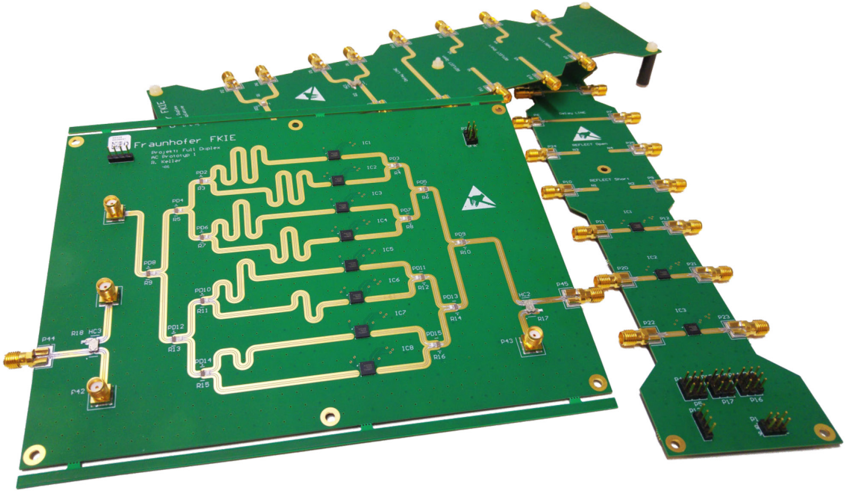


Figure 9: Center: Analog Cancellation Board with 8 Delay Lines; Top: Evaluation Board for RF Couplers/Splitters; Right: Evaluation Board for Digitals Step Attenuation Chips.

5.2.2 FKIE 802.11 Waveform (MAN 802.11mil)

One of the basic challenges of using the full-duplex technique is a precise estimation of the channel characteristics of the circulator's path with the self-interference signal superimposing the received signal. Also due to previous work a WiFi related waveform was developed at the FKIE institute which is called MAN 802.11mil. The MAN 802.11mil differs from the WiFi standard in terms of some technical parameters. The most important parameters of the physical layer are listed in comparison in Table 2.

In the context of full-duplex, burst synchronization and equalization are particularly important since the algorithms used here form the basis for the self-interference channel. The crest factor is critical for the use of RF front ends in the lab, i.e., in the prototype's framework. Regarding full-duplex radio, the waveform implementation provides interfaces with regard to the framework's aspects, e.g., including an interface to the UHD driver. This allows a connection to the used USRP B205 mini-i front ends via the driver to be established.

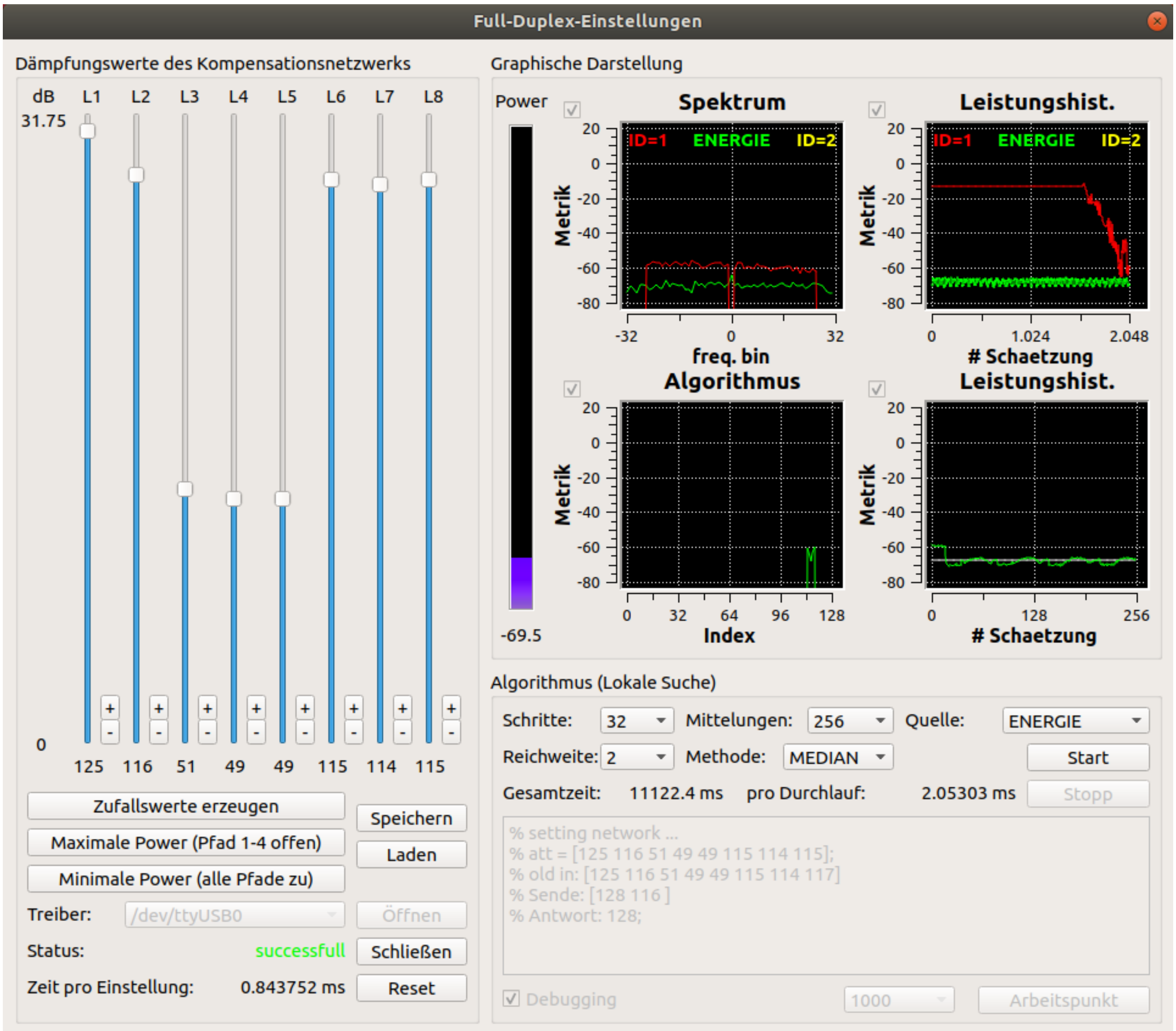
Table 2: Comparison Between IEEE 802.11 Specifications and Waveform Implementation MAN 802.11mil Developed by FKIE Institute.

PHY Parameters	IEEE WLAN 802.11a/g/n	MAN 802.11mil
Signal Bandwidth	5/10/20 MHz (802.11g) 40 MHz (802.11n)	Up to 2 MHz (limited by lab conditions; GPP architecture)
Modulation Schemes	BPSK, QPSK, 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM t-DBPSK, f-DBPSK
Channel Coding	Convolutional codes G = [133 171]8 Rate 1/2, 2/3, 3/4, 5/6 LDPC codes (802.11n)	Convolutional codes G1 = [133 171]8, G2 = [5 7]8 Rate 1/4, 1/2, 2/3, 3/4, 5/6 LDPC Codes (to be investigated)
OFDM Subcarriers	64 / 128 (802.11n)	64
OFDM Data Carriers	48 / 108 (802.11n)	48
OFDM Pilot Carriers	4 / 6 (802.11n)	4
Guard Interval	1/4 or 1/8 (802.11n)	1/4
Carrier Frequency	2.4 GHz / 5 GHz (802.11n)	Not specified
Crest Factor	≈ 12 dB	ACE algorithm ≈ 12 dB (by default), ≈ 7.5 dB (using ACE)
Burst Synchronization and Equalization	• Static with two long preamble symbols • Dynamic with pilot carriers	• Static with two long preamble symbols • Dynamic with pilot carriers Receiver: Based on least square estimation

5.2.3 Self-Interference Cancellation

The current FKIE full-duplex demonstrator system is using energy-based algorithms to iteratively optimize the analog cancellation network. There are mainly two different algorithms used in the RX chain to set the filter network. Both differ in terms of how the metric is calculated. The default one uses a part of the incoming signal to calculate an averaged energy metric while not separating the own self-interference signal from a potentially received one from a distant radio. Another more complex one is also able to distinguish the signals that are fed into the RX branch to only include the self-interference signal for energy calculation. Both algorithms aim at different situations, but for an initial optimization procedure the default one is the better choice due to its faster convergence, especially when assuming that there is no incoming signal on the air interface.

Figure 10 shows the GUI of initial optimization process. The bar positions on the left represent the final attenuation values or coefficients for all delay lines. On the right, one can see the power density spectrum as well as the progress of the energy metric measured in the waveform software for the self-interference signal (red colored curves; ID = 2). The green curves for the spectrum and energy progress (see the two diagrams on top) are related to a non-identified receive signal or noise, respectively. Since the figure shows an initial optimization process with no additional RX signal, there is no yellow curve as this would require successful waveform synchronization with a distant transceiver's TX signal (ID = 2).



125 116 51 49 49 115 114 115

Treiber: /dev/ttyUSB0

Status: successfull

Zeit pro Einstellung: 0.843752 ms

Schritte: 32 Mittelungen: 256 Quelle: ENERGIE

Reichweite: 2 Methode: MEDIAN

Gesamtzeit: 11122.4 ms pro Durchlauf: 2.05303 ms

```
% setting network ...
% att = [125 116 51 49 49 115 114 115];
% old in: [125 116 51 49 49 115 114 117]
% Sende: [128 116 ]
% Antwort: 128;
```

☑ Debugging 1000

Figure 10: Initial Compensation of Self-Interference (Red Curves; ID = 1).

With the waveform implementation running on a GPP architecture, there are limitations in computation intensive factors such as the maximum sample rate and thus in the bandwidth of the used waveform. However, with the current prototype setup the system can achieve up to 50 dB of cancellation with maximum sample rate of 2 MSamples/s in stable condition.

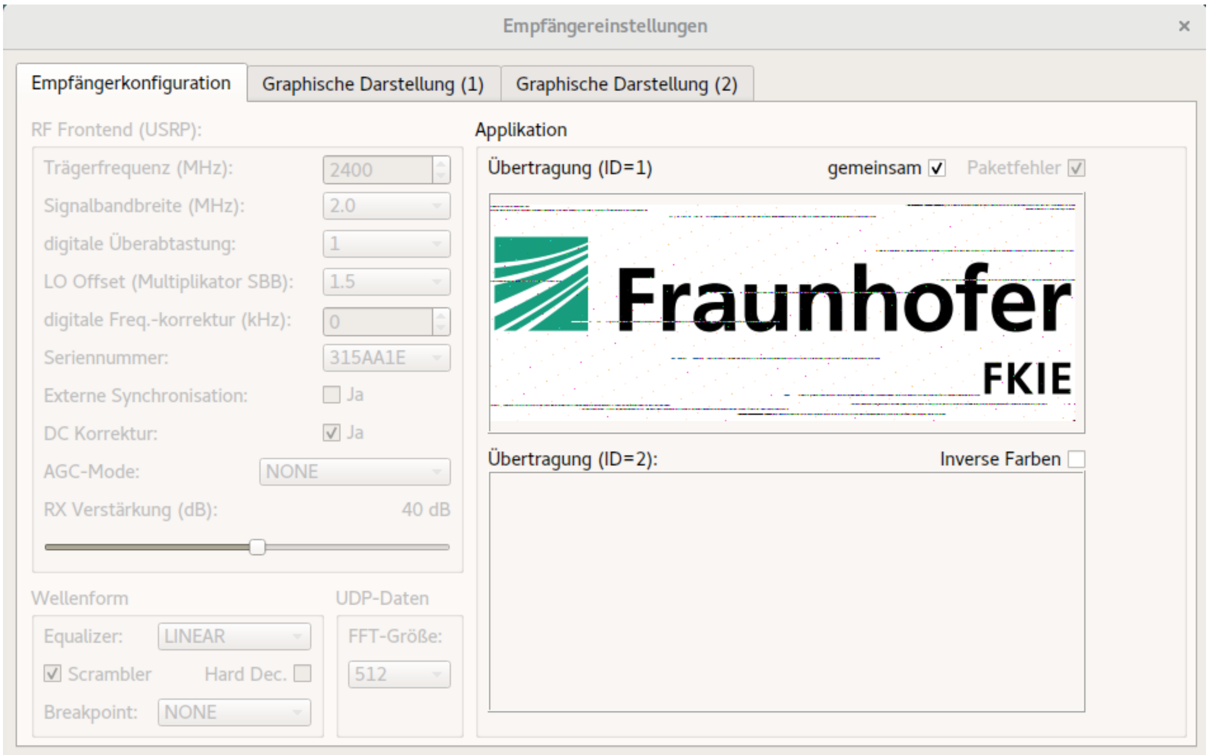
Figure 11 and Figure 12 show the waveform's TX and RX configurations including the data received ("Fraunhofer" picture). The other full-duplex node is simultaneously receiving the "Bundeswehr" picture.

RF Frontend (USRP):
Trägerfrequenz (MHz): 2400
Signalbandbreite (MHz): 2.0
digitale Überabtastung: 1
LO Offset (Multiplikator SBB): 1.5
digitale Freq.-korrektur (kHz): 0
Seriennummer: 315AA21
Externe Synchronisation: ☐ Ja
Digitale Skalierung: 1.0
TX Verstärkung (dB): 60 dB

Wellenform
MCS: QPSK12
Pause [Sp]: 2000
☑ Scrambler

Applikation
Bild: /FullDuplexDemo/bundeswehr.bmp
ID: 2
Bytes/Paket: 512

Figure 11: TX Configuration with the Chosen Picture to be Transmitted.



RF Frontend (USRP):
Trägerfrequenz (MHz): 2400
Signalbandbreite (MHz): 2.0
digitale Überabtastung: 1
LO Offset (Multiplikator SBB): 1.5
digitale Freq.-korrektur (kHz): 0
Seriennummer: 315AA1E
Externe Synchronisation: ☐ Ja
DC Korrektur: ☑ Ja
AGC-Mode: NONE
RX Verstärkung (dB): 40 dB

Wellenform
Equalizer: LINEAR
☑ Scrambler
Hard Dec. ☐
Breakpoint: NONE

UDP-Daten
FFT-Größe: 512

Applikation
Übertragung (ID=1)
gemeinsam ☑
Paketfehler ☑
Übertragung (ID=2):
Inverse Farben ☐

Figure 12: RX Configuration: The picture is Received from the Distant Transceiver While the Self-Interfering TX Signal ("Bundeswehr" Picture) is Cancelled.

5.3 RMA NATO NBWF Framework

5.3.1 NATO NBWF Transmitter

The STANAG 5631 / NATO NBWF uses bandwidths of 25 kHz and 50 kHz with on-air bit rates up from 10 to 82 kbps described in terms of modes. The parameters for generating on-air physical layer modes of the NATO NBWF are given in Table 3.

Table 3: VHF Basic Waveform Physical Layer Modes.

Mode	Data Rate (kbps)	h	Pulse Shape	Code Rate	Symbol Rate (ksps)	BW (kHz)
NR	10	1/2	2-REC	1/3	30	25
N1	20	1/2	2-REC	2/3	30	25
N2	31,5	1/4	2-REC	¾	42	25
N3	64	1/6	3-REC	4/5	80	25
N4	82	1/9	3-REC	6/7	96	25
N5	40	1/2	2-REC	2/3	60	50
N6	63	1/4	2-REC	¾	84	50

A NATO NBWF burst can fit into a half/single/multiple number of 22.5 ms slots and is characterized by its mode, interleaver type (A-B-E-F-G) and its number of merged slots. Any NATO NBWF burst except the "G" burst follows the description in Figure 13. It consists of:

- One Continuous Wave (CW) signal with length of 9 (AGC) + 45 (preamble) symbols (1.8 ms).
- One CPM-N1 pseudo random sequence signal, also called Start of Message (SOM) with length of 63 symbols (2.1 ms).
- One CPM-N1 parameter register signal (Par) which includes fields such as interleaver type and number of merged slots of length of 48 symbols corresponding to 12-bits using rate 1/4 double Golay block code also called extended Golay (24, 12) code (1.6 ms).
- One CPM-N1 and possible several CPM-(N1-N6) transition bits signal (Tr) for the phase to arrive in a known state (L = 2 or 3 symbols).
- One or several CPM-N1 equalization sequence signal (Eq) for possible equalizer training (16 and 64 symbols for 25 kHz and 50 kHz bandwidth respectively).
- One or several CPM-(N1-N6) data sequence signal (D) in which data has been convolutional encoded with code rate 1/3, constraint length 4 and octal generators (13, 15, 17), punctured to lead to the target code rate 2/3, 3/4, 4/5, 6/7, and interleaved with interoperable interleavers.

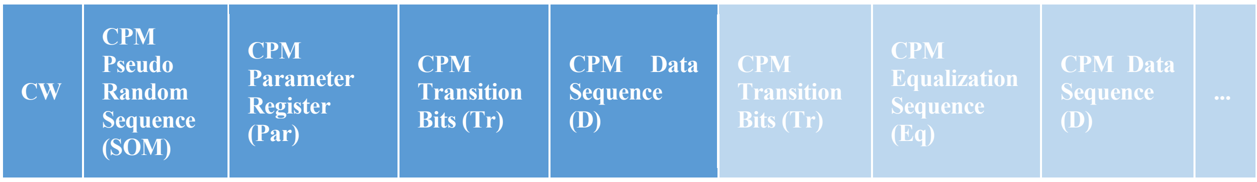


Figure 13: VHF Basic Waveform A-B-E-F Bursts.

The “G” burst follows the description in Figure 14. It consists of:

- One Continuous Wave (CW) signal with length of 54 symbols (1.8 ms).
- One CPM-N1 SOM short (SOMs) pseudo random sequence signal with length of 63 symbols (2.1 ms).
- One CPM-NR data sequence signal (D) in which data has been convolutional encoded with code rate 1/3, constraint length 4 and octal generators (13, 15, 17) and interleaved with an interoperable interleaver.

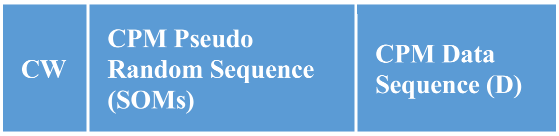


Figure 14: VHF Basic Waveform G Burst.

5.3.2 NATO NBWF Receiver

The complex baseband representation of a CPM signal is given by:

$$x(t,\mathbf{a}) = e^{j\psi(t,\mathbf{a})} \tag{1}$$

with:

$$\psi(t,\mathbf{a}) = \pi h \textstyle\sum_i a_i q(t - iT) \tag{2}$$

and with h the modulation index, T the symbol period, $\mathbf{a} = \{a_i\}$ the information belonging to the binary alphabet $\{\pm 1\}$, $q(t)$ the phase response of the system with $q(t) = \int_0^t g(u)du$ and satisfying the condition $q(LT) = 1$, L the pulse length, $g(t)$ the shaping pulse time-limited to the interval $[0, LT]$ and satisfying the condition $g(t) = g(LT - t)$. The NATO NBWF is a partial response CPM $(L > 1)$ and has rectangular shaping pulses (L-REC). Assuming transmission over an Additive White Gaussian Noise (AWGN) channel, the complex baseband representation of the received signal can be written as:

$$y(t,\mathbf{a}) \quad = Ae^{j(2\pi\alpha t + \phi)} x(t - \tau, \mathbf{a}) + n(t) \tag{3}$$

with A the received signal amplitude, α the carrier frequency offset, ϕ the carrier phase offset, τ the time offset and $n(t)$ the AWGN with variance $N_0/2$ per dimension. The received samples can be written as:

$$y(k) = y(t,\mathbf{a})\Big|_{t=\frac{kT}{F}} \tag{4}$$

with F the oversampling factor. The low-complexity generic receiver depicted in Figure 15 is used.

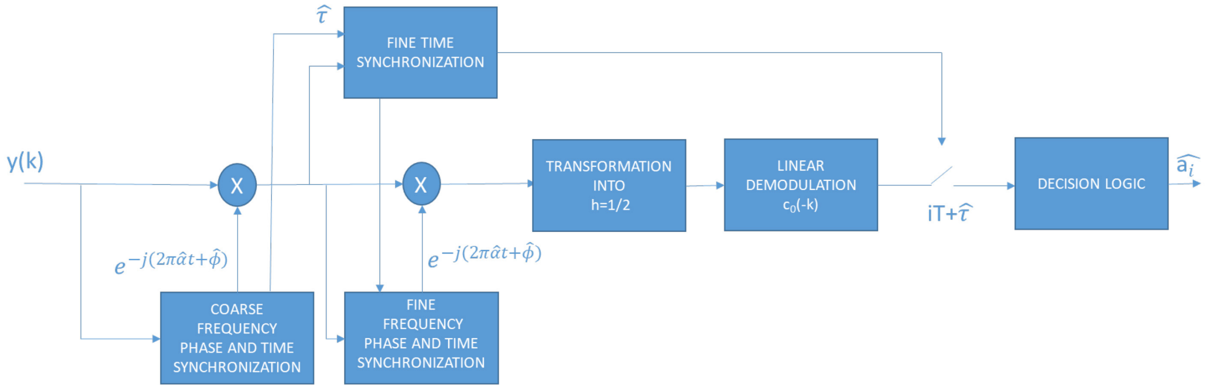


Figure 15: Block Diagram of the Low-Complexity Receiver [46].

The low-complexity generic receiver consists of 6 steps:

1) Joint coarse carrier frequency, phase and time synchronization is performed on the CW signal.
2) Fine time synchronization is performed on the CPM pseudo random sequence signal.
3) Fine carrier frequency and phase synchronization is performed on the CPM signal.
4) Exponentiation transforms the CPM signal with modulation index h < 1/2 into a CPM signal with modulation index h = 1/2.
5) Linear demodulation filters the synchronized signal with the first pulse of Laurent's linear representation of CPM signals.
6) Decision logic is applied to the filtered signal to recover the data sequence.

5.3.3 Digital Cancellation of the NATO NBWF for Full-Duplex Operations

The digital cancellation of the NATO NBWF for full-duplex operation is represented in Figure 16.

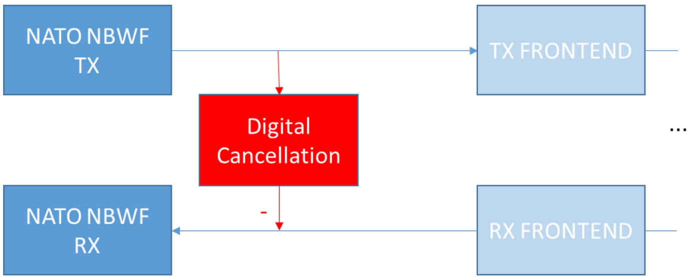


Figure 16: Digital Cancellation of the NATO NBWF in Full-Duplex Operations.

In a full-duplex operation, the received signal can be written as:

$$y(t, \mathbf{a}_{SI}, \mathbf{a}) \quad = A_{SI} e^{j(2\pi\alpha_{SI}t+\phi_{SI})} x_{SI}(t-\tau_{SI}, \mathbf{a}_{SI}) + A e^{j(2\pi\alpha t+\phi)} x(t-\tau, \mathbf{a}) + n(t) \tag{5}$$

with a Self-Interference (SI) part and useful signal part. The goal of digital cancellation is to estimate all the self-interference parameters (amplitude, frequency, time and phase offsets) knowing the transmitted symbols during a training phase and to remove the self-interference signal from the received signal.

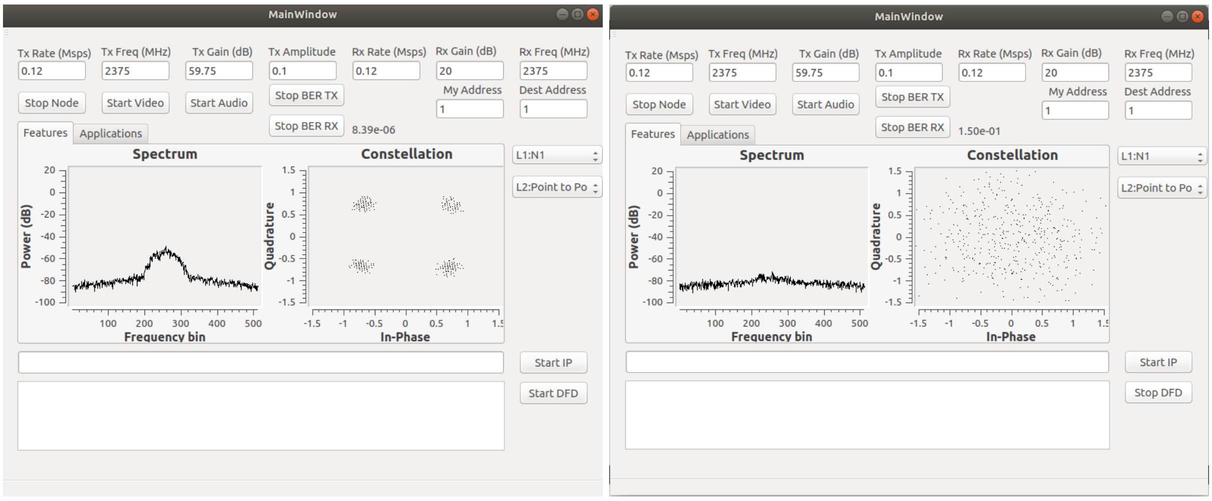
$$y(t, \mathbf{a}) \quad = y(t, \mathbf{a}_{SI}, \mathbf{a}) - A_{SI} e^{j(2\pi\alpha_{SI}t+\phi_{SI})} x_{SI}(t-\tau_{SI}, \mathbf{a}_{SI}) \tag{6}$$

5.3.4 Implementation of the NATO NBWF Digital Cancellation and Tests

The NATO NBWF digital cancellation has been implemented in C++ and tested with USRP B205 mini. A GUI-based software has been developed to provide several services such as the audio MELP, video, text, IP and Bit Error Rate (BER). The software allows to modify the transmit and receive sampling rates, frequencies, gains and addresses and shows spectrum and constellation figures. Some tests have been performed by sending mode N1 with interleaver (A) bursts continuously in slots of 22.5 ms. Figure 17 shows the spectrum and constellation tests before digital cancellation (left) and after digital cancellation of the NATO NBWF self-interference in the training phase using the BER service. A digital cancellation of up to 30 dB is achieved.

After the training phase, a second node transmits an audio MELP service to the first node leading to Figure 18. Reception of MELP voice is performed at the same time as transmission of a BER service (which can also be thought as a jammer sending NATO NBWF bursts of random bits).

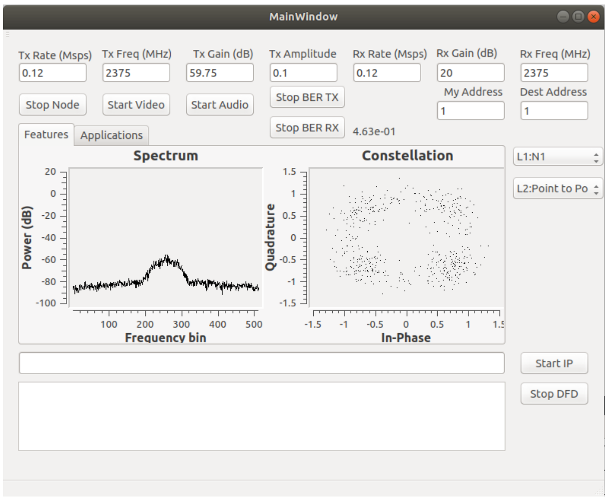
Future tests are planned in the future RTG on full-duplex to take into account timed transmissions, full-duplex voice MELP service, different physical layer NATO NBWF modes in order to verify the feasibility of having a network of NATO NBWF USRP radios performing full-duplex operations.



Tx Rate (Msps): 0.12
Tx Freq (MHz): 2375
Tx Gain (dB): 59.75
Tx Amplitude: 0.1
Rx Rate (Msps): 0.12
Rx Gain (dB): 20
Rx Freq (MHz): 2375
My Address: 1
Dest Address: 1
8.39e-06
L1:N1
L2:Point to Po

Tx Rate (Msps): 0.12
Tx Freq (MHz): 2375
Tx Gain (dB): 59.75
Tx Amplitude: 0.1
Rx Rate (Msps): 0.12
Rx Gain (dB): 20
Rx Freq (MHz): 2375
My Address: 1
Dest Address: 1
1.50e-01
L1:N1
L2:Point to Po

Figure 17: NATO NBWF Digital Cancellation Software in the Training Phase.



Tx Rate (Msps): 0.12
Tx Freq (MHz): 2375
Tx Gain (dB): 59.75
Tx Amplitude: 0.1
Rx Rate (Msps): 0.12
Rx Gain (dB): 20
Rx Freq (MHz): 2375
My Address: 1
Dest Address: 1
4.63e-01
L1:N1
L2:Point to Po

Figure 18: NATO NBWF Digital Cancellation Software in Operation Phase.

5.4 Combined Demonstrator

In advance of the final ET-101 meeting in October 2018, a practical workshop took place at Fraunhofer FKIE in Wachtberg, Germany. The goal was to combine the FKIE framework including its analog cancellation stage with the digital cancellation capabilities of the RMA system. Furthermore, this setup shall demonstrate the use of a military NBWF and therefore also the ability of the cancellation to be in principle waveform-independent.

Both prototype systems have been merged into one demonstrator as shown in Figure 19. Therefore, the MAN 802.11 waveform part of the FKIE framework is substituted by the RMA NBWF as well as its surrounding components including the digital cancellation algorithm. The FKIE framework provides the optimization and control of the analog cancellation. Since the prototype algorithms of the AC are based on an energy metric given by the waveform's RX chain, both systems are interconnected using User Data Protocol (UDP) sockets. Thus, on the one hand the FKIE analog cancellation has to be fed by an optimization metric, i.e., an energy value from the NBWF. On the other hand, the RMA NBWF had to follow the physical frame conditions given by the AC board. Therefore, the waveform implementation had to be configured to operate on a carrier frequency of 2.4 GHz since the AC board has been designed for WiFi applications.

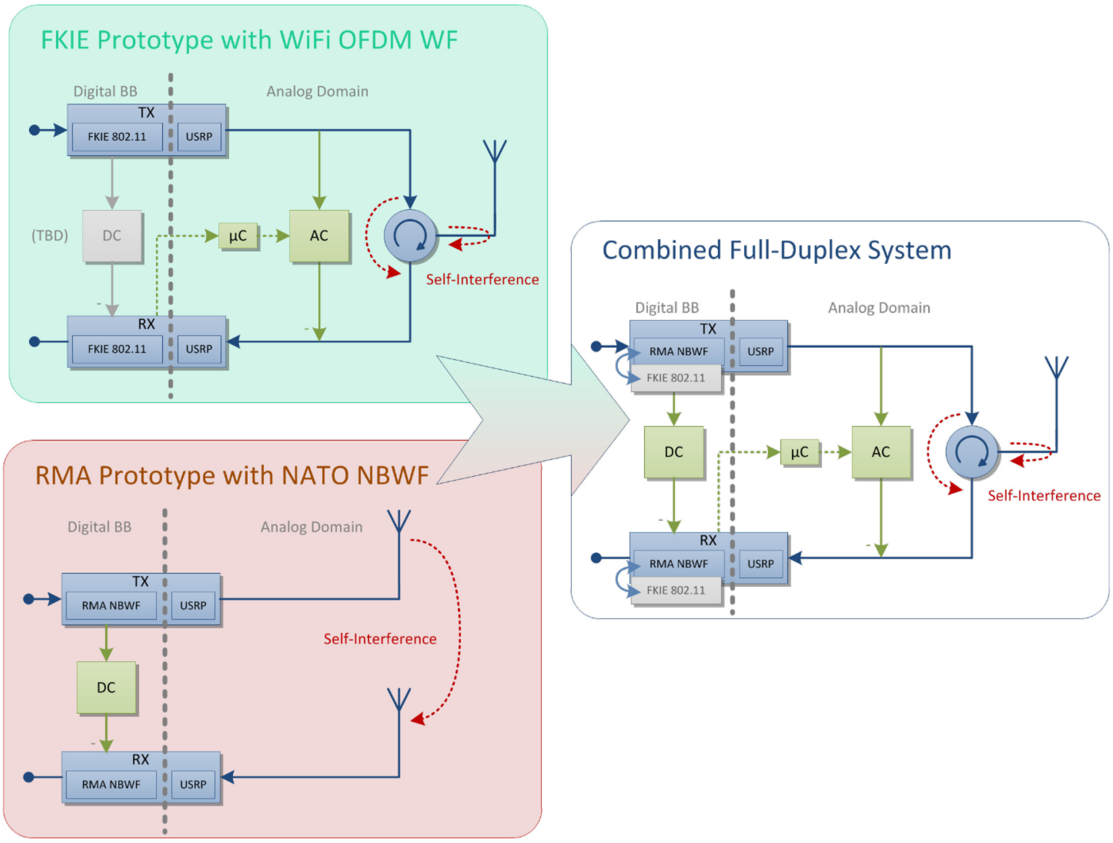
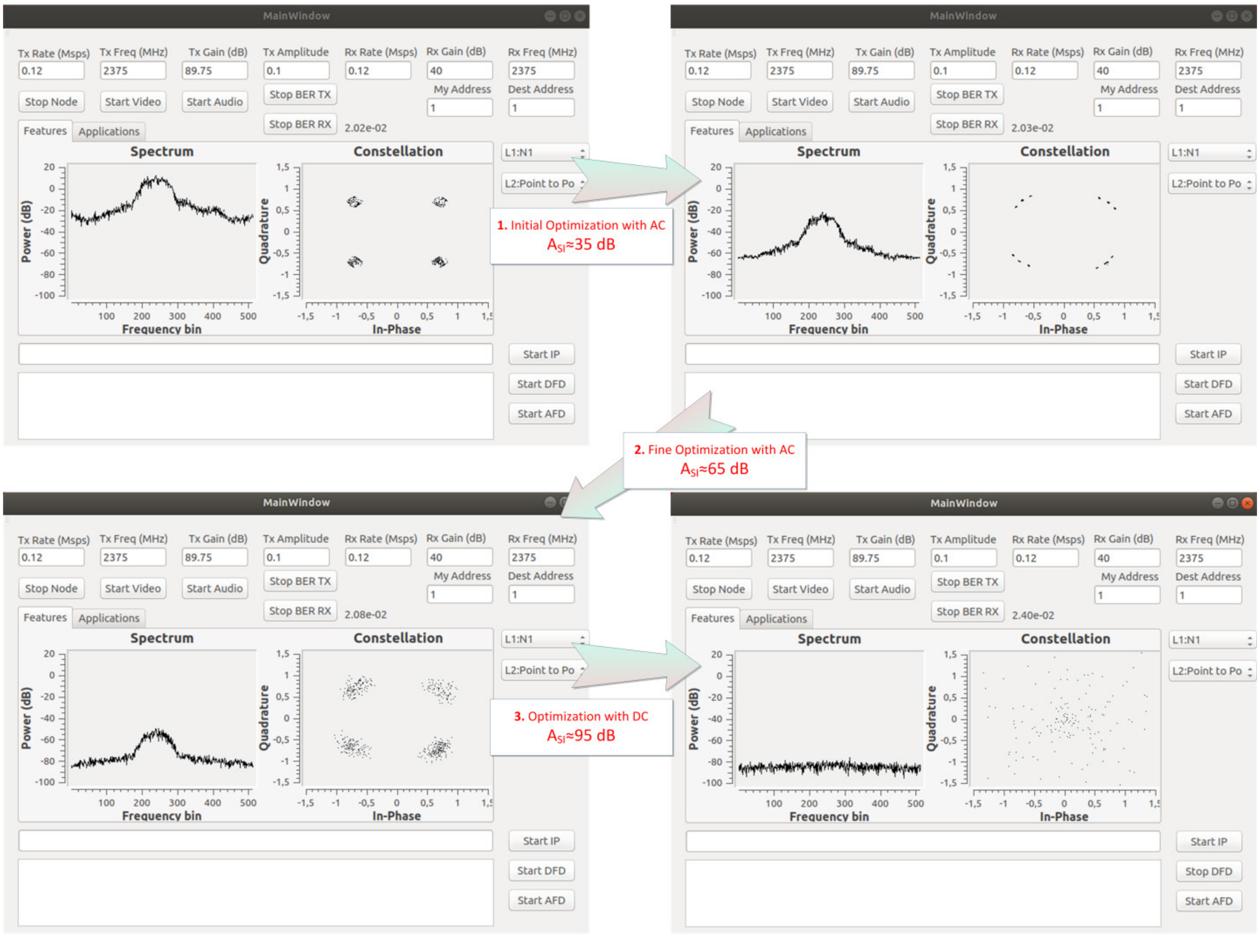


Figure 19: Combining the FKIE Framework and the RMA System.

5.5 Results

The resulting combined full-duplex prototype setup can achieve approximately 95 dB of self-interference cancellation. As shown in Figure 20, a first initial optimization of the analog cancellation can reach about 35 dB. A second optimization with changed parameters of the AC's algorithm 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 reduced and scanned more granularly. The higher performance of the AC (compared to 50 dB as mentioned in Section 5.2.3) is due to the smaller bandwidth of the NBWF.

Then, a final digital cancellation results in an overall cancellation of 95 dB, what is also the limitation given by the testbed's configuration. With RX gain set to 40 dB the self-interference components are pushed below the noise floor. Thus, both nodes were able to successfully operate in simultaneous full-duplex mode, i.e., one direction has been used for the voice MELP service and the other one for the BER service and vice versa. Due to the limited scope of the workshop, a few implementation issues have not been solved yet, e.g., enabling the NBWF's MELP service to operate simultaneously in both directions. The same counts for a further modularisation of cancellation and waveform components, i.e., by excluding the digital cancellation from the RMA system.



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
L1:N1
L2:Point to Po

1. Initial Optimization with AC
A_{SI}≈35 dB

2. Fine Optimization with AC
A_{SI}≈65 dB

3. Optimization with DC
A_{SI}≈95 dB

Figure 20: Self-Interference Cancellation Performance of the Combined Prototype System.

With the given combined system, a first prototype system of a multinational in-band full-duplex transceiver has been realized. The results of self-interference cancellation have shown that the full-duplex principle does in general not depend on the specific waveform. Future work may also give more insight to other aspects of military interest. The definition of Application Programming Interfaces (APIs) might be a first step to provide a consistent framework where transceiver components can be easily exchanged by the multinational participants. This increased flexibility will also allow addressing further constraints like lower transmit frequencies (military VHF and UHF bands) as well as higher transmit powers.

6.0 OUTLOOK

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 [47]. However, most findings published so far are not specific for military use cases and side constraints such as typical military frequency bands and transmit powers. Further research is needed to evaluate and demonstrate the benefits of the in-band full-duplex transceiver technology in both military domains, 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 group the gain of the "true" full-duplex approach over a classic approach to "quasi" full-duplex operation can be determined.

Thus, a follow-on RTG may investigate one or more of the following areas of interest:

- **Introducing Full-Duplex Technology into Military Operation**. Assuming that powerful solutions for all the technical challenges mentioned below can be found, the RTG might work on topics which support the transition of the new technology from the lab environment into military operation. For this purpose, a roadmap and a migration plan for the full-duplex technology need to be established. The roadmap might show, e.g., the expected Technology Readiness Levels (TRL) over time. In addition, a migration plan might address the coexistence with legacy radios as well as the potential impacts on waveform and protocol designs.
- **Solving Technical Challenges specific for the Military Domain**. As already mentioned above, most findings published so far, are not specific for military use cases and side constraints such as typical military frequency bands and transmit powers. Thus, concepts and technical solutions need to be proposed which allow the use of the full-duplex technology also at higher transmit powers (e.g., 50 Watts) as well as at lower frequencies (e.g., military VHF/UHF bands). In addition, the benefits of the full-duplex technology in highly mobile operations as well as in networking environments (e.g., mesh networks) need to be investigated. Last, but not least the impact of hardware constraints (e.g., antennas, circulators) need to be studied in detail.
- **Identifying Future Military Applications for the Full-Duplex Technology**. There is a wide range of military applications which might benefit from the full-duplex technology. First ideas, where full-duplex transceivers can beneficially be applied in tactical communications and electronic warfare have already been discussed in the present report. An in-depth analysis might follow. Also, the military Internet of Things (IoT) is a candidate application which requires a careful management of duty cycle and power constraints.
- **Discussing Properties of the Waveforms.** There exists a considerable diversity of waveforms (e.g., sensing, satellite, navigation, and communications) that needs to be considered. These waveforms can be narrowband or wideband, they might be with or without frequency hopping, they might require low-latencies, etc. All these properties have an impact on the complexity as well as the performance of a full-duplex transceiver.
- **Setting Up a Multinational Demonstrator.** Finally, the follow-on RTG might work on a multinational demonstrator which integrates components from different nations. For instance, one nation might provide the analog cancellation circuit, another one might provide the digital cancellation software and a third nation might provide its waveform. In order to integrate all these

components into a single multinational demonstrator, the Application Programming Interfaces (APIs) between all the different components of a full-duplex system need to be defined.

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14. Abstract

This report 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.

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