Full-Duplex Tactical Information and Electronic Warfare Systems

Karel Pärlin, Taneli Riihonen, Vincent Le Nir, Mark Bowyer, Thomas Ranström, Erik Axell, Börje Asp, Robert Ulman, Matthias Tschauner, and Marc Adrat

***Abstract*—Electromagnetic spectrum is a scarce resource becoming increasingly congested as information technologies advance. This is particularly concerning in the military domain, where frequencies are contested for by both CIS and EW systems. The success of NATO activities necessitate mission-critical communications with increasing throughput, hidden from enemy signals intelligence, robust against electronic attacks, and compatible with host EW tasks. In response, the NATO STO IST-175 research task group is working on the disruptive concept of FD radio technology to address those challenges. Military FD radios promise to increase the spectral efficiency and robustness of CIS and improve the performance of EW tasks through simultaneous operation and multifunctionality.**

Introduction

Tactical communication and information systems (CIS) utilize electromagnetic (EM) spectrum for sharing voice and data between battle units. At the same time, electronic warfare (EW) systems aim at achieving superiority in use of the same EM spectrum. Inevitably, CIS and EW affect each other, and consequently, both disciplines of military operation can benefit from coordinated use. This is especially evident as bandwidth requirements for CIS grow hand in hand with other battlefield technological advancements and congestion of EM spectrum becomes increasingly problematic.

Consequently, military radios must use spectrum efficiently to fulfill the communication needs without compromising reliability requirements [1]. Thus, the outcome of future military operations will depend on information services being provided with increased data throughput, strict timing requirements, robustness against adversarial EW, and compatibility with host EW systems. However, in practice compatibility between CIS and EW systems is often difficult to achieve because both may require to operate on the same frequency bands. This is, for instance, almost always true when considering compatibility between interrelated EW tasks such as signals intelligence and jamming.

Karel Pärlin is with Rantelon; Taneli Riihonen is with Tampere University; Vincent Le Nir is with the Belgian Royal Military Academy; Mark Bowyer is with Airbus Defence & Space; Thomas Ranström, Erik Axell, and Börje Asp are with the Swedish Defence Research Agency (FOI); Robert Ulman is with the US Army Research Office; Matthias Tschauner and Marc Adrat are with Fraunhofer FKIE.

Similarly to most radio technology, CIS and EW technology have evolved into their current state with the assumption that same-frequency simultaneous transmit and receive (SF-STAR) operation, also referred to as in-band full-duplex (FD) operation, is intractable. This technological limitation is a significant contributor to spectral congestion problems and ineffectiveness to carry out simultaneous CIS and EW tasks. However, recent research is forcing a paradigm shift as this assumption is being overturned by FD radios [2].

In the civilian domain, many challenges related to FD radios have already been solved and the technology is seriously being considered for inclusion in next generation wireless communication standards [3]. However, current solutions cannot be directly adopted for the military domain because of significantly different operational conditions like lower carrier frequencies, higher transmit powers, and narrower bandwidths. Overcoming these challenges and taking advantage of this paradigm shift in the military domain can result in technological superiority in the battlefield over conventional half-duplex (HD) radio technology as illustrated in Fig. 1.

As testament to that, the NATO Science and Technology Organization (STO) IST-175 research task group (RTG), which succeeds IST-ET-101 exploratory team [4], is working on introducing FD radio technology into the military domain, in order to enhance both CIS and EW applications. The RTG's aim is to first outline the specific applications and use cases for FD technology in the electronic battlefield and subsequently to solve some of the military-specific challenges related to implementing FD radios for those applications. In this article, we describe the scenarios focused on and capabilities developed within the RTG.

Full-Duplex Radio Technology

To date, most radio technology (civilian and military) is of HD type, meaning that simultaneous transmission and reception on the same frequency is impossible. This is because when a radio is transmitting a signal, it inevitably reaches the same radio's receiver, as illustrated in Fig. 2, causing self-interference (SI) that drowns out any signals-of-interest transmitted by other distant radios. Until recently, this limitation was considered too ambitious to overcome, and has therefore been circumvented and hidden from the user by employing either frequency-division duplex (FDD) or time-

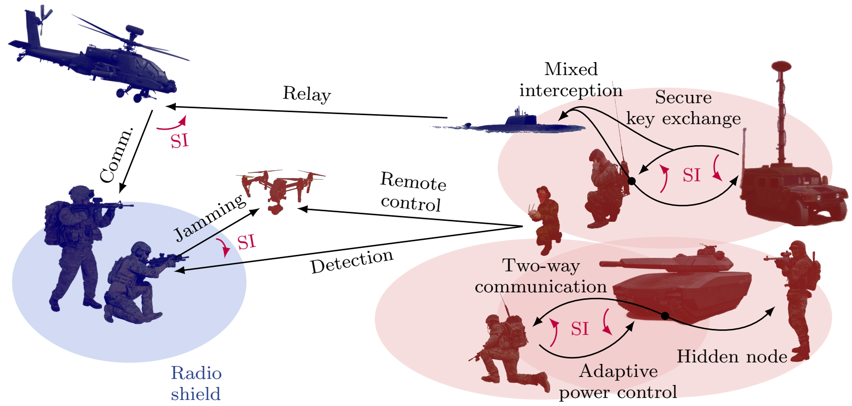

Figure 1. Conceptual use of military FD radios in the battlefield for enhanced CIS and EW.

division duplex (TDD) operation in almost every wireless application. Thus, different frequencies or time slots are used for transmission and reception.

The principal difference in FD radios compared to HD radios is addition of SI cancellation methods, shown in Fig. 2, to suppress different types of SI that inevitably leak into the receiver path. Ideally, SI would be cancelled digitally, however, because of the dynamic range limitations in analog-to-digital conversion, digital cancellation needs to be accompanied by analog methods [3]. The analog canceller typically needs to be designed for a specific carrier frequency and it delays and filters a copy of the transmitted signal so that the copy is in opposite phase to the SI, thus suppressing the SI. The digital canceller is frequency agnostic and works under similar principles as the analog canceller, additionally modelling nonlinearities that affect the SI. Altogether, both stages prevent powerful SI from overpowering the typically weak received signal-of-interest. Current state-of-the-art FD radio prototypes, including those that have been developed by RTG members, achieve SI cancellation in excess of 100 dB [4] and provide reasonable communication conditions in non-military wireless applications [3]. The most obvious advantage of FD radios is to **double the capacity in a point-to-point communication** — which alone is a significant advantage over FDD and TDD operating modes.

For large wireless networks, such as tactical mobile ad hoc networks (MANETs) [5], the advantages of FD operation can be equally influential. Although FD operation inherently increases interference within a network as the number of simultaneous transmissions increases, the overall **throughput of an FD network is improved** compared to an HD network, so long as sufficient SI cancellation is provided and a medium access control protocol designed for FD operation is used [6].

Throughput is not the only aspect improved by FD operation in wireless networks. Tactical MANETs are expected to provide completely self-forming, self-healing, and decentralized platforms for tactical units to join and leave swiftly; particularly in highly time-varying topologies, typical where battlefield infrastructure is lacking or inaccessible due to rapid deployment [1]. Such MANETs face numerous challenges, including cognitive spectrum usage, relaying, and hidden nodes, which all can be addressed with FD operation.

When considering EW aspects, consequences of FD radio technology can result in an equivalent of a wireless superpower, especially as FDD and TDD have severe limitations for many EW tasks, such as detection and neutralisation [7]. The former, FDD, is almost never considered for combined detection and neutralisation, because that would mean detecting and neutralising on different frequencies. When signals of interest fall into either frequency range, only one of two outcomes can arise — detection without neutralisation or neutralisation without detection, neither of which is desirable.

Therefore, TDD is typically used, forcing a trade-off between situational awareness and neutralisation efficiency. By dividing detection and neutralisation operations in time, situational awareness and neutralisation efficiency depend

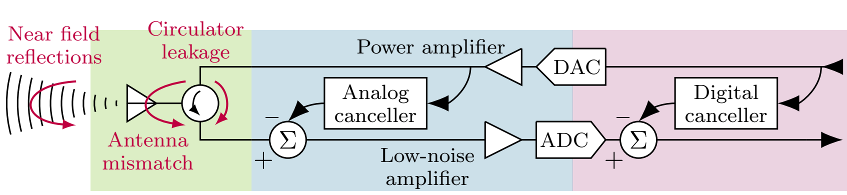

Figure 2. General architecture of FD radios, with passive, analog, and digital cancellation of SI. Digital-to-analog converter is abbreviated as DAC and analog-to-digital converter as ADC.

on the portion of time spent in either state. This is where the FD radio technology excels — it removes that trade-off and opens the way for combining different EW tasks on the same frequency simultaneously. Furthermore, EW tasks can be combined with CIS, introducing EW capabilities to devices that are classically used only for communications. Thus, FD radio technology is a **key enabling technology to develop multifunction military radios** combining CIS and EW functions, which has long been coveted by defence forces [8].

One such case is jamming and signals intelligence, where by using HD radio technology, it is impossible to simultaneously achieve continuous jamming efficiency and situational awareness. Thus, neutralising hostile wireless communications is often approached in an all or nothing way, through jamming the entire enemy frequency band. This is a robust approach given the limitations of modern HD radio technology. However, it requires a lot of power to cover large frequency bands and is also likely to damage friendly communications within the covered frequency bands.

Alternatively, with FD radios, jamming energy can be directed on demand to target only the radio frequency (RF) communications used by the enemy, hence making sure that **collateral damage is minimized**. This is possible because FD technology allows simultaneous jamming, analysis of jamming effectiveness, and to sense if the jammed signal changes its operation mode. Consequently, jamming can be adapted to be more effective and focus only on the malicious RF systems. Not only do FD radios give an advantage to defensive technologies, they also benefit attack-minded applications, which itself is motivation not to forgo this radio superpower.

Enhanced Communication and Information Systems

Within the first of its two demonstrator groups, the RTG is working towards applying the FD radio technology for augmenting CIS. When enhancing tactical CIS, the aim is similar to civilian FD applications. In both cases the objective is, ideally, to double spectral efficiency. This is a significant advantage over conventional HD radio technology, especially when considering how congested and limited military spectrum allocations are.

The main differences between the military and civilian domains arise in frequency bands used and battlefield operating conditions. Many military communication systems operate at either high frequency (HF), very high frequency (VHF), or low ultra high frequency (UHF) band, with higher powers and narrower bandwidths than typical in high UHF band, where the FD radio technology has so far mostly been demonstrated to be feasible with lower powers and comparatively wider bandwidths.

While 100 dB of SI cancellation is considered sufficient for many civilian applications, a military FD radio needs to provide additional 50 dB or more of SI cancellation. Due to the lower carrier frequency, the analog canceller circuit needs delay lines in the order of meters of electrical wavelength leading to challenges in compact design. Furthermore, with respect to typical tactical communication scenarios, fast analog canceller tuning is needed. However, due to the narrow signal bandwidth, the SI estimation can only be provided at very low rates, which subsequently leads to degraded SI cancellation.

Aside from these challenges, the improvement in wireless network throughput resulting from FD operation may fall short of ideal due to the typically asymmetrical data flow, imperfect SI cancellation, and increased inter-node interference. Nevertheless, as discussed next, FD radio technology has potential to improve several other aspects of CIS networks, which in turn can enhance situational awareness and network security.

Cognitive Radio Networks

One of the most promising technologies considered for coping with the limited nature of RF spectrum is dynamic spectrum sharing through cognitive radio (CR). The fundamental idea behind CR is to opportunistically share RF spectrum as opposed to operating within predetermined frequency and time spaces. This allows better use of spectral resources based on operational needs. However, CR relies first and foremost on having an overview of the spectrum usage before deciding to use any spectrum areas. It is also beneficial to retain that overview during transmissions, in order to continue learning from the environment and keep adapting to it, e.g., to detect multi-access collisions or adversarial intervention.

It has been shown that FD-enhanced CR offers higher throughput, higher probability of detection and reduced sensing time, all of which empowers CIS [6], [9]. In tactical scenarios, CR expands beyond just dynamic spectrum sharing as CRs can work around adversarial electronic attacks, especially when enhanced with FD capabilities. For example, FD enables swift and adaptive power control to lower the probability of detection, or enables to detect a jamming attack from an adversary, while simultaneously transmitting tactical communications to an ally on the same frequency channel [10]. Successful detection of electronic attacks enables the radio to take appropriate countermeasures against the attacks, e.g., switching the channel frequency. A combination of cognitive and FD capabilities enables truly multifunctional military radios capable of efficient fusion between CIS and EW based on operational needs.

Moreover, cognition is often envisioned to become a capability of the network, not just being limited to the individual radio. As such, a CR network can build local knowledge about environment (spectral and topological) to reach overall network goals. In military applications, cognitive networking capabilities are especially of interest as a mechanism for intelligently adapting to the dynamics of the theater of war and coping with the temporal nature of tactical networks [11]. Through cross-layer management and information exchange between all layers of the OSI protocol stack, the spectrum information gathered by an FD-enhanced CR could be propagated throughout the adaptive tactical network to improve resilience, lower probability of detection, and increase throughput of tactical end-to-end communications.

Relaying

Information flow from data sources to consumers in the modern battlefield is crucial to the success of military operations. However, in the hostile environments where military networks typically operate, provision of robust and dependable connections is a significant challenge. The entirety of CIS systems is often complex, consisting of scattered networks across the battlefield from tactical edge networks (TENs) to the theater of war. In order to tackle those issues, self-organizing and information-centric networking paradigms have been recently proposed [12]. Further, integral to self-organizing and information-centric networking is the use of relays, sometimes referred to as gateways, between the different scattered networks. Traditionally, using conventional HD radios, relaying is achieved by TDD or FDD, where the relay has receive and transmit time slots or frequency channels.

Compared to HD relays, FD operation promises to increase relaying channel capacity, as a single frequency channel is used simultaneously for receiving and forwarding [6]. Additionally, FD radio technology enables relays to seamlessly combine legacy CIS networks and systems that are not designed to work with relays specifically. That is because FD is a more transparent option than HD, in the sense that FD relaying does not introduce timing nor frequency constraints imposed by the use of TDD or FDD. As such, FD relays, including airborne relays for beyond line-of-sight coverage [13], could be used to extend the operational range of CIS networks as illustrated in Fig. 3. However, as with most FD applications, residual SI becomes the performance limiting factor and the full extent of the advantages of using FD over HD in relaying depend on the SI cancellation performance.

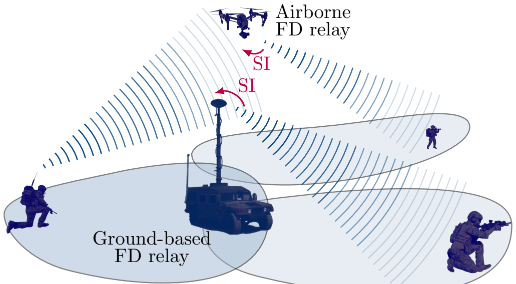

Figure 3. Tactical FD relays can seamlessly extend the coverage of CIS networks.

In hostile environments, FD relays can play an important role in delivering robustness and physical security. Instead of simultaneous reception and transmission, tactical relays with FD capabilities can monitor for adversarial interference while at the same time transmitting information to allies or receive information from allies while simultaneously interfering with its reception by adversarial intelligence. In the first case, interference awareness can aid self-organization within tactical networks. In the second case, simultaneous reception and jamming can create an FD radio shield over the TEN and prevent adversaries from intercepting the host forces' communications or locating units within the TEN. Should the operational scenario require, FD relays can effortlessly become amplify-and-forward eavesdropping relays for carrying out signals intelligence on approaching adversaries.

Out-of-Band Interference

As with in-band SI, radio systems that use closely located frequencies may also, due to out-of-band (OOB) emission, suffer from strong interference when transmission and reception occur simultaneously. This problem is particularly prevalent when radios are co-located on the same platform and subject to limited physical separation [8]. The lack of space due to co-siting may equate to poor EM isolation between radios, which results in appreciable interference even when OOB emission requirements are met. This issue is especially prominent in military applications, where it can have a significant negative effect on robustness to interference, communication range, as well as frequency allocation.

When co-located radios are treated like an FD transceiver, the transmitted signal can be forwarded to receiving radios on the platform. Each radio can then perform interference cancellation in their respective spectrum, reducing OOB interference. Though additional hardware is necessary, implementation of such OOB interference cancellation can be done without introducing complex scheduling, or requiring additional time or frequency resources [14]. Consequently, removing OOB interference can significantly boost both robustness of radios on the same platform as well as enable functional communications in situations where this was previously not possible. Furthermore, cancellation of OOB interference can enable integrating multiple RF tasks simultaneously onto a single platform, which is of significant interest in the military domain and has been pursued through programs such as the Advanced Multifunction Radio Frequency Concept and Integrated Topside [8]. For example, radar, EW operations, and communications could be integrated into a multifunction radio with shared aperture.

NATO Narrowband Waveform

In general, FD radio technology is waveform agnostic, meaning that the type of waveform used does not affect the capability to transmit and receive simultaneously on the same frequency. Yet, some properties of a waveform (e.g., bandwidth, crest factor, and frequency hopping) do have an impact on the complexity and performance of an FD radio. Furthermore, in order to take advantage of FD radios in multi-hop configuration, networking protocols need to take FD capabilities into account [3]. As such, the NATO Narrowband Waveform (NBWF) is a prominent candidate to benefit from FD radio technology. It is a modern combat-net radio standard that includes both the waveform and networking capabilities, with the aim to enhance interoperability among NATO forces in multinational missions.

The standardization of NBWF covers the three lowest layers of the OSI networking model: physical, data link, and network layers. On physical layer, the NBWF employs continuous phase modulation (CPM) for spectral efficiency, where the constant envelope property allows transmitter power amplifiers (PAs) to operate near saturation, improving energy efficiency. The same properties that make CPM spectral and energy efficient are also expected to result in efficient SI cancellation. On data and network link layers, NBWF is designed for limited link capacity and harsh interference environments, employing crosslayer link metrics to manage interference and link quality issues. Those characteristics and capabilities are essential to managing residual SI and inter-node interference in FD-capable radio networks.

The NBWF is essentially a single-channel MANET, offering several transmission modes, supporting occupied bandwidths of 25 kHz and 50 kHz, and providing data throughput from 20 kpbs up to 82 kbps. The design allows radios to adapt waveform and power parameters to achieve the desired quality-of-service without wasting resources. Similarly to a general MANET, a multi-hop NBWF network suffers from the hidden node problem, degrading a NBWF network's throughput. Fortunately FD operation is a promising candidate to solve the hidden node challenge [3]. The RTG members have been studying, implementing, and demonstrating FD radio technology using the NBWF as an example tactical waveform. The results of RTG's multinational demonstrator provide a proof of concept for increasing spectral efficiency of the NBWF through FD radio technology [4].

Enhanced Electronic Warfare

In parallel with CIS enhancement efforts, the RTG is working towards applying FD radio technology for EW tasks. Specifically for counter-drone purposes as drones pose an increasingly large threat and RF-based counter-drone methods are prominent [15]. In FD operation mode, a counter-drone node can simultaneously interfere with various RF systems used by a drone and itself receive those signals uninterrupted. The interference creates an invisible EM dome, a so called FD radio shield, around the FD node as illustrated in Fig. 4. Interfering could, in this case, mean either jamming or spoofing, and the concept of FD radio shield has already been shown feasible in a laboratory environment by the RTG for, e.g., disabling drone remote control (RC) links by jamming while simultaneously detecting the same [10].

Ground-Based Radio Shield

A ground-based FD radio shield (either mobile or stationary) can be used to prevent:

- drones from communicating within the swarm while at the same time monitoring the swarms' attempts to communicate within itself — this allows simultaneously preventing the swarm (even an autonomous swarm) from operating as a coherent unit (as communications within the swarm are essential for the functioning thereof) and to track drones by their RF fingerprints (classify and locate individual drones).
- ground station from directing the drone swarm while at the same time intercepting command and control signals — this means that within the radio shield, the swarm is completely cut off from its operator, but the FD node can still observe (classify and locate) the ground control station.
- drones inside the swarm from determining their geographical position using global navigation satellite systems (GNSSs) while at the same time retaining the FD node's own access to GNSS — the swarm can not determine its position using GNSS but the FD node can, which is essential in case of a mobile FD node.
- drones from positioning each other inside the swarm using RF-based methods (two-way ranging or radar-based positioning) while at the same time detecting those efforts — the ability to position each other within the swarm is essential for the operation of a swarm and without this, the swarm becomes paralyzed, yet with FD capabilities those positioning attempts can still be detected.

On the other hand, a ground-based FD radio shield also facilitates:

- locating drones while simultaneously jamming their RC links and other RF systems by using joint radar and jamming waveforms — FD radio technology can become

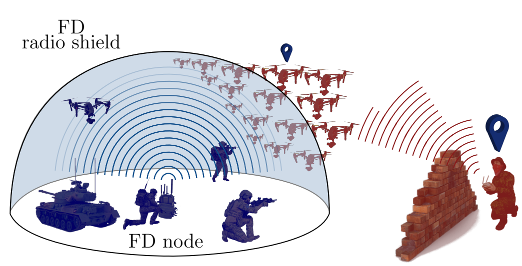

Figure 4. Defensive FD radio shield — simultaneously restricting unauthorized drones access to the defended airspace and monitoring the RF spectrum (detection, classification, and locating of drones and their control stations).

a key enabler for multifunction military radios and RF convergence that have for long been coveted by armed forces [8].
- controlling an allied drone (or drone swarm) from the ground station while at the same time simultaneously sensing for enemy drone's RC signals and electronic attacks within the same frequency band that is used for allied drone RC.

Aerial Radio Shield

Another, more proactive, option is to use FD radios for countering drones as illustrated in Fig. 5. Instead of using a ground-based FD radio shield, a drone itself could be equipped with FD capabilities, allowing to

- interfere with the entire RF spectrum (ground control, inter-drone communications, two-way-ranging, radar) used by a malicious swarm, while itself retaining the ability to communicate with its control station — when the host drone operates on the same frequency as the adversarial drones, FD technology is needed so that the host drone can transmit interference and receive commands at the same time.
- transmit spoofed GNSS signals while itself receiving the actual ones — this could be used to direct the malicious swarm away from its target, although successful GNSS spoofing itself can be expected to be a highly complicated task.
- jam from air, which can be much more energy efficient than jamming from ground, especially if the drone can get close to the swarm — this is a considerable advantage of FD radio technology as this would simultaneously paralyze the swarm but also complicate localization of allied forces on the ground by the enemy (that is typically a high priority).
- use the drone for scouting (e.g., transmitting aerial video feed) while at the same time detecting for frequency usage on the same frequencies by adversarial drones.

Full-Duplex Adversaries

It is also relevant to consider, how FD capabilities in the hands of adversaries affect the electronic battlefield. When facing two adversarial HD nodes that utilize FDD for communication, as is quite typical for drones, a jammer needs to target both the uplink and the downlink frequency channels to completely cut the communication link. In the case of two adversarial FD nodes, only one common frequency channel needs to be targeted. On the other hand, if the enemy is using FD link between two nodes, e.g., for operating a drone, then radiolocating the nodes or eavesdropping on the communication link can be complicated due to the mixed reception of the two signals. As a result, adversarial FD communications can become an easier target compared to HD communications when intentionally interfering but a tougher target when monitoring.

But of course the adversary is not limited to applying FD only for communications. The adversary can combine its communications with EW operations or simply combine different EW operations as proposed throughout this article so far. In this case, when the host is limited to HD capabilities, the FD benefits will simply work for adversary's advantage. When both teams use FD capabilities, the playing field becomes increasingly complex. For example, when the adversary is using FD radios to enhance physical layer security and prevent the host from eavesdropping, the host could counter-strike with simultaneous jamming and eavesdropping to pressure the adversary into increasing communication transmission powers.

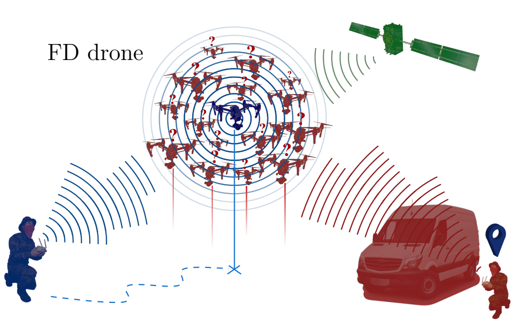

Figure 5. Disruptive FD drone — simultaneously operating on and jamming the same frequencies that are used by the adversarial drones.

Cognitive and Multifunctional Electronic Warfare Systems

The aspects considered in this section are made possible by FD radios or FD radio technology significantly improves on the performance that can be achieved when compared to conventional HD radio technology. This is one of the next steps in radio evolution that will enable the growing list of requirements that modern EW faces in congested spectrum environments. However, the advantages to EW applications extend beyond the counter-drone context, which is the main focus of the RTG's second demonstrator group and was described in detail above.

Much more widely, the importance of EW as a whole is on the rise as EM spectrum is recognised as a key operational environment. Classically, all EW tasks have been separated from CIS functions to large extent, so that EW operations do not interfere with the host's CIS [8]. Similarly to the simultaneous combination of different counter-drone aspects, the advent of FD radios enables that paradigm to shift. As a result, and in the future, many of the CIS tasks can be combined with EW tasks to enhance both aspects. Broadly, these combinations mean either simultaneous communication and jamming, interception and communication, or interception and jamming [7]. Such combinations enhance CIS and EW with an added layer of physical security or perception of spectral environment.

Conclusions

Research into FD radio technology has progressed in strides over the recent decade with mostly civilian/commercial applications in mind. However, the technology is yet to make its way into standardized networks and it is evident that in order to take advantage of the FD concept in CIS and EW systems, much work still lays ahead. Specifically operating frequency ranges and SI cancellation levels must be extended to satisfy the wide requirements set by military radio equipment.

The NATO STO IST-175 RTG is working on overcoming these challenges to take advantage of the FD concept and enhance both CIS and EW systems. In this article, we have discussed the military specific challenges of FD radios and outlined the most promising applications for FD enhancement in the defence domain. As a result of FD operation, the spectral congestion issue within CIS can be alleviated, compatibility with EW equipment improved, and robustness against EW attacks enhanced. Moreover, FD enables truly multifunctional military radios that can simultaneously carry out both CIS and EW functions.

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Biographies

Karel Pärlin (karel.parlin@rantelon.ee) received his M.Sc. degree in electrical engineering from Tallinn University of Technology, Estonia, in 2017. He is an engineer at Rantelon in Tallinn, Estonia.

Taneli Riihonen [S'06, M'14] (taneli.riihonen@tuni.fi) received his D.Sc. degree in electrical engineering from Aalto University, Finland, in 2014. He is a tenure-track assistant professor at Tampere University, Finland.

Vincent Le Nir (vincent.lenir@rma.ac.be) received his Ph.D. degree in electronics from the National Institute of Applied Sciences, France, in 2004. He is a senior researcher at the Royal Military Academy in Brussels, Belgium.

Mark Bowyer (mark.bowyer@airbus.com) received his Ph.D. in solid state electronics from the University of Kent, United Kingdom, in 1993. He is a senior expert in secure communications at Airbus Defence & Space in Portsmouth, United Kingdom.

Thomas Ranström (jranstrom@usf.edu) received his M.Sc. degree in electrical engineering from Linköping University, Sweden, in 2018. He is a research engineer at the Swedish Defence Research Agency (FOI) in Linköping, Sweden and a Ph.D. student at the University of South Florida in Tampa, United States.

Erik Axell (erik.axell@foi.se) received his Ph.D. degree in communication systems from Linköping University, Sweden, in 2012. He is a senior scientist at the Swedish Defence Research Agency (FOI) in Linköping, Sweden.

Börje Asp (borje.asp@foi.se) is a research director at the Swedish Defence Research Agency (FOI) in Linköping, Sweden.

Robert Ulman (robert.j.ulman.civ@mail.mil) received his Ph.D. degree in electrical engineering from the University of Maryland, United States, in 1997. He is a program manager at the US Army Research Office in Triangle Park, North Carolina, United States.

Matthias Tschauner (matthias.tschauner@fkie.fraunhofer.de) received his Dipl.-Ing. degree in electrical engineering from RWTH Aachen University, Germany, in 2011. He is a research assistant at Fraunhofer FKIE in Wachtberg, Germany.

Marc Adrat (marc.adrat@fkie.fraunhofer.de) received his Dr.-Ing. degree in electrical engineering from RWTH Aachen University, Germany, in 2003. He is the head of the SDR research group at Fraunhofer FKIE in Wachtberg, Germany.