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SUMMARY REPORT

Full-Duplex Radio Technology in Military Applications: Theoretical Foundations (Suomeksi: Full-duplex radioteknologia sotilaskäytössä, osahanke B)

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Abstract: Inspired by the recent advances in wireless in-band full-duplex (IBFD) communications in the civilian/commercial domain, this theoretical feasibility study characterized whether and how the progressive simultaneous transmit and receive (STAR) capability of IBFD radio transceivers is advantageous in military applications as well. Whereas IBFD operation allows doubling spectral efficiency by frequency reuse in two-way data links, the STAR capability may also revolutionize military radio systems by merging tactical communications and electronic warfare.

1. Introduction

In-band full-duplex (IBFD) operation is one of the great, disruptive innovations proposed for civilian/commercial wireless communications in this century. The concept is significant, because it can as much as double the spectral efficiency of wireless data transmission by exploiting the newfound capability for *simultaneous transmission and reception* (STAR) that is facilitated by advanced *self-interference cancellation* (SIC) techniques. As the first of its kind, our feasibility study surveyed the prospects and challenges of exploiting the emerging IBFD radio technology in military communication applications as well. In addition to spectrally efficient two-way data transmission, the STAR capability could give a major technical advantage for armed forces by allowing their radio transceivers to conduct electronic warfare at the same time that they are also receiving or transmitting information signals at the same frequency band. After reconsidering IBFD transceiver architectures and SIC requirements in the military communications domain, this project outlined and analyzed all the most potential defensive and offensive applications of the STAR capability.

2. Research objectives and accomplishment plan

After few earlier visionary publications, academic research on IBFD communications began in the end of the last decade concurrently in various institutes around the globe. Almost all the scientific advances have focused so far on non-military, i.e., commercial or civilian, communications at cellular mobile radio bands. The first challenging technical problem has been to cancel the *self-interference* (SI) due to STAR operation and so demonstrate that it is feasible to implement IBFD transceivers to begin with. Thereafter, the recent research has generated thorough understanding on the prospects and challenges of IBFD radios in non-military applications for improving spectral efficiency. Currently, the basic scientific work has already given way for applied projects in the telecom industry and the first products will be available soon. Military spectra are scarce and congested too, whereupon the defense industry shares the telecom industry's motivation to improve spectral efficiency in tactical communications, but the main originality in our research objective actually pertains to envisioning and characterizing other, novel, applications in the battlefield.

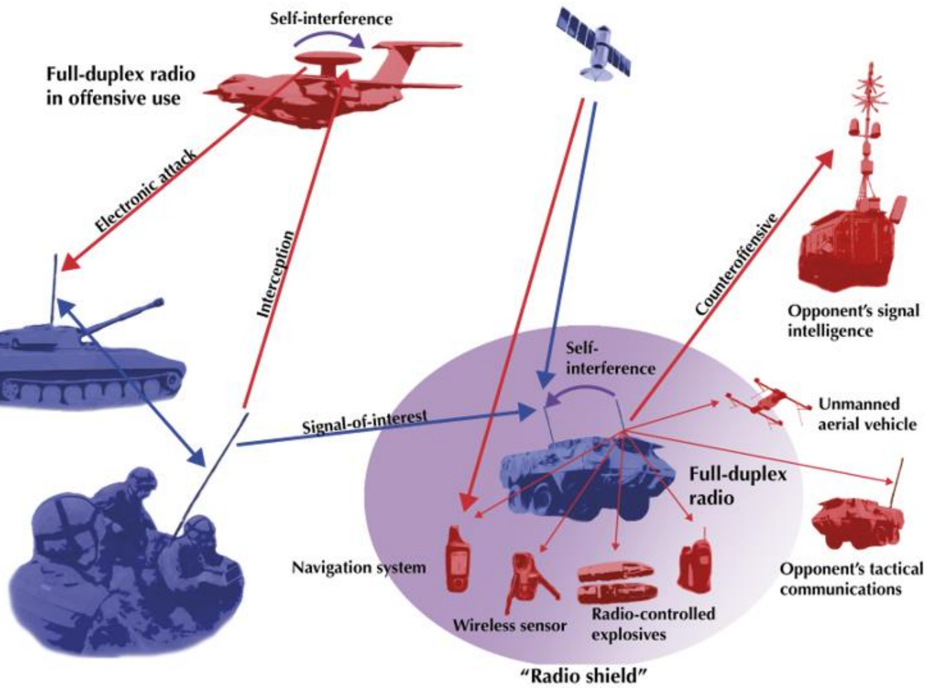

Figure 1: In-band full-duplex radios in tactical communications and electronic warfare. [3]

When extending beyond the communication context, prospective military IBFD radios will have the progressive capability for STAR operation by which they can conduct electronic warfare at the same time when they are also using the same frequency band for communication or perform an electronic attack with simultaneous signals intelligence. A general overview of various potential military usage scenarios is shown in Fig. 1. Studying the prospects and challenges of such applications was the main objective of the project.

It is rather obvious that, by utilizing the superpower of the STAR capability, armed forces could adopt new techniques and tactics in their battle over spectrum that are simply impossible with conventional technology. Thus, we proposed and studied two open research questions related to this potentially disruptive technology in military systems as follows.

1) How do we implement the STAR capability for military applications to begin with? Apart from requiring both extreme sensitivity for desired signals and extreme robustness against strong hostile signals, many military radios would actually operate at HF or VHF bands whereas almost all academic prototypes demonstrate the feasibility of SIC at upper UHF bands only. Thus, it is still somewhat unknown whether and how the STAR capability could be implemented for military radio systems.

2) What are the best ways to exploit IBFD radios in cyber-electromagnetic battles? We envision that armed forces could gain a major technical advantage from radio transceivers that conduct electronic warfare, e.g., signals intelligence or jamming, simultaneously when they are receiving or transmitting other signals, e.g., tactical communications, at the same band. Thus, our project characterized all and, especially, the best uses for the STAR capability at battlefield scenarios.

Resolving the above points may induce a paradigm shift in tactical communications and electronic warfare. Eventually, IBFD radios may even become de rigueur for modern troops whenever an opposing side possesses corresponding technology, necessitating rethinking of communication procedures and tactics as a countermeasure.

3. Materials and methods

As a starting point for the project, we performed a thorough literature survey. Thereby, we could confirm that the only explicit and elaborate prior reference to in-band full-duplex military radios has been the following passage:

> "In military applications, jammers flood the airwaves with strong transmission to prevent other devices from communicating (e.g., cell phones to activate improvised explosive devices). But as it does so, it also prevents its own radios from transmitting, making communication impossible. With SIC technology, the military could continue to disrupt enemy communications and at the same time listen to its own troop communications, thus saving lives in the field."
>
> — S. Hong, J. Brand, J. I. Choi, M. Jain, J. Mehlman, S. Katti, and P. Levis, "Applications of self-interference cancellation in 5G and beyond," *IEEE Communications Magazine*, vol. 52, no. 2, p. 120, February 2014.

In addition, the earlier literature has discussed only two other radio transceiver concepts that implicitly relate to military systems, namely some specific radars and the so-called physical layer security, although studies on the latter almost never explicitly mention the potential military use. In particular, continuous-wave (CW) radars are inherently based on the STAR capability, and the general field of information theory has recently begun to analyze the Shannon capacity of communication links, where an IBFD receiver hinders eavesdropping by simultaneously broadcasting a jamming signal.

Any CW radar transceiver employing respectively one or two co-located antennas (monostatic or pseudo-bistatic) is technically similar to a single-antenna or two-antenna full-duplex radio transceiver. However, the fundamental conceptual difference between CW radars and IBFD radios is that, except for near-end local leakage, echo components looping back to a radar receiver are actually desired and useful by revealing information about a potential target while the corresponding SI signal is completely harmful for IBFD systems. Moreover, the isolation provided by circulators developed for monostatic radars is usually insufficient for communication purposes. On the other hand, bistatic radars are similar to multiple-access communication scenarios since they need to separate the direct leakage from the transmitter and echoes from a target (cf. signals from another transmitter).

The main research method of this feasibility study was to survey literature on non-military IBFD technology jointly with that on tactical communications and electronic warfare. This led to the synthesis of information that introduced the theoretical foundations of the new technology to the military domain. In addition, we performed theoretical performance analysis based on the mathematical modelling of cyber-electromagnetic battles.

4. Results and discussion

4.1. SELF-INTERFERENCE CANCELLATION IN FULL-DUPLEX MILITARY RADIOS

In a typical IBFD transceiver, the necessary SIC is implemented in three separate stages as shown in Fig. 2. A so-called circulator allows the transmitter and receiver to share the same antenna, while also providing some passive isolation between them. Typically, the SI is attenuated here by roughly 20–30 dB. Alternatively, the transceiver may employ separate transmit and receive antennas that offer physical isolation between them. After the circulator, the SI is suppressed by an active analog radio frequency (RF) canceller, which ensures that the SI power entering the actual receiver chain is not too high to saturate it. The RF canceller can be expected to suppress the SI by 40–50 dB, depending on the bandwidth. Finally, the SI remaining after the first two stages is suppressed in the digital domain by a digital canceller. By utilizing advanced nonlinear modelling, the digital canceller can attenuate the SI by as much as 40 dB, thereby cancelling it almost perfectly.

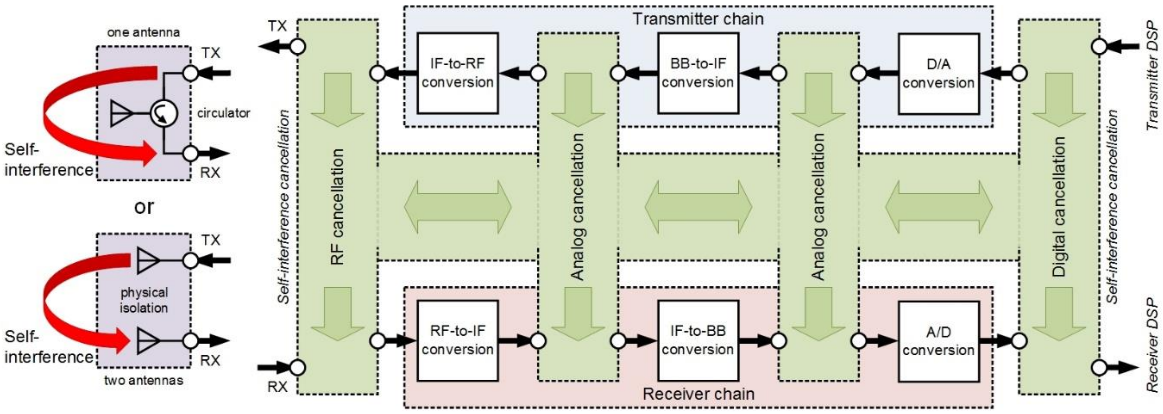

Figure 2: Full-duplex transceiver with various self-interference cancellation solutions. [3]

While state-of-the-art IBFD radios can achieve up to 100–110 dB of SIC, their effective use in military systems likely requires even much more. Especially, usage in the battlefield sets special requirements for extreme robustness to electronic warfare, not to mention that they may operate at military HF or VHF bands instead of the spectrum near commercial cellular mobile radio bands. Moreover, differences between required receiver sensitivity levels and transmission power levels are considerably larger in military systems (especially with signals intelligence or jamming) than in non-military cellular communication. Thus, practical military scenarios are rather different from academic laboratories, where scientists have already demonstrated that the IBFD technology is a viable concept for non-military use at upper UHF bands. Nevertheless, we believe that the same transceiver architectures and advanced SIC techniques at large can still be used for successful military STAR operation once they have been re-engineered carefully.

4.2. MILITARY APPLICATIONS FOR FULL-DUPLEX RADIOS

As the largest part of the project, we identified the potential defensive and offensive applications of IBFD military radios. We classified them into five different categories as shown by Fig. 3. The STAR capability could be used for defense in the form of a "radio shield" that protects its operator from an opponent. In fact, the jamming scenario postulated in the above quote is a specific example of protective applications, but we discovered many others too as discussed in [1]–[3]. In the offensive applications, the radio operator uses the STAR capability for attacking an opponent. For example, it is reasonable to envision that an attacker could send jamming to force an opponent to increase its transmission power and thus facilitate its own simultaneous signals intelligence, e.g., locating the used frequency band and transmitters or intercepting communication. Instead, if the opponent had full-duplex radios too, the smart countermove for jamming would be to launch jamming against potential interception whenever increasing transmit power is necessary.

Finally, we analyzed simplified cyber-electromagnetic battles, where two opposing teams (blue and red) operate on the same frequency band for tactical communications and/or electronic warfare. We assumed that the band could be used for transfer of information (e.g., voice, data, or an activation signal) over a link between two radios in either team and signals intelligence or an electronic attack that targets a radio in the other team. Two-way IBFD data links without electronic warfare were not considered at this time, because they have already been widely studied in the non-military context, although the technology could be advantageous for facilitating high-rate tactical communications as such.

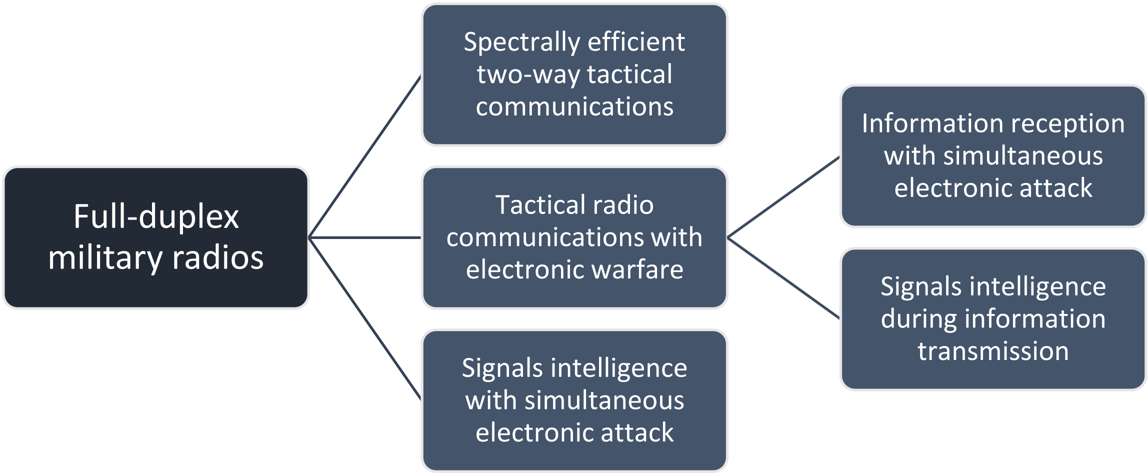

Figure 3: Classification of applications for IBFD radios in military communications. [3]

In particular, we simulated the performance of the red receiver (RX) when it is receiving a communication signal from the red transmitter (TX) or trying to intercept the blue transmission. Moreover, only the blue receiver is capable of STAR operation, and the red team does not possess the IBFD technology. The study assumed operation at the 2.4 GHz industrial, scientific and medical (ISM) band instead of typical military HF or VHF bands for two reasons. First, we aim at corroborating these results by measurements on a real prototype setup in our follow-up project, for which we will need to use some unlicensed band. Second, the ISM band has actually become relevant for armed forces nowadays, because adversaries are using cheap off-the-shelf radio transceivers to operate unmanned aerial vehicles (UAVs), or even toy multicopters, and improvised explosive devices (IEDs).

In the numerical results, the red transmitter’s power used for controlling the UAV or IED is set to 17 dBm, while the blue team is using a transmit power of 20 dBm for both communication and jamming. The path loss at distance d [km] is modeled as $125 + 36 \cdot \log_{10}(d)$ [dB], which roughly represents urban Hata propagation at the ISM band with typical antenna height. Furthermore, the noise floor in all the receivers is assumed to be at -90 dBm. This modelling allowed us to determine signal-to-[interference-plus-]noise ratios (S[I]NRs) at the receivers based on link budget calculations given the radios’ positions.

Figure 4 illustrates the red receiver’s signal quality when it is located at different positions while the other transceivers are located at the coordinates indicated by respectively colored circle markers. For reference, the SNR of the blue communication link without simultaneous jamming is about 21 dB, while the corresponding SINR depends on the residual SI level that would be achieved in practice. The upper part of each plot shows signal quality in the red receiver when the blue receiver is using its STAR capability for transmitting jamming, while the lower part shows the corresponding reference case without jamming. In principle, the lighter yellow color indicates better signal quality for the red team, while the signal level is below noise and jamming interference in the dark green region. We see that jamming in the IBFD radio act as as a "radio shield" preventing the red team from controlling the UAV, detonating the IED, or intercepting the blue transmitter near the blue receiver.

The other two analyzed battlefield scenarios were the following: (c) simultaneous interception and communication that does not affect the blue team's own performance (so it comes at no cost during operation, if the radio has the STAR capability); and (d) simultaneous interception and jamming. In general, the results indicated that the red team usually suffers from a significant technical disadvantage, if it does not possess the IBFD technology.

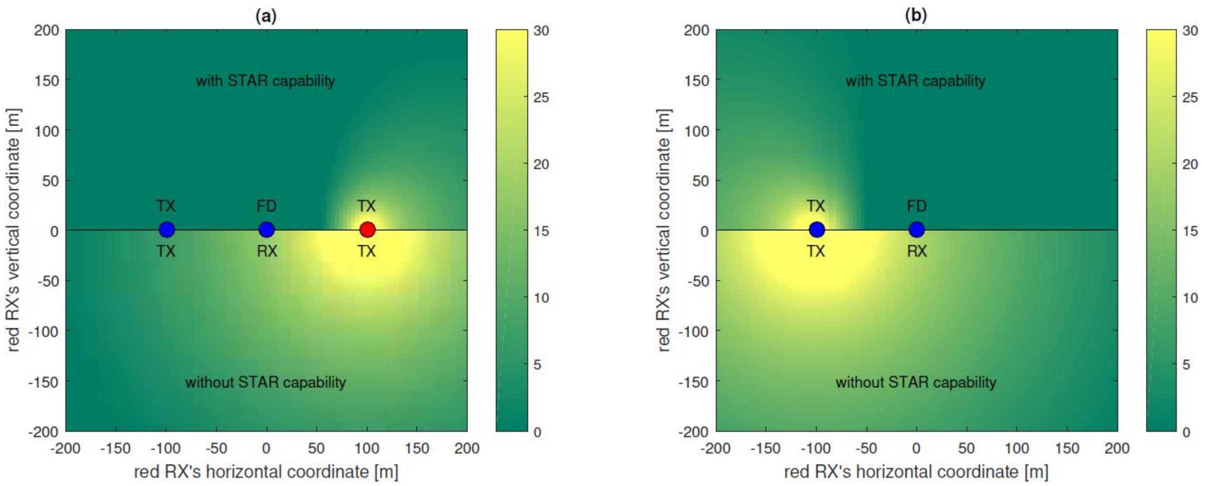

Figure 4: Comparison of conventional half-duplex and new full-duplex (FD) systems: (a) *SNR* [dB] without STAR capability and *SINR* [dB] in simultaneous communication and jamming against communication; (b) *SNR* [dB] without STAR capability and *SINR* [dB] in simultaneous communication and jamming against interception. [3]

5. Conclusions

Extrapolating from the rapid advances in civilian/commercial IBFD radios, we believe that the disruptive and unprejudiced idea of in-band STAR operation also finds its way in some form to the field of military communications sooner or later. We may even be witnessing the beginning of a paradigm shift in tactical communications and electronic warfare at the moment. Thus, our feasibility study explored the prospects of IBFD technology in cyber-electromagnetic battles in order to inspire more scientific research on this emerging topic and to disseminate the idea within the military communications community. It is not out of the question that armed forces could gain a major technical advantage over an opponent that does not possess IBFD technology, or that they need renewed communication procedures and tactics to counteract opponents' STAR capability. In conclusion, we see that there is much room for original, potentially high-impact research in this area.

6. Scientific publishing and other reports produced by the research project

The project produced the following three scientific publications [1]–[3]. Figures and a part of the text in this final summary report have been adapted from the original publications that report all the research results in an unabridged form.

[1] T. Riihonen, D. Korpi, O. Rantula, and M. Valkama, “On the prospects of full-duplex military radios,” in *Proc. International Conference on Military Communications and Information Systems*, Oulu, Finland, May 2017.

[2] D. Korpi, T. Riihonen, O. Rantula, M. Valkama, and R. Wichman, “In-band full-duplex radios for military communications,” in *Proc. XXXIV Finnish URSI Convention on Radio Science*, Helsinki, Finland, September 2017.

[3] T. Riihonen, D. Korpi, O. Rantula, H. Rantanen, T. Saarelainen, and M. Valkama, “Inband full-duplex radio transceivers: A paradigm shift in tactical communications and electronic warfare?,” *IEEE Communications Magazine*, vol. 55, no. 10, pp. 30–36, October 2017.