2018 / 2500M-0092

ISSN 1797-3457 (verkkojulkaisu)
ISBN (PDF) 978-951-663-042-0

SUMMARY REPORT

Full-Duplex Radio Technology in Military Applications: Practical Experiments (Suomeksi: Full-duplex radioteknologia sotilaskäytössä, Osahanke A)

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Abstract: Inspired by the recent advances in wireless in-band full-duplex (IBFD) communications in the civilian/commercial domain, this two-part feasibility study characterized whether and how the progressive same-frequency simultaneous transmit and receive (SF-STAR) capability of IBFD radio transceivers can be advantageous in military applications as well. Whereas IBFD operation could allow doubling spectral efficiency in two-way tactical communications, the SF-STAR capability may also revolutionize battlefield systems by integrating tactical communications and electronic warfare in the form of a multifunction military full-duplex radio (MFDR). The second part of the project reported herein demonstrated the practicability of selected military applications of the IBFD/SF-STAR capability with indoor and outdoor laboratory experiments.

1. Introduction

In-band full-duplex (IBFD, or just FD) operation is potentially one of the most disruptive innovations proposed recently in the field of wireless communications. The concept is significant, because it can as much as double the spectral efficiency of wireless communication links w.r.t. conventional half-duplex (HD) operation by enabling the progressive capability for *same-frequency simultaneous transmission and reception* (SF-STAR).

The academic research on IBFD communication systems has already begun about ten years ago. The first challenging technical problem has been to demonstrate that it is feasible to cancel the self-interference due to SF-STAR operation and so it is not impossible to implement IBFD transceivers in the first place. Thereafter, the recent research has generated thorough understanding on the prospects and challenges of IBFD radios for improving spectral efficiency in communication applications. Currently, the basic scientific work is already giving way for more applied R&D projects in the telecom industry.

All the scientific advances have focused so far on non-military, i.e., commercial or civilian, communications at cellular mobile radio bands. Thus, 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. The study was especially motivated by the vision that the SF-STAR capability could give a major technical advantage for armed forces by allowing their radios to conduct electronic warfare at the same time that they are also receiving or transmitting information signals at the same frequency band.

After reconsidering the architectures and requirements of IBFD transceivers in the military domain, the first part of this project carried out in 2017 outlined and analyzed the most potential applications of the SF-STAR capability. The second part of the project reported herein demonstrated with practical experiments in a laboratory and outdoors that some of the proposed applications for a *multifunction military full-duplex radio* (MFDR) are viable.

2. Research objectives and accomplishment plan

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 totally different kinds of novel applications in the battlefield. Namely, when extending beyond the communication context, prospective multifunction MFDRs will have the progressive capability for SF-STAR operation by which they can conduct electronic warfare or sensing at the same time when they are also using the same frequency band for tactical communications or perform an electronic attack with simultaneous signals intelligence. Studying the prospects, challenges, and feasibility of such applications related to RF convergence was the main objective of the project.

As a starting point for the work in 2017, we formed the following two open research questions related to this potentially disruptive technology in military systems:

1) How to implement the SF-STAR capability for military applications to begin with?
2) What are the best ways to exploit MFDRs in cyber-electromagnetic battles?

In the first part of the project, we addressed the above research questions at a theoretical level by identifying and analyzing the potential defensive and offensive applications of IBFD capability as well as characterizing the requirements for MFDR transceivers. The outcomes have been reported in [1]–[4]. 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 IBFD radios at upper UHF bands only. Nevertheless, it seems obvious 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.

Apart from compelling theoretical evidence, it still remained somewhat unknown whether the SF-STAR capability could be useful for military radio systems in practice. Thus, it became necessary to consider also the following research question when continuing the work:

3) Is it reasonable to expect that the blue-sky concepts could be viable in reality too?

In particular, the second part of the project reported herein took the feasibility study to a practical level by experimenting with few example applications in laboratory settings, aiming at providing a general proof-of-concept and answering to the third question.

Fully resolving all the above three points may induce a paradigm shift in tactical communications and electronic warfare, especially if the answer to the last point is positive w.r.t. many applications. Eventually, IBFD radios may even become de rigueur for modern troops whenever an opposing side possesses corresponding technology, or necessitate rethinking of communication procedures and tactics as a countermeasure.

3. Materials and methods

The research method in the second, practical, part of this project was to implement example system scenarios for MFDRs and perform laboratory experiments to assess the feasibility and advantage of IBFD operation. The research materials were the measurement data collected in the experiments. In particular, four measurement campaigns were conducted during the period from January 2018 to October 2018, the first three taking place indoors and the last outdoors. All the considered system scenarios are combined in Fig. 1, where the blue team employs a full-duplex (FD) transceiver to transmit protective jamming while simultaneously receiving tactical transmission, intercepting an opponent's half-duplex (HD) transmission, or detecting an improvised radio control (RC) system.

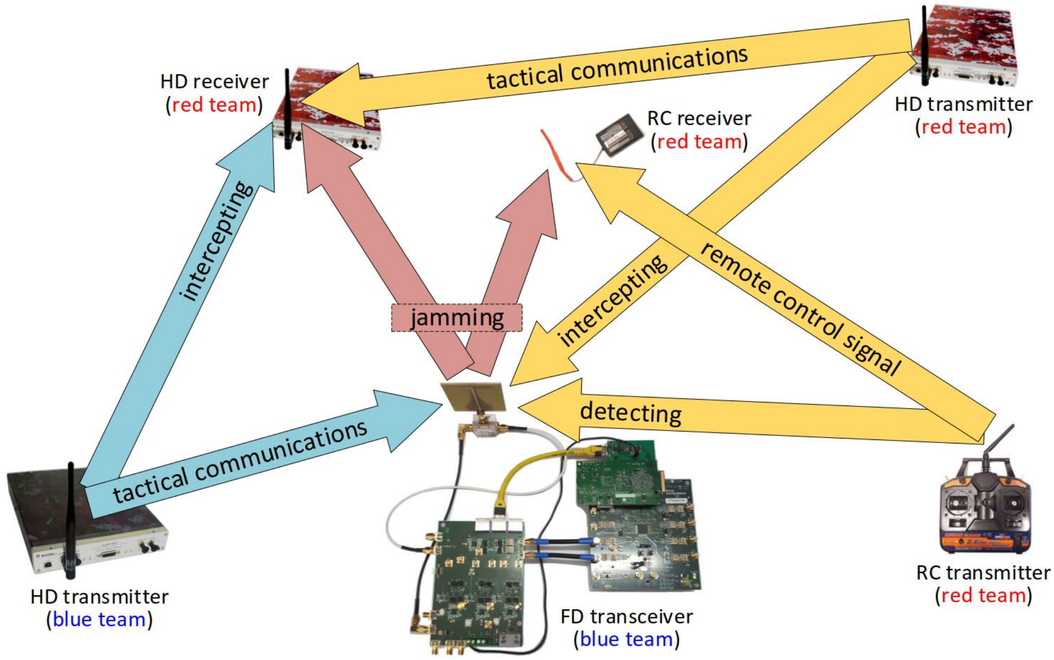

Fig. 1. In-band full-duplex radio in tactical communications and electronic warfare.

4. Results and discussion

The results of the first three indoor experiments are already reported in detail by [5]–[7]. Thus, this summary report only briefly introduces their objectives and conclusions while the main attention is given to the two-phase outdoor experiments in the last subsection.

4.1. Simultaneously detecting and preventing improvised explosive device activation

The first indoor experiment in January 2018 demonstrated that an IBFD transceiver can be used for simultaneously detecting a radio control (RC) transmitter while also broadcasting jamming that disconnects RC receivers from the RC transmitter. The experiment represents a scenario, where an enemy has built an improvised RC trigger system for explosive devices using off-the-shelf consumer electronics components that could be scavenged, e.g., from a model airplane or a recreational multicopter. The results have been archived in [5].

4.2. Simultaneously jamming and intercepting enemy tactical communications

The second indoor experiment in April 2018 demonstrated that, by employing an IBFD transceiver, one can simultaneously transmit jamming against an opponent while intercepting its tactical communications. This results in technical advantage, because the opponent may increase its transmission power as a countermeasure to jamming due to which interception becomes easier. The results have been archived in [6].

4.3. Full-duplex radio shield for protection against enemy receivers

The third indoor experiment in April 2018 studied how well an IBFD transceiver can receive tactical communication signals from the same team's HD transmitter while simultaneously transmitting jamming to prevent an enemy from intercepting the communications or using an improvised RC system on the same frequency band. The measurements showed that, with the prototype IBFD transceiver used in all the experiments, the quality of the tactical communications signal remains almost constant irrespective of jamming power. Thus, IBFD operation allows one to create a protective "radio shield" of jamming at a reasonably low cost of reduced communications capability. The results will be archived in [7].

4.4. Outdoor experiments on a full-duplex radio shield

The fourth measurement campaign took place outdoors at Hervanta campus lawn in front of Tietotalo and Kampusareena from June 2018 through October 2018. Implemented in two phases, the purpose of these experiments was to study how well an IBFD transceiver can be used as the "radio shield" that prevents an opponent's receiver from operating in the vicinity of the IBFD transceiver while it receives communications signals from the same team's HD transmitter. The performance of jamming was tested against the improvised RC system used also in the first experiment in January 2018, i.e., the outdoor experiment represents a scenario, where the radio shield allows preventing an opponent from activating their RC explosive devices. Furthermore, the measurements are repeated with two different jamming signals: generic wideband jamming that is effective against any receiver operating on the band and RC-specific jamming, where all the transmission power is focused on the frequencies used by the RC transmitter at hand.

The first phase of the outdoor experiments during summer 2018 determined the coverage areas of the two jamming signals with different transmit power settings and two locations for the RC transmitter. The second phase investigated in October 2018, how well the self-interference cancellation of the IBFD transceiver performed in this military application, aiming at demonstrating that the device is able to receive successfully WLAN and Bluetooth signals while simultaneously transmitting jamming signals. Like in all the aforementioned experiments, the measurements were conducted on the 2.40–2.48 GHz industrial, scientific and medical (ISM) band at rather low transmit power. The RC transmitter was located about 125 meters from the IBFD transceiver while this distance was about 40 m in another reference scenario. The WLAN and Bluetooth signals were transmitted 10 m and 30 m from the IBFD device in all measurements. The radius of the jamming coverage area in different directions was determined by locating positions at maximum distances, where the RC receiver is still unable to receive the corresponding RC transmission.

Figure 2 illustrates the key measurement results from the outdoor experiments. The subfigures on the left show the signal-to-interference-and-noise ratio (SINR) values estimated from received signals using the known transmitted signals as pilots when broadcasting wideband or RC-specific jamming. The subfigures on the right show the corresponding coverage areas of the radio shield with different jamming powers, i.e., the boundaries of regions, where the RC receiver was disconnected from its RC transmitter.

In Figs. 2(a) and 2(c), the measured SINR values show that the residual self-interference is independent of the jamming power, except for the highest values. There is little difference between the two HD transmitter positions. The reception of Bluetooth transmission suffers more from the residual self-interference than that of WLAN transmission and the effect is pronounced with the RC-specific jamming signal. In general, the RC-specific jamming signal also results in slightly lower SINR than wideband jamming at same power.

In Figs. 2(b) and 2(d), the effectiveness of the RC-specific jamming signal is significantly better than that of the wideband jamming signal as expected. In all scenarios, jamming coverage areas are larger towards left, because the IBFD transceiver's antenna is facing that way and radiating mostly forward. The best coverage radii achieved with wideband jamming using a transmit power of 20 dBm were 17 m forward from the IBFD transceiver and 6.5 m behind it. With RC-specific jamming and a transmit power of 20 dBm, the corresponding radii were 40 m forward and 25 m behind of the IBFD transceiver. It is also worth noting that with a transmit power of only 0 dBm, the RC-specific jamming signal was as effective as the wideband jamming signal with a transmit power of 20 dBm, despite there is mathematically only less than 10 dB difference in power spectral density. When the RC transmitter is brought closer for reference, the jamming coverage areas are reduced significantly. However, at transmission power of 20 dBm and 0 dBm, the respective wideband and RC-specific jamming signals still have similar effectiveness.

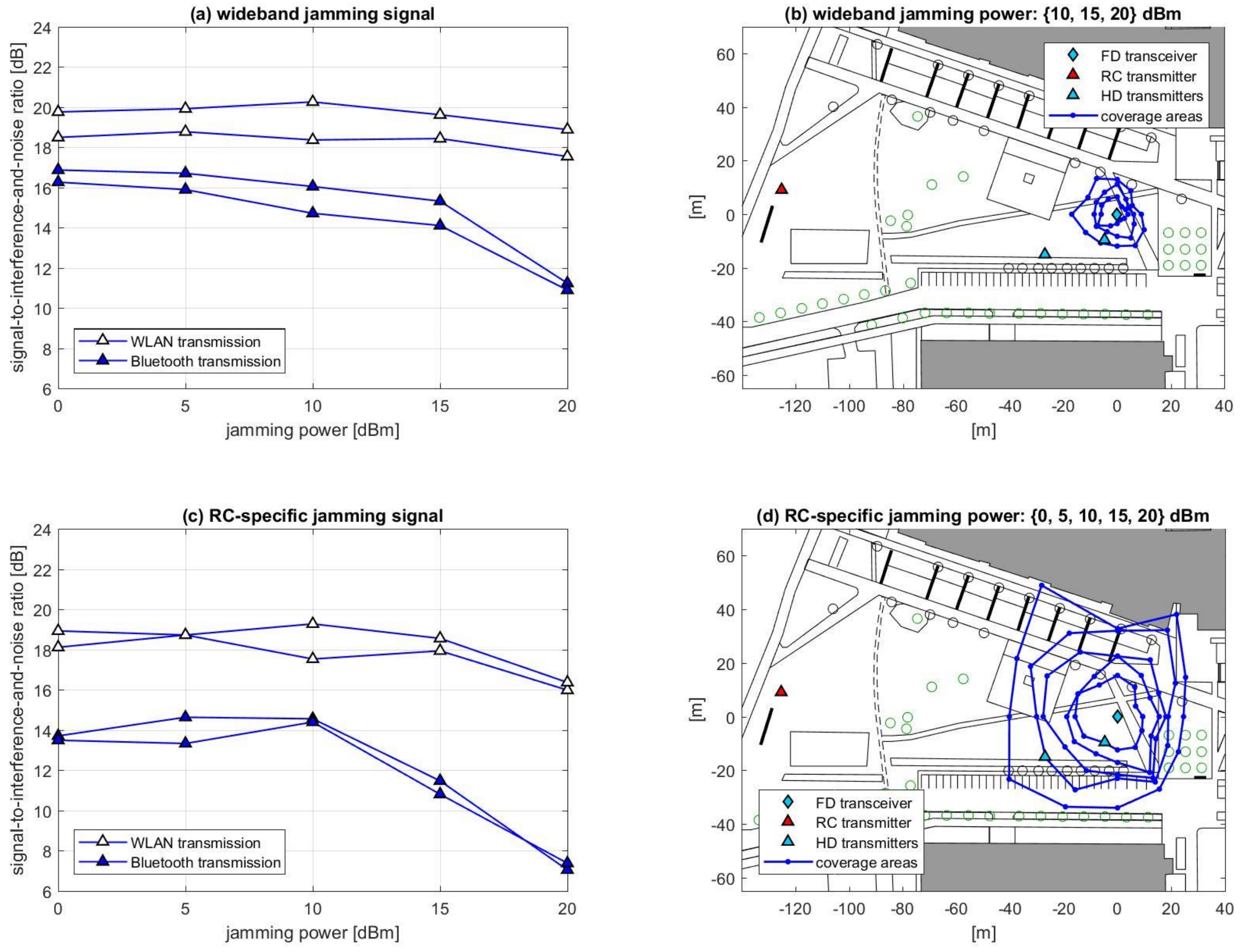

Fig. 2. A summary of key measurement results from the outdoor experiments at Hervanta campus lawn.

5. Conclusions

Extrapolating from the rapid advances in civilian/commercial IBFD radios, we believe that the disruptive idea of SF-STAR operation will be soon adopted to military communications too. Especially, the concept of multifunction MFDRs is linked to the vision of RF convergence by which all battlefield radio devices and systems become united and the conventional division between different kinds of electromagnetic operations disappears. Consequently, we may be witnessing the beginning of a paradigm shift in tactical communications, signals intelligence, and electronic warfare. Our feasibility study explored the prospects of multifunction MFDRs in cyber-electromagnetic battles in order to initiate scientific research on this emerging topic and to disseminate the idea within the defense research community. In conclusion, we strongly recommend that defense forces notice developments in this area since it is not out of the question that one could gain a major technical advantage over an opponent that does not possess the IBFD technology, or that troops need renewed communication procedures and tactics to counteract opponents' SF-STAR capability.

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

The first part of the project resulted in three scientific publications [1]–[3] related to the theoretical foundations of the research area as discussed in the summary report [4], while the second part of the project reported herein produced three conference papers [5]–[7]. A part of the text in this final summary report was adapted from the original publications that report 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.

[4] T. Riihonen, D. Korpi, O. Rantula, M. Valkama, and R. Wichman, "Full-duplex radio technology in military applications: Theoretical foundations," in *Summary Reports of MATINE Projects*, Finnish Scientific Advisory Board for Defence, December 2017.

[5] T. Riihonen, D. Korpi, M. Turunen, and M. Valkama, "Full-duplex radio technology for simultaneously detecting and preventing improvised explosive device activation," in *Proc. International Conference on Military Communications and Information Systems*, Warsaw, Poland, May 2018.

[6] T. Riihonen, D. Korpi, M. Turunen, T. Peltola, J. Saikanmäki, M. Valkama, and R. Wichman, "Tactical communication link under joint jamming and interception by same-frequency simultaneous transmit and receive radio," in *Proc. IEEE Military Communications Conference*, Los Angeles, California, October 2018.

[7] T. Riihonen, D. Korpi, M. Turunen, T. Peltola, J. Saikanmäki, M. Valkama, and R. Wichman, "Military full-duplex radio shield for protection against adversary receivers," in *Proc. International Conference on Military Communications and Information Systems*, Budva, Montenegro, May 2019, to be submitted.