Tactical Communication Link Under Joint Jamming and Interception by Same-Frequency Simultaneous Transmit and Receive Radio

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***Abstract*—This paper explores a way in which a military full-duplex radio (MFDR) could be used at the cyber-electromagnetic battleground to impede the wireless communications of an opposing team while simultaneously intercepting the same signals. The proposed concept is based on MFDR devices' ability for same-frequency simultaneous transmission and reception (SF-STAR), which facilitates the joint jamming and sensing. The feasibility of this offensive strategy is evaluated with experiments that involve a prototype MFDR transceiver and an over-the-air tactical data link between software-defined radios. The results prove that the MFDR can prevent communications between the two nodes of the opposing team's tactical network while also improving its own performance in intercepting the transmissions, thanks to its SF-STAR capability. This means that utilizing MFDR devices could allow one to gain technical superiority over an enemy.**

I. INTRODUCTION

In-band full-duplex (IBFD) communications is a recent paradigm shift in the field of wireless networking [1], [2]. It has the potential to transform the way in which radio links operate by facilitating *same-frequency simultaneous transmission and reception* (SF-STAR). As for civilian/commercial applications, the main benefit of such IBFD—or just full-duplex (FD)—systems is the resulting twofold increase in spectral efficiency, and consequently the technology has been receiving a lot of attention worldwide. It is already evident from the various prototype implementations that the prospects of IBFD communications are becoming a reality.

What still remains a largely unknown aspect of the IBFD technology is its potential as a *military full-duplex radio* (MFDR). As we have recently envisioned (cf. [3] and [4]), SF-STAR could facilitate joint tactical communications and electronic warfare, thereby giving any armed forces a considerable advantage over an enemy. Hence, theoretical and measurement-based analyses are urgently needed to uncover the true possibilities of the IBFD technology also in this domain. Moreover, to obtain meaningful results, the experiments should be performed under as realistic circumstances as possible, preferably using an actual MFDR prototype.

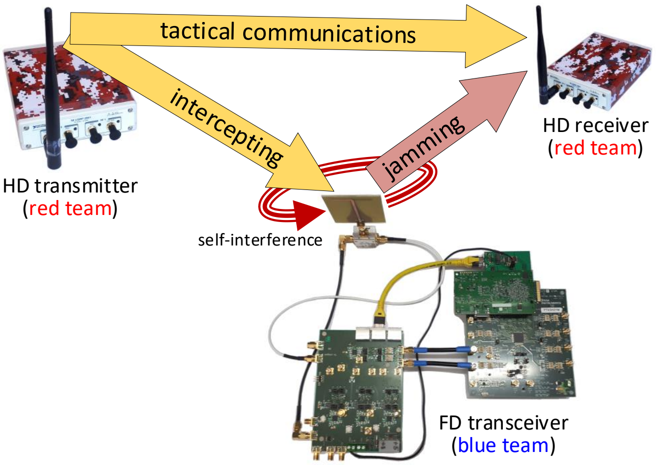

Fig. 1. A sketch of the considered battlefield scenario, where the blue team exploits an in-band full-duplex (FD) transceiver for simultaneously jamming and intercepting the red team's half-duplex (HD) tactical communication link.

To this end, we perform real-life measurements (see also [5], [6]), considering the battlefield scenario shown in Fig. 1. The basic premise is that, with the help of the MFDR, the blue team can intercept the communications link of the red team, while also jamming the intended receiver, thanks to its ability to transmit and receive over the same time–frequency resource. In particular, the jamming signal forces the red team to use higher transmit power, which makes it easier for the blue team to intercept the transmission while the red team's receiver is still incapable of decoding it. To ensure the validity of the obtained results, the measurements are carried out using our IBFD transceiver prototype reported, e.g., in [7], [8]. Correspondingly, the red team's tactical communication system is a realistic over-the-air radio link between two universal software radio peripheral (USRP) half-duplex (HD) transceivers.

In what follows, the laboratory setup and the different communications links are described in Section II, alongside with the prototype MFDR transceiver. The obtained measurement results are then presented in Section III, while the discussion and analysis of the results is carried out in Section IV. Finally, Section V concludes the paper.

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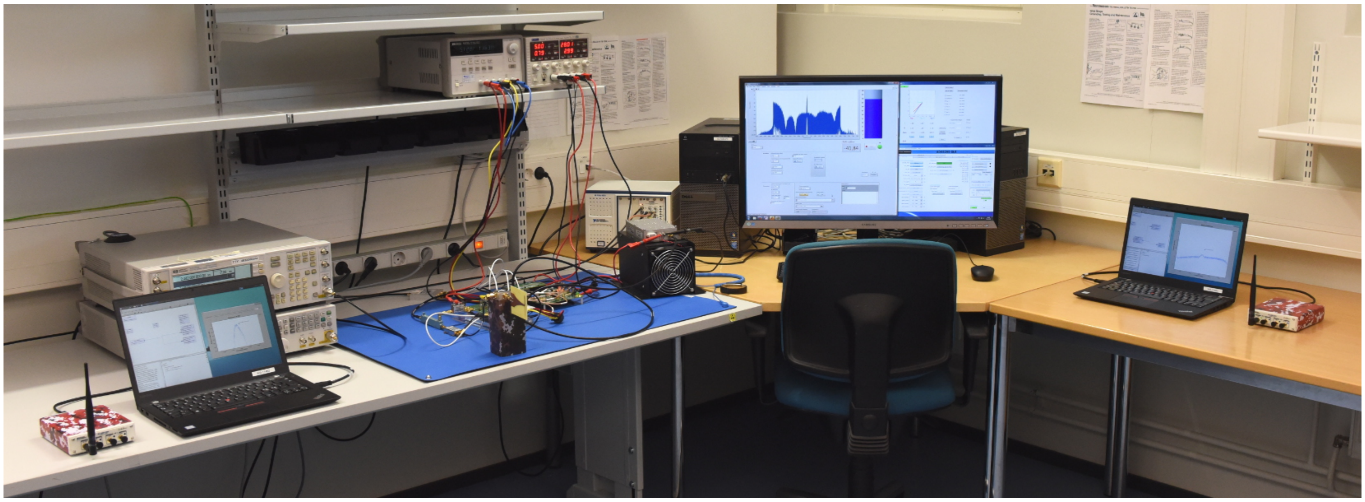


Fig. 2. The laboratory equipment used for demonstrating that the military full-duplex radio (MFDR) technology can create significant technical advantage in electronic warfare by facilitating joint jamming and interception with the new same-frequency simultaneous transmit and receive (SF-STAR) capability that has non-military origins. The red team's tactical communication radios were much farther away in the actual experiments as illustrated in Fig. 3 below.

II. LABORATORY SETUP

The experimental system described shortly and its geometry in the measurements are shown in Figs. 2 and 3, respectively. We are forced to carry out the over-the-air experiments at the unlicensed 2.4-GHz industrial, scientific and medical (ISM) band, because we cannot transmit on real military frequencies. Thus, some of the results contain inevitably interference from other devices, such as wireless local area networks, operating on the ISM band. However, whenever possible, badly cluttered measurements have been discarded in a pre-processing stage.

A. Red Team: Tactical Communication Link

The red team's tactical communication link is implemented with two National Instruments (NI) USRP-2901 software-defined radios that are controlled using the GNU Radio toolkit on two respective host laptops. These portable radio devices are visible on the left and right edges of Fig. 2. Essentially, the tactical communication waveform is uploaded to the transmitting USRP, which continuously broadcasts it using selected transmit power. The receiving USRP simply records its received signal for further offline processing.

To reflect a realistic scenario in the experiments, the red team communicates with a so-called soldier radio waveform (SRW), which has been shown to be especially suitable for military systems [9]–[11]. The modulation scheme is Gaussian minimum-shift keying (GMSK) with a symbol rate of 1.75 MHz, a bandwidth–time product of 0.1, and a modulation index of $1/2$. The resulting bandwidth of the signal is 1.2 MHz.

B. Blue Team: Experimental Full-Duplex Transceiver

The prototype MFDR utilized by the blue team follows the architecture that was originally developed for non-military IBFD communication applications as reported in [7], [8], and our other publications. It is built on an NI PXIe-5645R vector signal transceiver (VST), which acts as the basic transceiver component with an external high-power amplifier.

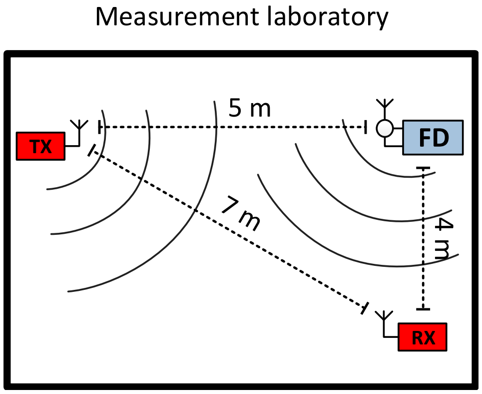


Fig. 3. The relative locations of the devices in the experiments. Due to the very limited space in the laboratory room, we did not consider any other system geometry but only varied transmit power in communication and jamming.

The SF-STAR operation is facilitated by the following three processing stages, which target at suppressing the own transmit signal, i.e., the self-interference (SI), coupling to the receiver so that, as a result, the MFDR is capable of simultaneously jamming as well as monitoring the spectrum within its vicinity:

- **passive isolation** between the transmitter and the receiver provided by a circulator, which connects the transmitter output and the receiver input to a shared antenna;
- **prototype cancellation circuit**, which uses the transmit signal to further suppress the SI in the RF domain; and
- **digital cancellation** that is performed offline in software, for which the VST saves the original jamming waveform and records a vector of the signal after RF cancellation.

Together, these stages provide 90–100 dB of isolation between transmission and reception within the experimental MFDR.

In the experiments, the blue team's jamming signal is a basic randomized—Gaussian noise-like—orthogonal frequency-division multiplexing (OFDM) waveform, whose bandwidth is either 3 MHz or 80 MHz in different measurement scenarios.

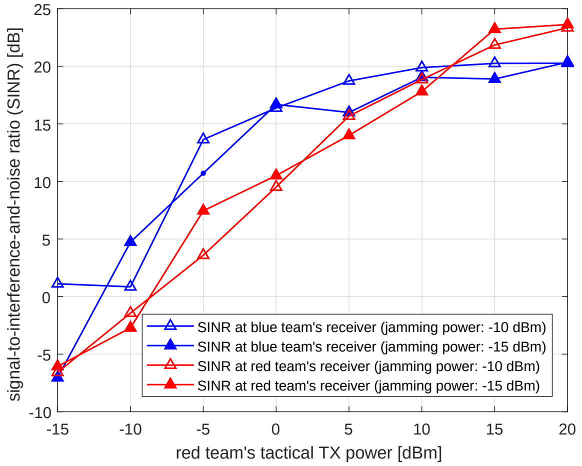


Fig. 4. Estimated SINR at the receivers in terms of the transmit power that the red team uses for tactical communication when the blue team transmits the 80-MHz jamming signal at the lowest powers considered in the experiments.

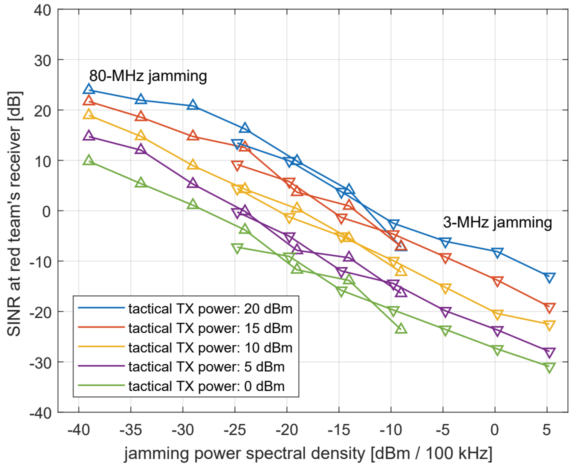
TABLE I
ESSENTIAL MEASUREMENT PARAMETERS

Parameter		**Value**
Center frequency		2.44 GHz
Red team	Waveform	SRW-like GMSK
	Bandwidth	1.2 MHz
	Tactical TX power	$\{[-15, -10, -5], 0, 5, 10, 15, 20\}$ dBm
	Sampling rate	10.5 MHz
Blue team	Waveform	Gaussian noise-like OFDM
	Bandwidth	3 MHz or 80 MHz
	Jamming power	$\{[-15], -10, -5, 0, 5, 10, 15, 20\}$ dBm
	Sampling rate	120 MHz

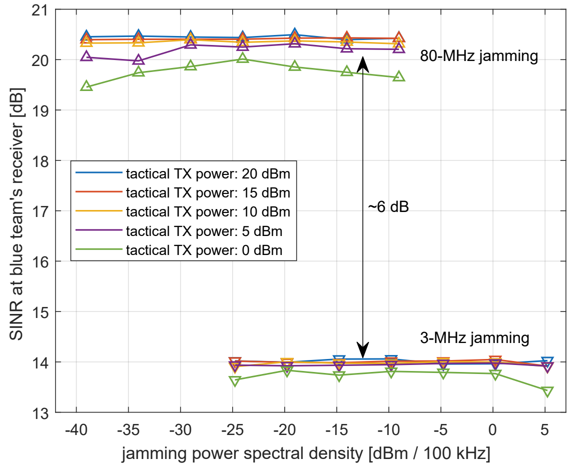
III. EXPERIMENTAL RESULTS

The experiments reported herein are obtained under the scenario depicted in Fig. 3, which illustrates the relative positions of the relevant nodes within our measurement laboratory. As described in the introduction, the blue team's MFDR, situated at the top-right corner in Fig. 3 (cf. at the center of Fig. 2), is trying to intercept the tactical communication link of the red team while also trying to prevent the red team's HD receiver from successfully decoding the same signal.

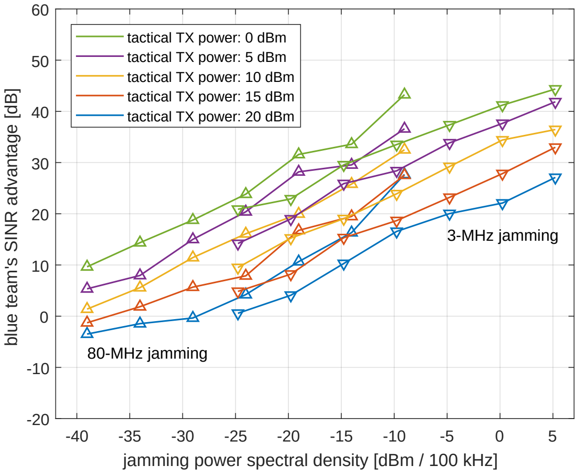
The quantities that are varied in the forthcoming results are the transmit (TX) powers used by the red team and the blue team in communications and jamming, respectively, alongside with the jamming bandwidth. For each transmit power pair, several received signal vectors from the receiving USRP and the VST are collected, which are then used for estimating the signal-to-interference-plus-noise ratio (SINR) of the red team's transmission. In the case of the MFDR transceiver, digital SI cancellation is first performed on the received signal, using the nonlinear cancellation algorithm reported, for instance, in [8]. The main parameters, such as the used bandwidths and the transmit power ranges, are collected in Table I.



(a) tactical communication performance

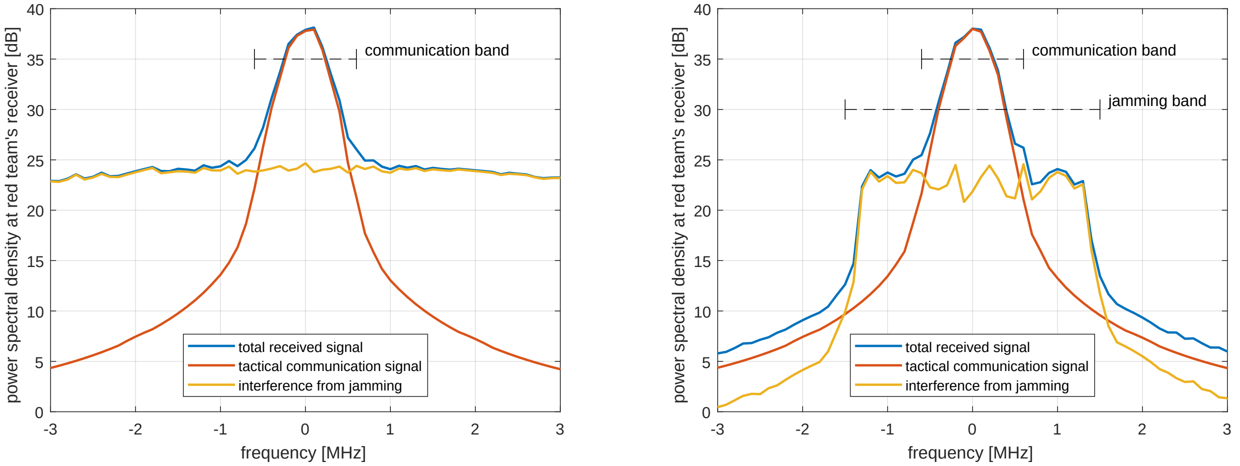


(b) signal interception performance



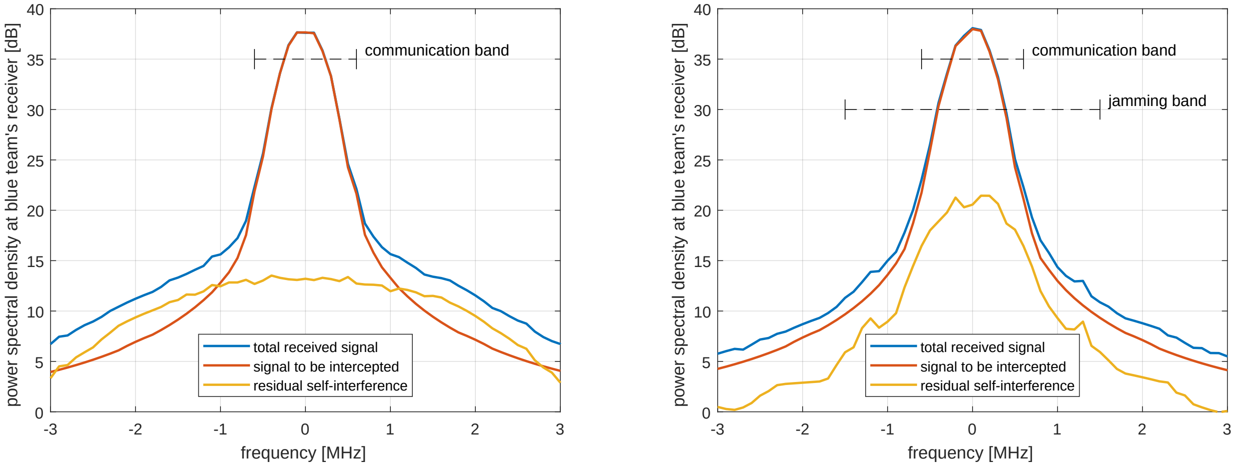
(c) blue team's technical advantage

Fig. 5. The estimated SINR of the red team's tactical communication signal (a) at the red team's own receiver and (b) at the opposing blue team's receiver, i.e., the intercepting MFDR, as well as (c) the SINR advantage of the blue team's interception over the red team's communication.



(a) spectrum at the red team’s receiver under 80-MHz jamming

(b) spectrum at the red team’s receiver under 3-MHz jamming



(c) spectrum at the blue team’s receiver under 80-MHz self-interference

(d) spectrum at the blue team’s receiver under 3-MHz self-interference

Fig. 6. Spectra of received signals in the system when the red team’s tactical TX power is 20 dBm and the blue team’s jamming power spectral density is -19.4 ± 0.4 dBm / 100 kHz. The mean power density of the tactical communication signal over the 10.5-MHz band of interest is normalized to 25 dB.

Figure 4 shows the SINRs at the blue team’s intercepting FD transceiver as well as at the red team’s intended receiver. The SINR curves are plotted in terms of the red team’s tactical transmit power and for two different jamming power levels, using a jamming bandwidth of 80 MHz. Let us note that, due to a temporary flaw during the measurements, the data point corresponding to the tactical TX power of -5 dBm and the blue team’s jamming power of -15 dBm is omitted in Fig. 4.

Figures 5(a) and 5(b) show the SINRs at both teams’ receivers with respect to the power spectral density of the jamming signal, the different tactical TX powers and jamming bandwidths being represented by the different curves. Defining the horizontal axis in terms of the power density allows for presenting the results of the two jamming bandwidths together. Correspondingly, it can be noted that the 3-MHz jamming signal results theoretically in 14.3 dB higher jamming power spectral density than the 80-MHz jamming signal with the same transmit power, but it requires that the blue team knows the center frequency used by the red team. Using the data of Figs. 5(a) and 5(b), the SINR advantage of the blue team is then shown in Fig. 5(c). The advantage is quantified simply as the difference between the SINRs achieved by the combating teams, and it shows directly how beneficial the jamming is for the blue team despite the self-interference.

Figure 6 shows the power spectral densities (PSDs) of the relevant signals for the two considered jamming bandwidths. In particular, Figs. 6(a) and 6(b) show the PSDs of the total signal, the estimated noise signal, and the estimated intended signal for the 80-MHz and 3-MHz jamming signals at the red team’s HD receiver, respectively, while Figs. 6(c) and 6(d) show the same PSDs at the blue team’s MFDR. The PSDs are given for the case, where the blue team’s jamming power spectral density is round -10 dBm / 1 MHz, which is achieved with a transmit power of 10 dBm (resp. -5 dBm) and a jamming bandwidth of 80 MHz (resp. 3 MHz), and the red team’s tactical TX power is 20 dBm.

IV. DISCUSSION ON RESULTS

Investigating first Fig. 4, we can confirm that increasing tactical TX power at the red team's transmitter improves the SINRs of both the red team's communication and the blue team's interception as expected. This means that, under certain circumstances, the blue team's MFDR can increase its own interception SINR by forcing the red team to use higher transmit power. It can achieve this by transmitting a jamming signal, as the red team must then increase its tactical transmit power to retain a sufficient SINR. However, under the path loss conditions prevailing in these measurements, this phenomenon is visible only with the very lowest TX powers of the red team.

Observing then the SINRs with respect to the jamming PSD in Fig. 5(a), it can be seen that the SINR of the red team's receiver is inversely proportional to the jamming power, as can be expected. Under this measurement scenario, the blue team's MFDR could essentially render the red team's tactical link inoperable even when the red team used the highest possible tactical TX power. Moreover, as is evident from Fig. 5(b), at the same time the SINR achieved by the blue team remains high enough for successfully intercepting the signal.

Furthermore, Fig. 5(b) yields the conclusions that 1) the jamming power does not affect the SINR of the intercepted signal; and 2) increasing the red team's transmit power beyond 0 dBm does not increase the SINR of the intercepted signal. The first indicates that the MFDR prototype's SI suppression performance is not limited by SI power. The second stems from SI channel estimation performed within the SI canceller of the MFDR. Namely, from the perspective of SI cancellation, the intercepted signal is noise, which reduces channel estimation accuracy. As a result, increasing the power of the intercepted signal beyond a certain point (viz. 0-dBm transmit power herein) does not improve the resulting SINR, as it degrades SI cancellation at a similar rate. In the measurements reported herein, at lower power levels the red team's tactical TX power still affects the SINR as is evident from Fig. 4. This phenomenon has been discussed before in [12], [13].

Considering then the SINR advantages in Fig. 5(c), the benefit obtained by jamming is evident therein. Namely, with sufficiently high jamming power, the SINR at the blue team's intercepting FD transceiver can be 10–40 dB higher than at the intended HD recipient. As a result, the blue team can intercept the red team's communication, while the red team finds it difficult to maintain its tactical link. In fact, under these measurement conditions, the blue team's SINR advantage is nearly linearly dependent on the jamming power, demonstrating the efficacy of the proposed concept.

The aforementioned effect is illustrated also by the corresponding signal spectra in Fig. 6. Namely, it can be observed from Figs. 6(a) and 6(b) that the relative noise-plus-interference level is much higher at the red team's receiver than the corresponding relative interference floor of the blue team's MFDR in Figs. 6(c) and 6(d). In other words, the jamming experienced by the red team is much more harmful than the residual SI at the blue team's intercepting MFDR.

V. CONCLUSION

In this paper, we provided experimental results on how to use full-duplex radio devices within wireless military networks. In particular, we evaluated a strategy where such a full-duplex device engages in simultaneous jamming and sensing, thereby preventing the enemy receiver from successfully decoding its intended signal while intercepting the said signal itself. The experimental results confirmed the feasibility of this strategy and demonstrated the efficacy of simultaneous jamming and interception when utilizing a military full-duplex radio prototype. Namely, the jamming significantly degraded the SINR of the enemy receiver while the SINR of the intercepting full-duplex device remained on a level high enough for successful interception. The demonstrated potential of this type of an offensive maneuver indicates that full-duplex radio devices can be one of the key technologies in the tactical communications and electronic warfare systems of the future.

REFERENCES

[1] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 9, pp. 1637–1652, Sep. 2014.

[2] Z. Zhang, K. Long, A. V. Vasilakos, and L. Hanzo, "Full-duplex wireless communications: Challenges, solutions and future research directions," *Proceedings of the IEEE*, vol. 104, no. 7, pp. 1369–1409, Jul. 2016.

[3] 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*, May 2017.

[4] 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, Oct. 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*, May 2018.

[6] 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*, May 2019, to be submitted.

[7] D. Korpi, J. Tamminen, M. Turunen, T. Huusari, Y.-S. Choi, L. Anttila, S. Talwar, and M. Valkama, "Full-duplex mobile device: Pushing the limits," *IEEE Communications Magazine*, vol. 54, no. 9, pp. 80–87, Sep. 2016.

[8] D. Korpi, "Full-duplex wireless: Self-interference modeling, digital cancellation, and system studies," Ph.D. dissertation, Tampere University of Technology, Dec. 2017.

[9] T. R. Halford, M. Johnson, S. Kim, and C. Kose, "On the design of a modern broadband communications waveform for tactical air-to-ground links," in *Proc. IEEE Military Communications Conference*, Oct. 2009.

[10] S. Kim, M. Johnson, O. W. Yeung, and D. Yin, "On the design of a modern broadband physical layer for teleoperations links," in *Proc. IEEE Military Communications Conference*, Nov. 2011.

[11] A. Blyskun, M. Johnson, S. Kim, J. Speros, G. Thatte, and D. R. Williamson, "Improving the SRW waveform via a physical layer retrofit," in *Proc. IEEE Military Communications Conference*, Nov. 2013.

[12] D. Korpi, L. Anttila, and M. Valkama, "Impact of received signal on self-interference channel estimation and achievable rates in in-band full-duplex transceivers," in *Proc. 48th Asilomar Conference on Signals, Systems and Computers*, Nov. 2014.

[13] D. Korpi, T. Riihonen, and M. Valkama, "Achievable rate regions and self-interference channel estimation in hybrid full-duplex/half-duplex radio links," in *Proc. 49th Annual Conference on Information Sciences and Systems*, Mar. 2015.