Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 205 (2022) 179–187

Procedia Computer Science

www.elsevier.com/locate/procedia

International Conference on Military Communications and Information Systems (ICMCIS 2022)

RF self-interference canceller prototype for 100-W full-duplex operation at 225–400 MHz

Miika Vuorenmaa, Mikko Heino*, Matias Turunen, Taneli Riihonen

Unit of Electrical Engineering, Faculty of Information Technology and Communication Sciences, Tampere University, Korkeakoulunkatu 1, Tampere 33014, Finland

Abstract

Military applications require more and different characteristics from in-band full-duplex radio technology than what the research prototypes developed for civil/commercial applications can offer. While the challenge of cancelling the strong transmit–receive coupling, i.e., self-interference (SI), in a full-duplex radio has been largely resolved at higher ultra high frequency (UHF) bands for low-power transmission, tactical communication and electronic warfare applications require major research efforts toward supporting lower military-relevant frequencies and significantly higher transmission power levels. In this paper, we present a prototype of a radio-frequency SI cancellation circuit for the lower UHF band at 225–400 MHz and transmit power of up to 100–200 W. The experimental results demonstrate that the canceller can suppress SI by 40–50 dB depending on the operation frequency within the band. It is targeted for the military application of simultaneous full-duplex jamming and interception of communications, where we can estimate that a 5-W signal-of-interest could be intercepted from 10 km away when simultaneously jamming with 100 W power.

Keywords: in-band full-duplex; tactical communications; electronic warfare; signal interception; jamming; RF canceller

1. Introduction

Since ICMCIS'17 and [16] thereof, in-band full-duplex (FD) radio technology [18, 21, 9] has been making its way to military systems [15, 2, 20, 11, 13, 14, 12], which range from tactical communications to electronic warfare (EW). The technology readiness level (TRL) has increased through innovating new military-specific application scenarios and redeveloping the technology of civilian/commercial origins to meet the high(er) requirements of the electromagnetic battlefield. It has now reached TRLs 3–4 to some extent with successful experimental demonstrations

* Corresponding author
E-mail address: mikko.heino@tuni.fi

10.1016/j.procs.2022.09.019

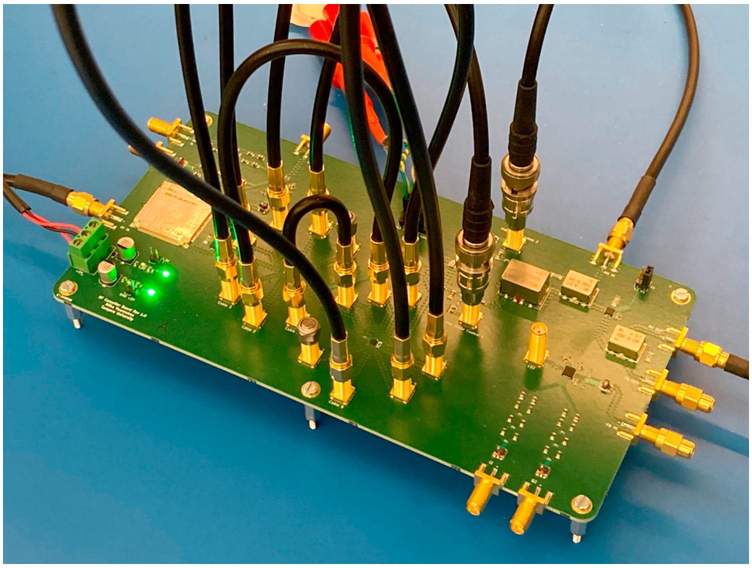


Fig. 1. Photo of the manufactured RF self-interference canceller prototype with six loop-back coaxial cables installed in its delay bank.

of proofs-of-concepts and validation in laboratory environments, while basic research is still needed to fully establish TRL 2 by verifying all the yet undiscovered potential applications [14].

The suppression of the self-interference (SI) that results from simultaneous transmit and receive operation is the key technical challenge that has been largely solved for civilian/commercial full-duplex communication applications during the last ten years — required techniques take place in electromagnetic antenna domain, radio-frequency (RF) or analog base-band electronics, and intermediate-frequency or base-band digital signal processing. However, as a rough generalization, the previous research on non-military communication scenarios has been limited to low transmit powers up to 1–2 W and fixed bandwidths up to 80 MHz at 2400–2480 MHz [9].

The technical challenges to be solved for increasing the TRL of military FD radios are to support other frequency bands and significantly higher transmission powers [20, 14], while operation on wider bandwidths is relevant too [4]. To that end, the objectives for our present work towards enabling full-duplex EW applications are to support transmission power of at least 100 W and reception with (rather narrow) 100 kHz instantaneous bandwidth that can be chosen anywhere within the wide frequency range 225–400 MHz, i.e., NATO Band I.

The specific full-duplex EW application that is in the focus of this study is simultaneous jamming and reconnaissance of tactical radio communications. In [5], we presented an original RF canceller design concept that satisfies the aforementioned objectives in the considered application scenario as well as simulations and measurements on a primitive, incomplete proof-of-concept prototype thereof. The results validated the correct operation of the design concept.

In this paper, we report the implementation and manufacturing of the complete prototype canceller board illustrated in Fig. 1 as well as measurements that demonstrate the SI cancellation and signal interception performance thereof. The results show that, using the canceller, a military FD radio would be able to transmit jamming with 100 W power while simultaneously intercepting signals from a significant distance at any 100 kHz subband within 225–400 MHz.

2. Simultaneous Jamming and Signal Interception in Full-Duplex Electronic Warfare

The system scenario consists of an in-band full-duplex transceiver and an intercepted transmitter of an adversary as seen in Fig. 2. The full-duplex transceiver transmits a high-power wideband signal to jam the communication of the adversary while at the same time detecting and receiving the adversary's transmit signal, i.e., the signal-of-interest (SOI). This enables to gain information about the adversary's communication and effectiveness of the jamming. In contrast, such simultaneous operation would not be possible with conventional out-of-band full-duplex or time-division

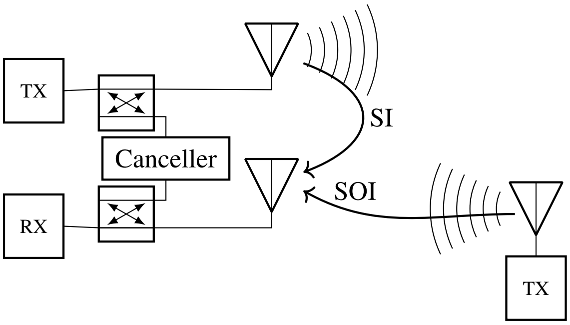


Fig. 2. Simultaneous jamming and remote signal interception.

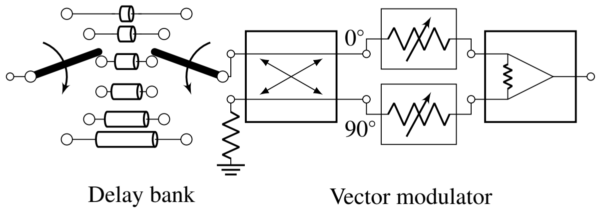


Fig. 3. Block diagram of the canceller design.

half-duplex systems, which would require either pausing of the jamming or intercepting signals outside the jamming band.

The considered scenario is related to full-duplex jamming with simultaneous interception of tactical communications [17], detection of radio-control systems [19] and spectrum monitoring [10]. However, our earlier experiments reported in the referenced papers are limited to the 2.4 GHz band and low transmit powers so they are not so solid for validating real military applications unlike the present study.

The intercepted signal of the adversary has drastically lower power than the interference coupled from the transceiver's own jamming signal. This requires successful cancellation of the self-interference to bring the SI down close to the noise floor of the receiver to enable the successful detection of the SOI. To achieve this over 120 dB of SI cancellation, methods to increase antenna isolation, RF self-interference cancellation circuits and digital cancellation are required. We concentrate on the RF self-interference cancellation and only consider the experimentation of an RF canceller in this paper. However, on top of the 37–51 dB of RF cancellation that we demonstrate with our prototype, we expect that antenna isolation and digital cancellation could also provide 40–50 dB and 30–40 dB, respectively, towards the total SI suppression.

3. Self-interference Cancellation Circuit for High-Power Military Full-Duplex Radio

3.1. Design

Let us briefly overview the canceller concept here despite it is fully described in [5]. The canceller structure consists of a delay bank from which a fixed delay can be chosen with a switch. The second key component is a vector modulator, which is in series with the delay bank as illustrated in Fig. 3. The vector modulator provides amplitude control and 90° phase tuning range for each delay. Together with the delay bank, the phase coverage is extended to 360° for the whole operating band with an amplitude tuning range of 35 to 40 dB. The canceller is designed to operate in the wide 225–400 MHz band and reaches it maximum peak cancellation over a narrow 100 kHz bandwidth. The canceller supports high transmission powers beyond of 100 W (i.e., 50 dBm), while the canceller's input power reaches its maximum value of 1 W (i.e., 30 dBm).

The RF canceller couples a low power signal sample from the antenna feed, matches its amplitude and aligns the phase to be opposite to the received self-interference, and then combines it with the received signal. Due to the wave superposition, the self-interference is cancelled. The input coupler has to be placed in between of the transmitter output and antenna feed so the canceller input signal contains all of the non-idealities, such as distortion and harmonics, caused by the components in the transmitter chain. Thus, these effects can also be cancelled from the received signal, which renders better overall cancellation performance.

The input coupler affects how much of the transmission power is coupled to the input of the canceller. The canceller input power must be higher than the power of received self-interference so the signals can be matched by attenuating the input signal. Thus, the coupling of the input coupler together with available antenna isolation must satisfy following condition:

$$\text{Antenna isolation(dB)} - S_{21}(\text{Canceller}, \text{min}) > \text{Input coupler(dB)}, \tag{1}$$

where $S_{21}(\text{Canceller}, \text{min}) \approx 18.5$ dB for this prototype. For example, 100-W transmission power and 40 dB of antenna isolation require a 20 dB input coupler — in this case, the canceller input power would be 30 dBm.

Cancellation can be improved in two different ways. First, we can try to increase the antenna isolation as much as possible. The isolation depends on antenna distance, radiation pattern, polarization and the different isolation enhancing methods used. E.g., approximately 40–50 dB of antenna isolation can be realistically achieved for closely located dipole antennas [6]. Another option to improve cancellation is to reduce the input power of the canceller because at higher input powers the components become increasingly non-linear. They start producing distortion such as harmonics and intermodulation products which negatively affect the cancellation performance.

3.2. Implementation

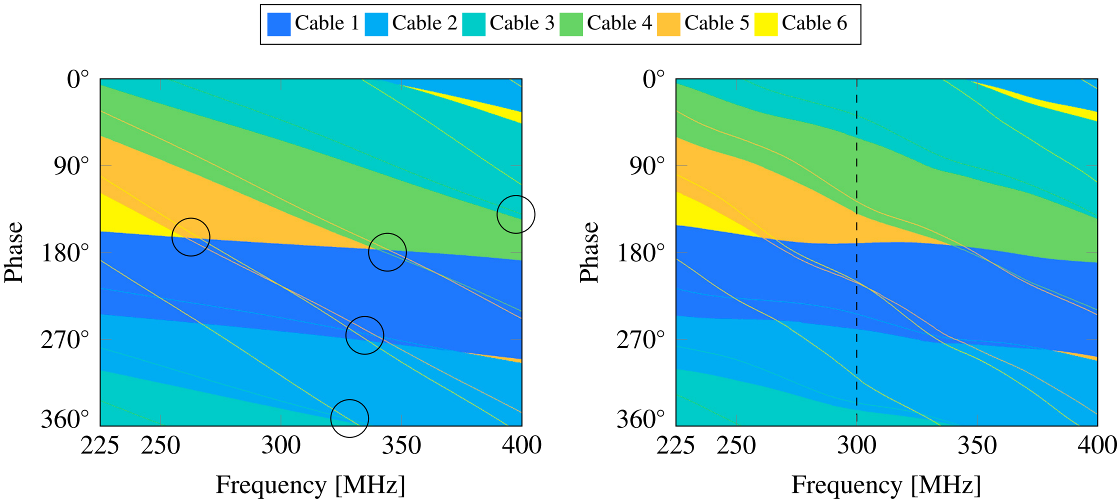
In this section, we describe the implementation of the RF canceller prototype. Both the delay bank and the vector modulator are included on a single printed circuit board (PCB), as opposed to them being previously built on separate PCBs in the primitive prototype of [5]. The new components are selected so that their power handling capability is higher than the projected input power of the canceller, thus avoiding the possibility of any of parts breaking or malfunctioning. In this case, the maximum input power of the components must be at least 30 dBm but preferably a few decibels higher. However, it is not enough for the components to withstand high input power but they should also operate in a linear region. In particular, the chosen NXP BAP70Q PIN-diode attenuators are vulnerable to transition into a non-linear region if low control voltages are used with high input powers. In practice, this slightly limits the safe operation range of the PIN diodes, as small control voltages below 0.5 V are typically avoided to increase the accuracy of the phase control.

The RF canceller design supports configurations with 6–8 delay lines by utilizing Skyworks SKY13418-485LF single-pole eight-throw (SP8T) switches in the delay bank. The canceller board has a built-in internal delay and connector slots for total of seven coaxial cables. If a cable slot is unused, it requires an external termination. The internal delay is optional in the six-delay line configuration because all of the delays can be implemented as coaxial cables. However, it offers an ability to use the internal cable together with only five external cables. A fixed delay is activated by applying 3-bit control voltages to the delay switches.

The delay switches are unfortunately not capable of hot-switching, which is why separate switches need to be added for this purpose. Thus, two Tagore TS7225FK single-pole dual-throw (SPDT) switches were added to the circuit board. The purpose of the first switch is to protect the delay bank during the delay change and to allow canceller disconnection without interrupting the transmission. The second switch can be used to protect the receiver from possible transients and increased RX power in case of adversary's counter operation, i.e., jamming.

The canceller board has two Analog Devices ADL5387 I/Q demodulators that provide down-converted baseband signal samples from the canceller input and the output. The information from these baseband signals can be used by an upcoming control circuit to select an optimal delay line and tune the weights for the PIN-diode attenuators in order to achieve the best possible cancellation. The baseband signal needs to be filtered in order to prevent I/Q demodulator's local oscillator (LO) from leaking and mixing with the signal. This has been accomplished by adding a sixth-order Butterworth low-pass filter with a cutoff frequency of 10 MHz.

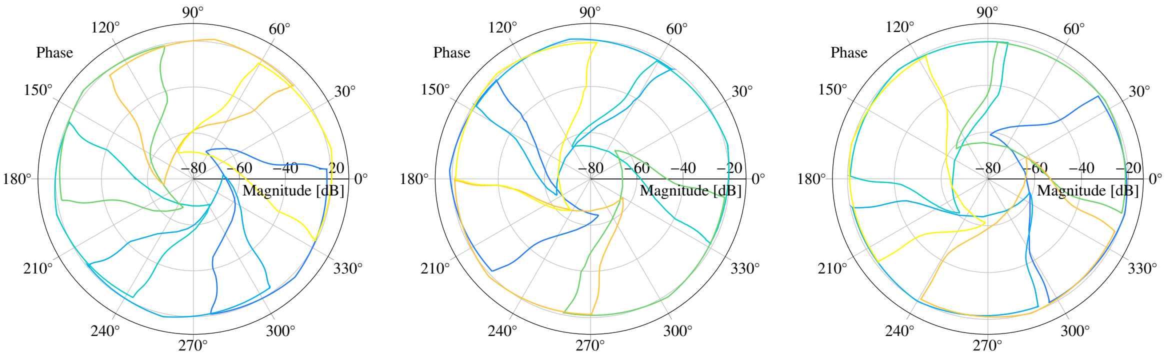
The manufactured cable lengths are shown in Table 1. The designed cable lengths were chosen relative to Cable 1, which was decided to be about 10 cm long due to practical reasons. The LMR-195 coaxial cable was used for manufacturing the delay lines with relatively high specified propagation velocity of $0.8c_0$ to minimize the error due to limited accuracy in manufacturing [1]. However, in practice, the measured propagation velocity was lower than the specified value requiring further manual tuning of the cable lengths. The cable lengths were improved compared to [5] to include better overlap between each each cable, as in [5] a small hole was noted in the measured phase range at the lowest frequency.



(a) at low input power (0.0 dBm)

(b) at high input power (29.5 dBm)

Fig. 4. Measured phase maps with six-line delay bank and 90-degree tuning range in the vector modulator. The potential critical points (that are avoided as gaps in the whole input power range of interest) are circled, and the dashed vertical line indicates the tuning region shown in Fig. 5(b) at 300 MHz.



(a) at 225 MHz

(b) at 300 MHz

(c) at 400 MHz

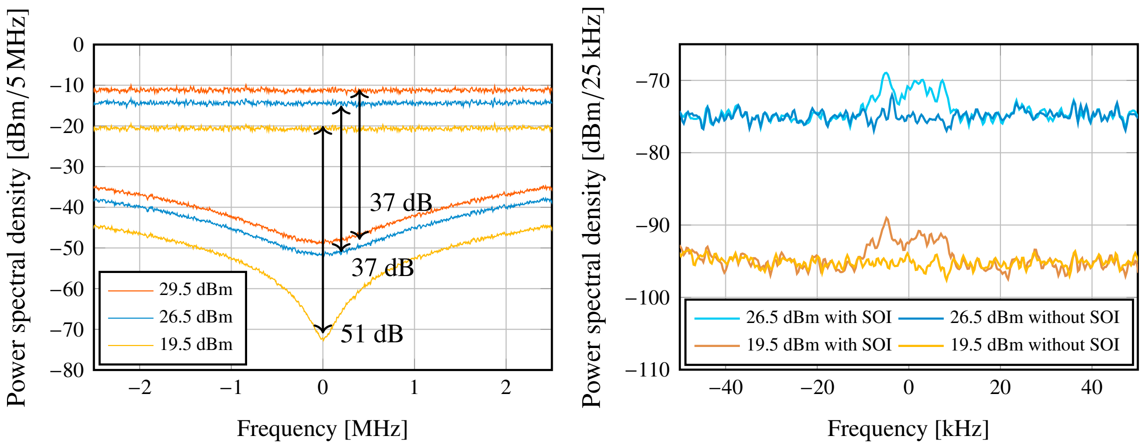
Fig. 5. Measured output phase and attenuation tuning regions with each cable at high input power (29.5 dBm). The legend is the same as for the above figure.

Table 1. Manufactured cables' specifications in the delay bank.

			Measured loss [dB] at		
	Approx length [cm]	Measured delay [ns]	225 MHz	300 MHz	400 MHz
Cable 1	11	0.47	0.14	0.18	0.23
Cable 2	27	1.20	0.18	0.16	0.19
Cable 3	45	1.99	0.16	0.18	0.21
Cable 4	60	2.65	0.11	0.12	0.13
Cable 5	76	3.37	0.15	0.18	0.21
Cable 6	95	4.22	0.17	0.19	0.23

3.3. Phase and Amplitude Tuning Ranges

Figure 4 shows the measured phase ranges obtainable with each cable measured with the whole canceller PCB. The outline of the tuning range for a single cable is obtained by sweeping the first PIN-diode attenuator's control



(a) zoom-out without cancellation and without signal-of-interest (b) zoom-in with cancellation and with(out) signal-of-interest

Fig. 6. Measured spectrum plots showing reference power level without cancellation, with cancellation and with the signal-of-interest.

voltage V_1 from 0 to 20 V, while the second PIN-diode attenuator's control voltage V_2 is set either at 0 V or 20 V, and then switched vice versa. This is repeated with each delay cable in Table 1 to obtain the phase map both at low input power of 0 dBm and maximum available input power of 29.5 dBm. The constant delay caused by the canceller board without the delay cables has been removed from the phase map to make it clearer. It is seen in Fig. 4(b) that, with maximum power, the non-linear performance of the diode attenuators cause ripples in the phase response with each cable. However, as the cables had overlap in their phase ranges, full 360° coverage is maintained across the whole frequency range.

The measured tuning ranges for three different frequencies are illustrated in Fig. 5, where the subfigures (a)–(c) represent the canceller operation in lower, middle and upper frequencies of the targeted band, respectively. The results prove that a full 360° tuning range is achieved in all of the cases. There is better overlap between the cables, especially at lower frequencies, when compared to the previous cable design in [5]. The measured amplitude tuning range for the whole frequency range is from about 50 dB down to 40 dB as it varies depending on the frequency.

In Fig. 5, it seen that the response of the vector modulator is not linear, i.e., the edges of each tuning range move towards higher phases when the attenuation is increased. This is caused by non-linear phase response of single-diode attenuators, the effect of which is analyzed with more detail in [5]. However, this curving happens similarly with each cable and holes in the phase tuning range of the canceller are thus avoided.

4. Canceller Performance

In this section, we report the measurements and experimental results. Firstly, they demonstrate the plain self-interference cancellation performance of the canceller prototype without an external signal-of-interest (SOI). Secondly, they assess the signal-to-interference-and-noise (SINR) that can be achieved for intercepting an external signal and, based on link budget calculations, characterize the distance at which it could be detecting a low-power SOI while simultaneously jamming in the full-duplex manner using high power. The system is designed so that 19.5 dBm, 26.5 dBm and 29.5 dBm canceller input power would correspond to roughly 20 W, 100 W and 200 W transmitted jamming power, respectively, in a practical system where antenna isolation is about 40 dB. For the interception results, the signal-of-interest is frequency-modulated audio-band noise with 5-kHz deviation and 20-kHz bandwidth.

Figure 6 shows signal spectrum plots with and without the SOI. The top three spectral signals indicate the power of the interference signal without any cancellation. These signals are used as a reference when calculating the total cancellation at a given power. The bottom three curves show spectral signals after RF cancellation when optimal cancellation is achieved. Cancellation is calculated as the difference between the upper and lower signals in a given bandwidth and power. A narrow valley forms in the middle of the spectrum, which describes the efficiency of can-

Table 2. The measured received power of the signal-of-interest when the SINR for its interception is 3 decibels.

Canceller input power	19.5 dBm	26.5 dBm	29.5 dBm
Corresponding jamming power	~ 20 W	~ 100 W	~ 200 W
227.5 MHz	−84.0 dBm	−61.0 dBm	−56.1 dBm
Operation at 300.0 MHz	−83.9 dBm	−63.9 dBm	−61.8 dBm
397.5 MHz	−91.9 dBm	−71.9 dBm	−60.7 dBm
Average of the above	−86.6 dBm	−63.7 dBm	−58.8 dBm

cellation. At low input powers, the valley is deep because there are several tens of decibels of cancellation. However, the cancellation deteriorates as the input power increases as the non-linearity of the components begins to limit the operation of the canceller.

Figure 7 illustrates the self-interference cancellation results at three frequencies, which represent canceller performance at lower, middle and upper parts of the target frequency range. Cancellation is measured by starting from low input powers approaching a maximum power of 29.5 dBm in this case. Each time the power is increased, the canceller must be readjusted because the signal amplitude and phase may change slightly. At low powers, up to 60–70 dB cancellation is achieved which decreases towards maximum power and resulting about 30–40 dB at maximum available input power. Canceller operates better at high frequencies than at low frequencies.

Figure 8 shows the SINR results, where a narrowband 20-kHz signal is intercepted within the designed 100-kHz band. The SINR is calculated from the 25 kHz channel. The power of the SOI is set so that it results in about 3 dB of SINR with maximum canceller input power at 300 MHz. All of the other SINR values are measured using this same power level in the SOI. The SINR results depend greatly on how accurately the cancellation has been adjusted to the SOI. This has higher effect to the low input power results because the cancellation is more sensitive to changes.

Figure 9 illustrates theoretical interception distances based on the received power levels in Table 2 in the two cases of 20 W and 100 W of jamming power. Received SINR value of 3 dB after the self-interference cancellation is assumed as the threshold for successful interception of the SOI. The transmitter distance corresponding to this SINR value is calculated using the path loss obtained from the Okumura–Hata radio propagation model with open area correction and RX and TX antenna height of 5 meters above the ground [3]. The transmitted SOI power is swept from 1 W to 10 W and the transmitter is assumed to have an omnidirectional antenna with 0 dBi gain. The receiver antenna gain is assumed to be 8 dBi. With 20 watts of jamming power, an interception distance of about 5–12 km is achieved depending on the frequency and power of the SOI transmitter. In the target case of 100 W of jamming power, the modelled interception distances decrease to 2–4 km.

However, it should be noted that the foregoing modest interception distances would be obtained solely using analog RF cancellation — adding digital cancellation would improve the SINR significantly. Thus, the SOI could definitely be detected further away in practice. For example, adding 30 dB of digital cancellation to the current analog cancellation with jamming of 100 W would result in at least 13 km of interception distance with a SOI of 5 watts at 300 MHz. This performance can be regarded as very promising, because the 100 W jamming would likely be ineffective at that distance and beyond.

5. Conclusion

In this paper, we presented the prototype of a full-duplex self-interference cancellation circuit for the military-relevant 225–400 MHz band and beyond 100-W power handling. The performance of the manufactured canceller was demonstrated with measurements of the phase–attenuation characteristics, achieved cancellation, and SINR for the interception of a test signal-of-interest. We also estimated the feasible interception distances while simultaneously transmitting jamming at high power and can conclude that they are viable for practical electronic warfare operations. The presented results have two limitations since they represent research work-in-progress. Firstly, the canceller was controlled manually in the experiments reported in this paper. Thus, our next research step will be to design and implement control electronics and algorithms along the lines of [7, 8]. Secondly, the experiments were done in a cable and the performance of simultaneous jamming and interception was estimated from them based on theoretical

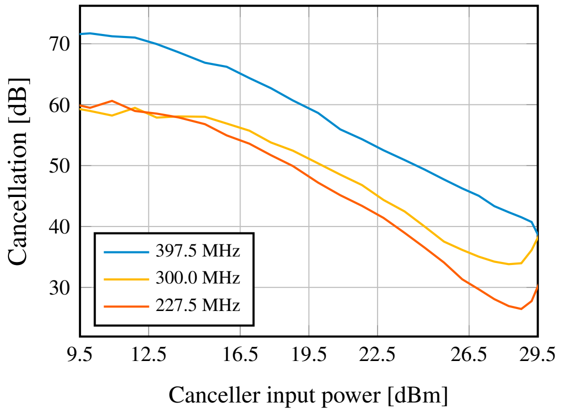


Fig. 7. Measured self-interference cancellation performance at three different frequencies versus canceller input power.

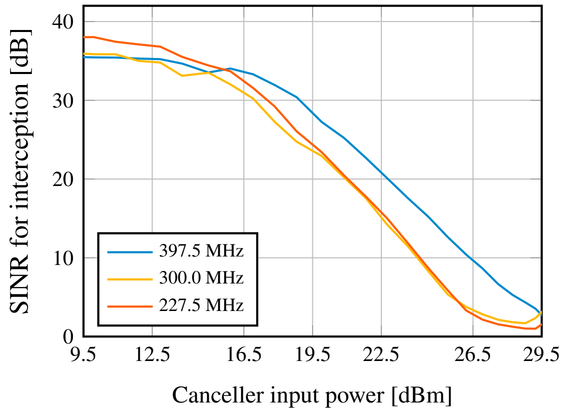


Fig. 8. Estimated signal-to-interference-and-noise ratio (SINR) at three different frequencies versus canceller input power.

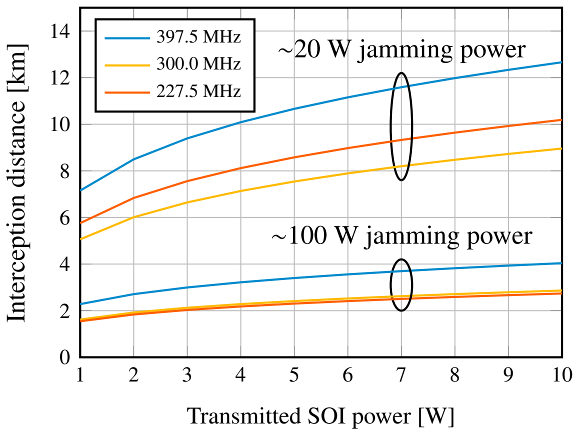


Fig. 9. Calculated interception distances for varying signal-of-interest (SOI) transmit power, when employing only RF cancellation for SI suppression.

propagation modelling. Thus, we will pursue over-the-air measurements and ultimately aim at reaching TRL 5 with our full-duplex military radio prototype in field experiments.

Acknowledgements

This research work was supported in part by the Academy of Finland, in part by the Support Foundation for National Defence, and in part by the Finnish Scientific Advisory Board for Defence (MATINE).

References

[1] , 2021. LMR-195 datasheet. Technical Report. Times Microwave Systems. URL: https://www.timesmicrowave.com/DataSheets/CableProducts/LMR-195.pdf.

[2] Adrat, M., Keller, R., Tschauner, M., Wilden, S., Le Nir, V., Riihonen, T., Bowyer, M., Pärlin, K., 2019. Full-duplex radio — Increasing the spectral efficiency for military applications, in: Proc. International Conference on Military Communications and Information Systems.

[3] Hata, M., 1980. Empirical formula for propagation loss in land mobile radio services. IEEE Transactions on Vehicular Technology 29, 317–325. doi:10.1109/T-VT.1980.23859.

[4] Heino, M., Marin, J., Hiltunen, K., Riihonen, T., 2022. On the prospects of in-band full-duplex radios as monostatic continuous-wave noise radars, in: Proc. IEEE Radar Conference.

[5] Heino, M., Turunen, M., Vuorenmaa, M., Riihonen, T., 2021. Design of RF self-interference cancellation circuit for 100-W full-duplex radio at 225–400 MHz, in: Proc. International Conference on Military Communications and Information Systems.

[6] Iwamoto, K., Heino, M., Haneda, K., Morikawa, H., 2018. Design of an antenna decoupling structure for an inband full-duplex collinear dipole array. IEEE Transactions on Antennas and Propagation 66, 3763–3768. doi:10.1109/TAP.2018.2835301.

[7] Kolodziej, K.E., Cookson, A.U., Perry, B.T., 2021a. Adaptive learning rate tuning algorithm for RF self-interference cancellation. IEEE Transactions on Microwave Theory and Techniques 69, 1740–1751.

[8] Kolodziej, K.E., Cookson, A.U., Perry, B.T., 2021b. RF canceller tuning acceleration using neural network machine learning for in-band full-duplex systems. IEEE Open Journal of the Communications Society 2, 1158–1170.

[9] Kolodziej, K.E., Perry, B.T., Herd, J.S., 2019. In-band full-duplex technology: Techniques and systems survey. IEEE Transactions on Microwave Theory and Techniques 67, 3025–3041.

[10] Marin, J., Turunen, M., Bernhardt, M., Riihonen, T., 2021. Self-interference cancelation performance in full-duplex jamming and spectrum monitoring, in: Proc. International Conference on Military Communications and Information Systems.

[11] Pärlin, K., Riihonen, T., 2020. Full-duplex transceivers for defense and security applications, in: Alves, H., Riihonen, T., Suraweera, H.A. (Eds.), Full-Duplex Communications for Future Wireless Networks. Springer Singapore. chapter 9, pp. 249–274. doi:10.1007/978-981-15-2969-6_9.

[12] Pärlin, K., Riihonen, T., Le Nir, V., Bowyer, M., Ranström, T., Axell, E., Asp, B., Ulman, R., Tschauner, M., Adrat, M., 2021. Full-duplex tactical information and electronic warfare systems. IEEE Communications Magazine 59, 73–79.

[13] Ranström, T., Axell, E., 2020. Full duplex based digital out-of-band interference cancellation for collocated radios, in: Proc. Wireless Communications and Networking Conference. doi:10.1109/WCNC45663.2020.9120615.

[14] Riihonen, T., 2021. Military applications, in: Kolodziej, K.E. (Ed.), In-Band Full-Duplex Wireless Systems Handbook. Artech House. chapter 17, pp. 301–318.

[15] Riihonen, T., Korpi, D., Rantula, O., Rantanen, H., Saarelainen, T., Valkama, M., 2017a. Inband full-duplex radio transceivers: A paradigm shift in tactical communications and electronic warfare? IEEE Communications Magazine 55, 30–36.

[16] Riihonen, T., Korpi, D., Rantula, O., Valkama, M., 2017b. On the prospects of full-duplex military radios, in: Proc. International Conference on Military Communications and Information Systems.

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

[18] Sabharwal, A., Schniter, P., Guo, D., Bliss, D.W., Rangarajan, S., Wichman, R., 2014. In-band full-duplex wireless: Challenges and opportunities. IEEE Journal on Selected Areas in Communications 32, 1637–1652.

[19] Saikanmäki, J., Turunen, M., Mäenpää, M., Saarinen, A.P., Riihonen, T., 2019. Simultaneous jamming and RC system detection by using full-duplex radio technology, in: Proc. International Conference on Military Communications and Information Systems.

[20] Task Group IST-ET-101, 2020. Full-Duplex Radio — Increasing the Spectral Efficiency for Military Applications. Technical Report. NATO Science and Technology Organization.

[21] Zhang, Z., Long, K., Vasilakos, A.V., Hanzo, L., 2016. Full-duplex wireless communications: Challenges, solutions and future research directions. Proceedings of the IEEE 104, 1369–1409.