Inband Full-Duplex Radio Transceivers: A Paradigm Shift in Tactical Communications and Electronic Warfare?

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Abstract

Inband full-duplex (FD) operation has great potential in civilian/commercial wireless communications, because it can as much as double transmission links' spectral efficiency by exploiting the new-found capability for simultaneous transmission and reception (STAR) that is facilitated by advanced self-interference cancellation (SIC) techniques. This article surveys the prospects of exploiting the emerging FD radio technology in military communication applications as well. In addition to enabling high-rate two-way tactical communications, 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 when they are also receiving or transmitting other signals at the same frequency bands. After introducing comprehensively FD transceiver architectures and SIC requirements in military communications, this article outlines and analyzes all the most promising defensive and offensive applications of the STAR capability. It is not out of the question that this disruptive technology could even bring about a paradigm shift in operations at the cyber-electromagnetic battleground. At least, forward-looking innovators in the military communications community would have right now a window of opportunity to engage in original, potentially high-impact scientific research on FD military radio systems, which we also would like to spur by this speculative tutorial article.

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INTRODUCTION

Inband full-duplex (FD) wireless communication [1], [2] means that a radio device is receiving and transmitting information signals at the same time and at the same center frequency, as opposed to conventional half-duplex (HD) operation. Especially, to avoid misconception, one should note that neither time-division duplexing nor frequency-division duplexing (TDD nor FDD) is regarded as "real" FD operation when adopting the contemporary terminology despite them allowing simultaneous two-way conversation, because the perspective is shifted to spectrum usage at the physical layer. While the prospects of the FD radio technology in civilian/commercial applications are already largely understood, this article proceeds to its novel military applications. To that end, one should again note that all off-the-shelf "full-duplex military radios" employ TDD or FDD (or both) and so they are not actually FD radios in the scope of this article.

In general, when extending beyond the plain communication context, prospective military FD radios will have the progressive capability for simultaneous transmission and reception (STAR) 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 as shown in Fig. 1. It is quite obvious that, by utilizing this superpower, armed forces could gain a major technical advantage over an opponent that does not possess similar technology. However, viable FD operation relies on efficient antenna isolation and self-interference (SI) cancellation [3], [4], because the strong electromagnetic field radiated by a FD transceiver leaks back to its own receiver circuitry, interfering with the reception of remote signals-of-interest that are after wireless propagation usually much weaker than the local transmission.

The origins of FD communications date back to circa 2008–2010 when the research idea popped up simultaneously and independently in various institutes around the world (cf. [3], [5], [6] and references therein). Currently, the research field has gained solid stature and is still receiving increasing attention while, after many credible academic prototypes, the first commercial products are now under development. In contrast, scientific discourse on the military applications of the FD radio technology is in its absolute infancy in the open literature. To the best of our knowledge, so far the only explicit and elaborate references to FD military radios are three sentences on jammers in [3] and the initial conference presentation of our vision [7]. By this article, we aim at bringing forward the prospects of FD military radios in order to induce more interest in this emerging research topic in the scientific community.

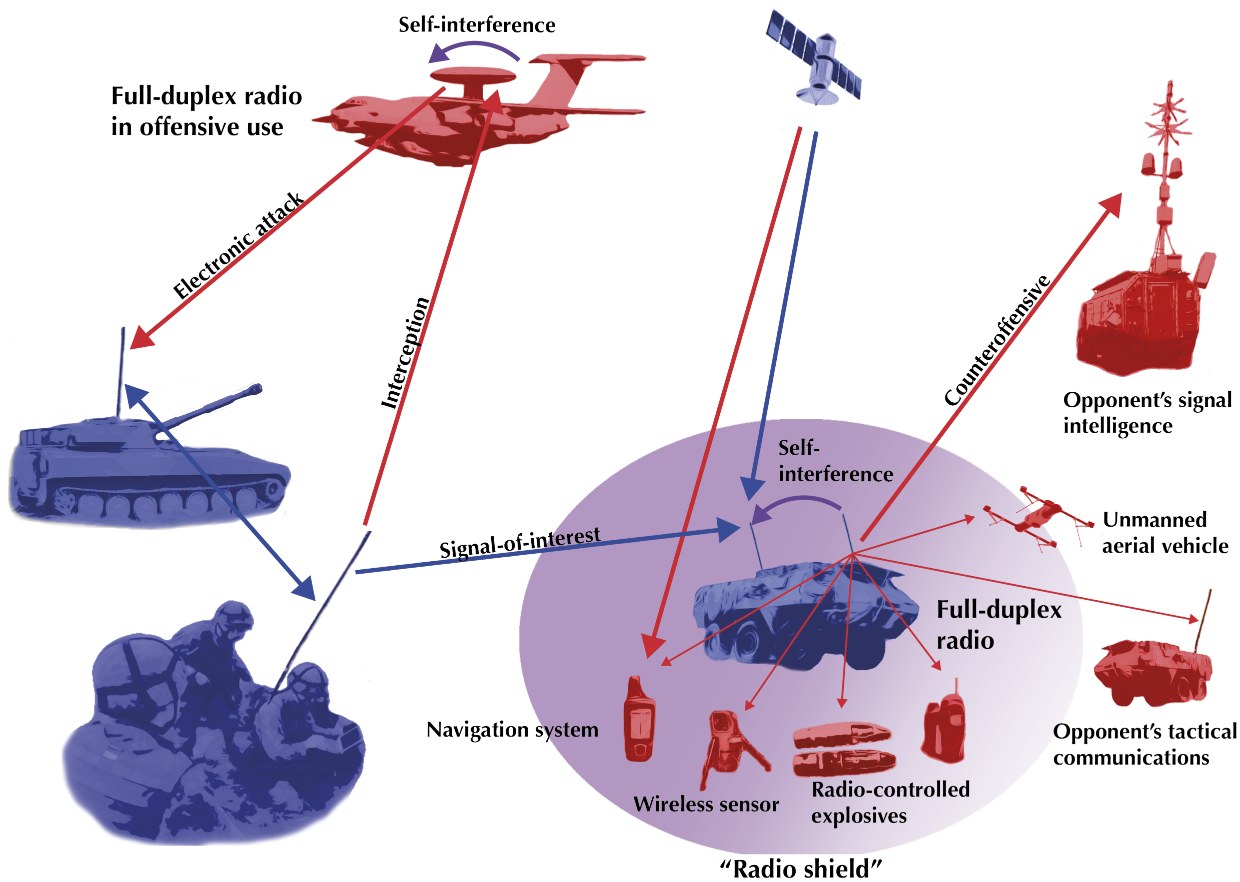

Fig. 1. Conceptual view of using inband full-duplex radio transceivers in tactical communications and electronic warfare.

Open literature has discussed two specific FD concepts that implicitly relate to military systems though, namely some radars [1] and so-called physical layer security [8]. In particular, CW (continuous-wave) radars are inherently based on the STAR capability [1], and researchers in the field of information theory have recently begun to develop the Shannon theory of communication links, where FD receivers hinder eavesdropping by simultaneously broadcasting jamming signals [8]; studies in the latter context almost never explicitly mention the potential military use. However, the conceivable applications of the STAR capability in tactical radios and electronic warfare are actually much more ample and diverse than the earlier research has ever realized.

In what follows, we first present an overview of general FD transceiver architectures developed originally for civilian/commercial wireless communications and extrapolate their requirements for military radios. While state-of-the-art FD radios can achieve up to 100 dB of SI cancellation (SIC), their effective use in military systems likely requires even more and, moreover, usage in a battlefield sets special requirements for extreme robustness to electronic warfare, not to mention that they may operate at HF or VHF (high or very high frequency) instead of commercial cellular mobile radio bands. Thus, practical military scenarios are rather different from academic laboratories, where the FD technology is already demonstrated to be feasible for nonmilitary use at upper UHF (ultra high frequency) bands. Nevertheless, we believe that the same transceiver architectures and advanced SIC techniques at large can be still used for successful military STAR operation once they have been re-engineered carefully.

We then analyze the potential defensive and offensive applications of FD military radios, including those shown in Fig. 1. The STAR capability is used for defense in the form of a "radio shield" that protects its operator from an opponent. In fact, the jamming scenario postulated in [3] is a specific example of protective applications, but we can discover many others as well. 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 used frequency band and transmitters or intercepting communication.

In summary, we could be witnessing a paradigm shift in tactical communications and electronic warfare provided that the military communications community solves the following two research problems related to this potentially disruptive technology:

- How to implement the STAR capability for military applications in the first place?
- What are the most suitable ways to exploit FD radios at cyber-electromagnetic battles?

Eventually, FD 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. While our study is only one of the very first steps toward addressing the above questions, we expect that this emerging open research area affords ample opportunities for making original, potentially high-impact contributions in the coming years.

Origins in Nonmilitary Communications

In the nonmilitary context, the FD operation has mainly been considered for inband relaying [5], or for boosting the capacity of the existing communication systems [3], [6]. In both of these cases, suppressing the SI is the main research challenge, and consequently a large body of literature has been produced regarding the different SIC techniques (see, e.g., [1], [2] and references therein). In the context of inband relaying, the used SIC methods might somewhat

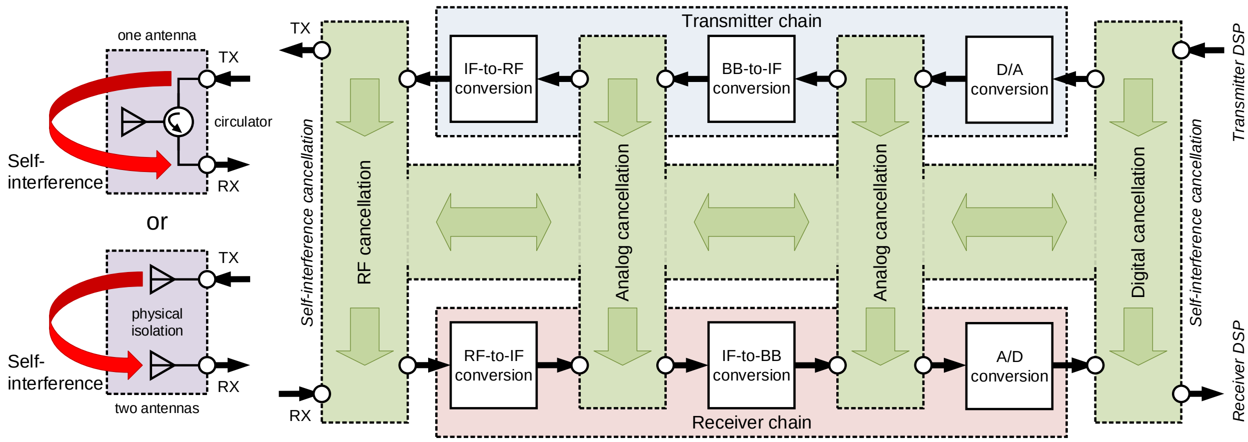

Fig. 2. Generic illustration of an inband full-duplex transceiver with various self-interference cancellation solutions.

differ from those used in the more generic bidirectional data transfer applications. In particular, different spatial suppression schemes have been widely considered for multiple-input multiple-output (MIMO) relays [5], while RF and/or digital domain cancellation has been the prevalent choice for the generic FD devices [6]. Since such cancellation schemes can be readily applied to all types of transceivers, including relays and radars, they are in the focus of this section.

Self-interference Cancellation in Full-Duplex Radios

A generic illustration of an inband FD device is shown in Fig. 2. It includes also the various alternative SIC solutions, which differentiate the considered FD transceiver from a legacy HD transceiver. In principle, SI cancellation is simply done by subtracting the own transmit signal from the received signal, although after appropriate modifications to ensure that the cancellation signal resembles the true SI as closely as possible. Figure 2 also demonstrates that in FD devices the transmitter and the receiver are never truly independent due to the SI and the corresponding SI cancellers. Through them, the transmit (TX) and receive (RX) chains are essentially connected from the signal processing perspective, a fundamental paradigm shift from the HD radios where TX and RX parts are more or less independent.

Considering then the SI suppression mechanisms in Fig. 2, the antenna interface provides the first stage of isolation between the transmitter and the receiver. There are two widely considered alternatives for providing the passive isolation in this interface: using a shared TX/RX antenna together with a so-called *circulator* or simply using different TX and RX antennas. In the former case, the circulator provides the necessary passive SI isolation, attenuating the SI by roughly 20 dB, as reported in [9] for the 2.4 GHz ISM (industrial, scientific, and medical) band. Alternatively, if separate TX and RX antennas are employed, physical isolation is provided simply by the propagation path loss, with roughly 40 dB of isolation typically reported for the ISM band of 2.4 GHz [6].

After the passive suppression, further *active cancellation* is still required before the RX chain to protect the delicate receiver circuitry. There are two prevailing techniques for such RF cancellation: one where the transmitter output signal is used to generate the RF cancellation signal [9], and one where a separate transmitter is used to upconvert a digitally generated RF cancellation signal [6]. The benefit of the former option is that there is no need to explicitly model the transmitter-induced impairments as they are already included in the RF cancellation signal, while the auxiliary transmitter based procedure profits from the fact that most of the processing can be carried out in baseband (BB) on the digital domain. The downside of using an auxiliary transmitter are then correspondingly the various imperfections in the main transmitter, which remain unaffected by the RF cancellation. Altogether, the RF canceller can be expected to provide 40–50 dB of SI suppression, depending on the bandwidth [9].

If employing a superheterodyne architecture in the transceiver, then further analog cancellation can be performed also in the intermediate frequency (IF). In addition, also analog cancellation in the baseband (BB) could be considered to decrease the SI level before the analog-to-digital (A/D) conversion. Reducing the power of the SI as much as possible before the A/D interface is highly beneficial as then a smaller number of bits for the A/D converter is sufficient to still accurately reconstruct the signal of interest in the digital domain. However, it should be noted that typically the RF canceller alone can suppress the SI sufficiently low for the A/D conversion [9].

Finally, the SI remaining after the RF/analog cancellation stages is then suppressed in the digital domain by a *digital canceller*. In essence, a typical digital canceller regenerates the residual SI based on the *original transmit data*, using some predefined signal model. This means that the task of the digital SI canceller is in practice to *(i)* estimate the unknown parameters of the signal model, *(ii)* reconstruct the observed SI using the estimated parameters, and *(iii)* subtract the hereby obtained cancellation signal from the received signal. By utilizing advanced nonlinear signal models, the digital canceller can attenuate the SI by as much as 25 dB [9], thereby cancelling it almost perfectly.

Altogether, a total SI suppression of roughly 90 dB is reported in [9] for a bandwidth of 80 MHz, where a circulator, an RF canceller, and a nonlinear digital canceller are used to cancel the SI. In [4], on the other hand, 100 dB of SI cancellation is obtained over 20 MHz by utilizing active cancellers and a high-isolation relay antenna. Furthermore, and perhaps more importantly, the architectures in [4] and [9], together with various other demonstrator implementations, are capable of suppressing the SI close to the level of the receiver noise floor, and hence the doubling of the spectral efficiency is attainable. This is a promising result since it is reasonable to presume that similar transceiver designs can be used for military applications as well, albeit with somewhat different and more demanding requirements. For instance, the so far reported results on SI cancellation are typically obtained at upper UHF bands, while the much lower frequencies at HF, VHF, and lower UHF bands are widely used by military systems instead. Although there are practically no existing works investigating STAR operation on these bands, it is likely that the same SIC solutions can still be successfully applied there. However, the amount of physical isolation between the TX and RX chains is likely to be somewhat less with these lower frequencies, increasing the performance requirements for the active SI cancellation stages.

STAR for Doubled Spectral Efficiency

The main reason for FD operation in civilian/commercial systems is the increased spectral efficiency, which results in higher data rates without increasing the bandwidth of the system. This is highly desirable nowadays due to the heavy congestion of the available spectrum, a challenge that also the military communication systems are facing. In the simplest case of two FD-capable nodes engaging in bidirectional data transfer, the FD operation doubles the spectral efficiency [1], [2]. However, such a symmetric point-to-point link is not a very practical scenario, and in actual real-world applications the FD devices must provide an improvement in the spectral efficiency also under much more diverse conditions. For this reason, various deployment scenarios have been suggested to utilize the FD capability in different ways.

Perhaps the most intuitive application for an FD device is to use it as an inband relay or a gap-filler [4], [5]. In this case, the FD transceiver merely retransmits the signal it receives, meaning that the communication scenario is fully symmetric as the same amount of time is used for both transmission and reception. Such symmetry is well suited for FD devices since then its FD capability is utilized to the fullest extent.

Another widely considered scenario is a FD-capable base station that is serving half-duplex mobile users [1], [2]. Such a base station could serve the uplink and downlink mobiles at the same time using the same frequency band, greatly increasing the spectral efficiency of the network.

However, this type of a deployment scenario is already a bit more problematic since the uplink transmissions will in fact interfere with the downlink signals, thereby decreasing the downlink data rate. Consequently, a twofold improvement in the spectral efficiency might not be obtainable under all circumstances. Thus, further research is still needed for determining the feasibility and benefits of deploying FD nodes on a network level, both in nonmilitary and military context.

Continuous-Wave Radar

A very specific field, where the STAR capability has already been used since at least the 1940s, are CW radars (as opposed to pulsed radars) [1]. In this case, the direct leakage between the own transmitter and the own receiver must be efficiently suppressed, while echoes from targets must be successfully received, meaning that some form of SI cancellation is needed [1]. In fact, a CW radar using one or two co-located antennas (monostatic or pseudo-bistatic) is technically similar to a one or two antenna FD radio. In the former, circulators can be used to suppress the direct leakage from the transmitter, while separate antennas are used to provide the necessary isolation in the latter.

When acknowledging that radar systems typically require less isolation than FD data transfer applications, it is clear that the state-of-the-art SIC solutions, achieving 90–100 dB of SI suppression, could be readily used for low-power military radar applications. Furthermore, even though these radars typically use much higher frequencies than the reported FD prototypes, many of the SI cancellation solutions could potentially be applied also to mm-wave systems. Consequently, the current FD prototypes already provide many features necessary for military CW radars.

Full-Duplex Military Radio Transceivers

Requirements for Military Radios

When considering radios intended to military use, the requirements for the hardware and system level details, listed in Table I, are different compared to commercial applications. Military applications face many challenges, including the requirements for bandwidth, latency, stability, security, connectivity and especially reliability [10]–[12]. Furthermore, impeding the radio communication of the enemy forces is also an important aspect that should be given some attention [13].

Perhaps the most distinguishing feature of the wireless systems designed for military use is their distributed and dynamic nature [12], [14]. This means that the network topology is heavily

TABLE I

Requirements and possibilities of the full-duplex radios in military communications.

Requirements	Possibilities
Time-variant topology, stability, latency, connectivity	Communications middleware for constant radio topology awareness
Bandwidth	Full-duplex, co-operation between the radar and communication systems
Tolerance for jamming, secured communications	CSS, DSSS, FHSS, TH
Jamming and interception capability	Simultaneous full-duplex communications and jamming/interception

time-variant and the different radios must be capable of constantly updating their knowledge regarding their close-by peers. Such stringent requirement on the topology awareness calls for some sort of a communications middleware approach where each radio should be capable of listening for the relevant information, while also informing friendly radios about its presence.

Military radios must also be tolerant to jamming or spoofing attacks, where a strong interfering signal is maliciously transmitted to disturb the data communication [3], [11], [14], [15]. Namely, since constant situational awareness is an essential requirement in modern military context, each transceiver must be capable of delivering and receiving at least some data, even when there is a strong interfering signal present. Furthermore, it would be greatly beneficial if a transceiver was capable of simultaneously communicating and jamming enemy nodes on the same frequency, a feature that could be facilitated in a relatively straightforward fashion by the STAR capability as envisioned in this article. For instance, a remarkable battlefield application could be spoofing or jamming opponents' satellite navigation receivers without affecting one's own positioning.

In addition, high security level within the network is required in military applications, meaning that the transmitted data must be encrypted by some means [14]. A variety of approaches exist for achieving this, such as chirp spread spectrum (CSS), direct-sequence spread spectrum (DSSS), frequency-hopping spread spectrum (FHSS) and time-hopping (TH). The tactical data link (TDL) network standard Link 16 has become the major information channel within the military communication systems of the US Joint Services and forces of NATO [14]. Link 16 utilizes FHSS for improving immunity to jamming and introducing redundancy, although it is based on legacy HD transceivers.

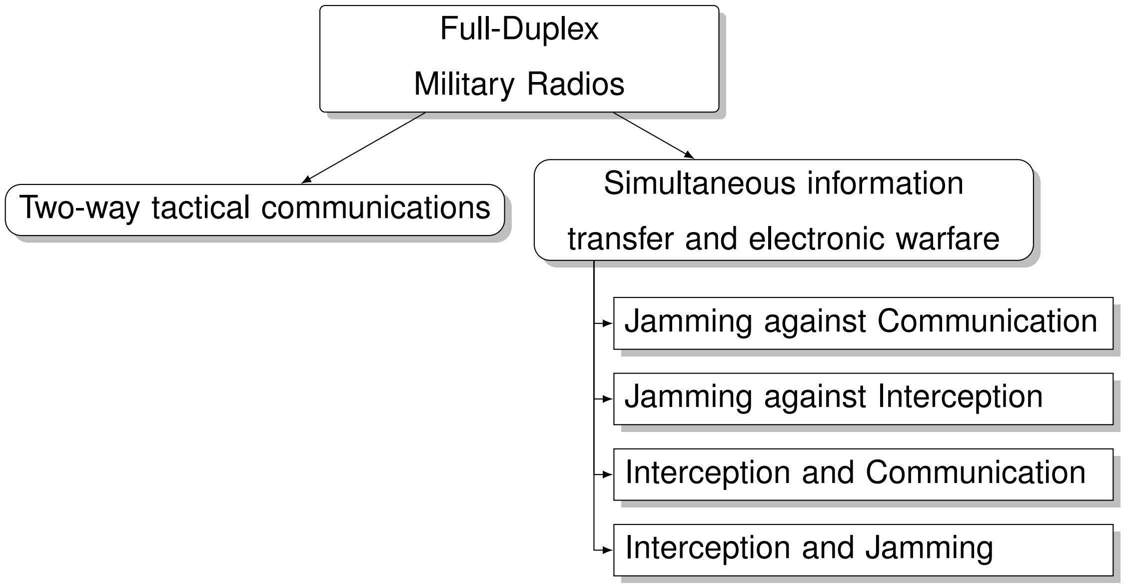

Fig. 3. Classification of applications for inband FD radios in military communications.

Further limitations are caused by congestion of the available spectrum, which means that the spectral efficiency of the military networks must be as high possible so that all the communication needs can be fulfilled without compromising reliability and security requirements [12]. In the legacy systems, this has been achieved by high spectral reuse, efficient waveforms, and prioritizing the information that is disseminated within the network. In the future, the spectral efficiency can be further improved, for instance, by improving the co-operation between the radar and the communication systems, or by utilizing some of the recent advances in transceiver design, such as inband FD communications [9].

Using Full-Duplex Radios in Military Networks

When envisioning the usage of inband FD transceivers in military communication networks, the above different requirements must be carefully considered. Table I shows how FD transceivers can help in dealing with these requirements, while some of the potential application modes for inband FD radios are illustrated in Fig. 3. Firstly, inband FD communications helps in coping with the scarcity of the available bandwidth, since it can potentially provide a two-fold increase in the spectral efficiency [1], [9]. This is obviously a crucial advantage in helping to ensure the situation awareness and the tactical communication capabilities under all circumstances. In this regard, many prototype implementations can already cancel the SI by a sufficient amount to realize the throughput improvements [4], [9].

In terms of the distributed nature of the network, the FD capability also allows for more efficient searching of the close-by radios, since it facilitates simultaneous transmission and sensing. This has already been investigated in the context of cognitive radio systems, and shown to be feasible. Furthermore, the capability to cancel the own transmission also means that a jamming signal can be emitted while receiving useful data [3]. Thereby, it is clear that the FD capability creates some new possibilities also beyond the improvements in spectral efficiency.

MILITARY COMMUNICATION APPLICATIONS FOR FULL-DUPLEX RADIOS

Let us consider a cyber-electromagnetic battle, where two opposing teams (blue and red) operate on the same frequency band for tactical communications and/or electronic warfare. The band can 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. Plain two-way FD information transmission without electronic warfare is not considered herein, because it is already widely studied in the nonmilitary context, although the technology could be advantageous for facilitating high-rate tactical communications as such.

Full-Duplex Radios Only in the Blue Team

We first assume that only blue radios can operate in the FD mode and the red team does not possess such technology. As shown in Figs. 4(a)–(e), we can identify five different battlefield scenarios when both teams have one or two radios and they can be used for receiving either a communication signal or an interception signal and transmitting either a communication signal or a jamming signal.

Jamming against Communication: In the application of Fig. 4(a), both teams use the same frequency band for their communications. In a conventional case without any FD radios, the blue and red teams' communication links would achieve signal-to-noise ratios (SNRs) of $\mathsf{SNR}_{\mathrm{bb}}$ and $\mathsf{SNR}_{\mathrm{rr}}$, respectively. The STAR capability allows the blue receiver to transmit a jamming signal, causing extra interference to the red receiver at the cost of suffering from residual SI. Thus, the blue and red teams' communication links achieve signal-to-interference-and-noise ratios (SINRs) of $\mathsf{SINR}_{\mathrm{bb}}$ and $\mathsf{SINR}_{\mathrm{rr}}$, respectively, for which obviously $\mathsf{SINR}_{\mathrm{bb}} < \mathsf{SNR}_{\mathrm{bb}}$ and $\mathsf{SINR}_{\mathrm{rr}} < \mathsf{SNR}_{\mathrm{rr}}$ due to the fact that jamming is harmful for both teams. However, in principle,

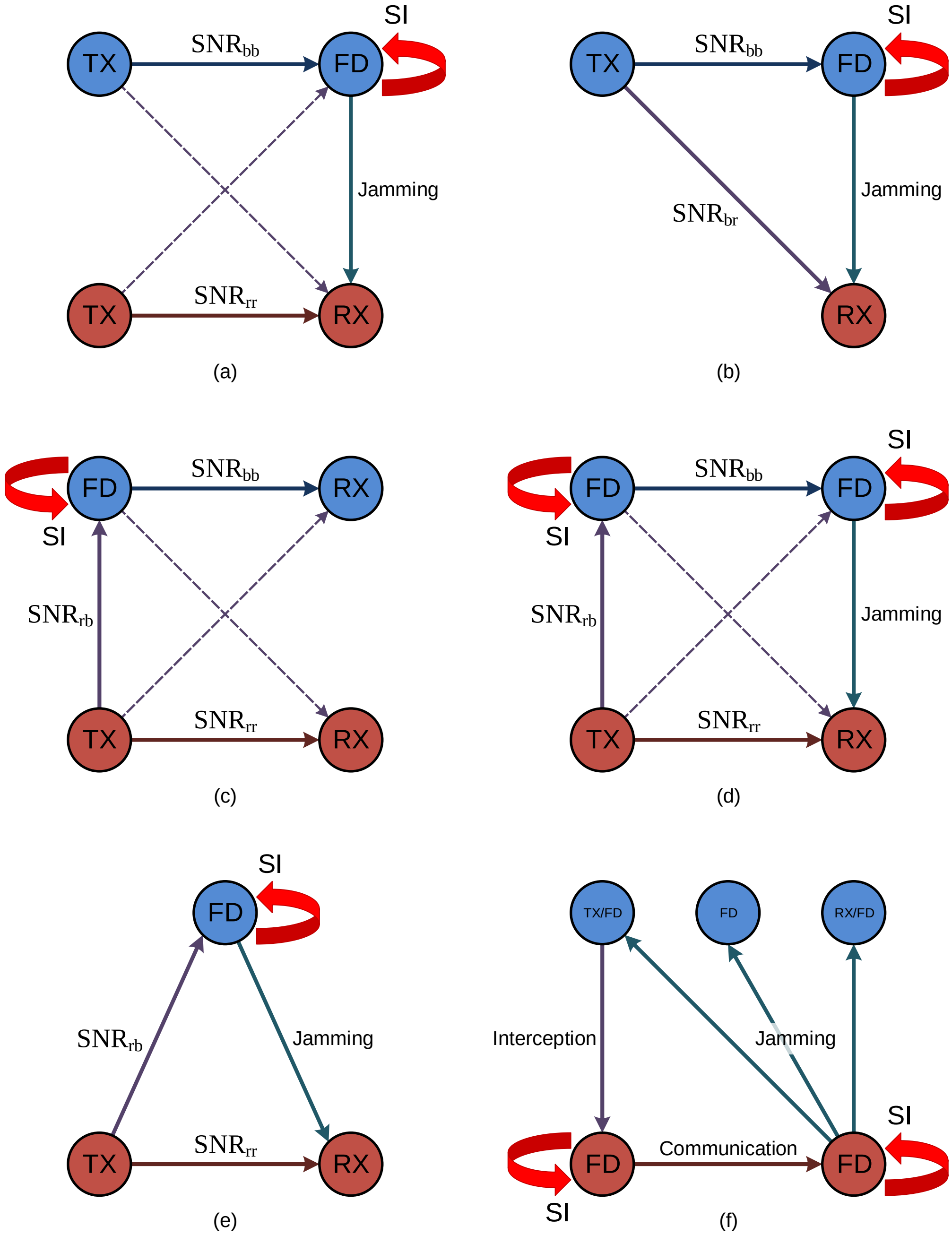

Fig. 4. Military applications of the STAR capability of FD radios at the cost of SI: a) simultaneous communication and jamming against communication; b) simultaneous communication and jamming against interception; c) simultaneous communication interception and communication; d) communication with simultaneous interception and jamming; e) simultaneous interception and jamming against communication; f) counterparts with FD radios in both teams. Solid lines denote intended signals while dashed lines represent unintended co-channel interference.

the known SI signal can be suppressed more efficiently than the unknown jamming signal so that $\mathsf{SINR}_{\rm bb}/\mathsf{SNR}_{\rm bb} \gg \mathsf{SINR}_{\rm rr}/\mathsf{SNR}_{\rm rr}$. Thereby, it actually may be worthwhile for the blue team to tolerate some self-inflected performance loss in order to make much bigger impact on the red team's communications.

Jamming against Interception: The application of Fig. 4(b) is similar to the above one except that the jamming signal is now used as a countermeasure for interception. With jamming, the SINR for intercepting the blue communication link in the red receiver is given by $\mathsf{SINR}_{\rm br}$ when the corresponding SNR without jamming is $\mathsf{SNR}_{\rm br}$. The information rate of the blue communication link is the same as in the above scenario while a part of the information leaks from the blue transmitter to the red receiver. Obviously, if $\mathsf{SNR}_{\rm br} > \mathsf{SNR}_{\rm bb}$ (e.g., the red receiver is closer to the blue transmitter than the blue receiver) then fully covert transmission is impossible with conventional HD technology. In contrast, it is possible to achieve $\mathsf{SINR}_{\rm br} < \mathsf{SINR}_{\rm bb}$ with STAR operation even if $\mathsf{SNR}_{\rm br} > \mathsf{SNR}_{\rm bb}$. Thus, the blue link gains electromagnetic camouflage despite its total transmission rate being decreased.

Simultaneous Interception and Communication: In the application Fig. 4(c), the blue communication link uses the STAR capability for simultaneous interception. The SNR for interception would be $\mathsf{SNR}_{\rm rb}$ without simultaneous information transmission while it decreases in FD operation due to residual self-interference. It should be especially noted that performing simultaneous interception with information transmission does not affect the blue team's own rate so it comes at no cost during operation, if the transceiver has the STAR capability. Thus, it is always worthwhile to do as long as $\mathsf{SINR}_{\rm rb}$ is reasonably large such that the chances for interception are non-negligible in the first place.

Simultaneous Interception and Jamming: The application Fig. 4(d) employs two FD radios for simultaneous interception and jamming in addition to communication while the corresponding case with only one FD radio is shown Fig. 4(e). The blue team transmits jamming to the red team's receiver in order to decrease its link quality from $\mathsf{SNR}_{\rm rr}$ to $\mathsf{SINR}_{\rm rr}$ which also decreases the link quality for interception from $\mathsf{SNR}_{\rm rb}$ to $\mathsf{SINR}_{\rm rb}$. However, the red team may try to compensate the jamming by increasing transmission power to achieve link quality $\mathsf{SINR}'_{\rm rr}$ ($\mathsf{SINR}'_{\rm rr} > \mathsf{SINR}_{\rm rr}$) by which the link quality for interception increases to $\mathsf{SINR}'_{\rm rb}$. It is possible that $\mathsf{SINR}'_{\rm rb} > \mathsf{SNR}_{\rm rb}$, i.e., it may be worthwhile to tolerate some self-interference in order to gain back much more from the opponent's countermove. That is, the red transmitter increases its transmission power such that the link achieves information rate that is equal to the original case without jamming.

Consequently, signal quality for interception in the blue transceiver improves significantly.

Full-Duplex Radios in Both Teams

There are many more battlefield scenarios when also the red team employs FD radios as shown in Fig. 4(f). We see that in the above cases the red team suffers from technical disadvantage, because they do not possess the FD technology. For example, when the blue team is performing jamming, the smart countermove from the red team would be to launch jamming against potential interception if increasing transmit power is necessary.

NUMERICAL RESULTS FOR JAMMING AGAINST COMMUNICATION AND INTERCEPTION

Let us continue with the battlefield scenarios discussed above and illustrated in Figs. 4(a) and 4(b). In particular, we simulate the performance of the red receiver when it is receiving a communication signal from the red transmitter or trying to intercept the blue transmission, respectively. The study assumes operation at the 2.4 GHz ISM band instead of typical military HF or VHF bands for two reasons. Firstly, we aim at corroborating these results by measurements on a real prototype setup in our future work, for which we will need to use some unlicensed band. Secondly, 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).

For 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 -90 dBm. These assumptions allow us to determine receiver SINRs based on link budget calculations, given the radios' positions.

Figure 5 illustrates the red receiver's signal quality when it is located in different positions while the other transceivers are located at the coordinates shown in the figures. For reference, $\mathsf{SNR}_{\mathrm{bb}} \approx 21$ dB while corresponding $\mathsf{SINR}_{\mathrm{bb}}$ 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, lighter yellow color indicates better signal quality for the red team while the signal level is below noise and jamming

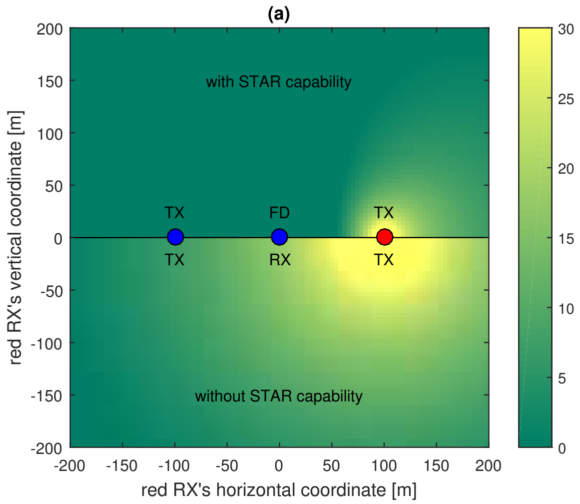

Fig. 5. Comparison of HD and FD systems: a) $\mathsf{SNR}_{\mathrm{rr}}$ [dB] without STAR capability and $\mathsf{SINR}_{\mathrm{rr}}$ [dB] in simultaneous communication and jamming against communication; b) $\mathsf{SNR}_{\mathrm{br}}$ [dB] without STAR capability and $\mathsf{SINR}_{\mathrm{br}}$ [dB] in simultaneous communication and jamming against interception.

interference in the dark green region. We see that jamming in the FD radio act as as a "radio shield" preventing the red team from controlling the UAV, detonating the IED, or intercepting the blue transmission in the vicinity of the blue receiver.

Conclusions

Extrapolating from the rapid advances in civilian/commercial FD radios, we believe that the disruptive and unprejudiced idea of inband STAR operation finds its way in some forms also 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, this article explored the prospects of the FD 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 the FD technology, or that they need new communication procedures and tactics to counteract opponents' STAR capability. In conclusion, we see that there is much room for original research in this area.

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