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In-Band Full-Duplex Radio Military Applications

Heikki Rantanen, Sami Peltotalo
Finnish Defence Research Agency

Taneli Riihonen
Tampere University

In-Band Full-Duplex (IBFD) radio can simultaneously receive and transmit voice or data. Today's radios, such as the 5G mobile phone and its base station, are also often referred to as full-duplex radio, but this is only true as experienced by the user of the radio — in reality, transmission and reception are separated in time or frequency domain. The transmitter and receiver are not operating simultaneously. This article explains what IBFD radio is and why both military communications and, at the latest, the next generation of mobile networks, i.e., 6G, are adopting this technology. In both military and civilian radio systems, IBFD radio will provide significant new performance. This easy-to-follow article discusses the basics of IBFD technology, its development path and, in particular, the new military performance that can be achieved.

Introduction

Traditionally, radios use either time or frequency division multiplexing techniques at the Medium Access Control (MAC) layer of the OSI model. Therefore, radio transmitter and receiver are not simultaneously in operation. In the old GSM technology, terminals even had both time and frequency division in use at the same time. This traditional paradigm is being challenged by modern In-Band Full-Duplex (IBFD) technology, which eliminates the need for transmission–reception alternation — the technical challenges this poses can now be solved.

In TDD (Time-Division Duplexing) channelisation, transmission and reception take place in turn, with the length of each time frame being on the order of a few milliseconds. When these short bursts of transmissions or receptions are combined into a consecutive stream, for example, the speech appears as being real time to the listener. For the user of an old-fashion analogue combat radio, the time interval is determined by when they press the push-to-talk button and are unable to hear the transmissions of others at the same time. FDD (Frequency-Division Duplexing) channelisation means that radio transmission and reception take place in frequency bands far enough from each other so that they can take place without interfering with each other. This is achieved by a so-called duplex filter, which provides a sufficiently high passive attenuation between the transmitter and the receiver. This also allows the use of a common antenna. As described earlier, IBFD radio can simultaneously receive and transmit a radio signal on the same frequency. Figure 1 shows the operation of the techniques described above in time and frequency domain.

Figure 1 is also a good graphical representation of how the capacity of a radio channel per frequency unit can be up to double with IBFD radio. From a mobile operator's point of view, this means at best doubling the data transmission capacity or achieving the same capacity with half the spectrum allocation, culminating in a direct economic gain or cost reduction. In practice, how much capacity benefit can be achieved depends on whether the transmission paths are balanced, i.e., whether it is even necessary to transmit and receive the same amount of information and how well modern radio technology can attenuate the self-interference signal inherent in IBFD radio. Self-interference, i.e., interference to radio reception due to its own transmission, has traditionally been avoided by TDD or FDD channelisation.

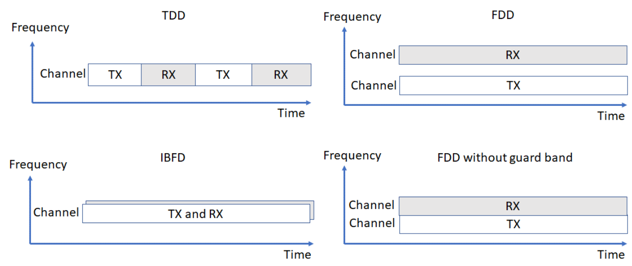

Figure 1. The operation of time-division multiplexing (TDD), frequency-division multiplexing (FDD) and IBFD radios in time and frequency domains. TX stands for transmission and RX for reception.

Anyone looking for more scientific information on the subject should be aware that a beloved child often has many names — also in this case. The short term Full Duplex (FD) radio is often used to refer to IBFD radio, and confusion arises from the fact that traditional FDD has also been called FD. Similarly, instead of IBFD, the term Same-Frequency Simultaneous Transmit-and-Receive (SF-STAR)[1] is often used, especially when the application is something other than data transmission, to which the word duplex refers. SF-STAR is the correct term especially in radar technology. Division-Free Duplex and Listen-and-Talk are also used in literature, although less frequently, and FD has also been given prefixes other than In-Band.

Capabilities Developed for Military Radios

The improvement in performance is even more significant in the case of military radios. In addition to spectrum efficiency, significant new capability will be gained in electronic warfare. IBFD radio allows the radio transmitter and receiver to work simultaneously. In practice, this enables real-time information on whether a fast follower-jammer has entered on the frequency in use, or whether the frequency in use is otherwise interfered. In this case, extremely fast cognitive spectrum management can replace jammed or otherwise poorly performing frequencies with new ones.

[1] Janes, 1.2.2021, *US Army seeking simultaneous transmit and receive tactical radios,* [Online], [Referenced 31.1.2023]. Available at: https://www.janes.com/defence-news/news-detail/us-army-seeking-simultaneous-transmit-and-receive-tactical-radios

The new performance described above is very significant, but an even greater performance advantage can be achieved. In practice, an IBFD radio can simultaneously receive information from its own forces and transmit jamming signal to prevent the enemy forces from operating. A major problem in the Afghanistan war was the use of radio-controlled roadside bombs. The IBFD radio is capable of handling communications between members of a military vehicle convoy, while simultaneously monitoring whether, for example, a new potential roadside RC (Radio Control) radio transmission appears in the radio spectrum, which it can quickly mask with its own jamming and thus prevent an explosion. Traditional radio without IBFD capability leaves a vulnerability, because the adversary troop has an incentive to use the same frequencies as the blue forces for harmful transmissions, making it impossible to jam them without harming oneself or own troops. Jamming enemy drones is a similar problem.

Military radios have long lifespans, often decades. For this reason, external accessories are now available on the market to which the jammer described above and the military radio used for own communication can be connected. This external accessory cancels the jamming signal in the same way as an IBFD radio cancels its own transmission. An example of an accessory product is the Joint Analog and Digital Interference Cancellation (JADIC) system from TrellisWare Technologies[2].

Software-Defined Radio's New Generation

Today's 5G mobile phones, 5G base stations and also military radios are Software-Defined Radios (SDR). However, the implementation of SDR radio is different between commercial and military radios. The core component of today's most modern military software-defined radio is a general-purpose RFSoC (Radio-Frequency System-on-Chip) chip with an integrated broadband RF unit, multiple programmable processor cores and high-speed computing FPGA (Field Programmable Gate Array) circuits. Such an RFSoC chip could be used for both 5G phones and military radios. But in practice this is not happening. A 5G mobile phone will be built around extremely high-density, ultra-high computational power Mobile SoC chips specifically tailored to the optimal implementation of 2G, 3G, 4G and 5G radio waveforms, from Qualcomm, Mediatek, Apple, Samsung, etc. The market is so large that optimised, customised chips can be used in mobile devices. And yet the price of the chip is incredibly low given its computing power.

IBFD radio can be seen as a new generation of software-defined radio. It is a programmable radio in the same way as the previous generation, but with the addition of three function blocks that attenuate the Self-Interference (SI) signal from the transmitter via antenna to its own receiver, step by step, to such a low level that in practice only the desired signal received by the antenna remains. For a long time, radios and their waveforms were implemented using traditional TDD and FDD solutions without realising that things could be done differently. Great inventions come from questioning what was thought to be impossible — IBFD is a remarkable example of this.

IBFD radio has rightly been described as a paradigm shift in tactical communications and electronic warfare, as a single device can perform multiple functions simultaneously and flexibly without the need to allocate time or frequencies to these functions. The applications of IBFD radios in military use are outlined in Figure 2.

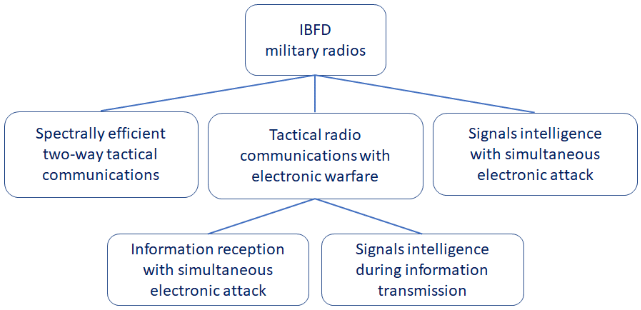

Figure 2. Military application categories of IBFD radios. Improving spectrum efficiency is a common interest with the commercial 5G and 6G communities. (Rewritten from source[3])

More Efficient Spectrum Use

As noted earlier, IBFD radio has the potential to double spectrum efficiency in military and civilian radio networks and, as the technology becomes more widely deployed, especially in future 6G networks. This doubling of spectrum efficiency is significant. However, as data transmission becomes increasingly wireless, there will inevitably be a shift from static spectrum sharing to dynamic spectrum management between civilian and military radio systems. The demand for spectrum for 5G and future 6G networks is already so high that spectrum previously reserved for military use must be made available, at least partially, for mobile communications when it is not being used for military purposes. Examples of this can already be found in the US, where in one case a commercial operator is allowed to use a frequency originally used by the military, if it has a verified spectrum sensing system and a spectrum sharing database in place to ensure that the spectrum is cleared immediately when required by the primary user, in this case the military.

Dynamic spectrum allocation is also known as cognitive spectrum use. The European Defence Agency (EDA) research project MAENA[4] (Multiband Efficient Networks for Ad Hoc Communication), which ended in 2021, investigated the efficient co-use of a VHF radio network (i.e., a military radio network) and a higher data rate UHF military radio network, in particular from the perspective of cognitive spectrum use. The study concluded that each node in the VHF radio network performs TDMA (Time-Division Multiple Access) spectrum monitoring of its own environment in time slots where it is not itself transmitting or receiving information. On this basis, the VHF radio network can perform low-level dynamic spectrum management by excluding jammed/interfered frequencies. On the other hand, the upper level of dynamic spectrum management would have the right to allocate new frequencies to the VHF network. The concept would therefore allow dynamic spectrum management between civilian and military radio networks. With IBFD radio, the response to interference and jamming would be extremely fast.

Multiple radios installed in military vehicles, operating simultaneously on different command networks, are a major technical

[2] TrellisWare Technologies, *Joint Analog and Digital Interference Canceller (JADIC),* [Online], [Referenced 31.1.2023]. Available at: https://www.trellisware.com/advanced-communications/interference-cancellation/

[3] NATO, STO Technical Report TR-IST-ET-101, 2020, *Full-Duplex Radio: Increasing the Spectral Efficiency for Military Applications*.

[4] Jerzy Lopatka, Tuomas Paso, Raphaël Massin & Xavier Leturc, 2022, *Multi band efficient networks for ad hoc communications,* International Conference on Military Communications and Information Systems (ICMCIS 2022), Procedia Computer Science.

problem today. The antennas are typically placed in the extreme corners of the roof to maximise mutual attenuation, but even so, so-called co-site interference can disrupt the receiver to such a degree that the radio range is significantly reduced. In this case, you must be able to dynamically control interference from all neighbouring radios to your receiver, and in addition, own radio link may be jammed by the adversary troops. Indeed, interference between different radio networks can be a challenging problem. The same technique that IBFD radio uses to attenuate its own transmit signal in its own receiver has been used to solve this problem. In this case, there are several signals to be attenuated.

The Basics of IBFD Technology and Future Developments

IBFD radio differs from conventional radio in having a) RF-circulator, b) an analogue attenuator and c) a digital attenuator, which suppress the strong transmitted signal at the receiver to such a low level that it can eventually be phased out once the exact transmitted signal is known. Figure 3 shows the general IBFD radio architecture. The single-antenna solution shown is ideal for mobile devices. However, in some applications it is possible to achieve better attenuation than the RF-circulator offers by using separate transmit and receive antennas.

Total attenuation can be as high as 100–150 dB[5] [6], which in practice allows a very low-power receive signal and a very high-power transmit signal to travel in different directions at the same frequency and at the same antenna interface. It is estimated that about 100 dB, perhaps a little more, is sufficient attenuation for commercial radios, while the attenuation required for military radios could be as high as 150 dB.[7] Of course, it is not quite as simple as that, since attenuation of a very wideband signal is more challenging than attenuation of a narrowband signal.

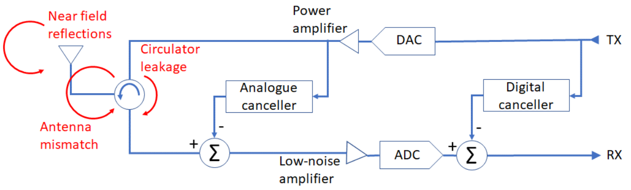

Figure 3. General architecture of IBFD radios including analogue and digital attenuation of self-interference. DAC stands for digital-to-analog converter and ADC for analog-to-digital converter. (Modified from source[8])

So far, attenuations in the order of 100–130 dB have been reported for various IBFD radio demonstrators with a Technical Readiness Level (TRL) of 5–6.[9] It is also worth remembering that the real world is not ideal. As described earlier, your own transmit signal is easily attenuated by simply phasing it out. In practice, the situation may not be quite so simple and some residual signal may remain.

Research for Military Applications

NATO's Science and Technology Organisation conducted an Exploratory Team (ET) IST-ET-101 in 2018, which resulted in the report Full-Duplex Radio: Increasing Spectral Efficiency for Military Applications[3]. Following the ET work, it was decided to establish a full-fledged research task group, IST-175, in which the Tampere University participated on behalf of the Defence Forces under the leadership of Associate Professor Taneli Riihonen. Professor Riihonen was also involved in the ET task force. The IST-175 working group started its work in 2019 and its duration was extended to the end of 2023.

The IST-175 working group proposes in its publication[8] that IBFD radio could be a multifunctional radio combining data transmission, signal intelligence and jamming at the local level. At present, these are more or less separate entities. Operated locally, the previous three functions provide the optimum result. With a real-time local signal intelligence information, the performance of a cognitive spectrum-based communication network is optimised, and similarly, jamming of adversary forces can be optimally carried out as short-range jamming.

Figure 4 shows a scenario developed by the IST-175 team in which a defender is able to defeat a drone swarm attack using the new capability provided by the IBFD radios. The scenario, which is called the radio shield, will proceed as follows:

1. Blue's radio communications are based on its own real-time spectrum sensing and the signal intelligence of the adversary, made possible by the IBFD radios. This way, blue's radio communication is optimised and protected in its own network.

2. Blue's self-organising radio network detects jamming in near real time and is able to optimise the parameters of the radio transmission to minimise the impact of jamming.

3. All blue radio nodes participate in signal intelligence of adversary troops alongside their own radio communications and the information is distributed to all radio nodes. This way, a drone swarm attack on own area of operation is detected.

4. Simultaneously, as the blue network communicates counter-attack information to all nodes, each node has launched optimised jamming based on signal intelligence.

5. In addition, a blue drone will be sent to carry out effective free-space propagation jamming against the drone swarm. At this point at the latest, the attacking swarm will be destroyed as they collide, scatter or fall to the ground due to loss of control and positioning information. The blue took the victory with the superior performance of the new generation IBFD radio.

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[5] Miika Vuorenmaa, Mikko Heino, Matias Turunen & Taneli Riihonen, 2022, *RF self-interference canceller prototype for 100-W full-duplex operation at 225–400 MHz,* International Conference on Military Communications and Information Systems (ICMCIS 2022), Procedia Computer Science.
[6] Anh Tuyen Le, Xiaojing Huang & Y. Jay Guo, 2022, *A Two-Stage Analog Self-Interference Cancelation Structure for High Transmit Power In-Band Full-Duplex Radios,* IEEE Wireless Communications Letters, Vol. 11, No. 11, November 2022.
[7] Mark Hickle, 2021, *Providing Simultaneous Transmit and Receive Capabilities for Defense Systems,* Microwave Journal, June Supplement 2021, Aerospace & Defense Electronics, Volume: 64, Edition: 06 Sup, [Online], [Referenced 31.1.2023]. Available at: https://www.microwavejournal.com/articles/36133-providing-simultaneous-transmit-and-receive-capabilities-for-defense-systems
[8] Karel Pärlin, Taneli Riihonen, Vincent Le Nir, Mark Bowyer, Thomas Ranstrom, Erik Axell, Börje Asp, Robert Ulman, Matthias Tschauner & Marc Adrat, 2021, *Full-Duplex Tactical Information and Electronic Warfare Systems,* IEEE Communications Magazine, August 2021.
[9] Business Wire, 19.8.2021, *Kumu Networks Awarded $1.5M Applied SBIR Phase 2 Contract to Develop the Highest Performing Self-Interference Cancellation Module to Date,* [Online], [Referenced 31.1.2023]. Available at: https://www.businesswire.com/news/home/20210819005032/en/Kumu-Networks-Awarded-1.5M-Applied-SBIR-Phase-2-Contract-to-Develop-the-Highest-Performing-Self-Interference-Cancellation-Module-to-Date

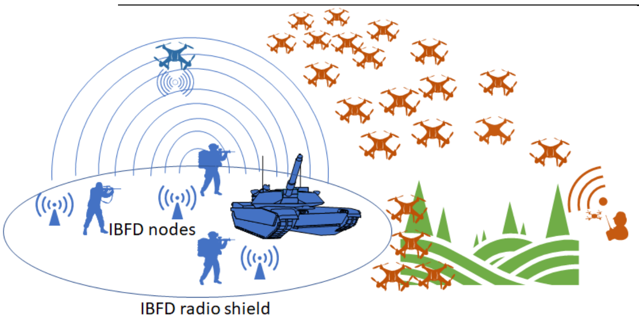

Figure 4. Radio shield scenario for IBFD radios. Blue is able to defend itself against a drone swarm attack. (Modified from source[8])

A relay scenario for IBFD radios, which enables range extension, is shown in Figure 5. The use of IBFD radios as relaying radios instead of conventional radios increases the capacity when it is possible to transmit and receive simultaneously. Bidirectional radio links between two command posts are a straightforward way to benefit from the doubling of spectral efficiency and the higher frequencies typically used in these links somewhat ease self-interference attenuation.

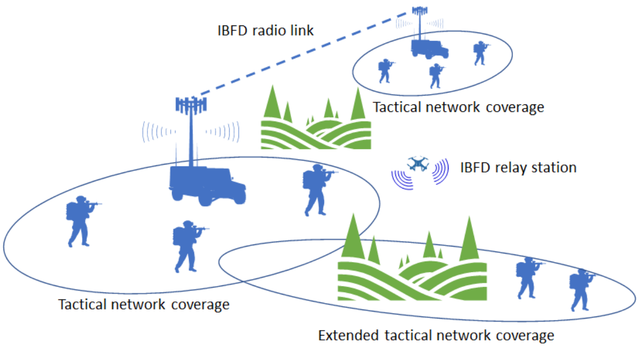

Figure 5. Applications of IBFD radios in tactical C3 systems. The range of a tactical network can be increased spectrally efficiently via ground or airborne IBFD relay stations, and separate tactical networks can be interconnected via bi-directional IBFD radio links.

IBFD Radio Prototypes in the UHF Band

The IST-175 working group is developing two prototypes and a radio demonstrator for military applications, shown on either side of the middle row in Figure 2. The first demonstration is focused on spectrum-efficient tactical communications, while the second develops a new capability for signal intelligence and simultaneous electronic jamming. In this context, the Tampere University is developing prototypes of an IBFD radio self-interference analogue attenuator and antenna for the UHF band[5] (NATO Band I 225–400 MHz) with project funding from the National Support Foundation for Defence.

In the developed compact antenna prototype, the directional (Yagi–Uda) transmit and receive antennas are placed 1.4 m apart as shown in Figure 6. A resonator between the antennas captures the power from the transmitting antenna and couples it to the receiving antenna in the opposite phase. This reduces self-interference. The isolation between the antennas improves with the resonator from 40 dB to over 90 dB at the 300 MHz design frequency. This is shown in the simulated frequency response on the right-hand side of Figure 6. This way, by using separate antennas, self-interference is attenuated to as low as a factor of one million (-60 dB) compared to the thousand-fold reduction that can be best achieved with single-antenna solutions with RF-circulator. On the other hand, RF-circulator would be a more broadband solution than a resonator tuned only for single point frequency.

The analogue attenuator (Figure 7) is designed for high power handling and programmable frequency control over a wide bandwidth of 225 to 400 MHz. The attenuator operates as shown in Figure 3 by splitting a portion of the signal going to the transmitting antenna after the power amplifier, into an attenuator circuit which adjusts the amplitude and phase to match the self-interference so it can be subtracted from the signal at the receiving antenna. The attenuator first performs a coarse 90-degree phase adjustment using a delay bank with separate cables, and then a fine adjustment of amplitude and phase using a 90-degree vector modulator implemented with PIN diodes. The prototype has a self-interference attenuation in the order of 40–50 dB.

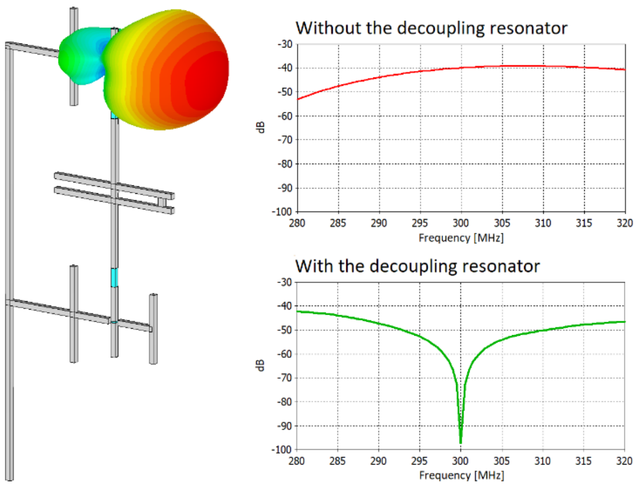

Figure 6. Concept of an IBFD self-interference suppression antenna for the UHF band and passive isolation between the antennas. (Figure: Mikko Heino/Tampere University)

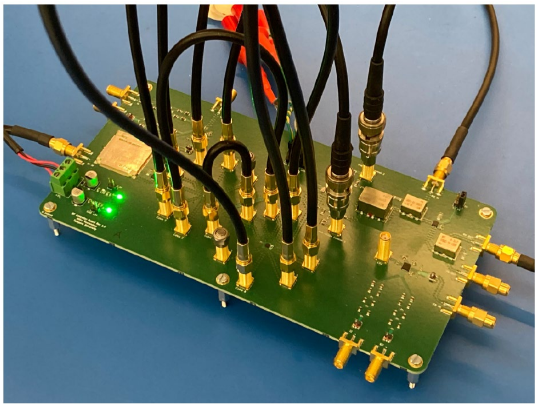

Figure 7. IBFD radio's self-interference canceller prototype for the UHF-band[5]. (Figure: Miika Vuorenmaa/Tampere University)

Digital interference suppression algorithms are not very dependent on the operating frequency. Therefore, after antenna isolation and analogue attenuation, digital signal processing for final interference suppression can be performed using methods found in the IBFD literature. It has already been demonstrated through measurements and computational analysis that, for example, a military IBFD radio with an attenuator and designed antenna can transmit a jamming signal at 100 W and at the same time intercept a signal transmitted at 5 W from 10 km away.

On the Markets in the 2030s?

In January 2021, it was reported[10] that a multi-vendor team led by US company TrellisWare Technologies had successfully demonstrated a 200 Mbps data link with an IBFD radio. Their IBFD prototype radio, marketed as SF-STAR, was developed and demonstrated in the US Army's Military Full Duplex Radio (MFDR) programme. A contract worth $15.7 million was signed in 2017 to develop the prototype. In comparison, Finland has achieved staggering results with research funding of only two to three percent of that. The rapid growth of mobile data services has also put pressure on the US Department of Defense to abandon or share spectrum in bands reserved for military radio systems. IBFD radios can transmit more data in the same bandwidth or the same amount of data in a smaller bandwidth than conventional radios, helping to alleviate the challenge of spectrum scarcity. The TrellisWare-like prototype described earlier is suitable for high-speed data transmission in both commercial and military systems.

The SF-STAR radio was developed at TRL-6 level and supports bands from UHF to S-band. The receiver sensitivity is reported to be at least as good as or better than conventional radios. TrellisWare's advanced interference cancellation technology allows 50 W of transmission power while receiving a distant signal that can be 130 dB weaker than the transmitted signal. TrellisWare's next goal for the coming years is to enable 1 Gbps links.

The aforementioned prototype project can be used as a reference to estimate that IBFD radios could enter the military radio market sometime in the 2030s, perhaps even by the end of the 2020s. Finnish industry has a good chance of commercialising the military IBFD radio after NATO's IST-175 study and, in the best case, it could be on the market within this decade thanks to Finland's strong scientific and research leadership.

The 3GPP, the organisation responsible for standardising mobile networks, releases new functionalities iteratively for each generation of the standard. Three versions of the current fifth generation (5G) standard have already been released (Releases 15, 16 and 17). Typically, the time between releases is around 1.5 to 2 years. Prior to 6G, three more versions of the 5G standard are planned (Releases 18, 19 and 20), which will define the so-called 5G Advanced phase. In the early 2030s, the first version of the 6G standard is expected to be released.

The introduction of new duplex functionalities for 5G/6G standards will start with Release 18. Research for this has already started in 2022. The aim is to identify and evaluate potential ways to develop duplexing in the 5G NR TDD (New Radio, Time-Division Duplexing) spectrum. However, the first full-duplex functionalities will be included in Release 19 and subsequent versions. One of the first functionalities in this development path is Non-Overlapping Sub-Band Full Duplex (SBFD), which is implemented only in the network base station radio and not at all in the mobile user devices. In true IBFD radio, the transmit and receive signals are interleaved over the entire available frequency band (Figure 1). For example, in an SBFD base station with a total bandwidth of 100 MHz, the downlink could use 2x40 MHz and the uplink 20 MHz). Using IBFD radio attenuation techniques, an "old-fashioned" FDD duplex filter can be implemented without a guard band.[11] [12]

In the future, the 6G standard will also aim to implement true IBFD, which the 3GPP refers to as Single-Frequency Full-Duplex (SFFD), and this technology may also be used in future 6G networks. There has also been much interest in so-called "5G/6G full-duplex MIMO", where highly directional MIMO antennas are used to achieve high spatial attenuation between transmit and receive signals already in the propagation path before the radio receiver. Laboratory measurements have already shown 80–90 dB isolation between transmitting and receiving flat panel antennas in the millimetre-wave range. [12] [13]

But why are the SBFD and 5G/6G full-duplex MIMO technologies so interesting from the point of view of the 3GPP organisation, which is doing the standardisation of the 5G/6G technology? The clear reason is the more efficient use of spectrum, a big step towards simultaneous transmission and reception with very low delay, but also the fact that these technologies can work in parallel with existing base station technologies. In principle, the terminal can be a traditional mobile device without the implementation of IBFD.

Preliminary Assessment of the Deployment and Benefits of IBFD Radios

IBFD radio can be seen as a new hardware generation of software-defined radios. It can bring new capabilities and performance to the battlefield. The large number of conventional military radios and their very long lifespan slow the deployment of IBFD. IBFD radios were already expected to be introduced in 5G base stations, but the roll-out is moving to the next generation of 6G base stations. In any case, the development work in the commercial sector will give a further boost to the development of IBFD technology.

Obviously, it will take some time before there is a mass adoption of IBFD technology in military radios. Until the technology is integrated into every military radio, it could very likely be applied, for example, as a technique to mitigate interference between different radio networks in military vehicles. Another use case example mentioned earlier could be a stand-alone device that allows a convoy of vehicles to maintain its own radio communications while intelligently jamming enemy roadside bombs or swarms of drones.

The use of IBFD radio technology in electronic warfare could improve the effectiveness of jamming and save resources if, for example, as proposed by the IST-175 group, separate long-range jamming was abandoned and jamming was carried out locally in a simultaneous manner with radio transmission. Today, assessing the impact of an electronic attack typically requires interrupting the jamming or using a separate electronic support measure station. IBFD radio technology allows simultaneous jamming and detection of changes in the spectral use of a target system. In a high-flying vision, any combat net radio could take part in electronic warfare operations if it had the resources to do so.

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[10] Business Wire, 21.1.2021, *TrellisWare Demonstrated Full Duplex Radio Capable of 200 Mbps Throughput Developed Under U.S. Army Program*, [Online], [Referenced 31.1.2023]. Available at: https://www.businesswire.com/news/home/20210121005173/en/TrellisWare-Demonstrated-Full-Duplex-Radio-Capable-of-200-Mbps-Throughput-Developed-Under-U.S.-Army-Program

[11] 3GPP, November 2022, draft version 0.1.0, *3GPP TR 38.858 Study on Evolution of NR Duplex Operation*.

[12] Qualcomm, January 2022, *Setting off the 5G Advanced evolution*, [Online], [Referenced 31.1.2023], Available at: https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/setting_off_the_5g_advanced_evolution_web.pdf

[13] Qualcomm, November 2022, *Why and what you need to know about 6G in 2022*, [Online], [Referenced 31.1.2023], Available at: https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/web-why-and-what-you-need-to-know-about-6G-in-2022.pdf

IBFD radio brings new and even revolutionary capabilities to both radio communications and electronic warfare. The new capabilities presented in this article cannot be achieved with traditional military radio waveforms, but must be designed and implemented on an entirely new basis. If IBFD is to be a feature of the next generation of SDR radios, the waveform running in the new radios will also need to be developed into a new version to achieve much better performance on the digital battlefield.

For More Information

M.Sc., Heikki Rantanen (tel. +358 299 800) is a principal scientist at Finnish Defence Research Agency.

M.Sc., Sami Peltotalo (tel. +358 299 800) is a senior research scientist at Finnish Defence Research Agency.