Some Current and Recent RF-Spectrum Research and Development, Applications, Management, and Interference Mitigation

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***Abstract*— This short descriptive paper provides a sense of the recent state of radiofrequency (RF) electromagnetic (EM) spectrum research and development (R&D), applications, management, and interference mitigation. Some historical developments, current research efforts and applications, and possible areas of research are noted. The discussion focuses on RF spectrum activities since 1995.**

Keywords—RF spectrum, RF convergence, waveform diversity, spectrum sharing

I. INTRODUCTION

The world at large now faces serious radiofrequency (RF) spectrum-compatibility problems that require new, innovative solutions. Increased spectral congestion and crowding are especially challenging, and these problems are exacerbated by the incredible proliferation of commercial cellular systems, resulting in extremely spectrally dense environments and fierce competition for spectrum that traditionally has been the dominion of non-communication RF devices as the primary legal users. Communications applications have become so highly ingrained in global society that they are widely deemed as indispensable necessities.

Because the RF spectrum is so precious, it is the object of widespread conflict (globally and nationally) over its use. This conflict has been caused by the unabated, unrelenting, accelerating, consumer pressure for 4G/5G/6G/NextG wireless communications and the Internet of Things (IoT). Furthermore, one can readily envision an Internet of Space (IoS), a deployment of 1) suborbital-based high-data-rate communications networks of satellites around the Earth and 2) geographically local networks of unmanned aerial vehicles (UAVs) that would be enabled by the burgeoning number of commercial satellites and drones, respectively. While such developments would globally impact humanity in a positive manner by delivering high-bandwidth information to the entire world, especially to underserved regions, it will also significantly worsen the overcrowded spectrum problem. In fact, the idea for an IoS as the future backbone for the IoT was proposed by the IEEE MTT-S (led by Dr. Tim Lee) and supported by the IEEE AP-S as an initiative to the IEEE Future Directions Committee (FDC) in 2016 [1]. Although the IoS FDC proposal lost to a 5G proposal, leaders in some technologically advanced companies have begun to consider IoS seriously, and the European Space Agency (ESA) and the US National Aeronautical and Space Administration (NASA) have both prepared plans that involve the deployment of networks of satellites around the Earth, Mars, and the Sun.

The authors believe that the growing worldwide contention over RF electromagnetic (EM) spectrum usage and management is fundamentally a struggle between the commercial benefits of wireless expansion and the needs of every other RF user (scientific research, national defense, public safety). In addition, nearly all RF services want greater bandwidth, which only exacerbates the competition for this extremely valuable commodity. Because spectrum allocation involves trade-offs among the many needs of each nation, such decisions possess a significant political element as well.

Although the authors have attempted to be objective, the ensuing discussion is derived from their work experience in radar at the United States (US) Naval Research Laboratory (NRL) and the University of Kansas (KU). However, much of the discussion is pertinent more broadly to all RF users, especially since high-power radars significantly impact them and vice versa. In fact, much of the spectrum research at NRL and KU was motivated by the need for harmonious interaction among RF systems [2],[3]. For the purposes of this discussion, RF is loosely defined to extend from 1 MHz to 300 GHz (apologies to lower-frequency applications and communities). A small sampling of the many developments of the last twenty-five years are discussed, and some ideas to mitigate spectral congestion that might lead to harmonious co-existence among the various competing users are noted.

This paper addresses a small number of relevant historical developments, R&D efforts and applications, and possible areas of research. The discussion concentrates on modern RF spectrum activities since 1995. The foundation laid by the Advanced Multifunction Radio Frequency Concept (AMRFC) program of the US Office of Naval Research [4] and the Waveform Diversity community, initially under the auspices of the IEEE AES-S (since 2002) and subsequently supported by the IEEE SP-S, are discussed. In addition, very recent (since 2018) R&D variations of the above efforts that have been promoted vigorously by the IEEE ComSoc, IEEE MTT-S, and IEEE SP-S are mentioned (e.g. Joint Communications and Sensing (JCAS) and Integrated Sensing and Communication (ISAC)).

II. SOME HISTORICAL DEVELOPMENTS

Beginning circa 1995, the US Office of Naval Research (ONR) funded a series of programs to demonstrate the integration of important shipboard RF functions (radar, electronic warfare (EW), communications, calibration) into a common set of broadband apertures and development of the requisite signal and data processing, signal generation, and display hardware. These programs were a joint government-industry collaboration led by the NRL. The initial effort, the AMRFC program, was sponsored to mitigate the deleterious impacts from the tremendous growth of topside antennas (i.e. antenna "farms") and the attendant self-induced RF interference on U.S. Navy ships in the 1980s – ships were likened to floating Christmas trees. To that end, the AMRFC program successfully developed and demonstrated a wide-band, generic, active array architecture that simultaneously transmitted and received multiple independent beams for any combination of RF functions at NRL's Chesapeake Bay Detachment facility. The transmit array and receive array are collocated, separated by eleven feet [4].

The AMRFC test bed provided a first look at the benefits, challenges, and requisite research for fielding multifunctional RF systems. The program established that necessary important improvements include: 1) developing new techniques for transmit-to-receive isolation; 2) improving the management of resource allocation; and 3) system architecture designs that minimize production costs, perhaps the prime driver for US Navy programs. The program established the feasibility of using common antenna arrays and common hardware for signal generation and distribution that support diverse multifunctional operational needs. A major contribution was software-defined RF functionality, a capability that is now becoming pervasive with the increasing proliferation of software-defined radio/radar (SDR) and RF system-on-chip (RF-SoC) platforms that are available at relatively low cost.

Upon completion of the AMRFC program in 2005, ONR used its developments as the foundation for the Multifunction Electronic Warfare (MFEW) Advanced Development Model (ADM) program [5]. The goals of MFEW were to provide the technology base for replacing the outdated AN/SLQ-32 Surface Ship Electronic Warfare (EW) system. The resultant upgrade provided improved situational awareness, synergistic combat-system coordination, threat detection, and threat identification. The MFEW design was modular, open, and capable of scaling to the sizes and operational requirements of different platforms. Further, it had growth potential to include additional EW functions and could be incorporated into an integrated sensor and communications system-of-systems under the real-time control of a Resource Allocation Manager (RAM).

As an evolution and technology maturation of the AMRFC and MFEW programs, ONR established the Integrated Topside (InTop) program in 2008, which developed an integrated multifunctional system of communications, radar, and EW capabilities that can be scaled and adapted to multiple classes of naval vessels. The key INTOP contribution was a modular, open architecture that permits change and expansion as technologies and naval needs evolve [6],[7].

In parallel to these developments for monolithic systems, numerous activities and research took place to overcome RF spectrum difficulties by trying to achieve spectral harmony, efficiency, and better performance. In particular, the US Air Force Research Laboratory (AFRL), the US Army Space and Missile Defense Command (SMDC), and NRL formed the Tri-Service Waveform Diversity Working Group (WDWG) in 2002 for the joint pursuit of a long-term roadmap for research, development, and manufacturing in the broad area of Waveform Diversity. The group's statement of purpose was:

> "The electromagnetic spectrum has become increasingly crowded in recent years, and all indications are that this trend will continue. Efficient use of bandwidth is essential to meet the needs of a wide variety of technological disciplines that utilize waveform design. The importance of waveform design and specification for countermeasure, sensor, and communication/navigation systems has long been recognized. However, it is only relatively recent and expected advances in hardware technology that are enabling a much wider range of design freedoms to be explored. Moreover, emerging and compelling changes in system requirements, such as more efficient spectrum usage, higher sensitivities, greater information content, and improved tolerances to errors mandate the need for diverse waveforms."

For more information on WDWG formation and efforts prior to 2010, consult [2] and [3].

Waveform-Diversity concentration areas included: spectral harmony and management, adaptive interference suppression, cognitive RF, simultaneous multi-mission multifunction operation, distributed apertures, RF convergence, and multistatic operation. In particular, recent R&D has been trying to achieve *RF convergence*, a holistic perspective that collectively addresses signal processing, EM, and RF systems engineering across different applications [8]. This perspective seeks to improve the capabilities of the AMRFC/MFEW/InTop progression and to extend them to a broader set of RF devices.

The WDWG led to: 1) long-term seedling research efforts at AFRL and NRL; 2) the inclusion of Waveform Diversity and Spectrum as a subcommittee of the Radar Systems Panel of the IEEE AES-S (now the Spectrum Innovation subcommittee); 3) several international conferences related to these topics; 4) the definition of Radar Waveform Diversity in IEEE Standard 686; and 5) an article in the *IEEE Proceedings* on spectrum engineering, management, and regulatory issues [9].

One notable US Air Force program was the Multi-University Research Initiative (MURI) on "Adaptive Waveform Diversity for Full Spectrum Dominance," from 2005-2010 [10]. During that same period, NRL Radar Division's internally funded research included a shared-spectrum multistatic radar concept [11], enabled by multistatic adaptive pulse compression [12], for addressing radar fratricide caused by loss of spectrum deconfliction across systems in the same geographical region. This research evolved to activities on radar-embedded communications at KU [13]-[15] and joint radar and communications via OFDMA protocols [16],[17]. In addition, German researchers proposed joint radar-communication using OFDM [18]. References [16]-[18] are precursors that helped lay the groundwork for the numerous recent research areas promoted by the IEEE ComSoc, MTT-S, and SP-S.

For the past 20 years, the commercial communication community has been voraciously pursuing and acquiring spectral primacy in the bands of other users. Major reasons for their successes are the tremendous economic benefits and new user capabilities that they provide, with the confluence of untethered access to data and a wealth of smart-phone applications completely transforming the way we live. Indeed, NextG communications promises an ever-growing list of use-cases from telemedicine to virtual/augmented reality that not too long ago were the sole realm of science fiction. Smart phones and devices make huge profits for companies and are mass produced in large volumes; whereas the devices for other RF applications tend to be significantly fewer in number and are generally not intended for commercial profit (instead for serving broader scientific, defense, and safety functions).

Radiofrequency spectrum management is a topic of interest to both the civil and military sectors. For example, the high densification of RF functions in the battlefield requires finding solutions to manage coexistence in a dynamic manner, just like what is done for commercial cellular, automotive radar deconfliction, etc. This highly sought resource is used for diverse non-military, non-communication purposes like air traffic control, astronomy, automotive safety, geophysical monitoring of Earth resources from space, humanitarian demining, infrastructure protection, radio navigation, radio and television broadcasting, search-and-rescue, severe weather tracking, etc. Unlike cellular communications, the diversity of RF-sensing applications means that no formal standards for operation exist, aside from spectral compliance masks in the Red Book [19] (see Fig. 1).

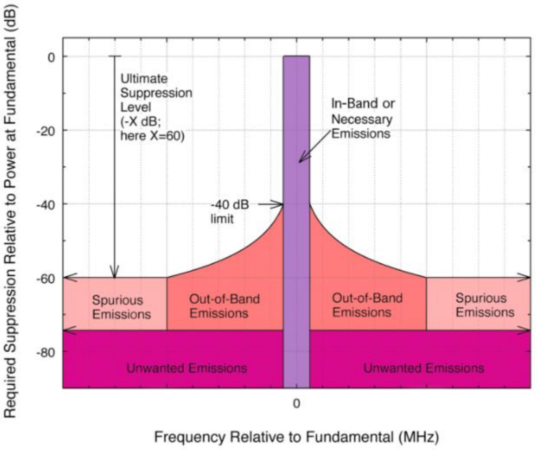

Fig. 1. Radar spectrum engineering criteria (RSEC) mask [NTIA]

Space constraints preclude a comprehensive discussion of the myriad spectrum activities, but two examples are noted: ISART™ and the DARPA-funded SSPARC effort. The International Symposium on Advanced Radio Technologies (ISART)™ has been forecasting the development and application of advanced radio technologies since 1999 [20]. The Shared Spectrum Access for Radar and Communications (SSPARC) [21] of the Defense Advanced Research Projects Agency (DARPA) sought to improve the capabilities of communications and radar through spectrum sharing.

III. FOUR EXAMPLES OF SPECTRUM LOSS

Four examples of spectrum loss by non-communications systems in US RF auctions since 2005 are briefly discussed. Three of them involve the radar band from 3450 to 3700 MHz, a subset of the 3450-3980 Band, and the other example involves the Advanced Wireless Services AWS-3 Band. Specifically, these auctions took place in

2005 (3650-3700 MHz Radar Band),
2012 (1695-1710 MHz AWS-3 Band),
2015 (3550-3650 MHz Radar Band),
2020 (3450-3550 MHz Radar Band.

A. 3450-3980 MHz Band

1) Auction of 3650-3700 MHz Radar Band: In 2005, the 3650-3700 MHz Radar Band began sharing with terrestrial wireless broadband operations per a revision of the US Federal Communications Commission (FCC) rules to open the band. Under the licensing mechanism adopted for the band at that time, the FCC issued an unlimited number of non-exclusive nationwide licenses to non-Federal entities for commercial use. Those licenses served as a prerequisite for registering individual fixed and base stations [22]. Unfortunately for the US Navy, that band was the top 50 MHz of its AN/SPN-43 system, which operated over 3500-3700 MHz and had been the marshalling air traffic control (ATC) radar system on all aircraft carriers and amphibious assault ships for vectoring aircraft into final landing approach. This loss of spectrum caused the Navy to conduct analyses of alternatives to replace this radar. Doing so was very costly and time consuming for a number of reasons, and it was not until 2021 that the new shipboard AN/SPN-50 radar began replacing the AN/SPN-43. Part of the difficulty with changing shipboard radars is that they are large, complex, high-power systems with significant support hardware, and the procurement and production processes are very lengthy.

2) Auction of 3550-3650 MHz Radar Band: In 2015, the 3550-3650 MHz Band was auctioned to the Citizens Broadband Radio Service (CBRS) for shared wireless broadband use of 3550-3700 MHz [23]. CBRS access and operations must be managed by an automated frequency coordinator, known as a Spectrum Access System (SAS), which may incorporate information from an Environmental Sensing Capability (ESC). The ESC is a sensor network that detects transmissions from US Department of Defense (DoD) radars and transmits that information to a SAS. Both a SAS and an ESC must be approved by the FCC. This auction reduced DoD's full access to 3500-3550 MHz, a loss of 75% of the band, which leads to the next example.

3) Auction of 3450-3550 MHz Radar Band: In 2020, to support US global leadership in 5G, the White House sought to make an additional 100 MHz of contiguous spectrum available in Mid-band (1-6 GHz) by developing a sharing plan for electromagnetic spectrum (EMS) with the DoD [24]. To that end, Dr. Kelvin Droegemeier, the then Director of the White House Office of Science and Technology Policy (OSTP), formed a group of subject matter experts in early 2020 (including the authors of this paper) to assess the feasibility of sharing. Subsequently in April 2020, the OSTP Team and the DoD Chief Information Officer formed America's Mid-Band Initiative Team (AMBIT). Working closely with the military services, the FCC, and the National Telecommunications and Information Administration (NTIA), AMBIT devised a spectrum-sharing framework for the 3450-3550 MHz Band by August 2020 that would support the US 5G industry's need for additional Mid-band spectrum, while hopefully protecting critical requirements for national security. In May 2022, applications for this band were granted by Public Notice DA 22-462. With this additional 100 MHz, the US now has a contiguous 530 MHz of Mid-band spectrum from 3450-3980 MHz for enabling higher-capacity 5G networks.

B. 1695-1710 MHz AWS-3 Band

The next example is the auction of 1695-1710 MHz, the Advanced Wireless Services (AWS-3) Band [25]. As a result of the Middle-Class Tax Relief and Job Creation Act of 2012, the Department of Commerce recommended that 15 MHz of the 1675-1710 MHz Band, which is used by weather satellite systems of the National Oceanic Atmospheric Administration (NOAA), be auctioned to commercial wireless Long-Term Evolution (LTE) carriers to be shared with NOAA.

Based on the FCC-led Auction 97 of AWS-3 that ended in 2015, wireless cell phones were permitted in April of 2018 to operate at the same frequencies used by the 17 NOAA ground stations that receive data from weather satellites. In addition to these ground stations, other users of this spectrum in the DoD and the Department of the Interior were identified as requiring protection from potentially harmful RF interference. Consequently, NOAA had a competition to design and develop a Radio Frequency and Interference Monitoring System (RFIMS) to monitor cellular signals interfering with critical weather satellite data and to design, test, and deploy an RFIMS at the 17 NOAA ground stations. The RFIMS is supposed to detect and classify RF interference in real time, to identify the sources of interference, and to notify NOAA operators of interference. In 2023 the Harris Corporation was awarded the contract to build this monitoring system.

IV. RECENT VARIATIONS ON THEMES

In more recent times, a plethora of acronyms with nearly identical meanings have been promoted, including Dual-Function Radar-Communication (DFRC), Joint Communications and Sensing (JCAS), Integrated Sensing and Communications (ISAC), Joint Communications and Radar (JCR), Joint Radar-Communications (JRC), Communication and Radar Spectrum Sharing (CRSS), Coexisting Radar and Communication (CRC), and Radar-Communications (RadCom), etc. It is not clear why so many distinct names are needed for the same field of research. Moreover, there has been a veritable deluge of surveys performed in the recent short timeframe [26]-[38], many of which are purely theoretical and largely ignore the practical problems. Another troublesome aspect of these developments is the lack of coordination by the IEEE ComSoc and SP-S societies with the IEEE AP-S and AES-S, particularly since AP-S has purview over the essential EM physics associated with transmission, propagation, and reception of RF waves via antennas and through various media, and AES-S focuses on systems that integrate these essential functions in a physically meaningful and realistic way. This disconnection between units of IEEE underscores the pervasive disconnect with practical problems.

V. SUGGESTED RADAR SPECTRUM RESEARCH DIRECTIONS

Given the sheer breadth of topics in this space, the following discussion highlights a few general perspectives that may be useful when planning research directions and objectives.

A. How to meet transmit power requirements while being more spectrally clean?

Radar fundamentally depends on receive signal-to-noise ratio (SNR), which itself depends on the energy-on-target scattered back to the radar. Therefore, a common requirement is for a transmitted waveform to have constant amplitude. Furthermore, the two-way path and scattering losses mandate megawatts (MW) of peak transmit power to detect 10^{-18} W to 10^{-15} W of received energy. Producing that much power gets spectrally messy and invariably leaks out of the band, a phenomenon typically called spectral splatter.

Spectrum leakage is largely caused by pulsed operation, high-power amplification, and choice of waveform. Higher power efficiency generally means the high-power amplifier (HPA) is operating in the nonlinear regime. One means to improve spectral containment is to slow the rise and fall times of a pulse. For solid-state HPAs, this approach is feasible and available now; however, it is more complicated for microwave tubes (e.g. TWTs and klystrons), because such components effectively behave like on/off switches, making more gradual rise/fall times quite difficult.

A related issue is the use of phase codes, which theoretically possess abrupt phase changes that incur spectral spreading, as well as distortion of the pulse envelope that could potentially damage the transmitter. For example, Fig. 2 displays the impact of a class-AB amplifier on (what should be) a constant-magnitude P4-coded waveform. Consequently, codes should first be mapped into a continuous signal structure via DPSK, MSK, BTQ, or PCFM [39]. Put another way, any work involving optimization of codes should necessarily include this mapping in order to be physically relevant.

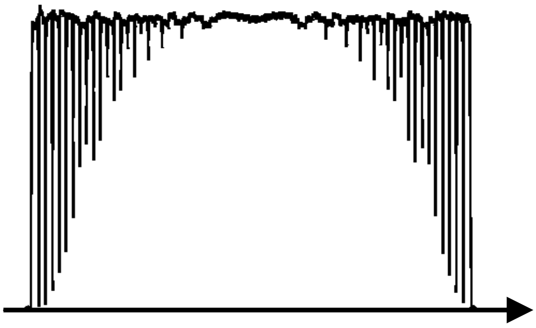

Fig. 2. Measured pulse envelope for a P4 code through a class-AB amplifier.

While not a panacea presently, moving to a nonrepeating FM continuous-wave (CW) radar mode would address the rise/fall issue, while also permitting lower peak power for the same energy on target (e.g. [40]-[42]). The nonrepeating attribute avoids the limitation encountered by traditional FMCW in which the range-ambiguity interval tends to be rather short. Moreover, a change from X% to 100% duty cycle means that the coherent integration gain (thus interference separability) provided by receive pulse compression would enjoy a $100/X$ improvement. However, adequately contending with transmit/receive isolation (otherwise handled by the T/R switch in pulsed mode) is another problem that remains to be solved.

Finally, the driver toward wideband, digital-at-every-element arrays to achieve greater operational flexibility must be considered in this spectrally clean context. Given the inherent complexity of fully digital arrays (e.g. see papers in the special issue/section of [43],[44]), it is likewise important to incorporate calibration effects and associated antenna trade-offs into waveform design, especially as hardware becomes more sophisticated, e.g. multiple-input multiple-output (MIMO).

B. *How to pivot from noise-limited to increasingly interference-limited operation?*

Radar has traditionally performed whatever interference cancellation is necessary with the goal of reaching a state in which the residual response can be assumed noise-limited, with detection processing then being performed. The proliferation of cellular users in the same bands as a radar means that this condition can no longer be achieved when operating near any population center. Further, while base stations are known fixed points, mobile users are, by definition, regularly in motion and highly distributed (though some degree of clustering around buildings, highways, etc. could certainly be assumed). In short, the expectation of being able to cancel the interference from these myriad dynamic sources may simply be impossible, given the finite degrees of freedom with which a radar must operate. Consequently, exploring modes such as the CW notion above and incorporating expected interference levels that will remain pervasive are certainly design considerations for the future.

C. *How can a radar achieve greater multi-mode use of fixed spectrum resources?*

By far the most common consideration for a dual-function marriage of radar is with communications, meaning the radar emission would therefore also convey some information payload in addition to doing the job of sensing. However, the conveyance of information requires a degree of variability that is generally not used in radar, which instead tends to rely on repetition of multiple pulses so that receive processing in fast-time (range) and slow-time (Doppler) are separable, easy to perform, and amenable to simple sidelobe suppression via tapering. In contrast, incorporating time-varying information introduces a nonstationary modulation onto illuminated scattering that can also be viewed as a coupling of the fast/slow-time domains [45]. In other words, radar operation is made considerably more complex to compensate for these effects … though it can be done (e.g. [46],[47]). Of course, incorporation spatial degrees of freedom to enable MIMO capabilities further complicates this endeavor, necessitating consideration of digital array trade-offs as noted above.

D. *How to leverage cognitive RF for increasingly complex and dynamic environments?*

Many a seasoned radar engineer will tell you that cognition in some form has been part of operational radar systems for many years, since the radar must automatically adjust center frequency to avoid interference while also performing cancellation of interference (may be dynamic) in real time. There is the matter of "how cognitive" a system can truly become, referring to the speed at which automated decisions can be performed, the nature and complexity of those decisions, and the impact of disparate systems attempting to "out-cogitate" one another [48].

While a super majority of the work on cognitive radar involves the development of new signal-processing solutions, it is absolutely key that they be posed in the context of the physical hardware with which they will reside. For example, any optimized waveform is only as good as the unavoidable distortion it encounters in a high-power transmitter. Moreover, the zero-order hold operation performed in most digital-to-analog converters (DACs) introduces amplitude modulation [49],[50], although the degree is lessened by how much the signal representation is oversampled related to bandwidth (assuming the signal is reasonably well-contained to start). In short, a holistic perspective subsuming signal processing, trade-offs for digital arrays, RF systems engineering, and physical phenomenology is required. Taken together with the growing complexity of the RF spectrum, one could therefore argue that we are actually rather far being able to implement modern cognitive radar capabilities.

E. *Can innovative antenna elements and arrays be developed that are conducive to multifunctional RF co-design?*

To achieve multifunctional RF co-design, the following research areas are suggested for refining antennas: 1) include platform structure and its proximate site in concert with near-field scatterers in any developments; 2) consider spatio-temporal energy distribution for joint radar/communication or MIMO development; 3) antenna technologies for active arrays that are adaptable and accurately integrate EM theory and signal processing; 4) antenna configurations that are integrated into subsystems behind the aperture to increase parameter-control so as to effect improved radiated system performance; and 5) incorporation of antenna characteristics as design parameters for the transmitter.

VI. CONCLUSIONS

One can with certainty state that demand for spectrum will only continue to increase; hence research into spectrum sharing will likewise grow since spectral resources are inherently finite. This situation is not new and has actually been underway in some form or another for decades. Hopefully, the historical context herein will reduce some of the inevitable "repeated invention" that otherwise occurs and will point the way toward general considerations when exploring this field of research.

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