CONTRIBUTED PAPER

Radar Spectrum Engineering and Management: Technical and Regulatory Issues

This paper presents the spectrum congestion problem from a radar perspective and describes a number of possible approaches to its solution from a technical and regulatory point of view.

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ABSTRACT | The radio-frequency (RF) electromagnetic spectrum, extending from below 1 MHz to above 100 GHz, represents a precious resource. It is used for a wide range of purposes, including communications, radio and television broadcasting, radionavigation, and sensing. Radar represents a fundamentally important use of the electromagnetic (EM) spectrum, in applications which include air traffic control, geophysical monitoring of Earth resources from space, automotive safety, severe weather tracking, and surveillance for defense and security. Nearly all services have a need for greater bandwidth, which means that there will be ever-greater competition for this finite resource. The paper explains the nature of the spectrum congestion problem from a radar perspective, and describes a number of possible approaches to its solution both from technical and regulatory points of view. These include improved transmitter spectral purity, passive radar, and intelligent, cognitive approaches that dynamically optimize spectrum use.

KEYWORDS | Radar; radar transmitters; radio communication; radio broadcast transmitters; interference

I. INTRODUCTION

The radio-frequency (RF) electromagnetic (EM) spectrum, extending from below 1 MHz to above 100 GHz, represents a precious resource. It is used for a wide range of applications, including communications, radio and television broadcasting, radionavigation, and sensing. These applications are strongly influenced by the propagation characteristics of the environment and the directivity achievable by antennas, both of which are dependent upon the choice of frequency. The allocation of spectrum is regulated by the International Telecommunication Union (ITU) and continually reviewed at an international level by the World Radiocommunication Conference (WRC), with some bands assigned to services on an exclusive basis while other bands are shared between a number of services.

Radar represents a fundamentally important use of the EM spectrum. It is used for a variety of purposes, including air traffic control, geophysical monitoring of Earth resources from space, automotive safety, severe weather tracking, and surveillance for defense and security. As a sensor, it has the merits of allowing day or night and all-weather operation (at frequencies below about 10 GHz) and providing information such as target range and bearing, atmospheric measurements, onboard altimetry, long-range imaging capabilities, and collision avoidance.

Nearly all services have a need for greater bandwidth. In the case of communications and broadcasting, greater

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bandwidth is needed to satisfy the growing consumer demand for higher data rates, particularly to mobile devices (e.g., streaming movies to a smartphone or a tablet PC [1]). In contrast, higher bandwidth for radar translates into finer range resolution, which directly relates to sensing capability (e.g., to detect an inbound hostile target). As the demand continues to grow for more access to spectrum by all these interested parties, there will be ever-greater competition for this finite resource.

The problem of meeting this demand may be addressed both by improved technology and by more intelligent frequency regulation [2]. A major impact of increased demand is that many users will be forced to coexist within a finite spectrum allocation, which in turn yields an increased likelihood of mutual interference. The ways in which different services may interfere with one another is not always well understood, and this misinformed perspective may cause over/undercautious decisions to be made with regard to spectrum allocation. Better appreciation of the nature and effect of interference from/to various users may allow different services to operate within the same or nearby band with a tolerable level of disruption. Improved technology may also help to alleviate this problem, such as through adaptive control of emissions—in the frequency, time, space, polarization and coding domains—that could potentially allow for more efficient use of the spectrum for the coexistence of different services.

Just as digital technology has enabled the telecommunication industry to make a quantum leap in terms of capacity and quality of service in recent years; it is likewise facilitating the potential for tremendous improvement in radar receiver performance and the control of radar emissions. For example, precise wide-bandwidth radar waveforms can now be generated and varied dynamically, potentially on a pulse-by-pulse basis. In addition, ongoing improvements in power amplifier and filter capabilities can provide better spectral purity to allow closer channel spacing.

The purpose of this paper is to explain the nature of the spectrum congestion problem from a radar perspective, and to describe a number of possible approaches to its solution, both from technical and regulatory points of view. It is written on behalf of the radar community, but is aimed at all users of the EM spectrum, making the case for radar's use of the spectrum and explaining what is presently being done to contend with spectral congestion and what may be done in the future. The authors come from different countries and have participated in a number of different national and international studies on the subject of radar spectrum usage.

II. RADAR SPECTRUM ENVIRONMENT

The spectrum environment in which radar operates is absolutely critical to the particular sensing operation, of which there are numerous forms, including surveillance, imaging, and tracking along with the myriad different applications of each. Whereas communications and broadcasting use spectrum as a channel through which to convey information, radar derives information from the environment itself with the particular frequency band having a significant impact upon the exact nature of that information.

Inspection of a typical frequency allocation chart [3] shows that the allocation plan is certainly complicated. The spectrum is allocated to different services (broadcasting, radiolocation, land mobile, aeronautical mobile, etc.). In the United States, some portions are further allocated on a government exclusive basis, some government/nongovernment shared, and some nongovernment exclusive.

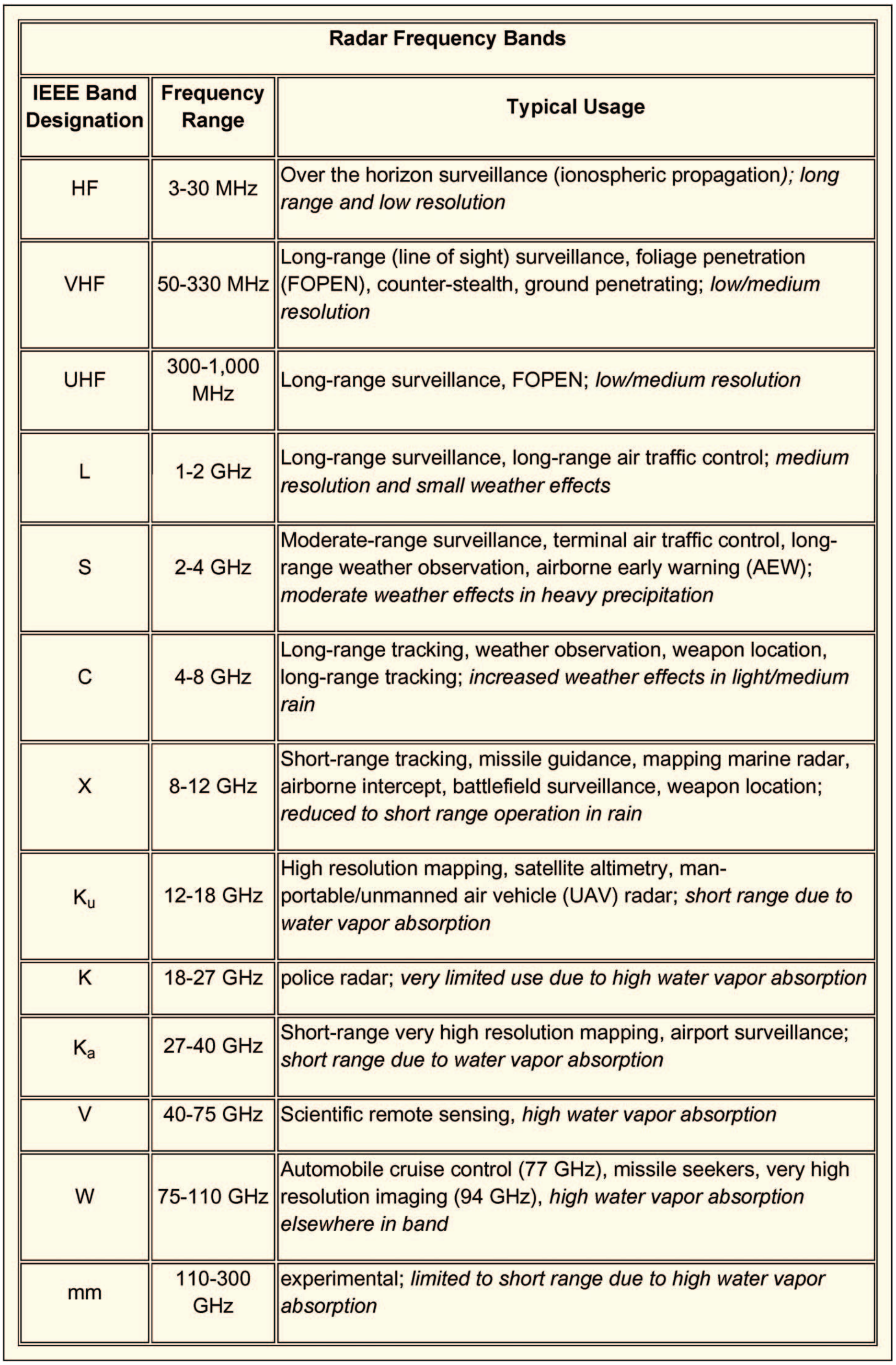
Table 1 lists the frequency bands where radars operate and highlights the various sensing modes that are performed in each band. By convention, some radar bands are designated by letters, for example L-band (1–2 GHz), S-band (2–4 GHz), C-band (4–8 GHz), X-band (8–12 GHz), and so on [4].

An individual radar will not usually occupy the total frequency allocation in any particular radar band. The bandwidth of a radar determines its ability to resolve targets in range. The bandwidth that an individual radar will occupy will depend not only on the range resolution required, but also on the need to reduce the potential for interference with other radars in the same band, by operating on different frequencies. In some scenarios, there may be very many radars operating in close vicinity. For example, in a busy shipping lane within, say, a 20-nmi radius, there may be many tens of large ships, fishing boats, and recreational craft, each with a radar operating in S-band or X-band. There may be a civil aviation flight path above, with each aircraft operating a weather radar in X-band. It is easy to imagine that more than 100 emitters might be simultaneously detected by a wideband receiver.

The higher frequency bands provide some advantages to radar. For a fixed fractional bandwidth, increasing the operating frequency subsequently increases the achievable bandwidth, thus providing finer range resolution. In addition, for a fixed angular beamwidth, the antenna size decreases as the wavelength is reduced (antenna beamwidth in one dimension is proportional to λ/D, where λ is the RF wavelength and D is the antenna aperture width).

However, in these higher bands, long-range operation becomes more strongly affected by attenuation due to the atmosphere, especially in the presence of rain or clouds. As such, radar sensing via these bands is limited to short-range applications like automotive collision avoidance, police radar, airport surveillance, and scientific remote sensing. Furthermore, the lower bands offer some unique capabilities such as ionospheric propagation for over-the-horizon surveillance [at high frequency (HF)], foliage and ground penetration [at very high frequency (VHF) and ultrahigh frequency (UHF)], and long-range surveillance, tracking, air traffic control, and weather monitoring (at L-, S-, and C-bands). Because the world is so complex, the task of sensing clearly does not have a "one size fits all" solution.

Table 1. Standard Radar Frequency Letter Bands and Radar Operating Modes [4]



Radar Frequency Bands		
IEEE Band Designation	**Frequency Range**	**Typical Usage**
HF	3-30 MHz	Over the horizon surveillance (ionospheric propagation); *long range and low resolution*
VHF	50-330 MHz	Long-range (line of sight) surveillance, foliage penetration (FOPEN), counter-stealth, ground penetrating; *low/medium resolution*
UHF	300-1,000 MHz	Long-range surveillance, FOPEN; *low/medium resolution*
L	1-2 GHz	Long-range surveillance, long-range air traffic control; *medium resolution and small weather effects*
S	2-4 GHz	Moderate-range surveillance, terminal air traffic control, long-range weather observation, airborne early warning (AEW); *moderate weather effects in heavy precipitation*
C	4-8 GHz	Long-range tracking, weather observation, weapon location, long-range tracking; *increased weather effects in light/medium rain*
X	8-12 GHz	Short-range tracking, missile guidance, mapping marine radar, airborne intercept, battlefield surveillance, weapon location; *reduced to short range operation in rain*
K_u	12-18 GHz	High resolution mapping, satellite altimetry, man-portable/unmanned air vehicle (UAV) radar; *short range due to water vapor absorption*
K	18-27 GHz	police radar; *very limited use due to high water vapor absorption*
K_a	27-40 GHz	Short-range very high resolution mapping, airport surveillance; *short range due to water vapor absorption*
V	40-75 GHz	Scientific remote sensing, *high water vapor absorption*
W	75-110 GHz	Automobile cruise control (77 GHz), missile seekers, very high resolution imaging (94 GHz), *high water vapor absorption elsewhere in band*
mm	110-300 GHz	experimental; *limited to short range due to high water vapor absorption*

Many airborne radars, such as airborne interception (AI) radars in fast jets, or those used for surveillance of the land and sea, will use X-band. This is a good compromise between an acceptable antenna size for an airborne platform and the ability to operate over long ranges in poor weather.

The radar allocations are interleaved, or in some cases shared, with the equivalent communications and broadcast bands. In the HF bands, the primary uses are communications and broadcasting. Very long-range communications are possible at these frequencies, depending in the propagation conditions which can change considerably over both short and long timescales. There have previously been no designated frequency allocations for HF radars, which may operate anywhere from about 3 to 50 MHz. Such operation has been done as a secondary user, having to avoid interference with primary users. However, the

2012 WRC proposed a number of primary allocations for the radiolocation service between 3 and 50 MHz to support HF oceanographic radar operations [6].

At VHF and UHF, the spectrum is also very crowded, being particularly used for communications and broadcasting. Again, radar operation in these bands is generally on a secondary basis. At microwave frequencies, the radar L-band and above, there are radar allocations as a primary user, but there is a growing number of applications putting pressure on the available bandwidth. Typical applications around the radar L- and S-bands include mobile telecommunications, in particular, and also wireless local area networks (LANs), Bluetooth, and the Global Positioning System (GPS). At higher frequencies, up to about 30 GHz, uses will include radioastronomy, microwave communications links, satellite television broadcasting, and communications satellites.

III. RADAR EMISSIONS

Radar systems transmit RF signals, known generally as the radar waveform, modulated in such a way as to enable measurement of range and the Doppler shift due to relative motion between radar and target, and to resolve distinct scatterers. The specification of the radar signal is dictated by sensing requirements such as range resolution (which is bandwidth dependent), Doppler resolution, maximum ambiguous range, and radar sensitivity. The selection of a particular waveform or class of waveforms is made according to the various performance tradeoffs conveyed by these requirements.

The most prominent class of radar emissions is based on the successive transmission of pulses, where phase or frequency may in turn be modulated during the pulse. These pulses may be as short as 100 ns to longer than 100 μs, depending on the application and possess a pulse repetition frequency (PRF) from around 300 Hz up to 100 kHz. The intervals between pulses are used to receive the signals reflected from objects (conventionally known as radar targets) at various distances from the radar, and such intervals may typically be at least 1000 times longer than the pulse length. In other words, the radar spends most of its time “listening” for the faint echoes from distant targets for which it requires exclusive access to the requisite part of the spectrum in time, frequency, and space.

The choice of pulse length and PRF will be dependent on the tasks being performed by the radar. A radar with a PRF of value f_r will be able to listen for a time period of about $1/f_r$, before the next pulse is transmitted. The receiver is usually blanked during transmission, to prevent damage to its very sensitive front–end circuits. This means that targets out to a range of $c/(2f_r)$ can be measured unambiguously, before being potentially confused with returns from later pulse transmissions. So, for example, a radar with a PRF of 1 kHz can measure range unambiguously out to 150 km. The pulse length τ for a given peak power level P_t, from the transmitter, determines the total energy in each pulse $P_t\,\tau$. The power averaged over time is then given by $P_{av} = (P_t f_r \tau)$, where the value of $f_r\ \tau$ is known as the duty cycle (i.e., the fraction time available to listen for returns). At a given range, the minimum detectable target size will be proportional to the average power. However, it should also be noted that the minimum range that can be measured by the radar will also be determined by the pulse length, since the receiver is blanked during transmission. So a pulse length of 10 μs will give a minimum range of about 1.5 km. Radars also measure the Doppler frequency shift imparted by relative radial motion between the radar and the target. A relative radial velocity v will induce a Doppler frequency shift of $2v/\lambda$ Hz. So a radial velocity of 1 m/s will give a Doppler shift of 66.7 Hz in X-band ($\lambda = 0.03$ m). The Doppler frequency shift is usually very small compared to the pulse bandwidth and has to be measured by observing the successive phase shifts of returns over burst of pulses. In these circumstances, the maximum unambiguous Doppler shift that can be measured is $\pm f_r/2$. This is another constraint on waveform design.

The other class of radar emissions is known as continuous wave (CW). These radars transmit the interrogating waveform and receive reflected signals simultaneously, thus requiring separate transmit and receive antennas with very good isolation to prevent saturation of the receiver. Once again, the ability of these radars to resolve targets in range is determined by the bandwidth of the transmissions. In a CW radar, bandwidth is achieved by sweeping the frequency over the required bandwidth, usually with a linear rate of frequency change over time. A typical frequency-modulated continuous wave (FMCW) radar might sweep over a bandwidth of 100 MHz in a repetition period of 2 ms. This can be compared with a pulsed radar with the same bandwidth, which might sweep the frequency over the same bandwidth within the time duration of a pulse, which might be, for example, 5 μs.

For both classes of radars, it is standard for the emissions to possess a constant envelope (i.e., no amplitude modulation effects) so as to maximize the energy incident upon, and subsequently reflected from, the illuminated objects and to thereby maximize the achievable sensitivity. The use of constant envelope pulses is also motivated by the need to drive power amplifiers in saturation to obtain the best power efficiency. However, it may also be noted that driving the amplifiers in this way also causes a high degree of nonlinearity, which can cause a broadening of the transmitted spectrum.

The center frequency of the radar emission is determined by the mean carrier frequency, which may be fixed or variable over time, say from pulse to pulse, according to some preselected basis (the latter is known as frequency agility). The instantaneous bandwidth of the waveform is determined by the modulation that is applied to the pulse. A radar bandwidth B can provide a range resolution ρ of $c/(2B)$, where c is the velocity of light. For

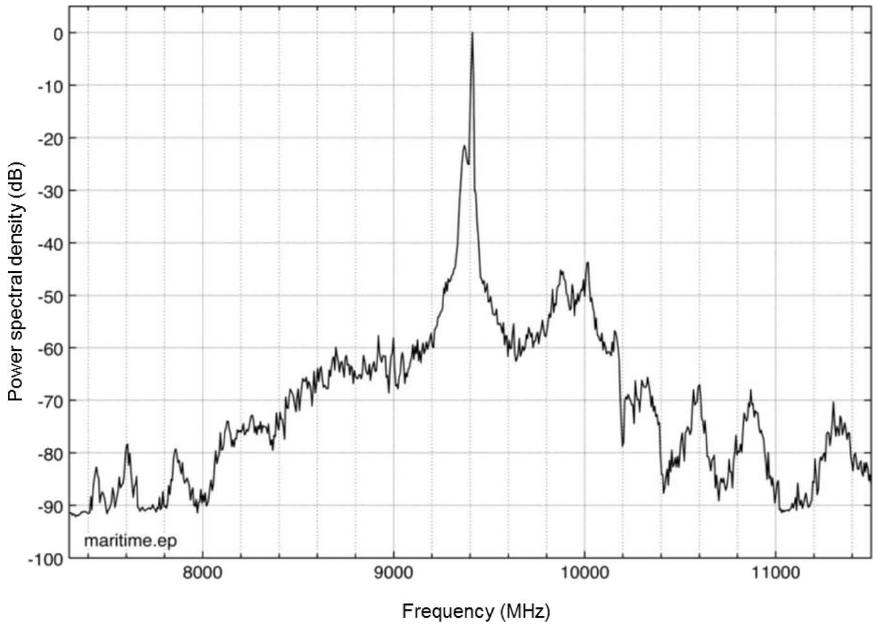


Fig. 1. ***Power spectral density of a radar using a pulsed magnetron (Furono Model 1953C X-band maritime surface radar), with a pulse length of 100 ns giving a nominal bandwidth of 10 MHz.***

example, a radar pulse might be characterized as having a center frequency of 9.6 GHz, a pulse length of 5 μs, and a bandwidth of 100 MHz, with the radar being frequency agile over a total band of 500 MHz or more. The bandwidth of a radar pulse determines its ability to resolve targets at different ranges. For example, a bandwidth of 100 MHz implies a maximum range resolution of 1.5 m. Some radars, especially those used to image the ground using synthetic aperture radar techniques, may have bandwidths of more than 1 GHz, implying a potential range resolution better than 15 cm. Such wide bandwidths may be needed to classify targets and accurately measure their position in a complex scene.

A. Radar Transmitters

The radar transmitter is the component responsible for the generation and amplification of the radar waveform, thus providing the energy required to detect objects at long ranges. Depending upon the particular sensing application, the generated peak power can be anywhere from milliwatts to megawatts. The transmitter may be based on either vacuum tube or solid-state technology. The simplest and most widespread method of generating high-power RF energy is with a magnetron tube, which is a high-powered oscillator that can be pulsed. The cross field amplifier (CFA) or Amplitron is used to further boost the output power from magnetrons. While inexpensive, the magnetron suffers serious drawbacks in terms of spectral purity. A modulating pulse initiates the magnetron; as the buildup of RF energy grows from noise to a critical point, the magnetron begins to oscillate. These oscillations differ from pulse to pulse. The artifacts resulting from this process are rather steep asymmetrical sidebands on either side of the spectral mainlobe (Fig. 1). These frequency sidebands can cause adjacent channel interference to other occupants of the spectrum. Bandpass filters have been employed on magnetron-type transmitters as a means of reducing this out-of-band (OOB) interference, though the cost of this improved spectral purity is a significant loss of effective transmitter power. Note in this example that the half power bandwidth is about 10 MHz, commensurate with a pulse length of 100 ns. However, at the level 40 dB below the peak, often used in defining spectrum occupancy, the spread of frequencies is of the order of 100 MHz. If this magnetron had a peak power level of 1 MW, which is quite feasible, then even these OOB signals at a level 40 dB below the peak will be equivalent to a transmitter with a 100-W peak power transmitting over a bandwidth of more than 100 MHz. This may interfere with other radars or services operating in adjacent frequencies.

In contrast to the magnetron, all other types of radar transmitters rely on separate amplifier and waveform generation stages to enable better control of the waveform characteristics. In many modern radar systems, the waveform generator is a digital synthesizer operating with very stringent frequency tolerances and extremely low levels of sideband energy. The master clock in the digital synthesizer is used to derive all timing for the radar, including the PRF. The digitally synthesized waveforms are converted to analog format and passed to a power amplifier, before radiation by the antenna. Commonly used radar power amplifiers based on tube technology include the klystron, traveling wave tube (TWT), and CFA. Klystrons can generate megawatts of peak power but are limited in bandwidth due to the restrictions of their resonant cavities. For example, the Bendix AN/FPS-20 air surveillance radar, which used a klystron-based transmitter of 1950s vintage, had a peak power of 2 MW, a pulse length of 60 μs, and operated between 1.25 and 1.35 GHz. Traveling wave tubes provide peak powers of the order of 0.1–50 kW, and typically have much broader bandwidths than klystrons (up to two or three octaves). While ongoing work is seeking to improve the spectral purity of these tube devices, the reality is that legacy systems, particularly for defense applications, will be in abundance for the next 50 years due to the long acquisition cycle for such systems and the enormous costs involved with building large modern radar systems.

Solid-state power amplifiers have been employed for several years in radar applications, as standalone amplifiers, as replacements for amplifiers using vacuum tube devices, and in distributed modules as part of active electronically scanned arrays (AESAs) [6]. At lower frequencies, say below 3 GHz, silicon bipolar transistors may be used with duty cycles of $<$ 10% to generate peak powers of the order of 100 W. At higher frequencies (usually up to about 30 GHz) GaAs devices are used. A transmit/receive module with two or more devices in parallel in an AESA radar at X-band might generate a peak power of 10 W. A small AESA may have 1000 transmit elements giving a total peak transmitter power of 10 kW, with duty cycles up to 20%. Newer materials such as GaN are under development for higher power transmitter modules. GaN has a greater power density than GaAs and can operate at higher voltages. GaN devices have the potential to develop higher powers and to operate at higher frequencies (i.e., $>$ 30 GHz). However, a more important benefit may be the potential for improved power efficiency compared to GaAs devices.

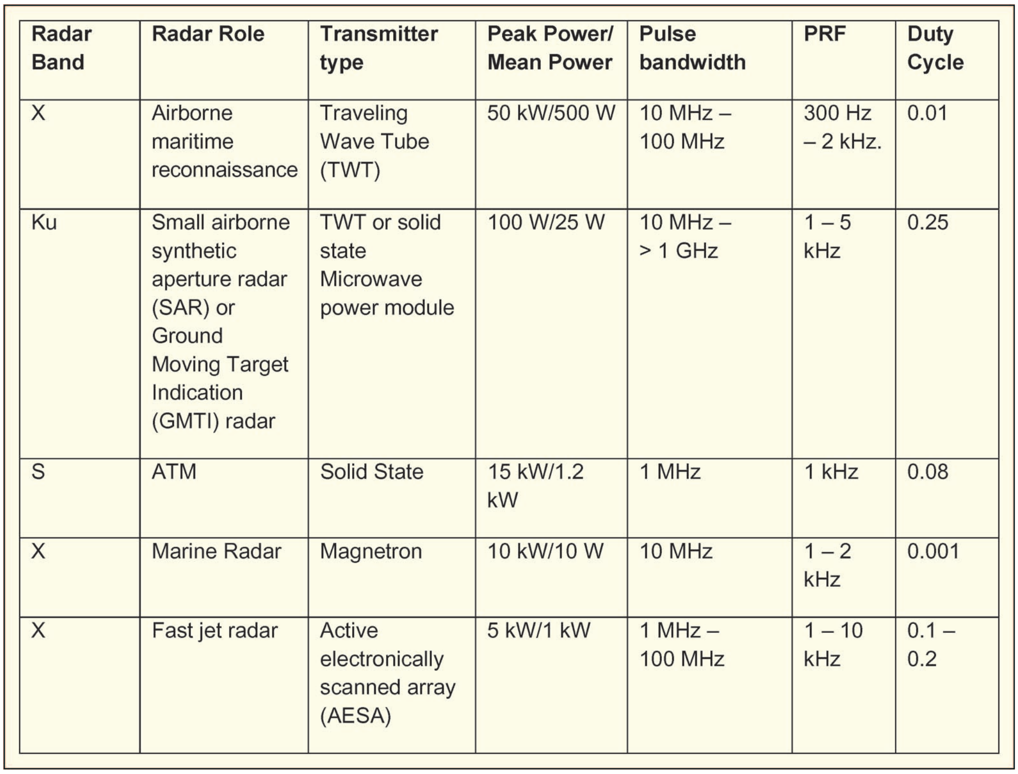
Solid-state-based radars have the advantage of being amenable to techniques for controlling OOB spectral emissions such as bandpass filtering and amplifier linearization [13]. As a general rule, solid-state amplifiers cannot provide the high peak power of tubes but they are usually able to sustain a much higher duty cycle (the product of pulse length and PRF), which causes solid-state radars to rely on waveforms with large duty cycles to provide commensurate "energy on target." It must be kept in mind that, currently, solid-state amplifiers represent a small minority of the total number of operating systems. They do, however, offer much scope for improved spectral control.

There are many different types of radar with widely varying power levels, bandwidths, and spectral characteristics. A small number of generic examples are listed in Table 2.

IV. ISSUES WITH SPECTRUM ALLOCATION FOR RADAR

The electromagnetic spectrum is becoming increasingly more congested as a result of rapid expansion by the commercial wireless industry and other RF applications. This

TABLE 2 Examples of Generic Radar Types and Their Transmitters (See Also [6])



Radar Band	Radar Role	Transmitter type	Peak Power/ Mean Power	Pulse bandwidth	PRF	Duty Cycle
X	Airborne maritime reconnaissance	Traveling Wave Tube (TWT)	50 kW/500 W	10 MHz – 100 MHz	300 Hz – 2 kHz.	0.01
Ku	Small airborne synthetic aperture radar (SAR) or Ground Moving Target Indication (GMTI) radar	TWT or solid state Microwave power module	100 W/25 W	10 MHz – > 1 GHz	1 – 5 kHz	0.25
S	ATM	Solid State	15 kW/1.2 kW	1 MHz	1 kHz	0.08
X	Marine Radar	Magnetron	10 kW/10 W	10 MHz	1 – 2 kHz	0.001
X	Fast jet radar	Active electronically scanned array (AESA)	5 kW/1 kW	1 MHz – 100 MHz	1 – 10 kHz	0.1 – 0.2

has been and continues to apply ever-greater pressure on the parts of the spectrum formerly reserved exclusively for radar. Consequently, as radar frequency allocation dwindles and assigned bands narrow, spectral crowding and deleterious effects of OOB leakage further compound this severe and growing problem. With more commercial users occupying spectrum previously assigned exclusively to the radar community and with guard bands disappearing, spurious emissions from consumer electronics are causing increased in-band interference in a multitude of airborne and ground-based radars. The demand for wireless access (particularly wireless video and data services) is increasing at an accelerating rate, further eroding the spectrum allocation assigned to radar applications, and is part of a trend that has roots going back over more than 30 years.

The issues of spectrum congestion and competition with radar by other services currently arise mainly in the frequency bands below 5 GHz (C-band). In the higher frequency bands, the use of bandwidth is still strictly regulated to prevent interference, especially to critical services such as airport surface movement radars and radio navigation systems. Since its inception in the 1950s, HF radar has always competed for spectrum with the primary users of HF communications and the amateur radio world. Since the late 1970s, the world's communication industries have shown greater interest in the UHF part of the spectrum and, in 1979, the World Administrative Radio Conference (WARC) decided to downgrade the primacy of radar in portions of the UHF band, specifically 420–430 and 440–450 MHz, to secondary status. In the language of spectrum management, downgrading to secondary status means that radars can operate only as long as they do not interfere with primary users. Over the last ten years, wireless industries have lobbied their member nations within the ITU to downgrade radar in the 3.4–3.7-GHz band to secondary status as well. Currently, the big competitor for the 3.4–3.7-GHz band is fourth-generation (4G) wireless communications [worldwide interoperability for microwave access (WiMAX) or long-term evolution (LTE); though all indications are that the latter will dominate].

As a more specific example, the UK, coordinated through the communications regulator, Ofcom, is examining the allocation of frequencies between 2.62 and 2.69 GHz to facilitate an expansion of WiFi services. This sits very close to the radar allocation at S-band that spans 2.7–3.1 GHz. S-band is predominately used by air traffic management and air defense radar systems. To determine the viability of such a move, the U.K. Government departments such as the Department for Culture, Media and Sport (DCMS), the Department for Transport (DfT), the Ministry of Defence (MOD), and the Civil Aviation Authority (CAA) supported by Ofcom have been working together to help radar operators make their systems more resilient to interference from interference due to emitters in the 2.6-GHz band. Studies have shown that OOB emissions will significantly degrade radar performance, reducing the maximum detection range [7]. However, they also show that a combination of moving up the frequency band and improving receiver filter design can mitigate this interference. Thus, although this effectively reduces the band allocated to radar, performance can still be maintained even in important safety critical applications such as air traffic management.

A. Spectrum Regulation

An important part of spectrum management is how frequency use and emissions are regulated (see [1] for a broad perspective on spectrum regulation). For radar, regulation is particularly complex due to the variety of different radar modes, their necessary power outputs (which dictates the nature of the specific transmitter), and the induced spectral emissions. Many, but not all, countries adopt ITU emission standard. In the United States, emission standards are determined by two organizations: the National Telecommunications and Information Administration (NTIA), the governing body for all U.S. federal government spectrum use; and the U.S. Federal Communications Commission (FCC), the regulatory authority on spectrum use by nonfederal entities like the commercial broadcasting industry. The ITU has published their manual of radio regulations since the dawn of wireless in 1906. Today the regulations cover the frequency range from 9 kHz to 1000 GHz for 40 different radio services, including radar (which falls under the classification of radiodetermination or radiolocation services), in a 1000+ page publication [7]. These regulations can only be changed by the WRC.

Within the ITU guidelines, provisions are made for the computation of emission masks that delineate OOB emissions that emissions from a real transmitter have to sit within. For example, Fig. 2 shows a typical emission mask that might be applied to a radar transmission. Broadly there is a band over which the radar is designed to

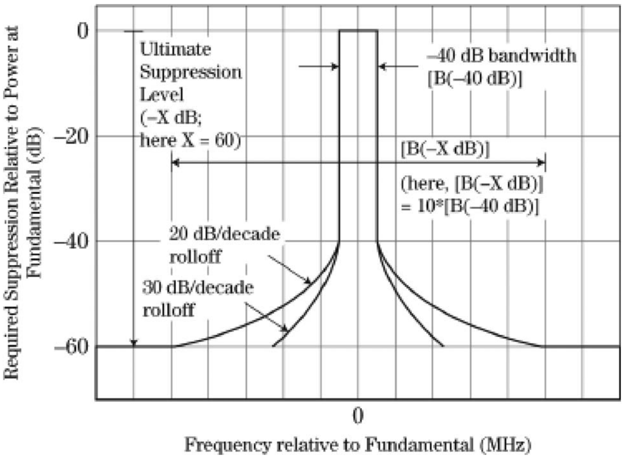
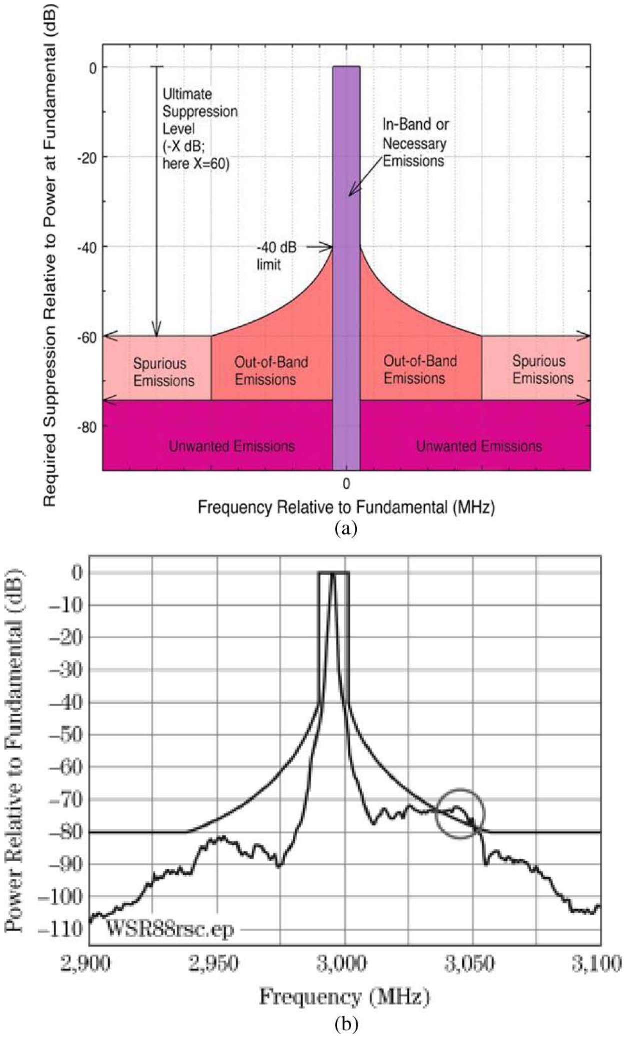


Fig. 2. ***Graph of a generic ITU spectral mask showing permissible regions of operation for differing rates of spectral roll-off [9].***

transmit that is fixed in frequency and goes down to −40 dB from the peak. Outside of this, at lower emission levels, various "roll-off rates" could be applied. Figure three shows two examples, one at a roll-off rate of −20 dB/decade of frequency and the other at −30 dB. A roll-off rate of −20 dB/decade is the current standard while 30 and 40 dB/decade is only under consideration. The radar emissions have to sit inside a mask whose power versus frequency shape of the mask is determined by the regulatory bodies. The shape of the masks has significant implications for radar design and performance. While lessening the potential for adjacent band interference to other services, a 40-dB/decade roll-off rate poses extreme challenges to the radar designer due to the intrinsic spectral spreading that results from pulsed operation combined with the requirement for high transmit power which tends to drive the use of tube technology and its subsequent limitations (i.e., nonlinear distortion in the form of intermodulation products).

In the United States, the NTIA publishes a guide: "Manual of Regulations and Procedures for Federal Radio Frequency Management," better known as the Red Book [10]. Of most relevance here is Chapter 5.5, wherein the radio spectrum engineering criteria (RSEC) are defined. In the RSEC, radars are divided into five classes, A through E. This partition considers such factors as frequency coverage, peak power output, type of waveform (pulsed versus nonpulsed), and functionality (wind profiler, etc.). The RSEC determines a spectral mask based on a 40-dB bandwidth with roll-off rates that are calculated with equations according to the criteria specified in the five class designations. Fig. 3(a) shows a generic example of an RSEC mask. The desired in-band radar emissions are contained within the 40-dB bandwidth as shown, with a subsequent allowable roll-off at today's −20 dB/decade down to a lower limit requirement of −60 dB at all other frequencies. The radar transmissions should not exceed the limits implied by this mask but unwanted emissions often occur. Unwanted emissions from a radar transmitter are composed of OOB and spurious components. These are generated by nonlinearities that occur within the transmitter together with the steep rise and fall times of the radar pulses. Fig. 3(b) shows an example of a radar emission relative to the RSEC mask for the current roll-off rate of 20 dB/decade. The radar operates in S-band with a transmitted signal that is designed to emit between 2990 and 3000 MHz only. Note that the radar emission is only marginally out of compliance in the upper sideband, i.e., it exceeds the value set by the mask. This requires modifications to be made to the transmitter so that it can meet the requirements demanded by the mask. There are potential methods to better control radar emissions, and these are discussed in more detail in Section VI. However, the effects of such a transgression on the performance of, say, a communication system operating in an adjacent band are unclear but will be a function of waveform and signal processing.



(a)

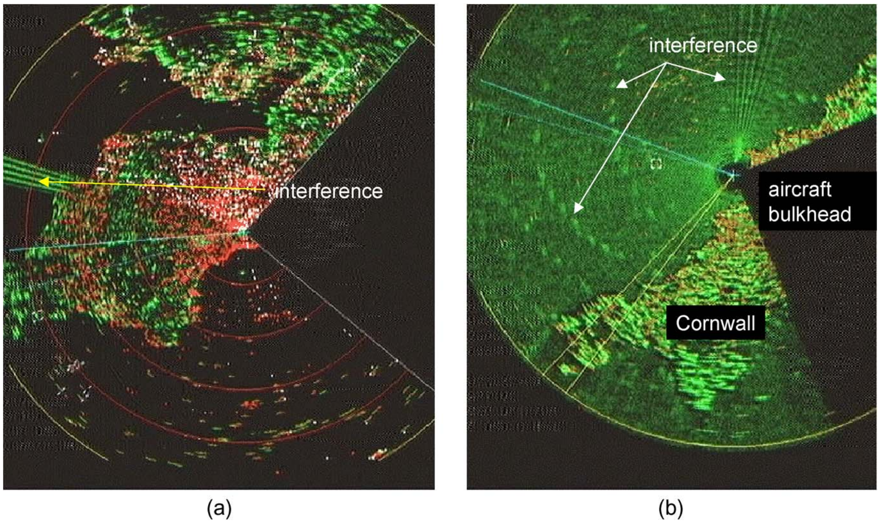
(b)

Fig. 3. ***(a) RSEC emission mask showing the signal domains and their permitted relative levels [8]. (b) Example showing a measured emission of an unmodulated pulse from a weather surveillance radar within the RSEC box. At around 3050 MHz the emission exceeds the allowable limit for the signal domain [8].***

V. EFFECTS OF RADAR INTERFERENCE ON OTHER USERS

A. Radar-to-Radar Interference

Most radars currently in service operate in a pulsed mode, with rotating antennas having narrow transmit and receive beamwidths and low spatial sidelobes. These features help to protect against interference from other radars. Any significant interference will tend to occur when the two radar beams are aligned, which is usually only for a short period of time. The pulsed nature of the systems also means that unless the PRFs of the two radars are synchronized, the interference will be suppressed in the receive signal processing. Given these features and the relatively small number of radars in a local area, it has in



(a) (b)

Fig. 4. ***Interference to an X-band airborne radar using pulse-to-pulse frequency agility. (a) High duty cycle or CW interference. (b) High and low duty cycle interferences.***

the past usually been possible to minimize radar-to-radar interference by careful allocation of operating frequencies and control of geographical location. For those radars employing traditional plan position indicator (PPI) detection displays, human operators are very good at identifying and addressing interference issues. Examples of interference observed on the PPI display of a noncoherent airborne radar are shown in Fig. 4. The green-colored plots on the PPI are an overlay of relatively unprocessed radar returns (the "raw" radar returns), which show the presence of clutter and interference before the main radar detection processing is applied. The radar was using pulse-to-pulse frequency agility. In Fig. 4(a), some high duty cycle or CW interference can clearly be seen. This interference is manifested as distinct spokes as only certain frequency channels in the radar receiver are affected. The interference is also only seen in the main antenna beam and near sidelobes as the radar scans past the interfering signal. Some similar interference can also been seen in Fig. 4(b). Also seen in this image is a spiral of pulse-like returns. This would have been due to another pulsed radar having a low duty cycle with a PRF similar to that of the radar being interfered with. In this case, the interference must have been entering the radar through the antenna sidelobes, because it is visible at all azimuth angles over the display. For a modern high-performance radar with advanced adaptive detection processing, such interference might not result in false detections. This is because the radar will be able to sense the interference and raise its thresholds accordingly. However, this in turn would reduce the sensitivity of the radar in the vicinity of the interference, making it difficult to detect smaller targets. Such effects can be quite insidious, with the radar losing performance without this being obvious to the operator.

In some circumstances, multiple radars may need to operate in the same narrow frequency band and in close proximity. One example is civil marine navigation radars on ships. For such systems, techniques of "de-fruiting" have been developed that allow for small adjustments to the radar's PRF and thereby reject signals that are not synchronous. In other systems, such as air traffic management radars, interference is avoided by very careful control of frequency allocations, very good front–end receiver filtering and, if interference is unavoidable, techniques such as sector blanking.

For some modern radars, where detections are processed without the oversight of a radar operator, interference may be more problematic if not properly addressed during the radar's design. Modern radars may also have reduced front–end frequency selectivity as a consequence of the need to operate over a very wide frequency bandwidth (e.g., >1-GHz bandwidth at K_u-band). In such cases, mitigation of interference by frequency planning is not usually possible within the constraints of the allocated bands. Where interference is likely, sophisticated coordination techniques will be required to operate the radars. In addition to the lack of selectivity when operating over wide bandwidths, radars are increasingly required to detect ever-lower signal levels (i.e., enhanced sensitivity). This requirement has led to the development of very low noise level front–end amplifiers, which often lead to a reduced dynamic range in the receiver and can result in saturation by large signals, including interference from within the band or from adjacent bands. Mitigation of this effect will predicate very careful front–end design and the development of highly linear components and filters with sharp responses.

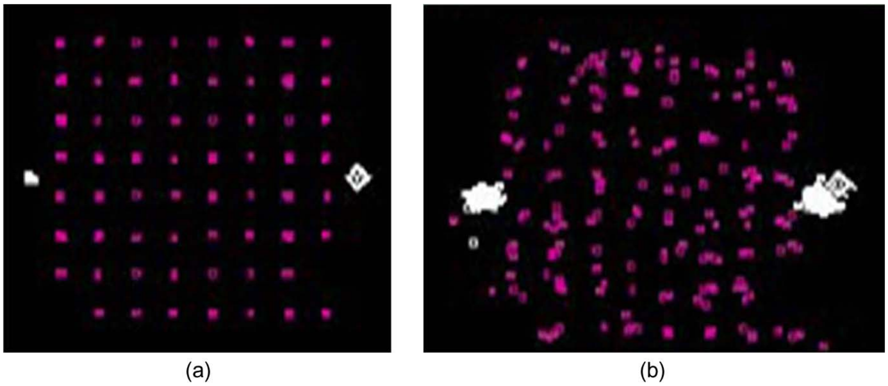


Fig. 5. *Sixty-four-QAM constellation (a) with no interference; and (b) with interference from an S-band radar.*

B. Radar Interference to Other Systems

Various cases of interference by radars with commercial electronic equipment have been reported from time to time. Examples include automatic teller machines (ATMs), satellite and terrestrial television receivers, and hearing aids. Sometimes, this is a problem of poor electromagnetic compatibility (EMC) design where improved screening and filtering within the victim equipment would mitigate the interference. However, even with the best EMC design, some problems may be unavoidable and such interference may well increase in the future without careful spectrum planning.

C. WiMAX and LTE Communication Systems

Wireless communications, particularly the push for 4G systems, is driving much of the worldwide pressure for spectrum. These 4G systems, based on either the LTE or WiMAX standards, rely on orthogonal frequency-division multiplexing (OFDM) and have variable modulation types [4, 16, and 64 quadrature amplitude modulation (QAM)] depending on channel conditions and required data rates. While the growing number of mobile users plays an important role in this demand for spectrum, it is really the proliferation of bandwidth-hungry streaming video that is the driving factor. The LTE and WiMAX systems operate in some spectrum currently used predominantly by radar. With the availability of inexpensive RF and signal processing chip sets in S-band (specifically 3.4–3.7 GHz), the wireless community has become a competitor to radar in this band. The potential for radar to interfere with LTE and WiMAX is significant. Fig. 5 illustrates a 64-QAM WiMAX constellation before [Fig. 5(a)] and during [Fig. 5(b)] interference from an S-band radar, measured in a bench test [11]. It is clear that, in the presence of radar interference, the ability of the WiMAX receiver to recover the transmitted symbol is severely degraded.

VI. CONTROLLING RADAR EMISSIONS

To sense the environment effectively, a radar must extract the reflected target echoes from noise and interference. Due to the two-way path loss, achieving sensitivity to the echoes from long-range scatterers necessitates the transmission of much higher energy than other spectral users that are subject only to one-way path loss. Furthermore, to resolve scatterers that are closely spaced in range, the radar emission must possess a high bandwidth (range resolution and bandwidth are inversely proportional). This high bandwidth emission could, in principle, be achieved via an extremely high-power pulse of short duration (commensurate with the range spacing of the scatterers to be resolved). However, it is generally far more practical to emit a longer pulse of lower power (albeit still quite high relative to "one-way path loss" users) that is phase/frequency modulated (the waveform, as discussed in Section III). This latter instantiation is known as pulse compression and can be viewed as a form of spread spectrum operation [the example of a linear frequency modulated (LFM) waveform is shown in Fig. 6]. While the lower peak transmit power enabled by pulse compression is obviously beneficial from the perspective of radar hardware requirements and the reduction in interference to other spectral users, it also involves a tradeoff with respect to sensitivity for the radar as the "range sidelobes" induced by filtering the transmitted waveform on receive generates a form of self-interference with which the radar must contend (see Fig. 7). As such, a topic of ongoing scrutiny within the radar community has been the

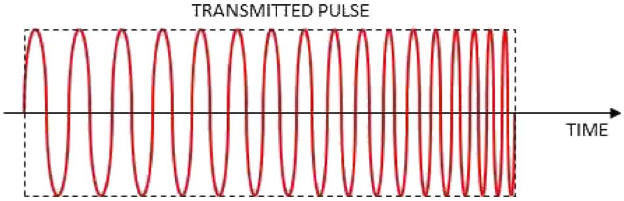


Fig. 6. *LFM radar waveform; in this case, an "up-chirp" since the frequency sweeps higher during the pulse.*

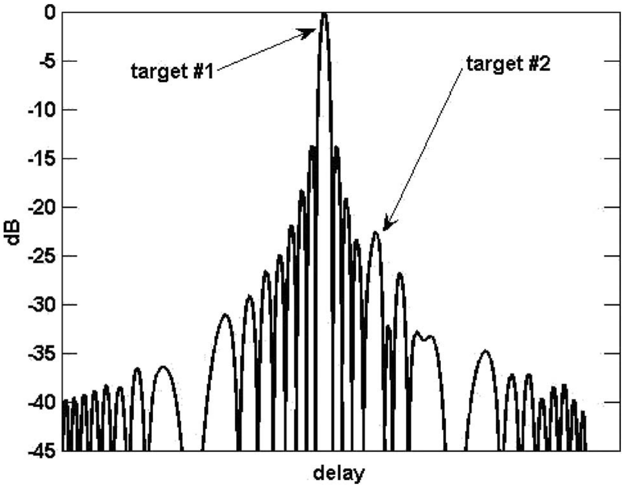


Fig. 7. ***Pulse compressed LFM waveform reflected from two targets that have disparate radar cross sections; it is desired that this range domain filter response to the transmitted waveform provides sufficient range resolution (narrow mainlobe) with minimal SNR loss and low range sidelobe levels to separately identify high dynamic range targets in close proximity to one another. These effects are determined by the design of the waveform and the pulse compression receive filter.***

development of optimal waveforms and receiver filters that minimize these range sidelobes. Therefore, any modification of the radar emission to address spectral containment must likewise consider the impact such a change would have on the pulse compression range sidelobes, and thus radar sensitivity. It is also important to note that, for FM-based waveforms which are commonly used in practice, a prominent attribute inducing spectral leakage is the pulse shape. A pulse envelope with fast rise and fall times will introduce a wider spread of frequency sidebands than the one with slow rise and fall times. However, as discussed earlier, operating with significant amplitude modulation on the pulse will reduce the power efficiency of the amplifier, which will deliver maximum power when the signal is in saturation. For an LFM waveform with a pulse width of 64 μs and a rather modest time-bandwidth product of 64, Fig. 8 illustrates the spectral content of the waveform by itself (in blue) and with the inclusion of the pulse envelope. Clearly the rise/fall time of the pulse has a significant impact on spectral content, though the seemingly easy fix of "slowing down" the rise/fall time is easier said than done, given the requirements on the transmitter hardware to achieve the high-power necessary to contend with two-way path loss and the associated loss in power efficiency that would be incurred.

Within the trade space of radar performance and cost, there are multiple existing approaches to limit the interference that radar emissions may induce upon other spectrum users. If the radar observes another in-band (or near-band) user, frequency avoidance can be employed to hop to another unoccupied frequency band (as long as such allocations are available). With some loss in transmitted power (and thus sensitivity), a bandpass filter could also be placed after the power amplifier at the output of the transmitter to suppress the OOB emissions [12]. However, for radars that employ frequency agility, such a filter would need to change its bandpass characteristics according to the operating frequency, thereby significantly increasing design complexity and cost. Alternatively, interference subtraction of OOB emissions could conceivably be realized by generating a replica of the OOB spectral components produced by the power amplifier and then subtracting this replica from the actual high-power emission prior to launching from the antenna [13]. The limitation of this approach is the calibration accuracy with which these OOB replica components can be obtained and subtracted [14]. For radars such as foliage penetration systems in which the necessary wide bandwidth and relatively low operating frequency (VHF/UHF) precludes complete avoidance of other in-band users, the radar emission must possess spectral gaps of sufficient depth and width to minimize the induced interference to other users. Of course, these modifications to the emission structure come at the price of significant degradation in sensitivity due to greatly elevated range sidelobes [15]. Likewise, to the degree that it is possible to characterize accurately the nonlinear aspects of the transmitter (primarily the power amplifier), inversion of this characterization may facilitate the use of predistortion techniques for linearization, as discussed in [13]. All of these techniques remain topics of continued investigation.

VII. RADAR SUSCEPTIBILITY TO INTERFERENCE

A typical radar, such as a primary surveillance radar used for air traffic control, may have a peak pulse power from the transmitter of 20 kW and an antenna with a directive gain of 30 dB, yielding an effective radiated power (ERP) of 73 dBW. However, the power levels detected in the radar receiver are expected to be noise limited, while the echo power from a distant target may be of the order of −110 dBW. In order to achieve the maximum detection performance for a given transmitter power, the radar will aim to achieve the best possible receiver sensitivity. It will usually be more cost-effective to improve the receiver sensitivity rather than attempting to increase the transmitter power by the same margin. For this reason, long-range radars will usually employ ultralow noise amplifiers at the receiver front–end.

For many applications, radar receivers have traditionally been designed on the assumption that the radar is the exclusive user of its allocated frequency spectrum and that performance will be limited by thermal noise in the receiver. It was assumed that interference from other radars in the same band could usually be managed by careful frequency

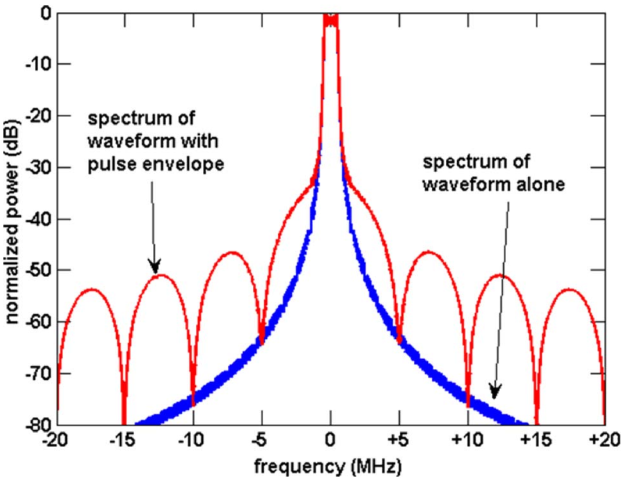


Fig. 8. ***Spectrum of an LFM waveform without the pulse envelope (blue) and with the pulse envelope (red). The pulse rise/fall time, which is very fast due to the switching nature of high-power amplifiers, has a significant impact on spectral content.***

planning and site selection for ground-based radars (see also Section V). With increasing demand for spectrum, there is growing potential for interference from other users, either those sharing the same frequency allocation or from those occupying adjacent frequencies. The effect on radar performance of interference from different sources can be quite complex to define. For example, a study of this problem was reported in [16]. This report concluded that interference at low duty cycles, such as from other radars, can often be sustained at interference-to-noise (I/N) levels as high as 30–60 dB without degrading the receiver performance (i.e., its ability to detect small targets). An example of the effects of such interference on a radar display can be seen in Fig. 5. Interference at higher duty cycles (above 1%–3%), such as from most communications signals, can cause target detection losses to begin at I/N levels between −10 and −6 dB, dependent on radar type. It was noted in [16] that the loss in performance may be very insidious. No obvious effects may be visible on the radar display but nevertheless target detections may be lost.

An area of current concern to radar users is the allocation of spectrum to communication systems, such as WiMAX and LTE, in the 2500–2690-MHz band. This band is immediately adjacent to the radar allocations for air traffic control (ATC) radar, 2700–2900 MHz, and maritime radars, 2900–3100 MHz. Also, the U.S. National Weather Service (NWS) Next Generation Weather Radars (NEXRAD) operate in the 2700–3000-MHz band. It has been found that OOB signals (i.e., the spectral sidebands) from WiMAX base station transmitters can at times cause cochannel interference to radar users in adjacent bands. Equally, the OOB response of typical ATC and maritime radar receivers, which had not been designed to cope with adjacent band signals of this sort, may also render then susceptible to interference. These problems have been found to occur even though both the radars and WiMAX base stations are compliant with the appropriate national EMC standards.

This problem has been widely investigated by national regulatory authorities. In the United Kingdom, Ofcom has undertaken its own studies and commissioned independent research, including the effects of radar transmissions on adjacent WiMAX systems. This has resulted in a proposed S-band remediation plan [17]. One outcome from this work has been to show that front–end filtering (e.g., a low-loss passive bandpass filter in the main antenna feed) in the radar receivers can considerably reduce the effects of high-power adjacent communications systems, without discernibly degrading radar performance.

In the United States, studies have been undertaken by the NTIA Institute for Telecommunications Sciences (ITS) [18]. These studies investigated sources of electromagnetic interference (EMI), how EMI is manifested within the radar receiver, and what technical solutions could be taken to mitigate the effects. In particular, it was found that the NEXRAD radars were susceptible to interference from WiMAX. The NTIA investigation quantified power levels of the interference in NEXRAD receivers under different conditions. It also assessed the amount of decoupling required to reduce the observed interference levels to a noninterference level, together with the amounts of decoupling required to mitigate the interference for various frequency and spatial separations. Because the interference is partly cochannel, the application of additional filtering (see discussion above) within the radar receiver will not totally eliminate the WiMAX EMI. Further mitigating procedures include careful local frequency planning (with a local frequency coordinator or manager to maximize the frequency differences between WiMAX transmitters and radars), management of the vertical beam angles of WiMAX base stations, and control of WiMAX antenna locations and heights.

Radars will increasingly have to coexist with other users. This necessity will require improvements to radar designs to minimize the effects of interference, together with careful frequency and site planning.

VIII. EMERGING TECHNOLOGY DEVELOPMENTS

Beyond those technology developments already discussed, pervasive spectral congestion will force future radar capabilities to rely increasingly upon emerging technologies in the areas of passive radar, waveform diversity, bioinspired design, and cognitive processing. These are areas of current research and, therefore, we can only speculate as to the impact and role they may have in helping to use the spectral resource more efficiently. Here we introduce these concepts to illustrate their potential utility.

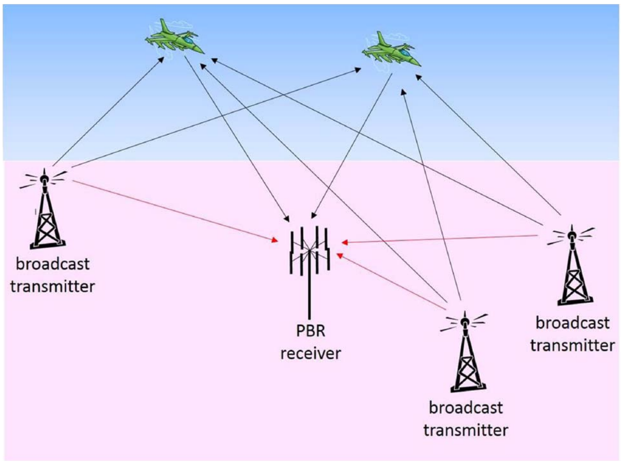


Fig. 9. *Passive bistatic radar.*

A. Passive Radar

Passive radar (or passive bistatic radar) is the name used to describe radar that exploits other transmissions (communications, broadcast, or radionavigation) rather than having its own dedicated radar transmitter. The passive receiver is thus located separately from the transmitter (see Fig. 9). Since such transmissions are often high power and favorably located within geographical regions of interest, the coverage of such passive sensing systems can be substantial. Further, the cost of the transmitter is avoided, making the system relatively inexpensive, and the receiving system may be completely undetectable, which may be advantageous for defense applications. Despite these attractive characteristics, since the waveforms are not fundamentally designed for radar purposes, and are often time varying, performance in a radar context can be far from ideal. In addition, it is necessary to choose the right waveforms present in the environment and to process them in the correct way [19]. It is generally necessary to have one antenna dedicated to acquiring the direct path signal from the selected emitter and another separate antenna, having a spatial null, or at least little gain, in the direction of the direct path emitter, from which the radar reflections are acquired. The direct path signal therefore serves as the reference waveform for pulse compression filtering of the reflected echoes.

It is important to note that passive radar is fundamentally different from radiometry, though both share the trait of operating in a passive manner. Radiometry performs remote sensing of physically separated sources like Earth (from a satellite) or astronomical objects, usually to extract various parameters regarding scientific phenomena such as temperature and moisture. In contrast, passive radar measures the scattering of signals from various objects of interest, albeit by leveraging the emissions from other RF/microwave sources such as radio, television, other radars, etc. In other words, the purpose of passive radar remains the same as that of active radar; the main difference is that the former has no control over or prior knowledge of the sensing waveforms.

Passive radar has attracted a great deal of research interest over the past decade, and numerous experimental systems have been built and demonstrated [20], [21]. These include systems based on FM radio, analog and digital television transmissions, cell phone base stations, HF shortwave broadcasts, and satellite GPS transmissions. It has been found that signals with digital modulation formats are more suitable for passive bistatic radar since the waveform is more noise-like and the performance does not depend on the type of modulation (for example, speech or music). These types of system have demonstrated detection and tracking of aircraft to ranges beyond 200 km [22], with Lockheed Martin [23] THALES [24], and Selex having developed commercial systems. However, it is difficult to guarantee performance levels, and, hence, they tend to be viewed more as a supplement to existing radar systems. Whether bistatic radar can be developed to take on the role of a primary sensor is far from certain.

Taking this further, it may also be desirable in the future to design the signals of passive bistatic radar illuminators so that they not only fulfill their primary function but also have favorable waveform properties for radar purposes. This has been termed "commensal radar"—literally "at the same table"—and is an example of the sort of approaches that will be necessary as the spectrum problem becomes worse.

B. Waveform Diversity

It is possible to use emissions far more efficiently than is currently the case. Modern digital technology means that it is now feasible to generate precise, sophisticated wide-bandwidth radar waveforms that can be varied, potentially even on a pulse-by-pulse basis. This capability forms the foundation for what has become known as "waveform diversity" [25], which includes the optimization of waveforms based on mission requirements and prior knowledge of the spectral environment; greater exploitation of available degrees of freedom for both transmit waveform design and receive filtering; and the general convergence of electromagnetic, systems engineering, and signal processing requirements and capabilities.

For example, it is possible to design radar waveforms that have spectral nulls at particular frequencies or frequency bands [26], [27], and potentially even to adapt these waveforms dynamically in response to a changing interference environment (the latter being an example of a cognitive system). Likewise, recent schemes [28] for the implementation and optimization of polyphase-coded FM (PCFM) waveforms based on the continuous phase modulation (CPM) framework demonstrate new avenues for the design of radar emissions with enhanced spectral containment. These latter techniques also highlight the prospective benefits to incorporating system-level effects such as

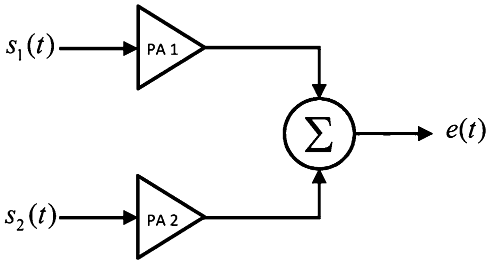


Fig. 10. ***Two constant amplitude, continuous waveforms are driven into separate saturated power amplifiers (needed for high power efficiency) and then combined in the 180° coupler sum channel. Their relative phases control the amplitude of the resulting emission $e(t)$. A difference channel (not shown) collects the power that is not radiated into a terminated load.***

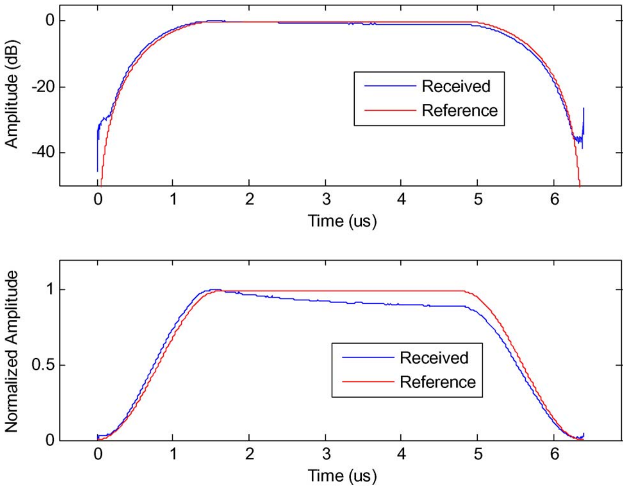


Fig. 11. ***Pulse envelope of measured (received) and theoretical reference $e(t)$ in the decibel scale (top) and normalized amplitude (bottom). In the decibel scale, the impact of imperfect channel calibration is revealed at the beginning and end of the measured pulse, while some amplitude droop is observed in the normalized amplitude scale.***

transmitter distortion directly into the waveform design process (as opposed to performing predistortion after the fact). Such hardware-in-the-loop design schemes enable a holistic view of the radar so as to address jointly the waveform performance and its actual emitted spectral footprint.

A particular open problem with regard to radar emission control is the spectral spreading induced by the rapid rise time and fall time of each transmitted pulse. High-power transmitters do not presently have a means to "slow down" the rise/fall time as they behave more like a switch that is either on or off. Furthermore, any action taken to alter the spectral content of the radar emissions also directly impacts the waveform structure and, by extension, radar sensitivity. Within this context of holistic, hardware-in-the-loop design through the use of linearization techniques [14], it may potentially provide a means to slow down the rise/fall time. For example, using the 180° coupler approach depicted in Fig. 10, which is a form of outphasing [13] otherwise known as linear amplification with nonlinear components (LINC), it was recently shown [29] that a pulse amplitude tapering can be obtained (see Fig. 11) while still operating the power amplifiers in saturation. The resulting improvement in spectral containment (Fig. 12) demonstrates about 15-dB improvement in spectral containment, though issues such as heat management (from the power not emitted), calibration, and signal-to-noise ratio (SNR) losses remain open issues.

Besides the LINC approaches, there are many more forms of linearizing methods for power-efficient operation, including the Kahn technique, envelope tracking, the Doherty technique, feedback and feedforward linearization, and others with new techniques continuing to emerge (see [30] and references therein for a detailed discussion of linearization methods). Generally speaking, these methods rely on a combination of two or more amplifiers that focus on specific attributes of the signal being amplified and digital signal processing (DSP) to separate the signal into the requisite components. Clearly, joint research is needed at the intersection of advanced transmitter configurations and radar waveform design to address the demands on radar spectral containment. For the radar application, additional considerations include ensuring high fidelity (to minimize mismatch-inducing distortion that degrades sensitivity, where the dynamic range may be several tens of decibels), achieving sufficient energy on target (minimal deviation from maximum power to maintain receive SNR), and operating with bandwidths of tens to hundreds of megahertz or more (many linearization methods require switching frequencies that are several times the operational bandwidth).

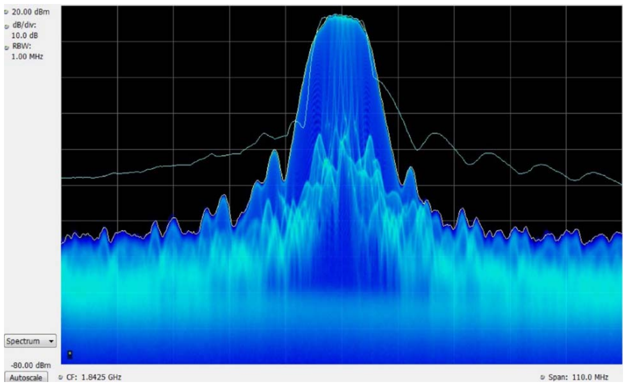


Fig. 12. ***Spectrum of a nonlinear FM (NLFM) waveform optimized for a standard transmitter architecture (higher trace) and optimized specific to the hardware in the LINC architecture (shaded spectrum), where the latter slows down the pulse rise/fall time while using saturated power amplifiers. Vertical increments are 10 dB.***

The increase in interference encountered by the radar may be addressed in part by expanding the purview of adaptive interference cancellation to incorporate additional degrees of freedom. For example, an airborne radar performing ground moving target indication (GMTI) will use the echoes collected from M pulses at N antenna elements to construct an adaptive filtering structure that operates jointly in the spatial and Doppler domains so as to suppress interference from ground echoes (i.e., clutter) and possibly jamming (otherwise known as space–time adaptive processing (STAP) [31]). Instead of being additive as $M + N$, this joint filtering approach provides $M \times N$ adaptive degrees of freedom for interference cancellation. By extension, ongoing research efforts are exploring how the different dimensions of range (the waveform domain), space, Doppler, polarization, and frequency can be combined to facilitate greater design freedom on transmit (e.g., [32]–[37]) and interference suppression capability on receive (e.g., [38]–[40]). Furthermore, leveraging the publicly available knowledge of different RF systems (e.g., wireless communication standards [41]) and their defined signal structure across these different dimensions could also enhance the radar's ability to contend with unintentional spectral encroachment.

C. Bioinspired Design

With many million years head start, it is no surprise that echo-locating animals such as bats and dolphins far surpass our active sensing capabilities [42]. For example, bats use sonar to sense, navigate, and communicate in a simultaneous manner through the same transmit aperture (their mouth) and possess only a two-element antenna array on receive (their ears) and yet can successfully hunt for food in a large swarm of other bats while not colliding with their environment or each other. Clearly bats leverage a very advanced form of waveform diversity that encompasses a form of simultaneous multimode emission coupled with very sophisticated and highly specialized receive signal processing [43], [44]. A bat can change the nature of this emission according to the particular information being sought (e.g., searching for available prey versus tracking specific prey) while dolphins exploit a form of pulse-to-pulse waveform diversity to distinguish linear scattering from nonlinear scattering [45], [46] (which proves useful in bubble-rich shallow waters). Likewise, bats may leverage echo location as a form of echoic flow for navigation [47], [48] in a manner similar to how other creatures use optic flow to navigate by vision. Further, while radar signal processing is linear and becoming predominantly digital, biological cognition, to the degree that it is actually understood, is clearly analog and considered to be rather nonlinear. Finally, the potentially useful lessons to be learned from nature regarding radar are also not solely limited to biosonar, as evidenced by recent work to mimic the rapid movements of the human eye [49] (a passive sensor) as means to achieve spatial modulation for active radar emissions [50].

From a spectrum usage standpoint, the key takeaway from observing nature is that the animal kingdom can far surpass our best technological capabilities and yet do so with what appears to be rather nonoptimal "equipment" [51], at least when taken componentwise. Nature takes the notion of "the whole being better than the sum of parts" to an extreme we still cannot fully comprehend. So the lesson to be learned is that we too must take a holistic view when designing systems so that the individual "components" of electromagnetic, systems engineering, and signal processing work in harmony, both within a given radar system and in its interaction with all other spectrum users. For example, codesign of the radar transmitter and waveforms may minimize the amount of spectral leakage while still optimizing mission requirements for search, tracking, and imaging modes. Furthermore, taking a Baldwinian evolutionary perspective [52], it is also clear that systems must be designed specifically for the spectral environment in which they will operate, which in turn results in further shaping of that environment. Factoring in the exorbitant cost of deploying new radar systems, we also must be cognizant of the tradeoff between niche-optimized systems and being sufficiently flexible to adapt when the environment or need changes.

D. Cognitive Approaches

The notion of cognitive radar can be viewed from two different perspectives: as the evolution of bioinspired control systems to higher level decision making [53], [54] or as the natural outgrowth of knowledge-aided sensor signal processing [55]. Regardless of its roots, in the most general sense, cognitive radar is essentially the application of Bayesian learning, through the use of prior knowledge and feedback, to facilitate the development of autonomous decision making within the radar.

If prior knowledge of the spectral environment exists, it can also be exploited. This approach has enabled cognitive radio to make great strides in recent years. However, cognitive radio has tended to concentrate on radio communication rather than considering the problem in its entirety. A more comprehensive approach would be to map out spectrum usage in terms of spectral, temporal, and spatial occupancy of all emitters and exploit this total "spectral landscape" in cognitive-type approaches. This perspective would enable cognitive approaches to embrace all emitters in an intelligent fashion. For example, most radar systems scan at a rate of less than one rotation per second. Most power is concentrated in the main beam whose width may only be a few degrees. Thus, at any one time, the vast majority of the swept volume (typically 90%) is not being used by the radar. As this operation is fully determinable in advance, there is considerable opportunity for further improving spectrum usage and possibly spectrum sharing. This form of approach clearly offers efficiency gains in spectrum use without sacrificing performance, thus making it an attractive topic of future study.

Existing radar procedures such as automated frequency agility to avoid other spectral users and dynamic time-division resource allocation to enable different sensing (and possibly other) modes to share the same antenna [56] can be considered as early examples of cognitive systems. However, ongoing research is also exploring more radical modifications such as by leveraging the burgeoning work in waveform diversity to enable the radar to design waveforms "on the fly" according to the observed spectral environment and mission requirements (e.g., [57]–[59]) through the use of complex feedback mechanisms and automated decision making. In other words, viewing active sensing as a question-and-answer exercise, how can we enable the radar to select the best questions (i.e., waveforms) so as to obtain the best answers (given the spectral usage constraints) in real time?

Besides the sensor-centric area of waveform diversity, cognitive radar research is also building from previous work in cognitive psychology and artificial intelligence to mimic our own attributes of learning, memory, attention, and intelligence [60], all with the goal of making the radar "smarter." Compared to the relative ease with which many animals can sense and interact with their environments, it is clear that we are only just beginning to realize the potential of artificial cognitive sensor systems, though continued research is necessary to quantify the likely gains that could be accrued.

IX. CONCLUSION

As with many of the facets of modern life, radar is such that most people would only become aware of its fundamental importance if it were absent. Radar enables the control and management of air traffic; it is used to monitor and track severe weather; it is a technological cornerstone for defense and homeland security; and in the not-too-distant future, it may even be integral to the establishment of networks of driverless automobiles [61]. Yet, to accomplish all of these and numerous other vital tasks, radar requires access to spectrum.

All users have a need for greater bandwidth, and the only thing that can be said with certainty is that the problem is only going to get worse. Yet, if spectrum usage were measured at a given point as a function of frequency, time, space, and polarization, it would certainly be found that the spectrum is currently not being used efficiently. Therefore, there is great potential for approaches aimed at using the spectrum in an efficient and dynamically controlled manner.

The regulatory framework has thus far taken a relatively conservative approach. However, it is important to have a proper quantitative understanding of the effect of interference of one service upon another in order to adopt appropriate regulation measures, rather than taking the view that no service should ever occupy the same part of the spectrum as any other.

A number of novel radar technology approaches have been described, including improvements to the spectral purity of transmitters; intelligent, cognitive approaches to dynamic frequency allocation; passive sensing based on the emissions of other RF applications; and even through learning to mimic the behavior of echo-locating animals. The same digital technology that has enabled the tremendous growth in communication capabilities is also facilitating a new paradigm in radar functionality, both through the generation of precise broadband waveforms and the development of new receive processing methods. As this cohabitation of the RF spectrum continues, even further advances in technology will be needed to contend with the growing congestion. ■

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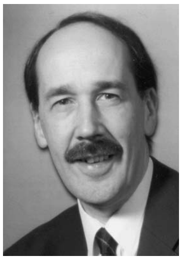

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