Coexistence Between Communications and Radar Systems: A Survey

Mina Labib[1], Vuk Marojevic[1],
Anthony F. Martone[2], Jeffrey H. Reed[1], and Amir I. Zaghloul[1,2]

[1]Virginia Tech, Blacksburg, VA, USA
E-mail: mlabib@vt.edu

[2]US Army Research Laboratory, Adelphi, MD, USA
E-mail: marko.mikkonen@aalto.fi

Abstract

Data-traffic demand in cellular networks has been growing tremendously, and has led to creating congested RF environments. Accordingly, innovative approaches for spectrum sharing have been proposed and implemented to accommodate several systems within the same frequency band. Spectrum sharing between radar and communications systems is one of the important research and development areas. In this paper, we present the fundamental spectrum-sharing concepts and technologies. We then provide an updated and comprehensive survey of spectrum-sharing techniques that have been developed to enable some wireless communications systems to coexist with radars in the same band.

1. Introduction

Billions of people rely on wireless infrastructures for communication and connectivity, to the extent that wireless communications have become a necessary part of human life. Data-traffic demand in cellular and wireless local-area networks has been growing tremendously, and has led to creating a congested radio-frequency (RF) environment. Spectrum regulators adopted the fixed spectrum-allocation policy, where bands were allocated to specific users or services. Since actual use of spectrum is way below its capacity, on average, this leads to inefficient use of spectrum. Several studies have shown that apart from the spectrum used for wireless communications, a large portion of the spectrum is quite lowly utilized [1]. Consequently, the concept of spectrum sharing has recently gained lots of interest, in order to help improve spectrum utilization. Spectrum sharing implies that two or more users (using different technologies) can share the spectrum and use it as needed and as available, without creating harmful interference to one another.

Spectrum sharing is becoming possible because of advances in cognitive radio technology, as well as more-flexible spectrum regulations and incentives to share resources. Considering the United States, for example, in June 2010, a Presidential Memorandum, "Unleashing the Wireless Broadband Revolution," was issued. The memorandum directed the National Telecommunications and Information Administration (NTIA) to collaborate with the Federal Communications Commission (FCC) to make a total of 500 MHz of spectrum available over the following 10 years for usage by wireless broadband systems, either on an exclusive-license basis or on a shared-access basis [2].

In June 2013, another Presidential Memorandum, "Expanding America's Leadership in Wireless Innovation," was issued. This urged identifying opportunities to share the spectrum that is currently allocated for exclusive use by federal agencies. This memorandum explicitly requested investigation of the possibility of either relinquishing or sharing the spectrum of the 1695-1710 MHz band, the 1755-1850 MHz band, and the 5350-5470 MHz and 5850-5925 MHz bands [3]. Consequently, the Department of Defense (DoD) issued a "Call To Action," wherein one of the objectives was to accelerate the fielding of technologies that enable spectrum sharing and improve access opportunities. One of the goals was to sharpen responsiveness to ongoing spectrum regulatory and policy changes [4].

In January 2015, the FCC completed an auction to license the 1695-1710 MHz, 1755-1780 MHz, and 2155-2180 MHz frequency bands to wireless operators. These bands are collectively called the AWS-3 (Advanced Wireless Service 3) band. Most of the federal systems will relocate to new bands, while a few systems will remain and share the spectrum with the wireless operators to which it is awarded. The auction generated more than 42 billion dollars in net profits. In March 2015, the DoD Chief Information Officer issued a brief to the DoD UAS (Unmanned Aerial Systems) summit where he indicated that spectrum access is being challenged by emerging commercial market needs, and the DoD is taking deliberate actions to advocate spectrum-sharing techniques [5]. In April 2015, the National Telecommunications and Information Administration announced a 12-month plan to cooperate with FCC and other stakeholders to study and develop sharing options that accommodate new applications and devices with the reserved 195 MHz of the 5 GHz band. Currently, this 195 MHz (5350-5470 MHz and 5850-5925 MHz) is mainly used by radar systems, and the major user of these bands is the DoD. The DoD uses this for different radar systems, which are mainly range and tracking radars, tactical anti-air warfare radar systems, navigation radars, and weather radars [6].

Radar systems are the main consumers of the frequency bands that are currently being considered for sharing in the US, such as the 5150-5925 MHz, which is called the Unlicensed National Information Infrastructure (U-NII) band, and the 3550-3700 MHz band, which is called the Citizen Broadband Radio Service (CBRS) band. Accordingly, spectrum sharing between communications and radar systems has become one of the important research and development areas. When a radar system shares the spectrum with a communications system, the interference caused to the radar can impede its correct functioning. This is because radars are not designed to coexist with communications. Communications systems are also not designed to operate with radars. Nevertheless, communications systems are easier to modify than legacy radars, because of the much shorter development and deployment cycles.

The authors in [7] provided an overview of some of the techniques that have been proposed for sharing the spectrum between radar and wireless communications systems. In this paper, we present the fundamental spectrum-sharing concepts and technologies. We then provide an updated and more-comprehensive survey of spectrum-sharing techniques that have been developed to enable some of the wireless communications systems to coexist within the same band as radar systems. The rest of the paper is organized as follows. Section 2 provides an analysis of the different radar systems that exist within the shared spectrum. Section 3 provides a general overview of the spectrum-sharing techniques. Section 4 presents our survey of the proposed spectrum-sharing mechanisms for radar and communications systems. We provide our conclusions in Section 5.

2. The Shared Spectrum: Radar Systems and Regulations

There are several frequency bands that are utilized by radar systems. They are currently considered for spectrum sharing in the US, such as Unlicensed National Information Infrastructure and the Citizen Broadband Radio Service bands. In order to emphasize the need for developing spectrum-sharing techniques for the coexistence between communications and radar systems, this section presents the different radar types within these two bands, as well as the current regulations governing these bands.

For the Citizen Broadband Radio Service band, the frequency range 3550-3650 MHz is allocated on a primary basis for federal use of both the Radiolocation Service (RLS) and the Aeronautical Radionavigation Service (ARNS) (ground-based). The Radiolocation Service radar is used by the military for the purpose of radiolocation, whereas the Aeronautical Radionavigation Service radar is used for the safe operation of military aircraft [8]. The authors in [9] analyzed the regulations governing this band.

For the 5 GHz band, there are several radar systems operating within this band:

- Radiolocation service for federal operation: The frequency range 5250-5950 MHz is allocated to radiolocation services for federal operation on a primary basis. The frequency range 5470-5650 MHz is allocated to radiolocation services for non-federal operation on a primary basis, as well. These types of radars perform a variety of functions, such as [10]:

  - Tracking space launch vehicles during the developmental and operational testing phases,
  - Sea and air surveillance,
  - Environmental measurements,
  - National defense.

- Space Research Services: Band Unlicensed National Information Infrastructure-2A and the frequency segment 5470-5570 MHz are both allocated on a primary basis to space research services for federal operation, and on a secondary basis to the space research services for non-federal operation.

- Aeronautical Radio Navigation Radars: These radars use the frequency range 5350-5460 MHz (Unlicensed National Information Infrastructure-2B). These types of radars are used for:

  - Airborne weather avoidance,
  - Windshear detection,
  - Safety service for flights.

- Maritime Radio Navigation Radars: The frequency range 5350-5460 MHz is allocated on a primary basis to the maritime radio navigation radars for both federal and non-federal operations. These types of radars are used for the safety of ships.

- Terminal Doppler Weather Radars (TDWR): The Federal Aviation Administration (FAA) uses the frequency range 5600-5650 MHz for Terminal Doppler Weather Radars to improve the safety of operations at several major airports (45 airports), as these radars provide

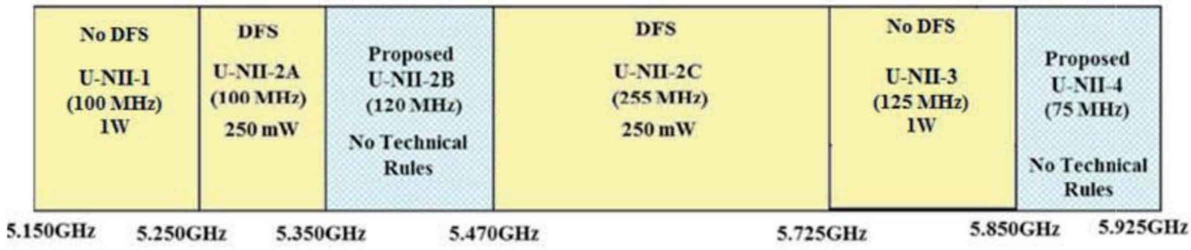

Figure 1. The 5 GHz regulations in the United States.

quantitative measurements for identifying weather hazards.

Furthermore, the DoD uses the 5 GHz frequency band for different military radar systems. The DoD radars can either operate on a fixed frequency, or can employ frequency-hopping techniques. In the past, these radars have operated on or near military installations. However, in support of homeland security, these radars may need to be deployed in urban areas, where Unlicensed National Information Infrastructure devices (commercial and industrial) will be heavily used, as is the case for today's 5 GHz Wi-Fi systems [6]. The interference issue between radar systems and the Unlicensed National Information Infrastructure devices thus needs to be addressed. These radar systems are used by different DoD agencies: the US Army, the US Navy and US Coast Guard, and the US Air Force. The major DoD radar systems operating within the 5 GHz band can be summarized as follows [6]:

- Range and Tracking Radars: These radars operate in 5400-5900MHz frequency band. During the development and testing phases of non-cooperative targets (such as rockets and missiles), these radars are used to provide accurate tracking data of these targets, and to maintain range safety.

- Weather Radars: These radars are used to determine the structure of weather hazards by analyzing the locations and the motions of several types of precipitations (i.e., rain, snow, hail, etc.).

- Shipboard Navigation Radars: These radars operate in the 5450-5825 MHz frequency range. The main function of this radar type is detecting anti-ship missiles and low-flying aircraft. These radars are also used for navigation and for general surface-search tasks.

- Airborne Sense and Avoid Radars: The US Air Force has been developing these types of radars to comply with the safety concerns of the FAA for Unmanned Aerial Vehicle (UAV) operations. The purpose of this radar is to avoid collision of the UAV by detecting and tracking other nearby aircraft. The 5350-5460 MHZ frequency range is the range that is currently considered for these radars, whereas the frequency range 5150-5250 MHz is being considered as an alternative.

The 5 GHz band falls under the FCC Part-15 regulations. The current spectrum regulations for the 5 GHz band in the US are depicted in Figure 1 [11], which identifies the maximum transmit power level allowed for devices in each subband.

Any device operating in the Unlicensed National Information Infrastructure-2A or the Unlicensed National Information Infrastructure-2C bands must employ transmit power control (TPS) and dynamic frequency selection (DFS). Dynamic frequency selection is a mechanism that is specifically designed to avoid causing interference to non-IMT (International Mobile Telecommunications) systems, such as radars. The dynamic frequency-selection requirements in the United States can be summarized as follows:

- Sensing bandwidth: The device must sense radar signals in 100% of its occupied bandwidth.

- Channel availability checking time: The device must check the channel for sixty seconds before using it.

- In-service monitoring: The device must continuously monitor the channel during operation, and must vacate the channel within ten seconds (called the channel move time) once the radar system starts transmitting. During these ten seconds, the device is only allowed 200 ms for normal transmission.

- Detection threshold: This is the received power levels when averaged over one microsecond, referenced to a 0 dBi antenna. Specifically:

  – −62 dBm for devices with maximum EIRP (effective isotropic radiated power) less than 200 mW (23 dBm), and an EIRP spectral density of less than 10 dBm/MHz (10 mW/MHz)
  – −64 dBm for devices that do not meet the above requirement for relaxed sensing detection.
- Detecting radar: once the radar has been detected, the operating channel must be vacated. The device must not utilize the channel for thirty minutes, which is called the non-occupancy period.

The FCC has identified six different radar waveforms that need to be used for testing the Unlicensed National

Table 1. Radar test waveforms for a dynamic frequency-selection algorithm.

Radar Type	Pulse Width (μs)	Pulse Repetition Interval (μs)	Number of Pulses	Number of Bursts	Minimum Detection Probability	Comments
1	1	1428	18	N/A	60%	Short pulse radar
2	1-5	150-230	23-29	N/A	60%	Short pulse radar
3	6-10	200-500	16-18	N/A	60%	Short pulse radar
4	11-20	200-500	12-16	N/A	60%	Short pulse radar
5	50-100	1000-2000	1-3	8-20	80%	Long pulse radar, with chirp width 5-20 MHz

Information Infrastructure devices that operate in this band. Table 1 provides the five test waveforms as defined by the FCC [6]. The sixth waveform is for frequency-hoping radar, with a pulse width of 1 μs, a pulse repetition interval of 333 μs, nine pulses per frequency hop, a hoping-sequence length of 300 ms, and a hoping rate of 333 Hz. The minimum detection probability of this test is 70%. For all of these test waveforms, the minimum number of trials to ensure that the device passes the test is 30 trials.

3. Spectrum-Sharing Overview

Dynamic spectrum sharing involves two main tasks: spectrum awareness and dynamic spectrum access (DSA).

3.1 Spectrum Awareness

Spectrum awareness refers to the way users capture information about the RF environment in order to be aware about other users using the spectrum. Figure 2 illustrates the common spectrum-awareness techniques.

Signal sensing refers to tuning to the band of interest, and receiving and processing I/Q samples to assess if there are detectable signals in the spectrum. This can be subdivided into two types: cooperative detection and transmitter detection. Cooperative detection refers to the case where there are several sensors that are geographically spread and share the spectrum measurements. If the information collected from different sensors is processed at a central unit, then it is called centralized detection. If the information collected from different sensors is shared among them, but each device makes its own decision, then it is called distributed detection [6]. For transmitter detection, the following techniques have been proposed [1]:

- Energy Detection (ED): This compares the energy received in a given band with a predefined threshold. This algorithm does not require knowing the nature of the transmitted signal, but it does not perform well under low SNR (signal-to-noise-ratio) conditions.

- Matched Filter: This correlates the received signal with the known signal. This algorithm requires knowing the characteristics of the transmitted signal, and performs well in low-SNR conditions.

- Cyclostationary Feature Detection: This correlates the received modulated signals with either sine-wave carriers, pulse trains, or cyclic prefixes. That is in turn based on knowing certain features of the received signal. The signal detection is performed by analyzing the spectral correlation function.
- Covariance-based detection (CBD): The detection is performed by comparing the correlations between the received signal and the non-zero lags with the correlations between the received signal and the zero lag.

- Sensing using MIMO (multiple-input multiple-output) systems: when the device is equipped with multiple antennas, it can use eigenvalue-based detection (EBD) for spectrum sensing.

For spectrum sensing, it is important that the devices initially monitor the channel, and periodically monitor it, as well. Some of the important parameters for spectrum-sensing algorithms are the detection threshold level, how often and how long the channel needs to be monitored.

Another method for spectrum awareness is using a geo-location database. This is useful for systems with fixed locations, as in the case of fixed radar systems (such as terminal Doppler weather radar systems). In this method, the device is equipped with a Global Positioning System (GPS), and it has access to a database that contains the locations of systems that have the right to use the spectrum

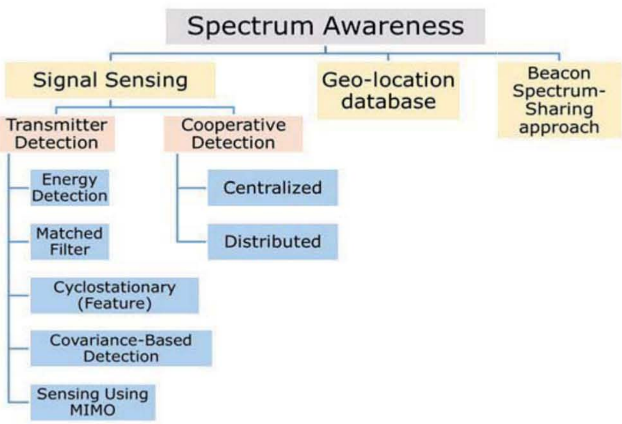

Figure 2. Common spectrum-awareness techniques.

in different geographical areas [6]. In beacon-spectrum-sharing approaches, the device that wishes to access the spectrum as a secondary user must have the ability to receive certain control signals sent by the incumbent system during the period that spectrum sharing is allowed. The device should not start transmitting without receiving this beacon signal, and it should stop once it stops receiving it [6].

3.2 Dynamic Spectrum Access

There are two main models for dynamic spectrum access: opportunistic spectrum access (OSA) and concurrent spectrum access (CSA). For opportunistic spectrum access, one of the users has priority access to the spectrum. This type of user is called the primary user (PU). Any other user sharing the spectrum with the primary user is called secondary user (SU). The secondary user cannot access the spectrum as long as the primary user is using it. The secondary user will use spectrum sensing or will query a database to determine the times that the primary user is not using the channel, in order to opportunistically access it. A good example for such an approach is the dynamic-frequency-selection algorithm mandated in the Unlicensed National Information Infrastructure-2A and Unlicensed National Information Infrastructure-2C bands. For concurrent spectrum access, different users are allowed to share the spectrum together as long as it is done in a fair manner, and as long as the interference generated at each receiver is below a certain threshold. In the next sections, we will examine the spectrum-sharing techniques proposed for the coexistence between communications and radar systems.

4. Spectrum Sharing Between Communications and Radar Systems

DARPA (the US Defense Advanced Research Projects Agency) has launched the SSPARC (Shared Spectrum Access for Radar and Communications) program to promote research and development for spectrum sharing between communications and radar systems [12]. In order to develop an effective spectrum-sharing algorithm, it is important to first analyze the effect that each system has on the other.

For analyzing the effect of communications systems on radar performance, the authors in [13] provided a mathematical model for the interference generated from a cellular system on radars in the 3.5 GHz band. They proved that the interference generated from cellular systems in a correlated shadow-fading channel had a log-normal distribution. They provided the bounds on the radar's probability of detection under cellular interference when there was no constraint on the transmitted power level of the cellular system. The paper showed that such interference can considerably degrade the performance of a radar system in terms of accurate detection of targets. The work in [14] used simulations to show that communications system interference can significantly degrade radar performance. The authors in [15] confirmed the same conclusion after examining the impact of in-band OFDM interference on radars. In [16], the authors performed system-level analysis for the coexistence between a time-division long-term-evolution (TD-LTE) system and a radar system in the 2300 MHz to 2400 MHz band, and studied the effects on each other under different isolation distances and frequency spaci For analyzing the effects of radar on communications system performance, the authors in [17] provided an analytical model to study the effect of an unaltered radar signal on the bit-error rate of a communications system. The authors in [18] analyzed the bit-error rate of TD-LTE in the 2300 MHz to 2400 MHz frequency band with the presence of radar-signal interference. In [19], a system-level analysis was performed for quantifying the impact of ship-borne radar on an outdoor LTE base station (eNodeB) in the 3.5 GHz band. The results showed that a radar signal can decrease the SINR (signal-to-interference-plus-noise ratio) at the LTE eNodeB, but the SINR level improved in between radar pulses. The results also showed that the exclusion zones set by the National Telecommunications and Information Administration to protect the performance of commercial communications systems when sharing the spectrum at 3.5 GHz were too conservative. The same conclusion was confirmed in [20], where a field experiment was performed in St. Inigoes, Maryland, for the coexistence between a TD-LTE system and a land-based AN/SPN-43C radar in the 3.5 GHz band.

These research contributions illustrated that when a radar system shares the spectrum with a communications system, it is more vulnerable to interference because of the radar system's sensitivity. Furthermore, LTE systems in particular deploy several interference-management mechanisms to reduce the effect of interference on the performance. For the downlink, the eNodeB can deploy a frequency-selective scheduler (FSS), which uses the channel-quality indicator (CQI) reporting from the UE, and can perform frequency-domain scheduling and avoid assigning physical resource blocks (PRBs) that have excessive interference or fading to that UE. Moreover, LTE can deploy interference shaping to minimize the inter-cell interference, where a low-loaded eNodeB does not rapidly change its frequency-domain allocations in order to improve the quality of the channel-quality indicator reporting for the UEs served by a neighboring high-loaded eNodeB [21]. For the uplink, LTE uses both open-loop and closed-loop power control with interference awareness, where the eNodeB takes into account the neighboring cells when adjusting the uplink power transmission for the UEs, thus reducing the inter-cell interference and improving the overall uplink data rates [22].

Several research campaigns have investigated developing spectrum-sharing techniques for coexistence between radar and communications systems. As shown in [7], the approaches for radar and communications systems can be broadly classified into three broad categories:

- Cognitive communications system: These communications systems are aware of the RF environment, and can dynamically adapt to avoid harmful interference to radar systems.
- Cognitive radars: The radar is cognitive and responsible for not affecting the performance of the communications system.
- Joint cognition: Both the radar and the communications system collaborate to avoid creating harmful interference to each other.

4.1 Cognitive Communications Systems

The term cognitive radio refers to a system that has the ability to sense the surrounding RF environment, to make short-term predictions, to learn how to operate in a given environment, and to dynamically adjust its transmitting parameters. These capabilities are used by a communications system that acts as a secondary user when sharing the spectrum with radar systems. The first example of this category is the dynamic frequency selection (DSF) mandated by the FCC for devices operating in the 5 GHz band. A very important aspect of dynamic frequency selection is spectrum sensing. Accordingly, several research efforts have been undertaken to improve the sensing capabilities of communications systems, such as employing cooperative sensing using multiple sensors [23, 24]. The authors in [25] investigated using a radio environment map (REM) to enhance spectrum awareness for communications systems sharing the frequency band with radars. In [26], the authors explored using multiple transmitting antennas at the communications-system side for sharing the spectrum with radars in the 5 GHz band, while still employing dynamic frequency selection and adhering to the regulatory constraints of the maximum transmitted power.

The authors in [27] introduced a spectrum-sharing algorithm to address the coexistence issue between an OFDM communications system and a rotating radar. One of the main requirements for this algorithm is that the base station, which is the secondary user, needs to be able to communicate with its mobile terminals over a different frequency band in addition to that shared with the radar system. Another constraint is that the base station must not generate harmful interference to the radar system, determined by the maximum interference-to-noise-ratio threshold at the radar. In other words, the detection capabilities of the radar must not be compromised. The basic concept is that the communications system can utilize the period when the antenna beam of the rotating radar is not within the range of the communications system's transmission. They showed that communications systems can achieve a significant increase in the downlink throughput if they can tolerate the interruptions due to radar rotations.

The authors in [28] investigated and validated the feasibility of adjacent-channel coexistence of an LTE system and an air-traffic-control radar (with a rotating main beam) in the L band through system-level simulation.

The authors in [29] investigated the coexistence between WiMax (Worldwide Interoperability for Microwave Access) networks and nearby ground-based radar systems that operated in an adjacent frequency channel within the S band. They proposed four different interference-mitigation techniques for WiMax, using either spatial, spectral, temporal, or system-level modification domains.

4.2 Cognitive Radar

The concept of cognitive radar was first introduced in [30]. Cognitive-radar techniques have shown the ability to improve the overall performance of the radar [31]. With cognitive techniques and with MIMO technology, radar systems can become more resilient by implementing interference-mitigation algorithms. When the radar acts as the secondary user, it will need to perform spectrum sensing, as shown in [32] and [33]. The approaches for spectrum sharing while using cognitive radars can be categorized into two sub-categories: waveform shaping and waveform design.

4.2.1 Waveform Shaping

When a radar employs a MIMO system, it becomes capable of reshaping the radar's waveform. In [34], a novel algorithm was proposed for a coherent MIMO radar that can minimize the interference generated by signals from communications systems coming from any direction: the main lobe or the directions of the sidelobes. In this approach, the radar transmits and receives coherent orthogonal phase-coded waveforms from each of the antenna elements. The work in [35] provided the mathematical proof for this approach, and the conditions for the MIMO radar's main-lobe interference cancellation. The authors in [36] provided a practical pre-coding approach for the coexistence between MIMO radar and multiple communications-transmitter-receiver pairs, where the radar transmitter applied a zero-forcing pre-coder that eliminated the interference at the communications-system's side. This approach required perfect knowledge of the interference-channel matrix at the radar's side. They therefore proposed a channel-estimation algorithm that required the multiple communications transmitters to coordinate in transmitting training symbols. In [37], the authors proposed an algorithm for spectrum sharing between a MIMO radar and a communications system by projecting the radar's waveform into the null space of the interference-channel matrix between the two systems. The authors in [38] extended that work from one communications system into multiple communications systems, and provided a new projection algorithm for this case. The authors in [39] extended the work in [37] for a maritime MIMO radar, where they considered the variations in the channel due to the motion of the ship.

4.2.2 Waveform Design

Since cognitive radars have the ability to modify their transmitted waveform based on the preceding returns, the authors in [40] investigated a radar waveform design for the coexistence with a friendly communications system. They proposed using an SNR-based water-filling technique that minimized the interference at the communications system. In [41], the authors proposed information-theoretic waveform design for MIMO radars in the frequency domain to reduce the amount of interference produced to a coexisting communications system. The authors in [42] designed a finite-alphabet binary-phase-shift-keying (BPSK) waveform for stationary and moving maritime MIMO radars in a way that did not generate interference to the communications systems operating in the same band. In [43], the authors introduced a mutual-information- (MI) based criterion for OFDM radar waveform optimization in a joint radar and multiple-base-station setup.

4.3 Joint Cognition

In recent years, joint radar and communications system spectrum-sharing techniques have gained a lot of interest, because of the potential to enhance the spectrum-sharing performance due to the additional degrees of freedom. In [44], the authors introduced the concept of bandwidth sharing between multimodal radar and a communications system. A multimodal radar has the ability to vary its bandwidth (and, accordingly, its resolution) based on its current needs. This allows the communications system to utilize the remaining bandwidth. The priority for the radar was determined using fuzzy logic, and the priority for the communications system was assumed. The authors in [45] pointed out the challenge of this approach, given the congestion of the RF spectrum. They hence developed novel spectrum-sharing techniques for adaptable radars, where using multi-objective optimization the radar selected the optimal sub-band in a highly congested frequency band to both maximize the SINR and minimize the range-resolution cell size. The authors in [46] proposed to design the OFDM waveform for both a multimodal radar and a communications system by assigning OFDM sub-carriers based on maximizing the radar's detection performance and the communications system's channel capacity. The authors in [47] proposed a joint design and operation between a radar and a communications system based on transmitting and receiving optimization procedures to maximize forward-channel SNR while simultaneously minimizing co-channel interference. The authors in [48] presented an algorithm for the co-design of a MIMO radar and a MIMO communications system for spectrum sharing based on a cooperative approach to mitigate mutual interference. The work in [49] extended this cooperative approach for a radar system operating in the presence of clutter. The work in [50] further extended it for a scenario where all radar targets fall in different range bins.

5. Conclusion

Spectrum sharing between radar and communications systems is one of the important solutions proposed to help with the RF congestion problem. The impact this technology may have is proportional to the amount of spectrum affected, and radar systems consume a huge amount of spectrum while operating. In this paper, we have presented different radar systems within the 5 GHz band along with the spectrum regulations in this band. We have presented the basic concepts of spectrum sharing, and have performed an updated survey of the spectrum-sharing contributions for the coexistence between communications and radar systems. We conclude that spectrum sharing between radar and communications systems is definitely feasible, but a lot of research is still required in order to ensure that the radar's performance will not be affected while improving the spectrum efficiency for communications.

6. References

1. Y. C. Liang, K. C. Chen, G. Li, and P. Mahonen, "Cognitive Radio Networking and Communications: An Overview," *IEEE Transactions on Vehicular Technology*, **60**, 7, September 2011, pp. 3386-3407.

2. Office of the Press Secretary, "Presidential Memorandum: Unleashing The Wireless Broadband Revolution," The White House, Press Release, June 2010, available: https://www.whitehouse.gov/the-press-office/presidential-memorandum-unleashing-wireless-broadband-revolution.

3. Office of the Press Secretary, "Presidential Memorandum: expanding America's Leadership in Wireless Innovation," The White House, Press Release, June 2013, available: https://www.whitehouse.gov/the-press-office/2013/06/14/presidential-memorandum-expanding-americas-leadership-wireless-innovations.

4. Deputy Secretary of Defense, "Electromagnetic Spectrum Strategy," Department of Defense, A Call to Action, September 2013.

5. F. D. Moorefield, DoD Chief Information Officer, "Assured Dynamic Spectrum Access, Evolving toward Revolutionary Change: DoD Prospective," Department of Defense, Brief to DoD UAS Summit, March 2015.

6. Rebecca Blank and Lawrence E. Strickling, "Evaluation of the 5350-5470 MHz and 5850-5925 MHz Bands Pursuant to Section 6406(b) of The Middle Class Tax Relief and Job Creation Act of 2012," Department of Commerce, Technical Report, January 2013.

7. H. T. Hayvaci and B. Tavli, "Spectrum Sharing in Radar and Wireless Communication Systems: A Review," International Conference on Electromagnetics in Advanced Applications (ICEAA), August 2014, pp. 810-813.

8. FCC, "Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band," Federal Communications Commission, Report and Order and Second Further Notice of Proposed Rulemaking, April 2015.

9. M. M. Sohul, M. Yao, T. Yang, and J. H. Reed, "Spectrum Access System for the Citizen Broadband Radio Service," *IEEE Communications Magazine*, **53**, 7, July 2015, pp. 18-25.

10. ITU, "Characteristics of and Protection Criteria for Sharing Studies for Radiolocation (except Ground Based Meteorological Radars) and Aeronautical Radionavigation Radars Operating in the Frequency Bands between 5 250 and 5 850 MHz," International Telecommunication Union, Recommendation ITU-R M.1638-1, M-Series, January 2015.

11. FCC, "Revision of Part 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) Devices in the 5 GHz Band," Federal Communications Commission, First Report and Order, April 2014.

12. Joseph B. Evans, "Shared Spectrum Access for Radar and Communications (SSPARC)," DARPA, Press Release, available: http://www.darpa.mil/program/shared-spectrum-access-for-radar-and-communications.

13. A. Khawar, A. Abdelhadi, and T. C. Clancy, "A Mathematical Analysis of Cellular Interference on the Performance of S-Band Military Radar Systems," IEEE Wireless Telecommunications Symposium (WTS), April 2014, pp. 1-8.

14. M. R. Bell, N. Devroye, D. Erricolo, T. Koduri, S. Rao, and D. Tuninetti, "Results on Spectrum Sharing Between a Radar and a Communications System," International Conference on Electromagnetics in Advanced Applications (ICEAA), August 2014, pp. 826-829.

15. B. D. Cordill, S. A. Seguin, and L. Cohen, "Electromagnetic Interference to Radar Receivers due to In-Band OFDM Communications Systems," IEEE International Symposium on Electromagnetic Compatibility, August 2013, pp. 72-75.

16. W. Liu, J. Fang, H. Tan, B. Huang, and W. Wang, "Coexistence Studies for TD-LTE with Radar System in the Band 2300-2400 MHz," International Conference on Communications, Circuits and Systems (ICCCAS), July 2010, pp. 49-53.

17. N. Nartasilpa, D. Tuninetti, N. Devroye, and D. Erricolo, "Let's Share CommRad: Effect of Radar Interference on an Uncoded Data Communication system," IEEE Radar Conference (RadarCon), May 2016, pp. 1-5.

18. J. Han, B. Wang, W. Wang, Y. Zhang, and W. Xia, "Analysis for the BER of LTE System with the Interference from Radar," IET International Conference on Communication Technology and Application (ICCTA 2011), October 2011, pp. 452-456.

19. M. Ghorbanzadeh, E. Visotsky, P. Moorut, W. Yang, and C. Clancy, "Radar In-Band and Out-Of-Band Interference into LTE Macro and Small Cell Uplinks in the 3.5 GHz Band," IEEE Wireless Communications and Networking Conference (WCNC), March 2015, pp. 1829-1834.

20. J. H. Reed, A. W. Clegg, A. V. Padaki, T. Yang, R. Nealy, C. Dietrich, C. R. Anderson, and D. M. Mearns, "On the Co-Existence of TD-LTE and Radar over 3.5 GHz Band: An Experimental Study," *IEEE Wireless Communications Letters*, **5**, 4, August 2016, pp. 368-371.

21. R. Agrawal, A. Bedekar, H. Holma, S. Kalyanasundaram, K. Pedersen, and B. Soret, "Small Cell Interference Management," in H. Holma, A. Toskala, J. Reunanen (eds.), *LTE Small Cell Optimization: 3GPP Evolution to Release 13*, West Sussex, United Kingdom, John Wiley & Sons Ltd, pp. 91-120, 2016.

22. Nokia Solution and Networks, "Smart Scheduler," 2015.

23. L. S. Wang, J. P. Mcgeehan, C. Williams, and A. Doufexi, "Application of Cooperative Sensing in Radar-Communications Coexistence," *IET Communications*, **2**, 6, July 2008, pp. 856-868.

24. L. Wang, A. Doufexi, C. Williams, and J. McGeehan, "Cognitive Node Selection and Assignment Algorithms for Weighted Cooperative Sensing in Radar Systems," IEEE Wireless Communications and Networking Conference, April 2009, pp. 1-6.

25. F. Paisana, Z. Khan, J. Lehtomäki, L. A. DaSilva, and R. Vuohtoniemi, "Exploring Radio Environment Map Architectures for Spectrum Sharing in the Radar Bands," 23rd International Conference on Telecommunications (ICT), May 2016, pp. 1-6.

26. J. Um, J. Park, and S. Park, "Multi-Antenna-Based Transmission Strategy in 5 GHz Unlicensed Band," Eighth International Conference on Ubiquitous and Future Networks (ICUFN), July 2016, pp. 651-655.

27. R. Saruthirathanaworakun, J. Peha, and L. Correia, "Opportunistic Sharing between Rotating Radar and Cellular," *IEEE Journal on Selected Areas in Communications*, **30**, 10, November 2012, pp. 1900-1910.

28. H. Wang, J. Johnson, C. Baker, L. Ye, and C. Zhang, "On Spectrum Sharing between Communications and Air Traffic Control Radar Systems," IEEE Radar Conference (RadarCon), May 2015, pp. 1545-1550.

29. A. Lackpour, M. Luddy, and J. Winters, "Overview of Interference Mitigation Techniques Between WiMAX Networks and Ground Based Radar," Annual Wireless and Optical Communications Conference (WOCC), April 2011, pp. 1-5.

30. S. Haykin, "Cognitive Radar: A Way of the Future," *IEEE Signal Processing Magazine*, **23**, 1, January 2006, pp. 30-40.

31. A. Martone, "Cognitive Radar Demystified," *URSI Radio Science Bulletin*, **350**, September 2014, pp. 10-22.

32. M. T. Mushtaq, F. A. Butt, and A. Malik, "An Overview of Spectrum Sensing in Cognitive Radar Systems," IEEE Microwaves, Radar and Remote Sensing Symposium (MRRS), September 2014, pp. 115-118.

33. P. Stinco, M. S. Greco, and F. Gini, "Spectrum Sensing and Sharing for Cognitive Radars," *IET Radar and Sonar Navigation*, **10**, 3, March 2016, pp. 595-602.

34. H. Deng and B. Himed, "Interference Mitigation Processing for Spectrum-Sharing Between Radar and Wireless Communications Systems," *IEEE Transactions on Aerospace and Electronic Systems*, **49**, 3, July 2013, pp. 1911-1919.

35. Z. Geng, H. Deng, and B. Himed, "Adaptive Radar Beamforming for Interference Mitigation in Radar-Wireless Spectrum Sharing," *IEEE Signal Processing Letters*, **22**, 4, April 2015, pp. 484-488.

36. A. Babaei, W. H. Tranter, and T. Bose, "A Practical Precoding Approach for Radar/Communications Spectrum Sharing," International Conference on Cognitive Radio Oriented Wireless Networks, July 2013, pp. 13-18.

37. S. Sodagari, A. Khawar, T. Clancy, and R. McGwier, "A Projection Based Approach for Radar and Telecommunication Systems Coexistence," IEEE GLOBECOM '12, December 2012, pp. 5010-538. A. Khawar, A. Abdel-Hadi, and T. C. Clancy, "Spectrum Sharing Between S-Band Radar and LTE Cellular System: A Spatial Approach," IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN), April 2014, pp. 7-14.

39. A. Khawar, A. Abdelhadi, and T. C. Clancy, "On the Impact of Time-Varying Interference-Channel on the Spatial Approach of Spectrum Sharing Between S-band Radar and Communication System," IEEE Military Communications Conference (MILCOM), October 2014, pp. 807-812.

40. K. D. Shepherd and R. A. Romero, "Radar Waveform Design in Active Communications Channel," Asilomar Conference on Signals, Systems and Computers, November 2013, pp. 1515-1519.

41. S. Amuru, R. Buehrer, R. Tandon, and S. Sodagari, "MIMO Radar Waveform Design to Support Spectrum Sharing," IEEE Military Communications Conference (MILCOM), November 2013, pp. 1535-1540.

42. A. Khawar, A. Abdel-Hadi, and T. Clancy, "MIMO Radar Waveform Design for Coexistence with Cellular Systems," IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN), April 2014, pp. 20-26.

43. M. Bica, K. W. Huang, V. Koivunen, and U. Mitra, "Mutual Information Based Radar Waveform Design for Joint Radar and Cellular Communication Systems," IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), March 2016, pp. 3671-3675.

44. S. Bhat, R. Narayanan, and M. Rangaswamy, "Bandwidth Sharing and Scheduling for Multimodal Radar with Communications and Tracking," IEEE 7th Sensor Array and Multichannel Signal Processing Workshop (SAM), June 2012, pp. 233-236.

45. A. Martone, K. Sherbondy, K. Ranney, and T. Dogaru, "Passive Sensing for Adaptable Radar Bandwidth," IEEE Radar Conference (RadarCon), May 2015, pp. 0280-0285.

46. S. Gogineni, M. Rangaswamy, and A. Nehorai, "Multi-Modal OFDM Waveform Design," IEEE Radar Conference (RadarCon), April 2013, pp. 1-5.

47. J. R. Guerci, R. M. Guerci, A. Lackpour, and D. Moskowitz, "Joint Design and Operation of Shared Spectrum Access for Radar and Communications," IEEE Radar Conference (RadarCon), May 2015, pp. 0761-0766.

48. B. Li, A. P. Petropulu, and W. Trappe, "Optimum Co-Design for Spectrum Sharing between Matrix Completion Based MIMO Radars and a MIMO Communication System," *IEEE Transactions on Signal Processing*, **64**, 17, September 2016, pp. 4562-4575.

49. B. Li and A. Petropulu, "MIMO Radar and Communication Spectrum Sharing with Clutter Mitigation," IEEE Radar Conference (RadarCon), May 2016, pp. 1-6.

50. B. Li, H. Kumar, and A. P. Petropulu, "A Joint Design Approach for Spectrum Sharing Between Radar and Communication Systems," IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), March 2016, pp. 3306-3310.