Survey of RF Communications and Sensing Convergence Research

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Survey of RF Communications and Sensing Convergence Research

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Abstract—Wireless mediums, such as RF, optical, or acoustical, provide finite resources for the purposes of remote sensing (such as radar) and data communications. Often, these two functions are at odds with one another and compete for these resources. Applications for wireless technology are growing rapidly, and RF convergence is already presenting itself as a requirement for both users as consumer and military system requirements evolve. The broad solution space to this complex problem encompasses cooperation or co-designing of systems with both sensing and communications functions. By jointly considering the systems during the design phase, rather than perpetuating a notion of mutual interference, both system’s performance can be improved. We provide a point of departure for future researchers that will be required to solve this problem by presenting the applications, topologies, levels of system integration, the current state of the art, and outlines of future information-centric systems.

Index Terms—RF Convergence, Radar Communications Co-existence, Joint Sensing-Communications, Wireless Resources

I. INTRODUCTION

The problem of spectral congestion is forcing legacy radar band users to investigate methods of cooperation and co-design with a growing number of communications applications. This problem has motivated government entities like the Defense Advanced Research Projects Agency (DARPA) to begin funding and investigating these methods to not only ensure military radar coverage is maintained as spectral allocation is renegotiated, but to potentially improve both military radar and military communications by co-designing the systems from the ground up [1]. However, these issues extend far beyond just commercial communications and military radar, and include a wide variety of applications such as next generation automobiles, medical devices, and 5G wireless backhaul. As a result, researchers have begun investigating not just methods of military radar and communications coexistence, but more fundamentally methods of joint remote sensing and communications.

These two functions, at their core, tend to be at odds with one another. For example, sensing typically sends a known waveform or stimulus and measures a response from the environment, often referred to as the channel. In the case of the radar system, the sent signal is known and the target channel is unknown and is desired to be sensed (estimated). However, a communications system typically sends an unknown signal with the assumption that the propagation channel is known or previously estimated. We can also consider the near inverse of this situation: passive radar. In this case, we must estimate the data as a nuisance parameter to obtain the information we care about (channel estimation). A non-adaptive communications channel, where the channel is stationary or controlled, is the dual of the traditional radar system. Therefore, when considering the general task of jointly sensing and communicating, it
becomes immediately apparent that the solution is non-trivial. A typical two-user topology and the problem of spectral congestion is illustrated in Figure 1. With opposing requirements, sensing and communications systems are often designed in isolation. The only consideration for the other user in legacy systems has been in the form of regulatory constraints, such as those imposed by the FCC in the United States. However, governmental regulation does nothing to incentivize either user to minimize interference beyond the required limits or assist each other to mutual benefit. As future systems vie for spectral resources, RF convergence and cooperation is the solution to an increasingly crowded wireless domain. We define the ultimate solution, RF convergence, to be the operating point at which a given bandwidth allocation is used jointly for radar and communications to mutual benefit. This includes but is not limited to multi-function transceivers, in-band full-duplex (IBFD) operation, shared waveforms, and dynamic time allocation.

Shown in Figure 2 is where the authors see the future of channel topologies heading. Rather than dedicated radar or communications elements, universal dynamic users are designed to adapt to meet instantaneous mission needs. Bandwidth, data rate, and estimation rate [2] are modulated depending on communications need, targets present, and target dynamics. While one may note both cognitive radio and cognitive radar are both active fields of development, cognitive radio has typically been developed in the context of resource sharing [3], while cognitive radar has traditionally focused more on intelligent radar systems to improve radar performance [4]. Previous surveys have looked at the spectral congestion problem from a dynamic access perspective with a focus on regulatory issues and signal processing [5]. However, the focus in that work is still on dynamic communications users, not necessarily including remote sensing users. Recent work surveyed spectrum sharing methods and underutilization of RF resources [6], focusing mainly on communications with some mention of sharing with non-communications users. This work focused more on existing spectrum sharing regulation, as opposed to future architectures and limits of coexistence.

In this work, we discuss the general problem of spectral congestion and the future solutions to this problem. For the two-user case, RF convergence is broken down into four topologies: the joint multiple-access channel, the monostatic broadcast channel, the bi-static broadcast channel, and the IBFD channel. These topologies have been explored in recent literature by various researchers as interest in RF convergence has resurfaced. The joint multiple-access channel problem is addressed in References [2, 7–15], while the bi-static broadcast channel topology is addressed in References [16, 17]. The monostatic broadcast channel is discussed in Reference [18]. Finally, the broad and complicated topic of IBFD is covered in detail in Reference [19]. While we frame the problem for applications concerning radar and communications, the discussion in this work applies to all mediums where sensing and communications are possible. The focus on RF is because the problem arises in the concern for optimizing a precious resource: RF spectrum.

In approaching the problem, we first look at the various applications that can benefit from co-designing systems that require remote sensing and communications in Section II. The special case of two-user topologies for joint radar-communications systems are developed in Section III. In Section IV, the different levels of system integration the two users can adopt are presented, ranging from mere coexistence (mitigating mutual interference) to completely co-designed systems. We present the state of the art for joint systems in Section V, and look toward bounds on future systems and solutions in Section VI. This work is meant to be a point of departure and collation of research to date for joint systems, and so we make some summarizing remarks in Section VII.

II. JOINT SENSING-COMMUNICATIONS APPLICATIONS

In this section, we discuss the various applications that could benefit from the more general joint sensing-communications paradigm, or are currently being researched from that perspective. These include mixtures of military and commercial users, medical devices, and light based applications, among others. Any systems or industries that have benefited or could benefit from advances in cognitive radio and cognitive radar can most likely greatly benefit from RF convergence, as the problems are closely related. This can also include other resource-limited sensing modalities such as acoustics and sonar-based systems. These applications each have different system goals, constraints, and regulatory issues. As many researchers are finding, marrying remote sensing and communications can be theoretically difficult [20], but the need is readily apparent and increasing in urgency.

A. Automotive Radar & V2V Communications

The smart car revolution has lead the way in research on intelligent transportation systems (ITS). With self-driving cars on the verge of becoming viable, two clear technological needs emerge: vehicle-to-vehicle (V2V) communications and navigational/avoidance radar. Both RF [21] and light based [22] solutions have been proposed for V2V communications as car technology evolves. Further, vehicle radar is already deployed to consumer vehicles for collision avoidance and self-driving features. However, researchers have already started looking at joint radar-communications systems for V2V applications since these needs are so closely coupled [22, 23].

B. Commercial Flight Control

In commercial flight air traffic control, a joint sensing-communications problem has been present for many decades. Radar-like functionality is desired for locating friendly aircraft, while communications with pilots is paramount to coordinating the flight of multiple aircraft near and around airports. Modern systems employ a Mode S beacon radar system, which combines an interrogating radar with a communications response [24]. In this sense, the Mode S commercial flight system can be thought of as a cooperative radar scheme, where targets respond to radar stimulus with information back to the radar. A related system is the automatic dependent surveillance-broadcast (ADS-B), in which complicit aircraft
self-locate via satellite navigation and broadcast their position to allow ground controllers and other aircraft to track their location [25]. New software-defined systems are attempting to integrate these various systems to minimize circuitry and maximize flexibility [26].

C. Communications & Military Radar

This is specifically an interest of the DARPA shared spectrum access for radar and communications (SSPARC) initiative, and has subsequently spawned a great deal of research in recent years. The communications user can be commercial or military/governmental, and non-military radar can apply solutions from this thread of research as well. With the accelerating demands of commercial communications, specifically cellular and broadband wireless internet usage, concerns are growing for the future of military radar allocation [27].

D. Medical Sensors and Monitoring

Medical devices are often deeply embedded biologically, and therefore operate at lower power. However, sensing is often a primary function of such devices, which can require significant power to complete effectively. Cloud based approaches have evolved where sensing elements communicate their measurements to external processing structures for further analysis [28]. This topology extends to non-medical applications as well, encapsulating deeply embedded low power sensor applications [29]. The need for combined sensing and communicating naturally arises in these systems, and to do so on a single radio is especially advantageous to minimize the invasiveness and physical footprint of medical implants. Getting a communications signal out of the body has its challenges as well, and researchers have begun looking at devices to estimate and equalize the human body channel prior to transferring data [30].

E. High Frequency Imaging and Communications

Systems employing upper millimeter-wave have been proposed for high throughput communications, and fine resolution sensing. For example, Google’s Project Soli performs precise motion detection using a 60 GHz radar targeted for mobile devices [31, 32]. The ultimate goal is low power, gesture based control for interfaces to the next generation of smartphones and tablets. This complements well with advances in high throughput device-to-device communications using the same frequency range and wireless backhaul applications [33]. A single radio could handle both sensing for input control, and communications for high bandwidth applications, potentially simultaneously.

F. Li-Fi and Lidar

Light based systems have been growing in interest as a solution to growing spectral congestion and stressing of 4G systems [34]. There have been numerous research threads investigating wireless communications using infrared and visible light [34]. New standards are being developed for Li-Fi, a light-based equivalent to Wi-Fi [35], and other indoor optical systems to meet growing consumer needs for high throughput, media rich systems [36]. There is an equally fast growing industry researching optics for remote sensing applications [37], such as Lidar for wetland mapping and monitoring [38], and remote sensing using optical systems for coastal resource management (e.g., monitoring sea levels) [39].

G. RFID & Asset Tracking

Near field sensing technologies like radio-frequency identification (RFID) currently integrate remote sensing and data transfer to some extent. Communications is already the core functionality of RFID technology, as tags communicate back identification, health, and status information [40]. In addition, RFID networks have been modeled as a virtual communications capacity problem [41]. RFID technology has also been researched for radar detection [42] and localization [43]. Far field RFID-like radar systems have also been investigated as a joint radar-communications solution with a cooperative target [44]. Given that a typical RFID requires external stimulus or application of RF energy to initiate the communications link, the parallels to radar naturally arise (sending RF energy to a target for a measurement), and the joint sensing-communications aspects are immediately clear.

III. HETEROGENEOUS TWO-USER TOPOLOGIES

In this section, we explore the various two-user radar and communications topologies seen in the real world and considered for solutions enabling RF convergence. For the topologies discussed here, we assume we have two users signaling in the same band, that are co-located or operating nearby. There are extensions and variations to the models discussed here, but the topologies in the following section represent an initial attempt at capturing two-user configurations of RF convergence. To start, we discuss the “problem topology,” the real world heterogeneous multi-user interference channel.

A. RF Convergence Model

Here we explore a real world channel that is representative of the spectral congestion problem. For this model, both radar and communications are developed in isolation and must compete for spectrum in a given space-time. Interference mitigation is often managed through regulation. However, provided the respective users adhere to regulatory requirements, neither user is incentivized to minimize their impact on the other user’s performance. In modern systems, users also employ signal processing to adaptively minimize interference that remains despite adherence to regulatory wireless standards.

An example of this topology is shown in Figure 1. Even in a simple single radar, single communications link scenario, there can be significant interference between systems. Adding communications users and targets, along with strong clutter reflections typical of real world environments, the various sources of unwanted RF energy at a given user’s receiver begins to compound. Adhering to regulations often does not prevent these types of complicated scenarios from occurring, burdening systems with additional interference mitigation design requirements or limiting system performance. In fact,
comprehensive view of the real world problem can be so complicated, research into joint radar-communications has been focused in some areas solely on methods of testing cooperative or co-designed techniques [45]. To assist in analysis and design of joint systems, simplified multi-user topologies are presented in the following subsections.

B. Joint Multiple Access Channel (MUDR)

The joint multiple access channel topology includes a common receiver for both radar and communications, but with independent transmitters. In this topology, User 1 is a monostatic radar transceiver (sends and receives radar signal), and simultaneously acts as a communications receiver. User 2 is a communications transmitter. This can easily be extended to $N$ communications users, and $M$ targets. This topology is shown in Figure 3. This architecture has numerous advantages. The radar user is sending a known waveform into the channel, and in some cases can obtain equalization data for the communications path. Since the tracking radar is dynamically estimating the target state, the predicted radar return can be subtracted from the signal to minimize radar interference for the communications user. This knowledge also allows the communications user to transmit at a higher rate when it knows the radar is not transmitting or listening for target returns, as opposed to being forced to sense spectrum use.

An example of a system exploiting this topology is known as the multiuser detection radar (MUDR), explored in References [2, 13], and other related works.

C. Monostatic Broadcast Channel

The monostatic broadcast channel uses a shared waveform for both the monostatic radar and the communications link. It is achieved by reversing the roles of the communications link from the previous topology, as shown in Figure 4. User 1 is now a monostatic radar transceiver (sends and receives radar signal), and simultaneously acts as a communications transmitter. User 2 is now the opposite role, functioning as a communications receiver. This too can easily be extended to multiple communications users and targets. While a seemingly subtle shift, the two systems are now much more tightly coupled as they must share a common waveform. This means that communications must be parasitic, and that radar performance may be a function of the data being sent.

D. Bi-Static Broadcast Channel

The bi-static broadcast channel also uses a shared waveform for both the communications link and the radar, which now operates bi-statically as shown in Figure 5. This has the same challenges as the previous topology, but with the added benefit that the bi-static radar inherently performs channel estimation to directly support the communications link equalization requirements. The passive radar fits within this topology.

E. In-Band Full-Duplex Channel

The IBFD channel is achieved by once again reversing the communications link as seen in Figure 6. Now User 2 on the right can provide feedback to User 1, the radar transmitter, regarding target information to support tracking. The topology is named due to the inherent system architecture from this bi-static radar and communications link. That is, both users are effectively attempting to operate in full duplex mode over the
same instantaneous band. Subsequently, the challenges of this architecture are readily understood and are subsumed by the vast literature base of this topic [19].

IV. JOINT SYSTEM DESIGN & INTEGRATION

In this section, we enumerate the various levels of integration of the joint sensing-communications problem. This facilitates exploration of the complex solution space, and helps identify what work falls into what category.

A. Non-integration (Isolation)

We define non-integration to mean that no attempt at physically integrating the sensing and communications systems is made, as illustrated in Figure 7. For example, if each system is completely isolated in spectrum-space-time, then there is no attempt at RF convergence. Realistically, perfect isolation is not achievable, and the various users operate to the limit regulatory laws allow. Often, in real world scenarios, the performance of all users is degraded. This is one of the incumbent solutions, and part of the problem. This architecture, shown in Figure 7, may represent the two users being adjacent in space and coincident in spectrum or collocated and adjacent in spectrum. Subsequently, both users are susceptible to interference from the other, and make no attempt to adaptively cancel one another.

B. Coexistence (Mitigation without Communication)

Coexistence methods burden radar and communications transceivers to treat one another as interferers. This means that any information required to mitigate the other system’s interference is not shared, and must be estimated. For example, cognitive radio blind spectrum sensing techniques are employed to inform space-time duty cycling of spectral access. This is close to where systems are today, but still preserves an attempted level of mutual mitigation instead of assumed isolation in space or time. This is also a legacy solution to the spectral congestion problem, and requires both systems to consider one another interference. One example is passive radar that takes advantage of communications broadcast to perform radar operation, but must mitigate the source of interference (direct path propagation). As a result, the architecture reflected in Figure 8 has added an adaptive canceler function to both users’ paths.

C. Cooperation (Communication to Mutual Benefit)

Cooperative techniques typically mean that some knowledge is shared between systems in order to more effectively mitigate interference relative to one another. More generally, the two users no longer consider each other interferers, but exploit the joint knowledge to improve both systems’ performance. In this regime, the systems may not significantly alter their core operation, but willingly exchange information necessary to mutually mitigate interference. This level of integration is the first step toward joint systems, and is aimed at seriously attempting RF convergence. For example, a passive radar system might receive dynamically updated information from the communications user, who has knowledge of the passive radar’s intended function, to facilitate with the remote sensing process and assist with direct path and co-channel interference mitigation. This shift in channel architecture is shown in Figure 9, where the systems now exchange information to benefit one another and assist in signal mitigation.

D. Co-design (Joint Design & Optimization)

Co-design is the paradigm shift of considering communications and radar jointly when designing new systems to maximize spectral efficiency. In this regime, systems are jointly designed from the ground up, and now have the opportunity to improve their performance over isolated operation. Note that this does not mean the systems are physically co-located
necessarily, but rather describes both systems being designed as a joint system. For example, our passive radar cooperative solution can be improved by co-design of the systems. The communications user can make the design choice to use codes, modulation schemes, and training sequences that benefit the passive radar operation. In turn, the passive radar user can provide multistatic channel estimation feedback to assist the communications user in the equalization process. This is reflected in Figure 10, where the two functions are now represented as a jointly designed system.

V. STATE OF THE ART

In this section, we investigate the state of the art of joint radar-communications, or more broadly joint sensing-communications. We look at systems that employ cognitive techniques, joint waveform/coding design, user subscription, passive communications, and passive radar, among others.

These solutions can typically be delineated by waveform. This can include what waveforms for each user help reduce mutual interference, and joint waveform designs that accomplish both sensing and communications. Transmitted waveforms are often central to modern joint radar-communications system design due to the sensitivity of both users to the choice of waveform. An example of this fundamental tradeoff is given in Figure 11. This is the autocorrelation function of two types of waveforms: a linear frequency-modulated (FM) chirp typical of radar systems (shown in blue), and an orthogonal frequency-division multiplexing (OFDM) waveform used often in modern communications (shown in orange). In the full autocorrelation, it is immediately clear that the OFDM presents significant ambiguity due to the cyclic prefix. For ranging of targets, this could be catastrophic, as the sidelobes are only 10-12 dB down from the main lobe, and very far away. Further, the autocorrelation is data dependent, and can vary significantly. This also affects the peak-to-average power ratio (PAPR) in a data-dependent way, which can cause significant issues for radar power circuitry [46]. The communications user is agnostic to this behavior, as pilot signals are used for alignment, and cyclic prefix is discarded to mitigate channel fading [47]. The linear FM chirp, on the other hand, would make a poor communications signal, as it contains no modulation where data could be encoded. However, it provides superior range estimation for global error scenarios. If we look at the main lobe function up close in the bottom part of the figure, we see the OFDM main lobe is nearly 2x narrower. This means for high signal-to-noise ratio (SNR) tracking scenarios, the variance of the radar measurement is much better for the OFDM waveform, at least for this particular bit pattern.

Another way to look at the problem is shown in Figure 12, which shows the full complex ambiguity function magnitude for both waveforms as a contour plot. Here, we see that linear FM chirps have range-Doppler coupling that further complicate processing, requiring compensation or the full complex ambiguity function calculation [48]. However, this can be seen as being Doppler resilient, and so may ultimately benefit over OFDM systems. In the case of the OFDM waveform, where the ambiguity function is shown in orange, the noise-like properties of the waveform result in a
near delta-function correlation shape. This can be beneficial for radar processing when ignoring global error, but may complicate matched filtering by adding significant straddle loss and driving significant processing power [48].

This simple trade illustrates the importance of waveform design, which is why much of the recent work in joint radar-communications has been focused on optimizing a joint waveform. We now discuss some of these systems in more detail and other state of the art methods achieving RF convergence.

A. Coexistence Methods

Preliminary research looked at the problems posed by spectrum sharing relative to each user. Immediately it was clear that unaddressed or unacknowledged, the effect on radar for even mild interference is large for in-band operation [49]. Therefore, coexistence methods have acknowledged the interference posed by spatially adjacent users to incorporate this interference model into their processing [50]. For example, recent works have looked at modifications to the optimal symbol decision regions for communications based on additive white Gaussian noise [51]. Researchers have also looked at spectrally managed systems with significant structure on radar estimation when ignoring global error, but may complicate matched filters for communications in the presence of the radar.

Conversely, others have looked at the effectiveness of communications interference with significant structure on radar estimation variance bounds [52]. Some researchers have investigated optimization at a circuit level, using Smith Tubes to adaptively manage radar and communications regulatory spectral masks through dynamic impedance matching [53]. Others have investigated radar waveform design in legacy communications bands where the communications systems are rigid and unable to adapt [54], where the radar waveform employs a form of water-filling. Researchers have also looked at spectrally

\[
Y_{rx} = \sqrt{S}X + \sqrt{I}e^{j\Theta} + Z,
\]

where \(Y_{rx}\) is the received signal, \(S\) is the communications signal power, \(I\) is the interference-to-noise ratio, \(X\) is the communications symbol from constellation \(\mathcal{X} = \{x_1, \ldots, x_N\}\), \(\Theta\) is the radar interference random phase term, and \(Z\) is a standard Gaussian noise source. Under the random radar phase term, the maximum likelihood symbol for a given received point in the constellation is given by [51]

\[
\hat{l}(y) = \arg \min_{l \in [1:N]} |y - \sqrt{S}x_l|^2 - \ln I_0 \left(2\sqrt{T}|y - \sqrt{S}x_l|\right),
\]

where \(y\) is the received signal, \(x_l\) is a hypothesis constellation point, and \(I_0(x)\) is the modified Bessel function of the first kind, order 0. It can be seen in Figure 13 that far from the origin, the decision regions are the standard, interference free regions. However, the decision symbol regions close to the origin are distorted by the spatial Bessel function term. This illustrates that even in this simple interference model, the communications decision logic is significantly altered by the presence of the radar.

Fig. 12. Magnitude of the complex ambiguity function, or CAF, for both the linear frequency-modulated chirp (shown in blue), and an OFDM communications signal (dashed orange). The random data of the OFDM waveform has noise like properties, and so the CAF surface falls off rapidly away from the zero-Doppler, zero-time shift origin. Shown are contours at -3 dB, -6 dB, and -10 dB from the peak at (0,0). The same contours are shown on the OFDM ridge. The linear contours are a result of range-Doppler coupling. This can be favorable in some processing conditions, where Doppler shifts do not eliminate range-only matched filters. However, they present a bias in range as a function of Doppler. The near perfect OFDM spike means the cross-ambiguity matched filter may need to be sampled at extremely fine granularity.

Fig. 13. Modified maximum likelihood decision region partitioning for 8-PSK communications signaling in the presence of a radar signal modeled as an interference random phase source. The different colors represent different symbol detection regions, one color for each of the 8 points in the constellation. The normal, interference-free constellation is present at radii greater than about 6. Closer to the unit circle results in a complicated decision region driven by a spatial Bessel function due to the random radar interference phase term.
constrained radar waveform design to determine the feasibility of future systems believed to be faced with growing regulatory requirements [55]. Some researchers have looked at radar estimation performance and integration time impacts on a communications user’s ability to cancel radar returns, specifically in high power radar scenarios [56]. Others have developed computationally feasible models for performance impact on meteorological radar from secondary communications users with dynamic frequency selection capability [57]. The link budget of Long-Term Evolution (LTE) systems operating in legacy radar bands at finite stand-off distances in urban environments has been calculated to determine the impact for cellular customers [58]. Others have studied regulatory exclusion zones for radar and cellular users, concluding that the stipulated stand-off range is overly conservative relative to the impact both users present to one another [59]. Some researchers have fused multiple LTE simulation and radar models to examine the impact of rotating radar users on LTE systems at various distances and cellular configurations [60].

B. Reconfigurable Systems

As a step toward joint systems, many researchers have focused on developing algorithms, waveforms, and other components to modern radio systems that can be reconfigured for either communications or radar at any given time. For example, OFDM platforms that can execute broadband communications or radar imaging depending on configuration [61, 62]. Others have used fuzzy logic to dynamically allocate bandwidth at the system level to either radar or communications depending on target dynamics [63].

C. OFDM Waveform Design

Almost immediately since the resurrected interest in joint radar-communications, multiple threads looked at OFDM as a viable option. Specifically, V2V applications were explored [64, 65]. This work was extended to include multiple targets [66], and multipath [67]. Others have worked the joint system into existing software-defined radio (SDR) architectures, using a given illumination to also simultaneously communicate the previous radar image [68]. However, often times results showed conflicting cyclic prefix requirements, data-dependent ambiguities, and trouble mitigating PAPR for typical radar power requirements. As these various problems arose, research shifted to designing joint systems to suppress side-lobes [69], maintain a constant envelope [70], or reduce PAPR [71]. Some methods attempted to remove the dependency of the data from the radar processing [23] but still suffered from conflicting cyclic prefix requirements. Others tried to minimize the effects by only allocating some sub-carriers to the radar operation [72]. In some research, combined OFDM-multiple-input multiple-output (MIMO) radar and communications is accomplished by nonuniformly spacing subcarriers to combat Doppler and range aliasing issues associated with other OFDM-based joint systems [73]. Improvements in range estimation were also found by weighting various sub-carriers to improve the joint waveform root mean square (RMS) bandwidth with constraints to control the PAPR [74]. Some have experimentally demonstrated OFDM-MIMO joint radar-communications systems employing adaptive interference cancellation [75]. Other researchers have looked at selection of OFDM phase codes in a tracking context, where prior knowledge of the target state is used to minimize Doppler ambiguity at the expense of increased PAPR [76]. Finally, work to combine MIMO radar, which itself requires orthogonal waveforms, with OFDM to create a joint system that senses radar imagery and then communicates this to users has been investigated [77]. However, Barker sequences were required to be overlaid onto the data for radar performance, greatly reducing the available communications rate. Limits to joint radar detection and data rate have been explored for OFDM systems with variable data/radar allocation in prior work as well [17].

D. Spread Spectrum Methods

Similar to OFDM, spread spectrum waveforms have been proposed for their attractive, noise-like autocorrelation properties. Some work focused on orthogonal spreading codes between the radar and communications users employing direct-sequence spread spectrum (DSSS) [78], while others looked at chirped spread spectrum (CSS) to avoid jamming between the two users [79, 80]. Ultimately, the performance of these systems is limited by the degree of orthogonality that can be obtained in the joint system, theoretically limited to the inverse of the time bandwidth product [81].

E. Adaptive Spatial Mitigation & MIMO Systems

Others looked at spatial mitigation as a method for enabling joint radar-communications coexistence. Ultimately, the systems adaptively cancel specific users by exploiting system degrees of freedom and performing array processing. For example, some researchers have looked at sharing spectrum exclusion zones for radar and cellular users, concluding that the further the angular separation, the less the radar SNR is affected by the presence of the interference. Non-trivial beamwidth separations degrade radar performance, especially at low interference SNR where the estimation and cancellation of the interference is impacted by the degradation of the signal.
between an S-band radar with LTE cellular systems by projecting the radar signal onto the null space of the interference matrix [82–84]. Some researchers have arrived at such solutions by equalizing MIMO radar systems in the presence of MIMO communications in-band interference [85], while others have developed similar results by solving for spatial filters to mitigate communications interference by exploiting MIMO degrees of freedom [86]. However, all of these spatial methods are merely a form of spatial isolation managed by radiation patterns of steered elements, and so once again rely on the classical assumption or driving to requirement of some form of isolation. Nulling interference using spatial degrees of freedom comes at a cost as well, as discussed in Reference [87]. For example, as shown in Figure 14, the degradation to radar SNR as the radar attempts to spatially mitigate an interfering communications signal is dependent on the signal strength of the interferer, as well as the beamwidth separation [47]. This unit of separation for two steering vectors $v_1$ and $v_2$ is defined as follows [47, 87]:

$$b = \frac{2}{\pi} \arccos \left( \frac{\|v_1 \cdot v_2\|}{\|v_1\| \|v_2\|} \right),$$

where $(\cdot)^\dagger$ denotes the Hermitian conjugate. This definition is normalized such that $b = 1$ corresponds to orthogonal array responses. Note also that a residual signal-to-interference-plus-noise ratio (SINR) term also remains at high interference SNR levels, as adaptive techniques match the pace of the increasing interferer strength [87].

True MIMO radar techniques have also been proposed, given the independent transmit elements could enable multiple communications receivers naturally within its framework. Some have looked at an information-based waveform design for MIMO systems that trades detection performance with favorable correlation properties while attempting to minimize communications interference [88]. Others have extended the null space projection methods previously mentioned to MIMO architectures to allow more fine control of the degrees of freedom [89]. Similarly, researchers have extended the interleaved subcarrier OFDM approaches of other work to function as a MIMO radar over traditional phased arrays [90]. Finally, matrix completion MIMO radar techniques that are inherently less susceptible to interference from an in-band MIMO communications user have been investigated in both non-cooperative and cooperative configurations [91]. The matrix completion methodology also has the advantage of requiring less bandwidth to send the radar image data to another site than traditional radar systems.

**F. Time & Polarization Orthogonalization**

Other methods of isolation include polarization [92] for co-designed systems, where a radar transceiver is on an orthogonal polarization axis relative to the communications receiver, though no performance with respect to isolation is given. Space-time dynamic isolation techniques have also been proposed, such as communications devices duty-cycling carefully to avoid spectral collisions with rotating radars [93–96] assuming knowledge of how the radar is transmitting as a function of time. In the absence of this knowledge, researchers have investigated dynamic communications schemes employing electronic intelligence (ELINT) techniques to augment knowledge aided databases and avoid active radar transmitting interference [97, 98]. As a means to combat radar interference in Wi-Fi systems, some have investigated detecting radar during Wi-Fi quiet times as a means to mitigate the radar signal within the Wi-Fi framework by switching to an interference-free channel [99]. A similar system detects radar pulse trains during quiet time and applies this knowledge to time-division duplexing (TDD) systems like WiMAX [100].

**G. Carrier Exploitation Methods**

Rather than cooperate with cellular systems, some have proposed employing the existing cellular framework as a solution to augment dwindling radar spectrum. For example, when radar functionality is required, systems can subscribe as cellular users and allocate bandwidth within the existing cellular framework [101]. We demonstrate an example of the concept outlined in Reference [101], known as radar as a subscriber technology (or RAST), in Figure 15. In this plot, the radar allocations 8 subscribers and selects 8 codes from the 32-bit Hadamard matrix to best approximate the ideal radar waveform for this system, a linear FM chirp. The approximation improves with the number of subscribers [101].

This is further enabled by recent additions to the cellular LTE standard that enable carrier aggregation, or user request of multiple carriers to access larger instantaneous bandwidth [102]. While bandwidth is still allocated to isolated users, it is done within a dynamic framework that supports needs-based resource distribution while enabling normal use of high performance cellular infrastructure. Other approaches accepting that cellular infrastructures will dominate aim to
design optimal radar waveforms that are robust to in-band, nearby cellular users and also minimize their interference to those users using non-convex optimization techniques [103].

H. Passive & Parasitic Systems

In the same line as carrier methods, many researchers sought to analyze cellular signals in a radar context should the next generation of radar systems be forced to passively exploit communications illuminations. Some researchers looked at the ambiguity function of OFDM communications transmissions [104], while others analyzed LTE waveforms and how they stack up when used for radar purposes [105]. The ambiguity function and Cramér-Rao lower bound (CRLB) for radar estimation were researched for multistatic passive radar exploiting Universal Mobile Telecommunications System (UMTS) signals in modern cellular architectures [106, 107]. Others have focused on detection for multistatic passive systems in both centralized and non-centralized processing scenarios [108]. Some researchers have investigated alternatives to matched filtering in passive radars exploiting Global System for Mobile Communications (GSM) signals using iterative least-squares methods of bounce-path estimation [109], while other research groups have employed multiple orthogonal radar waveforms with embedded communications transmissions, where one waveform is the reference and the remaining waveforms exploit the differential phase from the reference to extract the parasitic data transmission [110]. For example, in Reference [111], the authors optimize multiple spatial waveforms to modulate radar sidelobe levels while maintaining a fixed main lobe to keep radar performance constant. The modulation of the sidelobes in amplitude encode a parasitic communications data stream. A simple example of this scheme is shown in Figure 16, where two Chebyshev windows are chosen depending on if a 0 or 1 is to be transmitted. Here, there is some difference in the main lobe width since we have only modified the Chebyshev design parameter. More sophisticated optimization schemes such as those in Reference [111] ensure main lobe fidelity. Similarly, another parasitic embedded sidelobe level modulation communications scheme forms a traditional radar main beam from multiple sub-beams with various sidelobe level modulation targeted at the communications receivers [112]. Various extensions in this family of research have looked at other methods of embedding communications, for example an orthogonal waveform for each binary 1 to be encoded for the parasitic amplitude-shift keying (ASK) communications scheme, while omitting waveforms for each binary 0 [113, 114]. Others have embedded communications data streams in MIMO radars by shuffling which antennas transmit which orthogonal waveform at each illumination step in patterns defined by the data [115]. Others have looked at shared waveforms with OFDM-like schemes employing the fractional Fourier transform to modulate data onto chirped sub-carriers [116]. Some have looked at performing passive detection by observing the bit error patterns in Wi-Fi protocols [117], while others have exploited the output of a rake receiver to detect moving targets that present delayed and Doppler-offset reflections of the communications signals [118].

Signal selection relative to radar in contrast to signal selection relative to communications has been a long standing trade, tracing back over five decades [119]. Some approaches to shared waveform outside of coding have been investigated, including multiple threads researching embedded or parasitic communications. For example, some research has investigated phase modulating communications information on top of a linear FM chirp to add channel capacity while improving the ambiguity properties of the waveform with respect to radar [120]. Some have looked a more deeply embedded methods, such as a radar system modulating low-rate communications on the waveform sidelobe levels [121, 122]. Others have looked more explicitly at covert communications by embedding an OFDM waveform into a noise-radar spectrum [123]. Some researchers have looked at cooperative targets with known locations that re-radiate radar pulses back to the radar into one of many delay-Doppler cells to communicate within the radar physical layer [44, 124–126].

I. Cognitive Approaches

Advancements in cognitive radios and radar have been proposed as a natural solution to spectrum congestion problems. Traditionally, communications phenomenology has advanced beyond radar in terms of cognitive, bandwidth sharing techniques [3]. This is because radar has enjoyed access to excellent spectral resources and remained unchallenged for many decades [27]. Therefore cognitive techniques in a radar context were primarily for enhanced dynamic behavior in complex environments [127]. Researchers have begun to look at radar scheduling as an application for cognitive systems as the spectral scarcity problem has sparked interest in this area [128]. Some have looked at adapting waveforms to signal-dependent interference from communications users [129]. Others have employed cognitive techniques to estimate communications channel parameters to reduce the mutual interference between
a primary communications user and the secondary radar user [130]. This is analogous to the previously mentioned ELINT assisted techniques where the radar was the primary user. Researchers have looked to develop cognitive radar much more closely resembling cognitive radio by employing similar spectrum sensing techniques, emitter localization, and power allocation to avoid interference with cognitive radio users [131]. Others have developed cognitive techniques to extend prior work in information-theoretic waveform design for radar cross section estimation and detection to include a communications user sharing the same waveform [132, 133]. Information based techniques have been looked at for intelligent target scheduling in a cognitive framework [134], though similar to classical cognitive radios in that the resource is optimized within the radar phenomenology only. Preliminary work has compared cognitive operation of both users independently and jointly as well [135]. Nonrecurrent, nonlinear frequency-modulated continuous-wave (FMCW) waveforms with hopping spectral gaps with shaping to support range sidelobe roll-off were developed to support access from dynamic communications users and minimize interference [136]. Some researchers have noted that spectrum crowding is an issue within remote sensing allocations itself, and identified cognitive radar as a natural solution to the many user problem [137]. Other researchers have looked at various joint radar-communications mutual information criteria and means to maximize them, and noted that maximizing the mutual information did not always maximize radar probability of detection [138]. Finally, there have been examples of systems employing genetic algorithms to modulate radar spectral access opportunistically, similar to cognitive radio users [139]. A jointly cognitive system state diagram example is shown in Figure 17. Both users have to accomplish the spectrum sensing task, and so a joint receiver is used to sense both types of user in gray spectrum allocation. Once active, the dual function of the transmitter and receiver enable enhanced environmental sensing and feedback to adapt system configuration and maximize the joint mission.

### J. Joint Coding Techniques

Joint coding techniques, such as codes attractive from a communications and radar ambiguity standpoint, as well as codes that trade data rate and channel estimation error have been investigated as a solution at the symbol level. Some research has looked at direct relationships between radar estimation sidelobe ambiguity and communications channel coding [140], while others have suggested specific coding techniques that have favorable properties, such as finite Heisenberg-Weyl groups [141], Golay waveforms with Doppler resilient properties [142], and complementary sequences [143]. Complementary Golay sequences have attractive correlation properties when their autocorrelations are summed, and also bound the PAPR for OFDM communications waveforms to less than 3 dB. An example of the autocorrelation property from Reference [142] is shown in Figure 18. We used an example of the codes provided in the source paper to demonstrate the zero-sidelobe behavior of the sum. The individual autocorrelations for the two complementary sequences are shown in the solid blue line and the dashed red line. Their sum is shown in the thick, solid green line, and has no observable sidelobes to within the quantization noise of our system.

Recent work has looked at trading communications with channel state estimation [16]. However, in this case, the channel state estimation is a nuisance parameter to increasing communications throughput, not a desired radar or sensing modality. Some research has looked into coding as a means to sharing bandwidth between an OFDM radar and Global Positioning System (GPS) signal [144] to complement both operations. Oppermann sequences have also been proposed as a natural framework for developing radar waveforms with good ambiguity properties and multi-user communications access schemes [145]. Others have applied precoding to both

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**Fig. 17.** State diagram for joint radar-communications cognitive scheme. Both users need to perform the spectrum sensing task. However, in the joint case, this task is enhanced due to the dual-function circuitry which is optimized for both communications and radar sensing (instead of one or the other). Further, accomplishing both tasks in the same RF band provides improved overall sensitivity and environmental feedback into the reconfiguration task.

**Fig. 18.** Complementary Golay sequence autocorrelation properties. The two complementary codes have their individual autocorrelations shown in the solid blue line and the red dashed line. By themselves, they exhibit significant sidelobe activity. However, when the autocorrelations are summed, their complementary nature cancel all sidelobes, making them attractive for using radar ranging. This sum is shown in the solid, thick green line. For communications users, use of these codes has the benefit of bounding the potential peak-to-average power ratio.
a MIMO communications user and an in-band MIMO radar user operating in clutter, optimizing the radar precoding to maximize joint performance [146].

K. Modern Co-Designed Approaches

Modern techniques have proposed co-design and operation as a necessary construct for joint radar-communications [18]. Others have jointly maximized information criterion for radar and communications users to minimize mutual interference by varying radar waveform and communications OFDM parameters in response to dynamic bandwidth allocation [147]. In this work, the operational distance between the two users is proposed as a figure of merit. Other work has looked information exchange to reduce the minimum required standoff range between competing radar and communications users [148]. Similar work has looked at performance as a function of distance, and also the pitfalls of oversimplified models of interference in comparison to experimental results [149]. Others have investigated performance of systems in isolation compared to cooperation to demonstrate that cooperative nodes enjoy a mutual performance enhancement relative to classical isolated operation [150]. Others have begun to investigate joint radar communications in a similar context to full duplex communications, focusing on isolation between single hardware operation [151]. Some researchers are looking at highly flexible architectures to support not only radar and communications, but also electronic warfare, and are developing test beds to support future research in these areas [152]. Others have developed a Neyman-Pearson based cooperative metric that captures both radar detection performance and communications data rate in a joint cost metric with parameterizable weighting [153]. Researchers have also developed a more general framework for radar-communications joint resource management through development of joint figures of merits that encapsulate capacity, individual performance, and mutually beneficial performance [154]. Others have employed code division multiple access (CDMA)-like cancellation by decoding, re-encoding, and subtracting to mitigate interference for multiple, heterogeneous users [155]. Some researchers have looked at exploiting energy from communications users to bolster a separate radar user’s probability of detection, and optimizing the radar waveform with the in-band communications system operating as the primary user [156], while others have explored joint channel estimation as a means to measure communications data rate and radar probability of detection in the same band [157].

VI. Bounds on Jointly Optimized Systems

While state of the art systems have mild elements of co-design, future systems must be co-designed to jointly sense and communicate, maximizing spectral efficiency. Traditionally, communications performance related to spectral efficiency is measured by the channel capacity. This is the achievable, but maximum operating rate of arbitrary data communications for a given channel probability distribution [158]. For example, for a Gaussian, band-limited, power-limited system, the maximum communications data rate is defined as [159]:

\[
R_{\text{com}} \leq B \log_2 \left[ 1 + \frac{P_{\text{com},\text{rx}}}{N_0 B} \right],
\]  

where \(B\) is the receiver bandwidth, \(P_{\text{com},\text{rx}}\) is the received communications power, and \(N_0\) is the noise power spectral density.

Often, prior to recent work on information theoretic bounds, radar estimation performance limits are dictated by the CRLB. For radar range estimation, this is given by [160]:

\[
\sigma^2_{\text{CRLB}} = \frac{N_0 B}{8 \pi^2 B_{\text{rms}}^2 T_p P_{\text{rad,rx}}},
\]  

where \(T_p\) is the radar pulse duration, \(B_{\text{rms}}\) is the radar waveform RMS bandwidth, and \(P_{\text{rad,rx}}\) is the radar receive power.

While these metrics work in isolation for each user, they do not adequately measure joint performance. To address this, researchers have derived fundamental limits on joint radar and communications operation, and were successful in producing several alternative interpretations of joint radar-communications performance and bounds on those resulting joint metrics [161]. Next, we highlight several research threads that investigate bounds on joint radar-communications performance for future systems.

A. Radar Estimation Rate and Joint Bounds

To measure spectral efficiency, we look at recent research quantifying radar information as a function of time: radar estimation rate [2, 7–14]

\[
R_{\text{est}} = \frac{I(x; y)}{T},
\]  

where \(I(x; y)\) is the mutual information between random vectors \(x\) and \(y\), and \(T\) is the time period between spectral accesses. This can be a pulse repetition interval (PRI) or a target revisit period. This allows construction of joint radar-communications bounds, and allows future system designers to score and optimize systems relative to a joint information metric.

For a simple range estimation problem with a Gaussian tracking prior, this takes the form [13]

\[
R_{\text{est}} = \frac{1}{2T} \log_2 \left[ 1 + \frac{\sigma^2_{\text{proc}}}{\sigma^2_{\text{CRLB}}} \right],
\]  

where \(\sigma^2_{\text{proc}}\) is the range-state process noise variance, and \(\sigma^2_{\text{CRLB}}\) is the CRLB for range estimation given by Equation (5). One immediately notes the similarity to Equation (4), where the ratio of the source uncertainty variance to the range estimation noise variance forms a pseudo-SNR term in the Gaussian mutual information. An example of the joint multiple access channel (MAC) is shown in Figure 19 by plotting the communications data rate on one axis and the radar estimation rate on the other axis. Modern systems will attempt to get as close to the upper right hand corner of the outer manifold as possible. Here, inner bounds from prior work are shown to see how they compare to the joint theoretical limiting bounding box.
In Reference [15], a bound on radar information is formulated that looks very similar to the bound presented here. However, the mutual information in that work is between a multipath amplitude statistic before and after corruption with receiver noise. As a result, if no multipath is present, the mutual information is null. The bound shown in Figure 19 shows radar information sourced from a target tracking prior, before and after measurement. This information is typically desired (learn knowledge of target state), in contrast to the mutual information in Reference [15], which encapsulates the multipath uncertainty, typically a nuisance parameter.

B. Radar Capacity and MTI with Communications

In Reference [18], radar information capacity is formulated using range-bearing-Doppler binning moving target indicator (MTI). These capacity equations assume a discrete three-dimensional (3D) grid where a target could be present with an implicit probability of 0.5:

$$C_{\text{rad}} = \frac{1}{T} \frac{R_{\max}}{\Delta T_s} \frac{2\pi}{\Delta \theta} \Delta f_D,$$

where $R_{\max}$ is the maximum range that closes the radar range link budget, PRF is the pulse repetition frequency, $\Delta T_s$ is the sampling rate resolution, $\Delta \theta$ is the bearing resolution, $\Delta f_D$ is the Doppler resolution, and $T$ is the revisit time period. Communications rate is the same as the previous case. A similar example for this bounding interpretation is given by Figure 20. In this bound, each range cell represents a bit of information, with the probability of detection in each cell conservatively assumed to be 0.5. This means each spectral access learns through the multi-bin Bernoulli distribution. In practice, prior information reduces the probability of detection for each cell, but the plot is useful as a bound. While it may be tempting to compare Figure 20 with Figure 19, the two are inherently incompatible due to the fact they define radar information in two drastically different ways.

C. Constrained Channel Estimation and Communications

In Reference [16], information theoretic bounds on a joint capacity-distortion function are developed. In this work, the balance between sending arbitrary data and distortion in estimating the communications channel is explored. Sending less information and more known signals, the channel can be better estimated. A better channel estimate ultimately supports an increased channel capacity. However, the average rate is reduced in sending known symbols to estimate the channel.

It was shown in this work that, for a channel with uniform estimation costs, a system trying to transmit information and simultaneously perform channel state estimation can achieve the following rate-distortion tradeoff:

$$R \leq B \frac{1}{2} \log \left(1 + \frac{\gamma P_c}{P_n}\right),$$

$$D \geq \sigma^2_{\text{targ}} \frac{\gamma P_c + P_n}{\sigma_{\text{targ}}^2 + \sqrt{(1 - \gamma) P_c^2} + \gamma P_c + P_n},$$

where $B$ is the bandwidth of the system, $\gamma$ is a system parameter swept from 0 to 1, $P_c$ is the received communications power, $\sigma^2_{\text{targ}}$ is the radar residual variance after radar cancelation, and $P_n$ is the thermal noise power.

The distortion function given by Equation (10) can be viewed as the variance of estimation (channel state estimation or a more general parameter estimation) and can be applied...
to the estimation rate given by Equation (6), to obtain a ‘estimation cost’ rate. The communications rate versus the estimation cost rate curve is shown in Figure 21.

This example assumes a monostatic radar with an independently transmitted communications signal also broadcast to a destination node, or a modification to the monostatic broadcast channel covered earlier. Due to the monostatic return of the target, the radar knows the radar signal bounce path channel to the destination node, which is modeled as an additional additive Gaussian term after successive interference cancellation (SIC) processing. The joint curve shown represents the tradeoff the communications user has at estimating the bounce channel (performing radar state estimation) and communicating arbitrary data.

VII. SUMMARY

We see this work as a point of departure. We defined the problem of spectral congestion, and the more broad concern of allocation of wireless resources to remote sensing and communications systems. Applications for joint sensing-communications were discussed, both past and present. The primitive heterogeneous two-user system topologies that support RF convergence were enumerated and explored. The authors would like to thank Andrew Herschfelt, Richard Gutierrez, and Wylie Standage-Beier for their comments.

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