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Joint Radar-Communications Strategies for Autonomous Vehicles

Combining two key automotive technologies



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Self-driving cars constantly assess their environment to choose routes, comply with traffic regulations, and avoid hazards. To that aim, such vehicles are equipped with wireless communications transceivers as well as multiple sensors, including automotive radars. The fact that autonomous vehicles implement both radar and communications motivates designing these functionalities in a joint manner. Such dual-function radar-communications (DFRC) designs are the focus of a large body of recent work. These approaches can lead to substantial gains in size, cost, power consumption, robustness, and performance, especially when both radar and communications operate in the same range, which is the case in vehicular applications.

This article surveys the broad range of DFRC strategies and their relevance to autonomous vehicles. We identify the unique characteristics of automotive radar technologies and their combination with wireless communications requirements of self-driving cars. Then, we map the existing DFRC methods along with their pros and cons in the context of autonomous vehicles and discuss the main challenges and possible research directions for realizing their full potential.

Sensing and communication in autonomous vehicles

Autonomous vehicles are required to navigate efficiently and safely in a wide variety of complex uncontrolled environments. To meet these requirements, such self-driving cars must be able to reliably sense and interact with their surroundings. This acquired sensory information as well as data communicated from neighboring vehicles and roadside units are essential to avoid obstacles, select routes, detect hazards, and comply with traffic regulations, all in real time.

To reliably sense the environment, autonomous vehicles are equipped with multiple sensing technologies, including computer vision acquisition, i.e., cameras, lidar, laser-based sensors, GPS, and radar transceivers. Each of these technologies has its advantages and disadvantages. To allow accurate sensing in a broad range of complex environments, self-driving cars should simultaneously utilize all of these

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aforementioned sensors. Radar, for instance, provides the ability to accurately detect distant objects and is typically more robust to weather conditions and poor visibility compared to other competing sensing technologies [1].

Radar systems, which detect the presence of distant objects by measuring the reflections of electromagnetic probing waves, have been in use for over a century. Radar has been most commonly used in military applications, aircraft surveillance, and navigation systems. The application of radar for vehicles, referred to as *automotive radar* [2], is substantially different from traditional radar systems: most notably, automotive radar systems, which are used by mass-produced vehicles, are far more limited in size, power, and cost. Furthermore, while conventional radar aims to detect a relatively small number of distant targets, e.g., airplanes, automotive radar is required to sense in complex dense urban environments in which a multitude of scatterers at close ranges should be accurately detected. Despite these differences, today automotive radar is an established and common technology, and the vast majority of newly manufactured vehicles are equipped with radar-based autonomous driving assistance systems (ADASs) [1].

In addition to their ability to sense their environment, autonomous vehicles are also required to carry out various forms of communications, as illustrated in Figure 1: vehicle-to-vehicle (V2V) transmissions allow self-driving cars to share their attributes with neighboring vehicles; vehicle-to-infrastructure (V2I) messages facilitate intelligent road management by conveying information between cars and roadside units; vehicle-to-pedestrian (V2P) communications can be used to warn or alarm nearby pedestrians; and, finally, service providers and cloud applications exchange possibly large amounts of data with self-driving cars via vehicle-to-network (V2N) and vehicle-to-cloud (V2C) links, respectively. The resulting broad range of different tasks, which substantially vary in their latency, throughput, and reliability requirements, can be implemented by using individual communications technologies for each application or by using a unified vehicle-to-everything (V2X) strategy [3], possibly building upon the cellular infrastructure.

Automated cars, thus, implement two technologies that rely on the transmission and processing of electromagnetic signals: radar and wireless communications. A possible approach in designing self-driving cars is to use individual systems for radar and communications, each operating separately. An alternative strategy is to jointly design these functionalities as a DFRC system. Such schemes are the focus of extensive recent research attention [4]–[20]. In particular, it was shown that jointly implementing radar and communications contributes to reducing the number of antennas [21], system size, weight, and power consumption [6] as well as alleviating concerns for electromagnetic compatibility and spectrum congestion [5]. Utilizing such joint designs in vehicular systems can mitigate the mutual interference among neighboring cars, facilitate coordination, and improve pedestrian detection [22]. These benefits make DFRC systems an attractive technology for autonomous vehicles.

While the conceptual advantages of joint radar-communications designs for autonomous vehicles are clear, the proliferation of different DFRC strategies makes it difficult to identify what scheme is most suitable for which scenario. For example, some DFRC methods use existing V2X communications waveforms as radar probing signals, thus allowing high communication throughput with relatively limited sensing capabilities [17], [18]. Alternative schemes embed digital messages in the radar probing signals [15], [16], thus supporting low data rates, which may be more suitable to serve as an additional channel to the standard communications functionalities of autonomous vehicles.

The goal of this article is to review DFRC technologies in light of the unique requirements and constraints of self-driving cars, facilitating the identification of the proper technology for different scenarios. We begin by reviewing the basics of automotive radar, identifying its main challenges, recent advances, and fundamental differences from conventional radar systems. We then survey DFRC methods, dividing previously proposed approaches into four main categories: coordinated signals transmission methods utilizing individual signals for each functionality; communications waveform-based schemes, which use the communications signal

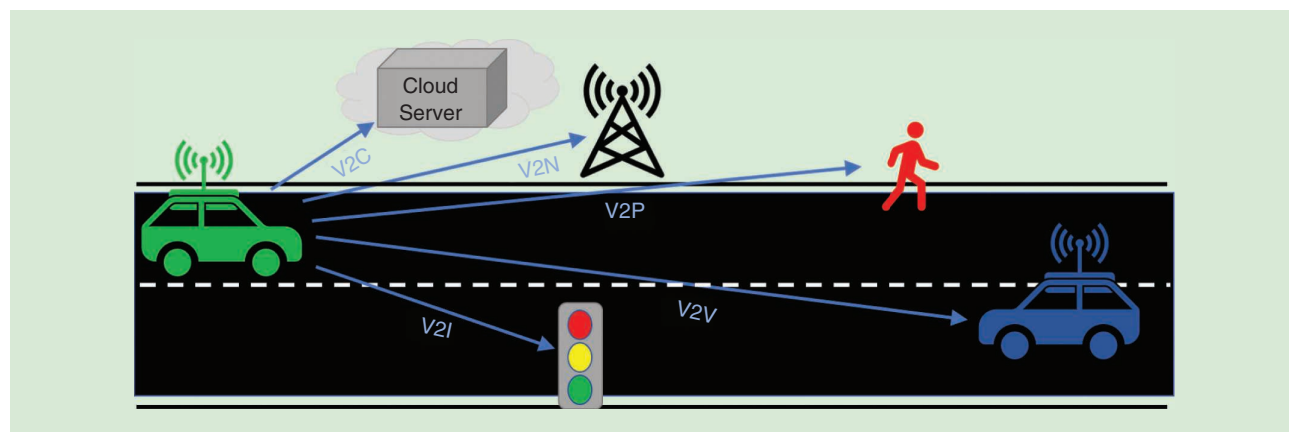


FIGURE 1. The autonomous vehicle communications links.

as a radar probing waveform; radar waveform-based techniques, which embed the digital message into the parameters of the radar signal; and the design of dedicated dual-function waveforms. We detail a representative set of DFRC methods for each category and provide a map of the existing strategies in terms of their radar capabilities, information rates, and complexity.

Basics of automotive radar

Past decades have witnessed growing interest in automotive radar to improve the safety and comfort of drivers. A typical ADAS implements various radar subsystems that enable functions including adaptive cruise control, blind-spot detection, and parking assistance [1]. To understand the benefits of combining automotive radar with digital communications, we first review the basics of automotive radar.

Automotive radars operate under different requirements and constraints compared to conventional radars, such as those utilized in military applications and air traffic control. First, conventional radar systems are required to detect a relatively small number of targets in ranges on the order of tens or hundreds of kilometers, while automotive radars must detect a multitude of objects in short ranges on the order of a few tens of meters. Furthermore, automotive radars are incorporated into mass-produced vehicles and, hence, have more strict constraints on cost, size, power consumption, and spectral efficiency compared to conventional radar. Finally, automotive radars are densely deployed in urban environments;

thus, they must be robust to interference while inducing minimal interference with neighboring radar systems.

Various techniques have been proposed to overcome the aforementioned challenges. In Table 1, we summarize the main challenges along with the leading methods to tackle them. It is noted that no single radar scheme is suitable to handle the complete set of requirements. For example, the popular frequency-modulated continuous-wave (FMCW) waveform (see “Frequency-Modulated Continuous-Wave Radar”), which can be operated using simplified hardware components, suffers from high sensitivity to interference;

Table 1. Automotive radar requirements.

Requirements	Possible Solutions
Operating in short ranges	Utilize separate transmit and receive antennas to process short-range echoes.
Limited antenna size	Operate at mm-wave bands using patch antennas. Increase virtual aperture (see “Multiple-Input, Multiple-Output Radar”).
Simplified hardware	Constant envelope signaling. Low-complexity dechirp recovery, e.g., FMCW (see “Frequency-Modulated Continuous-Wave Radar”).
Low-power amplifiers	Continuous or high duty cycle waveform, e.g., FMCW.
Interference robustness	Divide spectrum using OFDM (see “Orthogonal Frequency-Division Multiplexing Waveform Radar”). Introduce agility (see “Frequency Agile Radar”) to increase survivability.

mm-wave: millimeter-wave.

Frequency-Modulated Continuous-Wave Radar

Frequency-modulated continuous-wave (FMCW) radar is a continuous constant modulus radar waveform with a linearly modulated frequency, which can be generated and detected using simplified hardware. To present FMCW, we consider a radar system equipped with a single transmit antenna and a uniform linear array with L_r elements for receiving. In each radar coherent processing interval, M FMCW pulses of duration T_p are periodically transmitted with a pulse repetition interval (PRI) denoted by T_{PRI} , where T_{PRI} is slightly larger than T_p . The m th pulse is given by $s_m(t) = e^{j2\pi f_c t + j\gamma t^2}$, $t \in [mT_{\text{PRI}}, mT_{\text{PRI}} + T_p]$, where f_c is the carrier frequency, and γ is the frequency modulation rate.

To formulate the received signal, assume P targets are located in the far field. The distance, velocity, and angle of the p th target are denoted as r_p , v_p , and θ_p , respectively. For the p th target, with the far-field assumption, the round time delay between the transmit antenna and the l th receiver is $\tau_{l,p} = (2(r_p + v_p t) - ld \sin \theta_p)/c$, where d is the distance between adjacent elements in the receiving array, and c is the speed of light. The radar echo received in the l th receiving antenna during the m th transmit pulse is represented as $r_{m,l}(t) = \sum_{p=0}^{P-1} \alpha_p s_m(t - \tau_{l,p}) + w_l(t)$, where

α_p is the complex reflective factor of the p th target, and $w_l(t)$ is additive white Gaussian noise.

To process the received signal, $r_{m,l}(t)$ is mixed with the transmit signal. This procedure, referred to as *dechirp*, yields a demodulated signal given by $y_{m,l}(t) = r_{m,l}(t) \cdot s_m^*(t)$, i.e.,

$$y_{m,l}(t) = \sum_{p=0}^{P-1} \tilde{\alpha}_p e^{-j2\pi \left(\frac{2\gamma r_p}{c} + \frac{2v_p f_c}{c} \right) (t - mT_{\text{PRI}}) - j2\pi f_c \frac{2nv_p T_{\text{PRI}}}{c} + j2\pi \frac{ld f_c \sin \theta_p}{c}} + \tilde{w}_{m,l}(t), \quad (S1)$$

where $(\cdot)^*$ is the complex conjugate, $\tilde{\alpha}_p := \alpha_p e^{-j2\pi f_c \frac{2r_p}{c}}$, and $\tilde{w}_{m,l}(t) := w_l(t) \cdot s_m^*(t)$.

After dechirp, the waveform frequency is typically much smaller compared to the bandwidth of the transmitted waveform, and it can be sampled with low-speed analog-to-digital converters. It follows from (S1) that the targets' range, velocity, and direction can then be recovered from the 3D discrete Fourier transform of the sampled $y_{m,l}$ in the fast time domain (within a pulse), slow time domain (between pulses), and spatial domain (over antennas), respectively.

orthogonal frequency-division multiplexing (OFDM) radar (described in “Orthogonal Frequency-Division Multiplexing Waveform Radar”), which is suitable for multiuser scenarios, tends to require relatively costly hardware compared to alternative radars. An additional aspect that should be considered in selecting an automotive radar scheme is its capability to be combined with wireless communications. The fact that self-driving cars utilize both radar and digital communications motivates their joint design as a DFRC system, as discussed in the following section.

Overview of dual-function systems

Since DFRC systems implement both radar and communications using a single device, these functionalities inherently share some of the system resources, such as spectrum, antennas, and power. Broadly speaking, existing DFRC methods can be divided into four main categories as illustrated in Figure 2: coordinated separated signals transmission, communications waveform-based approaches, radar waveform-based schemes, and joint dual-function waveform designs. In the following, we review each of these categories and discuss their pros and cons in the context of autonomous vehicles. Throughout this section, we consider a DFRC system jointly implementing a radar transceiver as well as the transmission of digital messages using L_T transmit antennas (for both radar and communications) and L_R receive antennas (for radar). For simplicity,

we assume a single communications receiver equipped with a single antenna.

Separate coordinated signals

A common DFRC approach is to utilize different signals for radar and communications, designing the functionalities to mitigate their cross interference, as illustrated in Figure 2(a). Here, the $L_T \times 1$ transmitted signal can be written as

$$s(t) = s^{(r)}(t) + s^{(c)}(t), \quad (1)$$

where $s^{(r)}(t)$ is the radar probing waveform, and $s^{(c)}(t)$ is the continuous-time communications signal. The ability to jointly transmit two dedicated signals with limited cross interference is typically achieved using either orthogonality boosting by division in time and/or frequency or via spatial beamforming.

Time-frequency division

Arguably, the most simple method to mitigate cross interference is to allocate a different frequency band to each waveform, commonly dictated by regulated spectrum allocation, or, alternatively, a different time slot. In such cases, the signals $s^{(r)}(t)$ and $s^{(c)}(t)$ in (1) either reside in different bands (for frequency division) or satisfy $s^{(r)}(t)s^{(c)}(t)^T = \mathbf{0}$ at each time instance (for time division). Since system resources are allocated between both subsystems, these strategies

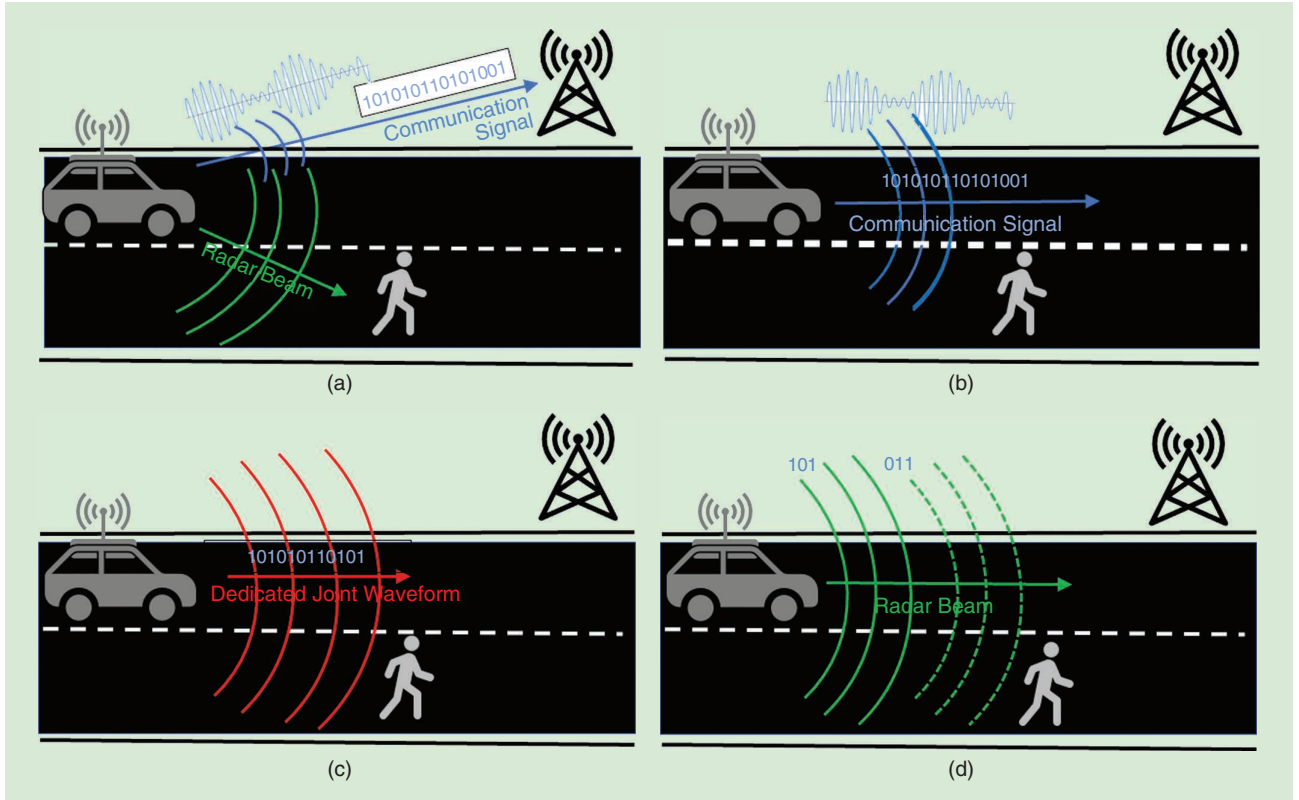


FIGURE 2. An illustration of DFRC strategies for autonomous vehicles: (a) coordinated signals, (b) communications waveform based, (c) dual-function waveform, and (d) radar waveform based. The blue, green, and red waveforms represent communications signals, radar beams, and dedicated dual-function waveforms, respectively.

inevitably result in a tradeoff between radar and communications performance [19].

A straightforward approach is to allocate the resources in a fixed or arbitrary manner. For instance, in [21], a DFRC system is achieved by using fixed nonoverlapping bands and antennas. A random antenna allocation scheme is proposed in [14], jointly enhancing the radar angular resolution and the communication rates. The work [20] proposed a media access protocol for automotive DFRC systems with time and frequency division to mitigate interference with neighboring radars. These approaches assume that each functionality has its own frequency band. Using OFDM signaling, i.e., letting the entries of $s^{(r)}(t)$ and $s^{(c)}(t)$ represent OFDM radar and communications waveforms (see ‘‘Orthogonal Frequency-Division Multiplexing Waveform Radar’’), respectively, allows the division of the spectrum in an optimized manner, as we detail next.

Consider a frequency band divided into N subbands. The discrete-time transmitted signal from the l th transmit antenna can be written as the $N \times 1$ vector s_l . Since the spectrum is divided into radar and communications, s_l is given by

$$s_l = \mathbf{F}^H [\mathbf{U}_l s_l^{(r)} + (\mathbf{I} - \mathbf{U}_l) s_l^{(c)}], \quad (2)$$

where \mathbf{F}^H is the inverse discrete Fourier transform (DFT) matrix; the $N \times 1$ vectors $s_l^{(r)}$ and $s_l^{(c)}$ denote the OFDM radar and communications symbols, respectively, in the frequency domain; and \mathbf{U}_l is a diagonal matrix of size $N \times N$ with elements zero or one, representing the subcarrier selection at the l th element.

Setting the matrix \mathbf{U}_l in (2) determines how the bandwidth is divided. The work [23] showed that when \mathbf{U}_l represents spectral interleaving, i.e., the support of its diagonal consists of multiple bulks of zeros and ones, radar resolution is comparable to that using the complete spectrum. When the DFRC system has a priori knowledge of the statistical model of the radar target response and the communications channel, the subcarrier selection matrix \mathbf{U}_l can be set to optimize a linear combination of the radar target-echo mutual information and the communications input–output mutual information, as proposed in [13].

Spatial beamforming

The utilization of multiple antennas enables the mitigation of mutual interference through spatial beamforming, for example, by projecting the radar waveform into the null space of its channel to the communications receiver [24], resulting in a zero forcing beamformer. While such beamforming was originally proposed for separate systems, it can also be utilized for a DFRC system.

In this model, the communications and radar signals are beamformed using the matrices $\mathbf{U}^{(c)}$ and $\mathbf{U}^{(r)}$, respectively, to mitigate the mutual interference while satisfying the performance constraints. The signals received at the communications receiver and the radar target with direction θ are, thus,

$$\begin{aligned} y^{(c)} &= \mathbf{h}^T (\mathbf{U}^{(r)} \mathbf{s}^{(c)} + \mathbf{U}^{(r)} \mathbf{s}^{(r)}) + w^{(c)}, \text{ and} \\ y_{\theta}^{(r)} &= \mathbf{a}^T(\theta) (\mathbf{U}^{(c)} \mathbf{s}^{(c)} + \mathbf{U}^{(r)} \mathbf{s}^{(r)}), \end{aligned} \quad (3)$$

where \mathbf{h} is the channel response from the DFRC transmitter to the communications receiver, and $\mathbf{a}(\theta)$ is the steering vector of the DFRC transmitter to the radar target in direction θ . Using (3), the beamforming matrices $\mathbf{U}^{(c)}$ and $\mathbf{U}^{(r)}$ are jointly designed to mitigate cross interference while satisfying the performance requirements, e.g., maximizing the signal-to-interference-plus-noise ratio (SINR) at the communications receiver while meeting a given radar beampattern [25].

A clear advantage of the separated signals transmission strategy is that it can provide a wide variety of possible performance combinations. For time–frequency division schemes, the performance is determined by how the system resources, such as spectrum and time slots, are allocated to each functionality. The performance tradeoffs may be potentially improved using spatial beamforming, allowing each functionality to utilize the full bandwidth and operate simultaneously at all time slots. However, the spatial beamformer is designed based on a priori channel knowledge, which may be unavailable for fast-moving vehicles. According to the previously given discussion, time–frequency division-based schemes are likely to be more attractive in automotive applications. Since properly optimizing the resource allocation to achieve a desired performance tradeoff requires considerable computation, fixed suboptimal allocations, such as spectral interleaving, may be preferable.

Communications waveform-based schemes

Another common DFRC strategy is to utilize standard communications signals for probing, as illustrated in Figure 2(b). The majority of communications waveform-based designs in the literature utilize OFDM signaling, especially for automotive applications. In the sequel, we first briefly review spread spectrum-based DFRC systems, followed by a more detailed presentation of shared OFDM waveforms and a description of how structured vehicular communications protocols can be used for sensing.

Spread spectrum waveforms

Spread spectrum techniques transmit a communications signal with a given bandwidth over a much larger spectral band, typically using spread coding or frequency hopping. The usage of spread spectrum signals for radar probing was studied in [9]. The main drawback of spread spectrum DFRC design is that the radar dynamic range is limited, which is a by-product of the imperfect autocorrelation properties of the spreading sequences [9]. In addition, accurately recovering the target velocity from spread spectrum echoes is typically computationally complex, limiting the applicability of such DFRC systems. Finally, high-speed analog-to-digital converters (ADCs) are required for wideband spectrum spread waveforms, as dechirp used in FMCW is not applicable, increasing cost and complexity.

OFDM waveforms

The most common communications waveform-based approach is to utilize OFDM signaling. OFDM is a popular digital communications scheme due to its spectral efficiency, inherent ability to handle intersymbol interference, and the fact that it

can be implemented using relatively simple hardware components. Since first proposed in [29], OFDM has received extensive attention as a radar waveform, especially for automotive radar, due to its high flexibility and adaptability in transmission and since, unlike FMCW, it does not suffer from range–Doppler coupling [30]. The fact that OFDM is commonly utilized in both radar and communications indicates its potential for DFRC systems.

Compared with the case where the coefficients $\{a_{m,n}\}$ in the OFDM waveform are specifically designed for radar (see “Orthogonal Frequency-Division Multiplexing Waveform Radar”), the complex weights of the dual-function OFDM waveform are the communications symbols. The setting of the waveform parameters can have a notable effect on each functionality. The work [31] designed the subcarrier spacing according to the maximum unambiguous range and the maximum velocity. In [6], channel knowledge was used to allocate power between the subcarriers to maximize the sum of the data rate and the mutual information between the received echoes and the target impulse response. Radar processing of OFDM waveforms utilizes matched filtering, which depends on the transmitted data, causing high-level sidelobes. This data dependency can be eliminated by dividing each subcarrier by its corresponding symbol [9]. The range and velocity of each target are then estimated using a 2D DFT in the carrier domain and slow time domain (between different symbols), respectively.

OFDM can be naturally combined with multiple-input, multiple-output (MIMO) radar, which transmits orthogonal waveforms from each antenna (see “Multiple-Input, Multiple-Output Radar”) by assigning different subcarriers to different transmit elements. Several works have studied how to divide the subcarriers among the elements. The proposed methods include division by equidistant subcarrier interleaving [23], nonequidistant subcarrier interleaving [32], and random assignments [33].

A drawback of using shared OFDM waveforms in vehicular systems stems from the fact that, when utilized from moving vehicles, OFDM exhibits subcarrier misalignment, degrading the maximal radar unambiguous range [30]. Additional drawbacks are related to hardware constraints: wideband OFDM waveforms require high-rate ADCs, affecting the system cost and power consumption. Another hardware limitation of OFDM compared to monotone waveforms is its high peak-to-average-power ratio, inducing distortion in the presence of practical nonlinear amplifiers. A weighted OFDM method was proposed to control the maximum peak-to-average power ratio [26], [27]. To utilize OFDM with narrowband transmissions, one can apply stepped frequency methods, as proposed in [33].

Protocol-oriented DFRC methods

An alternative strategy is to exploit the existing communications protocols, utilizing them as an automotive radar waveform. Here, there is no compromise in the communications part, and the radar functionality is a byproduct of the protocol, which is typically IEEE 802.11p or IEEE 802.11ad [17], [18], [35], [36]. The IEEE 802.11p standard focuses on vehicular communications and supports short-range device-to-device transmissions for safety applications. This protocol operates in the 5.9-GHz band and uses OFDM signaling. Consequently, its transmissions realize a DFRC system with an OFDM shared waveform, as proposed in [17].

IEEE 802.11ad is a generic standard for short-range millimeter-wave (mm-wave) communications operating at 60 GHz. Its large bandwidth enables higher data rates for communications and better accuracy/resolution for radar operation. To avoid the usage of data-dependent waveforms, it has been proposed that the a priori known IEEE 802.11ad preamble be used for radar probing [18]. As the preamble now affects radar performance, the work [36] studied the design of radar-suitable preamble sequences. In such mm-wave communications, highly

Orthogonal Frequency-Division Multiplexing Waveform Radar

For an orthogonal frequency-division multiplexing (OFDM) waveform radar with N subcarriers, the transmit signal at the m th pulse is

$$s_m(t) = \sum_{n=1}^N a_{m,n} \text{rect}\left(\frac{t - mT_O}{T_O}\right) e^{j2\pi(f_c + f_n)t}. \quad (\text{S2})$$

In (S2), $\{a_{m,n}\} \in \mathcal{A}$ are complex weights transmitted over the m th symbol on carrier f_n , which can be either fixed or randomized from some discrete set \mathcal{A} ; $\text{rect}(t)$ is a rectangular window of unity support; $T_O = T_S + T_{CP}$ is the OFDM symbol duration; T_S is the elementary symbol duration; T_{CP} is the duration of the cyclic prefix; and $f_n = (n - 1)(1/T_S)$. Using the notations in (S1), the radar echo from P targets observed by the l th receive antenna can be approximated by

$$y_{m,l}(t) \approx \sum_{p=1}^P \sum_{n=1}^N \tilde{\alpha}_p \cdot a_{m,n} \text{rect}\left(\frac{t - mT_O - \frac{2r_p}{c}}{T_O}\right) \times e^{j2\pi f_n \left(t - \frac{2r_p}{c}\right) - j2\pi f_c \frac{2v_p - l \sin \theta_p}{c} t} + w_l(t). \quad (\text{S3})$$

OFDM radar processing is based on matched filtering [S1]. Its performance is determined by the complex weights, which can be optimally designed according to some requirements, e.g., the maximum peak-to-average ratio of the transmit signal [26] or the Cramér–Rao bound [27].

Reference

[S1] D. Garmatyuk, J. Schuerger, and K. Kauffman, “Multifunctional software-defined radar sensor and data communication system,” *IEEE Sensors J.*, vol. 11, no. 1, pp. 99–106, 2010. doi: 10.1109/JSEN.2010.2052100.

Multiple-Input, Multiple-Output Radar

Multiple-input, multiple-output (MIMO) radar uses multiple transmit and receive antennas. By transmitting orthogonal waveforms from each antenna, one can generate a virtual array with larger aperture, increasing the angular resolution without requiring additional hardware elements. While MIMO radar can also be combined with nonorthogonal waveforms, we focus on such systems transmitting orthogonal waveforms, which is the common practice in MIMO radar [34].

To formulate MIMO radar transmission, let L_T and L_R be the numbers of transmit and receive antenna elements, respectively. The adjacent distances of the transmit antenna and the receive antenna are d_T and d_R , respectively. A common practice is to set $d_T = L_R d_R$. We use $\mathbf{s}(t) = [s_1(t), s_2(t), \dots, s_{L_T}(t)]^T$ for the transmit waveforms, which are orthogonal, namely, $\int s_i(t) s_j^*(t) dt = \delta(|l-l'|)$, where $\delta(\cdot)$ is the Kronecker delta. For simplicity, we consider a single pulse and targets associated with a particular range and Doppler bin. The received signal is

$$\mathbf{y}(t) = \sum_{p=1}^P \alpha_p \mathbf{a}^T(\theta_p) \mathbf{s}(t) \mathbf{b}(\theta_p) + \mathbf{w}(t), \quad (\text{S4})$$

where $\mathbf{a}(\theta) := [1, e^{j2\pi f_c d_T \sin \theta/c}, \dots, e^{j2\pi f_c (L_T-1) d_T \sin \theta/c}]^T$ is the transmit steering vector, $\mathbf{b}(\theta) := [1, e^{j2\pi f_c d_R \sin \theta/c}, \dots, e^{j2\pi f_c (L_R-1) d_R \sin \theta/c}]^T$ is the receive steering vector in direction θ , and $\mathbf{w}(t)$ is white Gaussian noise. Applying matched filtering and vectorization yields

$$\tilde{\mathbf{y}} = \text{vec}\left(\int \mathbf{y}(t) \mathbf{s}^H(t) dt\right) = \sum_{p=1}^P \alpha_p \mathbf{a}(\theta_p) \otimes \mathbf{b}(\theta_p) + \tilde{\mathbf{w}}, \quad (\text{S5})$$

where $\text{vec}(\cdot)$ is the vectorization operator, $\tilde{\mathbf{w}} := \text{vec}(\int \mathbf{w}(t) \mathbf{s}^H(t) dt)$, and \otimes is the Kronecker product. Since $\mathbf{a}(\theta_p) \otimes \mathbf{b}(\theta_p) = [1, e^{j2\pi f_c d_R \sin \theta_p/c}, \dots, e^{j2\pi f_c (L_T L_R - 1) d_R \sin \theta_p/c}]^T$ it holds that MIMO radar achieves an equivalent angle resolution of a phased array radar with $L_T L_R$ receive antennas in this configuration, effectively enhancing the angular resolution by a factor of L_T .

directional beams are used. Once the communications data link is established, radar can only reliably detect targets located in the assigned beam direction. Several approaches have been proposed to extend the scanning area at the cost of power reduction in [36].

The main benefit of protocol-based DFRC designs is that they implement radar with minimal effect on the communications functionality. As such, their radar capabilities are quite limited. The radar coverage area is restricted by the directionally beamformed mm-wave transmission. In addition to its restricted coverage area, the scheme has a relatively low radar duty cycle as only the preamble is utilized for probing, limiting its detection range in vehicular systems operating under peak power constraints.

To conclude, communications waveform-based DFRC approaches, and particularly those using shared OFDM signaling, enable the transmission of high data rates by utilizing conventional digital communications schemes. The fact that OFDM is widely studied for both radar and communications makes it an attractive DFRC design. In the context of autonomous vehicles, several drawbacks must be accounted for: first, to radiate enough power on the target, radar waveforms are typically beamformed to be directional. The communications receivers should, thus, be located in the radar beam to observe high signal-to-noise ratios. Such transmissions may, thus, be more suitable to serve as a secondary communications channel in addition to a possible cellular-based V2X technology, which can communicate with the receivers in the omnidirection. Similarly, protocol-oriented schemes, which utilize standard communications transmission while exploiting its structure for probing, are more likely to provide additional sensing capabilities to a dedicated automo-

tive radar. Finally, relatively costly hardware components are required for generating wideband waveforms and sampling their reflections. Despite these drawbacks, sensing using communications waveforms is considered to be a promising DFRC approach for autonomous vehicles [1].

Radar waveform-based techniques

DFRC systems can also be designed by embedding the communication message in conventional radar waveforms, as illustrated in Figure 2(d). These techniques are divided into two categories: the first approach modifies the radar waveform to incorporate digital modulations; the second method utilizes index modulation (IM), conveying data bits via the indices of certain radar parameters.

Modified radar waveforms

A possible approach to embed digital communications into an existing radar system is to modify the waveform to include modulated symbols. For example, the traditional FMCW (see ‘‘Frequency-Modulated Continuous-Wave Radar’’) can be modified to include phase-modulated symbols by replacing the m th pulse $s_m(t)$, defined in ‘‘Frequency-Modulated Continuous-Wave Radar,’’ with $s_m(t) e^{j\phi_m}$, where ϕ_m encapsulates the information message in the form of, e.g., continuous phase modulation as proposed in [37]. Alternatively, the linear frequency of the pulse can convey information via frequency modulation [39], for example, by using a positive frequency modulation rate γ to transmit the bit one and a negative value for zero. While these schemes are typically power efficient [9] and have low complexity, their communication rate is very limited.

Higher communication rates can be obtained by utilizing multiple orthogonal waveforms and beamforming. Assume J

A promising approach to tackle mutual interference between radars is to utilize frequency agile radar (FAR) [S2]. Here, a subband waveform (of a much narrower bandwidth compared to the available band) is transmitted in each cycle, and its central frequency varies randomly from cycle to cycle. These random variations reduce the spectral collision probability from neighboring radars.

To formulate the signal model, we use $\mathcal{F} = \{f_c + (n-1)\Delta f | n = 1, 2, \dots, N\}$ to denote the carrier frequency set, where Δf is the carrier spacing. During the m th transmit pulse, the transmitted signal is $s_m(t) = e^{j2\pi f_m t}$, where f_m is randomly chosen from \mathcal{F} . After demodulation, the signal observed at the l th receive antenna can be expressed using the notations of (S1) as

$$y_{m,l}(t) = \sum_{p=1}^P \alpha_p e^{-j2\pi f_m \frac{2r_p}{c} - j2\pi f_m \frac{2v_p(m-1)T_{\text{PRI}}}{c} + j2\pi f_m \frac{ld \sin \theta_p}{c}} + w_l(t). \quad (\text{S6})$$

orthogonal waveforms $\{s_j(t)\}_{j=1}^J$ are simultaneously transmitted from an antenna array, and let $\{\mathbf{u}_j\}_{j=1}^J$ be the corresponding beamforming vectors. The transmit signal is expressed as $s(t) = \sum_{j=1}^J \mathbf{u}_j s_j(t)$. In the communications receiver, the received signal is $y^{(c)}(t) = \mathbf{g}_c^T s(t) + w^{(c)}(t)$, where \mathbf{g}_c and $w^{(c)}(t)$ are the channel response and additive noise, respectively. By applying matched filtering with the orthogonal waveforms, the receiver obtains the vector $\mathbf{y}^{(c)} = [y_1^{(c)}, y_2^{(c)}, \dots, y_J^{(c)}]^T$, where $y_j^{(c)} = \mathbf{g}_c^T \mathbf{u}_j + w_j^{(c)}(t)$. The communication data bits can be conveyed by modulating the amplitude [7] or phase [8] of $\mathbf{g}_c^T \mathbf{u}_j$. Although the communication rates are improved by transmitting multiple waveforms, the system complexity is also increased, and the transmitter must have a priori knowledge of the communications channel \mathbf{g}_c . Furthermore, it is difficult to guarantee that the envelope of the transmit signal is constant modulus, which may reduce power efficiency in transmission.

IM-based techniques

IM is a promising communications technique, gaining growing interest due to its high energy and spectral efficiency [40]. Instead of using conventional modulations, IM embeds data bits into the indices of certain transmission building blocks [40]. These building blocks, including spatial allocation and frequency division, are also important waveform parameters for radar. IM-based DFRC techniques, thus, embed the digital message into the combination of radar waveform parameters. The term *index* represents the radar parameters, such as carrier frequency, time slot, antenna allocation, or orthogonal waveforms in MIMO radar with orthogonal waveforms. Consequently, such DFRC systems use unmodified conventional radar schemes, and the ability to communicate is encapsulated in the parameters of the transmission. While IM-based

Using matched filtering, FAR can synthesize a large bandwidth and enables the generation of high range resolution profiles. However, the random changing of carrier frequency leads to a high sidelobe level, which affects the detection of weak targets. To mitigate the sidelobe problem, compressed sensing methods can be applied for range–Doppler processing [S3], while recovery guarantees for such methods are provided in [S4] under sparse and block-sparse target scenes, respectively.

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DFRC schemes are the focus of ongoing research, existing methods typically build upon either MIMO radar or frequency agile radar (FAR) schemes. While MIMO radar can, in general, utilize orthogonal or nonorthogonal waveforms, we henceforth use the term *MIMO radar* for such schemes utilizing orthogonal waveforms, which is the typical approach in MIMO radar [35].

IM for MIMO radar

The work [40] proposed to combine MIMO radar with IM by embedding the bits in the assignment of the orthogonal waveforms across the transmit antennas. For a MIMO radar with L_T transmitting antennas, there are $L_T!$ possible arrangements in each pulse repetition interval (PRI), supporting a maximal rate of $\log L_T!$ bits per PRI. In [41], this approach was extended to sparse array MIMO radar configurations, where only K out of L_T transmit elements are active in each PRI. As a consequence, it requires only K transmit orthogonal waveforms, represented (with a slight notation abuse) by the vector $s(t) = [s_1(t), s_2(t), \dots, s_K(t)]^T$. The transmitted $L_T \times 1$ vector $\tilde{s}(m, t)$ in the m th PRI is a permutation of $s(t)$, i.e., it is given by $\tilde{s}(m, t) = \mathbf{\Omega}_M^T \mathbf{\Lambda}^T(m) s(t)$, where $\mathbf{\Lambda}(m)$ is a $K \times K$ permutation matrix, and $\mathbf{\Omega}_M(m) \in \{0, 1\}^{K \times L_T}$ is the antenna selection matrix, which has a single nonzero entry in each row. When the channel is memoryless, the signal received at the communications receiver is

$$y^{(c)}(m, t) = \mathbf{g}_c^T(m) \tilde{s}(m, t) + w^{(c)}(m, t), \quad (4)$$

where \mathbf{g}_c is the $L_T \times 1$ channel vector, and $w^{(c)}(m, t)$ is the additive noise. After matched filtering with the orthogonal waveforms, the obtained vector can be written as

$$\mathbf{y}^{(c)}(m) = \int y^{(c)}(t, m) s(t) dt = \mathbf{\Lambda}(m) \mathbf{\Omega}_M(m) \mathbf{g}_c + \mathbf{w}(m). \quad (5)$$

The communication message can be embedded in $\mathbf{\Lambda}(m) \times \mathbf{\Omega}_M(m)$ in (5), i.e., the product of the permutation matrix and selection matrix. As there are $\binom{L_T}{K}$ kinds of antenna selection patterns and $K!$ kinds of waveform permutations, up to $\log_2 \binom{L_T}{K} + \log_2 K!$ bits can be encapsulated in each PRI.

IM via FAR

FAR (see ‘‘Frequency Agile Radar’’) is a radar scheme designed for congested environments. The carrier frequencies of FAR change randomly from pulse to pulse, allowing the achievement of an ergodic wideband coverage, while utilizing narrowband waveforms and enabling the mitigation of interference from neighboring radars. The work [42] proposed a DFRC system that embeds a digital message into the permutation of the agile carrier frequencies. For a carrier set with N different carrier frequencies, there are $N!$ different carrier frequency permutations that can be utilized for information embedding.

In [15] and [16], a DFRC system is proposed based on multicarrier agile waveforms and IM. Unlike traditional FAR, here, multiple carriers are simultaneously sent from several subarrays of transmit antennas. For a DFRC system with L_T transmit antenna elements and a possible carrier frequency set \mathcal{F} of cardinality N , the corresponding information embedding consists of two stages: in the m th pulse, $K < N$ carriers, denoted by the set $\{f_{m,1}, \dots, f_{m,K}\}$, are first selected from \mathcal{F} . Then, the antenna array is divided into K subarrays, where each subarray has $L_K = L_T/K$ elements. The transmitted signal of the multicarrier frequency agile DFRC system in the m th PRI is expressed as

$$\tilde{s}(m, t) = \sum_{k=1}^K \mathbf{\Omega}_F(m, k) \mathbf{u}(\theta, f_{m,k}) \text{rect}\left(\frac{t - mT_p}{T_p}\right) e^{j2\pi f_{m,k}(t - mT_p)}, \quad (6)$$

where θ is the beamsteered direction; $\mathbf{u}(\theta, f_{m,k})$ is the radar beamforming vector for the k th carrier with frequency $f_{m,k}$; and $\mathbf{\Omega}_F(m, k)$ is the selection matrix, which determines the transmit antennas of carrier with frequency $f_{m,k}$. The communication message is embedded into the antenna allocation pattern as well as the selection of carrier frequencies. The number of antenna allocation patterns is $L_T! / (L_K!)^K$, and there are $\binom{N}{K}$ possible combinations of carrier selections. Hence, the total number of transmission patterns that can be used for information embedding is $\binom{N}{K} \cdot L_T! / (L_K!)^K$. An illustration of this scheme as well as a hardware prototype designed in [14] to demonstrate its feasibility are shown in Figure 3.

Since IM-based DFRC systems utilize conventional radar waveforms, radar detection is carried out using standard methods. For example, FAR detection is based on matched filtering followed by compressed sensing recovery [43]. Symbol detection at the communications receiver can be realized using the maximum likelihood rule or, alternatively, via a reduced complexity IM detector; see, e.g., [15].

The main advantage of radar waveforms-based DFRC methods is that they provide the ability to communicate with minimal degradation to the performance of the radar scheme from which the technique originates. For example, the radar performance of MIMO radar as well as FAR combined with IM are roughly equivalent to their radar-only counterparts [16], respectively. In particular, FAR is attractive for automotive radar due to its inherent applicability in congested setups and compliance with simplified hardware. Nonetheless, the communications functionality of radar waveform-based DFRC systems is relatively limited in throughput and typically results in increased decoding complexity, making it more suitable to serve as an alternative channel in addition to existing, e.g., cellular-based, vehicular communications, rather than replacing the latter.

Joint waveform design

The approaches detailed so far are all based on traditional radar and/or communications signaling. A DFRC system is

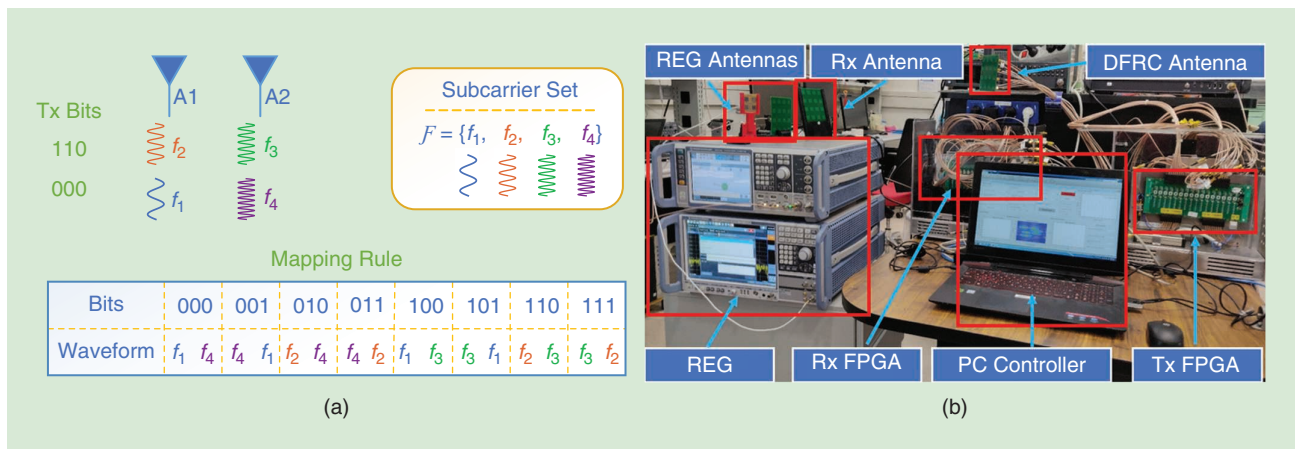


FIGURE 3. (a) An illustration of IM-FAR [16]. The array consists of $L_T = 2$ elements, divided into $K = 2$ subarrays of $L_K = 2$ elements. The carrier set is $\mathcal{F} = \{f_1, f_2, f_3, f_4\}$. The mapping rule represents the codebook. (b) A hardware prototype implementing IM-FAR [14] equipped with 16 antenna elements. Rx: receiver; Tx: transmitter.

then obtained by either designing the conventional waveforms to coexist, as detailed in the ‘‘Separate Coordinated Signals’’ section, or alternatively, by using only one standard waveform while extending it to be dual functional. Using traditional signaling techniques has clear advantages due to their established performance and applicability with existing hardware devices. Nonetheless, the fact that these waveforms were not originally designed for DFRC scenarios implies that one can achieve improvement by deriving dedicated dual-function waveforms, as illustrated in Figure 2(c).

Dedicated joint waveforms, which do not originate from conventional radar/communications signaling, are designed according to a dual-function objective, which accounts for the performance of both radar and communications [10]–[12]. Here, the transmitted joint signal is denoted by the $L_T \times J$ matrix \mathbf{X} , where J is the block length. We focus on a multiuser scenario with L_U single antenna receivers. The signal received at the receivers and at the radar target with direction θ can be expressed as

$$\mathbf{Y}^{(c)} = \mathbf{H}\mathbf{U}\mathbf{X} + \mathbf{W}^{(c)}, \text{ and } \mathbf{y}_\theta^{(r)} = \mathbf{a}^T(\theta)\mathbf{U}\mathbf{X}, \quad (7)$$

where \mathbf{H} is an $L_U \times L_T$ channel matrix, \mathbf{U} is the joint beamformer, and $\mathbf{W}^{(c)}$ is the additive noise term.

Using (8), one can design the joint waveform \mathbf{X} to approach some desired observations at the communications receivers as well as the radar target, as proposed in [10]. A possible drawback is that the signals received in other directions are not constrained, and, thus, the radar transmit beampattern may have a high sidelobe level outside the main lobe. This can be overcome by restricting the radar beampattern [11], [12], which is, in turn, achieved by constraining the signal covariance. In particular, [11] considered \mathbf{X} to be a communications signal and optimized the joint precoding to approach a predefined beampattern while meeting a minimal SINR level at each receiver. The work [12] designed the joint waveform \mathbf{X} to minimize the multiuser interference under specific radar constraints, such as

omnidirectional or directional beampatterns, constant modulus designs, and waveform similarity.

Dual-function waveforms specifically designed for DFRC offer the ability to balance radar and communications in a controllable manner. Furthermore, using joint optimization, without being restricted to conventional waveforms, can potentially yield any achievable performance tradeoff between radar and communications. Despite these clear theoretical benefits, their application in an automotive DFRC system is currently still limited due to practical considerations. For example, current joint waveform designs involve solving a relatively complex optimization problem, which depends on prior channel knowledge. In fast-moving vehicles, accurate instantaneous channel knowledge is difficult to obtain, and even when it is available, the optimization process must be frequently repeated, inducing increased computational burden.

Discussion

The DFRC methods surveyed here vary significantly in their characteristics, such as radar performance, communication throughput, complexity, and hardware requirements. Although several efforts have been made in the literature to characterize the achievable radar-communications tradeoff in DFRC systems [4, Ch. 6], to date, there is no unified joint measure that allows the rigorous evaluation of different schemes.

To demonstrate the challenge in comparing DFRC methods, we numerically evaluate two promising schemes: OFDM waveforms, which utilize communications signaling for radar probing, and the radar-based IM via the FAR method. In particular, we consider a single-antenna automotive radar in the 24-GHz band divided into 1,024 bins, using the same configuration as in [9]. OFDM utilizes the complete frequency band, while IM-FAR uses a single subcarrier at each instance, embedding the message in its selected index, i.e., a total of $\log_2 1,024 = 10$ bits/symbol. To guarantee that both methods operate with the same data rate, we group the OFDM subcarriers into 10 distinct blocks and assign a binary phase shift keying symbol

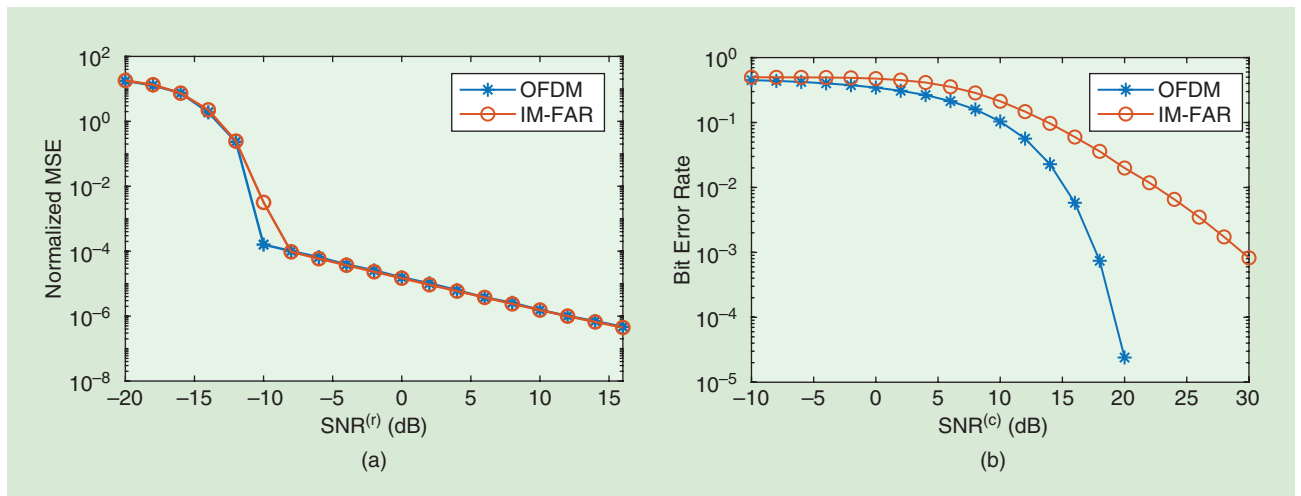


FIGURE 4. A numerical comparison of OFDM-based DFRC systems to FAR with IM. (a) The normalized MSE in range estimation. (b) The bit error rate. SNR: signal-to-noise ratio; (r): radar; (c): communications.

to each block. Both schemes use the same pulsewidth, PRI, and power, attempting to recover a point target with range 10 m and relative velocity 5 m/s, while communicating over a Rayleigh flat fading channel.

The resulting normalized mean-square error (MSE) in target range recovery as well as the communications bit error rate are depicted in Figure 4. Observing Figure 4, we note that OFDM achieves improved communications performance over IM-FAR, while their radar performance is relatively similar. The results in Figure 4, which are in favor of OFDM-based DFRC systems, are relevant for interference-free scenarios, where a single DFRC system probes the environment. In dense scenarios with multiple interfering devices, which model automotive systems in urban settings, FAR is expected to be more capable of mitigating the mutual interference due to its random spectral sparsity [16].

Due to the difficulty in comparing DFRC schemes, we schematically evaluate their radar versus communications performance tradeoff in Figure 5. Separate coordinated transmission methods, which utilize individual signals for each functionality, support a broad range of possible performance combinations, determined by how the system resources are allocated between the functionalities. In particular, beamforming techniques, which require a priori channel knowledge, allow the signals to utilize the full bandwidth and operation time and, thus, have the potential to achieve improved performance compared to time–frequency division strategies. Nonetheless, in the presence of multiple scatterers and communications receivers, which is the case in vehicular applications, obtaining accurate channel knowledge and mitigating mutual interference by beamforming may be infeasible, while spectral division can be applied with controllable complexity, regardless of the number of receivers and their physical location.

Communications waveform-based approaches, particularly when using OFDM transmission, support high data rates by utilizing conventional digital communications signals. Specifically, OFDM is a digital communications scheme that has some of the characteristics of good radar waveforms. In the context of autonomous vehicles, a major limitation of this approach is that, since a single directed beam is used, the receiver should be located in the radar search area. Furthermore, OFDM transmission requires relatively costly hardware, and its radar capabilities are degraded when utilized by a moving vehicle.

Protocol-oriented approaches, which represent an extreme case of using a communications waveform for radar probing, offer the ability to utilize existing vehicular communications protocols for sensing. They provide minimal communications degradation with limited radar capabilities. As such, these

methods can be considered as an additional sensing technology, which should not replace dedicated automotive radar.

Radar waveform-based schemes, especially IM-based DFRC systems, can be naturally integrated into automotive radar systems with minimal effect on their performance. While MIMO radar implementing instantaneous wideband waveforms offers improved radar performance over frequency agile waveforms, the latter may be preferable for vehicular applications due to their robustness to congested environments and reduced complexity. Nonetheless, the limited bit rates of IM and its associated decoding complexity make such DFRC schemes more suitable to provide an additional communications channel, independent of the cellular network. The usage of such channels for safety and emergency messages can be valuable in autonomous vehicles, increasing the probability of their successful transmission.

Joint waveform design techniques optimize a dual-function waveform in light of a combined constraint on each functionality. This joint approach has the potential of achieving any given tradeoff between radar and communications performances. Nonetheless, being a relatively new field of study, current dual-function designs may not be suitable for automotive applications. In particular, current designs require instantaneous channel knowledge, limiting their application for self-driving vehicles.

To conclude, there is no single DFRC method that is suitable for all scenarios and requirements encountered in autonomous vehicle applications. Understanding the advantages and disadvantages of each approach will allow engineers to properly select the technologies incorporated into future self-driving cars.

Conclusions and future challenges

Autonomous vehicles implement wireless communications as well as automotive radar, which both require the transmission

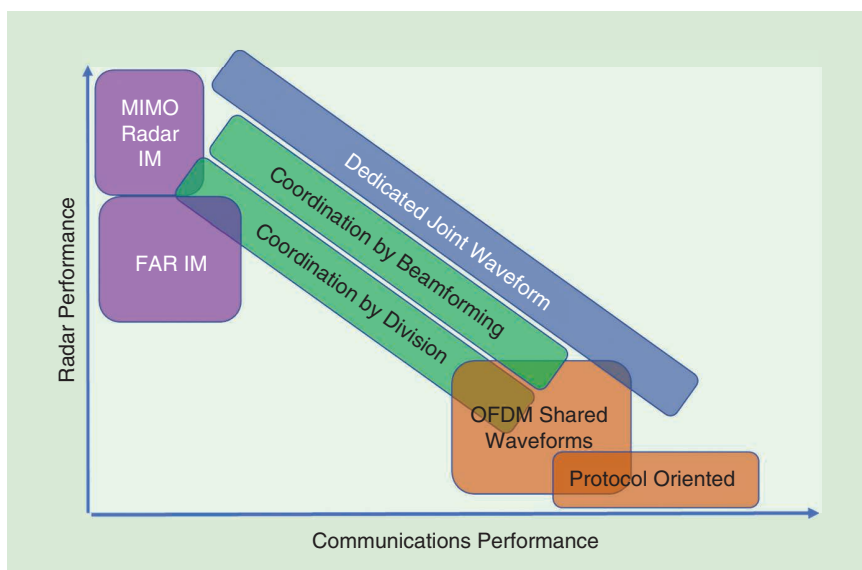


FIGURE 5. A schematic comparison between considered DFRC schemes in terms of their radar-communications tradeoff.

and reception of electromagnetic signals. Jointly designing these functionalities as a DFRC system provides potential gains in performance, size, cost, power consumption, and robustness, making it an attractive approach for autonomous vehicles. In this survey, we reviewed state-of-the-art DFRC designs, focusing on their application for autonomous vehicles. To that aim, we first reviewed the basics of automotive radars. Then, we mapped existing DFRC strategies, proposing their division into four main categories: coexistence schemes, which utilize independent waveforms for each functionality; communications waveform-based approaches, where conventional communications signals are used for radar probing; radar waveform-based schemes, which embed the digital message into standard radar technologies; and joint waveform design approaches, which achieve the DFRC system by deriving dedicated dual-function waveforms. The pros and cons of each category were analyzed according to the radar and communications requirements in vehicular scenarios. While we conclude that no single DFRC scheme is suitable for all of the scenarios in self-driving, our analysis can significantly facilitate the design of sensing and communications technologies for future autonomous vehicles.

While joint radar-communications designs have been studied for over a decade, they still give rise to a multitude of unexplored research directions, particularly in the context of autonomous vehicles. On the theoretical side, the lack of a unified performance measure makes it difficult to compare approaches, and one must resort to heuristic arguments, as was done in this article. Such an analysis will also uncover the fundamental limits of DFRC designs, characterizing their optimal gain over well-studied separate systems. From an algorithmic perspective, the utilization of joint nonstandard radar and communications waveforms, utilized in some of the aforementioned strategies, can be facilitated by the development of dedicated recovery and decoding algorithms.

For conventional waveforms, such as OFDM signals, efficient allocation of resources to optimize both functionalities is a relatively fresh area of study. Additionally, the presence of multiple sensing vehicular technologies, such as vision-based sensing and lidar, along with the ability to communicate with neighboring devices that also sense their environment, give rise to potential improved understanding of the surroundings by properly combining these technologies. Finally, on the practical side, future investigations are required to implement these strategies in vehicular platforms and test their performance in real road environments. Such combined studies should allow us to characterize the benefits and limitations of DFRC systems for self-driving cars, allowing their theoretical potential to be translated into performance gains in this emerging and exciting technology.

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