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Performance Trade-Off in an Adaptive IEEE 802.11ad Waveform Design for a Joint Automotive Radar and Communication System

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16. Abstract

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PERFORMANCE TRADE-OFF IN AN ADAPTIVE IEEE 802.11AD WAVEFORM DESIGN FOR A JOINT AUTOMOTIVE RADAR AND COMMUNICATION SYSTEM

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ABSTRACT

The IEEE 802.11ad waveform can be used for automotive radar by exploiting the Golay complementary sequences in the preamble of a frame. The performance of radar, however, is limited by the preamble structure. In this paper, we propose an adaptive preamble design that permits a trade-off between radar parameters' estimation accuracy and communication rate. To quantify this trade-off, we propose a minimum mean square error (MMSE) metric based on rate distortion theory. The simulation results demonstrate that by adapting the preamble structure, we can achieve decimeter-level range mean square error (MSE) per symbol duration and gigabit per second (Gbps) data rates simultaneously for a distance upto 280 m.

Index Terms— IEEE 802.11ad, automotive radar, vehicular communication, joint waveform design.

1. INTRODUCTION

Advanced driver-assisted applications will benefit from the integration of vehicle-to-vehicle (V2V) communication and automotive radar systems at the millimeter-wave (mmWave) band. Major advantages include efficient spectrum usage, reduced cost, size, and power consumption, high-resolution radar sensing, Gbps data rate, and higher penetration of mmWave communication-capable vehicles.

Most prior approaches for joint radar and communication system have either exploited proprietary radar or non-standardized communication waveforms [1]. In [2], the IEEE 802.11p vehicular communication waveform was also used for radar sensing in the 5.9 GHz band but the radar range and velocity estimates do not meet the desired accuracy requirements of automotive radar applications [3]. An alternative is to leverage the IEEE 802.11ad standard for automotive radar [4]. In our prior work, we used the preamble of an IEEE 802.11ad single carrier physical layer (SC PHY) frame for radar parameter estimation. The accuracy was limited, however, due to the small preamble duration in the IEEE 802.11ad standard.

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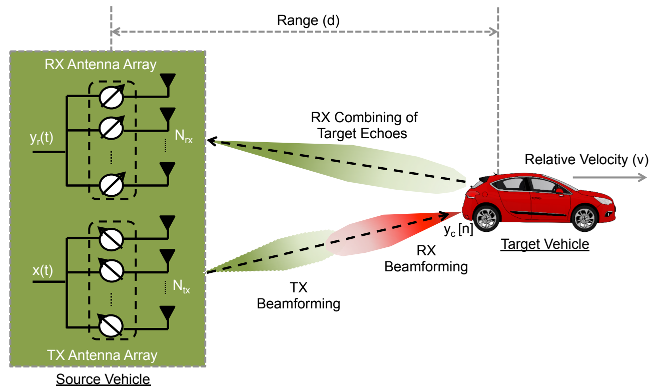


Fig. 1. A system model for joint vehicular communication and radar based on the IEEE 802.11ad standard.

In this paper, we propose an adaptive IEEE 802.11ad waveform design to combine radar and communication in a common analytical framework for different vehicular scenarios. First, we derive a trade-off between radar and communication performance for an adaptive preamble duration in a two-vehicle scenario. Then, we quantify the trade-off by developing an effective communication MMSE metric analogous to the distortion metric in rate distortion theory. Second, we optimize the preamble duration to adapt the waveform to different vehicular scenarios. The simulation results for the optimized preamble show that at a vehicle separation distance of 270 m, range MMSE decreases by a factor of 25 dB, while decreasing the spectral efficiency by 1.4 bits/s/Hz (still achieving Gbps data rate) as compared to the IEEE 802.11ad preamble.

2. SYSTEM MODEL

We consider the use case where a source vehicle sends an adaptive IEEE 802.11ad single-carrier physical layer (SC PHY) frame to a target vehicle via the vehicle-to-vehicle (V2V) communication service and uses the reflections from the target vehicle to derive its range and velocity, as shown in Fig. 1. The complex baseband continuous-time representation of the waveform is

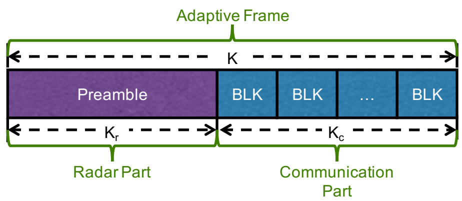


Fig. 2. Frame structure of an adaptive IEEE 802.11ad V2V-radar SC PHY waveform with variable K_c and K_r.

$$x(t) = \sqrt{\mathcal{E}_s} \sum_{n=-\infty}^{\infty} s[n] g(t - nT_s), \quad (1)$$

where $g(t)$ is the unit energy transmit pulse-shaping filter, T_s is the symbol duration, $\mathcal{E}_s$ is the symbol energy, and $s[n]$ is the transmitted symbol sequence of an adaptive IEEE 802.11ad frame. The symbol duration is related to the signaling bandwidth (B) as $T_s \approx 1/B$. We consider there are total K symbols in a frame, with $\alpha = \frac{K_c}{K}$ fraction of data symbols, as shown in Fig. 2.

We consider a multiple antenna system with N_{tx} co-located transmit (TX) antennas and N_{rx} co-located receive (RX) antennas configuration, as in [4], mounted on the source and the target vehicles. We assume that the TX and the RX antenna arrays on a vehicle are closely separated uniform linear arrays. We assume enough isolation and cancellation of the transmit signal to the receiver at the source vehicle such that there is no residual self-interference. For simplicity, we assume that the target vehicle is represented by a single point target, there is no blockage between the source and the target vehicles and the mmWave channel has a dominant line-of-sight (LOS) component [4]. The discrete-time communication signal received at the target vehicle after analog radio frequency (RF) combining, matched filtering, and time/frequency synchronizations can be represented as

$$y_c[n] = \sqrt{\mathcal{E}_s G_c} s[n] + w_c[n], \quad (2)$$

where $\mathcal{E}_s$ is the symbol energy, G_c denotes the communication channel gain corresponding to the one-way path, and TX/RX array gain, and $w_c[n]$ is the complex additive white Gaussian noise (AWGN) with power spectral density (PSD) of N_0.

The continuous-time radar signal received at the source vehicle after the analog RF combining and matched filtering can be represented as

$$y_r(t) = \sqrt{G_r} x(t - 2d/c) e^{j4\pi vt/\lambda} + w_r(t), \quad (3)$$

where d denotes the range or the separation distance between the source and the target vehicles, c is the speed of light, λ is the wavelength of the IEEE 802.11ad waveform, v denotes the relative velocity of the target vehicle with respect to the source vehicle, and $w_r(t)$ is the complex AWGN with power spectral density (PSD) of N_0. Assuming equal TX and RX gain at the source and the target vehicles, the radar channel gain at the target vehicle is $G_r \approx G_c/L_{PL}$ with $L_{PL} = (4\pi d^n)/\sigma_{RCS}$, where σ_{RCS} is the radar cross section of the target vehicle, and n is the path-loss exponent [5, 6, 7].

3. PERFORMANCE METRICS AND BOUNDS

In this section, we develop a new communication performance metric for assessing the trade-off between radar and communication performances for a joint waveform design.

3.1. Communication

Assuming $s_c[n]$ is distributed as $\mathcal{N}_{\mathbb{C}}(0, 1)$, the maximum achievable communication spectral efficiency for an adaptive IEEE 802.11ad V2V-radar system with $\alpha = 1$ is given by

$$r = \log_2 (1 + \text{SNR}_c) \quad (4)$$

where, $\text{SNR}_c = \mathcal{E}_s G_c / N_0$. When $\alpha < 1$, the effective maximum achievable communication spectral efficiency, r_{eff}, decreases by a factor of α and is expressed as

$$r_{\text{eff}} = \alpha \log_2 (1 + \text{SNR}_c) = \log_2 (1 + \text{SNR}_c)^{\alpha}. \quad (5)$$

3.2. Radar

The Cramer-Rao lower bound (CRB) is a lower bound on the variance of an unbiased estimator. For AWGN noise, the CRB is also a lower bound on the MSE for radar parameter estimation. In case of velocity estimation using the preamble of an adaptive IEEE 802.11ad frame, the CRB is given by [7]

$$\text{CRB}_v = \frac{6\lambda^2}{16\pi^2 (1-\alpha)^3 K^3 T_s^2 \text{SNR}_r}. \quad (6)$$

where $\text{SNR}_r = \mathcal{E}_s G_r / N_0$ is the radar SNR.

The CRB for the range estimation of a target vehicle using the preamble is [7]

$$\text{CRB}_d = \frac{c^2}{32\pi^2 B_{\text{rms}}^2 (1-\alpha) K \text{SNR}_r}, \quad (7)$$

where B_{rms} is the root-mean square bandwidth of $X(f)$, which is the Fourier transform of the preamble [8]. We assume a flat spectral shape of the preamble, which will allow better channel equalization of the communication system (e.g., Zadoff-Chu sequences used in LTE [9]) and better radar parameter estimation of the target vehicle (e.g., linear frequency modulated chirp used in automotive radar [10]). Due to the assumption of flat spectral shape, $B_{\text{rms}} = B/\sqrt{12}$ [8].

3.3. Joint Communication and Radar

The performance metrics of radar and communication are dependent on α, as can be seen from (4), (6), and (7). With an increase in α, the information rate improves, whereas the CRB for radar parameters estimation degrades. Therefore, we focus on optimizing α for the adaptive IEEE 802.11ad V2V-radar waveform design. This requires the development of a new metric to accurately quantify both radar and communication system performances.

In [11], a radar round-trip delay estimation rate is developed which parallels the concept of communication information rate and is bounded by

$$R_\tau \leq \frac{1}{KT_\mathrm{s}} \log_2 \left(1 + \frac{\sigma^2_{\tau,\mathrm{proc}}}{\mathrm{CRB}_d}\right), \tag{8}$$

where $\sigma^2_{\tau,\mathrm{proc}}$ is the variance of the round-trip delay fluctuation of the target echo due to some underlying target process. The round-trip delay is related to range as $\tau = 2d/c$.

The radar estimation rate metric is not drawn from a countable distribution [11]. Therefore, this metric is not an accurate representation of the radar performance. The derivation for radar round-trip delay estimation information rate is also not easily extendable to other radar parameters estimation because several underlying simplifications in [11] may become invalid for other parameters estimation [12]. Additionally, the number of radar performance metrics (e.g. range/velocity/direction of multiple targets, number of detectable targets, probability of detection and false alarm, range/velocity/angular resolution) that depend on α is much larger than the few performance metrics used in communication. Therefore, instead of deriving equivalent estimation or information rates for each of these radar parameters in different scenarios, as in [13], we derive the equivalent of communication information rate similarly to a radar performance metric.

Assuming $s_\mathrm{c}[n]$ is distributed as $\mathcal{N}_\mathbb{C}(0, 1)$, the MMSE estimator of $s_\mathrm{c}[n]$ based on the observation $y_\mathrm{c}[n]$ is linear. For the case of $\alpha = 1$, this estimator then yields [14]

$$\mathrm{MMSE} = \frac{1}{1 + \mathrm{SNR_c}} = 2^{-r}. \tag{9}$$

Therefore, for $\alpha < 1$, we define the average effective MMSE per symbol based on r_eff as

$$\mathrm{MMSE_{eff}} = 2^{-r_\mathrm{eff}} = \frac{1}{(1 + \mathrm{SNR_c})^\alpha} = \mathrm{MMSE}^\alpha. \tag{10}$$

According to (9) and (10), each bit of description reduces the MMSE by a factor of 2. This implies that as the spectral efficiency decreases by a factor of α, the effective average MMSE per symbol increases exponentially by the same factor α. Since there is a simple one-to-one relation between spectral efficiency and effective MMSE per symbol, it is easy to use and understand.

Additionally, the expressions (9) and (10) are analogous to the relation between mean squared-error distortion, D, and rate R in the rate distortion theory, where [15]

$$D = 2^{-R}. \tag{11}$$

Therefore, the effective average MMSE per symbol is arguably an appropriate metric of communication performance for assessing trade-off in a joint communication and radar waveform design.

4. SMART IEEE 802.11AD V2V-RADAR WAVEFORM DESIGN

In this section, we will develop an objective function to determine the optimal α for adaptive waveform design of an IEEE 802.11ad V2V-radar. One such formulation is the weighted sum of radar and communication MSE bounds. The MSE bounds for range estimation, velocity estimation and communication are substantially dissimilar with velocity estimation performance being the worst in most of the cases. We found that this tends to skew the value of α close to 0 and is not favorable for communication. This can, to some extent, be corrected by resorting to a proper choice of weighted sum, whose choice is itself not devoid of difficulty. This is because the MSE bounds are very different from each other and change very rapidly with different values of α.

The different MSE bounds is similar to the problem of resource allocation in multi-user communication, where the user SNRs are highly dissimilar and the balance between fairness and aggregate spectral efficiency is provided using a proportional fair point. Therefore, to achieve proportional MMSE fairness, the adaptive waveform design can be formulated as

$$\begin{aligned} \underset{\alpha}{\text{minimize}} \quad & \omega_d \log(\mathrm{CRB}_d) + \omega_v \log(\mathrm{CRB}_v) \\ & -\omega_\mathrm{c} \log(\mathrm{MMSE_{eff}}) \\ \text{subject to} \quad & 0 \leq \alpha \leq 1 \end{aligned} \tag{12}$$

where, the weighting factors ω_v, ω_d and ω_c are positive and can be adjusted adaptively to the requirements imposed by different vehicular scenarios. In (12), we use $K = 1$ to calculate both radar and communication MSE bound per symbol. From (6) and (7), we see that the velocity/range CRB bounds for a longer frame can easily be calculated by dividing the velocity MSE per symbol with K^3 and the range MSE per symbol with K.

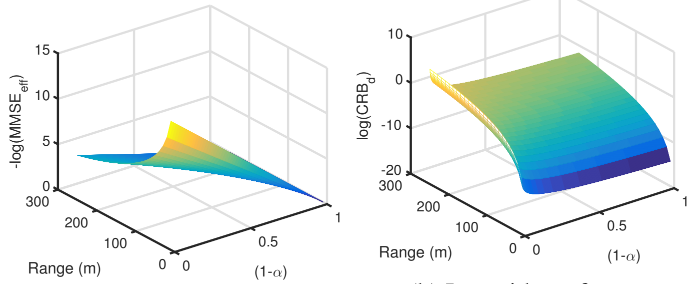
The optimization (12) can be reformulated as

$$\begin{aligned} \underset{\alpha}{\text{minimize}} \quad & \omega_d \log\left(\frac{\lambda_d}{1-\alpha}\right) + \omega_v \log\left(\frac{\lambda_v}{(1-\alpha)^3}\right) \\ & +\omega_\mathrm{c} \log(\mathrm{MMSE}^\alpha) \\ \text{subject to} \quad & 0 \leq \alpha \leq 1 \end{aligned} \tag{13}$$

where the parameters λ_d and λ_v are set accordingly to (7) and (6) respectively. Fortunately, (13) is a convex problem. For $\mathrm{SNR_c} > 0$, the optimal α for the unconstrained optimization corresponding to (13) is always < 1, whereas it is > 0 only when the weighting factors satisfy the condition

$$\frac{\omega_d + 3\omega_v}{\omega_\mathrm{c}} > r. \tag{14}$$

The positive α will always ensure fairness to the communication system, even at low SNR, by choosing the weights that satisfies (14).



(a) Spectral efficiency

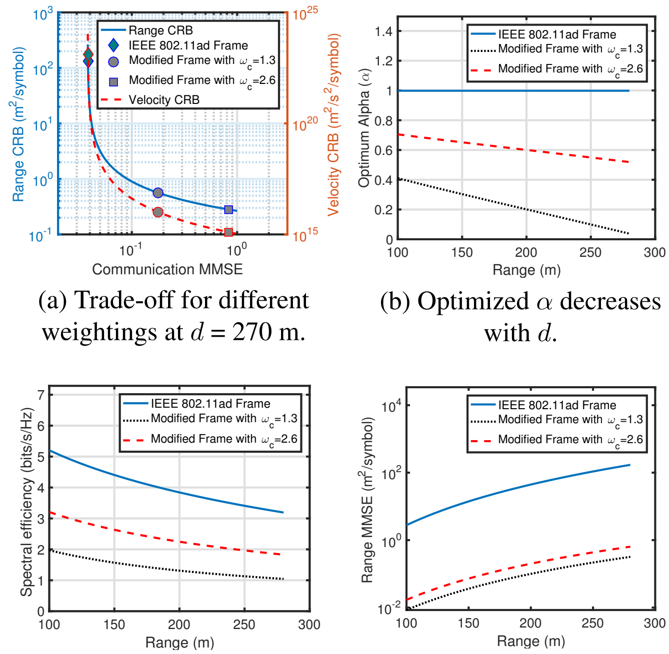
(b) Logarithm of range CRB per symbol

Fig. 3. Variation in radar and communication MSE bounds per symbol with change in d and α.

5. SIMULATION RESULTS

To investigate of the trade-off between radar and communication performance, we varied α from 0 to 1 and d from 10 to 250 m with a path-loss exponent of 2.0 [16]. Fig. 3 demonstrates that with an increase in vehicles separation, the range MSE bound per symbol degrades more severely than the communication effective MSE bound per symbol. Indeed, the degradation in velocity estimation MSE bound per symbol will be the worst because the velocity CRB per symbol gets effected thrice as much as the range CRB per symbol in logarithmic scale for a corresponding increase in α, as per (13). Additionally, the rate of change of communication rate is constant with respect to the change in α. However, the range and velocity estimation MSE bound per symbol decreases more drastically for α close to 1, which is before the dip in the α dimension. This implies that it is desirable to have the value of α at least as small as the one corresponding to the dip, which decreases with increase in the separation distance.

We design the adaptive 802.11ad waveform for a maximum range of 280 m. Therefore, we vary ω_c (subject to (14)) to study the effect of weighting on the choice of α and the radar/communication MSE bounds per symbol. Fig. 4(a) demonstrates the trade-off between radar and communication at a vehicle separation distance of 270 m. It shows that the range MMSE decreases by 100 m^2/symbol and meets the desired centimeter-level accuracy for automotive radar [3], while decreasing the spectral efficiency by 1.4 bits/s/Hz as compared to the IEEE 802.11ad preamble for a frame duration of 1 ms. Numerical simulations for a vehicle separation of 5 m with equal weighting, however, results in spectral efficiency increase by 1.4 bits/s/Hz, while increasing the range MMSE by a factor of 1.4 dB that still meets the desired accuracy requirement. The optimum α for this simulation is 0.6431 and the frame consists of 6400 samples. Fig. 4 (b), (c) and (d) depict that the optimum α for adaptive waveform design decreases with an increase in vehicles separation distance due to more degradation in radar CRB bound per symbol.



(a) Trade-off for different weightings at d = 270 m.

(b) Optimized α decreases with d.

(c) Spectral efficiency decreases with d.

(d) Range CRB increases with d.

Fig. 4. Trade-off between radar and communication MSE lower bounds for different communication weightings and comparison with IEEE 802.11ad frame.

6. CONCLUSION

In this paper, we designed an adaptive waveform for joint vehicular communication and radar by varying the preamble duration of an IEEE 802.11ad SC PHY frame. To formulate a joint communication and radar performance metric, we developed an effective communication MMSE metric analogous to the distortion metric in rate distortion theory. The simulations demonstrated that with an increase in the separation between the target and the source vehicles, the trade-off between radar and communication gets tightened and the range/velocity CRB bounds per symbol get degraded more severely than the communication MMSE per symbol. The optimum α for different weightings were explored, while maintaining Gbps communication data rate and cm-level range accuracy. At a vehicles separation distance of 270 m, the adaptive preamble design resulted in an improvement of the range MMSE by 3.2 cm^2, while decreasing the spectral efficiency by 1.4 bits/s/Hz as compared to the IEEE 802.11ad preamble. At 5 m distance, the spectral efficiency increased by 1.4 bits/s/Hz, while degrading the range MMSE by a factor of 1.4 dB and the velocity MMSE by 4.2 dB as compared to the IEEE 802.11ad preamble. This work can be extended to a large number of interesting time-domain duplex frameworks for joint radar and communication.

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