OFDM Waveform Optimization for Joint Communications and Sensing

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Abstract

The proliferation of mobile devices has resulted in the frequencies of operation of communication systems to coincide with those of the radar systems, causing mutual interference. To minimize the level of interference, a novel approach is to combine both systems in a single platform. This presentation considers a joint radar and communication system, where the radar transmitter and receiver as well as the communication transmitter are the same device while the communication receiver is at some distance. The same waveform is used for both systems and it is optimized such that it maximizes the performance of both systems.

1 Introduction

The objective of a radar system is to detect targets in the surrounding environment. Upon detection, it is possible to estimate the target's range and velocity up to a certain accuracy, by processing the received signal. A communication system is typically employed to carry information between two points, the transmitter and the receiver. These operate at fixed frequency ranges so that they do not interfere with other radio systems. The development of technology has resulted in an exponential increase of communication devices and thus their frequency ranges of operation have extended. As a result, both radar and communication systems work in the same frequencies and each system causes interference on the other. Thus, it is conspicuous that some form of co-ordination be done between the two systems so that this interference can be managed to a certain extent.

Different methods have been proposed to address the issue of managing the interference between the two systems [1], spanning from estimating the others' interference, co-operating between the systems to minimize the interference and joint design of both systems from the ground up. One of the novel concepts in this regard is termed radio frequency (RF) convergence, where a given bandwidth is shared between the two systems while also ascertaining the performance of both are maximized. This convergence of frequency is complemented by hardware convergence due to the emergence of software-defined radios where a single hardware platform can be used for both tasks.

In the present communication systems such as LTE and 5G New Radio (NR), the waveform used is orthogonal frequency-division multiplexing (OFDM). Such a waveform can also be used for sensing the environment and shown to have good accuracy in both target range and velocity estimation [2]. In the radio frames of these modern communication systems, there often exist some subcarriers which are unused and arbitrary data can be transmitted on these so that it is beneficial for the radar system. Subcarriers that are filled are termed as radar subcarriers while the rest as communication subcarriers. Depending on the modulation of the communication symbols, they can also be weighted. For example, amplitudes of phase-shift keying (PSK) symbols or phases of amplitude-shift keying (ASK) symbols can be modified. In our work, insertion of data on radar subcarriers and modifying weights of the communication subcarriers are found through an optimization algorithm. This is used to minimize the errors in estimation of the radar system while improving the signal-to-noise ratio (SNR) of the subcarriers used for communication.

The structure of the joint system is shown in Fig. 1. The radar transceiver (TRX) and the communication transmitter (TX) are the same device while its receiver (RX) is at some distance. The transmitted signal $x(t)$ is an OFDM waveform. The received signal at the radar TRX is denoted by $y_{\mathrm{r}}(t)$ whereas that for the communication system is given by $y_{\mathrm{c}}(t)$.

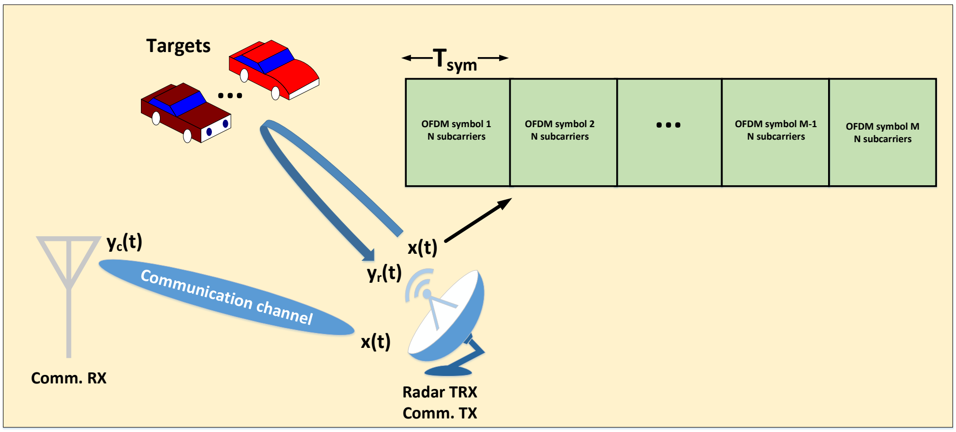


Fig. 1: System model and the signal structure.

2 Signal Model

The structure of the signal $x(t)$ is given in Fig. 1. The OFDM symbol duration is $T_{\text{sym}} = T + T_{\text{CP}}$, where T is the payload duration and T_{CP} is the time duration of the cyclic prefix (CP). For radar processing, a total of M OFDM symbols are used to estimate the target range and velocity. Both the radar and communication subcarriers are used for this while it is assumed that the communication receiver has knowledge about the locations of the radar and communication subcarriers.

2.1 Radar System

The transmitted frequency-domain symbol is denoted by $X_{n,m}$ where the n and m correspond to subcarriers and OFDM symbol indices, respectively, and the distinction between radar and communication subcarriers is denoted as $X_{\text{r},n,m}$ and $X_{\text{c},n,m}$. The transmitted time-domain signal $x(t)$ can then be written as

$$x(t) = \frac{1}{N} \sum_{m=0}^{M-1} p(t - mT_{\text{sym}}) \left(\sum_{n \in \mathscr{R}_m} X_{\text{r},n,m} e^{j2\pi n \Delta f (t - mT_{\text{sym}})} + \sum_{n \in \mathscr{C}_m} X_{\text{c},n,m} e^{j2\pi n \Delta f (t - mT_{\text{sym}})} \right), \quad (1)$$

where $\Delta f, p(t), \mathscr{R}_m, \mathscr{C}_m$ denote the frequency spacing between subcarriers, the pulse shape, and sets for radar and communication subcarriers of each OFDM symbol with $\mathscr{R}_m \cap \mathscr{C}_m = \varnothing$. The power of the radar and communication subcarriers can be denoted as

$$P_{\text{comm.}} = \frac{1}{MN} \sum_{m=0}^{M-1} \sum_{n \in \mathscr{C}_m} |X_{\text{c},n,m}|^2 \text{ and } P_{\text{radar}} = \frac{1}{MN} \sum_{m=0}^{M-1} \sum_{n \in \mathscr{R}_m} |X_{\text{r},n,m}|^2. \quad (2)$$

The transmit signal $x(t)$ is reflected from targets in the environment and received back at the radar TRX as

$$y_{\text{r}}(t) = \sum_{k=1}^{K_{\text{r}}} A_{\text{r},k} x(t - \tau_{\text{r},k}) e^{j2\pi f_{\text{r,D},k} t} + v_{\text{r}}(t), \quad (3)$$

where K_{r} denotes the total number of targets and $y_{\text{r}}(t)$ is the sum of attenuated and delayed versions of $x(t)$. Further, the phases are also varying due to the Doppler shift, which correspond to the relative speed between the target and the radar TRX. In particular, $A_{\text{r},k}$ is the two-way attenuation constant for the path between the radar TRX and each target while $f_{\text{r,D},k}$ and $\tau_{\text{r},k}$ are the Doppler shift and delay of each target, respectively. The noise $v_{\text{r}}(t)$ is assumed to be additive, white, and

Gaussian. The SNR at the radar TRX can be written as

$$\mathrm{SNR_r} = \frac{\mathbf{E}\{|\sum_{k=1}^{K_\mathrm{r}} A_{\mathrm{r},k} x(t-\tau_{\mathrm{r},k}) e^{j2\pi f_{\mathrm{r,D},k} t}|^2\}}{\sigma_\mathrm{r}^2}, \tag{4}$$

where $\mathbf{E}$ and σ_r^2 denote the expectation operation and the variance of the noise samples, respectively. Substituting (1) to (3) and performing the fast Fourier transform (FFT) operation and simplifying yields the relation between the transmitted and received frequency-domain symbol as [3]

$$Y_{n,m} = \sum_{k=1}^{K_\mathrm{r}} A_k X_{n,m} e^{-j2\pi n \Delta f \tau_{\mathrm{r},k}} e^{j2\pi f_{\mathrm{r,D,k}} m T_\mathrm{sym}} + V_{\mathrm{r},n,m}. \tag{5}$$

Considering the effect by a single target, it is seen that the received frequency-domain symbol on each subcarrier is attenuated by some factor while the phase is changed from that of the transmitted symbol due to the delay and Doppler shift of the target, with also noise added on top of that. Thus, these subtle changes in phase can be used to estimate the target's range and velocity.

2.2 Communication System

Employing similar methodology as for (5), the received frequency-domain symbol on the communication RX can be written as

$$Y_{\mathrm{c},n,m} = \sum_{k=1}^{K_\mathrm{c}} A_{\mathrm{c},k} X_{\mathrm{c},n,m} e^{-j2\pi n \Delta f \tau_{\mathrm{c},k}} e^{j2\pi f_{\mathrm{c,D},k} m T_\mathrm{sym}} + V_{\mathrm{c},n,m}. \tag{6}$$

The SNR of each communication subcarrier is then denoted by

$$\mathrm{SNR}_{\mathrm{c},n,m} = \frac{\mathbf{E}\{|X_{\mathrm{c},n,m}|^2\}|H_{\mathrm{c},n,m}|^2}{\sigma_\mathrm{c}^2}, \tag{7}$$

where $H_{\mathrm{c},n,m}$ is the per-subcarrier frequency-domain channel response.

3 Optimization Problem

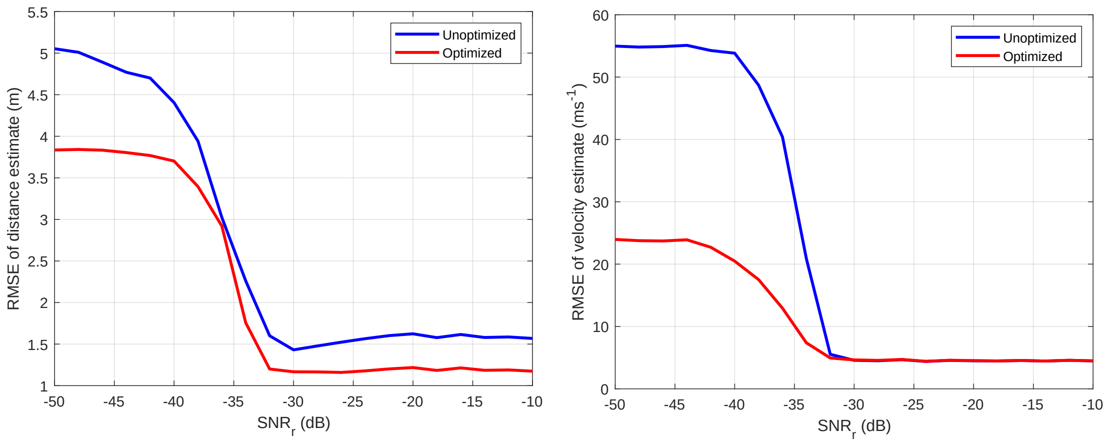
The goal of the optimization problem is to control the weights of the communication subcarriers and the complex data on the radar subcarriers such that it maximizes the performance of both radar and communication systems and this can be described in a general sense as

$$\text{minimize } \mathbf{var}(\hat{\tau}) \text{ or } \mathbf{var}(\hat{f}_\mathrm{D}) \text{ subject to } \begin{cases} P_\mathrm{comm.} + P_\mathrm{radar} = P_\mathrm{total}, \\ \mathrm{PAPR}_{x(t)} \leq \mathrm{PAPR}_\mathrm{max}, \\ \mathrm{SNR}_{\mathrm{c},n,m} \geq \mathrm{SNR}_\mathrm{min}, \end{cases}$$

where $\hat{\tau}, \hat{f}_\mathrm{D}$ and $\mathbf{var}(.)$ are the estimated delay and Doppler parameters and the variance operation of these estimates, respectively. The first constraint stems from power limitation for the transmit waveform. The second constraint ascertains that the waveform transmitted has an acceptable level of peak-to-average power ratio (PAPR), lower than some maximum level. The last constraint is for the communication subcarriers and dictates that each should have at least some minimum SNR.

4 Numerical Results

To evaluate the performance of the communication system, a multipath channel is simulated. It is observed that the addition of the SNR constraint improves the average SNR of the communication subcarriers. Without the constraint, it is around 6.9dB while with constraints of 4.8dB and 14.8dB, the average SNRs are around 20.7dB and 19.0dB, respectively.



(a) Distance measurement error

(b) Velocity measurement error

Fig. 2: Variation of RMSE of distance and velocity measurements with SNR for the optimized and unoptimized waveforms when $M = 20$ and $N = 1200$.

However, part of the spectrum corresponding to communication subcarriers is amplified w.r.t. the radar subcarriers, due to the per-subcarrier SNR constraint. Therefore, a significant amount of the TX power is spent on equalizing the attenuated communication subcarriers.

The suitability of the optimization problem for the radar system depends on the performance of practical estimators for range and velocity. To evaluate this, a practical scenario is implemented for a range of SNR values at the radar TRX. For each SNR, the target location and velocity are assumed to be uniformly distributed and the root mean square error (RMSE) of both target range and velocity estimates are measured. As such, Figs. 2(a) and 2(b) showcase the estimation of range and velocity when a quarter of the total subcarriers can be optimized. The radar subcarriers are symmetrically placed at the two edges of an OFDM symbol, while the communication subcarriers are at the center. These results show that, for low SNR values, the range measurement is better for the optimized waveform and, for higher SNR values, both optimized and unoptimized waveforms reach different error floors where the optimized one has a lower error. For the velocity measurement, it is seen that for low SNR values, the optimized waveform outperforms the unoptimized one whereas for higher SNR values, they both reach the same error floor.

Acknowledgments

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