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Comparison of OFDM and LFM Waveform Schemes for Ranging: A Correlation Perspective

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***Abstract*—Orthogonal frequency division multiplexing (OFDM) waveforms have been employed in communications systems for years and are the key waveform candidates for beyond-fifth-generation (5G) communication networks. In this paper, we compare OFDM waveforms to linear frequency-modulated (LFM) waveforms which are widely exploited in modern radar systems. We discuss the utility of OFDM waveforms for joint communications and sensing but also provide a comparison between the two in terms of their correlation properties. OFDM waveforms exhibit improved cross-correlation properties compared to LFM waveforms which can yield excellent resistance to interference between multiple radar transmitters without any cooperation. We express the theory behind our work and include simulations supporting our claims.**

I. Introduction

The integration of radar and communication systems, recognized as joint radar and communication (JRC), holds considerable significance owing to its capacity to optimize spectrum utilization, improve system efficiency, and facilitate a broad spectrum of applications [1]. Wireless ranging enables accurate distance measurements between communicating entities, a crucial aspect for radar sensing, localization, and target tracking within the JRC framework [2]–[4].

Linear frequency modulation (LFM) waveforms find widespread application in modern radar systems due to their established performance and reliability [5]. In the sphere of communications and JRC, orthogonal frequency division multiplexing (OFDM) offers dual functionality by allowing concurrent communication and radar-sensing operations through the shared use of hardware and frequency band resources [6]. Moreover, multi-user wireless ranging plays an indispensable role in JRC implementations [7]. Hence, this work concentrates on comparing OFDM and LFM waveforms, which are heavily demanded by the JRC and radar systems. In the literature, this comparison is dramatically open to be explored, particularly, in the case of enabling multiple users to transceive. Simulations display how three noncooperative users, using OFDM signals, can accurately detect the target location by exploiting the same time and bandwidth. Compared to OFDM signals, the LFM waveform, utilizing the same spectrum and time, is vulnerable the interference issue. In the matched filter output of LFM signals, non-differentiable ghost responses show up, making the range estimates challenging to detect.

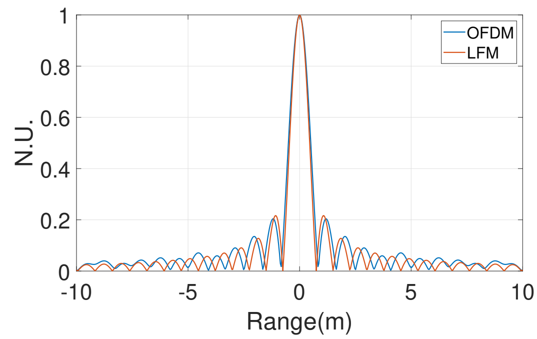

Fig. 1. Comparison between the autocorrelation responses of LFM and OFDM waveform schemes with 200 MHz of bandwidth.

II. Matched-Filter Ranging Using OFDM

A transmitted OFDM signal with N subcarriers in the time domain can be noted as

$$s(t) = \sum_{n=1}^{N} A_n e^{j\phi_n} e^{j2\pi n\Delta f t}, \tag{1}$$

where A_n and ϕ_n represent the amplitude and phase of the symbol on the nth sub-carrier, along with the sub-carrier spacing Δf [8]. In the event of a target positioned at a distance R, the reflected signal arriving at the receiver, denoted as $r(t)$ after quadrature down-conversion, can be expressed as follows:

$$r(t) = \sum_{n=1}^{N} \alpha_n A_n e^{j\phi_n} e^{j2\pi(n\Delta f)(t-\tau)} + w(t), \tag{2}$$

where α_n denotes the complex channel response at the nth sub-carrier, and $w(t)$ represents the noise encountered at the receiver. The parameter τ signifies the round-trip time delay, defined as $2R/c$, with c denoting the speed of light. This study adopts matched filter processing, strategically formulated to enhance the signal-to-noise ratio (SNR) at its output, in contrast to the sub-carrier-based approach. The expression for the output of the matched filter can be articulated as follows

$$x(\tau) = \int_{-T}^{T} s(\tau + t) r^*(t) dt. \tag{3}$$

The time delay $\hat{\tau}$ that maximizes the magnitude of the response from the matched filter can be translated to range using the speed of light in free-space. The same matched filter processing can be utilized for ranging using LFM signals.

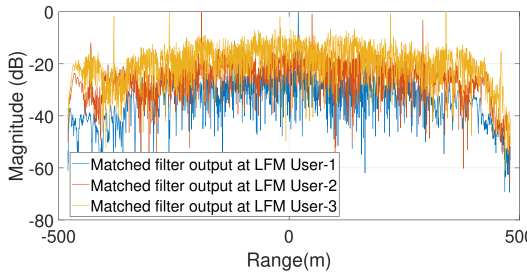

Fig. 2. Simulated matched filter output utilizing LFM waveforms generated by three distinct radars sharing identical bandwidth but different chirp rates.

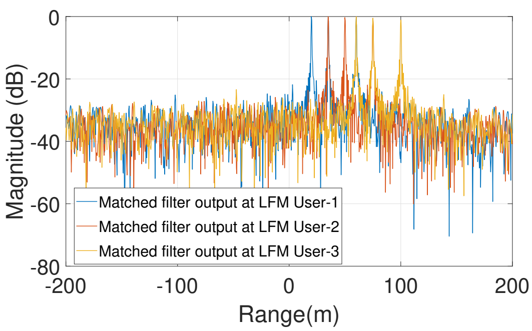

Fig. 3. Simulated matched filter output of three different LFM radars that share the same bandwidth with slightly different frequency offsets.

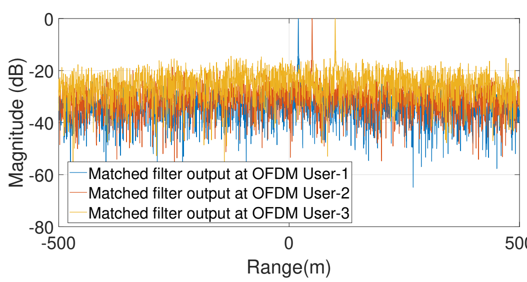

Fig. 4. Simulated matched filter output for OFDM signals generated by three different users exploiting the same bandwidth, by transmitting independent information using different digital modulation types. No ghost responses are present.

When multiple LFM radar systems are present in an environment, we can model the LFM signal of the ith user as

$$x(t) = e^{j2\pi(f_{0i}t + \frac{1}{2}\beta_i t^2)} \cdot 1_{[0,T_p]}(t), \tag{4}$$

where, f_{0i}, and β_i are the starting frequency and chirp rate of the ith user, respectively [9]. T_p depicts the pulse width, and the indicator function $1_{[0,T_p]}$ corresponds to unity during the pulse duration, otherwise, it is equal to zero.

The autocorrelation responses of OFDM signals with 200 MHz bandwidth, demonstrated in Fig. 1, offer impressive correlation properties for range estimation and localization as LFM waveform does.

III. Cross-Correlating OFDM vs LFM Signals

Next, we evaluated the correlation between different OFDM and LFM signals to examine performance under interference. Three identical transceivers are simulated utilizing OFDM and LFM waveform schemes. In all cases, signals are simultaneously transmitted and received by sharing the same time and bandwidth, which is 200 MHz. In all simulations, three users are present in the scene with distances of 20 m, 50 m, and 100 m away from the target of interest for User-1, User-2, and User-3 respectively. Fig. 2 illustrates the matched filter output for three LFM users with different chirp rates. $\beta_1 = 62.5\times10^{12}$ Hz/s is the chirp rate of User-1, while that of User-2 is $\beta_2 = 250\times10^{12}$ Hz/s, and the chirp rate of User-3 is $\beta_3 = 500\times10^{12}$ Hz/s. In this respect, it is obvious that inseparable ghost responses are introduced.

We subsequently varied the starting frequency f_0 of three LFM waveforms. Hence, in Fig. 3, starting frequencies are picked as 0 MHz, 30 MHz, and 50 MHz for User-1, 2, and 3, respectively. This case also ends up causing unwanted peaks in the matched filter output. Finally, Fig. 4 displays the result for employing OFDM signals exploiting the same frequency band, different information and modulation types for each user. Containing 2048 subcarriers, 16-QAM, 8-QAM, and 4-QAM are deployed to modulate the symbols in followingly User-1, 2, and 3. It is quite evident that the matched filter output of OFDM shows clear peaks at the correct range values without any ghost peaks. This is accomplished in the absence of cooperation and interference mitigation techniques.

IV. Conclusion

In this work, OFDM and LFM waveforms are compared regarding their correlation properties. Although both waveforms share similar autocorrelation performance, OFDM enables superior cross-correlation properties which is critical for interference mitigation and multiple accessing.

References

[1] X. Wan, Z. A. Huang, J. W. Wang, B. Y. Li, W. H. Wang, Q. Cheng, and T. J. Cui, “Joint radar and communication empowered by digital programmable metasurface,” *Advanced Intelligent Systems*, vol. 4, no. 9, p. 2200083, 2022.

[2] W. Bai, P. Li, X. Zou, Z. Zhou, W. Pan, L. Yan, B. Luo, X. Fang, L. Jiang, and L. Chen, “Millimeter-wave joint radar and communication system based on photonic frequency-multiplying constant envelope lfm-ofdm,” *Optics Express*, vol. 30, no. 15, pp. 26 407–26 425, 2022.

[3] S. Vakalis, S. Mghabghab, and J. A. Nanzer, “Fourier domain millimeter-wave imaging using noncooperative 5g communications signals,” *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 10, pp. 8872–8882, 2022.

[4] S. Vakalis, L. Gong, and J. A. Nanzer, “Imaging with wifi,” *IEEE Access*, vol. 7, pp. 28 616–28 624, 2019.

[5] Y. K. Chan, M. Y. Chua, and V. Koo, “Sidelobes reduction using simple two and tri-stages non linear frequency modulation (nlfm),” *Progress In Electromagnetics Research*, vol. 98, pp. 33–52, 2009.

[6] M. M. Şahin, I. E. Gurol, E. Arslan, E. Basar, and H. Arslan, “Ofdm-im for joint communication and radar-sensing: a promising waveform for dual functionality,” *Frontiers in Communications and Networks*, vol. 2, p. 715944, 2021.

[7] M. Steeg, F. Exner, J. Tebart, A. Czylwik, and A. Stöhr, “Ofdm joint communication–radar with leaky-wave antennas,” *Electronics Letters*, vol. 56, no. 21, pp. 1139–1141, 2020.

[8] J. Guan, A. Paidimarri, A. Valdes-Garcia, and B. Sadhu, “3-d imaging using millimeter-wave 5g signal reflections,” *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 6, pp. 2936–2948, Jun. 2021.

[9] D.-H. Kim, H.-J. Kim, and J.-H. Lim, “Design of optimized coded lfm waveform for spectrum shared radar system,” *Sensors*, vol. 21, no. 17, p. 5796, 2021.