2024 IEEE Wireless and Microwave Technology Conference (WAMICON) | 979-8-3503-4494-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/WAMICON60123.2024.10522865

Non-Cooperative High-Efficiency Multi-User Ranging Using OFDM Signals

Mehmet Yazgan
Electrical Engineering
University of South Florida
Tampa, USA
myazgan@usf.edu

Hüseyin Arslan
Electrical Engineering
Medipol University
Istanbul, Turkey
huseyinarslan@medipol.edu.tr

Stavros Vakalis
Electrical Engineering
University of South Florida
Tampa, USA
vakalis@usf.edu

***Abstract*—Joint radar and communication (JRC) is attracting increasing interest due to the finite nature of the electromagnetic spectrum and the importance of spatial positioning in modern communications networks. Focusing on the challenge of utilizing the same spectrum for both communication and sensing among multiple users, we discuss the exceptional properties of waveform orthogonal frequency-division multiplexing (OFDM) for joint communications and sensing. OFDM's excellent correlation properties make it particularly suitable for this purpose. We delve into the theory of performing ranging with OFDM signals, including their cross-correlation with other signals in the same spectral bands, and clarify how multiple users can operate in an environment without being multiplexed in the frequency or time domain. Simulations are presented alongside experimental measurements from a two-user OFDM radar system operating at center frequencies of 1.5 GHz and 1.55 GHz, demonstrating simultaneous operation and the efficient use of spectral resources.**

***Index Terms*—correlation, high-accuracy ranging, interference, joint communications and sensing, OFDM, radar, wireless coexistence.**

I. INTRODUCTION

The significance of positioning, one of the primary applications of radar systems, is underscored by standardized protocols such as the Long-Term Evolution (LTE) Positioning Protocol (LPP) and the New Radio Positioning Protocol A (NRPPa) [1], [2]. While a fourth-generation (4G) cellular system enables localization with an accuracy on the order of 10 meters, fifth-generation (5G) mm-wave systems will necessitate robust obstacle detection with accuracy on the order of several centimeters [3]. Positioning will play an even greater role in 5G and sixth-generation (6G) communication systems [4], and is already indispensable for applications such as navigation and robotics. [5], [6].

Joint radar and communication (JRC) has emerged due to the congestion of the electromagnetic spectrum, as well as to improve the quality of service in communications by utilizing spatial information [3], [7]. However, this endeavor is challenged by the fundamental differences between radar and communication systems, such that enhancing the performance of one modality often limits the performance of the other [8]–[10]. While many approaches attempt to mitigate interference through complex front-end designs or by overlapping radar with communication waveforms [11], in this work, we will utilize orthogonal frequency-division multiplexing (OFDM) waveforms, already employed in long-term evolution (LTE) and 5G systems, to demonstrate how multiple users can achieve wireless ranging and positioning without requiring cooperation

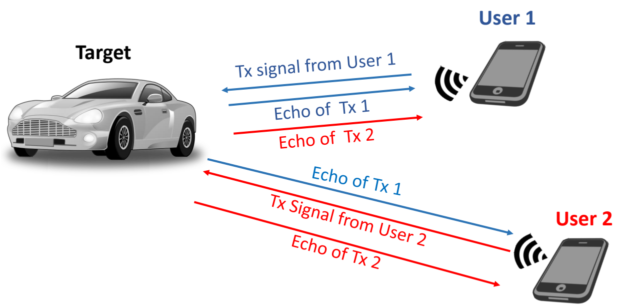


Fig. 1. Configuration of the simulation based on ranging using multi-user OFDM system.

The coexistence of multiple radar transceivers poses challenges related to interference and reliability. Therefore, the development of suitable ranging schemes is necessary to effectively address these issues [12]. Once two linear frequency-modulated (LFM) radars simultaneously transmit pulses within the same frequency band, coexistence might become complex. The overlapping signals generate interference, introduce ambiguities, and degrade radar performance, making it challenging to differentiate between interference and the targets of interest [13].

OFDM stands as a very promising candidate for JRC applications [14], [15] due to its extensive use in communications and its tolerance to Doppler effects. Additionally, our research demonstrates its capability to facilitate radar ranging operations for multiple users/transceivers sharing the same frequency band simultaneously. This suggests that within a wireless network, multiple users can concurrently utilize spectral and temporal resources for positioning and sensing purposes. Our study draws inspiration from the principles of noise radar systems [16], [17], which can also accommodate the transmission of multiple signals simultaneously, and applies a similar concept to the OFDM waveform. We discuss the theoretical underpinnings of our approach and present simulated

979-8-3503-4494-3/24/$31.00 ©2024 IEEE

results of ranging measurements using OFDM signals. We demonstrate why OFDM is a remarkable waveform for JRC that can achieve radar ranging and potentially support multiple users within the same band without requiring cooperation. This not only translates to increased spectral efficiency and more effective resource utilization but also ensures immunity to interference, while simultaneously providing both communication and sensing capabilities. Simulations and experimental measurements from a dual transmit/receive configuration at 1.5 GHz are included.

II. MATCHED-FILTER RANGING USING OFDM

A baseband OFDM signal with N subcarriers can be expressed in the time domain as

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

where, A_n and ϕ_n represent the amplitude and phase of the symbol on the nth subcarrier, respectively, while Δf denotes the subcarrier spacing [15]. The baseband signal is quadrature up-converted to a carrier frequency, f_c, before transmission through free space. Upon reflection from a target located at a distance R, the received signal, denoted by $r(t)$, is subject to quadrature down-conversion and can be described 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 illustrates the complex channel response at the nth subcarrier, while $w(t)$ represents the noise present at the receiver. The parameter τ corresponds to the round-trip time delay, which equals $(2R/c)$, with c representing the speed of light. In this work, matched filter processing will be employed, designed to optimize the signal-to-noise ratio (SNR) at its output, rather than subcarrier-based processing. The output of the matched filter can be expressed as

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

The determination of the time delay estimate, denoted as $\hat{\tau}$, involves identifying the value that maximizes the magnitude of the response from the matched filter. Subsequently, the range estimate can be computed using the following expression

$$\hat{R} = \frac{c\hat{\tau}}{2}. \tag{4}$$

III. RANGING USING OFDM SIGNALS IN THE PRESENCE OF MULTIPLE USERS

One unique characteristic of OFDM signals is their noise-like nature. OFDM signals are instantaneously wideband, with different information encoded in every subcarrier, which results in a noisy time-domain response. This noise-like nature offers several advantages to OFDM signals for ranging, including immunity from jamming and interference, and the ability to accommodate multiple radar transmissions within the same band. These benefits are often observed in coherent noise radar systems, which achieve ranging through matched-filtering [17].

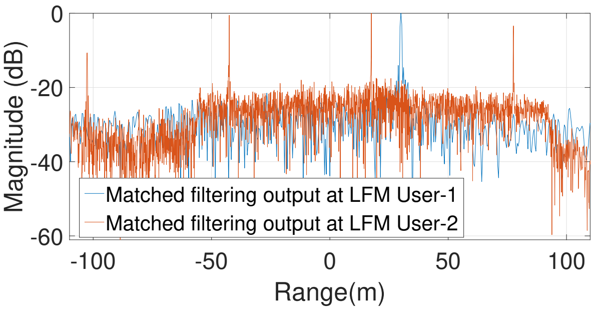


Fig. 2. Simulated matched filter output using LFM waveforms generated by two different radars occupying the same bandwidth. The distance of User-1 from the target is 30 m and the distance of User-2 is 70 m. Ghost responses appear at multiple distances.

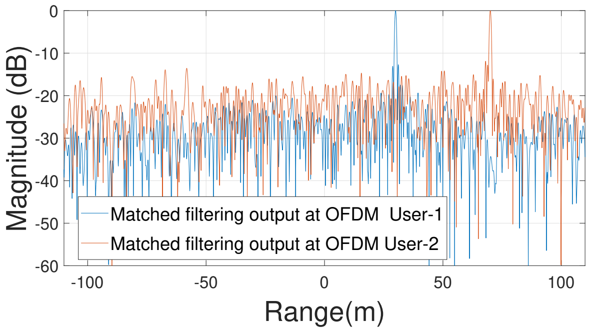


Fig. 3. Simulated matched filter output making use of OFDM signals generated by two different users for range estimation. The first user is located 30 m away from the object, and the distance of the second user is 70 m. No ghost responses or coupling is present.

The configuration illustrated in Fig. 1 was initially simulated to assess the utilization of LFM signals in the presence of two LFM users, similar to the two-user OFDM scenario. Both users were simultaneously transmitting a ranging waveform towards a target of interest and capturing the reflections. The target was located at a distance of 30 m from User-1 and 70 m from User-2. In the first scenario, both users transmitted a linear frequency-modulated (LFM) waveform with a bandwidth of 200 MHz within the same spectral bands. User-1's chirp rate was 62.5×10^{12} Hz/s, while User-2's chirp rate was 250×10^{12} Hz/s. The matched-filter responses are depicted in Fig. 2. Interference is evident in the responses, which can degrade performance and introduce additional ghost responses. Ideally, there should be a distinct response for User-1 at 30 m (indicated in blue) and another for User-2 at 70 m (indicated in orange). However, the presence of interference results in three additional peaks, making them non-differentiable.

Afterward, a simulation is conducted with two OFDM transceivers positioned at distances of 30 and 70 meters, respectively. The results are illustrated in Fig. 3. Quadrature Amplitude Modulation with 4 levels (4-QAM) and 8-QAM

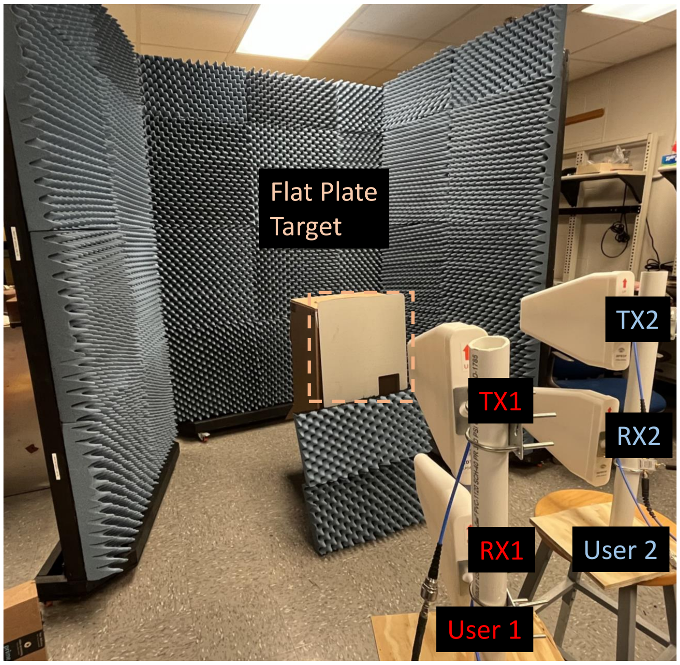


Fig. 4. Photograph of the experimental setup. User-1 is noted with red and User-2 with blue. The flat plate target is shown with a dotted line.

are used to modulate the symbols for User-1 and User-2, respectively. Both users occupy the same bandwidth of 200 MHz, and each utilizes 2048 subcarriers. It is readily observed that the two responses are completely separated, with no overlapping or ghost responses present. OFDM provides sharp responses at the locations where the targets are located for both users. This outcome is attributed to the excellent cross-correlation properties of noise-like signals, such as OFDM. In the next section, an experimental setup is constructed to verify the feasibility of this OFDM radar sensing operation within the same spectral resources.

IV. Experimental Measurements

The experimental measurements were conducted in a semi-anechoic environment, as depicted in Fig. 4. User-1 remained stationary, positioned 1.01 m away from the flat plate target. User-2 was initially situated 1.15 m from the 59 cm × 45 cm flat plate reflector and was subsequently relocated to distances of 1.25 m and 1.30 m. A block diagram of the setup is depicted in Fig. 5. Both transmit and receive antennas for both users were log-periodic antennas with 9 dBi gain. The transmitted signals from TX1 and TX2, with center frequencies of 1.5 GHz and 1.55 GHz respectively, were generated from a Keysight M8190 Arbitrary Waveform Generator (AWG), occupying the same bandwidth simultaneously. The subcarrier spacing Δf was 12.5 MHz, and 4-QAM was utilized, with 64 subcarriers for both users. The received signals at RX1 and RX2 were amplified using Mini-Circuits ZX60-53LN+ low-noise amplifiers and subsequently captured using a Keysight MXR404A oscilloscope. The total OFDM signal bandwidth was 800 MHz, wider than in the simulations due to shorter-range experiments conducted in a research lab.

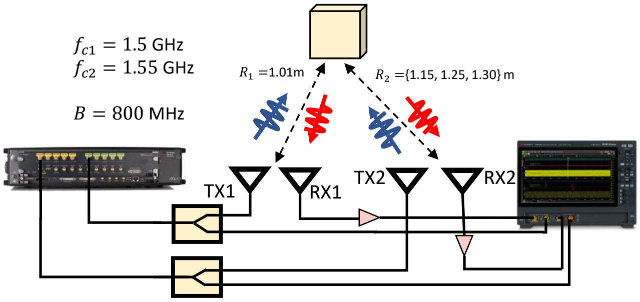
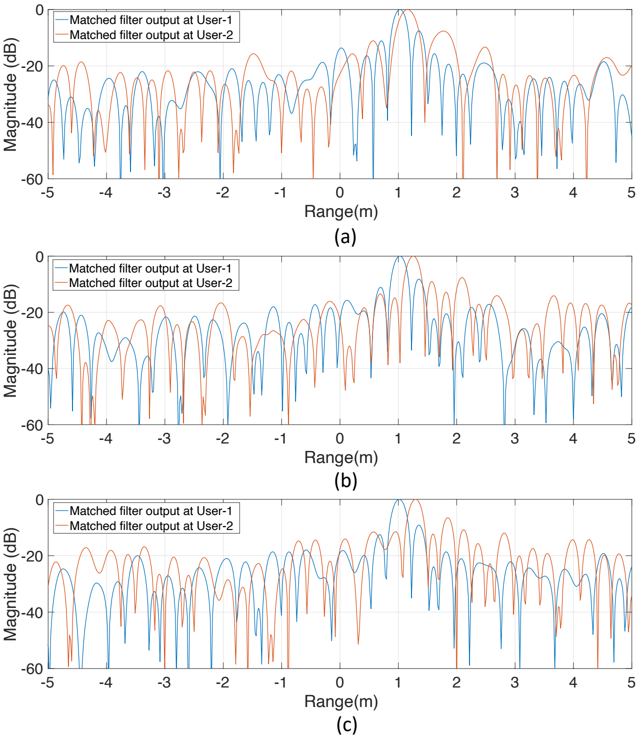


Fig. 5. Block diagram of the experimental setup. The arbitrary waveform generator (AWG) is used for transmission and the mixed-signal oscilloscope is used for reception.



(a)

(b)

(c)

Fig. 6. Experimental ranging measurements of the two users. (a) The first user is located at 1.01 m and the second user is 1.15 m away from the object. (b) The first user is located at 1.01 m and the second user is moved to 1.25 m away from the object. (c) The first user is located at 1.01 m and the second user is moved to 1.3 m away from the object.

The experimental ranging measurements are presented in Fig. 6. Both users independently achieved ranging measurements from the flat plate while utilizing overlapping spectral and temporal resources. In Fig. 6(a), User-1 was located at a distance of 1.01 m, and User-2 was located at a distance of 1.15 m. Moving User-2 to different distances resulted in changes in the peak location of the matched filter, as shown in Fig. 6(b) at a distance of 1.25 m and Fig. 6(c) at a distance of 1.3 m, respectively. All three plots demonstrate clear differentiation and very low interference between the two users. In contrast to the LFM simulations displayed in the previous section, OFDM enables simultaneous use of the spectrum for multiple users when employing the matched filter approach.

V. CONCLUSION

In this paper, the ability of multiple OFDM users to achieve radar sensing utilizing the same spectral and temporal resources is examined. OFDM has improved cross-correlation properties and does not require any cooperation between users. Our simulated results, along with experimental measurements, verify that simultaneous multi-user ranging can be achieved without any cooperation. Future work will investigate a larger number of users and analyze the effect of Doppler in non-cooperative OFDM multi-user ranging.

REFERENCES

[1] G. Destino, T. Mahmoodi, R. Shreevastav, D. Shrestha, and I. Siomina, “A new position quality metric for nr rat dependent otdoa positioning methods,” in *2019 16th Workshop on Positioning, Navigation and Communications (WPNC)*, 2019, pp. 1–5.

[2] T. Wild, V. Braun, and H. Viswanathan, “Joint design of communication and sensing for beyond 5g and 6g systems,” *IEEE Access*, vol. 9, pp. 30 845–30 857, 2021.

[3] F. Liu, C. Masouros, A. P. Petropulu, H. Griffiths, and L. Hanzo, “Joint radar and communication design: Applications, state-of-the-art, and the road ahead,” *IEEE Transactions on Communications*, vol. 68, no. 6, pp. 3834–3862, 2020.

[4] C. De Lima, D. Belot, R. Berkvens, A. Bourdoux, D. Dardari, M. Guillaud, M. Isomursu, E.-S. Lohan, Y. Miao, A. N. Barreto, M. R. K. Aziz, J. Saloranta, T. Sanguanpuak, H. Sarieddeen, G. Seco-Granados, J. Suutala, T. Svensson, M. Valkama, B. Van Liempd, and H. Wymeersch, “Convergent communication, sensing and localization in 6g systems: An overview of technologies, opportunities and challenges,” *IEEE Access*, vol. 9, pp. 26 902–26 925, 2021.

[5] M. Yin, A. K. Veldanda, A. Trivedi, J. Zhang, K. Pfeiffer, Y. Hu, S. Garg, E. Erkip, L. Righetti, and S. Rangan, “Millimeter wave wireless assisted robot navigation with link state classification,” *IEEE Open Journal of the Communications Society*, vol. 3, pp. 493–507, 2022.

[6] K.-C. Chen, S.-C. Lin, J.-H. Hsiao, C.-H. Liu, A. F. Molisch, and G. P. Fettweis, “Wireless networked multirobot systems in smart factories,” *Proc. IEEE*, vol. 109, no. 4, pp. 468–494, 2021.

[7] C. Sturm and W. Wiesbeck, “Waveform design and signal processing aspects for fusion of wireless communications and radar sensing,” *Proc. IEEE*, vol. 99, no. 7, pp. 1236–1259, Jul. 2011.

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

[9] 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.

[10] J. A. Zhang, M. L. Rahman, K. Wu, X. Huang, Y. J. Guo, S. Chen, and J. Yuan, “Enabling joint communication and radar sensing in mobile networks—a survey,” *IEEE Communications Surveys & Tutorials*, vol. 24, no. 1, pp. 306–345, 2021.

[11] A. R. Chiriyath, S. Ragi, H. D. Mittelmann, and D. W. Bliss, “Novel radar waveform optimization for a cooperative radar-communications system,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 55, no. 3, pp. 1160–1173, Jun. 2019.

[12] E. Iradier, L. Fanari, I. Bilbao, J. Montalban, P. Angueira, O. Seijo, and I. Val, “Analysis of noma-based retransmission schemes for factory automation applications,” *IEEE Access*, vol. 9, pp. 29 541–29 554, 2021.

[13] S. Rao and A. V. Mani, “Interference characterization in fmcw radars,” in *2020 IEEE Radar Conference (RadarConf20)*, 2020, pp. 1–6.

[14] Y. L. Sit, L. Reichardt, C. Sturm, and T. Zwick, “Extension of the ofdm joint radar-communication system for a multipath, multiuser scenario,” in *2011 IEEE RadarCon (RADAR)*, 2011, pp. 718–723.

[15] J. Guan, A. Paidimarri, A. Valdes-Garcia, and B. Sadhu, “3-d imaging using millimeter-wave 5g signal reflections,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 6, pp. 2936–2948, 2021.

[16] R. Narayanan and M. Dawood, “Doppler estimation using a coherent ultrawide-band random noise radar,” *IEEE Transactions on Antennas and Propagation*, vol. 48, no. 6, pp. 868–878, 2000.

[17] R. M. Narayanan, “Through-wall radar imaging using uwb noise waveforms,” *Journal of the Franklin Institute*, vol. 345, no. 6, pp. 659–678, 2008, advances in Indoor Radar Imaging. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0016003208000331