DOI. No. 10.1109/MAES.2023.3349228

# 20 Years of MIMO Radar

**Yılmaz Kalkan**, Khoja Akhmet Yassawi International Kazakh-Turkish University, 160200 Turkestan, Kazakhstan, and also Aydın Adnan Menderes University, 09010 Aydın, Türkiye

## INTRODUCTION

The introduction of the term "multiple-input, multiple-output (MIMO) radar" occurred 21 years ago within the radar community, notably at the 37th Asilomar Conference in 2003 [1], [2]. It was first mentioned in [1], where the authors highlighted the interpretation of radar within a MIMO context and the application of MIMO extension from communication to radar. Subsequently, the advantages of this approach, including degrees of freedom and enhanced resolution capability, were emphasized. A similar integration of MIMO concepts with digital array radar was presented in [2], focusing on wide angular coverage. These pioneering efforts were motivated by advancements in communication theory, particularly in MIMO communication [3], [4], [5].

In 2004, Fishler et al. introduced the idea of "MIMO radar" at the IEEE Radar Conference, presenting it as an idea whose time had come [6]. Actually, radar systems which include more than one spatially separated transmitter and/or receiver stations were used widely in last decades. These radar systems were called as multistatic radars, multisite radar systems (MSRS), and netted radars as well. In [7], multisite radar system is defined as "a radar system including several spatially separated transmitting, receiving and (or) transmitting–receiving facilities where information of each target from all sensors are fused and jointly processed." Exactly 11 years after this definition, the MIMO radar was defined as; "radar system employing multiple transmit waveforms and having the ability to jointly process signals received at multiple receive antennas" [8]. As seen from these definitions; MIMO radar is the subclass of MSRS. Using the spatially separated multiple stations was not a new idea with MIMO radar, perhaps using the uncorrelated, if possible orthogonal, signals from each transmitter could be thought as a new idea with MIMO radars.

The ensuing years witnessed a surge in publications, especially following the impactful articles by Stoica [9] and Haimovich et al. [10] in *IEEE Signal Processing Magazine* in 2007 and 2008, respectively. These article (Figure 1) garnered significant citations and brought heightened awareness to the potential of MIMO radar. Today, they have reached 1876 and 1658 citations in IEEE *Xplore* and 2136 and 1889 citations in Scopus, respectively.

This article provides a comprehensive summary of the past 20 years of MIMO radar by analyzing publication data from IEEE *Xplore* and Scopus databases. Instead of delving into detailed technical analyses, the focus is on the overarching themes of the publications, utilizing numerical values such as the number of publications and citations to elucidate key areas of MIMO radar research. These analyses aim to provide insights for researchers interested in exploring the MIMO radar domain.

This article is organized as follows. The section "MIMO Radar" provides a concise definition of MIMO

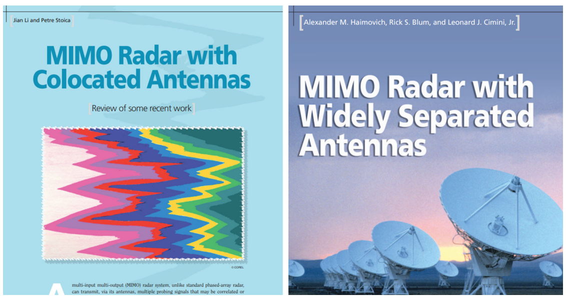


**Figure 1.**
Covers of 2 popular corner rock articles for MIMO radar [9] and [10].

Author's current address: The author is with the Faculty of Engineering, Department of Electrical Engineering, Khoja Akhmet Yassawi International Kazakh-Turkish University, 160200 Turkestan, Kazakhstan, and also with the Faculty of Engineering, Department of Electrical, and Electronics Engineering, Aydın Adnan Menderes University, 09010 Aydın, Türkiye (e-mail: yilmaz.kalkan@adu.edu.tr).
Manuscript received 31 October 2023; accepted 21 December 2023, and ready for publication 2 January 2024.
Review handled by Daniel O'Hagan.
0885-8985/24/$26.00 

radar. The section "Analysis of the Last 20 Years of MIMO Radar With Numbers" summarizes the last two decades of MIMO radar research, examining numerical values of publications; it further explores the current state and future directions of MIMO radar research, identifying emerging areas of interest. Finally, the "Conclusion" section offers concluding remarks.

## MIMO RADAR

A MIMO radar system constitutes a radar network employing multiple spatially distributed transmitters and receivers. While categorized as a type of multistatic radar in a general sense, the nomenclature distinguishes MIMO radar, highlighting unique features that align closely with MIMO communications [10]. Unlike conventional phased-array radar, which transmits scaled versions of a single waveform from its antennas, a MIMO radar system can transmit multiple signals via its antennas, whether correlated or uncorrelated [9]. Figure 2 provides a simple comparison between MIMO radar and phased-array radar [9].

With the publication of influential articles, MIMO radar systems diverged into two main branches based on the distance between antennas. The first scenario involves widely separated transmitting and receiving antennas to capture the spatial diversity of the target's radar cross-section (RCS). In the second scenario, waveform diversity is achieved through colocated transmit and receive antenna arrays. The advantages and disadvantages of both scenarios are summarized in review articles [9] and [10].

Today MIMO radar is still a hot topic in between researchers. All over the world many researchers from different countries have working on MIMO radar with big efforts and this can be seen clearly in Figure 3. By searching Scopus with "MIMO" and "radar" keywords and limiting our search in "Article Title" field, total of 4698 result in between 2003 and 2024 can be found. Figures 3 and 4 are obtained by using "Analyze Result" property of Scopus database.

MIMO radar continues to be a vibrant research area globally, as evidenced by the significant number of researchers contributing to publications worldwide (Figure 3). A diverse range of disciplines, including "Social Sciences" and "Chemistry" has embraced MIMO radar applications (Figure 4).

## ANALYSIS OF THE LAST 20 YEARS OF MIMO RADAR WITH NUMBERS

Over the past two decades, more than 3000 papers on MIMO radar have been published across various journals,

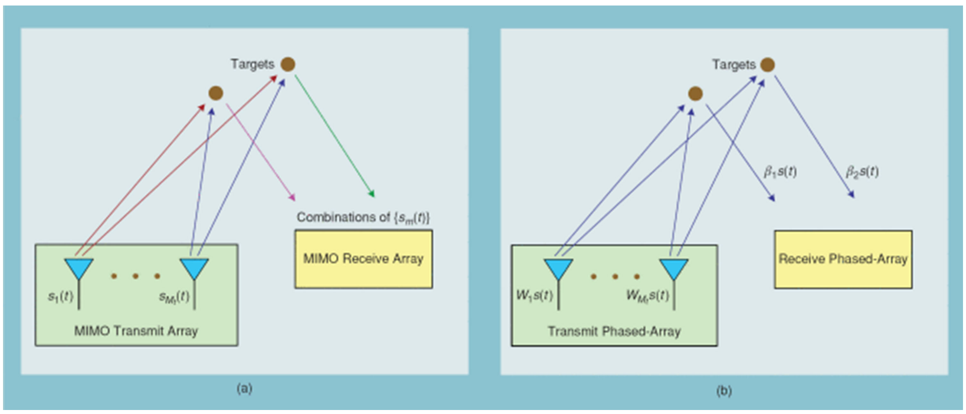


**Figure 2.**
(a) MIMO radar versus (b) phased array (from [9]).

**Table 1.**

| Publication Numbers in IEEE *Xplore* | | | | | |
|---|---|---|---|---|---|
| **Year** | **Conference** | **Journal** | **Magazine** | **Books** | **Total** |
| **2003** | 2 | - | - | - | 2 |
| **2004** | 7 | - | - | - | 7 |
| **2005** | 3 | - | - | - | 3 |
| **2006** | 29 | - | - | - | 29 |
| **2007** | 34 | 9 | 1 | 1 | 45 |
| **2008** | 62 | 8 | 1 | - | 71 |
| **2009** | 101 | 8 | 1 | 9 | 119 |
| **2010** | 141 | 36 | 1 | - | 178 |
| **2011** | 120 | 23 | - | - | 143 |
| **2012** | 128 | 27 | - | - | 155 |
| **2013** | 109 | 22 | - | - | 131 |
| **2014** | 141 | 32 | 2 | - | 175 |
| **2015** | 141 | 44 | - | - | 185 |
| **2016** | 169 | 27 | - | - | 196 |
| **2017** | 125 | 55 | 2 | - | 182 |
| **2018** | 140 | 77 | 3 | 1 | 221 |
| **2019** | 186 | 78 | - | - | 264 |
| **2020** | 128 | 93 | 2 | - | 223 |
| **2021** | 175 | 108 | 1 | - | 284 |
| **2022** | 165 | 121 | 2 | - | 288 |
| **2023** | 107 | 98 | - | 4 | 247 |
| **Total** | 2213 | 886 | 16 | 15 | 3118* |

**Total number is 3149, 31 early access papers are not included this total number.*

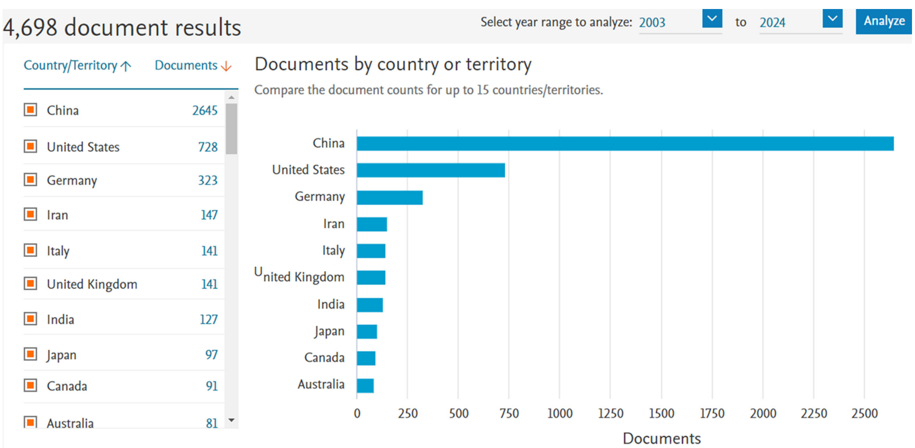


**Figure 3.**
MIMO radar documents by country or territory (source: Scopus).

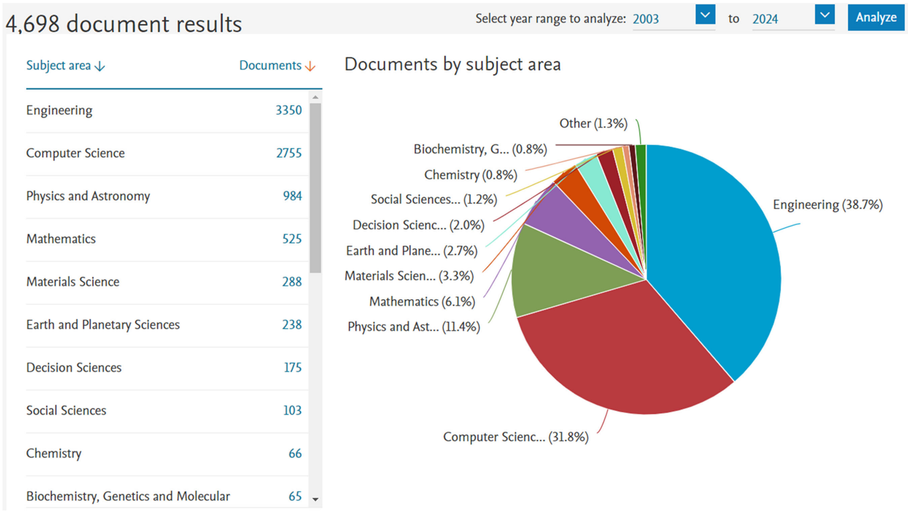


**Figure 4.**
MIMO radar documents by subject area (source: Scopus).

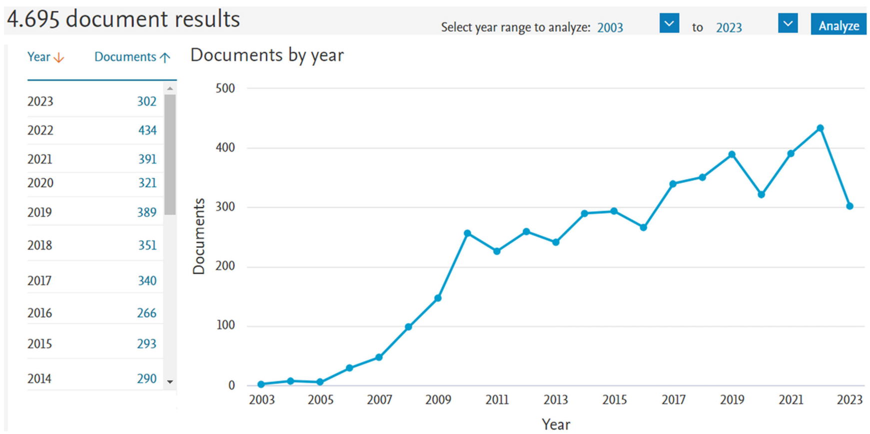


**Figure 5.**
Number of publications including “MIMO radar” in their’s title according to the years (source: Scopus).

magazines, conference proceedings, and books, with the contributions of dedicated researchers from all around the world as shown in Figures 3 and 4. The exact numbers are 3149 and 4698 in IEEE *Xplore* and Scopus, respectively, as of 25 November, 2023. Figure 5 illustrates the distribution of publications with “MIMO radar” in their titles across the years (source: Scopus). A similar analysis using the “Advanced Search” property of IEEE *Xplore* is presented in Table 1.

As can be seen from the results given in Table 1 and Figure 5, the MIMO radar still an active research field and many researchers have been continuing to work on it. The most cited 10 papers over the last two decades, based on IEEE *Xplore* data and citation numbers from Scopus, are provided in Table 2. Additionally, the most cited publications in the last three years, within the top 100 cited papers, are included. This includes patent citations as well.

## FUTURE OF MIMO RADAR

MIMO studies have predominantly focused on signal processing, waveform design, parameter estimation, target localization, and detection and estimation accuracy in recent decades. Table 3 presents the ten most cited papers in 2023 from IEEE *Xplore*, along with their citation numbers. Considering these are the latest papers, lower citation numbers are expected. Using the “Most Popular” criteria on IEEE *Xplore*, Table 4 presents the full text views of papers in 2023, providing insights into reader interest. Notably, the most cited and most viewed papers do not perfectly align, emphasizing the

**Table 2.**

| Ten Most Cited MIMO Radar Papers in IEEE *Xplore* (With the Addition of Last 3 Years) | | | | | |
|---|---|---|---|---|---|
| **No** | **Year** | **Title** | **Where** | **Total Cites** | |
| | | | | **IEEE** | **Scopus** |
| **1** | 2007 | MIMO Radar with colocated antennas [9] | IEEE SPM | 1876 | 2136 |
| **2** | 2008 | MIMO Radar with widely separated antennas [10] | IEEE SPM | 1658 | 1889 |
| **3** | 2004 | MIMO radar: an idea whose time has come [6] | IEEE Radar Conf. | 933 | 1583 |
| **4** | 2006 | Target detection and localization using MIMO radars and sonars [11] | IEEE TSP | 858 | 1017 |
| **5** | 2007 | On probing signal design for MIMO radar [12] | IEEE TSP | 648 | 751 |
| **6** | 2003 | MIMO radar and imaging: degrees of freedom and resolution [1] | Asilomar Conf. | 499 | 737 |
| **7** | 2007 | On parameter identifiability of MIMO radar [13] | IEEE SPL | 466 | 593 |
| **8** | 2010 | DOD and DOA estimation in MIMO radar with reduced-dimension MUSIC [14] | IEEE CL | 464 | 542 |
| **9** | 2010 | Target localization accuracy gain in MIMO radar-based systems [15] | IEEE TIT | 428 | 460 |
| **10** | 2007 | MIMO radar waveform design based on mutual information and MMSE estimation [16] | IEEE TAES | 425 | 495 |
| **32** | 2020 | MIMO radar for advanced driver-assistance systems and autonomous driving [17] | IEEE SPM | 213 | 183 |
| **34** | 2020 | Joint transmit beamforming for multiuser MIMO communications and MIMO Radar [18] | IEEE TSP | 207 | 204 |
| **67** | 2020 | Suppression of mainbeam deceptive jammer with FDA-MIMO radar [19] | IEEE TVT | 123 | 127 |
| **77** | 2020 | Resource scheduling for distributed MTT in netted colocated MIMO radar systems [20] | IEEE TSP | 116 | 118 |
| **96** | 2021 | Nested MIMO radar: coarrays, tensor modeling, and angle estimation [21] | IEEE TAES | 98 | 93 |

importance of full text views as a reliable indicator of reader interest. For example, the most cited paper in 2023 [22] is surprisingly not one of the most viewed. Similarly, the second most viewed paper [32] took only and only one cite. For future projection, number of full text viewing gives more reliable results as it projects the reader's interest on topic.

The future of MIMO radar appears promising, with continued emphasis on signal processing, waveform design, and applications in various domains [38]. It seems that MIMO radar and communication relationship will be one of the hottest research area in the next years. Similarly, MIMO and OFDM combination [39] is another most viewed title as CW or FMCW MIMO Radar topic. Smart systems, medical applications [23], [35], [36], autonomous driving technology [17], [29], and UAV/drone applications emerge as hot research areas. As autonomous vehicles will dominate the future of the vehicle technology together with electrical vehicles, MIMO radar will be expected to be in part of this especially in autonomous driving, autonomous parking, crash avoidance, and passenger safety systems [40], [41]. This is also valid for UAV and Drone applications [22]. MIMO radar will be used together with UAVs and also used to detect and to intercept drones [22], [42], [43], [44]. MIMO radar's application in these domains is expected to grow, driven by advancements in technology and the inherent advantages of MIMO topology. As we celebrated 20 years of MIMO radar in 2023, its sustained popularity is evident, and future research may address challenges such as energy consumption in larger MIMO systems.

**Table 3.**

| Ten Most Cited MIMO Radar Papers in IEEE *Xplore* in 2023 | |
|---|---|
| **Title of the Article** | **Cites** |
| 3-D positioning method for anonymous UAV based on bistatic polarized MIMO radar [22] | 27 |
| Wideband gain enhancement of MIMO antenna and its apps in FMCW radar sensor integrated with CMOS-based transceiver chip for human resp. monitoring [23] | 20 |
| 2D-DOD and 2D-DOA estimation using sparse L-shaped EMVS-MIMO radar [24] | 12 |
| High-resolution automotive imaging using MIMO radar and doppler beam sharpening [25] | 11 |
| MIMO radar transmit beampattern shaping for spectrally dense environments [26] | 9 |
| A bandwidth efficient dual-function radar communication system based on a MIMO radar using OFDM waveforms [27] | 6 |
| Efficient transceiver design for MIMO dual-function radar-communication systems [28] | 6 |
| Enhanced automotive sensing assisted by joint communication and cognitive sparse MIMO radar [29] | 5 |
| ICI-robust transceiver design for integration of MIMO-OFDM radar and MU-MIMO communication [30] | 5 |
| Joint strategy of power and bandwidth allocation for multiple maneuvering target tracking in cognitive MIMO radar with collocated antennas [31] | 5 |

**Table 4.**

| Ten Most Popular MIMO Radar Papers in IEEE *Xplore* in 2023 | |
|---|---|
| **(Number of cites) Title of the Article** | **Full Text Views** |
| (6) A bandwidth efficient dual-function radar communication system based on a MIMO radar using OFDM waveforms [27] | 3526 |
| (1) The impact of antenna array calibration errors on MIMO and multi-channel synthetic aperture radar imaging [32] | 2571 |
| (20) Wideband gain enhancement of MIMO antenna and its applications in FMCW radar sensor integrated With CMOS-based transceiver chip for human resp. monitoring [23] | 1316 |
| (3) Joint beamforming design for dual-functional MIMO radar and communication systems guaranteeing physical layer security [33] | 1136 |
| (3) range-division multiplexing for MIMO OFDM joint radar and communications [34] | 1000 |
| (2) Multiperson position estimation based on correlation between received signals using MIMO FMCW radar [35] | 939 |
| (5) ICI-robust transceiver design for integration of MIMO-OFDM radar and MU-MIMO communication [30] | 812 |
| (0) Distributed MIMO CW radar for locating multiple people and detecting their vital signs [36] | 761 |
| (6) Efficient transceiver design for MIMO dual-function radar-communication systems [28] | 703 |
| (3) Phase-coded FMCW for coherent MIMO radar [37] | 683 |

## CONCLUSION

In 2023, the radar community celebrated the 20th anniversary of MIMO radar, marking its enduring popularity since its introduction in 2003. Computational complexity, the primary challenge two decades ago, has become less significant with advancements in electronics and computers. The superiority of MIMO topology over SISO, SIMO, and MISO topologies ensures its continued prominence in future research. However, energy consumption may emerge as a significant concern as MIMO system sizes increase. Addressing this challenge through energy harvesting in MIMO systems represents a potential future avenue for exploration.

## ACKNOWLEDGMENTS

All data used in this article are sourced from the IEEE *Xplore* and Scopus databases. The development of digital technologies has made accessing and analyzing these databases more convenient than ever. The author expresses gratitude to the IEEE and Scopus institutions for providing these powerful tools.

## REFERENCES

[1] D. W. Bliss and K. W. Forsythe, "Multiple-input multiple-output (MIMO) radar and imaging: Degrees of freedom and resolution," in *Proc. 37th Asilomar Conf. Signals Syst. Comput.*, Pacific Grove, CA, USA, 2003, pp. 54–59, doi: 110.1109/ACSSC.2003.1291865.

[2] D. J. Rabideau and P. Parker, "Ubiquitous MIMO multifunction digital array radar," in *Proc. 37th Asilomar Conf. Signals Syst. Comput.*, Pacific Grove, CA, USA, 2003, pp. 1057–1064, doi: 10.1109/ACSSC.2003.1292087.

[3] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Spacetime codes for high data rate wireless communication: Performance criterion and code construction," *IEEE Trans. Inf. Theory*, vol. 44, no. 2, pp. 744–765, Mar. 1998.

[4] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Pers. Commun.*, vol. 6, no. 3, pp. 311–335, 1998.

[5] D. Chizhik, G. J. Foschini, M. J. Gans, and R. A. Valenzuela, "Keyholes, correlations, and capacities of multielement transmit and receive antennas," *IEEE Trans. Wireless Commun.*, vol. 1, no. 2, pp. 361–368, Apr. 2002.

[6] E. Fishler, A. Haimovich, R. Blum, D. Chizhik, L. Cimini, and R. Valenzuela, "MIMO radar: An idea whose time has come," in *Proc. IEEE Radar Conf.*, Philadelphia, PA, USA, 2004, pp. 71–78, doi: 10.1109/NRC.2004.1316398.

[7] V. S. Chernyak, *Fundamentals of Multisite Radar Systems: Multistatic Radars and Multistatic Radar Systems*. London, U.K.: Gordon and Breach Science Publishers, 1998.

[8] H. Godrich, A. M. Haimovich, and R. S. Blum, "Target localization techniques and tools for MIMO radar," *IET Radar, Sonar Navig. J.*, vol. 3, no. 4, pp. 314–327, 2009.

[9] J. Li and P. Stoica, "MIMO radar with collocated antennas," *IEEE Signal Process. Mag.*, vol. 24, no. 5, pp. 106–114, Sep. 2007.

[10] A. M. Haimovich, R. S. Blum, and L. J. Cimini, "MIMO radar with widely separated antennas," *IEEE Signal Process. Mag.*, vol. 25, no. 1, pp. 116–129, 2008.

[11] I. Bekkerman and J. Tabrikian, "Target detection and localization using MIMO radars and sonars," *IEEE Trans. Signal Process.*, vol. 54, no. 10, pp. 3873–3883, Oct. 2006.

[12] P. Stoica, J. Li, and Y. Xie, "On probing signal design for MIMO radar," *IEEE Trans. Signal Process.*, vol. 55, no. 8, pp. 4151–4161, Aug. 2007.

[13] J. Li, P. Stoica, L. Xu, and W. Roberts, "On parameter identifiability of MIMO radar," *IEEE Signal Process. Lett.*, vol. 14, no. 12, pp. 968–971, Dec. 2007.

[14] X. Zhang, L. Xu, L. Xu, and D. Xu, "Direction of departure (DOD) and direction of arrival (DOA) estimation in MIMO radar with reduced-dimension MUSIC," *IEEE Commun. Lett.*, vol. 14, no. 12, pp. 1161–1163, Dec. 2010.

[15] H. Godrich, A. M. Haimovich, and R. S. Blum, "Target localization accuracy gain in MIMO radar-based systems," *IEEE Trans. Inf. Theory*, vol. 56, no. 6, pp. 2783–2803, Jun. 2010.

[16] Y. Yang and R. S. Blum, "MIMO radar waveform design based on mutual information and minimum mean-square error estimation," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 43, no. 1, pp. 330–343, Jan. 2007.

[17] S. Sun, A. P. Petropulu, and H. V. Poor, "MIMO radar for advanced driver-assistance systems and autonomous driving: Advantages and challenges," *IEEE Signal Process. Mag.*, vol. 37, no. 4, pp. 98–117, Jul. 2020.

[18] X. Liu, T. Huang, N. Shlezinger, Y. Liu, J. Zhou, and Y. C. Eldar, "Joint transmit beamforming for multiuser MIMO communications and MIMO radar," *IEEE Trans. Signal Process.*, vol. 68, pp. 3929–3944, 2020.

[19] L. Lan, J. Xu, G. Liao, Y. Zhang, F. Fioranelli, and H. C. So, "Suppression of mainbeam deceptive jammer with FDA-MIMO radar," *IEEE Trans. Veh. Technol.*, vol. 69, no. 10, pp. 11584–11598, Oct. 2020.

[20] W. Yi, Y. Yuan, R. Hoseinnezhad, and L. Kong, "Resource scheduling for distributed multi-target tracking in netted colocated MIMO radar systems," *IEEE Trans. Signal Process.*, vol. 68, pp. 1602–1617, 2020.

[21] J. Shi, F. Wen, and T. Liu, "Nested MIMO radar: Coarrays, tensor modeling, and angle estimation," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 57, no. 1, pp. 573–585, Feb. 2021.

[22] F. Wen, J. Shi, G. Gui, H. Gacanin, and O. A. Dobre, "3-D positioning method for anonymous UAV based on bistatic polarized MIMO radar," *IEEE Internet Things J.*, vol. 10, no. 1, pp. 815–827, Jan. 2023.

[23] W. Wang et al., "Wideband gain enhancement of MIMO antenna and its application in FMCW radar sensor integrated with CMOS-Based transceiver chip for human respiratory monitoring," *IEEE Trans. Antennas Propag.*, vol. 71, no. 1, pp. 318–329, Jan. 2023.

[24] F. Wen, J. Shi, J. He, and T.-K. Truong, "2D-DOD and 2D-DOA estimation using sparse L-shaped EMVS-MIMO radar," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 59, no. 2, pp. 2077–2084, Apr. 2023.

[25] S. L. Cassidy, S. Pooni, M. Cherniakov, E. G. Hoare, and M. S. Gashinova, "High-resolution automotive imaging using MIMO radar and doppler beam sharpening," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 59, no. 2, pp. 1495–1505, Apr. 2023.

[26] E. Raei, S. Sedighi, M. Alaee-Kerahroodi, and M. R. Bhavani Shankar, "MIMO radar transmit beampattern shaping for spectrally dense environments," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 59, no. 2, pp. 1007–1020, Apr. 2023.

[27] Z. Xu and A. Petropulu, "A bandwidth efficient dual-function radar communication system based on a MIMO radar using OFDM waveforms," *IEEE Trans. Signal Process.*, vol. 71, pp. 401–416, 2023.

[28] C. Wen, Y. Huang, and T. N. Davidson, "Efficient transceiver design for MIMO dual-function radar-communication systems," *IEEE Trans. Signal Process.*, vol. 71, pp. 1786–1801, 2023.

[29] X. Wang, W. Zhai, X. Zhang, X. Wang, and M. G. Amin, "Enhanced automotive sensing assisted by joint communication and cognitive sparse MIMO radar," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 59, no. 5, pp. 4782–4799, Oct. 2023.

[30] H. Noh, H. Lee, and H. J. Yang, "ICI-Robust transceiver design for integration of MIMO-OFDM radar and MU-MIMO communication," *IEEE Trans. Veh. Technol.*, vol. 72, no. 1, pp. 821–838, Jan. 2023.

[31] Z. Li, J. Xie, W. Liu, H. Zhang, and H. Xiang, "Joint strategy of power and bandwidth allocation for multiple maneuvering target tracking in cognitive MIMO radar with collocated antennas," *IEEE Trans. Veh. Technol.*, vol. 72, no. 1, pp. 190–204, Jan. 2023.

[32] J. Geiss, E. Sippel, M. Braunwarth, and M. Vossiek, "The impact of antenna array calibration errors on MIMO and multi-channel synthetic aperture radar imaging," *IEEE J. Microw.*, vol. 3, no. 2, pp. 635–654, Apr. 2023.

[33] F. Dong, W. Wang, X. Li, F. Liu, S. Chen, and L. Hanzo, "Joint beamforming design for dual-functional MIMO radar and communication systems guaranteeing physical layer security," *IEEE Trans. Green Commun. Netw.*, vol. 7, no. 1, pp. 537–549, Mar. 2023.

[34] O. Lang, C. Hofbauer, R. Feger, and M. Huemer, "Range-division multiplexing for MIMO OFDM joint radar and communications," *IEEE Trans. Veh. Technol.*, vol. 72, no. 1, pp. 52–65, Jan. 2023.

[35] K. Endo, T. Ishikawa, K. Yamamoto, and T. Ohtsuki, "Multi-person position estimation based on correlation between received signals using MIMO FMCW radar," *IEEE Access*, vol. 11, pp. 2610–2620, 2023.

[36] P.-H. Juan, C.-Y. Chueh, and F.-K. Wang, "Distributed MIMO CW radar for locating multiple people and detecting their vital signs," *IEEE Trans. Microw. Theory Techn.*, vol. 71, no. 3, pp. 1312–1325, Mar. 2023.

[37] U. Kumbul, N. Petrov, C. S. Vaucher, and A. Yarovoy, "Phase-coded FMCW for coherent MIMO radar," *IEEE Trans. Microw. Theory Techn.*, vol. 71, no. 6, pp. 2721–2733, Jun. 2023.

[38] Y. Kalkan and B. Baykal, "Frequency-based target localization methods for widely separated MIMO radar," *Radio Sci.*, vol. 49, no. 1, pp. 53–67, 2014.

[39] İ. Baştürk, "Iterative channel estimation techniques for multiple input multiple output orthogonal frequency division multiplexing systems," M.S. thesis, Grad. School Eng. Sci. İzmir Inst. Tech., İzmir, Türkiye, 2007.

[40] X. Gao, S. Roy, and G. Xing, "MIMO-SAR: A hierarchical high-resolution imaging algorithm for mmWave FMCW radar in autonomous driving," *IEEE Trans. Veh. Technol.*, vol. 70, no. 8, pp. 7322–7334, Aug. 2021.

[41] O. Markish, "Design and measurements of MIMO radar arrays for autonomous vehicles," in *Proc. 20th Eur. Radar Conf.*, Berlin, Germany, 2023, pp. 34–37, doi: 10.23919/EuRAD58043.2023.10289174.

[42] J. Klare, O. Biallawons, and D. Cerutti-Maori, "UAV detection with MIMO radar," in *Proc. 18th Int. Radar Symp.*, Prague, Czech Republic, 2017, pp. 1–8, doi: 10.23919/IRS.2017.8008140.

[43] S. Kemkemian, M. Nouvel-Fiani, P. Cornic, and P. Garrec, "MIMO radar for sense and avoid for UAV," in *Proc. IEEE Int. Symp. Phased Array Syst. Technol.*, Waltham, MA, USA, 2010, pp. 573–580, doi: 10.1109/ARRAY.2010.5613309.

[44] A. Yazici and B. Baykal, "Detection and localization of drones in MIMO CW radar," *IEEE Trans. Aerosp. Electron. Syst.*, early access, Oct. 3, 2023, doi: 10.1109/TAES.2023.3321586.