**Tutorial 15: Monday 21st of October – 2PM/5PM**

# MIMO and waveform diverse array

This tutorial is devided into 2 distinct parts

**Control and Utilization of Range-Dependent Beampattern in Waveform Diverse Array Radars: New Applications and Trends**

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**Abstract:**

Waveform diverse array radars can obtain the range-dependent beampattern by modulating the frequencies/time delays/phases across different transmit antenna elements. In this respect, extra Degrees-of-Freedom (DOFs) are achieved, which opens up an innovative way to fulfil the tasks with enhanced system performance by jointly using the angle and range information. This tutorial covers the state-of-art developments of the range-dependent beampattern with waveform diverse array radars, with emphasis on the most recent applications in target detection, parameter estimation, clutter/jammer suppression, Synthetic Aperture Radar (SAR) imaging, as well as the experimental systems.

**Technical Content:**

The transmit antenna beampattern of the phased array radar is only a function of angle, limiting its ability to discriminate the targets from the same direction. Recently, the waveform diverse array radars expand the angle-dependent beampattern to an angle-time-range-dependent three-dimensional function by modulating the frequencies/time delays/phases across different transmit antenna elements. In this respect, extra Degrees-of-Freedom (DOFs) are achieved, which opens up an innovative way to fulfil the tasks with enhanced system performance by jointly using the angle and range information.

This tutorial introduces the developments of waveform diverse radars, including the Frequency Diverse Array (FDA), the Space-Time-Circulating-Array (STCA), the Element-Pulse-Coding (EPC), and Receive Delay Array (RDA) frameworks, with emphasis on the range-dependent beampattern from the basic properties upon how it is controlled. Moreover, the most recent applications in target detection, parameter estimation, clutter/jammer suppression, target tracking, and High-Resolution and Wide-Swath imaging (HRWS) Synthetic Aperture Radar (SAR) imaging are discussed. In addition, the experimental systems and results with measured data are introduced.

**Learning Outcome:**

The tutorial aims to provide learners with a comprehensive understanding of the waveform diverse arrays, along with the properties of the range-dependent beampatterm and its applications in various areas. It is also encouraged to collaborate with researchers, sharing insights on other promising fields.

**Expected Audience:**

This tutorial is suitable for Ph.D students, radar scientists, engineers and practitioners who are interested to new, innovative, and recent results in the context of diversity in array radar systems, aimed at addressing sophisticated/challenging array radar signal processing problems as involved in the recent radar applications.

**Table of Content:**

1. Introduction of waveform diverse array radars
2. Concept and properties of range-dependent beampattern

3. Detection and estimation with waveform diverse array radars
4. Suppression of mainlobe deceptive jammers/range-ambiguous clutter and unambiguous SAR imaging with waveform diverse array radars
5. Introduction of waveform diverse array systems and experimental tests
6. Conclusions and future trends
7. Q&A
8. Introduction of the city of Xi’an, China, and Xidian University

**Author’s Biography:**

Lan Lan is currently an Associate Professor with the National Key Laboratory of Radar Signal Processing, Xidian University. She received the B.S. degree in electronic engineering and the Ph.D. degree in signal and information processing from Xidian University, Xi'an, in 2015 and 2020, respectively. From July 2019 to July 2020, she was a Visiting Ph.D. Student with the University of Naples Federico II, Naples, Italy. Her research interests include waveform diverse array radar system design and signal processing, MIMO radar signal processing, target detection, and ECCM.

Dr. Lan has published almost 70 papers on IEEE journals and conferences with more than 1000 citations in Google Scholar. Additionally, she has been authorized more than 20 national patents. She is in charge of various important projects, such as the National Natural Science Foundation of China, Projects of International Cooperation of National Key Research and Development Plan, Joint Fund of Ministry of Education, etc. Dr. Lan was elected as the Youth Elite Scientist Sponsorship Program by China Association for Science and Technology in 2022, the Excellent Scholar in Shaanxi Province, the third most beautiful Sanqin Youth Science and Technology Star in 2021, and the XXXV-th URSI Young Scientists Award in 2023. She won the best paper of the 2016 CIE International Conference on Radar, the 2022 5th International Conference on Information Communication and Signal Processing, and the 19th National Annual Conference on Signal Processing.

Dr. Lan served as the TPC member & session chair of important conferences, including the IEEE ICASSP 2024, 2023 IEEE International Radar Conference, 2021 CIE International Conference on Radar, 2020 IEEE Radar Conference, and 2022 IEEE SAM. She was also the Technical chair for 2020-2023 International Symposium on Multi-model Sensing and Information Processing. Dr. Lan is on the editorial broad of <Digital Signal Processing>(Elsevier) and the guest editor of <IEEE Sensors Journal>.

# Digital Modulation for MIMO Radars - Waveform Design and Signal Processing

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## I. Abstract

Digital modulation is emerging as a new paradigm for MIMO Continuous Wave radars that, as of today, mostly use the venerable Frequency Modulated Continuous Wave (FMCW) waveform. Phase-Modulated Continuous-Wave (PMCW) and Orthogonal Frequency-Division Multiplex (OFDM) radars enjoy several system level advantages with a moderate increase in complexity that tends to reduce over time with CMOS scaling. This tutorial covers several aspects of PMCW and OFDM radars including waveform design, signal processing and compensation of analog front-end non-idealities.

## II. Technical Content

This tutorial will start by motivating the use of Digitally Modulated Radar (DMR) for automotive applications, Joint Communication and Sensing, distributed radars architecture,... We will show that for large scale MIMO radars, the use of DMR helps to detect, without ambiguity, high speed moving obstacles while this is more difficult with FMCW. We will also provide an overview of the challenges coming with DMR, especially, their sensitivity to Doppler frequency shift, which produces range sidelobes, or the Tx leakage, which cannot be removed by a baseband high-pass filter as in FMCW radars. This tutorial will focus on two popular waveforms for DMR: PMCW and OFDM.

We will cover waveform design techniques able to reduce the sidelobes due to Doppler frequency shift, remove the impact of IQ imbalance in DMR with techniques, improve robustness to phase noise, provide MIMO capabilities combined with high unambiguous Doppler, limit the impact of Tx leakage and improve robustness to transceiver non-linearity. For the specific case of OFDM radar, we will investigate low peak-to-average-power ratio (PAPR).

While the literature contains a lot of solutions to improve the radar performances by calibration techniques, the proposed approach is to mitigate the impact of front-end non-idealities by waveform design and/or low complexity signal processing techniques. Therefore, the radar dynamic range can be strongly improved without requiring the need for costly calibration processing and complex analog front-end design.

## III. Learning Outcome

Most of the techniques which will be presented in this tutorial have already been published separately in journals and/or conferences; the material is for the first time presented in a unified way, providing the big picture of MIMO DMR. The tutorial will help radar practitioners to better understand the design choices for modern radars using digital modulation and MIMO techniques. In addition, it teaches how to mitigate the impact of hardware non-idealities and Doppler on the ambiguity function.

## IV. Expected Audience

The tutorial targets engineers (students through experts, from academia or industry) who are interested in gaining an understanding of radars using digital waveforms combined with MIMO. The tutorial is accessible to all with a basic understanding of radar concepts. We expect 40+ attendees.

## V. Table of content

- Why digital modulations for MIMO radars?
- Basics of PMCW and OFDM radar: waveform, transceiver and signal processing
- PMCW radars with polyphase Constant Amplitude Zero AutoCorrelation (CAZAC) code sequences: front-end non-idealities and mitigation techniques
- OFDM radar: Low PAPR and IQ imbalance mitigation
- Mitigating the impact of Tx leakage signal in MIMO DMR: mixed-signal cancellation technique and waveform design
- QA

## VI. Author's Biography

**André Bourdoux** (Senior Member, IEEE) is the Scientific Director in the Advanced RF research group of IMEC. He is a system level and signal processing expert for both the mm-wave wireless communications and radar teams. He has more than 15 years of research experience in radar systems and 15 years of research experience in broadband wireless communications. He holds several patents in these fields and he is the author or co-author of over 250 publications in books and peer-reviewed journals and conferences. His research interests are in the field of distributed MIMO networks, mm-wave and sub-THz communications, mm-wave automotive radars, radar networks, imaging radars, digitally modulated radars, and joint communications and sensing

**Marc Bauduin** received the M.Sc. degree in electrical engineering from the Universite Libre de Bruxelles (ULB), Belgium, in 2012, and the Ph.D. degree in engineering science from the joint OPERA and LIQ Departments, ULB, in 2016. In 2016, he joined imec, where he is currently a researcher. His research interests include millimeter-wave MIMO radar signal processing, waveform design, automotive and healthcare radar applications.