Joint Automotive MIMO-Radar-MIMO-Communications Signal Processing

- Tutorial Proposal for 2020 IEEE International Radar Conference -

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Outline

Extreme crowding of electromagnetic spectrum in recent years has led to emergence of complex challenges in designing radar and communications systems. with the advent of novel technologies such as drone-based customer services, autonomous driving, radio-frequency identification, weather monitoring, radar systems are now deployed in urban environments and operate in bands that were earlier reserved for communications services. Similarly, with rapid surge in mobile network operators, there is a growing concern that mobile data traffic poses a formidable challenge toward realizing future wireless networks. Both radar and communications systems need wide bandwidth to provide a designated quality-of-service (QoS) thus resulting in competing interests in exploiting the spectrum. Hence, sharing spectral and hardware resources of communications and radar is imperative toward efficient spectrum utilization.

In particular, automotive sector has witnessed concerted and intense efforts toward realizing these joint radar-communications (JRC) systems. A JRC model has advantages of low-cost, compact size, transportation safety due to enhanced mutual information sharing and performance optimization, spectrum sharing, and better management of inter-vehicular interference. Most of the modern automotive JRC systems operate at millimeter-wave (mm-Wave) which brings a new set of challenges and opportunities for the system engineers when compared with centimeter-wave JRC. This band is characterized by severe penetration losses, short coherence times, and availability of wide bandwidth. While wide bandwidth is useful in attaining high vehicular communications data rates and high-resolution automotive radar, the losses must be compensated by using massive multiple-input multiple-output (MIMO) processing which employs large number of antennas at the transmitter and receiver. There is, therefore, a surge in research on joint MIMO-Radar-MIMO-Communications (MRMC) systems.

As one of the spectrum-efficient technologies, MIMO has proven to be advantageous in detection and estimation in both radars and communications. MIMO systems employ several antennas for transmission and reception. In wireless communications, MIMO configuration enhances the capacity, provides spatial diversity and exploits multipath propagation. Further, recent developments in massive MIMO have demonstrated that uplink/downlink (UL/DL) channel reciprocity can be exploited by deploying very large number of service antennas to serve a lower number of mobile users with the time-division-duplexing (TDD). Similarly, MIMO radars offer capabilities that outweigh an equivalent, standard phased array radar such as higher angular resolution, spatial diversity, adaptable antennas, and improved parameter identifiability. The angular resolution of MIMO radar is same as a *virtual* uniform linear phased array (ULA) with the same antenna aperture but many more antennas than MIMO. However, unlike a phased array radar, each of the MIMO transmitters emit a different, mutually orthogonal - in time, frequency, or code - probing signal.

Apart from MIMO, several signal processing and digital communication techniques are critical in implementation of mm-Wave JRC. Major challenges are joint waveform design and performance criteria that would optimally trade-off between communications and radar functionalities. Constraints on the low-power consumption and implementation friendly designs are sought, while robust radar and communication receive processing to perform respective tasks need to be implemented. There are opportunities to exploit recent advances in cognition, compressed sensing, and machine learning to reduce required resources and dynamically allocate them with low overheads. In this tutorial, we give an overview of these challenges while focusing on mm-Wave JRC and MRMC.

Syllabus

The tutorial will begin motivating the JRC based focussing on the automotive scenario in the mm-Wave scenario. For the uninitiated, some background on radar and communications signal processing will also be included. It then addresses the following aspects:

1) **Scenario and Architectures:** The technical issues depend on the application scenario and the nature of co-operation between the communication and sensing tasks. Some typical scenarios include bi-static or monostatic radar operation, single or multiple user communications; these bring their own challenges. Further, the topology of radar and communication sharing the spectrum could be one of co-existence or of co-design. The initial part of the tutorial will delve on these aspects to set the tone for the appreciating the design methodologies.
2) **Mm-Wave Channel:** The unique characteristics of the mm-Wave channel have a great impact on the design and the tutorial presents the channel models for both communication and radar systems. The similarities and the differences are highlighted. Concepts like path loss, attenuation, coherent times, target properties will be discussed and specialized to the scenarios and architectures presented earlier. The impact of these parameters on the system design, like the need for high sampling, large array sizes will be presented
3) **JRC Design methodology:** For the identified scenarios and architectures, the design parameters are identified. These include (i) waveforms, (ii) receiver processing and (iii) information exchange between radar and communication tasks. The nature of the parameters depends on the scenario and topology and this dependence would be impacted; it could be related to orthogonal waveforms for MIMO radar and those achieving diversity/multiplexing on the communication link. Naturally, the constraints arising on the system design including power, computations, waveform shaping etc are collected. Central to the design is the choice of an appropriate objective function that encompasses the radar and communication tasks. For this challenging task, several performance measures including those from information theory will be discussed.
4) **JRC Design Tools and an example design**: With the parameters, constraints and objective identified the challenge of an optimized design are then presented. Inherent difficulties in solving the optimization problem are listed and sophisticated tools from convex and non-convex optimization (e.g. coordinate descent) for the system design are presented. An example system design taking the audience through the entire process will be presented. Video demonstration of a JRC prototype will be shown.
5) **Joint Coding**: Recently, existing mm-wave communications protocols that are embedded with codes that exhibit favorable radar AFs are garnering much attention for JRC. In particular, the 60-GHz IEEE 802.11ad standard wireless protocol has been employed with time-division multiplexing of radar-only and radar-communications frames. By exploiting the preamble of a single 802.11ad frame for radar, the existing mm-wave 802.11ad waveform simultaneously achieves a cm-level range resolution and a gigabytes data rate. The limited-velocity-estimation performance of this waveform can be improved by using multiple fixed-length frames in which preambles are reserved for radar. Finally, we show how some improvements in the protocol are suited for extended automotive targets.
6) **MRMC**: A recent direction in JRC is extension to MIMO technology for both systems, where the antenna positions of radar and communications are shared with each other. Both systems may share information with each other to benefit from increased number of design degrees-of-freedom (DoFs). Not only the communication signals are decoded at the radar Rx for enhanced target localization but also the communications Rx extracts information from both the directly received communication signals and signals reflected from the radar target. We present adaptations of MRMC to automotive and other applications.

The tutorial concludes by summarizing the presented topics and, more importantly, highlighting ongoing research activities and a vision on the system evolution. Information and resources needed for interesting researchers to pursue the field will also be presented.

Intended audience

The tutorial will be four hours with a break of 30 mins. This session will be highly relevant for participants from diverse backgrounds - academia, industry, and government - all of whom have active interest and stake in automotive MRMC research. The intended audience includes

a) PhD students in signal processing and wireless communications
b) Faculty and early stage post-doctoral researchers desirous of pursuing a challenging field
c) Colleagues from sensor and communications solution providers, chip-set manufacturers
d) Scientists at government laboratories – defence, space, and civilian – wishing to integrate more functionalities in their current state-of-the-art

Learning Outcomes

While several seminal works have been published, the research field of JRC/MRMC is vast with several interesting avenues to be explored. Exposure to radar processing, communication system design and a clear understanding of the existing JRC landscape are essential to pursue impactful research in this emerging area. In this context, the tutorial introduces the signal-processing-communications (SPCOM) perspective of mm-Wave JRC systems reviewing the state-of-the-art, highlighting the key technical challenges and solutions offered in prior-art, detailing the architectures, system design methodologies and optimization tools as well as providing a vision for the system evolution.

A relevant tutorial titled, "Signal processing for vehicular systems," was delivered at IEEE ICASSP 2019. The speakers are given to understand that the ICASSP tutorial focused on the generic signal processing aspects of vehicular systems. The details and implications of joint sensing with communications were excluded. Our proposed tutorial takes a focused view on the JRC/MRMC detailing the design methodologies and tools at mm-Wave, which is a more recent research direction. Further, the example designs and experience from prototyping the JRC is presented specifically for automotive applications.

After attending the tutorial, participants will be able to understand

1) Current challenges and design criteria associated with mm-Wave JRC
2) Popular JRC waveforms and corresponding receiver processing algorithms
3) Hardware design aspects of example JRC designs
4) Emerging research challenges and solutions in MRMC

Suggested Prerequisites

The tutorial assumes no specific technical expertise is required aside from a general knowledge of digital communication and statistical signal processing. It would cover fundamentals of radar and communications before introducing very recent research concepts. The tutorial aims for providing both practical and theoretical exposure to the course participants.

Schedule for a four-hour lesson

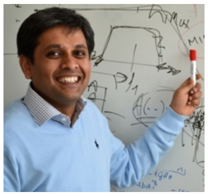
The tutorial aims to address the aforementioned aspects through the following presentation agenda

1) **<u>Fundamentals of radar and communications signal processing</u>** (15 mins): This covers basic building blocks of radar and communications systems and various design trade-offs.

2) **mm-Wave JRC: Definition and Motivation** (15 mins): This presents the various flavors of JRC and the need for the same with spectrum sharing, low cost design as motivating factors.
3) **mm-Wave JRC: Scenarios and architectures** (20 mins): This relates to item (1) above.
4) **mm-Wave JRC: Channel and impact on design** (20 mins): This relates to item (2) above.
5) **Co-existence Design** (30 mins) This deals with the scenario where the radar and communication system exist as separate units but work in a collaborative way through high level exchange of information. The waveform design, receiver processing and information exchanged to avoid interference will be highlighted. The design methodology and tools used will be discussed. It covers parts of item (3) and (4) discussed above.
6) **Co-design Methodologies** (30 mins): This deals with the scenario where the radar and communication system exist as a unified system and use one waveform for both the tasks. The waveform design and trade-offs achieved between communication and radar performance will be highlighted. The design methodology and tools used will be discussed. It covers parts of item (3) and (4) discussed above.
7) **Example JRC design** (20 mins): A bistatic JRC codesign scenario is considered and its design is highlighted; it covers parts of item (4) discussed above. Experience from a prototyping activity will be shared.
8) **Joint Coding** (30 mins): Recent developments in JRC using a common communications protocol such as IEEE 802.11ad.
9) **MIMO-Radar-MIMO-Communications (MRMC)** (30 mins): An updated extension of JRC to accommodate spatial diversity and MIMO technology. We will cover critical aspects, design issues, and example designs, not limited to only automotive applications.
10) **Conclusions and future outlook** (15 mins)
11) **Q/A** (15 mins)

Presenter(s) biographies

Kumar Vijay Mishra (S’08-M’15-SM’18) obtained Ph.D. in electrical engineering and M.S. in mathematics from The University of Iowa in 2015, and M.S. in electrical engineering from Colorado State University in 2012, while working on NASA’s Global Precipitation Mission Ground Validation (GPM-GV) weather radars. He received his B. Tech. *summa cum laude* (Gold Medal, Honors) in electronics and communication engineering from the National Institute of Technology, Hamirpur, India in 2003. During 2003-2007, he worked on military surveillance radars as a research scientist at the Electronics and Radar Development Establishment (LRDE), Defence Research and Development Organisation (DRDO) in Bengaluru. He is currently National Academies of Sciences, Engineering and Medicine (NASEM) Harry Diamond Distinguished Postdoctoral Fellow at United States Army Research Laboratory (ARL), Adelphi. He was a research intern at Mitsubishi Electric Research Labs (Cambridge) and at Qualcomm (San Jose) in 2015, and Andrew and Erna Finci Viterbi and Lady Davis postdoctoral fellow at the Viterbi Faculty of Electrical Engineering, Technion - Israel Institute of Technology during 2015-2017. He has been a Visiting Scholar at IIHR - Hydroscience & Engineering since 2015 and an honorary Research Fellow at SnT - Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg since 2018. He is on the board of Singapore-based automotive radar start-up Hertzwell as its Technical Adviser since 2018. He is the recipient of Royal Meteorological Society Quarterly Journal Editor's Prize (2017), Technion EE Excellent Undergraduate Adviser Award (2017), DRDO LRDE Scientist of the Year Award (2006), NITH Director’s Gold Medals for 1st rank in the Department of Electronics and Communication Engineering and entire university during the undergraduate commencement (2003), and NITH Best Student Award (2003). His research interests include signal processing, remote sensing, electromagnetics, communications, and deep learning.



M. R. Bhavani Shankar (SM'15) received Masters and Ph. D in Electrical Communication Engineering from Indian Institute of Science, Bangalore in 2000 and 2007 respectively. He was a Post Doc at the ACCESS Linnaeus Centre, Signal Processing Lab, Royal Institute of Technology (KTH), Sweden from 2007 to September 2009. He joined SnT in October 2009 as a Research Associate and is currently a Research Scientist at SnT. He was with Beceem Communications, Bangalore from 2006 to 2007 as a Staff Design Engineer working on Physical Layer algorithms for WiMAX compliant chipsets. He was a visiting student at the Communication Theory Group, ETH Zurich, headed by Prof. Helmut Bölcskei during 2004. Prior to joining Ph. D, he worked on Audio Coding algorithms in Sasken Communications, Bangalore as a Design Engineer from 2000 to 2001. His research interests include Design and Optimization of MIMO Communication Systems, Radar and Array Processing, polynomial signal processing, Satellite communication systems, Resource Allocation, Game Theory and Fast Algorithms for Structured Matrices. He is currently on the Executive Committee of the IEEE Benelux joint chapter on communications and vehicular technology, member of the EURASIP Special Area Team (SAT) on Theoretical and Methodological Trends in Signal Processing and serves as handling editor for Elsevier Signal Processing. He was a co-recipient of the 2014 Distinguished Contributions to Satellite Communications Award, from the Satellite and Space Communications Technical Committee of the IEEE Communications Society. He has co-organized special sessions in ICASSP (2017, 18), SPAWC (2015, 16) and EUSIPCO (2015, 16).

List of previous venues where the proposed tutorial has been presented, along with an estimate of attendance numbers.

The tutorial is based on the IEEE Signal Processing Magazine paper, the invited talk at URSI and the various conference presentations. This is the first time we are presenting this tutorial. The instructors have presented/will be presenting following related tutorials at the following venues:

1) Bhavani Shankar has presented a tutorial with a colleague titled "Signal Processing for High Throughput Satellite Communications: The Force Awakens" at *IEEE International Conference on Signal Processing and Communications (SPCOM)*, Bangalore.
   http://www.ece.iisc.ernet.in/~spcom/2016/tutorials.html
   Estimated attendance: 50
2) Kumar Vijay Mishra will be presenting a tutorial titled "Cognitive Radars" at *2020 URSI General Assembly and Scientific Symposium (GASS)*, Rome, Italy.
3) Bhavani Shankar and Kumar Vijay Mishra will be presenting a tutorial titled "Automotive Joint Radar Communications: When Hertz met Shannon in a Benz" at *IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, Goa, India.

The authors have been working in the field of joint radar communications for past few years, focusing on the waveform design, receiver processing, and performance evaluation of different JRC configurations. They have co-authored following publications

1) A paper titled, "Toward Millimeter Wave Joint Radar-Communications: A Signal Processing Perspective," to appear in the IEEE Signal Processing Magazine, details available at https://arxiv.org/pdf/1905.00690.pdf
2) A paper titled "A mmWave Automotive Joint Radar-Communications System," in IEEE Transactions on Aerospace and Electronic Systems, Volume 55, Issue 3, pages 1241-1260, June 2019.
3) Seven conference papers in IEEE PIMRC, ICASSP, SPAWC, and RadarConf. One of the papers co-authored with a student and titled, "Performance Analysis of mmWave Bi-static PMCW-based Automotive Joint Radar-Communications System," was a finalist in the student paper in the IEEE

Radar Conference, April 2019. Details are available at https://wwwen.uni.lu/snt/people/bhavani_shankar

4) The speakers are leading a JRC prototyping effort. A demonstration of MIMO-radar-MIMO-communications coexistence was included in the 2019 edition of IEEE SPAWC, http://www.spawc2019.org/program/tech_prog/#S1569569427
5) The authors presented an invited paper/talk on “Automotive Joint Radar-Communications in mmWave Band” at the 2019 URSI Asia Pacific Radio Science Conference, New Delhi, http://www.ursi.org/proceedings/procAP19/papers2019/ambURSIAPRASC2019SummaryPaperJRC.pdf