6th IRACON Training School on Machine and Deep Learning Techniques for (Beyond) 5G Wireless Communication Systems

Date: April 8-11, 2019
Location: Castelldefels (Barcelona), Spain
Venue: Centre Tecnòlogic de Telecomunicacions de Catalunya (CTTC)
Organizers: Carles Antón-Haro (CTTC), Adriano Pastore (CTTC)

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When Can Machine Learning Be Useful for Communication Systems?

Osvaldo Simeone, King's College London, UK

Given the unprecedented availability of data and computing resources, there is widespread renewed interest in applying data-driven machine learning methods to problems in which the deployment of conventional engineering solutions is challenged by modeling or algorithmic deficiencies. The talk starts by addressing the questions of why and when such techniques can be useful. Short introductions are then provided for supervised, unsupervised, and reinforcement learning problems. Finally, some exemplifying applications to communication networks are discussed by distinguishing tasks carried out at the edge and at the cloud of the network at different layers of the protocol stack.

Osvaldo Simeone is a Professor of Information Engineering with the Centre for Telecommunications Research at the Department of Informatics of King's College London. He received an M.Sc. degree (with honors) and a Ph.D. degree in information engineering from Politecnico di Milano, Milan, Italy, in 2001 and 2005, respectively. From 2006 to 2017, he was a faculty member of the Electrical and Computer Engineering (ECE) Department at New Jersey Institute of Technology (NJIT), where he was affiliated with the Center for Wireless Information Processing (CWiP). His research interests include wireless communications, information theory, optimization and machine learning. Dr Simeone is a co-recipient of the 2018 IEEE Signal Processing Best Paper Award, the 2017 JCN Best Paper Award, the 2015 IEEE Communication Society Best Tutorial Paper Award and of the Best Paper Awards of IEEE SPAWC 2007 and IEEE WRECOM 2007. He was awarded a Consolidator grant by the European Research Council (ERC) in 2016. His research has been supported by the U.S. NSF, the ERC, the Vienna Science and Technology Fund, as well as by a number of industrial collaborations. He currently serves in the editorial board of the IEEE Signal Processing Magazine, and he is a Distinguished Lecturer of the IEEE Information Theory Society. Dr Simeone is a co-author of two monographs, an edited book published by Cambridge University Press, and more than one hundred research journal papers. He is a Fellow of the IET and of the IEEE.

Autoencoders – Learn to Communicate: From Theory to Practical Over-the-Air Transmission

Sebastian Cammerer, University of Stuttgart, Germany

The fundamental problem of communication is that of "*reproducing at one point either exactly or approximately a message selected at another point*" or, in other words, reliably transmitting a message from a source to a destination over a (possibly noisy) channel by the use of a transmitter and a receiver. To approach the theoretically optimal solution in practice, transmitter and receiver are usually subdivided into several processing blocks, each taking care of a specific sub-task, e.g., source coding, channel coding, modulation, and equalization. In this tutorial, we break free from the conventional transceiver signal-processing block structure by using trainable neural networks (interpreted/trained as an autoencoder), enabling data-driven communication systems that perpetually learn and adapt to any environment. As such, autoencoder-based systems may trigger a paradigm shift of how we design future communication systems.

The goal of this tutorial is to provide an introduction to autoencoder-based end-to-end learning of communication systems, starting with the theoretical aspects of the autoencoder. Besides an overview of the very rapidly growing body of literature, we present several extensions (e.g., transformer networks and OFDM-like structures) of the neural network architectures towards practical scalability and simplified learning complexity. In the second part of this tutorial, we focus on the "unknown channel gradient" problem, which practically hinders any straightforward real-world implementation of the autoencoder-concept. Therefore, we consider three different approaches: namely "*Receiver Finetuning*", "*Generative Adversarial Networks (GAN)*" and "*Deep Reinforcement Learning*".

This tutorial aims to lower the barrier-to-entry for ML-newcomers to enable the implementation of own applications by providing practical Tensorflow code examples. Thus, the attendees receive tutorial slides and Jupyter notebooks containing state-of-the-art code examples, which allows them to quickly get up to speed with this new and exciting field. Finally, we demonstrate the world's first fully neural network-based communication system.

Sebastian Cammerer is a member of research staff at Institute of Telecommunications, University of Stuttgart, and is pursuing his Ph.D. He received the B.Sc. and M.Sc. degree (with distinction) in electrical engineering and information technology from University of Stuttgart, Germany, in 2013 and 2015, respectively. During his years of study, he worked as a research assistant at multiple institutes of University of Stuttgart. His research topics are channel coding and machine learning for communications. Further research interests are in the areas of iterative receiver algorithms, parallelized computing for signal processing and information theory. He is recipient of the Publication Award of the University of Stuttgart 2019, the Anton- und Klara Röser Preis 2016, the Rohde&Schwarz Best Bachelor Award 2015 and the VDE-Preis 2016 for his master thesis.

AI Architectures for Beyond 5G Networks

Mérouane Debbah, Huawei Paris, France

Mobile cellular networks are becoming increasingly complex to manage while classical deployment/optimization techniques are cost-ineffective and thus seen as stopgaps. This is all the more difficult considering the extreme constraints of 5G networks in terms of data rate (more than 10 Gb/s), massive connectivity (more than 1,000,000 devices per km2), latency (under 1ms) and energy efficiency (a reduction by a factor of 100 with respect to 4G network). Unfortunately, the development of adequate solutions is severely limited by the scarcity of the actual resources (energy, bandwidth and space). Recently, the community has turned to a new resource known as Artificial Intelligence at all layers of the network to exploit the increasing computing power afforded by the improvement in Moore's law in combination with the availability of huge data in 5G networks. This is an important paradigm shift which considers the increasing data flood/huge number of nodes as an opportunity rather than a curse. In this talk, we will discuss through various examples how the recent advances in big data algorithms can provide an efficient framework for the design of Next Generation Intelligent Networks.

Mérouane Debbah entered the Ecole Normale Supérieure Paris-Saclay (France) in 1996 where he received his M.Sc and Ph.D. degrees respectively. He worked for Motorola Labs (Saclay, France) from 1999-2002 and the Vienna Research Center for Telecommunications (Vienna, Austria) until 2003. From 2003 to 2007, he joined the Mobile Communications department of the Institut Eurecom (Sophia Antipolis, France) as an Assistant Professor. Since 2007, he is a Full Professor at CentraleSupelec (Gif-sur-Yvette, France). From 2007 to 2014, he was the director of the Alcatel-Lucent Chair on Flexible Radio. Since 2014, he is Vice-President of the Huawei France R&D center and director of the Mathematical and Algorithmic Sciences Lab. His research interests lie in fundamental mathematics, algorithms, statistics, information & communication sciences research. He is an Associate Editor in Chief of the journal Random Matrix: Theory and Applications and was an associate and senior area editor for IEEE Transactions on Signal Processing respectively in 2011-2013 and 2013-2014. Mérouane Debbah is a recipient of the ERC grant MORE (Advanced Mathematical Tools for Complex Network Engineering). He is a IEEE Fellow, a WWRF Fellow and a Membre émérite SEE. He has managed 8 EU projects and more than 24 national and international projects. He received 19 best paper awards, among which the 2007 IEEE GLOBECOM best paper award, the Wi-Opt 2009 best paper award, the 2010 Newcom++ best paper award, the WUN CogCom Best Paper 2012 and 2013 Award, the 2014 WCNC best paper award, the 2015 ICC best paper award, the 2015 IEEE Communications Society Leonard G. Abraham Prize, the 2015 IEEE Communications Society Fred W. Ellersick Prize, the 2016 IEEE Communications Society Best Tutorial paper award, the 2016 European Wireless Best Paper Award, the 2017 Eurasip Best Paper Award and the 2018 IEEE Marconi Prize Paper Award as well as the Valuetools 2007, Valuetools 2008, CrownCom2009, Valuetools 2012, SAM 2014 and 2017 IEEE Sweden VT-COM-IT Joint Chapter Best Student paper awards.

He is the recipient of the Mario Boella award in 2005, the IEEE Glavieux Prize Award in 2011 and the Qualcomm Innovation Prize Award in 2012

Learning to decode error correcting codes

Yair Be'ery, Tel Aviv University, Israel

Machine learning methods have been influencing drastically the research community and the industry. This class of learnable algorithms have led to major advancements across a variety of different fields and receive increased attention. The increase in interest has not overleaped by the error correcting codes researchers and engineers, where many started applying machine learning techniques into the decoding process in order to reach near maximum likelihood performances with substantial reduction of the computational complexity. The full potential is still uncovered, but there have been a few landmarks. We aim to present latest results and review the heterogeneous approaches employed in the field.

Yair Be'ery received the B.Sc. (Summa Cum Laude), M.Sc. (Summa Cum Laude), and Ph.D. degrees all in electrical engineering from Tel Aviv University, Tel-Aviv, Israel, in 1979, 1979, and 1985, respectively. He is a Professor with the Department of Electrical Engineering Systems, Tel Aviv University, where he has been since 1985. He served as the Chair of the Department from 1999 to 2003. He is the recipient of the 1984 Eliyahu Golomb Award from the Israeli Ministry of Defense granted by the President of Israel, the 1986 Rothschild Fellowship for postdoctoral studies at Rensselaer Polytechnic Institute, Troy, NY, and the 1992 Electronic Industry Award in Israel.
His research interests include digital communications, error control coding, iterative decoding, deep learning methods for decoding, combined coding and modulation, VLSI architectures, and algorithms for systolic and multicore arrays.

Wireless Network Intelligence @ the Edge

Mehdi Bennis, University of Oulu, Finland

In just a few years, breakthroughs in machine learning (ML) have transformed every aspects of our lives from face recognition, medical diagnosis, and natural language processing. This progress has been fueled mainly by the availability of more data and more computing power. However, the current premise in classical ML is based on a single node in a centralized and remote data center with full access to a global dataset and a massive amount of storage and computing, sifting through this data for inference. Nevertheless the advent of a new breed of intelligent devices and high-stake applications ranging from drones to augmented/virtual reality applications and self-driving vehicles, makes cloud-based ML inadequate. This talk will present our vision of distributed edge intelligence for resource-constrained devices focusing on key enablers, NN architectures, algorithms from training to inference and control. Finally, recent results stemming from a wide range of applications will be presented.

Mehdi Bennis (S’07, AM’08, SM’15) received his M.Sc. degree in electrical engineering jointly from EPFL, Switzerland, and the Eurecom Institute, France, in 2002. He obtained his Ph.D. from the University of Oulu in December 2009 on spectrum sharing for future mobile cellular systems. Currently he is an associate professor at the University of Oulu and an Academy of Finland research fellow. His main research interests are in radio resource management, heterogeneous networks, game theory, and machine learning in 5G networks and beyond. He has co-authored one book and published more than 200 research papers in international conferences, journals, and book chapters. He was the recipient of the prestigious 2015 Fred W. Ellersick Prize from the IEEE Communications Society, the 2016 Best Tutorial Prize from the IEEE Communications Society, the 2017 EURASIP Best Paper Award for the Journal of Wireless Communications and Networks, and the 2017 all-University of Oulu research award.

Learn to Communicate - Communicate to Learn

Deniz Gündüz, Imperial College London, UK

Machine learning and communications are intrinsically connected. The fundamental problem of communications, as stated by Shannon, "is that of reproducing at one point either exactly or approximately a message selected at another point," can be considered as a classification problem. With this connection in mind, I will tackle the fundamental joint source-channel coding problem using modern machine learning techniques. I will first introduce uncoded "analog" schemes for wireless image transmission, and show their surprising performance both through simulations and practical implementation. This result will be used to motivate unsupervised learning techniques for wireless image transmission. I will then present a "deep joint source-channel encoder" architecture, which behaves similarly to analog transmission, and not only improves upon state-of-the-art digital transmission schemes, but also achieves graceful degradation with channel signal-to-noise ratio, and performs exceptionally well over fading channels despite not utilizing explicit pilot signals or channel state estimation.

In the second part of the talk, I will look into distributed machine learning, particularly targeting wireless edge networks, and show that ideas from coding and communication theories can help improve their performance. I will introduce both coded and uncoded distributed stochastic gradient descent algorithms, and study the trade-off between their average computation time and the communication load. Finally, I will introduce the novel concept of "over-the-air stochastic gradient descent" for wireless edge learning, and show that it significantly improves the efficiency of machine learning across bandwidth and power limited wireless devices compared to the standard digital approach that separates computation and communication. This will close the circle, making another strong case for analog communication in future communication systems.

Deniz Gündüz received his M.S. and Ph.D. degrees in electrical engineering from NYU Polytechnic School of Engineering (formerly Polytechnic University) in 2004 and 2007, respectively. After his PhD, he served as a postdoctoral research associate at Princeton University, and as a consulting assistant professor at Stanford University. He was a research associate at CTTC in Barcelona, Spain until September 2012, when he joined the Electrical and Electronic Engineering Department of Imperial College London, UK, where he is currently a Reader (Associate Professor) in information theory and communications, and leads the Information Processing and Communications Lab.

His research interests lie in the areas of information theory, machine learning, communications and privacy. Dr. Gunduz is an Editor of the IEEE Transactions on Green Communications and Networking, and served as an Editor of the IEEE Transactions on Communications (2013-2018). He is currently serving as a Guest Editor for the IEEE Journal on Selected Areas in

Communications Special Issue on “Machine Learning for Wireless Communications”. He is the recipient of the IEEE Communications Society - Communication Theory Technical Committee (CTTC) Early Achievement Award in 2017, a Starting Grant of the European Research Council (ERC) in 2016, IEEE Communications Society Best Young Researcher Award for the Europe, Middle East, and Africa Region in 2014, Best Paper Award at the 2016 IEEE Wireless Communications and Networking Conference (WCNC), and the Best Student Paper Awards at the 2018 IEEE Wireless Communications and Networking Conference (WCNC) and the 2007 IEEE International Symposium on Information Theory (ISIT). He served as the General Co-chair of the 2018 International ITG Workshop on Smart Antennas, 2016 IEEE Information Theory Workshop, and the 2012 IEEE European School of Information Theory, and will serve as the Communication Theory Symposium Co-chair for the 2020 IEEE International Conference on Communications.

Moving to Data-Driven Machine Learning Communications Systems

Tim O'Shea, DeepSig & Virginia Tech, Arlington, US

This tutorial will briefly review the fundamental trends and enablers for the recent shift to large scale data driven machine learning in computer vision, audio processing and other fields. It will then highlight a number of areas and applications within wireless communications and radio signal processing, specifically at the physical layer, where such an approach to machine learning and data-driven design rather than model-driven design holds significant promise for future systems. We highlight recent applications and advances in radio sensing and dynamic spectrum access and interference mitigation, as well as in the synthesis of new layer one modulation, coding and synchronization approaches with a focus on practical usage and implementation. Finally, as such data-driven communications systems rely heavily on real world measurement data and iteration, we discuss a range of issues around software radio, implementation, optimization, and datasets. This will include brief introductions to tools such as GNU Radio, USRP and SigMF which may be used to rapidly prototype, test and deploy many new ideas in this field, and will also include demonstrations of similar learning-based sensing and communications system software capabilities developed at DeepSig and Virginia Tech.

Tim O'Shea is the CTO at DeepSig and a Research Assistant Professor at Virginia Tech where he is focused on building future wireless systems for 5G and beyond leveraging machine learning and data-centric design at the physical layer. He has led applied research and development in software radio, cognitive radio and security at VT, DoD, Hawkeye360, and Federated Wireless for 13+ years and is a core developer of the GNU Radio project. He has authored a number of key publications leveraging deep learning to advance solutions to core problems in wireless systems and is working to rapidly advance and build out ML driven software solutions to RF spectrum awareness and waveform adaptation. He is also currently serving as an editor of the IEEE Trans. Cognitive Communications and Networking and a Co-Chair of the IEEE Emerging Technology Initiative in Machine Learning for Communications, and Chair of the Technical Proceedings for the GNU Radio Conference.

Learning the Wireless Communication Channel: From Model-Based Parameter Estimation to Deep Neural Networks

Wolfgang Utschick, Technical University of Munich, Germany

We study a numerically efficient method for estimating M-dimensional structured channels that uses techniques from the field of machine learning. The considered channel model assumes channel vectors which are normally distributed given unknown second order statistics. The latter depends on random hyperparameters that are typically related to geometrical properties of the environment. If the channel model exhibits specific structures, the numerical complexity for computing a true MMSE estimator can be reduced to O(M log M); otherwise, it is much higher. To obtain an equally low-complex estimator for the general case of the considered channel model, the structure of the specific MMSE estimator is used as an informed guess for the architecture of a neural network. We discuss how this network can be efficiently trained with channel realizations to learn the MMSE estimator within the class of O(M log M) estimators. New results based on real channel measurements of a recently conducted field trial demonstrate the applicability of the proposed method in real-world applications.

Wolfgang Utschick (SM'06) completed several years of industrial training programs before he received the diploma degree in 1993 and the doctoral degree (both with Hons.) in 1998 in electrical engineering with a dissertation on machine learning, from Technische Universität München (TUM), München, Germany. Since 2002, he is a Professor at TUM where he is chairing the Professorship of Signal Processing. He teaches courses on signal processing, stochastic processes, and optimization theory in the field of wireless communications, various application areas of signal processing, and power transmission systems. Since 2011, he has been a regular Guest Professor at Singapore's new autonomous university, Singapore Institute of Technology, and since 2017 he is serving as the Dean of the Department for Electrical and Computer Engineering, TUM. He holds several patents in the field of multiantenna signal processing and has authored and coauthored a large number of technical articles in international journals and conference proceedings. He edited several books and is a Founder and the Editor of the Springer book series Foundations in Signal Processing, Communications and Networking. He has been a Principal Investigator in multiple research projects funded by the German Research Fund (DFG) and a Coordinator of the German DFG priority program Communications Over Interference Limited Networks. He is a member of the VDE and therein a member of the Expert Group 5.1 for Information and System Theory of the German Information Technology Society. He is currently chairing the German Signal Processing Section. He also had been serving as an Associate Editor for IEEE Transactions on Signal Processing and had been member of the IEEE Signal Processing Society Technical Committee on Signal Processing for Communications and Networking.

Learning-based Beam Selection for Hybrid Beamforming in mmWave bands

Carles Antón-Haro, Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)

This presentation focuses on how angle-of-arrival (AoA) information can be exploited by deep-/machine-learning approaches to perform beam selection in the uplink of a mmWave communication system. Specifically, we consider a hybrid beamforming setup comprising an analog beamforming (ABF) network with adjustable beamwidth followed by a zero-forcing baseband processing block. The goal is to select the optimal configuration for the ABF network based on the estimated AoAs of the various user equipments. To that aim, we consider (i) two supervised machine-learning approaches: *k*-nearest neighbors (kNN) and support vector classifiers (SVC); and (ii) a feed-forward deep neural network: the multilayer perceptron (MLP). We conduct an extensive performance evaluation to investigate the impact of the quality of CSI estimates (AoAs and powers) obtained via the Capon or MUSIC methods, fluctuations in the received power, the size of the training dataset, the total number of analog beamformers in the codebook, their beamwidth, or the number of active users. Computer simulations reveal that performance, in terms of classification accuracy and sum-rate, is very close to that achievable via exhaustive search.

Carles Antón-Haro holds a Ph.D. degree in telecommunications engineering from the Technical University of Catalonia (UPC). In 1999, he joined Ericsson Spain, where he participated in rollout projects of 2G and 3G mobile networks. Currently, he is a Senior Researcher and Director of R&D Programs at the Centre Tecnòlogic de Telecomunicacions de Catalunya (CTTC). As a Senior Researcher, his research interests are in the area of signal processing and estimation theory for communications, this including machine learning, sensor and IoT networks, M2M communications, array signal processing, MIMO, energy harvesting, and Smart Grids. He has published +130 technical papers in IEEE journals, books/book chapters and in international and national conferences. He is a recipient of the 2015 Best Paper Award of the Transmission, Access, and Optical Systems (TAOS) Technical Committee's (Green Communications Track, ICC), and the Best Paper Award of IEEE GLOBALSIP15 conference. He has supervised 5 PhD Theses (1 in progress). He is an Associate Editor to EURASIP's Journal on Wireless Communications and Networks (JWCN). He is also an appointed member of the International Scientific Advisory Board of the Internet Interdisciplinary Institute (IN3, Open University of Catalonia, 2017-present time). He was an elected member of the Steering Board of the Networld2020 European Technology Platform and representative at the 5G Industry Association (2014). He is a Steering Board Member of the 5G Barcelona Association. In recent years, he has been actively involved in the organization of major conferences such as the IEEE Wireless Communications and Networking Conference 2018 (General Chair), Workshop on Integrating Communications, Control, and Computing Technologies for Smart Grid @ ICC17 (TPC Chair), or European Signal Processing Conference 2011 (General Vice-chair). He is an appointed member of the Steering Board of the IEEE Wireless Communications and Networking Conference (WCNC, 2019-2021). He is a Senior Member of the IEEE.