Introduction to the Issue on Machine Learning for Cognition in Radio Communications and Radar

TO BORROW from the inaugural editorial of this Journal, that signal processing is always at the heart of the technology that differentiates today's generations from those of the past is reaffirmed once again by this special issue on Machine Learning for Cognition in Radio Communications and Radar. Machine learning is the technological disruptor of our time, achieving groundbreaking success in self-driving cars, gaming and virtual reality, natural language processing and business analytics. This special issue articulates its impact on signal processing research in radio communications and radar by showcasing a stunning diversity of research problems addressed by means of machine learning. As guest editors of this special issue, we aimed to show the variety of topics outlined in the call for papers. We were very pleased by the number and quality of submissions, which allowed us to select an excellent set of papers representative of that diversity. It appears that despite the lack of big data in communications and radar, the momentum from the deep learning revolution has had a spill-over effect, inspiring new and creative approaches to signal processing problems in these fields.

Our call for papers attracted numerous submissions worldwide. After the review process, 18 papers, or 30%, were accepted for publication. The contributions to this special issue went far beyond the concept of cognitive radio (CR), which has been at the intersection of signal processing, machine learning and communications for a period of time. Cognitive radio has established itself as an enabling methodology for smart spectrum allocation and management in dynamic spatial and temporal conditions. Several papers of this issue address the CR concept in the context of improved spectral utilization delivered by machine learning techniques in the complex scenarios of Fifth Generation (5G) cellular systems and Internet-of-Things (IoT). For example, "Constrained Bayesian Active Learning of Interference Channels in Cognitive Radio Networks," by A. Tsakmalis *et al.* tackles active learning within a sequential probing process where the cognitive element is the selection of the power levels of the secondary users which aim to learn the primary user's interference constraint with a minimum number of probing attempts. An optimal solution is derived and implemented with a sophisticated, accurate and fast Bayesian Learning method. "Spectrum Access In Cognitive Radio Using A Two Stage Reinforcement Learning Approach," by V. Raj *et al.* proposes a two-stage reinforcement learning approach for channel selection and sensing in cognitive radio networks, featuring a Q-learning method for greedy action selection and a Bayesian learning estimator of the idle-time traffic pattern of the primary users. Applying this approach allows the number of sensing operations by the secondary users to be minimized, and higher throughput achieved at a lower energy cost. "Online Wideband Spectrum Sensing Using Sparsity," by L. Flokas and P. Maragos, studies the problem of online sparse spectrum estimation for cognitive radio applications using sub-Nyquist sampling rates, including a way to estimate the sparsity parameter adaptively so that the estimation can gradually become sparser.

About one third of papers featured in this special issue addresses topics in radar, including coexistence of radar and radio communications. The interest in coexistence is inspired by the recent announcement that the 3550–3650 MHz band, currently used for military radar operations, is identified for spectrum sharing between military radars and communication systems. Taking a broader view on radar and machine learning, modern radars increasingly represent intelligent sensor systems with a variety of software-defined degrees of freedom. This special issue demonstrates that research is under way to enable cognition in radars capable of learning the environment and then optimally adapting radar waveforms and operational parameters to it. In "Adaptive Interference Removal for Un-coordinated Radar/Communication Co-existence," by L. Zheng *et al.* compressed sensing algorithms and those forcing an atomic norm constraint are applied to an un-coordinated scenario where a communication receiver is to operate in the presence of a number of radars, of which only a sub-set may be active, which poses the problem of estimating the active waveforms and the relevant parameters thereof, so as to cancel them prior to demodulation.

"Distributed ECM Algorithm for OTHR Multipath Target Tracking with Unknown Ionospheric Heights," by H. Lan *et al.* addresses over-the-horizon radar target tracking in the presence of a complicated ionospheric environment, for which it introduces a joint optimization scheme called distributed expectation-conditional maximization (DECM), which solves the target state estimation, multipath data association, and ionospheric heights identification simultaneously. "Cognitive Target Tracking via Angle-Range-Doppler Estimation with Transmit Subaperturing FDA Radar," by R. Gui *et al.* proposes a cognitive target tracking scheme via angle-range-Doppler estimation with transmit subaperturing frequency diverse array (TS-FDA) radar, which adaptively designs the transmit weight matrix for FDA according to the prior knowledge extracted from the cognitive observations. In "Deep Learning for Passive Synthetic Aperture Radar," by B. Yonel *et al.* we find a deep learning framework based on the recurrent auto-encoder for image reconstruction passive synthetic aperture radar, which shows great advantages over conventional methods when no

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information about the transmitter is available. "Machine Learning Techniques for Coherent CFAR Detection Based on Statistical Modeling of UHF Passive Ground Clutter," by N. del-Rey-Maestre *et al.* combines statistical and machine learning signal processing methods for cognitive functionality in passive radars, resulting in UHF passive ground clutter statistical models, particularly useful for on the detection of low Doppler shift targets.

A broad range of efficient machine learning algorithms is addressed in this special issue, the most popular classes being deep learning and reinforcement learning (about one third each). "Deep Learning Methods for Improved Decoding of Linear Codes," by E. Nachmani *et al.* introduces neural network (NN) architectures for decoding linear block codes, which yield significant improvements over the standard BP and min-sum decoders and offer a tradeoff between error-correction performance and implementation complexity. In every instance, the use of machine learning improves the performance of the decoder. In "Deep Learning-Based Communication Over the Air," by S. Dorner *et al.* the authors present how they build, train, and run a complete communications system solely composed of NNs using unsynchronized off-the-shelf software-defined radios (SDRs) and open-source deep learning (DL) software libraries. They apply transfer learning to the training of such a system. "An Iterative BP-CNN Architecture for Channel introduces Decoding under Correlated Noise," by F. Liang *et al.* concatenates a trained convolutional neural network with standard belief-propagation (BP) to remove the estimate errors of the BP decoder and obtain a more accurate estimate of the correlated channel noise.

"Deep Learning for RF Device Fingerprinting in Cognitive Communication Networks," by Merchant, *et al.* explores the use of deep learning to detect physical-layer attributes for the identification of cognitive radio devices. As an application, the authors train a convolutional neural network using the time-domain complex baseband error signal and demonstrate 91.29% identification accuracy on a set of 2.4 GHz commercial ZigBee devices. "Over the Air Deep Learning Based Radio Signal Classification," by T. O'Shea *et al.* features an in-depth study of the performance of deep learning modulation classification methods for over-the-air RF communication signals. This work demonstrates that in this context deep neural networks provide significant performance benefits compared to conventional feature extraction methods, with Residual Networks (ResNets) outperforming conventional Convolutional Neural Networks (CNNs) in terms of computational efficiency.

In "Optimal and Scalable Caching for 5G Using Reinforcement Learning of Space-time Popularities," by A. Sadeghi *et al.* the novel RL-based caching of prefetched popular content in small basestations (SBs) relies on a Q-learning algorithm to implement the optimal policy in an online fashion, thus enabling the cache control unit at the SB to learn, track, and possibly adapt to the underlying dynamics.

We also included some classic machine learning approaches with innovations in how they address some of the open problems in communications and radar. The paper "SV-Means: A Fast SVM-based Level Set Estimator for Phase-Modulated Radar Waveform Classification" by A. Pavy and B. Rigling, focuses on the difficult problem of radar waveform classification where algorithms must be designed knowing that a complete knowledge of all waveforms at training time is unlikely, and, therefore, a rejection option is needed. The authors propose a new algorithm that extends the quantile one-class support vector machine density estimation algorithm into a classification formulation. Distributed, sequential and online learning are also represented to showcase practical implementation issues related to computational complexity, delay and naturally decentralized and embedded environments. "Adversarial Multi-Agent Target Tracking with Inexact Online Gradient Descent," by Bedi *et al.* formulates a generic target tracking problem as a time-varying optimization problem and develops an inexact online gradient descent method for solving it sequentially. Using dynamic regret as a performance measure, the efficacy of the proposed framework is established on a multi-agent multi-target tracking problem.

Our selection of papers illustrates that learning is possible and useful in all layers of a communication or radar device from the channel (targets or clutter), via modulation and coding, to medium access control and network topology. "Generalized Global Bandit and Its Application in Cellular Coverage Optimization," by Shen, *et al.* proposes a novel multi-armed bandit model with the capability of handling non-monotonic but decomposable reward functions with multi-dimensional global parameters and switching costs. This framework is applied to the cell coverage optimization problem to achieve the optimal tradeoff between small cell coverage and limited macro cell leakage without prior knowledge of the deployment environment. "Learning Wireless Networks Topologies Using Asymmetric Granger Causality" by M. Laghate and D. Cabric, proposes a method to detect the directed links between incumbent users (IUs) of time multiplexing communication networks from their transmission start and end times. The method relies on a test statistic based on transfer entropy for detecting Granger causality between network IUs, i.e., the probability of an IU starting a transmission after another IU's transmission ends.

Finally, this special issue demonstrates some pioneering steps in systematically procuring the right amount and latitude of data needed for the machine learning to be effective. It is evident that the RF signal database is getting bigger, and that synthetic, simulated and over the air data is both borrowed from publicly available repositories, and made available for others to access. This is no match to ImageNet and similar repositories with millions of sample images and their associated labels, but it is important that some benchmarks be formed. We believe that further advancement of machine learning based cognition in communications and radar would benefit the most from a publicly available signal processing knowledge base of RF signals. We hope that this special issue on Machine Learning for Cognition in Radio Communications and Radar helped demonstrate the value of such an open-access repository.

The guest editors of this special issue wish to thank all the contributing authors for submitting high-quality papers. We would also like to thank all the reviewers for their thorough and timely effort in evaluating the papers, and for the feedback that helped improve the quality of this issue.

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