IEEE TCCN Special Section Editorial: Evolution of Cognitive Radio to AI-Enabled Radio and Networks

WE ARE delighted to introduce this special section of the IEEE Transactions on Cognitive Communications and Networking (TCCN), which aims at addressing the evolution of cognitive radio (CR) to intelligence radio and networks by exploring recent advances in artificial intelligence (AI) and machine learning (ML). We have selected 14 articles for this special section after a rigorous review process, which are briefly discussed as follows.

The first article, entitled "20 Years of Evolution From Cognitive to Intelligent Communications", authored by Qin *et al.*, presents an overview on the intelligent communications in the past two decades to illustrate the revolution of its capability from cognition to AI. Particularly, this article starts from a comprehensive review of typical spectrum sensing and sharing, followed by the recent achievements on the AI-enabled intelligent radio and networks. Research challenges in the future intelligent communications are discussed to show a path to practical intelligent radio and communications. Witnessing the glorious developments of CR in the past 20 years, this article provides a clear picture on how intelligent radio could be further developed to smartly utilize the limited spectrum resources as well as to optimally configure wireless devices in the future communication systems.

The second article, entitled "AI-Based Abnormality Detection at the PHY-layer of Cognitive Radio by Learning Generative Models", by Toma *et al.*, introduces a data-driven Self-Awareness (SA) module in CR to support the system to establish secure networks against various attacks from malicious users, which may manipulate radio spectrum in order to make legitimate CR users learning false behaviours and taking wrong actions. This article implements AI-based abnormality detection techniques at the physical layer in CR enabled by learning generative models. Two practical applications with different data dimensionality and sampling rates are presented. The first application uses a Conditional Generative Adversarial Network to investigate generalized state vectors extracted from spectrum representation samples to study the dynamic behaviour of the wideband signal. The second application is learning a dynamic bayesian network model from a generalized state vector, which contains sub-bands information extracted from the radio spectrum. Experimental results have shown that both of the proposed methods are capable of detecting abnormal signals in the spectrum and pave the way towards self-aware radio.

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The third article, entitled "Q-Learning Based Spectrum Access for Content Delivery in Mobile Networks", by Su *et al.*, investigates a Q-learning based spectrum access scheme for mobile users to access the optimal spectrum and maximize the transmission rate. Based on the optimal spectrum decision, a content delivery scheme is proposed for edge nodes, device-to-device (D2D) pairs and mobile users. The content delivery process is modelled among edge nodes, D2D pairs, and mobile users as a non-cooperative Stackelberg game to improve the efficiency of content delivery. Simulation results demonstrate that the proposed scheme can jointly maximize the throughput of mobile networks and improve the QoE of mobile users in comparison with the conventional schemes.

The fourth article, entitled "Deep Reinforcement Learning Based Edge Caching in Wireless Networks", by Zhong *et al.*, focuses on the content caching at the wireless network edge using a deep reinforcement learning framework with Wolpertinger architecture. Deep actor-critic reinforcement learning based policies are proposed for both centralized and decentralized content caching. For centralized edge caching, the authors ami at maximizing the cache hit rate. In decentralized edge caching, both the cache hit rate and transmission delay serve as performance metrics. The proposed frameworks are assumed to neither have any prior information on the file popularities nor know the potential variations in such information. Simulation results show the superiority of the proposed frameworks and are verified by comparing them with other policies, including least frequently used (LFU), least recently used (LRU), and first-in-first-out (FIFO) policies.

In the fifth article, entitled "Mobility-Aware Content Preference Learning in Decentralized Caching Networks", by Ye *et al.*, the user content preference is learned upon user mobility in a decentralized caching network. The tool of Markov renewal process is used to predict the moving path and sojourn time for mobile terminals, and integrate the mobility pattern with the decentralized regularized multi-task learning (DRMTL) model by reweighting the training samples and introducing a transfer penalty in the objective. The real trace driven experiments illustrate that the mobility-aware DRMTL model can provide a more accurate prediction on geography preference than DRMTL model. Besides, the hit ratio achieved by most popular proactive caching (MPC) policy with preference predicted by mobility-aware DRMTL outperforms the MPC with preference from DRMTL and random caching (RC) schemes.

The sixth article, entitled "Learning-Aided Intelligent Cooperative Collision Avoidance Mechanism in Dynamic

Vessel Networks", by Yang *et al.*, investigates the information transmission and the collision avoidance problem in the complex vessel networks. With the empowered learning ability in the networks, a novel two-step-smooth-turn cooperative collision avoidance mechanism for the dynamic vessel networks is proposed by considering the motion states of the vessels. In particular, the AI-powered vessels network motion model is designed, which can learn the motion information to predict the safety motion states by automatic collection of the information. Then, a K-Means algorithm combining with genetic algorithm is proposed by expanding the operation of cross genetic and genetic mutations, which can achieve the optimal multi-vessels coordination motion policy for the collision avoidance. Simulation results show that the proposed mechanism can achieve an optimal safety route plan for cooperative collision avoidance.

The seventh article, entitled "An Integrated Affinity Propagation and Machine Learning Approach for Interference Management in Drone Base Stations", by Wang *et al.*, presents a learning-based multiple drone management (LDM) framework. This article has developed unsupervised learning DSC management techniques: 1) affinity propagation interference management scheme to mitigate interference and energy consumption, and 2) K-means position adjustment to adjust the new 3-dimension positions of drones. Numerical results show that the proposed LDM framework combined with affinity propagation clustering, and k-means clustering can enhance the energy efficiency of DSCs by 25% and the signal-to-interference-plus-noise ratio of ground users by 56%, respectively.

In the eighth article, entitled "Fast Learning for Dynamic Resource Allocation in AI-enabled Radio Networks", by Qureshi *et al.*, a structured reinforcement learning algorithm, called contextual unimodal multi-armed bandit (MAB), is proposed for resource allocation problems in mmWave radio networks under unknown channel statistics and without any channel state information (CSI) feedback. The proposed algorithm's regret scales sublinearly both in the number of arms and contexts for a wide range of scenarios. Simulation results show significant improvement on resource allocation.

The ninth article, entitled "Energy-Efficient Power Control in Wireless Networks With Spatial Deep Neural Networks", by Zhang *et al.*, proposes a deep learning based power control scheme, termed PowerNet, that uses the devices' geographical location information (GLI). This article shows that it is possible to bypass the complex channel estimation process and directly perform power control with GLI when the channel state information (CSI) can be viewed as a function of distance dependent path-loss. Simulation results demonstrate that PowerNet can achieve a near-optimal performance at a remarkably high speed without explicit channel estimation. PowerNet also exhibits a great generalization ability in terms of problem sizes and channel fading types.

The tenth article, entitled "Deep Learning Based Channel Estimation Algorithm Over Time Selective Fading Channels", by Bai *et al.*, proposes a Deep Learning (DL)-based channel estimator under time varying Rayleigh fading channel. The proposed DL-based estimator can dynamically track the channel status without any prior knowledge about the channel model and statistic characteristics. Simulation results show that the proposed NN estimator has better Mean-Squared Error (MSE) performance compared with the traditional algorithms and some other DL-based architectures and its robustness with the different pilot densities.

The eleventh article, entitled "Optimizing Throughput Performance in Distributed MIMO Wi-Fi Networks Using Deep Reinforcement Learning", by Krishnan *et al.*, explores the feasibility of leveraging deep reinforcement learning (DRL) to enable dynamic resource management in Wi-Fi networks implementing distributed multi-user MIMO (D-MIMO). Through extensive simulation and online training based on D-MIMO Wi-Fi networks, this paper demonstrates the efficacy of DRL agents in achieving an improvement of 20% in user throughput performance compared to heuristic solutions, especially when network conditions are dynamic.

In the twelfth article, entitled "Learning-Based Spatial Reuse for WLANs With Early Identification of Interfering Transmitters", by Yin *et al.*, a reinforcement learning-based spatial reuse scheme for wireless local area networks (WLANs) is proposed and analyzed. The proposed scheme is compared with the spatial reuse operation in IEEE 802.11ax, which makes the spatial reuse decision only based on a binary identification of the detected interferer. A theoretical bound is derived on the gains in the value function, i.e., the discounted sum of delay, due to making non-binary identifications. Simulation confirms that the proposed scheme achieves high throughput by reducing the time of freezing backoff counter while not increasing the time of failed transmissions.

The thirteenth article, entitled "No Radio Left Behind: Radio Fingerprinting Through Deep Learning of Physical-Layer Hardware Impairments", by Sankhe *et al.*, presents a novel system based on convolutional neural networks (CNNs) to "fingerprint" (i.e., identify) a unique radio from a large pool of devices by deep-learning the fine-grained hardware impairments imposed by radio circuitry on physical-layer I/Q samples. This article shows how hardware-specific imperfections are learned by the CNN framework, then extensively evaluate the performance of ORACLE on several first-of-its-kind large-scale datasets of WiFi-transmissions collected "in the wild", as well as a dataset of nominally-identical (i.e., equal baseband signals) WiFi devices, reaching 80-90% accuracy is many cases with the error gap arising due to channel-induced effects.

Finally, the last article, "Market-Based Model in CR-IoT: A Q-Probabilistic Multi-agent Reinforcement Learning Approach", by Wang *et al.*, proposes a multi-agent reinforcement learning (MARL) algorithm to learn the optimal resource allocation strategy in an oligopoly market model. It models a multi-agent scenario with the primary users (PUs) as sellers and secondary users (SUs) as buyers. The Q-probabilistic multi-agent learning (QPML) is applied to allocate resources in the market. In the multi-agent learning process, the PUs and

SUs learn strategies to maximize their benefits and improve spectrum utilization.

Our Guest Editor team is pleased with the technical depth and span of this Special Section in the IEEE TCCN. We also recognize that it is hard to cover all emerging concepts from cognitive radio to AI-enabled radio and networks. We sincerely thank all the authors and reviewers for their efforts, and the Editor-in-Chief and Staff Members for their gracious support. We hope that the readers will enjoy this special section.

YUE GAO
University of Surrey
U.K.

EKRAM HOSSAIN
University of Manitoba
Canada

GEOFFREY YE LI
Georgia Institute of Technology
USA

KEVIN SOWERBY
University of Auckland
New Zealand

CARLO REGAZZONI
University of Genova
Italy

LIN ZHANG
University of Electronic Science and Technology of China
China

Yue Gao (Senior Member, IEEE) received the Ph.D. degree from the Queen Mary University of London (QMUL), U.K., in 2007. He is a Professor and the Chair in wireless communications with the Institute for Communication Systems, University of Surrey, U.K. He was a Lecturer, a Senior Lecturer, and a Reader in antennas and signal processing with QMUL. He currently leads a team developing fundamental research into practice in the interdisciplinary area of smart antennas, signal processing, spectrum sharing, millimetre-wave, and Internet of Things technologies in mobile, satellite systems. He has published over 180 peer-reviewed journals and conference papers, 2 patents, 1 book, and 5 book chapters. He was a co-recipient of the EU Horizon Prize Award on Collaborative Spectrum Sharing in 2016. He is an Editor of the IEEE INTERNET OF THINGS JOURNAL, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, and the IEEE TRANSACTIONS ON COGNITIVE NETWORKS. He is an Engineering and Physical Sciences Research Council Fellow from 2018 to 2023. He is the Chair of the IEEE Technical Committee on Cognitive Networks and the IEEE Distinguished Lecturer of the Vehicular Technology Society.

Ekram Hossain (Fellow, IEEE) is a Professor and an Associate Head (Graduate Studies) with the Department of Electrical and Computer Engineering, University of Manitoba, Canada. He is a Member (Class of 2016) of the College of the Royal Society of Canada. His research works have received over 28 000 citations to date (in Google Scholar, with H-index = 88). His current research interests include design, analysis, and optimization beyond 5G cellular wireless networks. He received the 2017 IEEE ComSoc Technical Committee on Green Communications and Computing Distinguished Technical Achievement Recognition Award "for outstanding technical leadership and achievement in green wireless communications and networking." He has won several research awards, including the 2017 IEEE Communications Society Best Survey Paper Award and the 2011 IEEE Communications Society Fred Ellersick Prize Paper Award. He was listed as a Clarivate Analytics Highly Cited Researcher in Computer Science in 2017, 2018, and 2019. He served as the Editor-in-Chief for the IEEE COMMUNICATIONS SURVEYS AND TUTORIALS from 2012 to 2016. He currently serves as the Editor-in-Chief for IEEE PRESS and an Editor for the IEEE TRANSACTIONS ON MOBILE COMPUTING. He is a Distinguished Lecturer of the IEEE Communications Society and the IEEE Vehicular Technology Society. He is an Elected Member of the Board of Governors of the IEEE Communications Society for the term from 2018 to 2020. He was elevated to an IEEE Fellow "for contributions to spectrum management and resource allocation in cognitive and cellular radio networks." He is a fellow of the Canadian Academy of Engineering.

Geoffrey Ye Li (Fellow, IEEE) was with AT&T Labs—Research, Red Bank, NJ, USA, as a Senior and a Principal Technical Staff Member from 1996 to 2000, and a Postdoctoral Research Associate with the University of Maryland at College Park, College Park, MD, USA, from 1994 to 1996. He is a Professor with the Georgia Institute of Technology, Atlanta, GA, USA. His publications have been cited around 40 000 times. His general research interests include statistical signal processing and machine learning for wireless communications. He has published over 500 journals and conference papers in addition to over 40 granted patents in the above areas. He has been recognized as the World's Most Influential Scientific Mind, also known as a Highly Cited Researcher, by Thomson Reuters almost every year. He was awarded IEEE Fellow for his contributions to signal processing for wireless communications in 2005. He won several Prestigious Awards from the IEEE Signal Processing Society (Donald G. Fink Overview Paper Award in 2017), the IEEE Vehicular Technology Society (James Evans Avant Garde Award in 2013 and Jack Neubauer Memorial Award in 2014), the IEEE Communications Society (Stephen O. Rice Prize Paper Award in 2013, the Award for Advances in Communication in 2017, and the Edwin Howard Armstrong Achievement Award in 2019). He also received 2015 Distinguished Faculty Achievement Award from the School of Electrical and Computer Engineering, Georgia Tech. He has been involved in editorial activities for over 20 technical journals, including the Founding Editor-in-Chief of IEEE 5G Tech Focus. He has organized and chaired many international conferences, including the Technical Program Vice-Chair of IEEE ICC'03, the Technical Program Co-Chair of IEEE SPAWC'11 and IEEE VTC'16 (Spring), the General Chair of IEEE GlobalSIP'14, and the General Co-Chair of IEEE VTC'19 (Fall).

Kevin Sowerby received the B.E. and Ph.D. degrees in electrical and electronic engineering from the University of Auckland in 1986 and 1989, respectively. He is the Chair of the Department of Electrical, Computer, and Software Engineering, University of Auckland, New Zealand. Since the first generation of cellular telephony, his research has focused on the planning of high capacity radio networks, with a particular interest in radio propagation measurement and modeling. Wireless-friendly building design, network reliability and security, and spectrum management are also subjects of his research activity. He conducted early propagation and measurement studies that highlighted the inefficiency of conventional radio spectrum use, motivating the development of cognitive radio systems. He has spent extended periods of research leave with Virginia Tech, Simon Fraser University, Motorola Research Labs, Georgia Tech, TNO, The Netherlands, and the Hong Kong University of Science and Technology. Within the IEEE he was the Founding Chair of the New Zealand's first Communications Society Chapter. He has served as the Chair of the New Zealand North Section and the New Zealand Council. He currently serves as the Past-Chair of the Award Committee for the IEEE Daniel E. Noble Award for Emerging Technologies.

Carlo Regazzoni (Senior Member, IEEE) received the M.S. and Ph.D. degrees from the University of Genova, Italy, in 1987 and 1992, respectively, where he has been a Full Professor of cognitive telecommunications systems with DITEN since 2005. He has been coordinating international interactive and cognitive environment Ph.D. courses with UNIGE since 2008. He has authored peer-reviewed papers on more than 100 international journals and 350 at international conferences. His research interests include cognitive dynamic systems, adaptive and self-aware multimodal signal processing, Bayesian machine learning, and cognitive radio. He served as the Vice President Conferences IEEE Signal Processing Society from 2015 to 2017, the General Chair, the Technical Program Chair, and other roles in several international conferences in its research field. He is/has been an Associate/Guest Editor of several international journal, including the PROCEEDINGS OF THE IEEE, the IEEE TRANSACTIONS ON IMAGE PROCESSING, the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY, and *IEEE Signal Processing Magazine*.

Lin Zhang (Member, IEEE) received the bachelor's degree in communication engineering from Sichuan University, Chengdu, China, in June 2011, and the Ph.D. degree from the National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China (UESTC), Chengdu, in June 2017, where he was a Postdoctoral Researcher from October 2017 to June 2019. He is currently an Associate Professor with UESTC. From October 2014 to April 2016, he worked as a visiting student with the School of Electrical Engineering, Royal Institute of Technology (KTH), Sweden. His research interests include cognitive radio, D2D communication, content caching, nonorthogonal multiple access, short packet communications, and intelligent wireless communications. He won the IEEE GLOBECOM 2012 Best Paper Award, the Student Travel Grant Award, the IEEE Region 10 Distinguished Student Paper Award in 2016, and the IEEE ICC 2019 Best Paper Award.