Intelligent Radio: When Artificial Intelligence Meets the Radio Network

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The advances in wireless communications have continuously been pushing the limit of radio technologies. Nowadays, radio networks can provide extremely high data rate, ultra-low latency, and high reliability to serve communication needs of sectors that could not be imagined before. However, radio technologies have become highly complex and call for new solutions. The recent advances in artificial intelligence (AI), including machine learning (ML), data mining, and big data analysis, bring significant promise for addressing hard problems in radio networks. It has been the increasing trend to move the intelligence beyond the spectrum access, which is primarily targeted by cognitive radio, to address various challenges in radio networks, including, but not limited to, channel modeling, modulation, beamforming, radio resource allocation, and network management. Radio technologies are on the way evolving to the intelligent radio, in which AI/ML frameworks and algorithms are applied to learn from environments and explore hidden characteristics of networks for new capacity, performance, and services. We believe the intelligent radio will be the prominent feature of next generation wireless networks. It calls for interdisciplinary research to integrate the advances in AI/ML, communications, computing, and cloud technologies. Both theoretical and applied breakthroughs are expected in this new area.

This Special Issue aims to provide a comprehensive overview on the recent development of the intelligent radio. Sixteen articles have been selected from the rigorous peer review process among 60 submissions. These articles cover topics on spectrum access, mobile edge computing, radio network modeling, mobility prediction, and new wireless applications.

The first two articles provide a broad survey on intelligent radio and network technologies. The article "Pathway to Intelligent Radio," by Z. Qin *et al.*, introduces recent advances in ML in wireless communications. It briefly introduces deep learning applied for physical layer communications and resource allocation. The pros and cons of data-driven or model-driven approaches in deep learning are discussed. It then addresses two classical problems (i.e., spectrum sensing and spectrum access) in cognitive radio. The generative adversarial network (GAN), intelligent cooperative, and intelligent compressive approaches are applied to spectrum sensing. Deep reinforcement learning and game-theory-based solutions are introduced in spectrum access.

The second article, "Artificial Intelligence Enabled Wireless Networking for 5G and Beyond: Recent Advances and Future Challenges" by C. Wang *et al.*, offers a comprehensive survey on AI technologies used in beyond 5G networks. The article covers a broad range of problems in wireless networks, including channel related problems, physical layer problems, and network management and optimization problems. It discusses how AI/ML algorithms and applications can be utilized to solve those problems. The current standardization activities to integrate AI/ML to communication systems are summarized.

Dynamic spectrum access remains an important problem in intelligent radio. The next five articles particularly cover spectrum access problems. The article "Multi-Armed-Bandit-Based Spectrum Scheduling Algorithms in Wireless Networks: A Survey" by F. Li *et al.* studies multi-armed bandit (MAB) algorithms to improve spectrum scheduling in adversarial radio environments. MAB uses representative reinforcement learning to handle the uncertainty in such an environment. The article introduces a way to model the spectrum access problem to the MAB framework, and provides an extensive survey on different MAB algorithms, classified by the number of players, centralized or distributed process, and interference models. The time complexity of centralized and distributed algorithms is compared.

In the article "Learning-Assisted Clustered Access of 5G/B5G Networks to Unlicensed Spectrum," Q. Cui *et al.* propose learning-assisted clustered access (LACA) to help small cell base stations share unlicensed spectrum with Wi-Fi networks. LACA is built on top of the license-assisted access (LAA) concept in unlicensed bands. The performance of four ML-based cluster algorithms is evaluated. The numerical results show how the clustering approach and learning algorithms work together to improve the coexistence of LAA and reduce transmission latencies.

Opportunistic spectrum access (OSA) is a promising solution to efficiently utilize the frequency spectrum. In the article

"Machine-Learning-Based Opportunistic Spectrum Access in Cognitive Radio Networks," Zhu *et al.* propose a machine-learning-based OSA framework by integrating MAB and matching theory. The proposed occurrence-aware OSA (OA-OSA) framework can achieve long-term optimal network throughput performance. Further, an occurrence-aware and collision-aware OSA framework is presented by integrating OA-OSA and the Gale-Shapley algorithm. Simulation results demonstrate the good performance of the proposed scheme.

The next article, "Intelligent Spectrum Sensing: When Reinforcement Learning Meets Automatic Repeat Sensing in 5G Communications" by T. Xu *et al.*, utilizes a reinforcement learning (RL) algorithm to control the repeating process of spectrum sensing according to different performance indicator goals. Four performance indicators are proposed, including sensing accuracy, false alarm probability, throughput performance, and energy cost. An RL agent is introduced to learn the gain toward the defined performance indicator goal and decide when to stop the repeated sensing process. Numerical results demonstrate the proposed sensing approach can adapt to various scenarios with different performance optimization targets.

In the article "Intelligent Resource Management for Satellite and Terrestrial Spectrum Shared Networking toward B5G," M. Jia *et al.* study the spectrum sharing in integrated satellite and terrestrial networks. The network extends the architecture from a standalone 5G network. A spectrum management unit is introduced to manage the spectrum sharing between satellite and terrestrial networks. It proposes convolutional neural network (CNN)-based spectrum prediction and support vector machine (SVM)-based spectrum sensing to improve the spectrum sharing between two networks.

Three articles handle the modeling issues in wireless systems when AI/ML is considered. In the article "A Deep-Tree-Model-Based Radio Resource Distribution for 5G Networks," M. Shamim Hossain *et al.* target an intelligent allocation of radio resources for 5G networks using deep learning. A framework consisting of a deep tree model and a long short-term memory network is proposed to predict future traffic congestion. Based on the prediction, the uplink and downlink ratio is adapted to utilize the resources optimally. Experimental results demonstrate that the proposed framework can achieve a low packet loss ratio and a high throughput.

Beamforming is evidently a core technology in recent generations of mobile communication networks. In the article "Model-Driven Beamforming Neural Networks," Xia *et al.* introduce general data- and model-driven beamforming neural networks (BNNs), present various possible learning strategies, and discuss complexity reduction for deep-learning-based BNNs. The authors also propose enhancement methods such as training set augmentation and transfer learning in order to improve the generality of BNNs, accompanied by computer simulation results and testbed results showing the performance of such BNN solutions.

In the article "Design of Noncoherent Communications: from Statistical Method to Machine Learning," Huang *et al.* review the design methods for noncoherent communications based on two statistical schemes that heavily rely on the models of the channel state information distributions. Then a data-driven ML method is proposed to design the noncoherent transceiver for short package transmissions, where the neural networks are trained separately or jointly by utilizing finite channel realizations to construct the training samples. It can be found from simulations that the proposed ML method outperforms the conventional statistical method for cases with imperfect knowledge of the channel state information distributions.

Mobile edge computing and caching have been an important solution to reduce latency and provide offloading to mobile applications. Intelligence plays an important role in making offloading decisions. Three articles cover topics on intelligent edge computing and caching. In the article "Toward Reinforcement-Learning-Based Service Deployment of 5G Mobile Edge Computing with Request-Aware Scheduling," Y. Zhai *et al.* propose a deep RL approach to help deploy services to edge servers with consideration of request patterns and resource constraints from mobile users. The authors model the problem as a Markov decision process (MDP) solved by the Dueling-DQN (Deep Q-network) algorithm. The experimental results show that learning-based algorithms achieve better performance than conventional approaches.

In the article "Intelligent Edge: Leveraging Deep Imitation Learning for Mobile Edge Computation Offloading," Yu *et al.* present a deep imitation learning (DIL)-driven edge cloud computation offloading framework for multi-access edge computing (MEC) networks. The authors propose to make fine-grained offloading decisions for a mobile device, and the problem is formulated as a multi-label classification problem with local execution cost and remote network resource usage considerations. To minimize the offloading cost, the decision making engine is trained by leveraging the DIL method.

The article "Cognitive-Caching: Cognitive Wireless Mobile Caching by Learning Fine-Grained Caching-aware Indicators" by Y. Hao *et al.* proposes a cognitive mobile caching architecture to minimize the caching cost. Fine-grained caching-aware indicator metrics that consider both user properties and content type for caching efficiency are defined to improve caching efficiency. These indicators are learned by MAB algorithms online. The experimental results show the performance of the proposed cognitive caching regarding the caching cost and learning regret.

Finally, three articles focus on application-related problems. In the article "AI-Assisted Low Information Latency Wireless Networking," Jiang *et al.* propose using information latency intead of communication latency as the metric to design ultra-reliable low latency communications (URLLC). Correspondingly, an AI-assisted situationally aware multi-agent RL framework for wireless networks is presented to address the information latency optimization challenge. Case studies of typical applications in autonomous driving are demonstrated. It can be found that information latency-optimized systems outperform conventional URLLC systems significantly.

Unmanned aerial vehicles (UAVs) can be powerful Internet of Things and cellular network components for many different tasks. In the article "Reinforcement Learning for a Cellular Internet of UAVs: Protocol Design, Trajectory Control, and Resource Management," Hu *et al.* utilize a learning approach to address the encountered dynamics and uncertainties of UAV sensing. A distributed sense-and-send protocol is proposed to coordinate UAVs for sensing and transmission.

Efficient beam tracking and alignment are necessary techniques to maintain robust millimeter-wave (mmWave) communication links. In the final article, "Learning to Predict the Mobility of Users in Mobile MmWave Networks," Liu *et al.* apply ML techniques to learn the mobility of mobile mmWave users and predict their moving directions. A deep neural network is learned and then used to predict a user's moving direction with up to 80 percent prediction accuracy in mmWave communication without the support of traditional channel estimation.

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