Theory and techniques for "intellicise" wireless networks

P Rajesh Naik, D Sirisha, B Narasimha Rao

Assistant Professor[1,2], Associate Professor[3]

Department of ECE,

prajeshnaik.ece@anurag.ac.in, dshirisha.ece@anurag.ac.in, bnarasimharao.ece@anurag.ac.in

Anurag Engineering College, Kodada, Telangana

Abstract

With the acceleration of a new round of global scientific, technological, and industrial revolution, the next generation of information and communication technology, i.e., 6G, will inject new momentum into industry transformation and upgrading, as well as into economic innovation and development. This will subsequently promote a global industrial integration. Wireless communication will be ubiquitous in all areas of future society, supporting novel applications with various performance requirements, such as immersive- or interactive-experience applications requiring a large bandwidth, autonomous driving and vehicle-to-everything applications requiring ultra- high reliability and ultra-low latency, and applications for industrial Internet requiring massive machine-type connectivity.

Key words: "intellicise" wireless networks

Inoduction

Facing the challenges of the post-Moore and post-pandemic era, wireless communication needs breakthroughs in network architecture to im- prove the intelligence, security, robustness, band- width, and heterogeneity. With this background, sev-eral important tendencies have emerged in the de- velopment of 6G wireless communications:

1. Future wireless networks will evolve from "human-to-human" communications into intelligent "human-to-machine" communications. In addition to enabling communications among humans, future wireless networks will be able to support close connections among humans and ma- chines. The behavior and intent of humans will be sensed and communicated to machines that will ac- cordingly adjust their operations. Typical scenarios include smart building, intelligent transportation, mixed reality (MR), and others.

2. Network nodes will evolve from carrying out only traditional communications to carrying out communication, sensing, computation, management, and caching in an integrated manner.To meet the diverse service requirements of mobile MR, intelligent transportation, industrial In- ternet of Things, and other areas, future networks will possess multiple functionalities. For example, by sensing human head position, pre-caching necessary content, and rendering high-quality images, network nodes can provide fully immersive MR experiences. In addition, with artificial intelligence (AI), network nodes can manage multi-dimensional resources in an on-demand fashion, where intent-driven network management and control can be realized.

3. Network architecture will focus on collabora-tions between the cloud and the network edge, which will become more heterogenous.To shorten latency and alleviate the backhaul/fronthaul burden, the network edge must collaborate with the cloud. The first method of collaboration is that the cloud finishes AI model training and then deploys AI models into the network edge, which supports the so-called edge intelligence. In the second method, users demanding high throughput are served via a cloud radio access

mode, while users requiring ultra-low latency can benefit from edge computation and caching. As for architecture heterogeneity, future networks are envisioned to incorporate unmanned aerial vehicle (UAV) networks, satellite communica-tion networks, and dense cellular networks, bringing three-dimensional and hierarchical network coverage. In short, the evolution of existing 5G technolo-gies and the development of 6G need to address more stringent and diverse application scenarios, a more strict energy constraint, and the orchestration of multi-dimensional resources.

4. These challenges call for an *intellicise* wireless network operation paradigm, where "intellicise" is a new adjective that we coin, standing for intelligence-endogenous and primitive- concise. Built upon the integration of AI and next- generation networking technologies, an intellicise wireless network continually explores and exploits new intelligent primitives, e.g., semantic base (Seb) in semantic communications, proactively takes sys- tematic entropy reduction as the global optimization objective, adaptively reshapes the core models of in- formation systems, and ultimately endows itself with endogenous intelligence and primitive conciseness.

In this context, the journal *Frontiers of Infor- mation Technology & Electronic Engineering* has organized a special feature on the theory and tech- niques for intellicise wireless networks. This special feature covers information theory, architecture design, and intellicise wireless networks for achieving air- space-ground-sea integration, resource management, hardware testbeds and platforms, as well as related applications. In addition, this feature is intended to provide a review of advancements and future research directions in the research field of intellicise wireless networks. After a rigorous review process, six papers have been selected for this feature, including one review article and five research articles.

Reference

Yaohua SUN and his collaborators undertook a comprehensive literature review in terms of the ar- chitectures, key techniques, and experimental plat- forms of intelligent wireless networks. Specifically, they first introduced an intent-driven wireless net- work, an autonomous driving network, an O-RAN reference architecture, and other elements. Then, they presented a deep discussion on AI-driven network slicing, intent perception, intelligent operation and maintenance, AI-based cloud-edge collaborative networking, and intelligent, multi-dimensional re- source allocation. To fill the gap between theoretical study and practical implementation, they further surveyed recent progress in developing experimental platforms to demonstrate the benefits of network AI.

Intellicise Internet-of-Things (IoT) networks can provide ultra-low-power communication connecting numerous miniaturized devices, for which, however, traditional software-defined radio (SDR) platforms are insufficient, making fast algorithm implementa- tion and evaluation difficult. Fei XIAO and her col- laborators provided an ultra-low-power SDR design to meet ultra-low-power or even battery-free re- quirements. The core idea is to use µW-level backscatter in the design instead of power-hungry active RF chains. An evaluation was conducted with different modulation schemes, and a data rate of 100 kb/s was reported with less than 200 µW of power consumption.

Equipped with a large number of reflection elements, intelligent reflecting surfaces (IRSs) can generate desired reflection beams and create favora- ble propagation conditions, a promising technique for intellicise networks. Yu ZHANG and his collabora- tors proposed to integrate IRSs into cloud radio access networks to further enhance capacity and coverage. They investigated a scenario with multiple IRSs de- ployed between the users and remote radio heads, and developed a successive convex approximation ap-proach to handle the non-convexity of an uplink sum-rate maximization problem under fronthaul ca- pacity constraints. Via the proper design of user transmit beamformers, IRS passive beamformers, and compression noise covariance matrices, the cloud radio access network (C-RAN) uplink rate can be significantly improved.

Edge AI plays a vital role in enabling intellicise networks to support complex and dynamic tasks in an industrial wireless environment. Chi XU and his collaborators adopted multi-agent deep reinforcementlearning (DRL) to orchestrate the computation and communication resources of both industrial devices and edge servers with each device being seen as a self-learning agent. Compared to a traditional DRL approach, their proposal was shown to achieve better adaptation to the computation capacity of edge serv- ers, data size, computation resources required, and thenumber of industrial devices.

The coverage of intellicise networks can be greatly extended with UAVs. However, interference between terrestrial links and UAV-ground links can degrade the performance of the whole network. To address this, Jing GUO and her collaborators used thecoordinated multipoint (CoMP) technology to miti- gate the interference in a three-dimensional, multi- layer UAV-terrestrial heterogeneous network (Het- Net). A rigorous analytical study was conducted usingstochastic geometry theory, resulting in a tractable mathematical framework for coverage probability evaluation. Its accuracy was further validated via numerical results.

Conclusion

To better support applications with stringent re- quirements, such as virtual reality (VR), multi- dimensional resource management is essential. In this field, Chenxi LIU and his collaborators presented a mobile, VR delivery framework where both uplink and downlink transmissions were considered. They characterized the round-trip latency of the VR serviceand revealed its dependence on communication, cach-ing, and computation resource allocation. Then, they proposed a simple yet efficient optimization algo- rithm to minimize round-trip latency, while satisfyingpractical constraints on caching, computation capa- bility, and transmission capability in the uplink and downlink. Numerical evaluations illustrated that the proposed algorithm can effectively reduce the round-trip latency compared with various benchmarks.

Overall, a broad spectrum of current research topics relevant to the theory and techniques of intel- licise wireless networks is covered in this special feature, from software-defined-radio hardware and beamformer design, to AI-driven resource orchestra- tion, network coverage performance analysis, multi- dimensional resource management, and others. We hope that this collection of diverse but interconnected topics will be beneficial to those with an interest in intellicise networks or in related areas.

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