ITU Journal

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Future and evolving technologies

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The ITU Journal considers yet-to-be-published papers addressing fundamental and applied research. It shares new techniques and concepts, analyses and tutorials, as well as learning from experiments and physical and simulated testbeds. It also discusses the implications of the latest research results for policy and regulation, legal frameworks, the economy and society. This publication builds bridges between disciplines, connects theory with application, and stimulates international dialogue. Its interdisciplinary approach reflects ITU's comprehensive field of interest and explores the convergence of ICT with other disciplines.

The ITU Journal welcomes submissions at any time, and on any topic within its scope.

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Foreword

Doreen Bogdan

Secretary-General
International Telecommunication Union

ITU members work together to connect the world and ensure that our interconnections make meaningful contributions to society.

This commitment to the public interest is embodied by the ITU Journal on Future and Evolving Technologies.

Our journal is unique in publishing papers from world-renowned researchers at no charge to authors or readers.

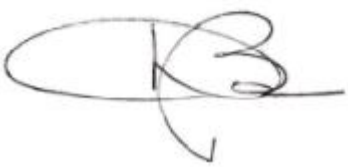
We seek global representation in our published papers and teams of reviewers and editors, and we welcome an interdisciplinary approach to the broad scope of topics addressed by ITU.

This inclusive character of our journal has received a warm welcome from academia.

We have had the pleasure of publishing 148 papers from 602 contributors since our journal's launch in 2020. 70 per cent of these contributors are academics. Academics also account for over 90 per cent of the editors, guest editors and reviewers making up our editorial boards.

In contributing to the journal and the work of ITU, leading minds in science and engineering are sharing insights on the latest breakthroughs in research to help everyone capitalize on new capabilities to innovate.

I extend my gratitude to everyone supporting our journal and I would especially like to thank our Editor-in-Chief, Ian F. Akyildiz, for the vision and dedication that define his leadership.



Doreen Bogdan
Secretary-General
International Telecommunication Union

Foreword

Seizo Onoe

Director
ITU Telecommunication Standardization Bureau

We continue to see growing synergy between industry and academia in the development and application of information and communication technologies (ICTs).

Academic and research institutes are key partners to industry players in research and development as well as sandbox initiatives to prove the market viability of new solutions.

Industry and academia are stimulating one another's work. This synergy is highly evident in the strength of academia's participation in ITU work and industry's support to the ITU Journal.

ITU Academia members contribute to ITU expert groups responsible for radiocommunication, standardization and development, strengthening the work of ITU and increasing the impact of research.

ITU Kaleidoscope conferences form another key avenue for academics to engage in our work, highlighting research into topics of growing strategic relevance to ITU standardization.

The ITU Journal is our latest initiative in service of ITU's collaboration with academia, and academia's collaboration with industry.

Our journal succeeds in offering comprehensive coverage of the latest developments in communications and networking thanks to its flourishing supporting community.

Our Editor-in-Chief, Ian F. Akyildiz, is instrumental in nurturing the growth of this community and I offer my sincerest thanks to Professor Akyildiz for his outstanding leadership.

ITU is committed to creating global access to new technologies and knowledge to help ensure that everyone benefits from the advances in ICT changing our world.

This commitment is demonstrated by the ITU Journal, and I extend my deepest gratitude to the community that gives our journal life.

Seizo Onoe
Director
ITU Telecommunication Standardization Bureau

Special issue on "Intelligent surfaces and their applications towards wide-scale deployment"

What if the wireless propagation could be customized, rather than being simply tolerated?

In recent years, a novel research direction has emerged to explore this topic in the context of wireless communications. This technology has the potential for a paradigm shift, especially in the much anticipated high frequency regime. Programmable and smart radio environments have already been widely socialized in the communications field, addressing previously insurmountable wireless communication problems from the aspect of the environment, apart from the device end points. Notably, in the timespan of just a few years, the field has had an impressive impact not only within academia, but within industry as well, with major companies such as DOCOMO, Samsung, ZTE, and Huawei presenting prototypes at global exhibitions, and with the formation of specialized technology standardization bodies.

A core component of the programmable wireless environments are the metasurfaces, i.e., planar, artificial structures, which have enabled the realization of novel objects with engineered and even unnatural electromagnetic functionalities in general. Metasurfaces can be designed for a wide range of operating frequencies and application domains. Networked metasurfaces can connect to the Internet of Things' ecosystem and expose their wireless manipulation capabilities to any context. New software components emerge that can virtualize metasurface functionalities such as parametric wave steering, absorbing, filtering and polarizing. Within a networked metasurface, novel energy-efficient electronic controllers are being developed, which translate the software directives into corresponding alterations of the metasurface structure to obtain the required macroscopic electromagnetic behavior.

Networked metasurfaces can be massively deployed to coat common objects such as walls, doors and sizable furniture, and be centrally orchestrated by an administrator to exert logical control over the way wireless propagation occurs within an environment overall, e.g., within a building. Thus, the environmental behavior can be dynamically optimized to the needs of wireless devices, such as mobile phones and laptops.

The derived practical benefits are highly promising.

Networked metasurfaces deployed within a space can mitigate previously unsurmountable, degenerative factors in wireless propagation, namely path loss, multipath fading and Doppler shift. This readily allows for lower-power transmissions, which favor the battery lifetime of the wireless devices. Moreover, the decreased scattering reduces cross-device interference, supporting an increased number of mobile users to coexist in the same space, without degrading their performance. Additionally, the traveling wave reaches the receiver via well-defined paths rather than via multiple echoes, allowing for increased data transmission rates and high-quality coverage even at previously "hidden" areas. From another aspect, this separation of user devices can target increased privacy. Waves carrying sensitive data can be tuned to avoid all other devices apart from the intended recipient, hindering eavesdropping. These interesting environmental behaviors, and more, can be expressed in software in the form of combinable and reusable modules. Thus, communication system designers and operators are enabled to easily and jointly optimize the complete data delivery process, including the wireless environment, supplementing the customizable wireless device behavior, and furthermore, reducing the complexity of the device design.

The control of waves via programmable wireless environments can find applications beyond classic communications. Electromagnetic interference constitutes a common problem in highly sensitive hardware, such as medical imaging and radar technology. In these cases, the internals of, e.g., a medical device can be treated as a programmable wireless environment as well, with the objective of canceling the interference to the imaging component caused by unwanted internal scattering. Such interference can be mitigated only up to a degree during the design of the equipment. Common discrepancies that occur during manufacturing can give rise to unpredictable interference, resulting in reduced equipment performance. However, assuming metasurface-coated device internals, interference can be mitigated, or even negated, after the device manufacturing, via simple software commands. Many more examples, even across energy domains, such as control over acoustic and mechanical wave propagation, outline some interesting extensions of this technology.

Presently, the programmable wireless environments are studied from the aspect of integration into other real-world systems.

However, to realize diverse support by applications in widely deployed systems, a comprehensive treatment of programmable wireless environments, covering all system aspects is required. These include end-to-end system models, models of the environment, the constituent hardware and software, the control approaches and protocols, the deployment economics, as well as the theoretical foundations permeating complete end-to-end systems, which remain largely unanswered and pose interesting and critical challenges.

This special issue has welcomed multi-layer studies on all aspects of smart wireless environments, from electromagnetic designs and electronics of networked metasurfaces and related manufacturing processes, to system integration and high-level control approaches, 56/6G wireless channel engineering applications, and the end-to-end behavior of systems incorporating networked metasurfaces.

At the **physical layer**, "*A dual-band 3-bit reconfigurable intelligent surface with independent control of phases*" is proposed to achieve decoupled programmatic control over the reflection phases in two frequency bands by designing two tunable structures without raising the profile. The presented design focused on achieving low sensitivity to incident angles between 0° and 50°.

At the macroscopic **electromagnetic function layer**, the "*RIS-aided mmWave beam-forming for two-way communications of multiple pairs*" provides interesting insights on the interplay between massive MIMO and networked metasurfaces in the mmWave band. The macroscopic modeling of this function is further elaborated in "*PHY0 network: Metasurface as PHY-beam router, is it possible? Challenges and open problems*".

At the **channel modeling layer**, the "*Performance analysis of RIS-assisted wireless systems with channel aging and spatial correlation*" proves that the channel information aging phenomenon degrades the system performance, while the application of a RIS can compensate for the loss.

At the **resource orchestration layer**, "*A scheduling framework for performing resource slicing with guarantees in 6G RIS-enabled smart radio environments*" provides an initial approach to defining the notion of a resource in the context of this new technology, and how to schedule their allocation to multiple users and objectives.

At the **application-layer**, an interesting study is performed "*On the use of intelligent metasurfaces in data centers*", discussing how programmable wireless environments can yield new data center architectures, with versatile internal connectivity. Moreover, exciting prospects of employing "*Artificial intelligence for RIS-aided wireless communications*" are discussed.

From the **socioeconomic aspect**, "*Circular economy pathways with programmable intelligent surfaces and materials*" explores the impact potential of the novel technology in well-established product lifecycles and the corresponding financial impact.

End-to-end studies are also presented in "*Shaping flattened scattering patterns in broadband using passive reconfigurable intelligent surfaces for indoor NLOS wireless signal coverage enhancement*", which showcases the mitigation of non-line of sight problems in the mmWave band, while "*Wireless physical-layer encryption with programmable metasurface in real environment*" demonstrates a novel security direction enabled by the smart wireless environments.

Thus, the authors in this special issue all identify highly relevant challenges relating to smart and programmable wireless environments and their metasurface constituents, and in so doing provide a number of novel and exciting opportunities for future theoretical development and experimental testing. We hope you will find inspiring avenues for future research in these papers which span the complete set of operational layers towards finding inventive ways for routing the wireless waves.

The Guest Editors

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Special issue on "Innovative network solutions for future services"

The role of future networks will go beyond connecting devices. A cornerstone of building future networks shall be intelligent control and management platforms that will enable a plethora of new services (e.g., control of industrial plants, medical applications, autonomous vehicles, entertainment and immersive experiences and disaster recover). These services shall test the limits of networks in several aspects, ranging from the transport of extremely high data rates to intelligent control and management platforms enabled by modular machine learning and artificial intelligence tools; and it goes without saying that this impacts cyber-securing the networks against any attack that may comprise their performance.

Typical applications may include:

- Automated industrial processes that require networks with medium data rates, in a limited geographical area, with extremely low latency communications, as the industrial instruments should be totally synchronized. Redundancy requirements amongst industrial instruments and tools will place further stringent requirements on allowable data latency;
- Remote surgery, requiring medium-to-high data rates, strongly synchronized flows (i.e., no jitter) sources connected across the globe;
- Driving assistance, requiring local coordination of vehicles (for lane merging, crossroad approaching and vehicle platooning provisioning), high reliability and in-time communications;
- The immersive experience in the metaverse, requiring high data rates and high reliable feedback responses, as well as low latency interactivity;
- High adaptability to localize users in order to provide fast restoration of communications for disaster relief measures;
- Personal body networks measuring vital body signs that will relay this crucial medical information to nearby cloud servers that could interpret the data, predict a potentially serious medical condition such as a stroke, thus alerting the user and directing medical emergency services. This will also require highly accurate localization services, minimum latency and jitter, and delivery of extremely high data rates from/to millions of mobile users.

In order to fulfill these requirements, sometimes in contrast with each other, future networks should be flexible and capable of anticipating the behavior of users, as well as of applications. Several strategies and methods are proposed in the literature to enabling novel services. Here is a limited list:

- Native artificial intelligence and machine learning implemented in all sections of the network, from the user equipment to the radio access network (or the fixed access network) to the edge and to the core of the cloud for managing flow splits and routing algorithms;
- Deploy contents close to the edge of the access network, thus reducing the latency and offloading the core network, as well as reducing the processing capabilities (and energy constraints) of the user terminals (e.g., head-mounted visor);
- Enhanced radio access networks, enabling lower latency access, a large number of sensors/actuators in small areas and possibly large bandwidth at higher frequencies;
- Seamless integration of all available networks such as local, mobile, non-terrestrial networks for highly adaptable and reconfigurable networks.

The papers presented in this special issue, tackle some of the above-mentioned topics.

Why and how edge computing can address performance and economic sustainability issues for telco domestic networks

Traditionally, telecommunication operators (namely telcos) focused on network services, i.e., the transport of IP packets. Performance improvement was obtained by Quality of Service (QoS)-based traffic management techniques, such as bandwidth reservation and packet prioritization. With the advent of Very High Capacity (VHC) networks, telcos afforded difficulties in managing effectively and efficiently the application services and their business sustainability. In a different way from tunnels applied at layer 2, the use of layer 4 techniques and ECC are effective in managing application performance improvement, as shown by the multiyear experience of Over-The-Tops (OTTs).

In this paper, the convergence of network and processing which is able to provide ultra-fast and low-latency data transmission is analyzed. The authors presented solutions for the telco industry based on network architecture transformation and the deployment of the ECC. The provided results showed the enhancement in Quality of Experience (QoE) and the reduction of the costs with ECC. An exhaustive description of the ECC is also provided. Furthermore, some interesting data of network connectivity in terms of throughput over bit rate measurements from Netflix and Ookla data are reported for Italy, Germany and France. Network interconnections and traffic flows between telco networks and ECC platforms are modelled, allowing us to define the speed-up parameter as a performance metric. Finally, analysis results on network cost savings with ECC is provided.

Federated learning for performance prediction in multi-operator environments

In order to deliver services, telecommunication operators continuously observe the network infrastructure and the service key performance indicator (KPI) metrics. In this paper, the authors proposed to adopt a Machine Learning (ML)-based technique to predict the service performance. Nevertheless, a data-driven approach requires extensive measurements and data collection from the telecom infrastructure. But this has three main issues: transferring data in a centralized location (e.g., a data center), large volume of data impacting network performance, and privacy on sensitive data cannot be respected.

The authors proposed a Federated Learning (FL) approach, while aiming to achieve a high ML model performance using a large volume of data for training obtained from other telecommunication operators and preserving privacy and reducing the data transferring. Federated learning is compared against local and central learning strategies for multi-operator performance prediction, and it is shown to balance the requirements on data privacy, model performance, and network overhead. Further, the paper provides insights on how data heterogeneity affects model performance, where the conclusion is that standard federated learning has certain robustness to data heterogeneity.

Terahertz networks for future Industrial Internet of Things

In this paper, the authors provided an overview of the forthcoming terahertz networks applied to the extremely challenging scenario of the Industrial Internet of Things (IIoT). New requirements in IIoT foresee a data acquisition periodicity of 1 μs, a latency lower than 100 μs and a spatial resolution of about 1 cm. The wireless network connecting all machines, sensors, actuators and PLCs might need to address totally different requirements in separate areas of the factory. Moreover, production in manufacturing plants is also characterized by time-varying needs; for maintenance reasons, or due to the steps of a sequential process, machines can change their scheduled activities very often; the presence of humans requires fast reaction times to possible dangerous situations. As a result, the requirements set by this multi-goal environment evolve in time and space and the wireless network supporting the production process must be able to follow these evolutions.

This opens up several challenges in Physical (PHY), Medium Access Control (MAC) and in the Integrated Sensing and Communication (ISAC). The paper analyzes the key enabling technologies in this field and reports the research direction for THz-based IIoT networks, such as high-rank MIMO, smart radio environment, new MAC protocols and on the cooperation of the communication and the localization of smart things. They have also proposed new PHY-MAC cross-layer approaches to devise goal-oriented scheduling schemes, which are able to allocate the radio resources available over multiple links with the purpose of satisfying the (possibly conflicting) requirements posed by the connected devices. Finally, the authors reported challenges on THz networks along with possible solutions and research directions that encompass multidisciplinary aspects ranging from EM theory, information theory, signal processing, and network theory.

Artificial intelligence support for 5G/6G-enabled Internet of Vehicles networks: An overview

The evolution and deployment of 5G have opened up new technologies and features that can provide the much needed high-mobility wireless networks for the emerging Internet of Vehicles (IoV). In this paper, the authors reviewed the application of Artificial Intelligence (AI) consisting of deep learning, machine learning, and Swarm Intelligence (SI) techniques in the IoV network. The possibility to have a large amount of generated data from various sources within the vehicular communication environment opens the applicability of data-driven methods enabling AI to address high mobility and dynamic vehicular communications and network issues, which allows us to overcome traditional solutions and approaches, such as network optimization techniques and conventional control loop design.

The paper discusses the strengths and weaknesses of the proposed AI-based solutions for the IoV networks by also integrating them within the layered IoV architecture and into 5G/6G systems with the aim of improving transportation efficiency and on-road safety using Intelligent Transportation Systems (ITSs). All these aspects considered road congestion and an increase in vehicle complexity. Finally, future IoV research directions and open issues that can benefit from the potential of DL, ML, and SI were identified, with a particular focus on trust issues with respect to legal liability and verification confusion at the occurrence of road accidents, since humans cannot directly interpret outputs generated by the current decision-making procedures used by ML algorithms.

A consensus-based approach to reputational routing in multi-hop networks

In multi-hop networks, nodes relay information amongst themselves, opening the data up to tampering by an intermediate device. In this paper, it is proposed a consensus-based approach for securing communications in a multi-hop network. The relay of information in the IoT network is validated through the reputation of nodes. According to the method proposed by the authors, nodes have the ability to analyze their neighbor’s behavior. Through the use of consensus-based validation, based upon the blockchain’s miners, all nodes can agree on the trustworthiness of all devices in the network. By expressing this through a node’s reputation, it is possible to identify malicious devices and isolate them from network activities. Instead of defining the best route based upon overall length, the proposed method may select the most reputable path available, thus traversing trustworthy devices. Results on this metric with respect to the classic and most popular Ad hoc On-Demand Distance Vector (AODV) routing protocol show a decrease in packet drop rates by approximately 48% and 38% when subjected to black-hole attacks (all received packets are destroyed) with 30 and 100 node networks respectively. The proposed method confirms its adaptability to different types of threats since it has been tested by varying degrees of dropping a packet by grey holes, which does not destroy all packets but a few of them are still delivered.

Boosting smarter digital health care with 5G and beyond networks

In this paper, the authors analyzed the impact of 5G and its benefit on medical and healthcare applications. They considered software-defined networking, 5G architecture, and edge and cloud computing as enabling techniques to boost applications in the health-care sector. Opportunities related to the adoption of 5G in e-health care are data sharing supported by high data rates and low latencies, computing resource sharing between different entities, making deep mining and processing of the medical data possible, and intelligence sharing by providing human expertise via high-definition video-based remote diagnosis, and also gathering/sharing machine and human intelligence via AI, machine learning algorithms and robotics, exposing best expertise and knowledge to a wide range of institutions. In addition, a variety of healthcare applications that will benefit from 5G, such as remote diagnosis/intervention and long-term monitoring for chronic diseases, remote surgery, and homecare with robots, are also introduced. It is highlighted how medical imaging as a major medical data type, due to its data-intensive, storage-intensive and computation-intensive nature, is appropriate for being employed as an ideal example to demonstrate the importance of 5G and cloud in the medical and health-care sectors.

Intent-based deployment for robot applications in 5G-enabled non-public networks

Cloud and edge computing, distributed AI, and most recently 5G/6G communications are coming together and changing the way we collaborate, connect, and interact. Networking will shift from supporting the end users to supporting the so-called vertical applications. Robotic applications are one of the most promising vertical applications, which are used in many sectors. Robots are supposed to tackle unknown situations and adapt in the long term by collaborating, connecting, and interacting with the digital world. Such applications generate versatile, perpetuated and rapidly changing transmission demands to the network. Then, according to the authors of this paper, specific applications based on collaborating robots that are connected and interact with the digital world in the industrial automation will be possible only through dedicated local 5G networks (namely Non-Public Networks (NPNs)). In addition to the traffic engineering on the network side, they present a method to shape the traffic on the application side in the NPN, which is able to guarantee the QoS required by a new generation of AI-powered robots.

We hope that this special issue will play an important role in future research and development endeavors. The guest editors would like to thank the Editor-in-Chief Prof. Ian Akyildiz for his guidance and encouragement throughout this process. We also extend our appreciation to Alessia Magliarditi and Erica Campilongo for their editorial help and support. Finally, we would acknowledge the authors and the reviewers for their effort and time.

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