TOWARD 6G TKμ EXTREME CONNECTIVITY: ARCHITECTURE, KEY TECHNOLOGIES AND EXPERIMENTS

Xiaohu You, Yongming Huang, Shengheng Liu, Dongming Wang, Junchao Ma, Chuan Zhang, Hang Zhan, Cheng Zhang, Jiao Zhang, Zening Liu, Jin Li, Min Zhu, Jianjie You, Dongjie Liu, Yang Cao, Shiwen He, Guanghui He, Fengyi Yang, Yang Liu, Jianjun Wu, Jianmin Lu, Ge Li, Xiaowu Chen, Wenguang Chen, and Wen Gao

ABSTRACT

Sixth-generation (6G) networks are evolving toward new features and order-of-magnitude enhancement of systematic performance metrics compared to the current 5G. In particular, the 6G networks are expected to achieve extreme connectivity performance with Tbps-scale data rate, Kb/s/Hz-scale spectral efficiency, and μs-scale latency. To this end, an original three-layer 6G network architecture is designed to realize uniform full-spectrum cell-free radio access and provide task-centric agile proximate support for diverse applications. The designed architecture is featured by super edge node (SEN), which integrates connectivity, computing, AI, data, etc. On this basis, a technological framework of pervasive multi-level (PML) artificial intelligence (AI) is established in the centralized unit to enable task-centric near-real-time resource allocation and network automation. We then introduce a radio access network (RAN) architecture of full spectrum uniform cell-free networks, which is among the most attractive RAN candidates for 6G TKμ extreme connectivity. A few most promising key technologies, that is, cell-free massive MIMO, photonics-assisted Terahertz wireless access, and spatiotemporal two-dimensional channel coding are further discussed. A testbed is implemented and extensive trials are conducted to evaluate innovative technologies and methodologies. The proposed 6G network architecture and technological framework demonstrate exciting potentials for full-service and full-scenario applications.

INTRODUCTION

While the roll-out of fifth-generation (5G) networks is speeding along at a spectacular pace, 6G research and development (R&D) initiatives have been launched by the leading powers across the world, such as the United States (US), European Union (EU), Korea, and China. Despite varied focuses, the major countries and institutions embrace the same visions, such as 6G will further expand connectivity ability and service coverage on the basis of 5G; further strengthen its capability as the key enabler and deepen the penetration in diverse vertical applications; and progress through the three stages: establishment of overall vision and technology framework, standardization, and large-scale commercial deployment, respectively, around 2023, 2025, and 2030.

The shared visions and expectations are built upon the increasingly stringent requirements in terms of network performance and intelligence imposed by the ongoing digitalization of society and economy. For instance, immense extended reality (XR) in maintenance and repair situations requires Tbps-scale data rate [1]; massive machine-type communications for Industry 4.0 requires Kb/s/Hz-scale spectral efficiency (SE) to guarantee quality of service [2]; and the expected latency and reliability for vehicular communications and industrial control are, respectively, at μs level and 99.999 percent [3]. Aside from the key KPIs, game-changing features, such as native AI for customized diverse applications and zero-touch network management are also envisioned in the future 6G. Nonetheless, all of the above is clearly beyond the capability of the current network architecture and technological framework.

In the light of the above observations, we coin a new acronym of three of arguably the most important key performance indicators (KPIs) TKμ for 6G evolution. Concretely, we deduce the following KPI estimates for the future 6G extreme connectivity. Specifically, 6G will require a data rate of 1 Tbps, SE of 1 Kb/s/Hz, and μs-level latency for vast applications. The fascinating new features and the consequential KPI demand of 6G has motivated leading companies and the research community across the globe to find ingenious and effective solutions. For example, Terahertz (THz) is recognized to be a promising technology to reach Tbps on the experienced data rate [4]. Intelligent and agile allocation of holistic network to satisfy diverse requirements is deemed as another disruptive feature of the future 6G network, which has received a lot of...
In this context, the following efforts are contributed: First, we propose a novel task-centric three-layer architecture for 6G networks, which undertakes the support provided by 6G for ultra-service and full-scenario applications. The proposed architecture features a decentralized model and employs super edge node (SEN) as the basic enabling facility to agilely allocate requested resources in the proximity of the mobile users. Together with the full spectrum (sub-6GHz, mmWave, and THz) technology including cell-free massive MIMO, technologies deployed in the edge distributed unit (EDU), an extreme connectivity capability of TKμ-level, is yielded. Second, on the basis of native AI and collaboration of core node and SEN layers, we build an innovative technological framework of PML native AI to further push TKμ connectivity to extreme. Knowledge graph representation is leveraged to generate the feature data set (FDS), which in turn drives the AI algorithm in all nodes and all levels of the system to optimize the quality of service. High-level self-driving and service customization are thus enabled. Then a full-spectrum cell-free radio access network (RAN) is designed and deployed with the proposed architecture. A series of emerging 6G technologies including cell-free distributed massive MIMO, photons-assisted Terahertz (THz)-band wireless transmission, and spatiotemporal two-dimensional (2-D) channel coding are applied therein to realize the TKμ KPIs. Finally, a prototype testbed is implemented and experiments are carried out to showcase the advantages of the proposed scheme with respect to the network intelligence, extremely high data rate and SE, and so on. The presented promising results can potentially serve as a reference and guideline for the future 6G research and development.

**Three-layer Architecture for 6G**

**Overall Architecture and Design Rationale**

6G networks will exhibit flexible adaptability to diverse vertical applications through a new compute plane as one of network functions of 6G network will act as the fundamental enabler for agile proximity services, and the decentralized trend will be characterized by the SENs. To this end, we propose an innovative hierarchical architecture design for 6G TKμ extreme connectivity. The rationale behind this architecture design is threefold. First of all, the current “chimney-style” mutually independent big data platforms, intelligent platforms, virtualized connection platforms, and storage platforms will be merged into an integrated whole. They will be unified in the form of edge data centers that are supplemented by various accelerator and plug-in acceleration cards. Second, a transformation in the morphological characteristics of base stations will be witnessed. More specifically, the accelerated and broadband-based baseband processing function will be gradually integrated into the edge data center. Third, the generation of network functions and application services will demonstrate APP-ization. In particular, the service subscribers will be able to conveniently use the network-side and terminal-side APP platforms to customize the network services and security policies via dynamic configuration of the computing, AI, storage, and connectivity resources in the super data center.

The proposed network architecture can be partitioned into three layers: core nodes (CoNs), SEN, and distributed units. The CoNs constitute the first layer, which is responsible for the non-RT control and management of the entire network. The second layer, SEN, provides edge agile services, including connectivity, computing, data, and AI for the specific service. This is the key layer in the 6G network architecture. The EDUs and the remote radio units (RRUs) are in the third layer of the proposed three-layer architecture. In the following, we elucidate the function and operating mechanism of the SEN layer.

**Super Edge Nodes**

The SEN layer is logically composed of several separate/converged functions, such as user plane function (UPF) and a portion of the baseband units (BBUs). This layer consolidates edge data acquisition/processing and AI functions to form multiple SENs. Each SEN provides nearby agile services in near-RT according to the task-centric model, which is the basic enabling node for the transformation of 6G wireless networks from session-centric to task-centric and decentralized. The architecture of the SEN network is shown in Fig. 1. The specific functions of SEN are implemented by network supermarket (NS), super-RAN intelligent platform (sRIP), and programmable BBU pool (pBBUP).

In terms of sRIP, the architecture of the RAN plays an important role in realizing 6G TKμ. The 6G RAN needs to support full spectrum access, including sub-6GHz, mmWave, and THz frequency bands. To this end, we need to design a unified implementation of cell-free RAN for different frequency bands. In the proposed cell-free RAN architecture, the EDU module is added in the system to connect with multiple RRs [7]. As such, the enhanced joint processing ability is yielded and the distributed receiver/predecoding can be realized at the EDU to achieve unlimited scale of cell-free network. On the other hand, the user-centric distributed unit (UCDU) enables decentralized cooperative combination and distribution of user data. The MAC layer and the radio resource control are implemented in centralized control unit (CCU). Therefore, compared with the traditional cell-free massive MIMO, the novel cell-free RAN architecture can achieve better cooperative transmission performance even with a limited-scale RRU [8].

Different from 5G that only supports non-RT intelligence in the CoN, in the 6G network architecture we propose that intelligence is hierarchically and distributedly embedded in the edge nodes, from the cloud to each BBU, from L3 and L2 to L1. Thus, it is referred to as native AI, which
enables near-RT/RT intelligent control, owing to its ability to achieve a high level of network autonomy. In the designed RAN architecture, physical layer (PHY) functions are implemented in two separate layers, which reaps the following three benefits: First, it enables the decoupling of high and low frequency systems. Second, it also decouples multi-user data streams, such that the scalability of cell-free massive MIMO is enhanced. Third, with EDU-UCDU separation, since the high-PHY processing is user equipment (UE)-oriented, it supports user-centric networks and cloudized pBBUP. Based on the above features, a full-spectrum cell-free RAN architecture was arrived at. On top of 5G, through the utility of virtualized and pooled pBBUs, the proposed cell-free RAN harmoniously integrates with the near-RT/RT resources enabled by native intelligence. As such, flexible and agile allocation of end-to-end full-spectrum air interface resources is accommodated. This, in turn, fulfills the need for dynamic adaptation of different services to the TK\textsubscript{m} air interface access capability, so as to realize the TK\textsubscript{m} extreme connectivity toward 6G. Integration of sensing, communication, and computation functionalities is notably a key feature of the emerging 6G networks [9], as well as the proposed architecture. The EDUs can sense the environment independently or collaboratively. Subsequently, the sensed information is uploaded to the pBBUP and processed in the sRIP, both of which are located in the aforementioned SEN.

**Key Enabling Technologies**

In the previous section, we elaborated the three-layer 6G network hierarchy and explained the potential advantages of the architecture to support the TK\textsubscript{m} communications. In this section, we elaborate on the key enabling technologies implemented under this architecture to achieve the expected 6G features and KPIs.

Specifically, a technological framework of PML AI is first proposed to realize task-centric near-RT resource allocation and network automation. Then a massive MIMO based cell-free architecture is designed as a uniform platform to enable full-spectrum TK\textsubscript{m} wireless access. The combination of PML AI and cell-free RAN facilitates agile adaption of TK\textsubscript{m} connectivity. Under the new architecture, a few wireless transmission technologies, including cell-free massive MIMO, photonics-assisted THz, and spatiotemporal 2-D coding are discussed.

**Near-RT AI-Empowered Centralized Unit**

At the very inception of 5G networks, incorporating AI natively is beyond the consideration of the designers. As a result, the current 5G systems integrate AI mainly by adopting the add-on and centralized styles, which brings along heavy pressure on transmission bandwidth and formidable challenges in data privacy and protection. In this context, we propose a PML AI technological framework, which mainly operates as a part of the upper two layers: CoNs and SENs, of the three-layer 6G networks elaborated in the previous section. It also represents a distinctive feature thereof. By creating innovative data plane and intelligence plane, we infiltratively and pervasively embed the data, computing power, and AI in all nodes and all levels of the system. Non-RT, near-RT, and RT intelligent optimizations are realized in multiple different and proper levels, so as to shape the true native AI and enable high level self-management and self-optimization, as well as high quality servitization of future 6G networks.

Figure 2a shows a diagram of the overall architecture of the proposed PML AI, which mainly comprises three parts: data plane, intelligence plane, and the intelligent slicing connecting the two planes [6]. The main responsibility of the data plane is to collect data from the network and then analyze the data to dynamically form the FDS as demand. The generated FDS data are then inserted into the intelligent plane through intel-

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**FIGURE 1. SEN architecture with pBBUP.**

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Intelligent slicing to drive the training and intelligent inference processes of corresponding AI models. In this way, true cognitive intelligence that is capable of perceiving and reasoning for diverse applications is enabled. However, trillions of data fields and indicators related to heterogeneous software/hardware, functions, and protocol stacks are continually generated during the network operation. The network structure, terminal type, terminal behavior, data service requirements, and system resources of the 6G networks exhibit high dynamics, strong timeliness, and mutual coupling.

In aware of the above facts, we propose to use knowledge graph to untangle the complicated connections among the wireless data fields, as well as characterize the types/attributes and the relationships between them. The generated datasets are required to be representative and redundancy-free.

To achieve a high-level end-to-end network autonomy and high-quality guarantee for differential multi-service concurrency requirements, espe-

**FIGURE 2.** Key enabling technologies to achieve high data rate and ultra-low latency communications: a) PML AI architecture; b) diagram of a photonics-assisted Tbps fiber-THz-fiber seamless transmission system; c) multi-antenna baseband transmitting system with the spatiotemporal 2-D channel coding.
Conventionally, agile adaptation to various requirements on the TKμ connectivity ability, the intelligence plane in the PML AI allocates multiple dimensional communication/computing/caching resources in task-centric manners via hierarchical intelligence control [10]. This involves non-RT AI models at the core nodes, near-RT and RT AI models at the SENs and the DUs, respectively. In addition, statistics of statistics can help design hierarchical approaches for problem simplification. Therefore, some RT tasks, for example, interference optimization and beamforming control [11], require effective collaboration between non-RT and RT AI models. The design of RT AI models for the PHY layer functions can generally be more challenging.

For instance, in mmWave massive MIMO systems, acquiring channel state information via beam training, especially for fast-changing channels, gives rise to large overhead. In this case, an interactive learning design paradigm [12] that incorporates domain knowledge into deep reinforcement learning was proved to be effective in adapting to dynamic environments and extracting interesting statistical information from limited samples.

**Full Spectrum Cell-Free RAN for 6G TKμ**

In the lower and DU layers, recent evolution in RAN architecture also opens up new opportunities for delivering more agile services and advanced capabilities to end users. Among the candidates for RAN architecture, full spectrum uniform cell-free RAN arguably represents the most appealing one toward 6G TKμ. In the full spectrum cell-free RAN architecture, cell-free massive MIMO can be deployed in both high- and low-frequency bands to improve the system's spectral efficiency, peak rate, and reliability. For sub-6 GHz band, with the deployment of massive RRRs and scalable implementation, spectral efficiency of Kbps/Hz can be achieved. With the large bandwidth and multi-beam technology offered by the THz/mmWave bands, Tbps peak rates can also be delivered. For cell-free RAN combined with mmWave/THz techniques, digital precoding, multi-user detection and the associated analog beamforming can be computed in the EDUs, which controls the mmWave/THz radio-frequency frontends, while the Tbps-peak-rate coding and decoding are performed at the UCDUs. In the cell-free RAN, by leveraging large number of RRRs together with spatiotemporal 2D coding, multiplexing gains can be compromised to attain diversity in the ultra-reliable low-latency communications. In the following, we introduce a few of the most promising examples of RAN technologies for 6G TKμ.

**Cell-Free Massive MIMO for Kbps/Hz SE:**

In the new architecture, joint transceiver for multiple users and multiple RRUs can be implemented in the EDU. Due to the distributed deployment of RRUs, the distances from multiple users to multiple RRUs are different, and the frequency selectivity of the channel is more serious than that of centralized MIMO. Therefore, we derived an optimized precoding vector within multiple resource blocks (RBs) to decrease the complexity of downlink precoding of wideband OFDM systems. Additionally, in order to reduce the complexity of user-centric collaborative trans-
mission, the association of UCDU with users can be used to achieve dynamic load balancing in the actual deployment. The acquisition of channel state information is the bottleneck of cell-free system. Due to the large number of users and limited pilot overhead, pilot reuse needs to be studied. For the cell free RAN architecture, the RRUs managed by the EDU send calibration signals to each other and exchange the received calibration signals. The method in literature [7] can be used to obtain the reciprocity calibration coefficients of RRUs.

Photonics-Assisted THz Wireless Access for Tbps Rate: The existing communication technology is incompetent to meet the explosive data rate requirements of ultra-high bandwidth communication networks. This motivated the exploration of alternative radio-frequency spectrum, including the THz-band (0.3~10 THz). Therefore, we propose a photonics-assisted Tbps fiber-THz-fiber seamless integration system, as shown in Fig. 2b. The prototype system mainly contains three key components: Tbps optical transceivers, optical-to-THz (O/T) module, and THz-to-optical (T/O) module. The baseband polarization-division-multiplexing (PDM) optical signal ($f_{Rx,signal}$) is generated from optical transmitters and transmitted over optical fiber. At the optical-to-THz (O/T) conversion front-end, optical signals are heterodyne beat with the local oscillator ($f_{Rx,LO}$) via ultra-fast uni-travelling-carrier photodiode (UTC-PD) to generated PDM THz-wave signals ($f_{THz} = f_{Rx,signal} - f_{Rx,LO}$). After $2 \times 2$ MIMO wireless transmission, the THz optical wave is converted into PDM double-sideband optical signals ($f_{Rx,LO}$) via two parallel intensity-modulators (IMs). Finally, one sideband filtering from an optical filter as baseband optical signal ($f_{Rx,LO}$). The prototype system mainly contains three key components: Tbps optical transceivers, optical-to-THz (O/T) module, and THz-to-optical (T/O) module. The baseband polarization-division-multiplexing (PDM) optical signal ($f_{Rx,signal}$) is generated from optical transmitters and transmitted over optical fiber. At the optical-to-THz (O/T) conversion front-end, optical signals are heterodyne beat with the local oscillator ($f_{Rx,LO}$) via ultra-fast uni-travelling-carrier photodiode (UTC-PD) to generated PDM THz-wave signals ($f_{THz} = f_{Rx,signal} - f_{Rx,LO}$). After $2 \times 2$ MIMO wireless transmission, the THz optical wave is converted into PDM double-sideband optical signals ($f_{Rx,LO}$) via two parallel intensity-modulators (IMs). Finally, one sideband filtering from an optical filter as baseband optical signal ($f_{Rx,LO}$).

This seamless integrated fiber-THz-fiber scheme has many potential application scenarios. For instance, THz wireless transceivers can be used to replace optical fibers or cables to achieve high-speed wireless backhaul transmission among base stations in areas where optical fibers cannot be deployed. Besides, this conceptual scheme can potentially provide emergency communication services to replace the interrupted large-capacity long-distance fiber link during natural disasters, including hurricanes, earthquakes, and floods. THz wireless communication between inter-rack and intra-rack is considered to be used in data centers due to its ultra-high communication rate to save data center space costs and cable maintenance costs. The proposed architecture can meet the demands of future THz seamless communication with low power consumption, low cost, and miniaturization.

Spatiotemporal 2-D Channel Coding in Massive MIMO for μs-Level Latency: Aside from the data rate and SE, latency is another important KPI in the 6G networks. The 6G network is envisioned to facilitate application domains with more rigorous end-to-end latency constraint, such as completely autonomous vehicles and industrial internet of things (IIOT), which cannot be supported by the present 5G networks. Traditional channel coding schemes are commonly applied in the time domain and the decoding latency is high for long packets, such as eMBB services, while the reliability is degraded for short packets in the URLLC applications. As a matter of fact, very limited room is left for channel coding design in the time domain, since 6G systems require μs-level transmission with high reliability. On the other hand, as hundreds of antennas are employed in the cell-free massive MIMO system, the extra degree of freedom in the space domain can be fully utilized, and this motivates us to propose the spatiotemporal 2-D channel coding scheme. The channel coding is based on the codeword trellis shown in Fig. 2c, which can be divided into two categories according to the encoding order: time-space mode and space-time mode. In the time-space mode, the bit-streams are encoded in parallel and the time-domain codes. The coding order of space-time mode is exactly reversed from the time-space mode. In real applications, the mode can be selected by users as per the specific requirements. At the receiver side, log-likelihood ratios (LLRs) of different space-domain decodings are performed in parallel, then the time-domain decodings are performed to achieve the outputs of decoded information bits. By carefully designing the spatiotemporal 2-D channel coding scheme, extremely low-latency but reliable transmissions at a μs-level can be achieved in the 6G networks with cell-free massive MIMO systems [13].

Implementation and Experiment Evaluations of Open Testbed

Taking the proposed 6G wireless network architecture characterized by SEN as the blueprint, we built the sub-systems of 6G CoN, SEN, and DU on the basis of an open 5G platform. As illustrated in Fig. 3, by assembling these components together, we established the world's first task-centric, integrated, intelligent, and open 6G testbed that supports Tbps full spectrum cell-free distributed massive MIMO. The implementation of the full spectrum cell-free RAN of the testbed is based on the open interface. It supports sub-6GHz, mmWave systems, THz communications, as well as ultra-low-latency and ultra-high-reliability transmission. For cell-free massive MIMO in sub-6GHz and mmWave bands, taking 100 MHz bandwidth as a baseline, a single EDU can support 16T16R and be further extended to 64T64R. In realizing the PML native AI network intelligence, the SEN is capable of performing RT complete acquisition of wireless network air-interface data based on which the knowledge graph of network data is established in the CoN in a non-RT way. To support the near-RT intelligent optimization for varying applications, the knowledge-graph-based FDS is generated on-demand in the wireless data platform in the SEN, and further used in the near-RT.
RAN intelligent server to implement AI training/reference, and the resultant dispatch in the BBU where 20 ms control granularity can be achieved.

**Experimental Configuration and Results**

a) Test of cell-free massive MIMO technologies; b) Test of photonics-assisted THz-Band wireless access (courtesy of Zhang et al. [14]); c) Implementation and performance evaluation of the intelligent ICIC case.

**Experiment of Cell-Free Massive MIMO Based on COTS-RRU**

We develop a cell-free massive MIMO prototype platform shown in Fig. 4a as a demo system of the 6G DU to verify the cell-free distributed MIMO technologies in the 6G testbed. Specifically, the 5G commercial-off-the-shelf (COTS) RRUs are used for both base-station and UEs, and the interface between RRU and baseband unit is compatible with eCPRI [15]. The hardware specifications of the UE and BS are identical. The system operates in the 4.9 GHz band, and the RRU of each BS/UE is equipped with four antennas. All the RRUs for the BS share the same reference clock from the BBU. Each RRU uses an independent local oscillator.
The prototype system can serve 12 UEs and realize parallel transmission of 48 data streams. Each UE uses 64QAM and a 0.89 code rate of LDPC, with considering the overhead of pilot and cyclic prefix, the real time average spectral efficiency of the system reaches 209 bps/Hz. We perform the offline spectral efficiency analysis on the channels collected from the prototype system. We consider three receivers: joint zero-forcing (J-ZF), joint minimum-mean-squared-error (J-MMSE), and joint MMSE with perfect successive interference cancellation (J-MMSE-SIC). J-MMSE-SIC can be considered as an optimal receiver, which can achieve the maximum sum rate. The result shows that when using J-MMSE detection and J-MMSE-SIC, theoretically the average SEs are about 323 bps/Hz and 380 bps/Hz, respectively. For the real time SE, if we neglect the overhead, the average spectral efficiency of the system is 265.7 bps/Hz, which can achieve the 82 percent of the theoretical J-MMSE detection. Compared with a 5G small cell system with the same deployment, the cell-free massive MIMO system can get 10× performance improvement.

**EXPERIMENT OF PHOTONICS-ASSISTED THz-BAND WIRELESS ACCESS**

To further confirm high data-rate transmission capability at the THz-band and the associated access technologies in the 6G testbed, we build an RT single-channel transparent fiber-THz-fiber 2 × 2 MIMO seamless transmission system with a record net rate of single-channel 103.125 Gb/s and dual-channel 206.25 Gb/s at WR2.2 band (330–500 GHz) using the commercial digital coherent optics (DCO) modules [14]. Considering low power consumption and miniaturization, O/T conversion at the transmitter is based on photomixing in a UTC-PD, and T/O conversion at the receiver is realized using hybrid opto-electronic down-conversion. As shown in Fig. 4b, the 125.516 Gb/s line data rate corresponding 31.379 Gbaud dual polarization quadrature-phase-shift-keying (DP-QPSK) modulation is successfully transmitted over a wireless distance of 3 m, two spans of 20 km fiber with 15 percent bit-error-rate-forward-error-correction (SD-FEC) of 1.56 × 10⁻³. We also develop a 100/200 GbE streaming service platform to test the stability of the transmission system by playing RT movie and live surveillance video. This is the first reported demonstration to realize > 100 Gb/s RT transparent fiber-THz-fiber link transmission at beyond 350 GHz band. This proof-of-concept study is certainly a concrete and inspiring step toward practical transparent fiber-THz-fiber link for future TKµ-standard 6G mobile communication system.

**EXPERIMENT OF INTELLIGENT NETWORK OPTIMIZATION**

Intelligent inter-cell interference coordination (ICIC) is a representative network optimization problem. As the third functional test, we validate the PML native AI in the testbed by evaluating the performance of intelligent ICIC. The proposed PML architecture allows finer-grained parameter control in terms of tunable parameter numbers and time granularity. In particular, as shown in Fig. 4c, the proposed intelligent ICIC scheme trains and maintains a reinforcement learning-based model in the non-RT basic optimization layer. By referring to the FDS distilled from the data plane, it adaptively adjusts the parameters in the resource allocation module deployed in the RT fine optimization layer, with a time granularity over hundreds of milliseconds. In the meantime, a resource allocation module based on the conflict graph model runs in the RT fine optimization layer, which operates in the order of hundreds of milliseconds or below. This module first intelligently identifies interferences among the UEs and the neighboring cells based on the interference FDS, that is, reference signal received power (RSRP). Then the physical resource block (PRB) resource sets are pre-configured and the cells schedule UEs in real-time accordingly. The non-RT basic optimization layer and RT fine optimization layer constitute a model-data dual-driven near-RT intelligent ICIC solution, which supports response in the order of hundreds of milliseconds.

In the testbed experiments, a CoN and a RAN intelligent server act as the non-RT basic optimization layer and RT fine optimization layer, respectively. Additionally, three RRU s and six UEs are deployed in the trials, as shown in Fig. 4c. In the experiments, for UEs in each cell, we place one close to the RRU and another far from the RRU. Iperf software is used to generate constant traffic for UEs, and the traffic of each UE varies from 20 Mb/s to 150 Mb/s. For comparison, the full reuse (FR) scheme, that is each cell can use the entire bandwidth, is chosen as the baseline. The results reveal that the proposed ICIC method can significantly improve the system throughput, especially in the case of heavy user traffic. Specifically, as the user traffic rises from 20 Mb/s to 150 Mb/s, the system throughput achieved by FR slowly climbs from 116 Mb/s to 164 Mb/s. By contrast, a sharp increase from 118 Mb/s to 303 Mb/s is achieved by the proposed ICIC scheme. As indicated in Fig. 4c, the system throughput is increased by 2 percent, 68 percent, and 85 percent, respectively. Note that inter-cell interference (ICI) deteriorates in the case of heavy user traffic, and, therefore, dominates the throughput. This implies that the proposed ICIC method can remarkably suppress the ICI.

**CONCLUSION**

In this article, we presented systematic architecture, technological framework, and testbed implementation toward the visions and expectations of 6G TKµ extreme connectivity. The overall architecture was totally redesigned to fully integrate the multi-dimensional resources and functions, such that a pervasive, converged, and intelligent information infrastructure can be established.

The SEN, as the core element, facilitates task-centric and decentralized operation paradigm, then, by virtue of which, high-quality service customization and high-degree network autonomy can be realized.
for TKμ and native intelligence. Some possible directions of our future work include update of the three-layer intelligent architecture, development of more emerging technologies and methodologies, accommodation of other critical KPIs, such as 90 percent coverage via territorial-satellite convergence, etc.

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Biographies
XIAOHU YOU has been with the National Mobile Communications Research Laboratory at the Southeast University, Nanjing, China, where he holds the rank of Director and Full Professor. Currently, he is also a Deputy Director of the Purple Mountain Laboratories, Nanjing, China, and a Deputy Director of Pengcheng Laboratory, Shenzhen, China. He was elected as a IEEE Fellow for leadership in the development of mobile communications in China, 2011. His current research interests include wireless networks, advanced signal processing, and its applications.

CHENG ZHANG is currently a Full Professor with the Southeast University, Nanjing, China, and an Expert of National 6G Technology R&D Overall Group. He has worked in the field of mobile communication over 30 years. Currently, he main
research area is 6G mobile communication networks and their applications.

Yang Liu is currently a Senior Researcher with the China Telecom Research Institute, Beijing, China, working on her RAN architecture design toward 6G. Her research interests include virtualization and intelligence for wireless networks.

JianJun Wu is the Chief Researcher and the Head of the Future Network Architecture Laboratory, Huawei Technologies, Shenzhen, China. He is leading the 6G network architecture design in Huawei. He is also a co-founder of the 6GANA (www.6gana.com), which aims to promote network AI as the key enabler of 6G networks to offer new services, such as AI4NET, NET4AI, AaaS, etc.

Jianmin Lu joined the Huawei Technologies, Shenzhen, China, in 1999, and he is currently the Executive Director of the Huawei Wireless Technology Lab. During the past two decades, he has conducted various researches on wireless communications, especially on physic and MAC layers, as well as 3G, 4G, and 5G products. His current research interest include signal processing, protocol, and networking for the next-generation wireless communications.

Ge Li is currently a Professor with the Peking University Shenzhen Graduate School, Shenzhen, China. His research interests include image/video processing and analysis, machine learning, digital communications, and signal processing.

Xiaowu Chen is now a Researcher with the Peng Cheng Laboratory, Shenzhen, China. His research interests include network big data, visual computing, artificial intelligence, and virtual reality.

Wenguang Chen is a Full Professor with the Tsinghua University and Peng Cheng Laboratory, Shenzhen, China. His research interest is in parallel and distributed systems and programming systems.

Wen Gao is the Director of Pengcheng Laboratory, Shenzhen, China, and a Boya Chair Professor with the Peking University, Beijing, China. He is a fellow of IEEE, a fellow of ACM, and a member of the Chinese Academy of Engineering. He works in the areas of AI methods and their applications to multimedia, wireless communications, etc.