Guest Editorial Emerging Technologies in Tactile Internet and Backhaul/Fronthaul Networks

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I. Introduction

THE Mobile Internet connects billions of smart phones and laptops. With this global connectivity, the stage is set for the emergence of: (a) *Tactile Internet* to deliver haptic experiences to remote users, and (b) flexible and integrated *Backhaul/Fronthaul* networks to support demands of such applications.

The Tactile Internet will underpin the internet of skills, a shift from content delivery to remote skill-set delivery, thereby introducing a broad range of novel applications such as tele-surgery, tele-medicine, tele-conferencing, interactive-gaming, and sending delay-sensitive control information. Due to the low-latency and high-reliability required by Tactile Internet, many parts of today's mobile networks may have to be radically redesigned, from the silicon level up with new codec design for physical remote interaction through PHY and MAC layer re-design to the overall network architecture and cloud computing solutions.

We also foresee that future networks will evolve from today's separate and incompatible fronthaul and backhaul into an integrated flexible cross-haul network. The development of smart backhaul/fronthaul solutions will enable ultra-low latency, high data-rates and high-reliability. Such integrated backhaul and fronthaul networks will meet the global information and communication requirements of future smart and resilient cities and provide ubiquitous connectivity. One of the main considerations the operators are faced with today is how to migrate existing backhaul/fronthaul networks toward an integrated and flexible smart backhauling/fronthauling infrastructure.

With the above vision, a Call for Papers for the emerging technologies issue in the IEEE Journal on Selected Areas in Communications, was published in October 2017. We want to highlight recent research results that may serve as a springboard for future work in these two emerging areas: Tactile Internet and Backhaul/Fronthaul. We selected 19 technical papers from both academia and industry. The papers are organized into two separed sections.

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II. Papers on Tactile Internet

To reduce latency and alleviate Internet congestion, the paper "Distributed optimization for energy-efficient fog computing in the Tactile Internet" advocates that fog computing is an important component of the Tactile Internet. The paper focuses on energy-efficient design of fog computing networks that support low-latency Tactile Internet applications.

Recent studies found that the packet arrival processes in Tactile Internet are very bursty. In "Burstiness aware bandwidth reservation for ultra-reliable and low-latency communications (URLLC) in Tactile Internet," a spectrally efficient resource management protocol is designed to meet the stringent delay and reliability requirements in Tactile Internet applications while minimizing the bandwidth usage.

The paper "Resource allocation and HARQ optimization for URLLC traffic in 5G wireless networks" investigates the efficient resource utilization of a 5G network for ultra-reliable and low latency communication traffic in downlink. The bandwidth utilization is evaluated for different retransmission schemes and a range of system parameters.

Mobile edge computing (MEC) is proposed to reduce the latency and improve the quality of service for cloud-based services. The paper "Adaptive replication for mobile edge computing" investigates algorithms for placing replicas of virtual machines at MEC servers depending on the number of read/write operations. The trade-off between operating costs vs. achievable QoS in terms of response latency is compared for cloud computing based on MEC and cloud data centers.

In the paper "Joint optimization of edge computing architectures and radio access networks," the authors present a modeling approach and a rigorous analytical framework, that minimizes virtualized Radio Access Network (vRAN) costs and maximizes the Multiple-Access Edge Computing (MEC) performance.

To achieve the Tactile Internet application requirements on the ultra-reliable and ultra-responsive network connection and proactive and intelligent actuation at edge devices, these devices need to share resources. The paper "Enabling edge cooperation in Tactile Internet via 3C resource sharing" discusses a general communication, computation, and caching

framework for efficient resource utilization by offering more flexibility in the device cooperation and resource scheduling.

The paper "Reliable and low-latency fronthaul for Tactile Internet applications" considers a cloud-RAN network deployment with an Ethernet fronthaul network. It investigates the reliability-latency trade-off for transmitting MAC frames from the central unit to multiple radio units. It is shown that by applying multi-path transmission with erasure coding a reduced latency and reliability can be obtained over the fronthaul for a traffic mix of ultra-reliable low latency communication and mobile broadband traffic.

The paper "Delay-constrained input-queued switch" studies the delay-constrained input queued switch where each packet has a deadline and it will expire if it is not delivered before its deadline. The authors focused on three fundamental problems centering around the timely throughput: Capacity regions, throughput-optimal scheduling policy and network-utility-maximization scheduling policy.

The paper "Energy-latency tradeoff in ultra-reliable low-latency communication with retransmissions" studies the fundamental energy-latency tradeoff in URLLC systems employing incremental redundancy (IR) hybrid automatic repeat request (HARQ).

III. Papers on Backhaul/Fronthaul Networks

The paper "Flexible and reliable UAV-assisted backhaul operation in 5G mmWave cellular networks" analyzes the use of UAVs to provide multi-hop mmWave backhaul links and quantifies both connectivity time and outage probability.

The subject of cooperative multi-hop transmission using UAVs as relays is treated in "A novel cooperative NOMA for designing UAV-assisted wireless backhaul networks." By formulating the optimization problem to maximize the sum of user throughputs over successive decoding order, beam-forming weights, power allocation, and UAV positions, the paper shows how iterative approaches can be applied to the resulting non-convex problem.

In the paper "Predictive bandwidth allocation scheme with traffic pattern and fluctuation tracking for TDM-PON based mobile fronthaul," the authors show how a dynamic approach to fronthaul bandwidth allocation based on distributed unit loading can decrease latency.

Low cost deployment of indoor CRAN is treated in "A novel distributed antenna access architecture for 5G indoor service provisioning" where the authors consider using LAN cables to connect the remote radio units to the distributed units. The problem of scheduling the real-time mapping between the antenna signals and the twisted pair/sub-carrier resources of the multi-pair cable is considered based on decoupling the power allocation and bandwidth allocation.

The important tradeoff on providing fronthaul connectivity between the CU/DU is examined in "A converged evolved Ethernet fronthaul for the 5G era," where the authors investigate and measure the implementation performance of Ethernet fronthaul for various CRAN functional splits.

In "SGCO: Stabilized green crosshaul orchestration for dense IoT offloading services," the authors investigate a unified cross-haul architecture that integrates heterogeneous fronthaul and backhaul technologies. The proposed SGCO is shown to enable offloading of computations between edge servers and the cloud while considering stability, energy efficiency, and latency.

In ultra-dense cloud radio access networks (C-RANs), it is typical for remote radio heads to coherently transmit data to the end user. In "The non-coherent ultra-dense C-RAN is capable of outperforming its coherent counterpart at a limited fronthaul capacity," the authors construct a weighted sum-rate maximization problem, ultimately solve with a sequential convex approximation (SCA) algorithm, and conclude that non-coherent transmission can achieve significant performance gains if the fronthaul has low capacity.

Coordinated Multi-Point (CoMP) techniques are well known for their potential to achieve significant throughput gains, but these improvements depend on cluster size and the latency in the network, among other factors. "Enhancing RAN throughput by optimized CoMP controller placement in optical metro networks" investigates the clustering of cells, the placement of the Radio Controller Coordinator (RCC), the entity that coordinates clusters, and the routing of traffic over the hierarchical metro optical network.

With hundreds of megahertz of bandwidth, mmWave technology has enormous potential for capacity improvement, but there are many challenges to fully realizing its potential. In "Design and experimental evaluation of equalization algorithms for line-of-sight spatial multiplexing at 60 GHz," the authors overcome the imperfections of mmWave transceivers with equalization methods that reduce inter-antenna and inter-symbol interference. Ultimately, the proposed techniques are evaluated with a hardware-in-the-loop demonstrator and shown to achieve nearly the same performance as the high complexity baseline.

The paper "Cost-aware resource allocation for optimizing energy efficiency in fog radio access networks" proposes the economical energy efficiency metric to comprehensively analyze the impacts on different aspects. By formulating an optimization problem and using the fractional programming solutions for both beamformer and transmitting method selection are achieved. The authors argue why the economical energy efficiency metric is a suitable system performance metric when different key impacts need to be comprehensively considered.

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We would like to thank all the authors who submitted their valuable contributions to this special issue. They provided both the reviewers and the editors with a full picture of the most recent research results on Tactile Internet and Backhaul/Fronthaul networks. We would also like to thank the reviewers who provided thorough and timely reviews that contributed to the success of this special issue.

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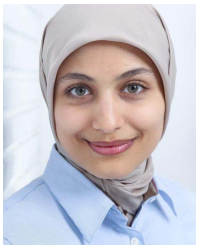

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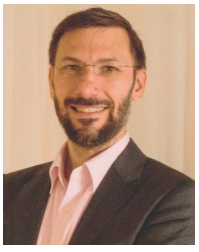

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