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Wireless technologies towards 6G

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Abstract

This Special Issue originates from the international conference 2021 Joint EuCNC & 6G Summit (Joint European Conference on Networks and Communications and 6G Summit), which was held in June 2021 in virtual format. The Technical Programme Chairs of the conference selected the best papers and invited authors to submit an extended version of their paper by at least one-third of their length. Only the top ranked papers were invited to this Special Issue, in order to fulfil its purpose. The main target was to collect and present quality research contributions in the most recent activities related to technologies, systems and networks beyond 5G. Through this Special Issue, the state-of-the-art is presented and the new challenges highlighted, regarding the latest advances on systems and network perspectives that are already being positioned beyond 5G, bridging as well with the evolution of 5G, including applications and trials. Therefore, the motivation for this Special Issue is to present the latest and finest results on the evolution of research of mobile and wireless communications, coming, but not exclusively (since Joint EuCNC & 6G Summit is a conference open to the whole research community), from projects co-financed by the European Commission within its R&D programmes.

5G has already entered the commercial phase, with networks evolving towards standalone approaches and other cutting-edge developments. From a research perspective, attention is shifting to address the aspects not yet implemented in 5G, extending existing concepts for advanced phases of 5G and, importantly, initiating the vision for 6G and its components. Backward compatibility remains crucial, as it is essential for 6G technologies to seamlessly integrate with 5G while introducing groundbreaking ideas.

Indeed, numerous coordinated activities and projects are already running worldwide to tackle 6G, emphasizing the importance of the subject. Although current topics such as new frequency bands (going beyond mmWaves), mobile IoT, network softwarisation, network architectures, wearables, security and privacy, and artificial intelligence in communications continue to be relevant, researchers anticipate the proposal of novel concepts.

The scope of this Special Issue aims to concentrate on innovative approaches beyond 5G, with a particular focus on the emerging landscape of 6G, while maintaining a strong connection to the implementation of 5G networks.

In what follows, we present a brief overview of the papers composing this Special Issue.

Joint scatterer localization and material identification using radio access technology, authored by Yi Geng, Deep Shrestha, Vijaya Yajnanarayana, Erik Dahlman and Ali Behravan, delves into the potential of 6G cellular networks to integrate both communication and radar functionalities through radio access technology (RAT)-based scatterer localization systems. These systems capitalize on communication signals exchanged between transceivers to pinpoint the location of scatterers present within and around propagation paths. The authors first identify the challenges associated with RAT-based scatterer localization systems and then, present single- and multiple-bounce reflection loss simulation results for three common indoor building materials. Then, they introduce two innovative methods for concurrently localizing and identifying the type of scatterers in rich scattering environments. The proposed techniques have far-reaching implications for a range of 6G applications, such as robotic perception, virtual reality, digital twins, and 3D digital mapping, by offering an added layer of material information in 3D digital maps. This innovative approach holds the potential to elevate user experiences in virtual environments and enhance the performance of autonomous driving systems.

ELIoT: enhancing LiFi for next-generation Internet of things, authored by J. P. M. G. Linnartz, C. R. B. Corrêa, T. E. B. Cunha, E. Tangdiongga, T. Koonen, X. Deng, M. Wendt, A. A. Abbo, P. J. Stobbelaar, P. Polak, M. Müller, D. Behnke, M. Martínez, S. Vicent, T. Metin, M. Emmelmann, S. M. Kouhini, K. L. Bober, C. Kottke & V. Jungnickel, explores the potential of LiFi (light communication) as a solution for the growing demands of future IoT applications, such as flexible manufacturing, augmented reality, and self-driving vehicles, which require high-capacity links that cannot be easily provided by the existing radio-based communication infrastructure. LiFi offers vast amounts of spectrum, increased security, and low-latency transmission without interference, even in densely packed settings. The authors present the current state-of-the-art in LiFi systems and introduce new features necessary for future IoT applications. They discuss results from a distributed multiple-input multiple-output (MIMO) topology with a fronthaul using plastic optical fibre, evaluate seamless mobility between light access points and handovers to 5G, as well as low-power transmission and integrated positioning. The paper also presents the EU ELIoT project, which focuses on the development, implementation, and standardization efforts towards future LiFi technology.

Beyond 100 Gbit/s Pipeline Decoders for Spatially Coupled LDPC Codes, authored by Matthias Herrmann and Norbert Wehn, investigates the implementation of spatially coupled low-density parity-check (SC-LDPC) decoders for throughputs beyond 100 Gbit/s, addressing the challenges posed by beyond 5G systems targeting data rates up to 1 Tbit/s. Conventional LDPC decoders are limited in their code block sizes due to routing congestion challenges, which results in suboptimal overall communication performance. SC-LDPC codes, however, have the potential to overcome these limitations. The authors conduct the first in-depth analysis of various high-throughput SC-LDPC decoding architectures, exploring design trade-offs such as row- and column-wise decoding, non-overlapping and overlapping window scheduling, and processor pipelining. They present a column-wise SC-LDPC decoding architecture for the first time in the literature and provide a comprehensive examination of the efficiency of the proposed decoding architectures down to the silicon level in a 22 nm FD-SOI technology.

A dark and stormy night: Reallocation storms in edge computing, authored by Lauri Lovén, Ella Peltonen, Leena Ruha, Erkki Harjula and Susanna Pirttikangas, addresses the phenomenon of reallocation storms in edge computing, which occurs when the number of superfluous workload reallocations grows significantly due to high edge server workload. The authors use a real-world data set of city-wide Wi-Fi network connections with over 47 million connections across 550 access points and simulate scenarios involving different edge server capacities and reallocation strategies. The study reveals that reallocation storms are linked to edge server capacity and vanish when it increases above a certain threshold. The few edge servers with the highest workloads are most associated with reallocation storms. The authors also identify conditions that elevate the risk of reallocation storms, such as summertime, weekends, and mass events like popular sports games. The authors recommend using a random reallocation strategy in dense edge server deployments, as it requires less coordination and performs similarly to the bottom-up strategy in terms of latency and reallocation storms. This paper aims to help understand the spatio-temporal dependencies behind reallocation storms and provides insights on how to avoid them in edge computing environments.

Integrated sensing and communication in 6G: a prototype of high resolution multi-channel THz sensing on portable device, authored by Oupeng Li, Jia He, Kun Zeng, Ziming Yu, Xianfeng Du, Zhi Zhou, Yuan Liang, Guangjian Wang, Yan Chen, Peiying Zhu, Wen Tong, David Lister and Luke Ibbetson, addresses the integration of sensing and communication capabilities in 6G technology, particularly focusing on the use of terahertz (THz) frequency bands for high-resolution sensing and imaging. The authors believe that 6G will usher in an era of Connected Intelligence, fusing the physical, cyber, and biological worlds by serving as a distributed neural network that provides sensing, communication, and computing capabilities. They discuss how integrated sensing and communication (ISAC) can enable a wide range of applications, including assistive technologies, gaming, health support, vehicle-to-vehicle sensing, and gesture recognition. The study specifically investigates the feasibility of providing millimeter-level THz sensing capability on portable communication devices, given the physical aperture constraints of such devices. A portable compact THz prototype with multi-channel integrated transceiver chips is developed, and the performance of two typical waveforms, FMCW and OFDM, is evaluated. Additionally, the paper presents a novel optimization method based on geometric interpretation for SIMO sparse imaging to achieve near-real-time centimeter-level imaging. This research contributes to the ongoing development of 6G technology and highlights the potential benefits of integrating sensing and communication capabilities in future mobile devices.

A beam broadening method for phased arrays in wireless communications, authored by Corentin Fonteneau, Matthieu Crussière and Bruno Jahan, investigates the adaptation of beam widths for large antenna arrays operating in the millimeter band, which is utilized in 5G and IEEE 802.11ay standards to provide multi-Gb/s user data rates. Due to the significant path-loss at such high frequencies, narrow beams are typically generated using large antenna arrays. However, broader and less directional beams are desirable for certain communication link management applications, such as reducing beam scanning latency time and improving link resilience. The authors propose a systematic phase-only beam broadening technique that relies on determining

a quadratic phase excitation law based on the desired beam width and steering angle. The method avoids exhaustive or iterative searches to find the appropriate control parameters and establishes a bijective function linking the parameters with the beam width and steering angle. The technique is applicable to various antenna array sizes and both boresight and non-boresight directions. The paper provides a thorough analysis of the radiation behaviour with respect to the coefficients of the quadratic excitation and demonstrates a near-linear relationship between the new variable and the beam width. By employing this beam broadening control method, the authors offer a flexible and efficient approach for adjusting the beam width in millimeter-wave communications, thus improving the performance of 5G and beyond 5G networks.

Positioning and power optimisation for UAV-assisted networks in the presence of eavesdroppers: a multi-armed bandit approach, authored by Xavier Alejandro Flores Cabezas, Diana Pamela Moya Osorio and Matti Latva-aho, addresses the physical layer security (PLS) opportunities provided by unmanned aerial vehicles (UAVs) in the context of 5G and beyond 5G networks. The authors focus on the secrecy performance of ground wireless communication networks assisted by N friendly UAV jammers in the presence of an eavesdropper. They introduce a new area-based metric, the weighted secrecy coverage (WSC), which measures the secrecy performance improvement due to friendly jamming over a specific physical area. The work aims to optimize the 3D positioning of UAVs and power allocation to maximize WSC. The authors propose a reinforcement learning-based solution that models the positioning problem as a multi-armed bandit problem with three variables: angle, height, and orbit radius. The results show that the proposed algorithm improves the system's secrecy over time in terms of WSC and converges to a stable state close to the exhaustive search solution for discretized actions. This creates a trade-off between expediency of positioning UAVs for better secrecy outcomes and energy consumption.

Reducing interference via *link adaptation in delay-critical wireless networks*, authored by Silvio Mandelli, Alessandro Lieto, Mark Razenberg, Andreas Weber and Thorsten Wild, presents Power Optimization for Low Interference and Throughput Enhancement (POLITE), a paradigm for link adaptation and power allocation targeting high-density scenarios in 6G wireless networks. These networks are essential for supporting applications like Industry 4.0 and ultra-reliable low-latency communication (URLLC) traffic. The POLITE approach aims to stabilize and reduce interference by leveraging available radio resources, resulting in increased throughput and reduced transmit power compared to existing baseline link adaptation schemes. The authors enhance the most recent POLITE schemes to minimize latency for critical traffic users and propose novel user selection and resource allocation mechanisms. Extensive system-level simulations of indoor factory floors demonstrate significant improvements in latency-critical traffic's reliability compared to baseline schemes. The results show POLITE's benefits for short inter-site distances and severe interference conditions in industrial scenarios, making it suitable for future sub-networks in Beyond 5G and 6G wireless systems.

Author contributions
All authors read and approved the final manuscript.

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