Guest Editorial Special Issue on Inter-Tower Communications and Networks

THE EVER increasing demand for new applications, and the augmented consumption of high-data-rate multimedia services are the driving forces for wireless communication systems' evolution. In particular, the latest use cases, such as augmented/virtual reality and unmanned mobility, request a considerable enhancement in performance since system capacity above 1 Tb/s, 99.99999 percent reliability, and latency below 1 ms are required [1], [2], [3]. Undoubtedly, the research community has achieved many remarkable advances in different areas to approach the requirements, such as coding schemes [4], [5], [6], multiplexing schemes [7], [8], Multiple-Input Multiple-Output (MIMO) schemes [9], [10], or modulation schemes [11], [12]. Nevertheless, the performance of traditional signal processing techniques is already very close to the Shannon limit, so the margin for further improvement at the Physical Layer (PHY) is minimal.

This idea has already reached the majority of wireless communication standardization entities. A good example is the roadmap that the 3rd Generation Partnership Project (3GPP) envisions for the discussion and future development of 6G. In general, the technical development of 5G has followed the technological path of previous mobile communication systems and can be considered an extension of 4G [13]. Consequently, the enhancements proposed within 5G needed to be more disruptive, and the performance goals could not be achieved. Therefore, a paradigm shift and the support of other technologies will be necessary for the complete success of 6G. Hence, several experts have identified native Artificial Intelligence (AI), multipurpose converged radio access networks (RANs), three-dimensional (3D) networks, and photonics-based communications as the key enablers of future 6G deployments [14].

One of the standard families that have evolved significantly over the last decade is terrestrial broadcasting and, especially, digital terrestrial television (DTT) standards. Traditional DTT standards are one-way (i.e., downlink-only mode), limiting the number of possible services. This limitation has been addressed by pushing for incorporating an Internet Protocol (IP) architecture in the standardization proposals [15]. Indeed, this evolution is ongoing worldwide in all the DTT standards but following different processes.

First, in Europe, Digital Video Broadcasting (DVB) is developing a set of complementary standards and amendments to its existing portfolio to facilitate a full IP environment (i.e., DVB-NIP or Native IP DVB) that addresses consumer and professional applications for DVB broadcast bearers [16]. Then, the Japanese Advanced Integrated Services Digital Broadcasting - Terrestrial (ISDB-T) proposes MPEG Media Transport (MMT) and Type-Length-Value (TLV) for content transport. MMT has IP at the center of its structural design, enabling this standard to provide services that combine broadcasting and other communication systems using IP packets [17]. More recently, the Call for Proposals for the "TV 3.0 Project" run by the Brazilian Digital Terrestrial Television System (SBTVD-T) described the prerequisite of an IP-based transport Layer [18]. In China, although the proposed Digital Terrestrial Multimedia Broadcast (DTMB-A) has put its primary efforts into improving the PHY, one of the largest cellular operators (i.e., China Broadcasting Network) has proposed a core network applicable to China radio and television for the rapid deployment of 5G broadcasting services [19].

Nevertheless, the first non-3GPP DTT standard to build on an IP-centric protocol stack to facilitate the delivery of IP media and other multimedia Internet content was the Advanced Television Systems Committee (ATSC) NextGen TV standards in 2013 (i.e., ATSC 3.0) [20]. Among the different Technical Groups (TGs) working concurrently in ATSC, Tower Network Implementation Team-5 (IT-5) should be remarked. IT-5 is working on designing, implementing, and testing an Inter-Tower Communications Network (ITCN) and In-band Distribution Link (IDL) cases within an ATSC ecosystem [21], [22]. IDL is a one-way wireless distribution system of the content to be transported to the broadcast tower that replaces the Studio to Transmitter Link (STL) using microwave or fiber links [21]. IDL is particularly designed for content distribution to SFN towers that re-uses the broadcast spectrum and reduces the broadcaster SFN implementation and operating costs. ITCN aims to interconnect all broadcast towers to create a communication network for control, monitoring, data communication, localized datacast and broadcast services [22]. These technologies are built on the in-band full-duplex (IBFD) concept, where transmission and reception coincide within the same Radio Frequency (RF) channel.

IBFD communication systems for ITCN can bring several advantages to broadcasting systems. On the one hand, theoretically, IBFD could double the spectral efficiency if compared with half-duplex systems [23]. In addition, radio spectrum limitations could be overcome with IBFD due to

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the significant improvement in efficiency [24]. Doubtlessly, this new paradigm in wireless communications opens the door to novel applications that could be satisfied with traditional DTT infrastructures, such as continuous system monitoring, connected cars, IoT, or cloud production systems [22].

However, although IBFD communications have already been studied for other technologies (e.g., Wi-Fi, cellular networks), the implementation of ITCN presents some specific research challenges that must be previously solved:

C1) *Interference management:* Due to the IBFD nature of ITCN, part of the transmitted signal power is coupled to the receiving antenna, generating a self-interfering signal (i.e., loopback signal). Moreover, due to the lower frequency UHF broadcast band, the low attenuation propagation path and the high transmission power give the loopback signal much greater power, up to 30 dB higher than the desired signal. Therefore, the system needs high-accurate loopback signal cancelation alternatives to decode the desired signal. During the last few years, several works have been published addressing the cancelation of the loopback signal in IBFD environments using digital and/or analog solutions [25], [26], [27]. Nevertheless, there is yet to be an optimum solution for ITCN since the performance of analog techniques is still quite limited, and the dynamic range constraint of the digital cancelation modules restricts the cancelation performance.

C2) *Transceiver characterization*: The transceiver infrastructure (i.e., broadcast transmission centers) is critical in the self-interference signal generation. In fact, the power level of the loopback signal depends strongly on the center architecture since the distance between transmission and reception antennas, the antenna radiation pattern, or the center frequency, among others, determines the power of the coupled loopback signal [28]. Consequently, an in-depth characterization of the parameters that affect the self-interference and quantification of the achievable signal isolation between transmission and reception antennas is necessary for the success of ITCN implementation.

C3) *Signal structure*: When several information signals are transmitted through a common RF channel, the resource organization is critical for the correct reception of each signal. Traditional alternatives apply time division multiplexing (TDM) or frequency division multiplexing (FDM). However, generally, the performance of those orthogonal multiplexing schemes is far away from non-orthogonal multiplexing (NOM) techniques, which is also called Layered Division Multiplexing (LDM), i.e., a Power Based-NOM (P-NOM) [29], [30], [31], [32]. In fact, several P-NOM alternatives have been proposed in broadcasting environments and have shown optimistic results. Nevertheless, combining traditional (i.e., TDM/FDM) and novel (i.e., NOMA) techniques may lead to optimal solutions. Although some authors have proposed different signal structure approaches for ITCN [21], [22], they are still preliminary, and there is an essential gap in this research area.

C4) *Synchronization & detection*: When ITCN is used to deliver the DTT distribution signal (i.e., wireless IDL), the time synchronization among the transmission towers involved poses a critical challenge. This issue requires that the STL data embedded in the transmission signal has a time advance concerning the service data [21]. This time advance is needed for the receiver to receive and decode the STL signal and to generate the service signal for re-emission. Therefore, a timing control mechanism must be designed to configure the relative timing between the STL data and the service data to align the operations of the different transmitters. In addition to time synchronization, ITCN signal detection must be studied [33]. Using ITCN, various signals and information are conveyed within a unique waveform, so the detection algorithms become critical.

C5) *Compatibility with other techniques*: ITCN communications could be combined with additional techniques to improve overall performance. For instance, MIMO techniques can be included to increase the achievable data rate [34]. This way, the bandwidth percentage dedicated to introducing the ITCN service inside the broadcast content waveform could be reduced. Another alternative is implementing Single Frequency Networks (SFN) in combination with ITCN to have better coverage and less co-channel interference. Then, advanced cancelation modules could be considered concerning the required interference cancelation, such as blind estimations [35] or AI-based solutions [36], [37].

C6) *Connectivity with other networks*: Although creating a broadcast tower mesh network would considerably increase the number of potential applications, a broadcast RAN controller is needed, as described in [20]. The broadcast core network (BCN) concept would provide higher scalability and more straightforward orchestration of the network nodes (i.e., broadcast centers). Nevertheless, it is necessary to guarantee interaction with other networks, such as 5G/6G, Wi-Fi, or satellite communications, to target a broader spectrum of potential applications for program feed and distribution [38]. Thus, research should be dedicated to designing and implementing protocols and algorithms that facilitate inter-network connectivity.

C7) *New use case implementation*: Applying ITCN to satisfy users' demands for new applications implies specific designs and requirements. Although applications like distribution signal delivery or backhauling are almost straightforward due to the current system architecture [21], [22], opening the door to other non-broadcasting applications requires further research and innovation. For example, some authors have suggested using ITCN to provide Internet-of-Things (IoT)-related applications and datacasting [39]. These use cases imply using gateways on the transmission tower and other evaluation metrics not typical in broadcasting communications, such as latency, jitter, or connectivity.

This year's 2023 Special Issue presents eight papers encompassing the progress of tower connectivity for future

DTT standards and related communication systems. Each paper introduces proposals, implementations, evaluations, and breakthroughs on inter-tower communication networks or potential ITCN use cases and pretends to provide solutions to the above-mentioned ITCN research challenges.

The editors of this Special Issue would like to thank all the authors and reviewers for their contributions, which helped make this Special Issue happen, and wish you a pleasant reading.

The first paper by Hong et al. [A1] studies the ITCN/IDL signal interferences in the SFN environment. The authors design and propose a novel frequency-domain iterative successive signal cancelation scheme to effectively mitigate the interferences in the ITCN/IDL signal detection process under ATSC 3.0 SFN environments where very long multipath delay spread is experienced.

The second paper by Iradier et al. [A2] focuses on characterizing real broadcasting centers. In particular, the article covers the signal isolation between transmission and receiver antennas. The authors present a measurement system to quantify the signal isolation in an ongoing broadcast transmitter. The signal isolation characterization is carried out regarding antenna distance and carrier frequency.

The third paper by Hong et al. [A3] targets proposing new MIMO schemes to be implemented in IDL and ITCN that maintain backward compatibility. The authors also studied the performance of multiplexing the MIMO signal with the broadcast service using TDM and LDM and the different MIMO self-interference cancelation alternatives.

The fourth paper by Kang et al. [A4] concentrates on the compatibility of MIMO solutions for simultaneous ITCN and legacy digital television transmissions. In particular, the paper presents a set of backward compatible (B-Comp) MIMO configurations regarding physical layer multiplexing and antenna assignment. The authors focus on practical issues in colocating spatially multiplexed (SM) MIMO and non-SM signals in the same frequency band, revealing tradeoffs among the classified B-Comp MIMO configurations. The research goes from a logical protocol analysis to the performance evaluation based on information-theoretic derivations.

The fifth paper by Wu et al. [A5] covers the existing signal structure gap in ITCN, combining TDM, FDM, and LDM. Data capacity is analyzed for mobile and fixed broadcasting services. Guaranteeing backward compatibility is one of the authors' most significant concerns, so they propose a standard agnostic solution that could be implemented on all existing DTT standards, while maintaining backward compatibility will all legacy TV receivers and services.

The sixth paper by Liu et al. [A6] focuses on different multiplexing and resource allocation alternatives to improve the spectrum efficiency and reduce demultiplexing complexity and latency in the wireless IDL and inter-tower networks and datacasting (ITND) of future terrestrial broadcasting systems. The authors propose signal structures with 2-layer and 3-layer power-based non-orthogonal multiplexing schemes. Several MIMO schemes are also suggested to enhance the efficiency of current IDL and ITND performance.

The seventh paper by Livanos and Anishchenko [A7] proposes an ultra-long-range wireless backhaul (ULRWB) system in the sub-1GHz frequency range to offer a novel use of ITCN for delivery of Internet service to rural and remote communities. The authors present and describe in detail the ULRWB solution architecture, which uses the IP-based backbone of ATSC 3.0.

The eighth paper by Wang et al. [A8] deals with the synchronization issue investigating the LDM-based unicast and broadcast transmission performance in IDL. The authors propose different N-layer LDM and 3-Layer LDM multiplexing schemes to combine the unicast and broadcast signals transmitted from the transmission centers. In addition, the article shows a novel design of a transmission signal waveform and the required detection algorithm at the receiver to solve the synchronization and detection problems.

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APPENDIX: RELATED ARTICLES

[A1] Z. H. Hong et al., "In-band full-duplex communications in ATSC 3.0 single frequency network," *IEEE Trans. Broadcast.*, vol. 69, no. 2, pp. 560–568, Jun. 2023.

[A2] E. Iradier et al., "Signal isolation characterization of ITCN in-band full-duplex communications," *IEEE Trans. Broadcast.*, vol. 69, no. 2, pp. 569–578, Jun. 2023.

[A3] Z. Hong et al., "Implementation of wireless backhaul and inter-tower communications with MIMO in ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 69, no. 2, pp. 579–588, Jun. 2023.

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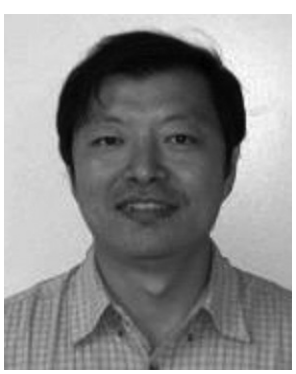

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