IEEE TRANSACTIONS ON BROADCASTING Special Issue on: Convergence of Broadcast and Broadband in the 5G Era

THE FIFTH generation of mobile broadband (BB) networks, popularly known as 5G, aims to revolutionize different vertical industries, including media broadcasting. Although it remains to be seen the real impact and timescale of the 5G revolution, 5G may represent an opportunity rather than a threat for broadcast (BC), especially when considering new approaches for BC and BB evolving into new converged platforms inter-connecting terrestrial BC and cellular/wired BB systems together [item 1) in the Appendix]. Hybrid BC-BB platforms are already a success in several countries, based, e.g., on HbbTV in EU, hybridcast in Japan and Ginga in Brazil. But the increasing importance of fixed and mobile BB IP delivery for television services, well-illustrated by the new IP-based ATSC 3.0 standard [item 2) in the Appendix] and the on-going DVB-I (Internet) specification, and the fact that the 5G system will support and be interoperable with non-3GPP access technologies, potentially allowing multiple access technologies to be used simultaneously for one or more services, opens the door to new convergence scenarios.

The first version of 5G (3GPP Release 15) only supports point-to-point (unicast) delivery. Without point-to-multipoint (multicast/broadcast) delivery capabilities, 5G will lack an efficient mechanism to deliver the most popular content simultaneously to a large number of users and/or devices [item 3) in the Appendix]. Work is on-going in 3GPP Rel-16 to support non-3GPP access networks with dual connectivity and also to define an LTE-based solution, known as Further evolved Multimedia Broadcast Multicast Service (FeMBMS) suitable for terrestrial BC [item 4) in the Appendix]. It should be pointed out that although FeMBMS is known as 5G Broadcast, it is based on 4G LTE. The introduction of multicast/broadcast in 5G New Radio (NR) [item 5) in the Appendix] and the service-enabled 5G Core (5GC) [item 6) in the Appendix] is expected to start in Rel-17.

Even being promising from the technical side, the successful deployment of new 5G BB-BC systems is also conditioned by business and regulatory related aspects. Meanwhile, there have been recent milestones that not so long ago were not considered feasible.

Thanks to the fully-Internet Protocol (IP)-compliant design of the latest Digital Terrestrial Television (DTT) standard - ATSC 3.0, a convergence service of BC and BB becomes possible in various system layers, more than a simple data bonding in the application/presentation layer. This means that convergence will not be limited to IP-layer. Even coordination in the physical layer becomes possible from the compatible numerologies of ATSC 3.0 and 5G enhanced mobile broadband (eMBB), up on the future extensable frame design over bootstrap versioning of ATSC 3.0. To itemize, object-based services such as multi-view and personalized captioning are capable at the presentation layer convergence, where traffic offloading and tower sharing are possible at the transportation/MAC layer and the physical layer convergences, respectively. In addition, the centralized architecture of 5G radio access networks (RANs), although the specific functional split can vary, is expected to ease the coordination with inherently centralized BCs. When the convergence is accomplished across all layers including the physical layer, the network will evolve into a completely integrated eco-system form facilitating High Power High Tower (HPHT) and Low Power Low Tower (LPLT) operations, organically.

One of the key features for the BC revolution in the BC-BB convergence is *interactivity*. As shown by the success of BB streaming, user-interactivity is an essential value for modern media and entertainment (M&E) industries, because the consumers these days prefer to be an active participant rather than remaining as a passive recipient. The most impressive realization of interactivity in BB media services is a customized content distribution model, so-called *narrowcasting*. On the other hand, unlike the streaming-over-BB case, media broadcasting in the new convergence era will find its momentum from interactivities among various platforms and systems, more than user-interactivity. Based on those interactions, the BC DTT will be able to identify itself through real-time programs enriched in broad dimensions, enhanced qualities of experience and service (QoE/QoS), etc. Further advantages of the BC-BB convergence for new media services can be addressed as follows:

1) Enhanced Quality: Multi-connectivity allows the BC DTT to provide high QoE services that are not achievable within a single Radio Frequency (RF) channel. The enhanced services include 4K/8K ultra-high definition (UHD) video, high-dynamic range (HDR) presentation, wide color gamut (WCG), ultra-wide vision (UWV), 360° visual media, etc., which are accounted as key innovations for future contents. On the top of BC connection as a primary link, the data shortfalls can be supplied via BB channels. Such use case will draw a significant synergy from BC and BB, enabling even virtual/augmented/mixed realities (VR/AR/MR)

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that require tremendous bitrate for pleasant visual experiences.

2) Traffic Stability: One convincing use case of the BC-BB convergence system is traffic offloading. In fact, the drastically increasing demands on massive video data are still notable burdens in 5G eMBB. In the context of sustainability against traffic congestions, DTT networks have been spotlighted due to its ultra-efficient point-to-multiple point (PTM) feature and powerful HPHT infrastructure. Through collaborations with BC and BB carriers, several manufacturer groups are on progress for BC-offloading solutions. Mainly associated with 5G, ATSC 3.0, or multimedia broadcast multicast service (MBMS), the current developments focus on scheduling and traffic monitoring middleware.

3) Mobile Continuity and Future Automotive: As the media lifestyle has been changed to incorporate on-vehicle services, seamless mobile has become a relevant QoE element. The role of BC-BB convergence is therefore foreseen better promising in future automotive. Due to the advance of autonomous vehicles, the passengers who became released from driving are expected to be eager for media, probably highly enhanced, services such as UHD video, immersive audio, or even VR during their ride. As been widely promoted, robust waveforms of ATSC 3.0 already support fine mobile high definition (HD) by itself. If the BB link is added up as a backup or a side channel, the high data rate services will also be available seamlessly at hand.

Moreover, BC-BB fusion is noted to fill the gap in future autonomous planning. Coupled with massive machine-type communications (mMTC) and ultra-reliable low-latency communication (URLLC)-based infra-to-vehicle (X2V) within 5G, combined datacasting over BC and BB will ensure a safe and intelligent self-driving ability of the connected cars. Even more, the datacast-embedded services will be capable of location- or trajectory-based media for connected car solutions.

4) Personalized Service and User-Interaction: Using BB reverse link feedbacks, broadcasters can provide user-dedicated deliveries over the traditional linear service. The use cases emerged from IP-based development of the 2nd generation DTTs: on-demand content launcher, T-commerce, voting/polling, targeted advertisement, etc., will be provided with further improved and enriched form in the 5G era. Since BC appears as a part of the Internet in this new paradigm, notably many business models are encouraged by flexible data fusion capability and the *affordance* feature of narrowcasting.

In fact, those use cases will not be the uttermost of the BC-BB convergence system. As 5G aims at 100 folds increase of simultaneous connections, the user-participating type content, which runs above real-time background rendering provided by BC transmissions, is expected to come with a massive user capacity. At the same time, localization over existing BC programs may also bring the user experience to be far diverse. Also, the new services will be provided in a device-compatible fashion so that highly diverged media terminals are commonly accessible to intended services, and interplays among the companion devices would be supported on the top of the service platform.

5) CAPEX/OPEX-Efficiency and Better Coverage via Tower Overlay: The waveform compatibility between BC and BB furthermore can create new market opportunities. For BB carriers, dual connectivity with a BC network is an attractive solution to reduce operating expenditure (OPEX) and capital expenditure (CAPEX), while expanding the service area. Routing the existing DTT network, which has already been optimized at the deployment stage, is way more efficient than establishing new national-wide HPHT infrastructure. At this point, broadcasters are considering a tower overlay business in the new BC-BB convergence ecosystem. On the top of physical layer convergence, the use of unified modulators allows the co-existence of BC and BB frames within the same RF stream, so that yields dynamic resource leasing become possible. At the same time, via the advance of cloud technologies and network function virtualization (NFV) in 5G, the complete convergence down to the physical layer level would intensify the network neutrality trend in content provider-subscriber markets by bringing the BC network as one of the neutral candidates.

In 2019, the IEEE Transactions on Broadcasting published a special issue on 5G for Broadband Multimedia Systems and Broadcasting [item 7) in the Appendix]. In this special issue, some papers dealt with the use and optimization of 5G for emerging multimedia applications and services [item 8) in the Appendix], [item 9) in the Appendix], [item 10) in the Appendix], and [item 11) in the Appendix]. Some other papers focused on the use of 5G for multicast/broadcast services, such as [item 12) in the Appendix], [item 13) in the Appendix], and [item 14) in the Appendix]. Other papers focused multicast/broadcast enablers on specific use cases such as [item 15) in the Appendix] (cellular vehicular systems), [item 16) in the Appendix], and [item 17) in the Appendix] (satellite systems).

This year's 2020 Special Issue presents 20 papers encompassing the progresses on the *convergence of broadcast and broadband in the 5G era and beyond*. Each paper introduces proposals, implementations, evaluations, and breakthroughs on BC-BB convergence systems or the benefits of BB connectivity on media services.

The editors of this Special Issue would like to appreciate all the authors and reviewers for their contribution making this special issue happen.

The first paper, "*5G Mixed Mode: NR Multicast-Broadcast Services*," by Garro *et al.* [item 18) in the Appendix], presents a potential solution for enabling the use of multicast/broadcast in the 5G New Radio Rel-17, called 5G NR Mixed Mode. The paper extends the air interface of 3GPP 5G New Radio Rel-15 to point-to-multipoint communications. The proposed solution, called 5G NR Mixed Mode, enables a flexible, dynamic and seamless switching between unicast and multicast or broadcast transmissions and the multiplexing of traffic under the same radio structures.

The second paper, "*5G Radio Access Network Architecture for Terrestrial Broadcast Services*," by Säily *et al.* [item 19) in the Appendix] proposes an enhanced Next Generation RAN architecture based on 3GPP Rel-15 with a series of architectural and functional enhancements to support an efficient, flexible and dynamic selection between unicast and multicast/broadcast transmission modes and also the delivery of Terrestrial Broadcast services. The paper elaborates on the Cloud-RAN based architecture design and proposes new concepts such as RAN Broadcast/Multicast Areas mechanism that allows a more flexible deployment in comparison to eMBMS.

The third paper, "*Towards NR MBMS: A Flexible Partitioning Method for SFN Areas*," by Liu and Wei [item 20) in the Appendix], studies the concept of dynamic MBSFN partitioning, including the consideration of the inter-bearer interference, for the enhancement of the system performance. The authors solve the partitioning problem introducing a graph-based greedy algorithm and the results show that the proposed solution provides near-optimal performance even for bigger networks sizes.

The fourth paper "*Enabling Multicast and Broadcast in the 5G Core for Converged Fixed and Mobile Networks*," by Tran *et al.* [item 21) in the Appendix], proposes an extension of the 5G Core to support broadcast and multicast capabilities. Two different approaches have been taken, one based as an evolution of LTE Broadcast and the second one featuring low imprint over the reference 5G architecture.

The fifth paper, "*IP-Based Cooperative Services Using ATSC 3.0 Broadcast and Broadband*," by Lee *et al.*, [item 22) in the Appendix], is focused on an IP-layer convergence of broadcast and broadband based on the ATSC 3.0 standard. As the all-IP based ATSC 3.0 enables feasibility of cooperative services with mobile networks, this paper presents a service scenario that takes advantages of both broadcast and broadband networks, implementation details enabling seamless switching between the broadcast and broadband, and real field testing.

The sixth paper, "*ATSC 3.0 Broadcast 5G Unicast Heterogeneous Network Converged Services Starting Release 16*," by Simon *et al.*, [item 23) in the Appendix], is focused on a broadcast core network architecture that can co-exist with the 5G core network. A possible use case is presented by allowing ATSC 3.0 as a non-3GPP radio acess aligned with 5G NR. This paper also prerersents possible new physical layer waveform options that can provide more flexibility when a convergence service with a mobile network is intended.

The seventh paper, "*Cellular Terrestrial Broadcast—Physical Layer Evolution From 3GPP Release 9 to Release 16*," by Sengupta *et al.* [item 24) in the Appendix], presents the latest developments in the evolution of the physical layer evolution for the transmission of MBMS over cellular networks.

The eighth paper, "*Overview of Physical Layer Enhancement for 5G Broadcast in Release 16*," by He *et al.* [item 25) in the Appendix], reviews the latest progress with respect to the ongoing study of LTE-based terrestrial broadcast in 3GPP. Enhancement schemes of CAS and two new numerologies specified in Release 16 are presented in this paper. CAS enhancement is used to guarantee the robust reception of the control signaling carried by the PBCH and PDCCH. The two new numerologies aims to support rooftop reception with 100km coverage and mobile reception with mobility up to 250km/h respectively.

The ninth paper, "*Enhancements on Coding and Modulation Schemes for LTE-Based 5G Terrestrial Broadcast System*," by Xu *et al.* [item 26) in the Appendix], investigates the weakness of the coding and modulation schemes in current LTE-based 5G terrestrial broadcast system and provides alternatives to enhance future MBMS system.

The tenth paper, "*Using Non-Orthogonal Multiplexing in 5G-MBMS to Achieve Broadband-Broadcast Convergence With High Spectral Efficiency*," by Zhang *et al.* [item 27) in the Appendix], proposes to use the power-based non-orthogonal multiplexing technology as a capacity enhancing tool to deliver mixed broadband and broadcast services in 5G. Significant capacity benefit is demonstrated to multiplex unicast and broadcast services in a 5G-MBMS system instead of the existing orthogonal multiplexing technologies, e.g., TDM and FDM.

The eleventh paper, "*Using NOMA for Enabling Broadcast/Unicast Convergence in 5G Networks*," by Iradier *et al.* [item 28) in the Appendix], proposes a new solution for broadcast/unicast convergence in 5G networks, which takes advantage of the properties of the Power-based Non-Orthogonal Multiple Access multiplexing technique. The paper completes the physical layer definition with a Frame Adaptation Layer and a Medium Access Control (MAC) proposal.

The twelfth paper, "*Lightweight 3-D Beamforming Design in 5G UAV Broadcasting Communications*," by Miao *et al.*, [item 29) in the Appendix] describes a new position correction method for Unmanned Aerial Vehicle (UAV) broadcasting communications in 5G.

The thirteenth paper, "*Future 5G mmWave TV Service With Fast List Decoding of Polar Codes*," by Hong *et al.* [item 30) in the Appendix], proposes a fast simplified multi-bit successive cancellation list decoding method for 5G polar codes, with FPGA implementation details.

The fourteenth paper, "*5G Internet of Radio Light Positioning System for Indoor Broadcasting Service*," by Shi *et al.* [item 31) in the Appendix], shows how enhancing home networks with multiple radio light access points, allows third party service providers the opportunity to create services such as location of user equipment indoors to an accuracy around 10 cm.

The fifteenth paper, "*Beamspace MIMO-NOMA for Millimeter-Wave Broadcasting via Full-Duplex D2D Communications*," by Li *et al.* [item 32) in the Appendix], proposes to incorporate layered division multiplexing into millimeter wave multiple-input multiple-output (MIMO) system with device-to-device (D2D) communications to simultaneously provide broadcast and unicast services.

In the sixteenth paper, "*Demonstrating Immersive Media Delivery on 5G Broadcast and Multicast Testing Networks*," by Mi *et al.* [item 33) in the Appendix], eight demonstrators and one showcase developed within the 5G-Xcast project are presented. They experimentally demonstrate and validate key technical enablers for the future of media delivery, associated with multicast and broadcast communication capabilities in 5G. Three existing test-beds: IRT in Munich (Germany), 5GIC in Surrey (U.K.), and TUAS in Turku (Finland), have been developed into 5G broadcast and multicast testing networks, enabling the demonstration of a converged 5G infrastructure with fixed and mobile accesses and terrestrial broadcast, delivering immersive audio-visual media content.

The seventeenth paper, "*Multimedia Public Warning Alert Trials Using eMBMS Broadcast, Dynamic Spectrum Allocation and Connection Bonding*," from Jokela *et al.* [item 34) in the Appendix], analyses requirements that need to be fulfilled to support multimedia warning message delivery in the 5G system and describes trials of a broadcast multimedia public warning alert system. The trials demonstrate delivery of multimedia public warning messages using eMBMS, dynamic spectrum management and bonded connections

The eighteenth paper, "*Media Casting as a Service: Industries Convergence Opportunity and Caching Service for 5G Indoor gNB*," by Jawad *et al.*, [item 35) in the Appendix], proposes a novel framework of Media Casting service and IoRL (Internet of Radio Light)-Cache service. IoRL-Cache service is a solution for improving IoRL small-cells caching efficiency. IoRL is an emerging 5G small-cell for indoor environment, which utilises mmWave and Visible Light Communications (VLC) as access technologies, while exploiting Software Defined Networking (SDN) and Network Function Virtualisation (NFV) technologies to offer flexible and intelligent services to its clients.

The nineteenth paper, "*A Utility-Based Framework for Performance and Energy-Aware Convergence in 5G Heterogeneous Network Environments*," by Montalban *et al.*, [item 36) in the Appendix], proposes a novel converged architecture for broadcast, broadband and cellular services with a Performance and Energy-aware Access network selection algorithm for choosing the optimal RAT network in multi-connectivity situations. The joint solution offers a balanced trade-off between the users perceived QoS and the network energy efficiency in challenging heterogeneous environments while guaranteeing a seamless reception even in indoor scenarios.

The special issue concludes with the twentieth paper, "*Smart Mode Selection Using Online Reinforcement Learning for VR Broadband Broadcasting in D2D Assisted 5G HetNets*," by Feng *et al.*, [item 37) in the Appendix], which proposes a hybrid transmission mode selection based on online reinforcement learning for VR broadband users that can be associated by one of the three modes: macro-cell broadcasting, mmWave small cell unicasting and D2D multicasting.

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APPENDIX
RELATED WORK

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35) N. Jawad *et al.*, "Media casting as a service: Industries convergence opportunity and caching service for 5G indoor gNB," *IEEE Trans. Broadcast.*, vol. 66, no. 2, pp. 579–588, Jun. 2020.
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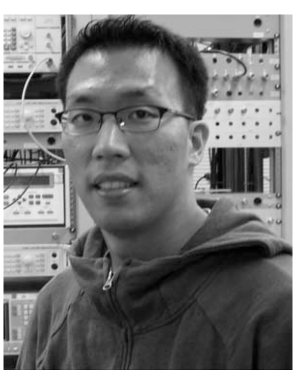

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