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5GCHAMPION – Disruptive 5G Technologies for Roll-Out in 2018

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The 5GCHAMPION Europe–Korea collaborative project provides the first fully-integrated and operational 5G prototype in 2018, in conjunction with the 2018 PyeongChang Winter Olympic Games. The corresponding technological advances comprise both an evolution and optimization of existing technological solutions and disruptive new features, which substantially outpace previous generations of technology. In this article, we focus on a subset of three disruptive technological solutions developed and experimented on by 5GCHAMPION during the 2018 PyeongChang Olympic Games: high speed communications, direct satellite-user equipment communications, and post-sale evolution of wireless equipment through software reconfiguration. Evaluating effectiveness and performing trials for these key 5G features permit us to learn about the actual maturity of 5G technology prototyping and the potential of new 5G services for vertical markets and end user enhanced experience two years before the launch of large-scale 5G services.

Keywords: 5G, Beamforming, mmWave, Satellite, Software reconfiguration.

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I. Introduction

During the past few years, a significant amount of progress has been made towards the definition and development of 5th Generation (5G) mobile network technology, whose mass deployment is targeted in 2020 [1]–[4]. The key novelty of 5G is the implementation of heterogeneous communication systems to support emerging applications requiring very high data-rate communications, ultra-low latency, and high reliability with a large number of connected devices [5], and to deal with the high quantity of uplink traffic due to the offloading of large amounts of data to the cloud [6]. Today, the 5G community has acknowledged that the key building blocks of 5G networks are millimeter-wave (mmW) backhauling, fronthauling or access, evolved packet core with advanced Network Functions Virtualisation/Software Defined Networking (NFV/SDN), and reconfigurable waveforms. Once these technologies are commercially available and well-integrated into a pervasive mobile network, 5G will become the enabler of a large variety of use-cases [7]–[10]. The aim of the 5GCHAMPION (5G Communication with a Heterogeneous, Agile Mobile network in the PyeongChang wInter Olympic competitioN) project is to deliver, at the Winter Olympic Games in Korea in 2018, the very first proof-of-concept (PoC) of a 5G system covering (i) enhanced mobile broadband with application scenarios such as shared virtual-reality and ultra-high definition video streaming, (ii) time-critical use-cases with application scenarios such as virtual-reality games and motion control, and (iii) moving hot-spots with application scenarios such as content sharing, video streaming, and virtual-reality in a moving bus.

Additionally, stand-alone 5G technology innovations will be developed in Europe for massive IoT applications and connectivity via satellite links below 6 GHz, seamless indoor–outdoor positioning, and ultra-high data-rate indoor connectivity; in Korea, high-user mobility in high-speed train scenarios will be also investigated.

The 5GCHAMPION project will showcase the 5G application experience for two users connected to two different 5G networks, one in Europe and one in Korea, and: (i) being served by either static or mobile mmW links; (ii) sharing a latency-critical service, for example, remote gaming or remote control using VR; and (iii) demanding broadband services, for instance, shared VR content. Compared to some of the most relevant 5G demonstrations that have been publicly announced by KT, SKT and LG for 2018, the 5GCHAMPION project takes a unique place in the overall 5G demonstration landscape by piloting, for the first, time trials on applications that cover IoT systems and broadband, ultra-high data rate, and interactive-VR or broadband content delivery in a moving bus.

The rest of the paper is organized as follows. In Section II, an overview on the overall architecture and use-cases of 5GCHAMPION is discussed, followed by three sections detailing key project technologies: (Section III) high-speed communication and (Section IV) direct satellite–user equipment communication. Finally, conclusions are drawn in Section V.

II. Overall Architecture of 5GCHAMPION and Use-Cases

The overall 5GCHAMPION system architecture is presented in Fig. 1. Two different radio access networks including high-capacity wireless backhauling, operating in the frequency bands 26.5 GHz to 27.3 GHz (Europe) and 25.14 GHz to 26.14 GHz (Korea), are interconnected by a virtualized mobile core network enabled by advanced Software Defined Networking (SDN) and Network Function Virtualizatoin (NFV). The 5G satellite communication component below 6 GHz is also included to investigate, for the first time, the possibility of using the 5G waveform for massive IoT applications.

The mmW radio interfaces use fixed beam- or analog beam-forming antenna arrays and require multiple access and advanced waveform technologies combined with advances in coding, modulation algorithms, and baseband computation. A 10 Gb/s fiber or Ethernet connections are used on interfaces.

The core network (CN) is based on a virtualized architecture, which will provide on-demand resource processing, storage, and network capacity wherever needed. Technologies to facilitate more flexibility for the creation of new services and applications, and the distributed and centralized control plane.

This set-up enables 5GCHAMPION to mainly address the following seven use-cases:

Use-case 1: stationary multi-Radio Access Technology (RAT) hot-spot connected via mmW backhaul to 5GTN;

Use-case 2: ultra-high data rate over 5G downlink using mmW;

Use-case 3: high-speed train communications;

Use-case 4: indoor–outdoor positioning;

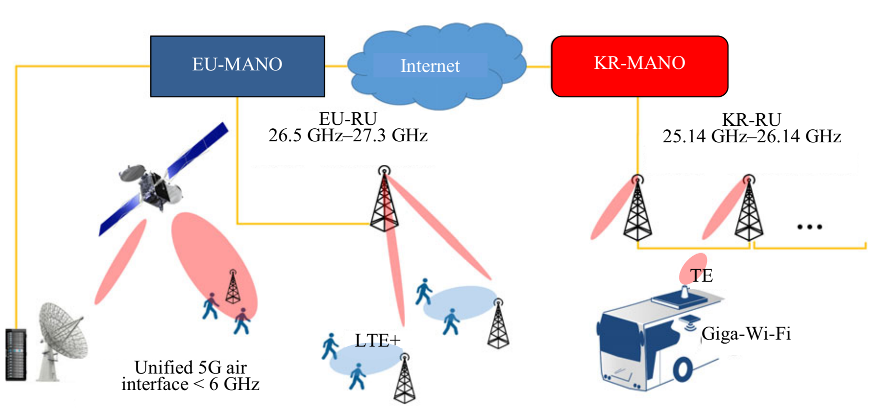

Fig. 1. 5GCHAMPION system architecture.

Use-case 5: satellite connectivity with 5G IoT devices;
Use-case 6: shared short-latency applications (for example, multiplayer remote gaming and multi-remote control);
Use-case 7: shared broadband applications.
The key performance indicators (KPI) are specified based on the 5GPPP use-case requirements [11] (Table 1). Further, ITU 5G technology requirements [12] are used as criteria to assess the advances in 5G technology development (Table 2). More details on each use-case and KPI are presented in [10].

1. 5GCHAMPION Demonstration at the Winter Olympics

At the Winter Olympics in Korea, the European (EU) and Korean (KR) 5G wireless backhaul testbeds will be deployed at the IoT street in the Gangneung Coastal Cluster (GCC), close to the Olympics venues. The KR mmW testbed will be used to connect a moving hot-spot (Fig. 2), whereas the EU mmW testbed will be used for stationary link connectivity. This testing environment will serve both use-cases 6 and 7.

More specifically, for use-case 6, we consider application scenarios with end-to-end latency of no more than 10 ms, of which 2 ms is the target over-the-air. Candidate applications are VR on-line gaming and remote control, where the UEs (for example, motion control for VR gaming) will interact in the same game, though connected to different radio access nodes. The low-latency requirement can be satisfied by maintaining user-plane functionality in the local (KR) EPC as well as by designing short radio frames for the mmW link. With respect to use-case 7, a candidate application scenario is shared VR content or shared UHD (4 k or 8 k) video-streaming. Two UEs (for example, virtual glasses) will be connected to two different radio access nodes and share the same content, which is provided either by a local cloud service in Korea or from a data-source in Finland. UE interaction is not expected, thus focus is on the data-rate and perceived user experience. End-to-end latency can range between 50 ms and 300 ms (maximum latency if the source is in Finland), based on the content source location. More specifically, 2.5 Gb/s data-rate over the mmW link is targeted, as well as a 100 Mb/s user experience in a stationary or moving hot-spot.

2. 5GCHAMPION Backhauling Architecture at 28 GHz

Based on the analysis of Radio Access Technique Group (RATG) 1 (IMT-2000) and RATG 2 (IMT-Advanced)'s

Table 1. Mapping of the 5GCHAMPION use-cases to 5G-PPP requirements.

KPI	Range	Use-case 1	Use-case 2	Use-case 3	Use-case 4	Use-case 5	Use-case 6	Use-case 7
Device	High: ≥ 10,000 devices per km^2			×				
Density	Medium: 1,000–10,000 devices per km^2	×				×	×	
	Low: < 1,000 devices per km^2		×					×
Mobility	No: Static users	×	×					
	Low: Pedestrians (0 km/h–3 km/h)	×			×		×	
	Medium: Slow moving (3 km/h–50 km/h)	×			×			
	High: Fast moving (> 50 km/h)			×	×	×		×
Infra-structure	Limited: No. infrastructure available or only macro cell coverage		×	×			×	
	Medium density: Small amount of small cells							×
	Highly available infrastructure: Big number of small cells available	×				×		
Traffic type	Continuous				×		×	
	Bursty		×					
	Event driven							
	Periodic			×				
	All types	×	×			×		×
User data rate	Very high data rate: ≥ 1 Gbit/s		×					×
	High: 100 Mbps–1 Gbit/s	×				×		
	Medium: 50 Mbps–100 Mbps	×			×			
	Low: < 50 Mbps			×	×		×	
Latency	High: > 50 ms	×		×		×		×
	Medium: 10 ms–50 ms	×						
	Low: 1 ms–10 ms		×				×	
Reliability	Low: < 95%							
	Medium: 95%–99%	×	×	×		×		×
	High: > 99%						×	
Availability (related to coverage)	Low: < 95%		×					
	Medium: 95%–99%	×		×	×	×	×	×
	High: > 99%							
5G service type, comprising	Extreme Mobile Broadband is the key service requirement.	×	×					×
	uMTC, where the reliability is the key service requirement.			×	×		×	
	The massive connectivity is the key service requirement.	×	×		×	×		

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Table 2. Mapping of ITU technology requirements to 5GCHAMPION use-cases.

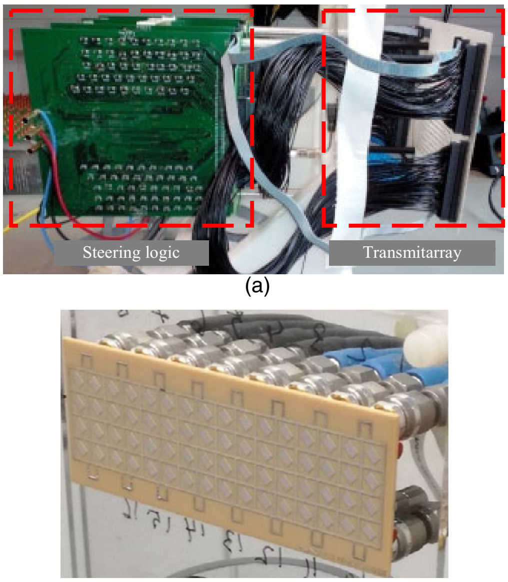
KPI	ITU target	5GCHAMPION applicability
Bandwidth	Minimum 100 MHz	Use-case 1, 2, 6, and 7
Peak data rate	DL: 20 Gbit/s; UL: 10 Gbit/s	Use-case 2
Peak spectral efficiency	DL: 30 bps/Hz; UL 15 bps/Hz	Use-case 2
Cell spectral efficiency	3x IMT-A	Use-case 1, 6 and 7
5th %-tile user spectral efficiency	3x IMT-A	Use-case 1, 6 and 7
User experienced data rate	No target KPI	Use-case 1 and 7
Area traffic capacity	No target KPI	Use-case 1
Latency (control plane)	10 ms	Use-case 1, 6 and 7
Latency (user plane)	eMBB: 4 ms UL, 4 ms DL URLLC: 0.5 ms UL, 0.5 ms DL	Use-case 1, 6 and 7 Not applicable
Latency for infreq. small packets	< 10 s in UL and MCL = 164 dB	Not applicable
Mobility interruption time	0 ms	Use-case 4, 6 and 7
Reliability	General URRLX: (1 − 10 − 5)/1 ms eV2X: (1 − 10 − 5)/ (2 − 10) ms	Not applicable Use case 6
Connectivity density	1 million devices/ km^2	Use-case 4
UE battery life	Beyond 19 years	Use-case 4
Coverage	MCL = 164 dB, for 160 bps	Use-case 6, 7
Extreme coverage	MCL = 140 dB @2 Mbps/60 kbps DL/UL 143 dB @1 M/30 k	Use-case 6, 7
Mobility speed	Up to 500 km/h	Use-case 5
Network energy efficiency	Efficient data delivery and granular DTX/DRX	Not applicable
UE energy efficiency	Efficient data delivery and granular DTX/DRX	Not applicable

requirements considering market demand, technological progress, and building of the network, the ITU-R forecasts that between 1,340 MHz and 1,960 MHz of the spectrum will be required by 2020 [13]. Therefore, various frequency bands, including those above 6 GHz, are being reviewed for 5G communications. For instance, Korea

Fig. 2. Experimental moving hot-spot that will be used for demonstration at the Winter Olympics.

officially proposed, as a WRC-19 agenda item, that frequency ranges between 6 GHz and 100 GHz should be considered for IMT identification during the 4th meeting of the APT Conference Preparatory Group for WRC-15 (APG15-2). Note also that the FCC has aggressively addressed the future spectrum need in the US through its "Spectrum Frontier" 5G initiative, which adds, in total, 10.85 GHz of spectrum bands above 24 GHz for applications such as mobile radio services (including 27.5 GHz to 28.35 GHz, 37 GHz to 38.6 GHz, 38.6 GHz to 40 GHz, and 64 GHz to 71 GHz). Note in particular, that at the World Radio Conference 2015, there was no agreement on the 28 GHz band, which is likely not to be available world-wide. Still, the US has included the band in its nation-wide ruling, and we expect that it will also become available in Korea. To the best of our knowledge, Korea proposed the 24.25 GHz to 29.5 GHz band to the ITU-R. Europe is expected to follow the World Radio Conference 2019 agenda. Today, the frequency bands around 28 GHz are not allocated for mobile services (MS) in Europe. However, due to the strong opening from other countries (US, Korea, and Japan), the European Commission (EC) recommends the 24.25 GHz to 27.5 GHz band as a pioneer band for 5G above 24 GHz [14]. However, a request for harmonization measures was also put forth, especially for the Earth Exploration Satellite Service (EES) and Space Research Service (SRS).

Two electronically-steerable antennas, an electronically steerable transmitarray (evolution of the antenna presented in [15]) and a phased array for MIMO beamforming, have been designed and fabricated in Europe. Both architectures are presented in Fig. 3, and can be used to implement backhaul links with beamforming capabilities. The 16-element phased array is connected on the European backhaul link based on a mmW radio transceiver designed for time-division–duplex (TDD) communication, where the transmission and receiving chain are not simultaneously utilized, but separated utilized through a switch [16]. Beamforming functionality



(a)

(b)

Fig. 3. 28 GHz antennas developed in the 5GCHAMPION project. (a) Electronically steerable transmitarray antenna and (b) phased array for MIMO beamforming.

is implemented with digitally controlled phase-shifters. The Korean backhaul link developed to show a Gigabits-per-second moving hot-spot is based on a preexisting architecture [17].

3. 5GCHAMPION Core Network Architecture Based on SDN/NFV/MANO

The CN architecture has been designed to support CN functionalities and agile management [18]. Specifically, the CN functionality is realized by leveraging SDN and NFV to facilitate the dynamic provisioning of CN functions with the support MANO functionality. By using SDN capabilities, dynamic control of traffic flow can be performed, redirecting the traffic to gateways, according to workload. Simultaneously, the introduction of NFV permits the separation of service functionalities from the capacity-constrained specific network entities and allows dynamic instantiation in commodities and powerful servers. We implemented such CN and MANO functions as a group of SDN applications for 5G. Some example applications are base station, backhaul, mobility management, performance monitoring, access, and secure service delivery applications. These applications are orchestrated via the controller northbound API.

The main CN functions are designed and implemented in the form of virtual functions, namely, vEPC (virtual Evolved Packet Core). Both the EU and KR sides provide their own implementation of vEPCs based on this architecture. They are described as follows.

A. European vEPC Architecture (5GTN)

The EU vEPC consists of the following VNFs:

- A Cloud Mobile Gateway (CMG), which provides the SP-GW, Gateway GPRS Support Node (GGSN) and Traffic Detention Functions (TDFs), evolved packet data gateway (ePDG), and trusted wireless access gateway (TWAG).
- A Cloud Mobility Manager (CMM), providing the mobility management entity (MME), and SGSN functions.
- A Dynamic Services Controller (DSC), built on the patented Agile Rules Technology (ART) rules engine, provides the Policy and Charging Rules Function (PCRF) and wireline Radius/Change of Authorization.
- The Service Aware Manager (SAM) provides end-to-end network management visibility across the entire mobile network.

To support the scalability required to meet the expected 5G and IoT service requirements, packet core VNFs provide three key design innovations:

- Packet core VNFs are decomposed into separate control and data plane virtual machine (VM) instances. This facilitates a distributed architecture, where data plane resources can be deployed in edge data centers closer to the device, while control plane resources can be centralized.
- State-efficient VNF processing, which unpins the subscriber/device state information from the VMs, freeing up the underlying computational resources, to be reused to process other subscribers/devices.
- Remote cloud database, which synchronizes the subscriber/device state information into a real-time data store.

B. Korean vEPC Architecture

Our architectural decision for 5G is to distribute mobile core functions to the edge nodes. The 5G core is generally divided into 5G Core UP (User Plane), in charge of bearer delivery, and 5G Core CP (Control Plane), in charge of signaling and control of the 5G core network. The key CN architectural design principle is a centralized CP with distributed UP over the edge nodes.

If the CN where bearers are terminated is located closer to cell sites, backhaul traffic will significantly decrease, facilitating cost reduction for continual backhaul enhancement. The architecture of Korean vEPC is realized

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as HSvEPC (Highly Scalable virtual Evolved Packet Core) [12].

C. MANO Architecture

The EU MANO architecture has two management entities:

- VNF manager – This is in charge of instantiating and controlling the EPC functions. It is responsible for interacting with, chaining, and handling the lifecycle (instantiation, maintenance, and so on) of VNFs. It is in charge of the operation and configuration of VNFs through the operations support system (OSS)/base station subsystem (BSS). It will handle multi-functional EPC components like the MME, HSS (Home Subscriber Server), and so on, as well as the specific functionality VNFs like Firewalls, Deep Packet Inspectors, and so on.
- Infrastructure manager – This entity interacts with (or incorporates the capability of) the SDN controller in the service stratum when deploying the VNFs for configuring the computing and storage resources for the VNF of interest. It also supports the networking part in attaching the VNFs to the border of the underlying transport network, to make them reachable from outside the data center. This is only for the service layer component. It also has to decide a path for the transport layer VNFs.

The KR MANO architecture is also based on NFV and SDN components. The management and orchestration architecture is comprised three different entities — the NFV Orchestrator (NFVO), VNF Manager (VNFM), and Virtual Infrastructure Manager (VIM).

The NFV Orchestrator is responsible for managing functions such as network service life-cycle management and overall resource management. Service management or orchestration deals with the creation and end-to-end management of the services by composing different VNFs. Resource management helps ensure that the NFV-infrastructure resources are abstracted cleanly (independent of VIM) to support the services that access these resources.

The VNF Manager oversees the lifecycle (typically involves provisioning, scaling, and terminating) management of instances of VNF. In this case, each VNF is associated with a VNFM that will manage that particular VNF's lifecycle. A VNFM may manage multiple instances of the same type of VNF or different types of VNFs.

The VIM controls and manages the NFV infrastructure (NFVI) compute, storage, and network resources. The VIM-component has received significant attention and various open-source solutions such as OpenStack, and has been used to realize the virtualized infrastructure management functionality of MANO.

Further information on CN and MANO architecture, functionality, implementation, and testing details are described in [19].

III. Key Enabling Technology: Architecture of High-Speed Train Communication System

The design of a high-speed train communications system in 5GCHAMPION, namely the mobile hotspot network (MHN)-enhancement (MHN-E) system, is one of the main tasks in the project. In 3GPP, a deployment scenario related to a high-speed train has been also introduced and studied since 3GPP release 14 [18]. The high-speed deployment scenario focuses on continuous coverage along the track in high-speed trains, aimed at providing consistent user experience even with very high mobility of up to 500 km/h. It includes both sub-6 GHz and 30-GHz carrier frequencies for the link between base station and relay installed on the train. The provision of a big data pipeline in 5GCHAMPION is in line with the 3GPP high-speed deployment scenario, as shown in Fig. 4. A chunk of bandwidth in the 24 GHz to 29 GHz band can be selected as moving wireless backhaul (MWB) frequencies between radio units (RUs) and terminal equipment (TE). In the train, passengers can access public Internet through wireless fidelity (Wi-Fi) access points or small cells through the TE. Benefits of this two-tier approach are i) to use a group handover and ii) to make better use of line-of-sight channels for coverage compared with direct access from base stations to passengers' devices. As depicted in Fig. 4, the network architecture of the MHN-E system consists of mmWave-based MWB links and on-board access links (for example, Wi-Fi) inside the train [20].

In the following subsection, the design of the MHN-E system and several enabling technologies, as well as analysis on link-level performance of the system, are presented.

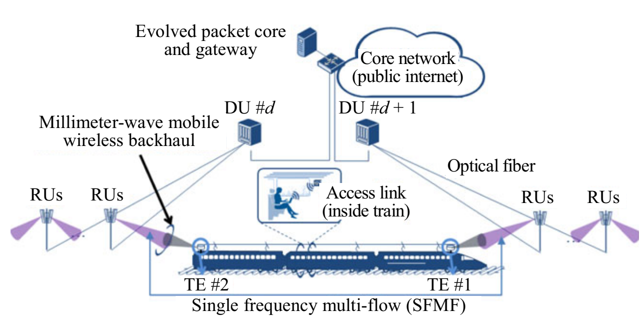

Fig. 4. 5GCHAMPION high speed approach.

1. Design of MHN-E System

The MHN system was initially designed for providing TE at speeds of up to 400 km/h with a broadband MWB. However, in order to meet mobility requirement of 500 km/h, one of the key requirements of IMT-2020, we conducted a study on the numerology for an MHN-E system under various numerology sets and 3GPP channel models [21]. From this study, we observed that in the case of higher modulation, such as 64-QAM and 256-QAM, at speeds of up to 500 km/h, numerology sets with subcarrier spacing greater than or equal to 120 kHz could achieve reasonable performance. Therefore, we concluded that the numerology of the MHN system summarized in the Table 3 can be used for the MHN-E system.

The radio frequency (RF) design of the MHN-E system incorporates the following considerations. The configuration of the RF transmit (TX) and receive (RX) paths are 2TX/2RX for the RU and 1TX/2RX for the TE, and we employ 8 component carriers (CCs) for carrier aggregation (CA). For the antenna design, dual linearly-polarized antenna arrays with 4 × 4 (16 dBi gain) and 6 × 6 (21 dBi gain) elements are used on transmit and receive antennas, respectively, to implement digital MIMO [3].

2. Key Enabling Technologies

A. Doppler Mitigation

Due to the very high speed of up to 500 km/h, along with the use of mmWave frequency bands, the transceiver experiences a very high Doppler shift/spread of up to tens of kHz. These highly time-varying channel characteristics should be considered in the system design, as follows:

Table 3. Numerology of MHN/MHN-E system.

Parameters	Value
Subcarrier spacing (kHz)	180
Sampling clock rate (MHz)	184.32
OFDM symbol duration without CP (μs)	5.56
CP duration (μs)	0.69
Number of symbols per TTI	40
TTI duration (ms)	0.25
Frame duration (ms)	10
Number of RBs in frequency domain	50
Number of subcarriers per RB	12
FFT size	1,024

- Use of large subcarrier spacing: In an orthogonal frequency-division multiplexing (OFDM) system, using larger subcarrier spacing reduces the symbol duration, thus preventing inter-carrier interference (ICI) due to the channel variation during the OFDM symbol duration. Therefore, as mentioned previously, in the MHN-E system, we employ the subcarrier spacing of 180 kHz, and its detailed numerology is given in Table 3.
- Frequent reference signal allocation: As the channel changes more rapidly, the reference signals for channel estimation should be allocated more densely in the time-domain. In the proposed system, the time interval between two adjacent reference signals is designed to be below the Nyquist criterion [22].
- Doppler shift estimation and correction: Frequency offset due to Doppler shift needs to be estimated and corrected at both downlink and uplink receivers. It is known that the effect of Doppler shift is more significant for uplink, double that of downlink, due to the downlink-locked oscillator [23]. In the MHN-E system, the uplink frequency offset can be estimated at the range of −26.67 kHz to 26.67 kHz. The estimated frequency offset is compensated using automatic frequency control (AFC). In Fig. 5, the effect of AFC is observed assuming that the train speed is 500 km/h. We can see that severe phase rotation and ICI can be compensated by AFC.

B. Multi-Antenna Techniques

We illustrate various multi-antenna techniques for the high-speed train scenario, which can be used to improve the spectral efficiency as well as the robustness of the links between the RUs and TEs. Several multi-antenna techniques suitable for the high mobility scenario can be used, as follows:

- Array beamforming: Owing to the characteristics of the mmWave frequency band, a large number of radiating elements can be packed into a small-form factor device

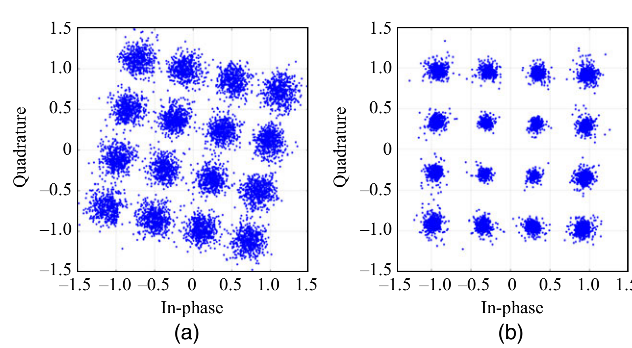

Fig. 5. Effect of AFC: (a) without AFC and (b) with AFC.

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(that is, tens of radiating elements can be placed within a few centimeters), facilitating fine beamforming with narrow and high-gain beams. These narrow beams are confined to propagate along the track, easily achieving coverage expansion and interference reduction.

• Spatial diversity techniques: To further improve the link robustness, we employ spatial diversity techniques both at the transmitter and receiver. Among the various spatial diversity techniques, spatial frequency block code (SFBC) is employed at the transmitter. At the receiver side, the maximal ratio combining (MRC) technique is used. Up to two RF chains are used for the spatial diversity techniques both at the transmitter and receiver, where these two RF chains are independently connected to the two different sets of antenna arrays. The two sets of antenna arrays have orthogonal polarization angles and/or are placed with enough distance between one another. Polarization-based multi-antenna schemes are particularly effective in a line-of-sight (LOS) dominant channel environment.

• Spatial multiplexing techniques: Considering rapid channel variation due to high-speed characteristics, we employ an open-loop spatial multiplexing (OLSM) scheme rather than a closed-loop scheme, requiring accurate channel state information (CSI) feedback with strict delay requirements. In addition, up to two spatial layers are supported, also considering the very high mobility and limited CSI feedback.

• Distributed antenna techniques: By fully taking advantage of the MHN-E system architecture, in which two TEs on the train are spatially separated, as shown in Fig. 4, the system is capable of supporting a distributed antenna scheme, called the single frequency multi-flow (SFMF) transmission scheme, in the system. In this scheme, as illustrated in Fig. 4, both RU and TE form very sharp beams, enabling each TE to transmit/receive independent data to/from its corresponding RU by mitigating inter-RU interference, which doubles the spectral efficiency.

C. Other Enhancements

Wireless backhaul links in the MHN-E system are unidirectional, to make better use of the high gains of beamforming antennas. As carrier frequencies increase, the free-space path loss becomes larger, and antenna sizes generally become smaller. Still, high-gain antennas can be implemented with small sizes, and this can be used to overcome the high path loss. Since high beamforming gains are usually accompanied by small beam widths, a unidirectional link is preferable to obtain good coverages opted for one dimensional train route.

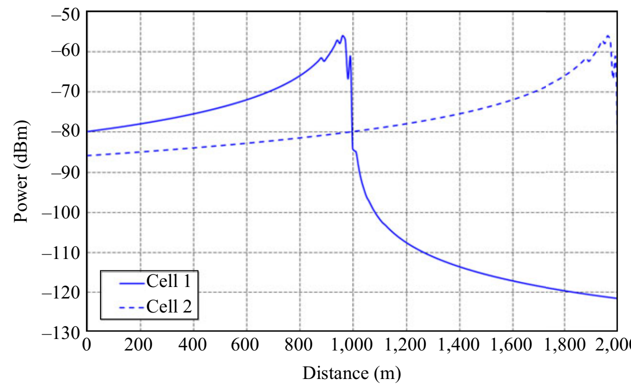

Fig. 6. Cell power distribution of two neighboring cells.

Figure 6 shows an example of cell power distributions of two neighboring cells, cell 1 (or RU 1) and cell 2 (or RU 2), where the antenna gain of both RU and TE antennas is equal to 22 dBi, and the 3-dB beam width of both antennas is 8°. We also assumed an antenna height of 2 m and an inter-RU distance of 1 km.

As a train runs from cell 1 to cell 2, TE needs to handover from cell 1 to cell 2. For the purpose of handover, the TE needs to carry out neighbor cell search functionality periodically, listing potential target cells. However, in the unidirectional network, neighbor cell searching is problematic, since the serving cell power is much higher than the neighbor cell power. This means that it is very difficult to obtain cell information and timing synchronization of a target cell for handover, until TE passes by the serving RU, and after the TE passes by serving RU, it will lose its connection to the serving cell, causing communication interruption, since the power of the serving cell drastically drops in a very short time, as shown in Fig. 6. To tackle this problem, we proposed a new frame structure in [20], which is one of the major enhancements of the MHN-E system compared with the previous MHN system from a physical layer point of view. The new frame structure not only provides a viable solution to the problem, but also supports CA, allowing the aggregation of a maximum of eight CCs, to attain a total transmission bandwidth of up to 1 GHz [20]. In the frame structure, three different cell types are defined, which are the primary cell (PCell), secondary cell (SCell), and tertiary cell (TCell), and the first two CCs can be configured by either PCell or SCell, depending on the location of RU, so that the serving cell and target cell always have different locations of PCell and SCell. Subsequently, since the synchronization signal and broadcast channel containing cell information are designed to be transmitted on PCell, by puncturing the corresponding resources in SCell of the serving cell, TE can receive the synchronization signal and broadcast channel of a target cell at the punctured resource location. Figure 7 illustrates the simulation results of neighbor cell searching with and without puncturing of frequency-time resources in SCell, for reception of synchronization signal. A Rician channel with a K-factor of 10 is assumed in the simulation. The proposed scheme (with puncturing) exhibits a signal-to-interference-plus-noise ratio (SINR) of –28 dB at 10% of the detection error rate (DER). Compared with a conventional method, a method without puncturing, the proposed scheme achieves 25-dB gain. Therefore, it can greatly contribute to handover success under > 20 dB of serving cell interference by improving neighbor cell search performance.

3. Link-Level Simulation

To validate the feasibility of the MHN-E system, we evaluate the link-level performance of downlink, particularly focusing on the performance of multi-antenna transmission schemes, including the transmit diversity (TXD) scheme of the SFBC and OLSM scheme.

A. Simulation Assumptions

The link-level simulation was conducted under the simulation parameters listed in the Table 4. By varying the K-factors of Rician fading and cross polarization discrimination (XPD), we would like to demonstrate the feasibility of the transmission schemes in various scenarios, such as rural and tunnel environments, which are the typical scenarios considered in high-speed train communications. We assume a multi-clustered channel with Rician fading, and two different K-factors of 13.3 dB and 7 dB, which are being considered for performance evaluation of a high-speed train scenario in 3GPP [18]. In addition, two different values of XPD, 0 dB and 25 dB, are taken into account. In the simulation, frequency offset due to the Doppler effect was compensated at the receiver using AFC.

B. Simulation Results

The link-level simulation result in Fig. 8 shows that in the case of the channel with a K-factor of 13.3 dB and XPD of 25 dB, the system using the 2 × 2 OLSM transmission scheme is able to achieve better throughput performance than that of 2 × 2 TXD most of the time. When the velocity of the train is 100 km/h or 300 km/h, the system using 64-QAM with 2 × 2 OLSM can achieve throughput exceeding 9 Gb/s, while a maximum throughput of 6 Gb/s at the speed of 500 km/h can be achieved using 16-QAM with 2 × 2 at SNR larger than 30 dB. From this simulation result, we can draw a conclusion that for a rural environment, where the channel has a dominant LOS path and large XPD, the OLSM transmission scheme is preferred, to increase the spectral efficiency.

Table 4. Simulation parameters.

Parameters	Value
Channel model	Multi-cluster channel model with Rician fading
K-factor	0 dB, 25 dB
Carrier frequency	26 GHz
Bandwidth	1 GHz
Code rate	0.8
Transmission scheme	2 × 2 TXD, 2 × 2 OLSM

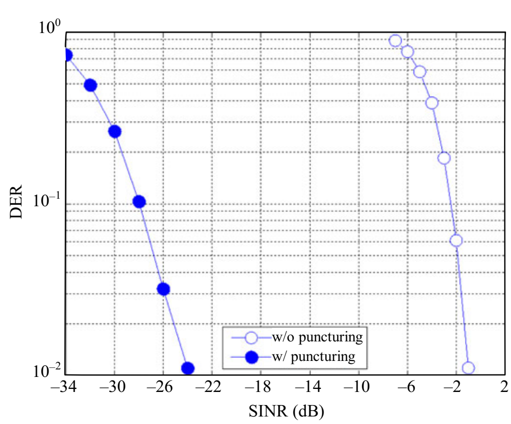

Fig. 7. Detection error rates of neighbor cells.

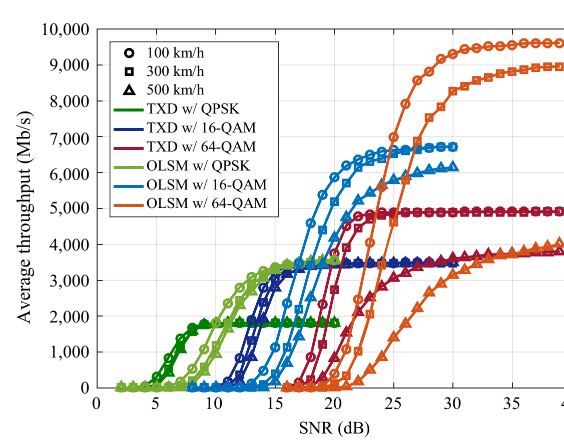

Fig. 8. Average downlink throughput of the MHN-E system (code rate = 0.8, XPD = 25 dB, K-factor = 13.3 dB).

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However, it is observed in the other simulation result (shown in Fig. 9), that in the case of the channel with a K-factor of 7 dB and XPD of 0 dB, only the 2 × 2 TXD transmission yields reasonable throughput performance, while the 2 × 2 OLSM scheme is unable to provide performance gain on spectral efficiency, which means that for a tunnel environment, where the channel has a weak LOS path and large multi-path components and XPD, the TXD transmission scheme is preferred.

4. Field Trial Results

We also present a preliminary result for the field trial conducted using 5GCHAMPION's phase one prototype of the MHN system. It occupies the 25 GHz to 25.5 GHz band and radiates 100 mW of power. Downlink (and uplink duplexing is based on time-domain duplexing with a 7-to-1 downlink-to-uplink time slot ratio. The distance mmWave signals reach inside a subway tunnel was the main concern during the test. Two transceivers were placed on separate cars. One of them had been rolled away from the other along rails. A computer recorded data throughput periodically during the movement, over a total distance of 1.1 km. Figure 10 shows the measured downlink and uplink data throughputs in the tunnel near Moran station of Seoul subway line 8. The downlink data throughput was larger than 1 Gb/s (peak value was 1.25 Gb/s) over approximately 80% of the route, and it decreased to 200 Mb/s at 1.1 km. These results will be used to design the next phase prototype of the MHN-E system, which will be applied at a proof-of-concept demonstration at the PyeongChang Olympics.

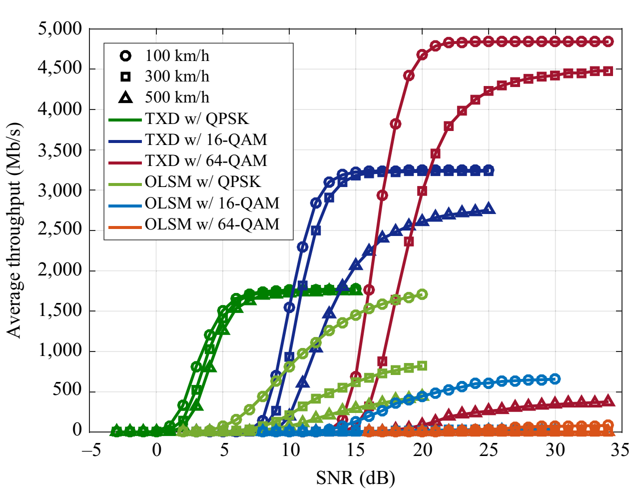

Fig. 9. Average downlink throughput of the MHN-E system (code-rate = 0.8, XPD = 0 dB, K-factor = 7 dB).

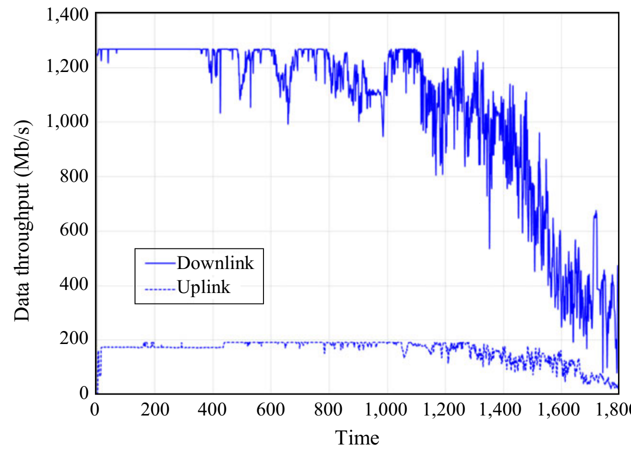

Fig. 10. Measured data throughput in a Seoul subway tunnel.

IV. Key Enabling Technology: Direct Satellite–User Equipment Communications

5G offers a promising opportunity to provide an integrated satellite/cellular service to 5G user equipment "as is," as depicted in Figs. 1 and 11. This can be made possible by taking advantage of the flexible front ends that will be implemented in user equipment to operate in a wide range of frequency bands below 6 GHz (for example, B65 at 2.1 GHz), and the flexible radio interface designed to provide narrow band and wide band communications over extended coverage while optimizing the UE power consumption.

The seamless access to the satellite, for IoT use-cases, through a 5G radio interface demonstrator, will be based on a proprietary flexible and programmable platform and a tailored channel emulator. A flexible implementation of the narrow-band IoT radio interface will be investigated with a special focus on physical layer performance evaluation.

The final objective is to employ Common-off-the-Shelf (COTS) Narrow-Band Internet-of-Things (NB-IoT)

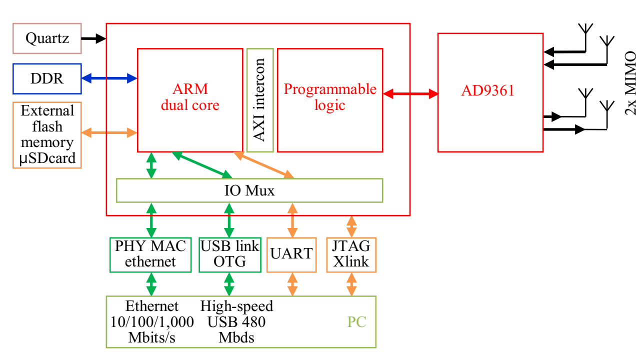

Fig. 11. Schematic of the hardware platform for direct satellite–UE communications.

Table 5. Obtained link-budget for the direct satellite–UE communications.

Use-case	Achievable C/(I + N) (dB)	Achievable data-rate (kb/s)
1,500 km forward	−0.5	107.4
1,500 km return	−4.6	0.84
800 km forward	−0.5	107.4
800 km return	−2.4	1.35
10,000 km forward	−0.5	107.4
10,000 km return	−2.4	1.35
GEO forward	−2.4	107.4
GEO return	−2.4	1.35

devices, in order to facilitate direct communication of a UE with satellites. From this point of view, we perform a link budget analysis under the following assumptions: (i) one to three geostationary satellites to cover the world *between the latitudes of 70° N and 70° S*; (ii) Medium Earth Orbit (MEO) satellites between 6,000 km and 10,000 km altitude, and around 10 to 12 satellites to ensure worldwide coverage, considering inclined orbits at 45° on two planes and polar orbits on two or three planes; (iii) Low Earth Orbit (LEO) satellites between 800 km and 2,000 km altitude, considering inclined orbits at around 50°, and polar orbits or near-polar orbits at 89°.

To study the feasibility of the direct UE–satellite communications use-case, a link budget analysis is performed considering the following hypotheses. The system has been dimensioned for narrowband IoT applications with uplink and downlink data-rates around 1 kb/s (for 3.75 kHz BW) and 100 kb/s in 180 kHz, respectively. The link-budget obtained considering minimum propagation margins of 5 dB for clear LOS operation, a minimum elevation angle of 15°, and minimum C/(I + Noise) ratio of 10 dB, when the Doppler effect is pre-compensated and the ratio C/Im and interferences are included, is summarized in Table 5.

From the UE perspective, the following aspects would improve the link budget and ensure connectivity to satellite:

- Instead of having a 0 dB gain in the antenna, by making use of loop structures, a 3 dB to 4 dB gain can be realized over a 3 dB beam width of 90° or higher.
- If the form factor of UE is suitable for realizing circularly polarized antennas, polarization mismatch loss with respect to the satellite can be minimized.
- Doppler shift (in case of LEO satellites) could be corrected by integrating a GPS system.
- When TDD is chosen as the multiplexing scheme, duplex filters that increase insertion loss in the receiver path could be eliminated, directly improving NF. Simple harmonic rejection low-pass/notch filters could be employed.
- LNA NF reduction techniques can help in critical link-budget scenarios.
- Transmit scheme for sporadic applications could be optimized to achieve longer battery life.

V. Conclusions

Vertical markets and industries have a high expectation regarding a drastic 5G transformation, owing to the 5G-enabled technical capabilities available, which can trigger the development of new, cost-effective products and services. To satisfy these goals, a flexible, adaptable, and programmable architecture is required. While there has been a substantial amount of research at a conceptual level on this topic conducted by academia, industry, and standardization bodies such as 3GPP, today, these 5G concepts need to be put into practice. Today, 5G networks are reaching maturity from research and innovation, to prototyping PoC. 5GCHAMPION PoC activities will demonstrate a subset of three disruptive technological solutions, which are specifically developed and experimented on by 5GCHAMPION during the 2018 PyeongChang Olympic Games: high speed communications, direct satellite-UE communications, and post-sale evolution of wireless equipment through software reconfiguration. This unique visible PoC context is expected to motivate and convince vertical markets, the industry, and future 5G service providers regarding the effectiveness and suitability of 5G to new vertical industries that have not played a major role in legacy cellular communications. 5GCHAMPION PoC activities are thus expected to further convince relevant stakeholders well before commercial mass-market deployment of 5G technology. It will thus contribute to further broadening the client base and success of future 5G systems. From March 2018, videos and detailed documentation material and videos on 5GCHAMPION PoC will be available at http://www.5g-champion.eu/.

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