From Architecture to Field Trial: A Millimeter Wave Based MHN System for HST Communications Toward 5G

Heesang Chung, Junhyeong Kim, Gosan Noh,
Bing Hui and Ilgyu Kim
Mobile Application Research Dept.
ETRI, Daejeon, Korea
{hschung, jhkim41jf, gsnoh, huibing, igkim}@etri.re.kr

Youngmin Choi
Clever Logic, Daejeon, Korea
ymchoi@cleverlogic.co.kr

Changseob Choi and Myongsik Lee
Compact RU Group
KMW, Hwasung, Korea
{uranos73, cpls}@kmw.co.kr

Dongha Kim
Information and Communication Dept.
Seoul Metro Rapid Transit, Seoul, Korea
itnsea@smrt.co.kr

Abstract— **This report presents a mobile hotspot network system to provide mobile Internet services for the passengers in the high speed trains. 3GPP has been working on enhanced mobile broadband under many deployment scenarios such as indoor hotspots, dense urban, rural, high speed, etc. The high speed deployment scenario deals with continuous coverage along track in the high speed trains considering mobility of up to 500 km/h. The design concept of the mobile hotspot network system is in line with the 3GPP deployment scenario. The system will eventually provide the fifth generation mobile network services based on the very wide bandwidth of millimeter waves. The designs and architecture of the system will be disclosed. Also, the performance and mobility management issue will be addressed. A proof-of-concept demonstration with the system prototype will be presented.**

Keywords—5G; millimeter wave; mobile hotspot network; high speed train; railway communication;

I. INTRODUCTION

It is controversial when the fifth generation (5G) mobile services will be opened. However, from the standpoint of standardization, the 5G specification will be released in 2020 [1]. Although mobile network operators' 5G services rely heavily on the economy and business, faster and more reliable mobile networks based on the 5G standard are expected to emerge in the next couple of years, depending on technology challenges around the world [2-4]. Reference [1] defines 8 key performance indicators (KPIs) that characterize 5G - 20 Gbps of peak data rate, 100 Mbps of user experienced data rate, 3-fold spectrum efficiency, 500 km/h of mobility, 1 ms of latency, 1 million devices/km^2, a hundred times energy efficiency and 10 Mbps/m^2 of areal traffic capacity. These KPIs are closely related to usage scenarios. First, the enhanced mobile broadband scenarios rely on the data rate, spectrum and network energy efficiency and mobility. Second, the massive machine type communication scenarios relate to the connection density and network and energy efficiency. Last, the ultra-reliable and low latency communication scenarios are dependent on the latency and mobility.

Meanwhile, one big difference of 5G networks from those of the third or fourth generation (3G/4G) is that 5G will create an ecosystem for technical and business innovation so that many vertical markets will be considered in designing them. Third generation partnership project (3GPP) has studied deployment scenarios for enhanced mobile broadband, which include the high speed scenario [5]. It focuses on continuous coverage along track in high speed trains (HSTs) with very high mobility of up to 500 km/h. In this regard, we have developed a mobile hotspot network (MHN) system to provide broadband data to passengers on HST or subway trains [6].

In 2003, British rail company GNER launched onboard wireless fidelity (Wi-Fi) services with combination of satellite and GSM (Global System for Mobile Communications)/GPRS (General Packet Radio Service) [7]. Since then, several types of solutions have emerged around the world that use access technologies including WiMax (Worldwide Interoperability for Microwave Access), leaky coaxial cable and radio-over-fiber [8]. The data rates of wireless backhauls between a train and base station or satellite were 2-10 Mbps depending on the access technology used. However, the recent development of backhaul capacity is remarkable. Trackside backhaul solutions can achieve 100 Mbps or higher capacity by applying the long-term evolution (LTE) or LTE-Advanced (LTE-A) networks. On the other hand, unlicensed spectra around 5 GHz can also be used to achieve capacities greater than 100 Mbps at train speed of 350 km/h.

In the 5G CHAMPION (5G Communication with a Heterogeneous, Agile Mobile network in the PyeongChang wInter Olympic competitioN) project, Korean and European companies are working on wireless backhauls using millimeter wave (mmWave) for multi-gigabit data rates. This paper presents research activities and results for Korean partner's MHN system for wireless backhaul. The configuration is as follows. Section II describes the architecture and design of the

978-1-5386-3873-6/17/$31.00

MHN system and section III presents the performance of the system focused on high speed. Section IV reports a few mobility management issues in the 3GPP standardization work and section V introduces a field trial with an MHN system prototype that has been conducted recently and section VI concludes the paper.

II. ARCHITECTURE AND DESIGN OF MHN SYSTEM

This section provides a brief overview of the MHN system in terms of system architecture and design.

A. System Architecture

Fig. 1 illustrates the basic architecture of the MHN system including two main components. One part is for a network side with MHN NodeB (mNB). The mNB is made up of MHN digital units (mDUs) placed in a control center and MHN radio units (mRUs) deployed along railroad track. The other is for a moving hotspot side consisting of MHN terminal equipment (mTE) installed on the moving hot spot or train. As a result, mobile wireless backhaul links are formed between the mTE and mRUs.

In the MHN system, looking at the backhaul link, each mTE acts as a single user connected to a base station or mNB. On the other hand, the mTE inside the train provides mobile Internet services to user devices of onboard passengers. In this case, each device does not need to handover individually. That is, the mTE performs handover when it crosses cell edges. For the onboard access links, the commercial systems such as Wi-Fi or small cells can be used.

The MHN system is capable of executing single-frequency multi-flow transmissions by making full use of the system architecture. There are two mTEs in the example of Fig. 1 – one is in the head of the train and the other is in the tail. They are spatially separated from each other. In addition, the mTE and mRU are designed to produce very narrow beams. Each mTE receives independent signals from mRUs at different sites, resulting in doubling of the system’s spectral efficiency.

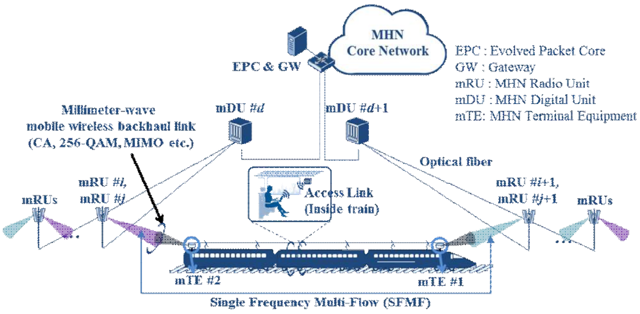

Fig. 1. System architecture of MHN system

B. Design of MHN system

Several techniques have been considered to further increase backhaul capacities and improve link reliability. The polarization based multiple input multiple output (MIMO) is a good one for backhaul capacity increase. We also introduced a novel frame structure supporting carrier aggregation (CA) and handover [9]. This subsection is dedicated to the numerology and antenna configuration of the MHN system.

1) Numerology

The MHN system defines the aggregation of up to eight component carriers (CCs) to make use of 1 GHz of transmission bandwidth. Both uplink and downlink are based on orthogonal frequency division multiplexing (OFDM). The numerology of the system is summarized in TABLE I.

TABLE I. NUMEROLOGY OF MHN SYSTEM

Parameter	Value
carrier frequency (GHz)	25.5
subcarrier spacing (kHz)	180
sampling rate (MHz)	184.32
system bandwidth of each CC (MHz)	125
Fast Fourier Transform (FFT) size	1024
number of used subcarriers	600
OFDM symbol duration w/o CP (μs)	5.56
cyclic prefix (CP) duration (μs)	0.69
number of OFDMsymbols per TTI	40
TTI duration (ms)	0.25

2) Antenna Configuration

Dual-polarized patch array antennas are implemented for both the mRU and mTE. Fig. 2 shows the configuration of the antennas. The mRU consists of 2 transmit (TX) antennas and 2 receive (RX) antennas whereas the mTE consists of 1 TX antenna and 2 RX antennas. The TX and RX antennas have vertical polarization and horizontal polarization when there are two TX or RX antennas on each device. They are designed to operate in the unlicensed frequency band of 25.14-26.14 GHz. Meanwhile, 24-26.5 GHz band must comply with the regulation in Korea. One of them is the regulation for ERIP (Effective Isotropic Radiated Power) of transmitters. The maximum allowed EIRP is 36 dBm. Fig. 2 also shows that the TX antenna size is smaller than the RX antenna size. The reason is that the TX antenna has 16 dBi or smaller gain to comply with the ERIP requirement. There is not restriction on the RX antenna gain. It was designed to get 22 dBi.

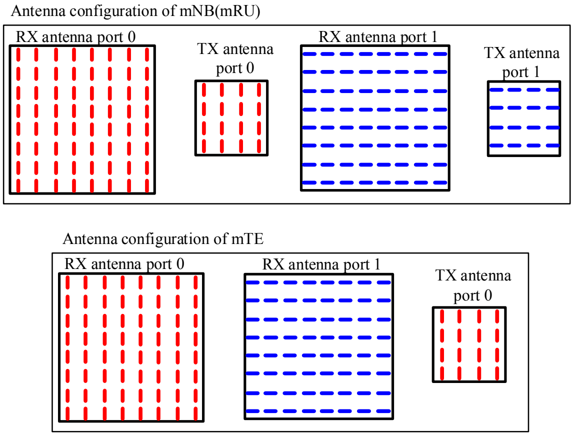

Fig. 2. Antenna configuration of mRU and mTE

III. HIGH SPEED PERFORMANCE

In this section, we evaluate six numerology sets under a realistic HST environment. The evaluations are based on agreed assumptions in 3GPP [5]. Candidate OFDM numerology sets include subcarrier spacing, FFT size, CP length and so on. The numerology parameters are carefully selected to reflect the fading channel characteristics such as Doppler shift/spread and phase noise characteristics.

A. *Candidate Numerology Sets*

Assuming a 30 GHz carrier frequency, we consider the following six subcarrier spacing sets: {15, 30, 60, 120, 240, 480} kHz. These subcarrier spacing values have scalable property with a scaling factor of 2^n with an integer n, which relieves the effects of Doppler shift/spread and phase noise. The numerology sets to be evaluated are shown in TABLE II.

B. *Simulation Parmeters*

The link-level simulation parameters are given in TABLE III. Note that the multi pole/zero phase noise model is considered [10]. In the simulation, the frequency offset due to the Doppler shift and common phase errors due to the phase error are compensated.

C. *Simulation Results*

We plotted the spectrum efficiency as a function of subcarrier spacing for different MCS sets at the UE speeds of {100, 300, 500} km/h in Fig. 3 (TDL-D with DS = 10 ns) and Fig. 4 (TDL-D with DS = 100 ns). We can see that larger subcarrier spacing values are more effective in achieving higher spectrum efficiency when DS = 10ns. However, for DS = 100ns, the largest subcarrier spacing value of 480 kHz results in reduced spectrum efficiency when 256QAM with 3/4 code is employed. Note that the spectrum efficiency becomes sensitive to the subcarrier spacing with higher modulation-coding scheme (MCS) set and higher train speed. For both DS values, subcarrier spacing values of 120 kHz and 240 kHz yield acceptable performance.

TABLE II. PROPOSED OFDM NUMEROLOGY SETS

	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6
Subcarrier spacing (kHz)	15	30	60	120	240	480
System bandwidth (MHz)	80	80	80	80	80	80
FFT size	8192	4096	2048	1024	512	256
Number of used subcarriers	4800	2400	1200	600	300	150
OFDM symbol length (us)	66.67	33.33	16.67	8.33	4.17	2.08
CP length of the 1st symbol (us)	6.05	3.08	1.54	0.82	0.46	0.28
CP length of the remaining symbols (us)	4.66	2.33	1.16	0.58	0.28	0.14

TABLE III. LINK-LEVEL SIMULATION PARAMETERS

Parameter	Value
Carrier frequency	30 GHz
System bandwidth	80 MHz
Channel coding	LTE Turbo
MCS	16QAM 2/3, 64QAM 3/4, 256QAM 3/4
Number of layers	1
Control channel	None
Channel estimation	Ideal
Equalizer	LMMSE
Channel model	TDL-A (10ns, 30ns), TDL-C (300ns, 1000ns), TDL-D (10ns, 100ns with K-factor = 13.3 dB)
Phase noise model	Multi-pole/zero model
UE speed	{100, 300, 500} km/h

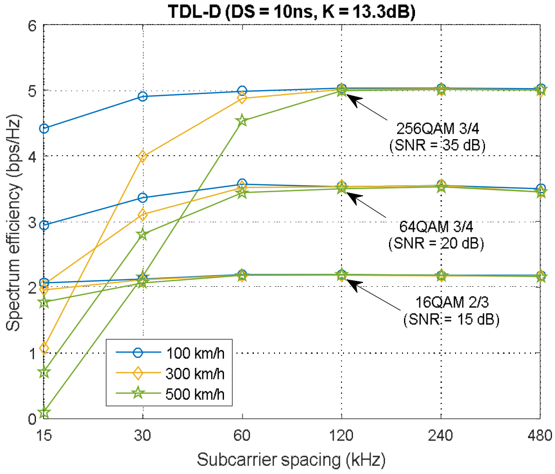

Fig. 3. Spectrum efficiency vs. subcarrier spacing for TDL-D channel (Delay spread = 10ns)

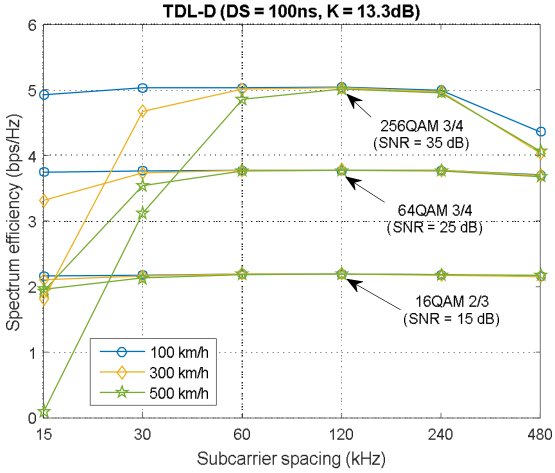

Fig. 4. Spectrum efficiency vs. subcarrier spacing for TDL-D channel (Delay spread = 100ns)

IV. MOBILITY MANAGEMENT

During 3GPP New Radio the study item phase, adoption of mmWave and directional network deployments are under consideration for high speed (HS) scenarios. Fig. 5 shows the directional network deployment for a HS scenario for 30 GHz [5]. Similarly in the MHN system design, an mTE located on the train is employed for configuring mmWave based wireless backhaul links. One of the main benefits of employing a relay configuration instead of establishing direct links from onboard users to the mRUs or remote radio head (RRH) is to apply the group handover concept.

A. Random Access Procedure

In the MHN system, when considering the wireless backhaul link between mTE and mRU, the challenges on enabling reliable and high data capacity communications can be summarized as follows:

1) Frequent handover due to high mobility:

In this case, the successful rate of random access (RA) procedure and handover interruption time should be well considered.

2) Severe radio link failure during handover in directional network:

The reason is that mTE is always attempting to handover from a source cell with strong received power to a target cell with weak received power, in which case the mTE may not be able to report the target cell to the source cell or receive a handover command.

3) RA procedure:

Conventional 4-step RA procedure for initial access and 2-step procedure for handover in LTE system are not suitable for HST in directional network, since for HST communication environment, it will be contention-free for RA.

4) Timing advance (TA) feedback:

Updating TA in time and accurately might be difficult due to the high mobility of a HST. Furthermore, the TA feedback may be not necessary for uplink synchronization of multiple UEs, since there is only one active mTE within the coverage of each cell for safety in most cases.

Therefore, based on the above considerations, a simplified 2-step RA procedure in Fig. 6 can be used for the HST communication to overcome these challenges, where message 1 includes not only a preamble but also a temporary mTE identification such as preamble index, for network registration and contention resolution in a non-severe contention environment. Additionally, the TA information is not necessary in message 2 transmission, which helps to reduce the uncertainty due to the TA estimation delay and feedback error as well as a processing delay.

B. Mobility management

Fig. 7 shows a proposed reference signal (PRS) design for multiple purposes including mobility measurement. It is multiplexed with synchronization signal (SS) block, and inserted into resources for physical broadcast channel (PBCH). This PRS design shows benefits with respect to

1) The PRS within PBCH can be used for layer 3 RRM (Radio Resource Management) measurement in IDLE mode and its wideband extension can be used in CONNECTED mode.

2) The PRS pattern can be used for indicating beam index (SS block index) in multi-beam system

3) The PRS can be used for PBCH demodulation as its demodulation reference signal for boosting PBCH demodulation performance in high speed environment. Also, it enables 2-port or multi-port transmission of PBCH.

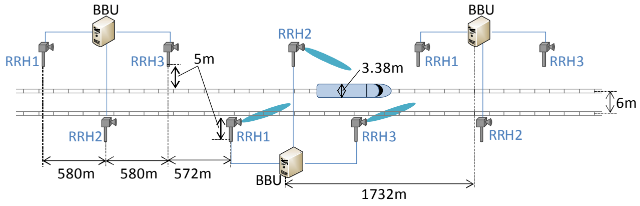

Fig. 5. Directional network deployment for HS scenario in NR

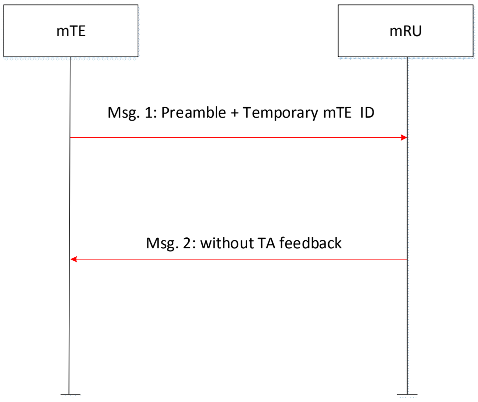

Fig. 6. Directional network deployment for HS scenario in NR

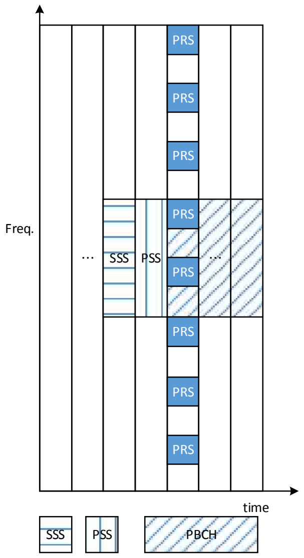

Fig. 7. PRS multiplexed in SS block

V. FIELD TRIAL

A field trial with an MHN system prototype had been conducted along 2.4 km long railway line through three stations of Seoul Subway Line 8. Five mRUs were installed inside the tunnel of the subway as in Fig. 8. The distance between adjacent mRUs were adjusted to cover all routes through three stations. As a result, the four mRUs were rather close to each other to cover the curved path whereas the other mRU was 1.2 km from the nearest mRU to cover the straight path. In the control center of Jamsil Station, five mDU cards were rack mounted to control the five mRUs that were connected through fiber optic cables. An mTE was right behind the front window in the engine room of a train running on the route. The carrier frequency of the prototype is 25-25.5 GHz (500 MHz bandwidth), and the antenna gains of the TX and RX are 16 dBi and 22 dBi, respectively, and the transmit power is 100 mW. The maximum train speed during the experiment was 80 km.

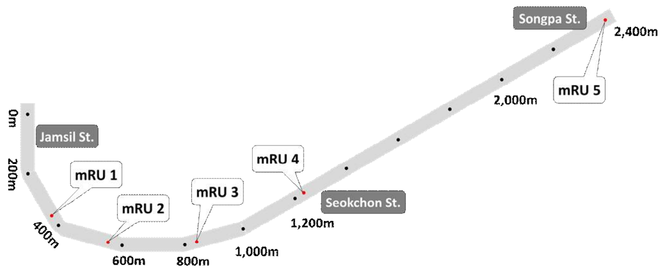

Fig. 8. Location of mRUs installed in Seoul Subway Line 8

Fig. 9 shows downlink/uplink data throughput measured during the 2.4 km run of the train with the mTE. Four red circles indicate handover regions. In the field trial, the downlink data throughput was close to 1.25 Gbps, excluding four handover points. That is, the deployed mRUs completely cover the path without coverage holes. Meanwhile, the uplink data throughput was close to 110 Mbps. We set the downlink-uplink time duration to 7:1 in time-domain duplexing.

Fig. 9. Measured data throughput during 2.4 km run

VI. CONCLUSION

Future 5G networks are predicted to come out in a couple of years. They will help innovate our business and society. For this reason, the ongoing standardization in 3GPP is considering many usage scenarios in association with KPIs. For example, the HST scenario is the usage case aimed at providing 100 Mbps of user experienced data rate for hundreds of passengers in the HST with very high mobility of up to 500 km/h. The research in 5G CHAMPION project is in line with the idea. In this regard, we presented the MHN mobile wireless backhaul system based on millimeter waves to support multi-gigabit data rates for the wireless backhaul link for the HST.

The MHN system was designed to keep robustness against the performance degradation from the high mobility of moving vehicles, the HSTs or the subway trains. In the numerology evaluation, we found out that 120 kHz or greater values are required as a subcarrier spacing to ensure good performance at 500 km/h of speed and at 30 GHz of carrier frequency. This was considered to select the OFDM parameters described in section II. Beamforming is important to compensate for the high free space loss of millimeter wave. The TX and RX antenna were designed to get reasonable cell coverages. The TX antenna had 16 dBi of gain and RX had 22 dBi of gain. In a field demonstration, these fixed beam-formed antennas were able to cover 1.2 km straight path. In the mobility management study, we concentrated on enhancement in the random access procedure. For example, a two-step random access to reduce handover interruption time has been discussed in the 3GPP. Finally, we developed the MHN system prototype, and had a proof-of-concept demonstration presenting its performance on the running train of Seoul Subway Line 8. It has shown that the downlink throughput was 1.25 Gbps and stable handovers were performed over 2.4 km path in the tunnel. The next phase of the MHN system is to fully utilize 1 GHz of mmWave and implement the polarization MIMO for 5 Gbps of data rate.

ACKNOWLEDGMENT

This work was supported by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIP) (No.B0115-17-0001, 5G Communication with a Heterogeneous, Agile Mobile network in the PyeongChang wInter Olympic competioN).

REFERENCES

[1] ITU-R Recommendation M.2083-0, “IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond,” Sep. 2015.

[2] 3GPP TR22.891, “Feasibility study on new services and market technology enabler,” V14.2.0, Sep. 2016.

[3] White Paper, “NGMN 5G White Paper, Feb. 2015.

[4] White Paper, “Cisco visual networking index: Global moible data traffic forecast update , 2016-2021,” Feb. 2017.

[5] 3GPP TR 38.913, “Study on scenarios and requirements for next generation access technologies,” Jun. 2016.

[6] S. W. Choi, H. S. Chung, J. Kim, J. M. Ahn, and I. G. Kim, "Mobile Hotspot Network System for High-Speed Railway Communication using Millimeter Waves," ETRI Journal, vol. 38, no. 6, pp. 956-958, December 2016.

[7] J. P. Conti, “Hot spots on rails,” Commun. Engineer, vol. 3, no. 5, pp. 18-21, Oct. – Nov. 2005.

[8] D. T. Fokum and V. S. Frost, “Survey on methods for broadband Internet access on Trains,” IEEE Commun. Surveys & Tutorials, vol. 12, no. 2, pp. 171-185, Second Quarter 2010.

[9] J. Kim, H. S. Chung, S. W. Choi, I. G. Kim and Y. Han, “Mobile hotspot network enhancement system for high-speed railway communication,” 2017 11th European Conference on Antennas and Propagation (EuCAP), Paris, 2017, pp. 2896-2900.

[10] R1-163984, “Discussion on phase noise modeling,” RAN1#85, May 2016.