mmWave-based Mobile Backhaul Transceiver for High Speed Train Communication Systems

Gosan Noh†, Junhyeong Kim†‡, Hee Sang Chung†, Bing Hui†, Young-Min Choi*, and Ilgyu Kim†

†Electronics and Telecommunications Research Institute (ETRI), Daejeon 34129, Korea
‡School of Electrical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Korea
*Cleverlogic Inc., Daejeon 34125, Korea
E-mail: {gsnoh, jhkim41jf, hschung, huibing, igkim}@etri.re.kr†, ymchoi@cleverlogic.co.kr*

***Abstract*—This paper presents a testbed for evaluating feasibility and potential effectiveness of the mmWave-based mobile backhaul transceiver in a high speed train communication system. Employing a hierarchical relay network architecture where each user inside a train accesses the network with the aid of an onboard relay deployed at the train, practical obstacles from large train carriage penetration loss and group handover can be easily resolved. We provide design and implementation details of the proposed mobile relay-based network architecture, namely mobile hotspot network (MHN). We focus on baseband and RF front-end, which are able to support over-Gbps data rate per train in a mmWave band at a very high mobility up to 500 km/h. We also provide an actual field trial result in Seoul subway line 8 as well as an indoor lab test result. The subway test results show that around 1.25 Gbps downlink data rate is attainable along most of the actual subway paths.**

***Index Terms*—High speed train, mmWave, modem, implementation, testing.**

I. Introduction

The fifth generation (5G) wireless communication technology targets to boost network performance to extremely high levels, i.e., 1000 times higher data rate, less than 1ms latency, and 100 times more connected devices compared with the current 4G wireless technology [1]. These 5G target requirements correspond to the 5G use cases, i.e., enhanced Mobile Broadband (eMBB), ultra-reliable and low latency communications (URLLC), and massive Machine Type Communications (mMTC). Along with these use cases, various 5G deployment scenarios have been identified such as indoor, urban, rural, high speed train, highway, and so on [2].

Among these deployment scenarios, the high speed train scenario has gained considerable interest as a result of the recent large-scale, worldwide deployment of high speed train systems [3]. The 5G high speed train scenario is supposed to provide very high data rate (i.e., over-Gbps per train) continuously along the railway at a very high speed (i.e., up to 500 km/h).

In order to satisfy these highly demanding requirements, we employ: 1) a millimeter wave (mmWave) frequency band having an enormous amount of available bandwidth required for supporting very high data rate, and 2) a hierarchical relay network architecture where each user inside a train can access the network through an onboard mobile relay, thereby enabling to overcome the obstacles such as large train carriage penetration loss and group handover-induced signaling storm. The proposed mobile relay-based network architecture, namely mobile hotspot network (MHN), can be a potential solution for supporting the 5G high speed train scenario [4], [5].

In this paper, we provide design and implementation details of the MHN system, mainly focusing on the baseband and RF front-end. Specifically, frame structure and baseband processing are designed to overcome severe Doppler effects occurred by high mobility. RF and antenna designs are conducted so as to meet mmWave hardware constraints and channel propagation characteristics. Field test trials using the developed MHN testbed are performed in indoor lab and real subway environments.

The rest of this paper is organized as follows. Section II presents the system description. We provide the baseband design of the MHN system in Section III and the RF front-end design in Section IV. Testing procedures and results are given in Section V, and Section VI concludes the paper.

II. System Description

We consider a hierarchical relay network where each user inside a train connects to the network via an onboard relay or, in other words, terminal equipment (TE) installed at the head and/or tail of the train, as seen in Fig. 1. This system architecture is particularly advantageous for overcoming high penetration loss from train carriage made of metal alloys and signaling storm caused by group handover [3]. Each TE communicates with the nearest radio unit (RU) deployed along the rail track. Each RU consists of RF transceiver and antenna. Several adjacent RUs are connected to a digital unit (DU) via radio-over-fiber (RoF) links. DUs are responsible for baseband processing and other important higher layer functionalities such as inter-RU mobility management. The access network is connected to the public internet through the gateway (GW).

We employ mmWave backhaul link between the RU and TE in a frequency band of 25 GHz. Both RU and TE are equipped with high-gain array antennas such that directional

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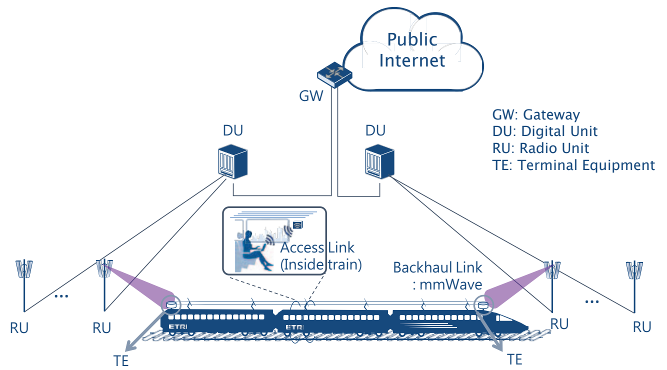

Fig. 1. Hierarchical relay network architecture for high speed train.

narrow beams oppositely facing each other are generated along the track. Since high speed rail tracks tend to be highly straight, additional gain from the beam steering is rather limited. Hence, we employ only fixed beamforming. In addition to the single transmission either at the head or tail of the train, simultaneous transmission both at the head and tail can be supported using the same frequency band. Assuming sufficiently long train length, the interference between transmissions at the head and tail is not significant.

Inside each train carriage, UEs access to the access point (AP) that are connected to the TE. WiFi or femto cell technology can be employed [6]. Since the radio propagation environment inside the train carriage is quite similar to the indoor environment, we focus on the backhaul link between the RU and TE throughout this paper.

III. Baseband Design

In this section, we firstly describe frame structure of the MHN system. Then, in order to tackle very high speed, we provide design considerations for Doppler mitigation. Lastly, we summarize the baseband processing procedure.

A. Frame Structure

We employ orthogonal frequency-division multiple access (OFDMA) as a multiple access scheme both for downlink and uplink. Since deployed on the train, TEs are less limited in power or size, reducing the need for the low peak-to-average power ratio (PAPR) schemes in the uplink such as single carrier frequency-division multiple access (SC-FDMA). The subcarrier spacing is chosen as 180 kHz, considering the characteristics of mmWave and high mobility. As a duplexing scheme, we employ time-division duplexing (TDD), which enables flexible downlink and uplink configuration and reduces implementation complexity [7]. In order to efficiently support wideband transmission, carrier aggregation (CA) is used where each component carrier (CC) is 125 MHz wide and the number of CCs are configurable from 2 up to 8.

Fig. 2 shows the frame structure, where each radio frame of 10 ms in length consists of 5 subframes. Each subframe is 2 ms long and further divided into 8 slots. A slot, a unit of transmission time interval (TTI), has a length of 250 μs. There are 40 OFDM symbols within a slot. Each OFDM symbol is 6.25 μs long with cyclic prefix (CP) length of 0.69 μs. The detailed system parameters are summarized in Table I.

Table I
System Parameters

Parameter	Value
CC bandwidth (MHz)	125
Number of CCs	2-8
FFT size	1024
Sampling rate (MHz)	184.32
Number of used subcarriers	600
OFDM symbol length (μs)	5.56
CP length (μs)	0.69
Number of symbols per slot	40
Slot length (μs)	250
Modulation schemes	QPSK, 16QAM, 64QAM
Channel coding	Turbo, Convolutional

B. Doppler Mitigation

We consider supporting high speed train communications with speed up to 500 km/h. At that speed along with mmWave frequency bands, the maximum Doppler spread can be tens of kHz. In this case, the channel is highly time-varying and its estimation is not a trivial task. In order to well estimate such a high mobility channel, we allocate downlink reference signal such that the time interval T_p between the two adjacent OFDM symbols containing reference signals is 25 μs, hence satisfying the Nyquist sampling theorem, i.e., $1/T_p \geq 2f_D$, where f_D is the maximum Doppler spread [3].

In addition to the Doppler spread, Doppler shift due to line-of-sight (LOS) components occurs large frequency offset, significantly degrading the link performance. The amount of Doppler shift is more significant for the uplink, i.e., doubled Doppler shift compared to the downlink due to the oscillator locked to the downlink signal [6]. The uplink reference signal of the MHN system is designed to estimate the uplink frequency offset up to the range of $[-26.67, 26.67]$ kHz. When the amount of frequency offset is correctly estimated, the Doppler-induced frequency offset can be efficiently compensated by, for example, automatic frequency control (AFC) in the time-domain.

C. Baseband Modem Design

Modem architectures of DU and TE are depicted in Fig. 3 and Fig. 4, respectively. The DU modem consists of several sub-modules including transport channel (TrCH) encoder/decoder, downlink modulator, and uplink demodulator. Similarly, the TE modem consists of TrCH encoder/decoder, uplink modulator, and downlink demodulator. Additionally, the TE modem includes the front-end controller and cell searcher. Front-end controller controls and monitors the operations of the RF front-end. Cell searcher is responsible for acquiring time/frequency synchronization, frame timing, and cell identity. For both DU and TE modems, interfaces to the corresponding L1 controller are configured. Additionally, the TE modem also provides control signalling for the antenna module.

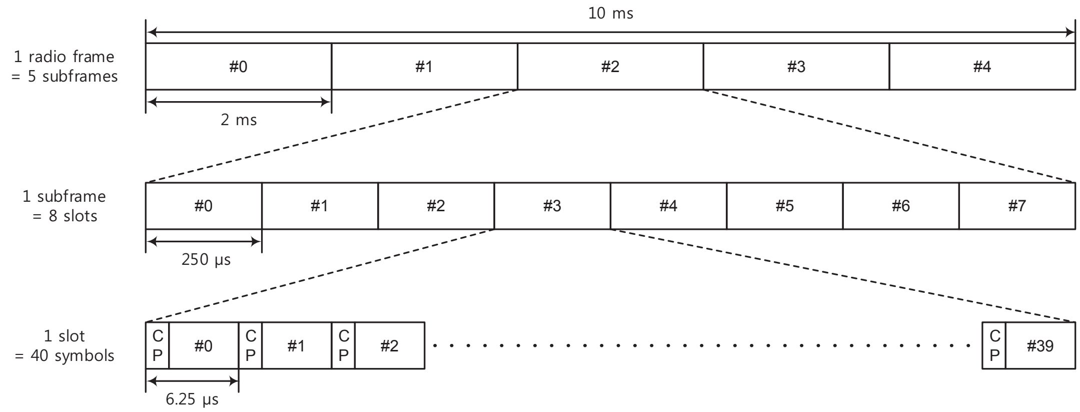

Fig. 2. Frame structure of the MHN system.

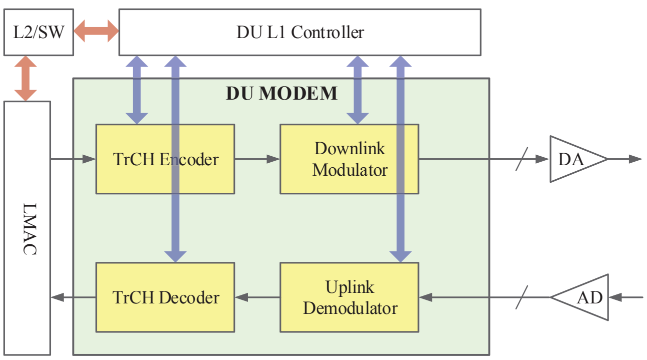

Fig. 3. DU modem architecture and interface to higher layer.

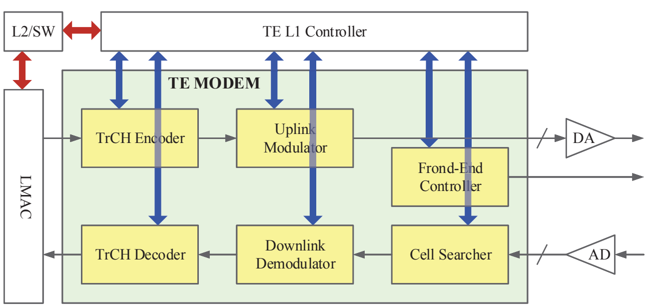

Fig. 4. TE modem architecture and interface to higher layer.

IV. RF Front-End Design

This section describes RF front-end design of the MHN system, which includes RF and antenna designs.

A. RF Design Requirements and Parameters

The RF design for the MHN system incorporates the following considerations. The RU has two transmit (TX) and receive (RX) RF paths. The TE has one TX and two RX RF paths. In the RF design, we employ 4 CCs for carrier aggregation, where the CCs are contiguously allocated in the same band as in [8], thereby minimizing the aggregated bandwidth. The detailed RF design requirements and parameters are summarized in Table II.

Table II
RF Design Parameters

	Parameter	Value
Common	Operating frequency (GHz)	25.1056-25.5376
	Bandwidth (MHz)	432 (w/o guard band)
	DIF frequency (MHz)	705.6-1137.6
	TDD switching time (μs)	< 5
	TRX isolation (dB)	> 55
TX	TX DIF input (dBm)	-20
	TX Output power (dBm)	$> +17$
	Gain (dB)	> 37
	Gain flatness (dB)	± 2.0
	TX spuriousness (dBc)	$<$ -40
	TX EVM (%)	< 3
	TX antenna array gain (dBi)	19
RX	Noise figure (dB)	8
	RX input level (dBm)	[-61, -20]
	Gain (dB)	> 51
	Gain flatness (dB)	± 2.0
	Gain control (dB)	$\geq 0.5/31.5$, ≥ 15
	DIF output (dBm)	-10
	RX antenna array gain (dBi)	22

B. RF and Antenna Designs

The RF design consists of three parts: intermediate frequency (IF), local oscillator (LO), and mmWave parts as shown in Fig. 5. The baseband signal is firstly up-converted to the IF band and then to the mmWave band. The IF and mmWave parts have two separate paths for transmission and reception, respectively. They correspond to the transmit antenna and receive antenna, respectively. The two paths are switched in the time-domain by single-point double-throw (SPDT) switches. The devices for digital attenuation and temperature compensation are also implemented.

Slotted waveguide array antennas are employed for the MHN system. Each TX antenna has 4x4 radiating elements with an array gain of 19 dBi. Each RX antenna has 6x6 radiating elements with an array gain of 22 dBi. The TX antenna should keep the regulatory output power in terms of equivalent isotropic radiated power (EIRP), i.e., the sum of the maximum output power and the array gain should be lower

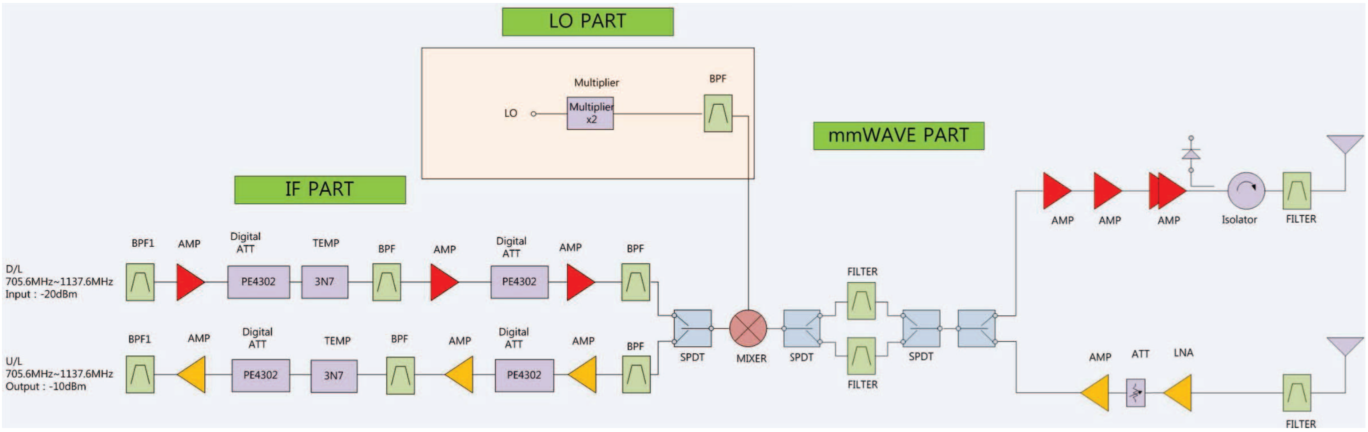

Fig. 5. RF block diagram.

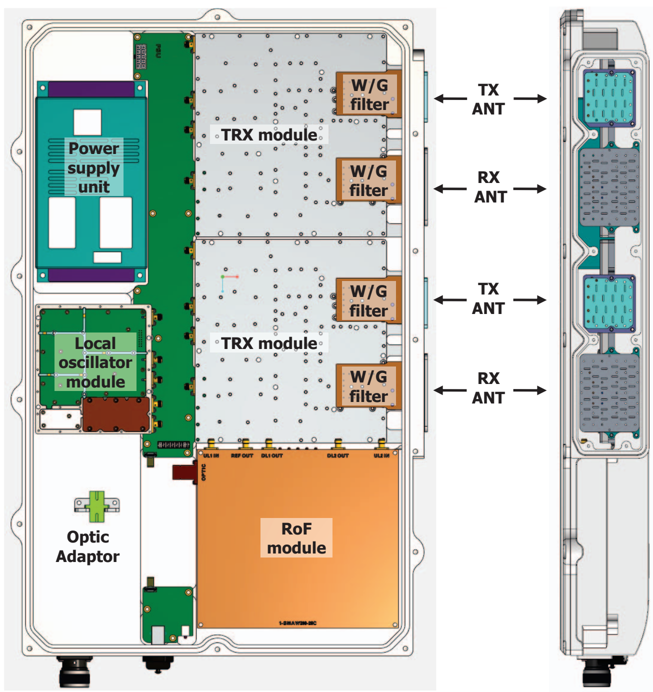

Fig. 6. RU layout including TRX module and antenna.

than 36 dBm. On the other hand, there is no regulation on the RX array gain, which can be set much higher to achieve the coverage requirements of 300m for curved path and 500m for straight path, respectively.

Fig. 6 shows the RU layout that includes two TRX modules and 2TX/2RX antennas, seen from two different angles. Besides the TRX modules, the RU includes a power supply module, local oscillator module, and RoF interface module. The RoF interface is used to connect the RU and the corresponding DU. The fiber length between the two units is up to 5km.

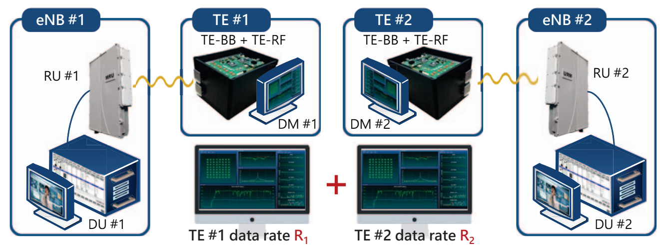

Fig. 7. Setup for the indoor lab test.

V. Testing Procedures and Results

The implemented baseband, RF, and antenna modules has been tested in various environments, i.e., indoor lab and subway. The testing procedures and results are discussed in the followings.

A. Indoor Lab Test

Primary functionalities of the MHN system are firstly tested in an indoor lab environment before moving to outdoor field tests. A test setup is shown in Fig. 7. An eNB consist of a DU and an RU. A TE includes a baseband part and RF part. The setup is for the dual-link test which mimics a scenario where simultaneous transmissions are done both at the head and tail of the train using the same frequency. Though they use the same frequency, the interference to the neighbor link was shown to be not significant. The peak data rate of 1.25 Gbps was observed at the diagnostic monitor for each link. The corresponding aggregated data rate was 2.5 Gbps.

B. Subway Field Test

In order to evaluate the MHN system in more realistic environment, we have conducted subway field test in Seoul subway line 8. The subway runs at up to 80 km/h inside the tunnel which is a typical example of a strong and fast fading environment. Fig. 8a shows a train path of Seoul subway line 8 where the MHN system was tested. Five RUs were installed from Jamsil Station through Seokchon Station to Songpa Station. After a mmWave propagation test, the locations of the

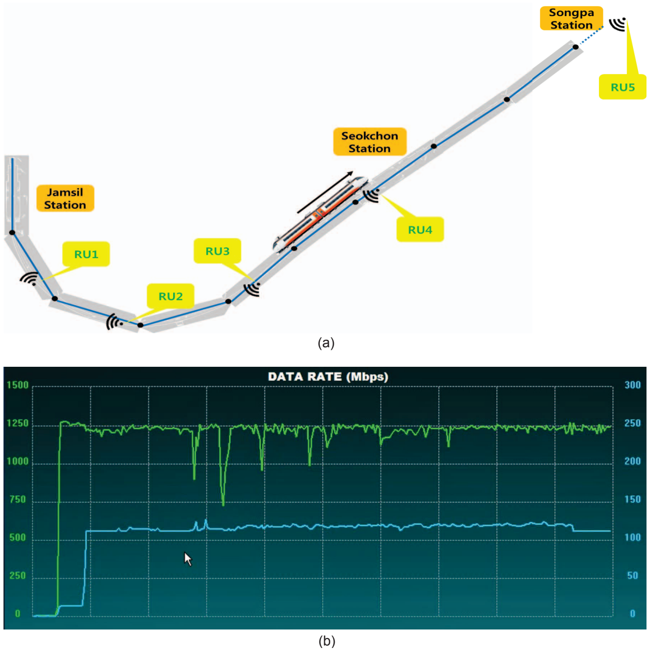

Fig. 8. Testing in Seoul subway line 8: a) Path for subway field test; b) Data rate results.

RUs were carefully determined so that the LOS paths between RUs and TE exist most of the time. At the same time, however, some additional non-LOS paths also exist due to reflections in the tunnel. Fig. 8b illustrates a captured performance monitoring display that includes downlink (green) and uplink (blue) data rates, along the subway path from Jamsil Station to Songpa Station. It is shown that downlink data rate of 1.25 Gbps can be achieved most of the time. We can see some points where data rate drops below 1 Gbps, which is mainly due to the loss from handover delay and signaling overhead. Note that uplink data rate is lower than the downlink data rate due to the employment of asymmetric downlink/uplink TDD configuration.

VI. Conclusion

In this paper, we presented mmWave-based mobile backhaul transceiver for high speed train communication systems, focusing on the design and implementation of baseband modem and RF front-end. The system design pursued to ensure the robustness to the severe Doppler effects induced by very high mobility up to 500km/h while achieving over-Gbps data rate. The developed testbed was tested in an indoor lab environment and an actual railway environment, i.e., Seoul subway line 8. Test results reveal that downlink data rate of 1.25 Gbps is achievable even in a strong and fast fading environment, i.e., tunnel. In addition, from indoor lab test, we expect that 2.5 Gbps downlink data rate is also achievable by generating two opposite beams at the head and tail of the train and simultaneously receiving from two RUs.

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