2017 11th European Conference on Antennas and Propagation (EUCAP)

Mobile Hotspot Network Enhancement System for High-Speed Railway Communication

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***Abstract*—The mobile hotspot network (MHN) system is a system for high-speed railway communications capable of providing a gigabit-per-second backhaul capacity employing millimeter-wave. This paper provides an overview of MHN enhancement (MHN-E) system that's been developed so far, and also addresses some of the major technical challenges that need to be overcome and discuss several viable technical solutions for further enhancements. One of the most important goals in the development of the MHN-E is to further increase wireless backhaul capacity and improve its reliability compared with the first version of the MHN system, which will meet the high-speed-related requirements set by ITU for IMT-2020 or 5G.**

***Index Terms*—millimeter waves, railway communication, high-speed scenarios, 5G.**

I. INTRODUCTION

Mobile communication has been one of the most successful technology innovations in modern history. According to Cisco's white paper, mobile data traffic has grown 4,000-fold over the past ten years, reaching 3.7 exabytes per month as of 2015 [1]. Moreover, owing to the proliferation of portable smart devices such as mobile phones and tablets, mobile data traffic even on the high-speed transportations such as bus, subway and high-speed train has been explosively increasing. However the existing standards including mobile worldwide interoperability for microwave access (WiMAX), long term evolution (LTE) and LTE-Advanced (LTE-A) as well as some commercialized systems are hard to meet the growing demand of users in this case.

Recently, Electronics and Telecommunications Research Institute (ETRI), as a pioneer in millimeter-wave-based railway communications technology, has developed a mobile hotspot network (MHN) system employing millimeter-wave [2], which is capable of providing a wireless backhaul data rate of Giga bits per second (Gbps) for high-speed railway (HSR) communication. ETRI also successfully gave a demonstration of the MHN system in the Seoul subway line 8, which was a world first prototype system demonstrated in the running subway train with passengers.

Meanwhile, in order to offer a better mobile Internet service in high-speed environments, some of the most relevant international standardization bodies have started focusing on high-speed scenarios. The 3rd Generation Partnership Project (3GPP) has recently started the 5G standardization effort in order to meet all the 5G requirements and use cases defined by the IMT-2020 [3]. Specifically in the Technical Specification Group (TSG) Radio Access Network (RAN), after a study item of "scenarios and requirements for next generation access technologies" was approved at the RAN#70 plenary meeting (in Mar. 2016), a new radio access technology has been being studied through an initial evaluation of various new physical layer techniques such as modulation, waveform, multiple access, channel coding, and MIMO for different deployment scenarios [4]. Among those various 5G deployment scenarios, the high speed scenario mainly focuses on providing an advanced specification based on frequency band of 4 or 30 GHz [2].

IEEE 802.15, a working group (WG) of the IEEE 802 standards committee, launched an Interest Group (IG) named High Rate Rail Communications (HRRC) in November 2014, based on the proposal made by ETRI [5]. The main objective of this IG is to focus on standardization of a mobile wireless backhaul for user groups located in the fast moving vehicles. In this IG, a wide range of frequency bands including millimeter-wave have been studied as candidates for the broadband wireless backhaul links for the fast moving vehicles through ray-tracing channel modeling and system demonstration, showing its infinite feasibility and potentiality [6][7][8]. The IEEE 802.15 IG HRRC holds a joint meeting with the 802.16 WG, and they have reached an agreement that they can consider the transition to a Study Group (SG) when enough interest has been identified.

The rest of this paper is organized as follows. In section II, we provide an overview of the MHN enhancement (MHN-E) system including its basic concepts, physical layer design and major differences compared with the conventional MHN system. Next, some of the technical challenges and possible solutions along with simulation results are presented in section III. Finally, we made conclusions of the paper with brief discussions of future work in section IV.

II. MHN ENHANCEMENT

Since a wide range of applications such as virtual reality (VR) and augmented reality (AR), which requires higher data rates and lower latency, are prospering nowadays, this motivates us to further develop MHN towards MHN-E that aims to further improve system performance, especially in terms of wireless backhaul capacity and link reliability. In this section, we give a brief overview of the MHN-E system that's been developed so far.

A. Basic System Architecture

The system architecture of both MHN-E and conventional MHN systems basically originates in the hierarchical two-hop network, which, as illustrated in Fig. 1, consists of mobile wireless backhaul (MWB) link outside using millimeter-wave and onboard access link. Since this network concept has several well-known advantages [9], it has already been applied to many commercialized railway communication systems [2], and is also being considered as one of the potential deployment scenarios by both 3GPP and IEEE 802 [3].

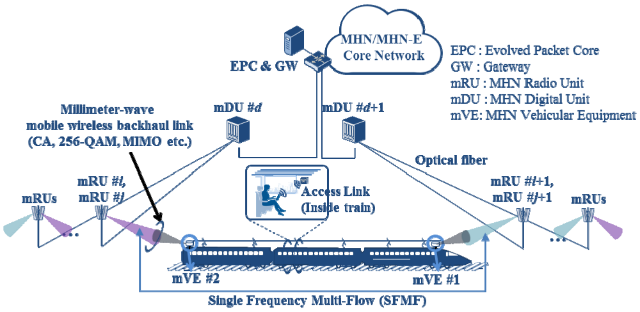

Fig. 1. System architecture of MHN/MHN-E

In the MHN/MHN-E network, MHN digital unit (mDU) and MHN radio unit (mRU) are separated from each other and interconnected via optical fiber, which forms an efficient cloud radio access network (C-RAN). Each individual mRU with its corresponding mDU functions as a base station, hence has a unique cell ID different from others. As illustrated in Fig. 1, the mRUs are deployed along the trackside, and two mRUs installed in the same location transmit sharp beams pointing to opposite directions. As a result, MHN vehicular equipments (mVEs) mounted on top of both head and rear sides of the train could receive independent signals sent from mRUs of different sites simultaneously. Each mVE behaves like a single user connected to onboard access link providing mobile Internet service to user equipments (UEs) carried by passengers in the train.

In this paper, we focus on the millimeter-wave MWBs, which are mainly responsible for Gbps wireless data backhauling between mRUs and mVEs. Onboard access link inside the train, on the other hand, is beyond the scope of this paper and a commercialized system such as wireless fidelity (Wi-Fi) may be a good candidate since it is basically similar to the indoor scenario.

B. MHN-E Design Goals

Our ambition to further develop MHN towards MHN enhancement is to significantly increase the capacity and improve link reliability through an introduction of advanced technologies. Hence, the MHN-E system has several characteristics that are distinct from the conventional MHN system, including a new frame structure supporting carrier aggregation (CA) and high-performance handover, MIMO technologies using polarization antennas and optimization of physical layer design.

TABLE I summarizes the development goals of the MHN-E comparing the specific parameters with the MHN, which will be validated in a future demonstration. Since we are planning to commercialize the MHN-E system, unlicensed frequency bands in the range of 25~26GHz, called Flexible Access Common Spectrum (FACS) in Korea, is chosen as the operating frequency. In this case, since the carrier frequency is lower than that of the MHN, it is advantageous for the system to support higher mobility of up to 500km/h, which is one of the key requirements of IMT-2020, without changing the subcarrier spacing of 180 kHz. However, it is mandatory to meet Effective Isotropic Radiated Power (EIRP) requirement regulated by Korean government, where the maximum EIRP allowed is 36dBm.

TABLE I. MHN-E DESIGN GOALS

Design Parameters	**Comparison**	
	MHN-E	***MHN***
Frequency	25.5 GHz	31.625 GHz
Bandwidth	1 GHz	250 MHz
EIRP	36 dBm	42 dBm
Mobility support	500 km/h	400 km/h
Modulation order	QPSK, 16QAM, 64QAM, 256QAM	QPSK, 16QAM, 64QAM
Antenna configurations	2x2 SFMF 2x2 MIMO	2x2 SFMF 1x1 SISO
Maximum throughput	10Gbps	1Gbps

C. Frame Structure

As aforementioned, one of the new features included in the MHN-E specification is a new frame structure supporting CA and high-performance handover as shown in Fig. 2. Each aggregated carrier, generally referred to as a component carrier (CC), has a bandwidth of 125MHz, and orthogonal frequency division multiplexing (OFDM) parameters of which are basically identical to that of the MHN [2]. The MHN-E allows the aggregation of a maximum of eight CCs to attain a total transmission bandwidth of up to 1GHz. Additionally, it is required that at least two CCs should be supported as mandatory and the different number of CCs, 2~8, can be configured depending on mVE capability.

Each configured CC in the MHN-E system employs OFDM for both uplink (UL) and downlink (DL) transmissions, same as the MHN system. It also supports both frequency-division duplex (FDD) and time-division duplex (TDD) as uplink-downlink duplexing. Considering that data traffic in high-speed scenarios is largely asymmetric in nature, where downloads typically accounts for most of the traffic, the DL is prioritized rather than UL in this case. In this regard, we focus on further enhancements to TDD for

MHN-E in the paper. Like other cellular systems, TDD of MHN/MHN-E is able to offer dynamic resource allocation where time durations are changed as required whereas equal bandwidth is usually allocated to both DL and UL in FDD.

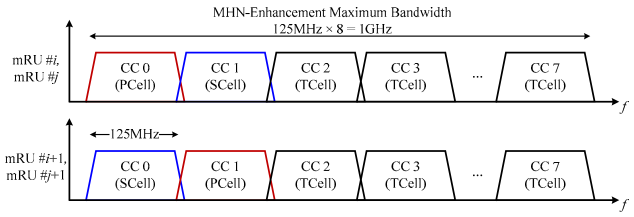

Fig. 2. Contiguous intra-band carrier aggregation of 8 × 125MHz component carriers in MHN-E

Fig. 3 shows the TDD frame structure of the MHN-E system. The second slot in each subframe of 2*ms*, *l*-th slot (*l*=1,9,17,25,33), is a special slot, which consists of downlink pilot time slot (DwPTS), guard period (GP), and uplink pilot time slot (UpPTS). Fig. 3 also shows three different UL-DL configuration supported in MHN-E, and their corresponding ratios of DL to UL.

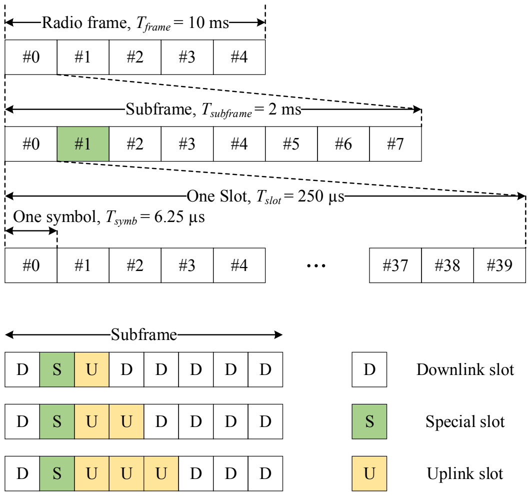

Fig. 3. TDD frame structure of MHN-E [2]

Due to the characteristics of received signal strength of mVE #1 as shown in Fig. 4 where the SNR received from serving mRU is much larger than that received from target mRU most of the time and drastically drops in a very short time, it is highly difficult to obtain cell information and timing synchronization of a target cell prior to handover. This is the main reason why three different cell types are defined in the MHN-E system, which are primary cell (PCell), secondary cell (SCell), and tertiary cell (TCell). Each CC can be configured by one of the cell types. The first and second CCs are configured by either PCell or SCell depending on the location of mRU as shown in the Fig. 2 and the remaining CCs are configured by TCell.

As illustrated in Fig. 5, the PCell is not only responsible for sending data and control channels, but also for sending MHN synchronization signal and cell information through MHN broadcast channel (M-BCH). The SCell and TCell, on the other hand, only send data and control information. The main difference between the two is that the SCell vacates the resource location where MHN broadcast channel (M-BCH) or synchronization signal is transmitted in the PCell in order to detect target cell signal without interference from serving cell.

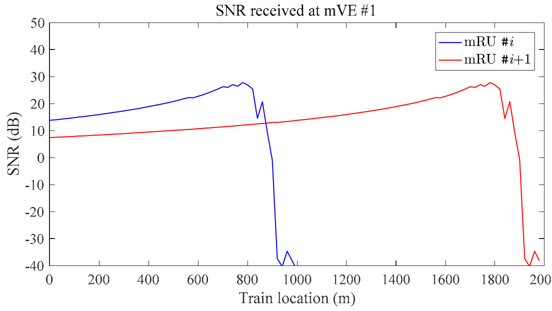

Fig. 4. Received SNR of mVE #1 in the case of fixed beamforming (BF) at both mRU and mVE

By contrast, the characteristic of the SNR received at mVE #2 will be reversed which can be simply deduced from the Fig. 4. In this case, a different approach needs to be developed for handover support and it will be presented in a future work along with handover procedure for both mVE #1 and mVE #2.

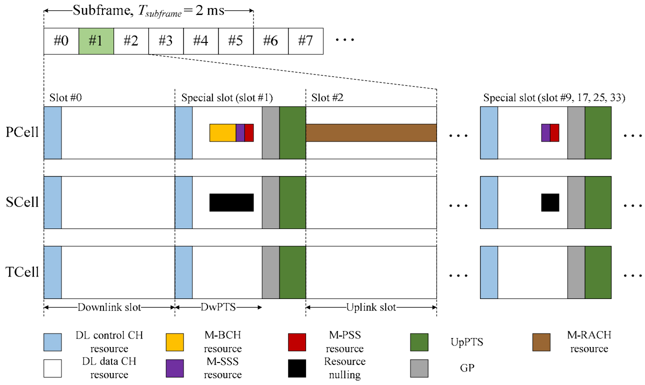

Fig. 5. A new frame structure for MHN-E carrier aggregation

Additionally, MHN random access channel (M-RACH), which mainly is used to get access to the network and obtain timing alignment information to synchronize uplink transmissions, is designed to be transmitted only in the PCell. Since in most cases, there is no train/mVE or only one train/mVE in a cell, there is almost little possibility of collision among the requests coming from multiple mVEs. At this point, the design of M-RACH could be a contention-free-based, and its procedure can be significantly simplified as compared with that of Cellular systems.

D. *Other Technical Enhancements*

By fully taking advantage of the MHN system architecture in which two mVEs on the train are spatially separated, the MHN-E system supports single frequency multi-flow (SFMF) transmission scheme. In this scheme, as illustrated in Fig. 1, both mRU and mVE form very sharp beams enabling each mVE to transmit/receive independent data to/from its corresponding mRU by mitigating inter-mRU interference, which will double the spectral efficiency. Besides, the MHN-E system will be able to further increase spectral efficiency by the adoption of MIMO technology that fully exploits the potential of polarization antenna suitable for millimeter-wave MIMO communications.

III. TECHNICAL CHALLENGES AND KEY ENABLING TECHNOLOGIES

Besides the new functionalities already introduced in the MHN-E specification as described in the previous section, several key enabling technologies are being considered to be supported in the MHN-E specification. Therefore, the main objective of this section is to offer a comprehensive discussion on the alternatives to the technical challenges and key technologies capable of further improving the performance.

A. *A Novel Handover Schemes based on Single Frequency Network*

For a MWB link of MHN-E, communication interruption could have a pernicious effect on service quality. In the MHN-E specification, we are targeting the system without interruption time when handover. However, considering that the distance between adjacent mRU is 1km and the velocity of the train is up to 500km/h, handover should be done in every 10 seconds, which results in extremely frequent handover. Moreover, if a hard handover scheme is used in the system, it makes the performance even worse, which is not acceptable to the MWB.

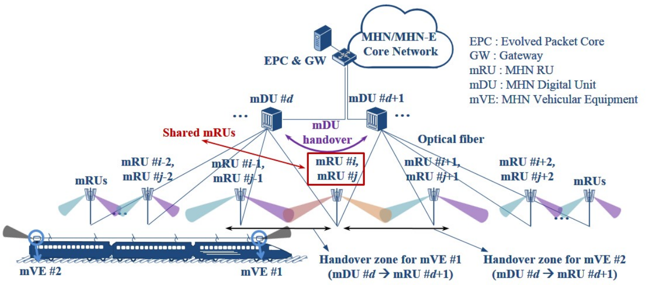

Fig. 6. A single frequency network with shared RU for HSR communications

For these reasons, single frequency network (SFN) and a handover scheme creating a proper handover zone are recently being considered in 3GPP as viable solutions to the beamforming-based HSR communications. Likewise, a shared RU-based SFN for MHN-E system as illustrated in Fig. 6 is being considered to be supported in the MHN-E. Even though it needs further elaboration before it can be included in the specification, it is expected to significantly improve handover performance and simplify its procedure. It is obvious that only inter-mDU handover is needed in this case while different inter-mRU and inter-mDU handover triggering conditions and related procedures are necessary to be defined for both mVE #1 and mVE #2. The inter-mDU handover is triggered after a mVE is connected to a shared mRU, and the handover process is performed while the mVE (mVE #1/mVE #2) is being connected to the shared RU (mRU #*i*/mRU #*j*), which could not only maintain the communication link between them, but also provide a sufficient time for the handover. More details on the handover mechanism including handover triggering condition for each side of mVE and the handover procedure are omitted here, and will be presented in a future work.

B. *Adaptive Beamforming*

In order to enlarge the signal coverage in millimeter-wave based communication systems, a proper beamforming is necessary. Hence, a simple computer simulation has been conducted to evaluate the performances of three different BF strategies in the MHN-E system based on the parameters listed in TABLE II. , which is basically the same methodology with almost same simulation settings in [10] except the carrier frequency, bandwidth as well as a different beam pattern of mRU as shown in the Fig. 7. The 3D beam radiation patterns of both TX and RX are given as the result of the antenna design, and the 3-dB beamwidths of TX and RX are 20 and 8 degrees respectively.

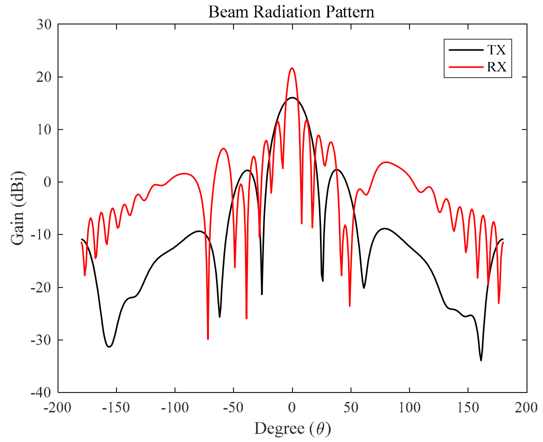

Fig. 7. Antenna radiation pattern of MHN-E

Performance evaluation mainly focuses on a wireless backhaul capacity per train, $C_{\text{MHN-E}}$, which is theoretically achievable and given as,

$$C_{\text{MHN-E}} = W \cdot \log_2 (1 + \gamma_1) + W \cdot \log_2 (1 + \gamma_2) \qquad (1)$$

where W is the bandwidth of the MHN-E system and γ_1 and γ_2 denote SINRs of mVE #1 and mVE #2 respectively.

In the simulation results of the papers [2][7][10] showing the SINR of each mVE versus train location, it was observed that except the near region, it is sufficient to apply the fixed BF scheme to both TX and RX sides most of the time from the implementation feasibility and performance perspectives. It is a plausible explanation as we can simply imagine that it is natural for a train running at a high speed to move in a straight line owing to safety issues, which can ensure a very good alignment between TX and RX beams. However, Fig. 8 shows the cumulative distribution function (CDF) of backhaul capacities for three beamforming strategies as assumed in [10], which implies that the adaptive BF is highly beneficial in increasing the backhaul capacity of a train.

TABLE II. SIMULATION PARAMETERS

Parameters	**Values**
Carrier frequency	f_c = 25.5 GHz
System bandwidth	W = 1 GHz
Transmit power	$P_{TX,dBm}$ = 20 dBm
Transmit beamforming gain	$P_{TX,dBm}$ = 16.04 dBi
Receive beamforming gain	$P_{RX,dBm}$ = 21.82 dBi
Free space path loss	[10]
Noise figure	$N_{F,dB}$ = 8 dB
mRU height	h_{mRU} = 10 m
mVE height	h_{mVE} = 3 m
Dist. between adj. mRUs	d_{mRU} = 1000 m
Dist. between adj. mVEs	d_{mVE} = 200 m
Dist. between railway track and mRUs	$d_{mRU\text{-}track}$ = 5 m

Furthermore, trains like subway and tram are most likely to run in either horizontal or vertical curved tracks at relatively low speeds, in which the adaptive BF will play a pivotal role.

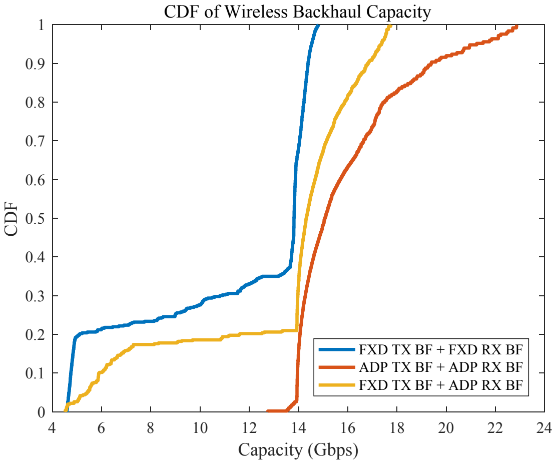

Fig. 8. CDF of the wireless backhaul capacity of MHN-E system

IV. CONCLUSION

ETRI, as a pioneer in millimeter-wave-based railway communications technology, successfully gave a demonstration of the MHN system in the Seoul subway line 8, which was the world's first demonstration of a millimeter-wave-based HSR communication system. Recently, we have embarked on a new research project aimed at developing the MHN-E system, an advanced system of the conventional MHN system, in order to meet the explosively growing data demand in high-speed environments. This paper provides a general overview of the MHN-E system and addresses several technical challenges and problems that give valuable insights into further enhancement for MHN-E system. A proof-of-concept implementation of MHN-E system will be realized to validate its performance and feasibility. For a future study, it is worth studying an effective feedback method for adaptive BF with a limited beam index in the MHN-E system.

ACKNOWLEDGMENT

This work was supported by Institute for Information & communications Technology Promotion(IITP) grant funded by the Korea government(MSIP) (No.B0115-16-0001, 5G Communication with a Heterogeneous, Agile Mobile network in the PyeongChang wInter Olympic competioN).

REFERENCES

[1] White Paper, "Cisco visual networking index: Global mobile data traffic forecast, 2015-2020," Feb. 3, 2016.

[2] S. W. Choi, H. Chung, J. Kim, J. Ahn, and I. Kim, "Mobile Hotspot Network System for High-Speed Railway Communications Using Millimeter Waves," *ETRI Journal*, vol. 38, no. 6, pp. 1042-1051, December 2016.

[3] 3GPP TR 38.913, "Study on Scenarios and Requirements for Next Generation Access Technologies," 2016.

[4] 3GPP TR 38.802, "Study on New Radio (NR) Access Technology Physical Layer Aspects," 2016.

[5] J. Kim, H. S. Chung, and I. G Kim, "Mobile Wireless Backhaul for Fast Moving Cells", IEEE 802.15-14-0671-00-wng0, Nov. 2014

[6] K. Guan and G. Li, "Mobile Channel Characterization in Typical Subway Tunnels at 30 GHz", IEEE 802.15-15-0666-02-hrrc, Sep. 2015

[7] K. Guan, G. Li, and B. Ai, "Ray-tracing based Study on Mobile Channel in Typical Urban Environment with Various Beamforming Strategies at 32 GHz", IEEE 802.15-15-0837-01-hrrc, Nov. 2015

[8] S. W. Choi, J. Kim, H. S. Chung, S. N. Choi, D. S. Choi, B. Hui, and I. G. Kim, "Performance Evaluation of Millimeter-wave-based Communication System in Subway Tunnels", IEEE 802.15-16-0185-01-hrrc, Mar. 2016

[9] J. Kim and I. G. Kim, "Distributed antenna system-based millimeter-wave mobile broadband communication system for high speed trains," *2013 International Conference on ICT Convergence (ICTC)*, Jeju, 2013, pp. 218-222.

[10] J. Kim, H. S. Chung, I. G. Kim, H. Lee and M. S. Lee, "A study on millimeter-wave beamforming for high-speed train communication," *2015 International Conference on ICT Convergence (ICTC),* Jeju, 2015, pp. 1190-1193.

[11] G. Li, B. Ai, K. Guan, R. He, Z. Zhong, B. Hui and J. Kim, "Channel Characterization for Mobile Hotspot Network in Subway Tunnels at 30 GHz Band," *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, Nanjing, 2016, pp. 1-5.