A Latency Reducing Method for TDD-based High-Speed Train Communications

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***Abstract*—Due to proliferation of portable smart devices (e.g., laptops, tablets, smart phones), mobile data traffic even in high-mobility environments has been explosively increasing. Hence, recently, high-speed train (HST) communications have particularly attracted a lot of attention. In order to provide emerging services (e.g., virtual reality (VR) / augmented reality (AR), video-conferencing, online gaming) in HSTs, the HST communications system is required to support not only higher data rate but also lower latency. However, recent studies are mostly focusing on increasing data rate while reducing latency is also indispensable, especially when the HST communications system is a time-division duplex (TDD) system. Therefore, this paper proposes a latency reducing method for TDD-based HST communications that involves a new TDD configuration and interference cancellation (IC) method. Simulation shows that the proposed scheme with IC is capable of efficiently reducing the latency without performance loss in data rate.**

***Index Terms*—High speed train (HST) communications, time-division duplex (TDD), latency reduction**

I. Introduction

According to Cisco's white paper [1], it was reported that mobile data traffic has grown 4,000-fold over the past ten years, reaching 3.7 exabytes per month as of 2015. In recent years, various types of mobile services (e.g., virtual reality (VR) / augmented reality (AR), video-conferencing, online gaming) that require not only higher data rate but also lower latency have emerged, and due to a rapidly growing population of global subscriber using portable devices (e.g., laptops, tablets, smart phones), providing such services on high-speed trains (HSTs) is becoming more and more indispensable. However, the existing standards including Worldwide Interoperability for Microwave Access (WiMAX), Long Term Evolution (LTE) and LTE-Advanced (LTE-A) are hard to meet the growing demand of users in this case. Therefore, studies on advanced technologies for HST communications have recently attracted considerable attention [2]–[6], and some of the most relevant international standardization bodies have started focusing on high-speed scenarios. The Institute of Electrical and Electronics Engineers (IEEE) 802.15, a working group (WG) of the IEEE 802 standards committee, approved an interest group for high rate rail communications (IG HRRC) in November 2014, mainly focusing on standardization of a mobile wireless backhaul (MWB) for mobile user groups in the HST. In this group, a wide range of frequency bands including millimeter-wave (mmWave) have been studied as a candidate for the MWB and several technical challenges and their viable solutions have been discussed [7] [8]. The 3rd Generation Partnership Project (3GPP) has recently started the fifth generation (5G) standardization efforts for developing access technologies of New Radio (NR) in Technical Specification Group Radio Access Network (TSG-RAN) and a next generation core network in TSG Service and System Aspects (TSG-SA). The NR will be non-backward compatible to the legacy LTE-A technology, and meet all the 5G requirements and use cases defined by the IMT-2020 [9]. The HST scenario is also considered as one of the 5G deployment scenarios, and it focuses on providing continuous coverage along HST tracks using either 4 or 30 GHz frequency band [10] [11].

Meanwhile, several research institutes and industries have embarked on developing a system for high-mobility and some of them have already conducted field trials to show feasibility of the system. Most of all, as a pioneer in HST communications, Electronics and Telecommunications Research Institute (ETRI) in South Korea has developed the Mobile Hotspot Network (MHN) system [2] [3], which is capable of providing a MWB of Giga bits per second (Gbps) for HSTs using mmWave. ETRI also successfully gave a demonstration of the MHN system in the Seoul subway line 8, which was the world's first prototype system demonstrated in a moving subway train.

However, most of recent studies, developments and standardization activities on the HST communications are focusing on increasing the data rate [4] [5]. Since several low-latency services have emerged as aforementioned, it is also necessary for the HST communications to adopt latency reducing techniques. Although the LTE adopts short Transmission Time Interval (TTI) transmission for supporting low-latency communication [12], which is also considered in 5G NR, it might not be enough to support future low-latency services. In addition, for HST communications systems based on time-division duplex (TDD), the potentially large asymmetry between uplink (UL) and downlink (DL) would not only make the UL transmission period larger, but it would also make L1 control signalling particularly challenging, especially for acknowledgement (ACK) / non-acknowledgement (NACK) signaling and channel state information (CSI) feedbacks. Therefore, there is a strong motivation and interest to investigate a latency reducing solution to TDD-based HST communications. In this regard, this paper proposes a latency reducing method for TDD-based HST communications that involves a new TDD

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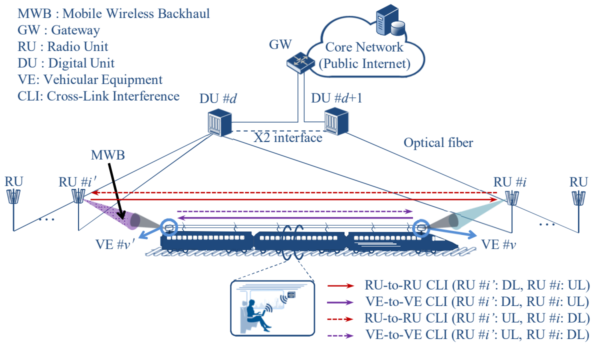

Fig. 1. The basic system architecture for the HST communications

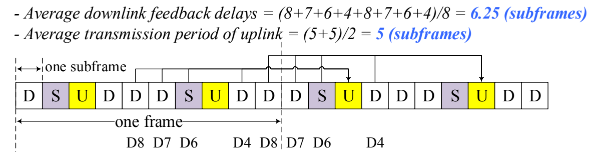

Fig. 2. An example of latency in a TDD-based system (D: downlink subframe, S: special subframe, U: uplink subframe)

configuration and interference cancellation (IC). Along with the short TTI transmission technology considered in 3GPP, the proposed method can be adopted as an efficient way to further reduce the UL transmission period and latency of downlink feedbacks (e.g., ACK/NACK, CSI).

The rest of this paper is organized as follows. In section II, we describe the system architecture of TDD-based HST communications and its challenges on latency. Next, the proposed latency reducing method enabled by a new TDD configuration and IC is presented in section III. In section IV, we evaluate the performance of the proposed method and discuss the simulation results. Finally, we make conclusions of the paper with brief discussions of future work in section V.

II. System Model

In this section, we provide a brief overview of the basic system architecture of TDD-based HST communications as well as the problems that need to be solved.

A. Basic System Architecture

The system architecture of HST communications basically originates in the hierarchical two-hop network as illustrated in Fig. 1. In the network, a vehicular equipment (VE) mounted on top of the train behaves like a single user communicating with radio units (RUs) of base station, and an onboard access link connected to the VE provides user equipments (UEs) carried by passengers in the train with mobile Internet service through a commercialized system like wireless fidelity (Wi-Fi). Moreover, the network is further configured to form an efficient cloud radio access network (C-RAN) where a centralized digital unit (DU) and multiple RUs deployed along the trackside are separated from each other and interconnected via optical fiber. Since the network architecture has several well-known advantages [6], 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 3GPP [10] [11].

In this paper, we focus on the first-hop, which is the MWB for HST mainly responsible for conveying data of numerous users on the train, and for the purpose of simplicity, we assume that two VEs are installed on top of the front and rear sides of the train respectively. The onboard access link is beyond the scope of this paper. The paper also focuses on the TDD-based HST communications system where a frame consists of 10 subframes and the subframe is a basic unit of a transmission on the radio link. The number of OFDM symbols in a subframe is equal to 14.

B. Problem Statement

Mobile data traffic pattern of users inside a train is highly similar to an indoor environment and is largely asymmetric in nature, where download typically accounts for most of the traffic. Therefore, TDD is prioritized in HST communications since the TDD 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 frequency-division duplex (FDD). However, as previously mentioned, in a TDD-based communications system, the potentially large UL/DL asymmetry would lead to serious latency problems as illustrated in Fig. 2. In Fig. 2, ”D” denotes a subframe reserved for downlink transmissions, ”U” denotes a subframe reserved for uplink transmissions and ”S” denotes a special subframe with the three fields: downlink pilot time slot (DwPTS), guard period (GP) and uplink pilot time slot (UpPTS). It is also assume that the VE processing time required to process and decode one subframe is 4 subframes. Then, average downlink feedback delay and average transmission period of uplink in this case can be simply calculated as shown in Fig. 2, indicating that it is hard to transmit downlink feedbacks (e.g., ACK/NACK, CSI) on uplink frequently which is particularly unsuitable for the HST communications where channel conditions between RU and VE vary rapidly. Moreover, in order to provide low-latency services in HSTs, minimizing the latency in HST communications is very critical. Although we can intuitively see that the latency can be reduced by changing the potion of downlink and uplink in the frame, it would significantly degrade downlink throughput. More importantly, it would not make sense if the system changes the ratio of DL and UL not by actual traffic demands from users, but for the purpose of latency reduction.

III. The Proposed Latency Reducing Method

In this section, an efficient latency reducing method for the TDD-based HST communications that involves a new TDD UL-DL configuration and IC method is proposed.

TABLE I
AN EXAMPLE OF THE PROPOSED TDD UL-DL CONFIGURATION

UL-DL config.	CS	subframe number within a frame									
		0	1	2	3	4	5	6	7	8	9
0	0	D	S	U	D	D	D	S	U	D	D
	1	D	D	S	U	D	D	D	S	U	D
	2	D	D	D	S	U	D	D	D	S	U
	3	U	D	D	D	S	U	D	D	D	S
	4	S	U	D	D	D	S	U	D	D	D
1	0	D	S	U	U	D	D	S	U	U	D
	1	D	D	S	U	U	D	D	S	U	U
	2	U	D	D	S	U	U	D	D	S	U
	3	U	U	D	D	S	U	U	D	D	S
	4	S	U	U	D	D	S	U	U	D	D
...	...	...	...	...	...	...	...	...	...	...	...
$N_c - 1$	...	...	...	...	...	...	...	...	...	...	...

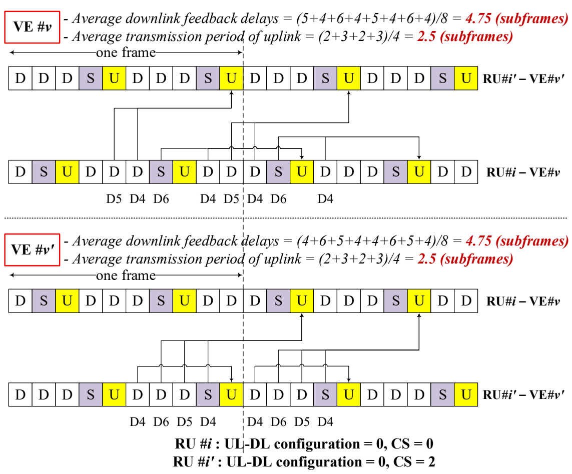

Fig. 3. An example of the proposed method for latency reduction

A. New TDD Configuration

First, we present the new concept of TDD UL-DL configuration, which introduce a newly defined parameter called cyclic shift (CS) as shown in TABLE I. The CS determines the number of subframes circularly shifted within a frame and N_c denotes the total number of TDD UL-DL configurations in a system.

Then the latency can be efficiently reduced by configuring two adjacent RUs with the different CSs making two VEs able to send their downlink feedbacks on the first available uplink subframe of the two links between RUs and VEs. As a result, we can see that it is able to reduce the average downlink feedback delay and transmission period of uplink as shown in Fig. 3. This is also highly advantageous to the system since it is not necessary to grudgingly change the ratio of DL and UL for latency reduction, which should be determined by actual traffic demands from users.

B. Interference Cancellation

Although the proposed TDD configuration provides a viable solution to reducing the latency, there is a critical problem that needs to be solved. It is noticed from the Fig. 1 and Fig. 3 that if different CSs are configured for i-th RU and i'-th RU, the communication directions (downlink or uplink) between the corresponding VEs at each time can be different. In other words, when one VE sends uplink data to its corresponding RU, the other VE can receive downlink data from its corresponding RU in the same subframe. Consequently, it will cause serious interferences both at a VE and at a RU at the same time, which significantly degrades the uplink and downlink performance. More specifically, there are two types of interferences possible to occur in this case as shown in Fig. 1. One is VE-to-VE cross-link interference (CLI) from one VE to the other VE and the other is RU-to-RU CLI from one RU to the other RU.

Since we assume one DU with two RUs and two VEs for simplicity, the downlink signals received by v-th VE and the uplink signals received by i-th RU with analog beamforming (BF) can be expressed as $\hat{\mathbf{r}}_v = \mathbf{P}^H_{\text{RX},v}\mathbf{r}_v$ and $\hat{\mathbf{y}}_i = \mathbf{W}^H_{\text{RX},i}\mathbf{y}_i$ respectively, where the downlink signals $\mathbf{r}_v$ received at the antennas of v-th VE in the presence of interferences can be expressed as

$$\begin{aligned}\mathbf{r}_v \;=\;& \mathbf{1}_{\xi_v^{(v,i)}}(t)\cdot\mathbf{H}_{v,i}\mathbf{d}_i + \mathbf{1}_{\xi_v^{(v,i)}\cap\xi_v^{(v',i')}}(t)\cdot\mathbf{H}_{v,i'}\mathbf{d}_{i'}\\ &+\; \mathbf{1}_{\xi_v^{(v,i)}\cap\eta_v^{(v',i')}}(t)\cdot\bar{\mathbf{H}}_{v,v'}\mathbf{x}_{v'} + \mathbf{1}_{\xi_v^{(v,i)}}(t)\cdot\mathbf{n}_v,\end{aligned}\tag{1}$$

and by assuming that TDD channel reciprocity holds, the uplink signals $\mathbf{y}_i$ received at the antennas of i-th RU in the presence interferences can be similarly expressed as

$$\begin{aligned}\mathbf{y}_i \;=\;& \mathbf{1}_{\eta_i^{(v,i)}}(t)\cdot\mathbf{H}^T_{v,i}\mathbf{x}_v + \mathbf{1}_{\eta_i^{(v,i)}\cap\eta_i^{(v',i')}}(t)\cdot\mathbf{H}^T_{v',i}\mathbf{x}_{v'}\\ &+\; \mathbf{1}_{\eta_i^{(v,i)}\cap\xi_i^{(v',i')}}(t)\cdot\hat{\mathbf{H}}_{i,i'}\mathbf{d}_{i'} + \mathbf{1}_{\eta_i^{(v,i)}}(t)\cdot\mathbf{z}_i,\end{aligned}\tag{2}$$

where $\mathbf{P}_{\text{RX},v} = [\mathbf{p}^1_{\text{RX},v}, \mathbf{p}^2_{\text{RX},v}, \cdots, \mathbf{p}^{U_{\text{RU}}}_{\text{RX},v}] \in \mathbb{C}^{N_{\text{VE,ant}}\times U_{\text{RU}}}$ and $\mathbf{W}_{\text{RX},i} = [\mathbf{w}^1_{\text{RX},i}, \mathbf{w}^2_{\text{RX},i}, \cdots, \mathbf{w}^{U_{\text{VE}}}_{\text{TX},i}] \in \mathbb{C}^{N_{\text{RU,ant}}\times U_{\text{VE}}}$ are the analog receive BF weight vectors applied at the v-th VE and i-th RU respectively. $\mathbf{d}_i \in \mathbb{C}^{N_{\text{RU,ant}}\times 1}$ and $\mathbf{x}_v \in \mathbb{C}^{N_{\text{VE,ant}}\times 1}$ are the signal vectors transmitted by i-th RU and v-th VE respectively, which can be expressed as, $\mathbf{d}_i = \mathbf{W}_{\text{TX},i}\mathbf{m}_i$ and $\mathbf{x}_v = \mathbf{P}_{\text{TX},v}\mathbf{s}_v$. $\mathbf{W}_{\text{TX},i} = [\mathbf{w}^1_{\text{TX},i}, \mathbf{w}^2_{\text{TX},i}, \cdots, \mathbf{w}^{U_{\text{RU}}}_{\text{TX},i}] \in \mathbb{C}^{N_{\text{RU,ant}}\times U_{\text{RU}}}$ and $\mathbf{P}_{\text{TX},v} = [\mathbf{p}^1_{\text{TX},v}, \mathbf{p}^2_{\text{TX},v}, \cdots, \mathbf{p}^{U_{\text{VE}}}_{\text{TX},v}] \in \mathbb{C}^{N_{\text{VE,ant}}\times U_{\text{VE}}}$ are the analog transmit BF weight vectors applied at the i-th RU and v-th VE respectively. $N_{\text{RU,ant}}$ and $N_{\text{VE,ant}}$ denote the number of antennas at RUs and VEs respectively, and U_{RU} and U_{VE} represent the number of symbols at RUs and VEs respectively. $\mathbf{m}_i$ and $\mathbf{s}_v$ are the vectors of transmitted symbols, such that $\mathbb{E}[\mathbf{m}_i\mathbf{m}_i^H] = \frac{P_{\text{TX}}}{U_{\text{RU}}}\mathbf{I}_{U_{\text{RU}}}$, $\mathbb{E}[\mathbf{s}_v\mathbf{s}_v^H] = \frac{P_{\text{TX}}}{U_{\text{VE}}}\mathbf{I}_{U_{\text{VE}}}$. P_{TX} is the average total transmitted power, and $\mathbf{1}_T(t)$ represents the indicator function defined as,

$$\mathbf{1}_T(t) = \begin{cases} 1, & \text{if } t \in T \\ 0, & \text{otherwise} \end{cases}\tag{3}$$

In the paper, i-th RU is the serving RU of v-th VE and i'-th RU is the serving RU of v'-th VE. $\mathbf{H}_{v,i} \in \mathbb{C}^{N_{\text{VE,ant}}\times N_{\text{RU,ant}}}$ stands for the channel matrix of v-th VE and i-th RU. $\bar{\mathbf{H}}_{v,v'} \in \mathbb{C}^{N_{\text{VE,ant}}\times N_{\text{VE,ant}}}$ and $\hat{\mathbf{H}}_{i,i'} \in \mathbb{C}^{N_{\text{RU,ant}}\times N_{\text{RU,ant}}}$ are the VE-to-VE CLI and RU-to-RU CLI channels respectively. For the three channel matrices ($\mathbf{H}_{v,i}$, $\bar{\mathbf{H}}_{v,v'}$, $\hat{\mathbf{H}}_{i,i'}$), a geometric channel model ([5]) with the average received channel power between i-th RU and v-th VE, $\rho_{v,i}$, which mainly depends on path loss. $\mathbf{n}_v \in \mathbb{C}^{N_{\text{VE,ant}} \times 1}$ and $\mathbf{z}_i \in \mathbb{C}^{N_{\text{RU,ant}} \times 1}$ are the additive white Gaussian noise (AWGN) vectors at v-th VE and i-th RU respectively, which are the independent and identically distributed (i.i.d) complex Gaussian variables with zero mean and variance σ^2. $\xi_k^{(v,i)}$ and $\eta_k^{(v,i)}$ represent the set of time resource indices (e.g., OFDM symbol number in time domain) of k-th node (RU or VE) where downlink and uplink signals between v-th VE and i-th RU are received respectively.

Since it is an undesirable situation, we need to come up with a method to effectively mitigate the CLIs. Fortunately, thanks to the intrinsic characteristics of HST communications architecture, in which two VEs on the train are spatially separated and communicate with the respective RUs in the opposite direction, we can easily figure out a simple method to suppress the VE-to-VE CLI by creating very sharp beams at each VE. In this case, since two beams point toward the opposite direction, the VE-to-VE CLI signal, $\mathbf{P}_{\text{RX},v}^H \bar{\mathbf{H}}_{v,v'} \mathbf{x}_{v'}$, transmitted from back lobe of a VE is received by back lobe of the other, which will significantly reduce the interference signal strength. Even though it is not sufficient to perfectly eliminate the interference, there are various ways to further reduce. For example, it is possible to physically block the propagation path between two VEs.

On the other hand, the RU-to-RU CLI, $\mathbf{W}_{\text{RX},i}^H \hat{\mathbf{H}}_{i,i'} \mathbf{d}_{i'}$, received by main lobe of a RU comes from main lobe of the other and thus significantly affects uplink performance, which is the major problem that we are concerned about. Fortunately, it is noticed that both RUs transmitting and receiving the interference are connected to the same DU, which is able to share their packets between them. Even if two RUs are connected with different DUs, it is still possible to share packets between the RUs via a link such as X2 interface. Therefore, as long as the channel between them is known to the RU, the interference can be reconstructed and subtracted from the received signal as follows,

$$\begin{aligned}
\tilde{\mathbf{y}}_i &= \hat{\mathbf{y}}_i - \mathbf{1}_{\eta_i^{(v,i)} \cap \xi_i^{(v',i')}}(t) \cdot \tilde{\mathbf{H}}_{i,i'} \mathbf{m}_{i'} \qquad (4) \\
&= \mathbf{1}_{\eta_i^{(v,i)}}(t) \cdot \mathbf{W}_{\text{RX},i}^H \mathbf{H}_{v,i}^T \mathbf{x}_v \\
&+ \mathbf{1}_{\eta_i^{(v,i)} \cap \eta_i^{(v',i')}}(t) \cdot \mathbf{W}_{\text{RX},i}^H \mathbf{H}_{v',i}^T \mathbf{x}_{v'} \\
&+ \mathbf{1}_{\eta_i^{(v,i)} \cap \xi_i^{(v',i')}}(t) \cdot (\mathbf{W}_{\text{RX},i}^H \hat{\mathbf{H}}_{i,i'} \mathbf{W}_{\text{TX},i'} - \tilde{\mathbf{H}}_{i,i'}) \mathbf{m}_{i'} \\
&+ \mathbf{1}_{\eta_i^{(v,i)}}(t) \cdot \mathbf{W}_{\text{RX},i}^H \mathbf{z}_i \qquad (5)
\end{aligned}$$

Obviously, the accurate estimation of the effective baseband (BB) channel, $\tilde{\mathbf{H}}_{i,i'}$, of RU-to-RU CLI plays a crucial role in the IC. As long as it is perfectly known to the RU (i.e., $\tilde{\mathbf{H}}_{i,i'} = \mathbf{W}_{\text{RX},i}^H \hat{\mathbf{H}}_{i,i'} \mathbf{W}_{\text{TX},i'} \in \mathbb{C}^{U_{\text{VE}} \times U_{\text{VE}}}$), the interference signal $\mathbf{W}_{\text{RX},i}^H \hat{\mathbf{H}}_{i,i'} \mathbf{d}_{i'}$ can be eliminated, and then the proposed scheme with the IC can achieve a similar uplink performance as the conventional scheme. Other interferences, $\mathbf{P}_{\text{RX},v}^H \mathbf{H}_{v,i'} \mathbf{d}_{i'}$ and $\mathbf{W}_{\text{RX},i}^H \mathbf{H}_{v',i}^T \mathbf{x}_{v'}$, which can be mitigated by various techniques (e.g., multiple-input and multiple-output (MIMO)), are beyond the scope of this paper.

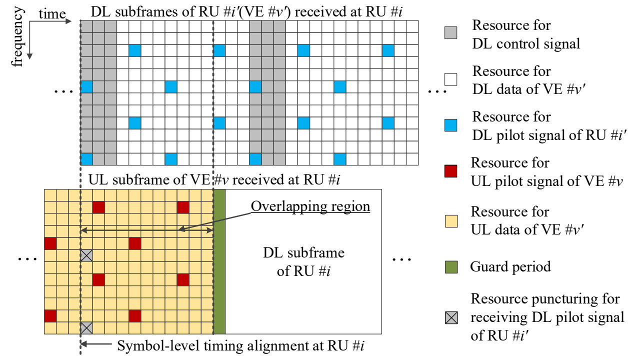

Fig. 4. An example of the proposed uplink frame structure

C. Frame Structure and Timing Synchronization of Uplink

For the IC, it is necessary for the RU to receive pilot signals of the interfering RU used for the estimation of the RU-to-RU CLI channel. Considering that the pilot signals of the interfering RU may collide with the uplink signals of the VE, we propose a new uplink frame structure that is designed to puncture the radio resources overlapping with the pilot signals of the interfering RU as shown in Fig. 4. Moreover, thanks to very large coherence time of interfering channel, only a few resources in the overlapping time domain need to be punctured for receiving the pilot signals.

Moreover, due to different propagation delays, the difference between received signal timings of the interfering RU and the VE may be larger than cyclic prefix (CP) length of OFDM symbol, making the signals received from both sides unsynchronized in a symbol-level. In this case, the receiver is unable to decode the desired uplink signal through the IC. In order for the signals to be synchronized, a simple way that we propose is to adjust the uplink transmission timing so that the received boundary of the uplink signal is aligned with that of the signal received from the interfering RU in a symbol-level. As illustrated in Fig. 1, since the distance between adjacent i'-th RU and i-th RU is fixed, the propagation delay of the interfering RU (i'-th RU), $\delta_1^{(i,i')}$, can be known to the i-th RU. In addition, round-trip time (RTT) between v-th VE and i-th RU, $\delta_2^{(v,i)}$, can be estimated through the signals (e.g., random access channel (RACH) preamble or sounding reference signal (SRS) in LTE) transmitted from VE. Then, as illustrated in Fig. 5, by taking both $\delta_1^{(i,i')}$ and $\delta_2^{(v,i)}$ into account, the proposed timing advance (TA) value, δ_{TA}, sent to v-th VE, can be calculated as follows,

$$\delta_{\text{TA}}^{(v,i)} = (\delta_1^{(i,i')} \bmod T_{\text{symb}}) + \delta_2^{(v,i)} \qquad (6)$$

where T_{symb} denotes the length OFDM symbol with CP.

IV. Performance Evaluation

In this section, a simple computer simulation has been conducted to investigate the performance of the proposed TDD scheme with/without IC by comparing with the conventional TDD scheme.

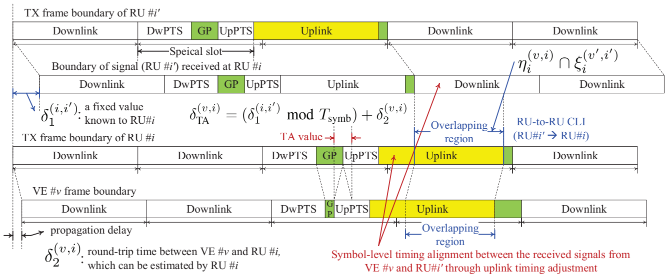

Fig. 5. An example of the proposed uplink timing adjustment

A. Assumptions

In the simulation, both RU and VE employ a fixed analog BF and the direction of each beam is set in the same way used in [4] where each RU directs its beam to the point in the middle of track between the adjacent RUs, and the beam directions of two VEs are simply set to direct in the direction and opposite direction of movement respectively. In addition, it is assumed that the same 3D beam radiation pattern is used on both RU and VE. In the HST communications, signals between RU and VE experience the wireless channel with a dominant line-of-sight (LOS) path and few reflectors and scatterers most of the time, especially under the environment of wide plain. Hence, for the purpose of simplifying analysis, only the LOS path is taken into account in the simulation. Plus, we assume $U_{\text{RU}} = 1, U_{\text{VE}} = 1$, such that the effective BB channel matrix can be simplified. For example, the effective BB channel matrix of downlink, $\mathbf{P}_{\text{RX},v}^{H}\mathbf{H}_{v,i}\mathbf{W}_{\text{TX},i} \in \mathbb{C}^{U_{\text{RU}}\times U_{\text{RU}}}$, is simplified to $h_{v,i} = \sqrt{\rho_{v,i} \cdot g_r\left(\phi_{v,i}^r, \theta_{v,i}^r\right) \cdot g_t\left(\phi_{v,i}^t, \theta_{v,i}^t\right)}$, where $g_r\left(\phi_{v,i}^r, \theta_{v,i}^r\right)$ and $g_t\left(\phi_{v,i}^t, \theta_{v,i}^t\right)$, the functions of azimuth (elevation) arrival and departure angles, $\phi_{v,i}^r(\theta_{v,i}^r)$ and $\phi_{v,i}^t(\theta_{v,i}^t)$, are the receive and transmit BF gains, respectively. The TDD configuration of zero is configured for both i-th RU and i'-th RU, and the CSs for i-th RU and i'-th RU are 0 and 2 respectively. In addition, the number of OFDM symbols for DwPTS, GP, UpPTS are 10, 2, 2 respectively. Other simulation parameters are summarized in TABLE II.

B. Achievable Rate

The performance analysis mainly focused on theoretically achievable rates for both downlink and uplink, and a conventional scheme where both RUs are configured by the TDD configuration of zero with CS of zero is considered for comparison. In this paper, the maximum ratio combining (MRC) is applied at the receiver and propagation delay is not considered. Then, the downlink and uplink achievable rates of the conventional scheme can be simply given as,

$$R_{\text{DL}}^{\text{conv}} = \sum_{\substack{v\in\{1,2\},\\ v'\in\{1,2\}\backslash v}} \mathfrak{T}_v^{(\text{D,D})} \cdot \mathfrak{L}\left(\frac{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v,i}\|^2}{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v,i'}\|^2+\sigma^2\|h_{v,i}\|^2}\right) \quad (7)$$

$$R_{\text{UL}}^{\text{conv}} = \sum_{\substack{v\in\{1,2\},\\ v'\in\{1,2\}\backslash v}} \mathfrak{T}_i^{(\text{U,U})} \cdot \mathfrak{L}\left(\frac{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v,i}\|^2}{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v',i}\|^2+\sigma^2\|h_{v,i}\|^2}\right) \quad (8)$$

TABLE II
SIMULATION ASSUMPTIONS FOR PERFORMANCE EVALUATION

Parameters	Values
Carrier frequency, f_c	27 GHz
System bandwidth, W	1 GHz
Transmit power, P_{TX}	20 dBm
Free space path loss, P_{PL}	90.4+20log$f_{\text{c,GHz}}$ +20logd_{km} (dB)
Noise figure, $N_{\text{F,dB}}$	8 dB
RU height, h_{RU}	10 m
VE height, h_{VE}	3 m
Distance between adjacent RUs, d_{RU}	1000 m
Distance between adjacent VEs, d_{VE}	200 m
Distance between railway track and RUs, $d_{\text{RU-track}}$	10 m

and the downlink and uplink achievable rates of the proposed scheme without IC can be respectively expressed as follows,

$$\begin{aligned} R_{\text{DL}}^{\text{w/o-IC}} = \sum_{\substack{v\in\{1,2\},\\ v'\in\{1,2\}\backslash v}} \Bigg\{ & \mathfrak{T}_v^{(\text{D,G})} \cdot \mathfrak{L}\left(\frac{P_{\text{TX}}\|h_{v,i}\|^2}{\sigma^2}\right) \\ & + \mathfrak{T}_v^{(\text{D,D})} \cdot \mathfrak{L}\left(\frac{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v,i}\|^2}{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v,i'}\|^2+\sigma^2\|h_{v,i}\|^2}\right) \\ & + \mathfrak{T}_v^{(\text{D,U})} \cdot \mathfrak{L}\left(\frac{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v,i}\|^2}{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v,v'}\|^2+\sigma^2\|h_{v,i}\|^2}\right)\Bigg\} \end{aligned} \quad (9)$$

$$\begin{aligned} R_{\text{UL}}^{\text{w/o-IC}} = \sum_{\substack{v\in\{1,2\},\\ v'\in\{1,2\}\backslash v}} \Bigg\{ & \mathfrak{T}_i^{(\text{U,G})} \cdot \mathfrak{L}\left(\frac{P_{\text{TX}}\|h_{v,i}\|^2}{\sigma^2}\right) \\ & + \mathfrak{T}_i^{(\text{U,U})} \cdot \mathfrak{L}\left(\frac{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v,i}\|^2}{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v',i}\|^2+\sigma^2\|h_{v,i}\|^2}\right) \\ & + \mathfrak{T}_i^{(\text{U,D})} \cdot \mathfrak{L}\left(\frac{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v,i}\|^2}{P_{\text{TX}}\|h_{v,i}^{*}\cdot \hat{h}_{i,i'}\|^2+\sigma^2\|h_{v,i}\|^2}\right)\Bigg\} \end{aligned} \quad (10)$$

where $\mathfrak{L}(x) = W \cdot \log_2(1+x)$ and W denotes the bandwidth of the system. $\mathfrak{T}_v^{(\text{D,G})} = \frac{|\xi_v^{(v,i)}\cap\zeta_v^{(v',i')}|}{\mathfrak{T}_v^{\text{sum}}}$, $\mathfrak{T}_v^{(\text{D,D})} = \frac{|\xi_v^{(v,i)}\cap\xi_v^{(v',i')}|}{\mathfrak{T}_v^{\text{sum}}}$, $\mathfrak{T}_v^{(\text{D,U})} = \frac{|\xi_v^{(v,i)}\cap\eta_v^{(v',i')}|}{\mathfrak{T}_v^{\text{sum}}}$, $\mathfrak{T}_i^{(\text{U,G})} = \frac{|\eta_i^{(v,i)}\cap\zeta_i^{(v',i')}|}{\mathfrak{T}_i^{\text{sum}}}$, $\mathfrak{T}_i^{(\text{U,D})} = \frac{|\eta_i^{(v,i)}\cap\xi_i^{(v',i')}|}{\mathfrak{T}_i^{\text{sum}}}$, $\mathfrak{T}_i^{(\text{U,U})} = \frac{|\eta_i^{(v,i)}\cap\eta_i^{(v',i')}|}{\mathfrak{T}_i^{\text{sum}}}$ represent the normalized time resources for six possible combinations of two RUs' configurations, and $\mathfrak{T}_k^{\text{sum}} = |\zeta_k^{(v,i)}| + |\xi_k^{(v,i)}| + |\eta_k^{(v,i)}|$. $\zeta_k^{(v,i)}$ represents the set of time resource indices of k-th node (RU or VE) where GPs between v-th VE and i-th RU are received, and $|\cdot|$ denotes the cardinality of a set. By the assumption of perfect knowledge of RU-to-RU CLI, the uplink achievable rate of the proposed scheme with IC, $R_{\text{UL}}^{\text{w/-IC}}$, can be expressed as,

$$\begin{aligned} R_{\text{UL}}^{\text{w/-IC}} = \sum_{\substack{v\in\{1,2\},\\ v'\in\{1,2\}\backslash v}} \Bigg\{ & \left(\mathfrak{T}_i^{(\text{U,G})} + \mathfrak{T}_i^{(\text{U,D})}\right) \cdot \mathfrak{L}\left(\frac{P_{\text{TX}}\|h_{v,i}\|^2}{\sigma^2}\right) \\ & + \mathfrak{T}_i^{(\text{U,U})} \cdot \mathfrak{L}\left(\frac{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v,i}\|^2}{P_{\text{TX}}\|h_{v,i}^{*}\cdot h_{v',i}\|^2+\sigma^2\|h_{v,i}\|^2}\right)\Bigg\} \end{aligned} \quad (11)$$

In the simulation, two different 3D beam patterns, the respective half power beamwidths (HPBWs) of which are 8

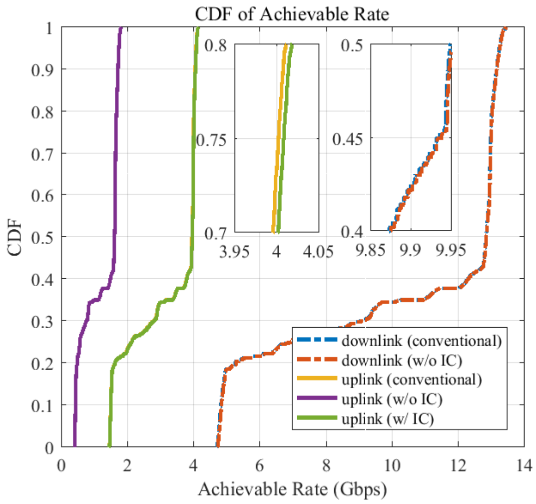

Fig. 6. The CDF of achievable rate (HPBW = 8 degrees)

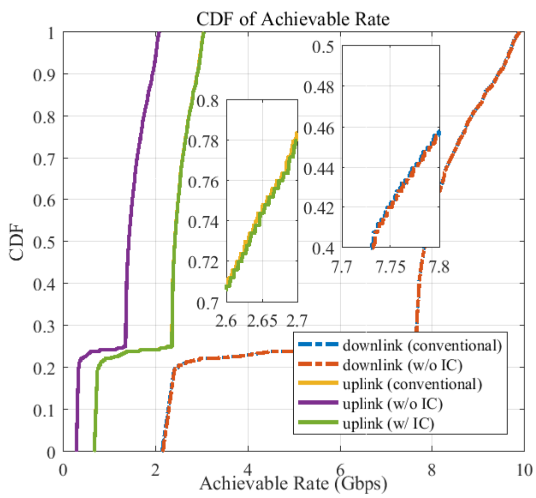

Fig. 7. The CDF of achievable rate (HPBW = 20 degrees)

and 20 degrees in both horizontal and vertical directions [3], are considered, and Fig. 6 and Fig. 7 show the respective cumulative distribution functions (CDFs) of the achievable rates. As expected earlier, in the proposed method without IC, serious performance degradation was observed in the uplink transmission due to the CLI while CLI is negligible in the downlink transmission. Hence, in the case of the uplink transmission with the proposed TDD configuration, it is mandatory to adopt the IC, and as long as the RU-to-RU CLI channel from interfering RU is perfectly estimated, the CLI can be subtracted from the received signal. Consequently, the proposed scheme is able to reduce latency without any performance degradation in both downlink and uplink throughputs as compared with the conventional scheme.

V. Conclusion

Recently, HST communications have attracted a lot of attention, and in order to provide various mobile services inside the train, high data rate and low latency techniques are required. In this paper, we proposed a latency reducing method for TDD-based HST communications that involves a new TDD configuration and IC. We could simply see that the proposed scheme is capable of efficiently reducing the latency of the system by adopting different CSs at the two RUs. It is also highly beneficial in a sense that there is no need to change the ratio of uplink and downlink. Only challenge we faced in the proposed scheme is the CLIs. In the simulation, we observed that while there is no performance degradation in downlink throughput, the signal from adjacent RU causes very serious interference which significantly degrades the uplink throughput. However, as long as the RU-to-RU CLI channel is perfectly estimated, the proposed scheme with IC is able to provide the similar uplink throughput as the conventional scheme. Besides, for the purpose of the uplink IC, we also proposed the uplink frame structure and timing synchronization method. In a future work, more comprehensive simulation will be conducted to further investigate the performance of the proposed method.

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