A Transmit Beamforming Algorithm for High-Speed Train Communication

Qinglin Luo, Wei Fang, Tao Yang, Dongyao Wang

***Abstract*—A new time-domain transmit beamforming algorithm is proposed for cancelling inter-channel-interference (ICI) due to Doppler frequency shift under high speed train communication scenario. Simulation results show that by employing the algorithm a high speed train communication system is capable of providing continuous 100Mbps data rate for passengers at a speed of 450km/h. This would guarantee continuous data-intensive services for today's high speed train passengers.**

***Index Terms*— High Speed Train Communication, Beamforming, Doppler Frequency Shift, Remote Radio Head, Baseband Unit**

I. INTRODUCTION

Wireless broadband has become reality in recent years. Online multimedia, gaming, mobile application downloading, etc., become dominating traffic of the mobile network. To provide the present data-intensive applications to passengers on the train, for example the China Railways High-speed (CRH) train between Beijing and Shanghai at a speed of 350km/h, it is desirable to develop an access network characterized by high bandwidth and resilience to high mobility.

For the conventional high-speed train communication (HSTC) system [1] [2], with the increase of speed, the system is subject to both handover failure and Doppler frequency shift. Handover failures may cause call drops, while Doppler frequency shift degrade communication link quality.

To reduce the possibility of handover failure, a straightforward approach is to have an overlapped area between adjacent cells. In [3], some analysis is provided on the cell radius constraints due to this overlapping requirement. It was shown that by proper cell planning, the handover failure rate can be reduced significantly.

Doppler frequency shift causes inter-channel-interference (ICI) which degrades the link data rate. Most conventional HSTC solutions consider only user equipment (UE) side ICI cancellation techniques [4]. Since onboard UEs are usually less capable than the trackside base stations, i.e., limited power supply, less computing capability, less antennas, etc, the enhancement at the UE side may not always be preferred. More importantly, the performance of UE side ICI cancellation usually varies from vendor to vendor. UE side ICI cancellation techniques cannot provide unified experience for users with UEs from different vendors.

In this paper, our target is to mitigate the impact of Doppler frequency shift and increase the data rate of users at high speed. We first establish a signal model for an OFDM MIMO system under high mobility. Then, we derive the SINR expression based on this model and formulate the SINR maximization into a generalized Rayleigh quotient issue. A new transmit beamforming algorithm is thus proposed by solving this issue. With simulations, it is verified that by employing the new beamforming algorithm a system can provide a data rate of more than 100Mbps for passengers at a speed of 450km/h. This would guarantee reliable data-intensive services for today's high speed train passengers.

The paper is organized as below. Firstly, we described a typical high speed train communication system in Section II. In Section III, we derived the new transmit beamforming algorithm for compensating Doppler frequency shift. Section IV is devoted for numerical evaluation of the new algorithm. Section V concludes the paper.

II. HSTC SYSTEM

Figure.1 shows the architecture of a typical HSTC system. The system consists of three components, the In-Train Network, Train-to-Ground network, and Ground Network. In the following we provide a high-level summary on the functionalities of the networks and highlight how to achieve the high data rate at high mobility with the aid of our proposed algorithm.

In-Train Network (ITN): It consists of various user terminals such as mobile phones, laptops, gaming consoles etc., and multi-standard access points (MAPs) supporting GSM/UMTS/LTE accessing for passengers with different terminal equipments. Each carriage may be equipped with one or multiple MAPs depending on traffic volume. When a user terminal is turned on in the carriage, the MAP serves as access point to it. An MAP receives signals from different users, and forwards it to the *Train-to-Ground Network* via optical fiber links.

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Train-to-Ground Network (TGN): It consists of onboard train access units (TAU), trackside RRHs and baseband units (BBU).

The TAU is responsible for gathering user traffic from/to the MAPs and communicating with the trackside RRHs via the air-interface channel. The number of TAUs equipped on a train depends on the user traffic volume and the train-to-ground transmission bandwidth. Typically, two TAUs may be deployed: one on the front and the other at the end. This reduces the opportunity of interference between TAUs, while providing sufficient spatial diversity for the trackside RRHs to exploit advanced MIMO transmission technologies for higher data rate. The TAUs and MAPs are connected by optical fiber so as to provide bandwidth for broadband services with significantly low latency.

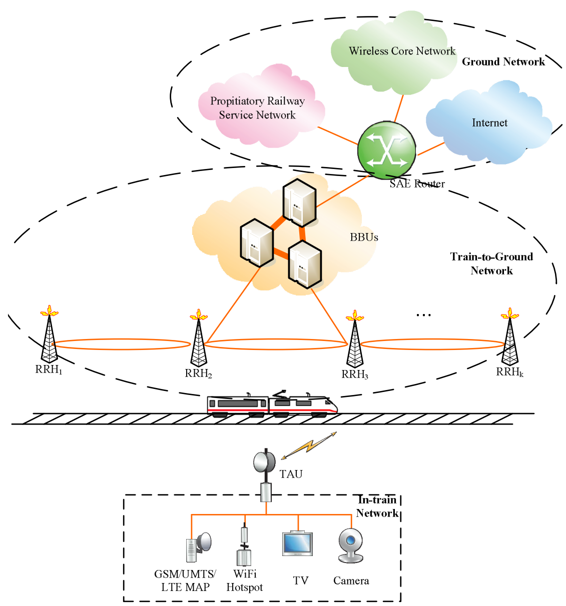


Figure 1. High-Speed Train Communication System

The trackside RRHs have capability of processing radio and intermediate frequency signals. Each RRH may have multiple transmit and receive channels, for instance, up to eight similar to a TD-LTE RRH. They are connected to BBUs via CPRI. The CPRI interface supports various topologies, such as star, chain, tree, and ring. In the context of HSTC where linear coverage is desired, RRHs can be connected by an optical ring network, as shown in Figure 1.

The Baseband processing unit (BBU) is responsible for baseband processing of radio signals. BBUs supporting different communication protocols (GSM, WCDMA, TD-SCDMA, LTE, etc.) may be deployed and the protocol running in it is defined by software.

Ground Network (GN): It consists of a service accessing entity (SAE) connected to operators' core networks, propitiatory railway service network, and internet. Operation and management (OAM) servers provides OAM services to operators. Various propitiatory applications can be deployed on the GN network for added-value railway services.

Typically, the data rate bottleneck of an HSTC system lies in the *TGN*. In the following, we will focus on enhancing the air interface capability of the *TGN*.

III. Doppler Compensation via Transmit Beamforming

In this section, we establish a signal model for OFDM systems under high mobility, and describe in detail an efficient transmit beamforming scheme for mitigating the impact of frequency shift due to high-speed.

We consider the transmission of OFDM signals with a transmitter equipped with K antennas. Signals from different transmit antennas experience a different time varying channel to a receive antenna. However, there exists some correlation among these channels depending on the angle-of-departure (AoD) distribution of the scattered signals, the antenna spacing between the antenna elements and the electromagnetic coupling among them.

We only consider the ground-to-train direction since it is more likely to be the bottleneck of data-intensive broadband services (online video, gaming, downloading, etc.) on high-speed train. We also assume that the trackside BBUs have the information of correlation among the fixed part of the channels, $E[H_{j,n}^{H}(t_0)H_{k,n}(t_0)]$, the time-varying parts of the channels, $E[H_{j,n}'^{H}(t_0)H_{k,n}'(t_0)]$, and also the cross-correlation among them, $E[H_{j,n}'^{H}(t_0)H_{k,n}(t_0)]$ where the expectation is taken over the time and subcarriers, and they form the $K\times K$ matrices, $\mathbf{R}_{HH}$, $\mathbf{R}_{H'H'}$, and $\mathbf{R}_{H'H}$, respectively. For a TDD system where uplink and downlink share the same band, this information can be obtained at the BBU side by exploiting uplink-downlink channel reciprocity. For an FDD system, this information can be obtained through downlink channel estimation and feedback..

In this context, different from the conventional beamforming schemes [6], we choose to do transmit beamforming in time domain for each OFDM symbol with time-varying beamforming weights of $\mathbf{w}(t)=[w_1(t),w_2(t),...w_K(t)]^T$ for K antennas. Thus, the beamformed signal can be expressed as

$$\mathbf{s}(t)=\mathbf{w}(t)u(t) \tag{1}$$

where $u(t)$ is the user signal. The choice $\mathbf{w}(t)$ depends on the correlation among the channels and the computational complexity requirements induced. Note that the beamforming weights $\mathbf{w}(t)$ can be approximated by using Taylor series expansion as

$$w_i(t)=w_i(t_0)+w_i'(t_0)(t-t_0)+\mathrm{O}((t-t_0)^2) \tag{2}$$

which forms the general beamforming weight vector of

$$\mathbf{w}(t)\approx\mathbf{w}_0+(t-t_0)\mathbf{w}_1 \tag{3}$$

Using (3), appropriate beamforming weights can be investigated up to a desired precision and complexity. In this paper, we restrict ourselves to the approximation up to the first-order term. Thus, the received signal can be approximated as

$$r_p(t) \approx D_p(t) + I_p(t) + n(t) \tag{4}$$

where

$$D_p(t) = \sum_{n=0}^{N-1} \mathbf{H}_n(t_0)\mathbf{w}_0 e^{j2\pi n f_s t} u_n \tag{5}$$

$$I_p(t) = \sum_{n=0}^{N-1} (t-t_0)[\mathbf{H}'_n(t_0)\mathbf{w}_0 + \mathbf{H}_n(t_0)\mathbf{w}_1] e^{j2\pi n f_s t} u_n \tag{6}$$

For a given $\mathbf{w}_0$ and $\mathbf{w}_1$, the power of the desired signal part and ICI generating part of the signal and can be expressed as

$$\begin{aligned} P_D &= E\{tr(D_p(t))\} \\ &= E\{tr(\mathbf{H}_n(t_0)\mathbf{w}_0\mathbf{w}_0^H\mathbf{H}_n^H(t_0))\} \end{aligned} \tag{7}$$

$$P_I = E\{tr(I_p(t))\} \tag{8}$$

$$P_N = \sigma_n^2 \tag{9}$$

And the desired signal to ICI ratio plus noise ratio (SINR) can be expressed as

$$SINR = \frac{P_D}{P_I + P_N} \tag{10}$$

For maximizing the receive SINR, we define a vector parameter for the SIR optimisation problem as

$$\boldsymbol{\omega} = \begin{bmatrix} \mathbf{w}_1 \\ \mathbf{w}_0 \end{bmatrix} \tag{11}$$

Let $\boldsymbol{\Theta}_n = [\mathbf{0}_{1\times K} \quad \mathbf{H}_n]$, $\boldsymbol{\Pi}_n = [\mathbf{H}_n \quad \mathbf{H}'_n]$, and select $t_0 = 1$, then the SINR can be reformulated as

$$\begin{aligned} SINR &= \frac{P_D}{P_I + P_N} \\ &= \frac{E\{tr(\boldsymbol{\Theta}_n\boldsymbol{\omega}\boldsymbol{\omega}^H\boldsymbol{\Theta}_n^H)\}}{E\{tr(\boldsymbol{\Pi}_n\boldsymbol{\omega}\boldsymbol{\omega}^H\boldsymbol{\Pi}_n^H)\} + \sigma_n^2} \\ &= \frac{E\{tr(\boldsymbol{\omega}^H\mathbf{R}_{\boldsymbol{\Theta}}\boldsymbol{\omega})\}}{E\{tr(\boldsymbol{\omega}^H\mathbf{R}_{\boldsymbol{\Pi}}\boldsymbol{\omega})\}} \end{aligned} \tag{12}$$

where $\mathbf{R}_{\boldsymbol{\Theta}} = \boldsymbol{\Theta}_n^H\boldsymbol{\Theta}_n$ and $\mathbf{R}_{\boldsymbol{\Pi}} = \boldsymbol{\Pi}_n^H\boldsymbol{\Pi}_n$. Since $\mathbf{R}_{\boldsymbol{\Theta}}$ and $\mathbf{R}_{\boldsymbol{\Pi}}$ are both covariance matrices, they are Hermitian positive definite. Hence, optimising the SINR is a generalized Rayleigh quotient issue [7], and the solution is the eigen vector corresponding to the maximum generalized eigen value of the matrix cluster $(\mathbf{R}_{\boldsymbol{\Theta}}, \mathbf{R}_{\boldsymbol{\Pi}})$, e.g.,

$$\begin{aligned} \boldsymbol{\omega} &= \arg\max_{\boldsymbol{\omega}} \left(\frac{E\{tr(\boldsymbol{\omega}^H\mathbf{R}_{\boldsymbol{\Theta}}\boldsymbol{\omega})\}}{E\{tr(\boldsymbol{\omega}^H\mathbf{R}_{\boldsymbol{\Pi}}\boldsymbol{\omega})\}}\right) \\ &= \mathbf{v}_{\text{max\_lambda}}(\mathbf{R}_{\boldsymbol{\Theta}}, \mathbf{R}_{\boldsymbol{\Pi}}). \end{aligned} \tag{13}$$

where $\mathbf{R}_{\boldsymbol{\Theta}}$ and $\mathbf{R}_{\boldsymbol{\Pi}}$ can be obtained from the known channel correlation information and $\mathbf{v}_{\text{max\_lambda}}(\mathbf{A}, \mathbf{B})$ is the maximum generalized eigen vector of matrix cluster $(\mathbf{A}, \mathbf{B})$. According to [11], the precoding weight $\mathbf{w}_0$ and $\mathbf{w}_1$ is the corresponding submatrix of vector $\mathbf{v}_{\text{max\_lambda}}$.

IV. Simulation Results

In this section, we provide numerical results to demonstrate that a system employing the new algorithm is capable of providing sufficient data rate for enabling broadband services to high-speed train passengers. We consider an HSTC system where each RRH is equipped with multiple directional antennas. By properly placing the antennas, an RRH covers both of its sides with radius R. Three adjacent RRHs are selected each time for serving the two TAUs equipped at the train front and the end, respectively. The two TAUs are configured into different bands, each occupying 20MHz bandwidth.

We model the mobility with a correlated Rayleigh channel generated based on an inverse Discrete Fourier Transform method [8]. The antennas of both the RRH and the TAU are assumed to be separated far enough, thus the components of matrix channel $\mathbf{H}$ are independent. The channel state information (CSI) is obtained at receiver via estimation based on reference signals, and at the transmitter by exploiting the TDD channel reciprocity with a delay of 1 transmission time interval (TTI). For OFDM channels from the RRHs two each TAU, we assume a total of $N = 2048$ sub-carriers. We also assume the TTI duration $T_{TTI} = 1$ millisecond and each TTI consists of $M = 14$ OFDM symbols, which is complying with the 3GPP LTE design [9]. The symbol rate of this system can be given by,

$$R_s = (1-\gamma)NM / T_{TTI}$$

where γ is the signalling overhead, up to 35% for LTE systems [9]. Then, the symbol rate can be calculated as $R_s = 18.637\times10^6$ symbols/s.

We employ rate-compatible turbo codes for error controlling. The system bit rate is determined by the modulation and coding scheme (MCS), which is capable of providing satisfactory error performance with regard to a given input SINR. Table I shows the required input SINRs to the demodulator in order to achieve a bit error rate (BER) of 10^{-5}, which is generally regarded as an 'error free' threshold for different MCSs.

Table.I Effective data rate of different MCSs and SNR requirements [9]

MCS Scheme	Input SINR for BER=1e-5 (dB)	Effective Bit Rate (bits/symbol)	Data Rate (Mbps/TAU)
QPSK, R=1/2	2.1	1	18.637
QPSK, R=3/4	3.0	1.5	27.956
QPSK, R=7/8	4.7	1.75	32.615
16QAM, R=1/2	6.8	2	37.274
16QAM, R=3/4	7.0	3	55.911
64QAM, R=3/4	10.6	4.5	83.867

From Table I, in order to guarantee the peak data rate of 100Mbps for the ground-to-train link on a train equipped with two TAUs, the system should use 16QAM and R=3/4 for modulation and coding, and guarantee a demodulator input SINR of 7.0dB. In the following, we will verify this SINR can be achieved with our new algorithm at the velocity of 450kmph.

We experiment with different antenna configurations at both the RRH and the TAU sides for different channel signal-to-noise (SNR) ratios. For the RRH side we consider 2, 4, 8, and 12 antennas, while for the TAU side we consider 2 antennas.

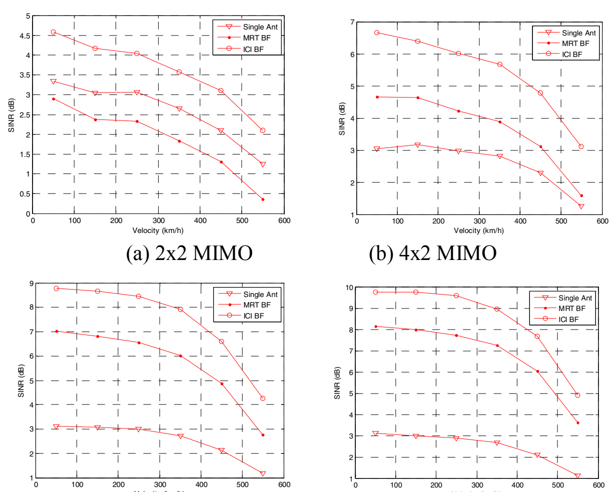
The carrier frequency is 2GHz. We employ MMSE receiver for receiving. There are 4 pilot subcarriers for channel estimation in each 3symbols x 4subcarriers resource block.

Figure 2 shows the receiver output SINRs (equivalent to the demodulator input SINRs) versus the velocity under different number of transmit antennas for three transmission algorithms and fixed 30dB of channel SNR.

Single Ant: Single antenna system.

MRT BF: MIMO system with conventional Maximum Ratio Transmission (MRT) beamforming algorithm [10].

ICI BF: MIMO system with the newly proposed ICI compensation via transmit beamforming algorithm.



(a) 2x2 MIMO (b) 4x2 MIMO

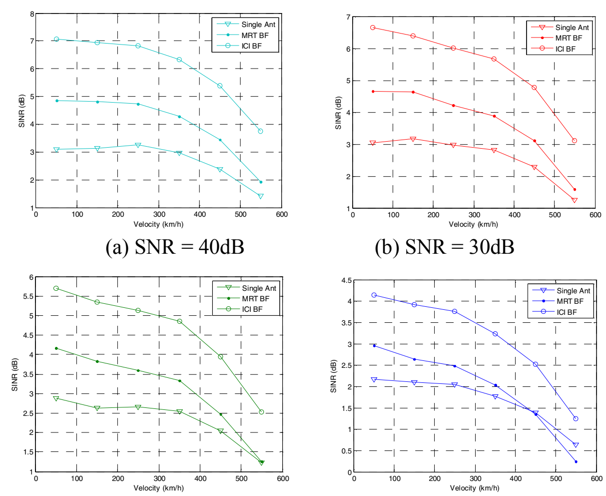
(c) 8x2 MIMO (d) 12x2 MIMO

Figure 2. SNR=30dB, different number of transmit antennas

The important observation is that the newly proposed ICI BF algorithm can provide obvious receiver output SINR gain, up to 2dB, over the conventional MRT BF. The reason is that MRT tries to maximize the signal-to-noise ratio. For 30dB of channel SNR, the dominating factor for system performance becomes interference due to Doppler shift, e.g. inter-channel-interference. At the velocity of 50kmph, the channel can be accurately estimated, thus the ICI BF shows the best performance gain. While at the velocity of 450kmph, the channel estimation becomes inaccurate, thus the performance of all configurations drops. But it is notable that the ICI BF algorithm still shows significant gain over the MRT BF.

It is also worth to note that conventional MRT BF cannot guarantee the required 7.0dB SINR even when configured with 12 transmit antennas. However, the newly proposed ICI BF can guarantee this SINR at least for the 12x2 MIMO case. Therefore, for typical antenna configurations, the system with the proposed ICI BF achieves the best SINR performance in all of the three algorithms from low to high mobility. These results demonstrate that the proposed ICI BF algorithm could significantly improve performance in a practical system with reasonable complexity.

Figure 3 shows the effects of the change of channel SNR, corresponding to the change of transmission power or transmission distance. We can see that with the increase of channel SNR, ICI BF algorithm maintains steady SINR performance improvement when compared to MRT BF and single antenna systems. In particular, with the decrease of the channel SNR, the ICI BF gain over MRT BF maintains. This demonstrates the advantage of our proposed algorithm.



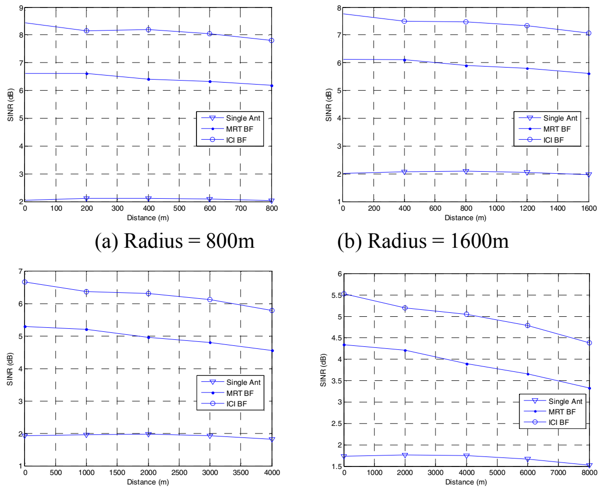
(a) SNR = 40dB (b) SNR = 30dB

(c) SNR = 20dB (d) SNR = 10dB

Figure 3. 4x2 MIMO, different signal-to-noise ratios

Based on above observations, we simulate an HSTC system where each RRH is equipped with 4 antennas, and each TAU is equipped with 2 antennas. The train is equipped with 2 TAUs and each time there are 3 adjacent RRHs are selected for joint transmission. We assume that the total transmission power is 46dBm and the noise floor is -90dBm. We employ the line of sight (LOS) path loss model [9] to simulate the large-scale signal attenuation due to propagation.

Figure 4 illustrates the effect of a change in RRH coverage radius on system performance. When the radius increases from 800 meters in Figure (a) to 8000 meters in Figure (d), the minimum receiver output SINRs decreases from 7.8dB to 4.4dB for ICI BF, and from 6.2dB to 3.3dB for MRT BF. It is important to observe that, the conventional MRT BF cannot achieve the performance target even with a small coverage radius of 800 meters. But by employing the newly proposed ICI BF algorithm, the 7.0dB of demodulator output SINR, which can provide a combined data rate of 100 Mbps at 450kmph for two TAUs according to Table I, can be guaranteed for a cell with radius up to 1600 meters.



(a) Radius = 800m (b) Radius = 1600m

(c) Radius = 4000m (d) Radius = 8000m

Figure 4. Pt=46dBm, Pn=-90dBm, LOS, 3 adjacent RRHs joint beamforming, 3x4x2 MIMO

V. CONCLUSION

This paper proposes a new time-domain transmit beamforming algorithm for mitigating the impact of Doppler frequency shift due to high mobility. The proposed algorithm enables a system to provide reliable broadband services to high-speed train passengers at super high speed, i.e., 450 kilo-meters per hour. Generally, as the train speed increases and the location changes, the solution we proposed can efficiently guarantee the user traffic to be transmitted to all receivers with little change in user-perceived quality.

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