Efficient Doppler Mitigation for High-Speed Rail Communications

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***Abstract*— Since the high-speed rail (HSR) communications are suffering from the huge Doppler shift, an efficient Doppler mitigation method is proposed in this paper. The proposed method mainly concerns about the mitigation of Doppler shift in OFDM based systems, especially for the case of employing mmWave with very high mobility. The proposed method can be used for both downlink and uplink of the system and it is quite robust to the time-varying mobility. Furthermore, the pilot-aided channel estimation for Doppler compensation is not necessary in most of the cases, which indicates the pilot density in time-domain can be reduced. Simulation results show that by using the proposed method, the residual Doppler shift can be compressed to 0 Hz with the probability of 90%.**

***Keywords*— Doppler mitigation, HSR communications, LTE, mmWave, OFDM**

I. INTRODUCTION

Recently, railroads are investigating solutions to provide broadband connectivity for their passengers with the request of providing high performance services up to 500 km/h. Long term evolution (LTE) and LTE advanced (LTE-A) systems employing orthogonal frequency division multiplexing (OFDM) technique are widely considered as candidates. However, the LTE(-A) air interface is optimized dedicated for terrestrial mobile communications, where a lot of fading, dense deployment of base stations (BS) and large number of terminal equipments (TEs) exist. Also, the carrier frequency of LTE(-A) systems is sub-6 GHz, and the performance requirements for high-speed TEs are functional. On the other hand, the scenarios for high-speed rail (HSR) communications are totally different. From the channel environment perspective, other than urban area, there are a lot of cases where the trains are traveling across the suburban, rural areas, mountains and tunnels etc. The line-of-sight (LoS) link almost always exists for HSR communications. Furthermore, the mobility of the trains is getting higher and higher and the quality of services (QoS) of passengers should be guaranteed. In order to providing higher data rate and avoid the interference to the existing terrestrial cellular systems, millimeter wave (mmWave) un-licensed band may be adopted for HSR communications.

When the OFDM based systems are considered for HSR communications, the Doppler frequency shift compensation techniques are vital due to the fact of that the OFDM systems

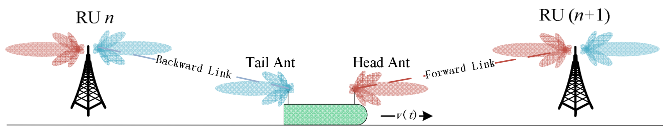

Figure 1. Network deployment of HSR systems with two antennas on train.

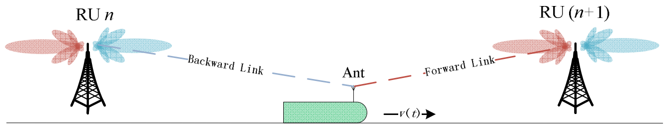

Figure 2. Network deployment of HSR systems with single antenna on train.

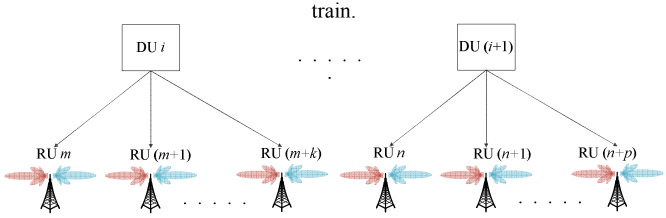

Figure 3. DU and RU deployment of HSR network

are vulnerable to the carrier frequency offset (CFO) which may introduce the inter-carrier interference (ICI) to the systems. Especially when the mmWave are considered for transmission, much higher Doppler shift will emerge. The existing pilot-aided channel estimation methods in LTE(-A) is not sufficient in this case since that the Doppler shifts cannot unambiguously be estimated from available pilot signals and thus a proper Doppler compensation on the received and/or transmitted signals is not possible. On the other hand, in order to improve the accuracy of CFO estimation, the estimation time or the number of samples for estimation should be increased, which will lead to high computational complexity and a significant load of measurements.

The accumulated Doppler spread from the downlink (DL) to the uplink (UL) in the existing terrestrial mobile communication systems, such as LTE(-A) systems, is another big challenge. In the DL from a BS to a TE, the discrete Doppler shift appears to the mobile TE receiver as an offset from the BS carrier frequency $f_{C,tx}$ of the transmitted downlink signal. The mobile TE receiver derives the carrier frequency of the transmitted downlink signal from the received downlink signal by frequency estimation methods [1], and cannot distinguish between a frequency offset at the BS transmitter or a frequency shift caused by the Doppler effect.

The TE receiver just adapts to the shifted frequency without any performance impact. For an UL transmission from the mobile TE to the BS, a mobile TE transmitter uses a carrier frequency derived from the Doppler shifted base station carrier frequency $(f_{C,tx}+f_{o,Doppler})$. For an LTE frequency division duplex (FDD) system this mobile TE uplink carrier frequency is the Doppler shifted BS carrier frequency $(f_{C,tx}+f_{o,Doppler})$ plus a duplex offset Δf_{FDD}. For LTE time division duplex (TDD) it is the Doppler shifted BS carrier frequency $(f_{C,tx}+f_{o,Doppler})$. As the uplink signal from the mobile TE transmitter also experiences the Doppler shift $f_{o,Doppler}$, has a frequency offset of twice the Doppler shift when it reaches the BS. This frequency offset of twice the Doppler shift can be beyond the estimation capabilities of the BS in the HSR scenario since the Doppler shift in HSR systems is much higher than cellular networks [2].

The motivation of proposed Doppler mitigation method is to mitigate the huge Doppler shift in HSR communication systems. The proposed method is suitable for TDD based HSR communication systems with arbitrary mobility, when a dominant path of channel exist such as the tunnel environment and the rural area.

II. Network Deployment and Channel Model

A. HSR Network Deployment

Figure 1 shows an example of HSR network deployment. Directional antennas (antenna arrays) are equipped on both radio units (RUs) and the train. The RUs are deployed along the railway, and two directional antennas facing to the opposite directions are located on each RU. The train is moving from left side to the right side with the time-varying mobility of $v(t)$. The head antenna and tail antenna of the TE located on the train communicate with the forward RU and backward RU through different links. The purpose of employing the directional antennas is to avoid the cross link interference, i.e., the interference from the $(n+1)^{\text{th}}$ RU to the tail antenna and the interference from the n^{th} RU to the head antenna. The handover happens when the train is passing over the RU, i.e., when the head antenna of the train passes over the $(n+1)^{\text{th}}$ RU, the forward link will be handed over to the $(n+2)^{\text{th}}$ RU; when the tail antenna passes over the $(n+1)^{\text{th}}$ RU, the backward link will handed over to the $(n+1)^{\text{th}}$ RU. Figure 2 shows another example scenario where only one omni-directional antenna is equipped on the train. If only one antenna is equipped on the train as shown in Figure 2, the handover for the forward link and backward link will be performed simultaneously. The structure of connection between digital units (DUs) and RUs is shown in Figure 3, where the i^{th} DU connects with k RUs and the $(i+1)^{\text{th}}$ DU connects with p RUs. The proposed Doppler mitigation method can by implemented for both DL and UL in the case as shown in Figure 1 and only for UL in the case as shown in Figure 2, due to the reason of that two receive antennas are necessary for implementing the proposed method.

B. Channel Model

The well-known tapped delay line (TDL) channel model for multipath multi-tap case is given as following. The impulse response of channel is

$$h(t,\tau)=A_r\cdot\sum_{m=1}^{M}\sqrt{P_m}\cdot T_m(t)\cdot\delta(\tau-\tau_m), \quad (1)$$

where A_r is the signal magnitude of the received signal, M is the number of multipath taps, P_m is the average power of the m^{th} tap, τ_m is the time delay of the m^{th} tap, and $T_m(t)$ is the time varying weight of the m^{th} tap.

The weight $T_m(t)$ for wide sense stationary uncorrelated scattering (WSSUS) is given as,

$$T_m(t)=\frac{1}{\sqrt{N_0}}\sum_{n=1}^{N_0}\left\{\beta_n^{(m)}\exp\left(j2\pi f_d\cos(\alpha_n)t\right)\right\}, \quad (2)$$

where N_0 is the number of scatters, $\beta_n^{(m)}\sim N(0,1)$ is a complex Gaussian random variable with the 0 mean and variance of 1, f_d is the maximum Doppler shift, and α_n is the arrival angels uniformly distributed in $[0,2\pi]$.

From (1) and (2), it is obvious that the component related to Doppler shift is a multiplier term to the channel impulse response.

III. The Proposed Doppler Mitigation Method

Since the oscillator frequency drift can be well controlled using hardware and out of the scope of this paper, it is considered to be perfectly matched at the BS and TE sides. The proposed Doppler mitigation method is suitable for the channel environment where a dominant path exists, such as tunnel environment and rural area. The channel characteristics of tunnel environment has been reported in [3] as an example. From [3], we know that rather than Doppler spread, in most of the cases the Doppler effect behaves to be maximum Doppler shift. Furthermore, because the tunnel environment is an extreme space limited environment, the dominant path has been formed. That is, the channel in the tunnel can be approximately considered as a one-tap channel with maximum Doppler shift for most of the cases. In this case, the TDL channel impulse response can be simplified as

$$h(t,\tau)=A_r\cdot\exp(j2\pi f_d t)\cdot\sum_{m=1}^{M}\sqrt{P_m}\cdot\frac{1}{\sqrt{N_0}}\sum_{n=1}^{N_0}\left\{\beta_n^{(m)}\right\}\cdot\delta(\tau-\tau_m). \quad (3)$$

Notice that in (3), the term of $\cos(\alpha_n)$ in Doppler component has been removed, and M=1 corresponds to one-tap channel. For simplicity, we rewrite (3) as (4) since this proposed method is focusing on the Doppler shift component of the channel rather than other components.

$$h(t)=a(t)\cdot\exp(j2\pi f_d t), \quad (4)$$

where

$$a(t)=A_r\cdot\sqrt{P}\cdot\frac{1}{\sqrt{N_0}}\sum_{n=1}^{N_0}\{\beta_n\}. \quad (5)$$

As shown in Figure 1 and 2, we define the Doppler shift of forward link is $f_{d,fwd}$ and the Doppler shift of the backward link is $f_{d,bwd}$. Therefore, the channels for forward link and backward links are given as

$$h_{fwd}(t) = a_{fwd}(t) \cdot \exp\left(j2\pi f_{d,fwd} t\right), \quad (6)$$

$$h_{bwd}(t) = a_{bwd}(t) \cdot \exp\left(j2\pi f_{d,bwd} t\right). \quad (7)$$

Notice that the head antenna and the tail antenna are located on the same train, which indicates that the mobility for the forward link and backward link is same but with opposite direction. As shown in Figure 4, recall that the maximum Doppler shift is given as

$$f_d = \frac{v}{C} \cdot f_C \cdot \cos(\theta). \quad (8)$$

Then we get the relationship between $f_{d,fwd}$ and $f_{d,bwd}$ in most of the cases that

$$f_{d,fwd} \approx -f_{d,bwd}. \quad (9)$$

Based on the observation of (9), the Doppler shift of HSR communication systems can be removed by multiplying the received signals from head and tail antennas, when the same OFDM symbol $S(t)$ is transmitted through the forward and backward links. In the DL of Figure 1 as an example, the received signals of head antenna and tail antenna on the radio frequency of f_C are

$$y_{head}(t) = h_{fwd}(t) \cdot S(t) + n_{head}(t), \quad (10)$$

$$y_{tail}(t) = h_{bwd}(t) \cdot S(t) + n_{tail}(t), \quad (11)$$

where $n_{head}(t)$ and $n_{tail}(t)$ indicates the additive white Gaussian noise (AWGN) on the head and tail antennas, respectively. The OFDM symbol is given as

$$S(t) = \sqrt{s(t)} \cdot \exp\left(j2\pi f_C t\right). \quad (12)$$

where $s(t)$ is the baseband OFDM symbol. After multiplying the two received signals, we have

$$\begin{aligned} Y(t) &= y_{head}(t) \cdot y_{tail}(t), \\ &= [h_{fwd}(t) \cdot S(t) + n_{head}(t)] \cdot [h_{bwd}(t) \cdot S(t) + n_{tail}(t)], \\ &= a_{fwd}(t) a_{bwd}(t) \exp[j2\pi(f_{d,fwd} - f_{d,bwd})t] \cdot s(t) \exp(j4\pi f_C t) \\ &\quad + h_{fwd}(t)\sqrt{s(t)} \cdot \exp\left(j2\pi f_C t\right) n_{tail}(t) \\ &\quad + h_{bwd}(t)\sqrt{s(t)} \cdot \exp\left(j2\pi f_C t\right) n_{head}(t) \\ &\quad + n_{head}(t) n_{tail}(t). \end{aligned} \quad (13)$$

In (13), only the first term is the desired signal which will be processed later, the second and the third terms are interference to the desired signal, and the forth term is the AWGN. By using the high-pass filter (HPF), the interference terms can be removed since that the desired term has the frequency of $2f_C$, while the interference terms has the frequency of f_C. Figure 5 shows the way of multiplying two received signals and removal of the interference terms. Notice that when the very high carrier frequency, such as mmWave, is employed for transmission, in order to demodulate the signal in (13), the oscillator frequency of $2f_C$ should be used,

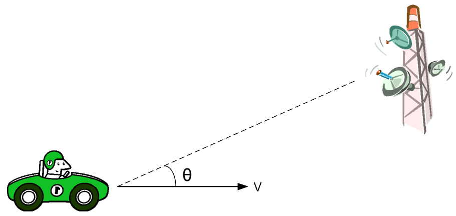

Figure 4. Doppler shift calculation

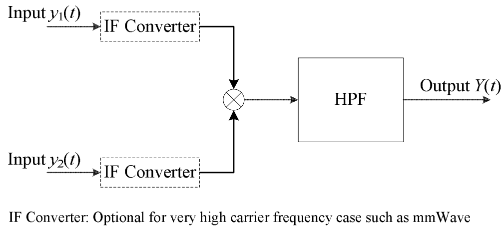

Figure 5. Time domain configuration before RF for interference removal

in which case the cost of the hardware may increase a lot correspondingly. As a solution, an intermediate frequency (IF) converter is suggested for each received signal before multiplication. In this case, the very high carrier frequency can be converted to the relatively low frequency IF first, and the cost of receiver can be well controlled. Therefore, the IF converters are optional for the cases of employing very high carrier frequency such as mmWave. Finally the signal $Y(t)$ will be considered as the received signal and be further processed. Notice that after multiplication, the Doppler shift of the desired signal has been mitigated to be $\Delta f_d = (f_{d,fwd} - f_{d,bwd})$. The similar method can be used in the UL of the scenarios as shown in both Figure 1 and Figure 2. Notice that the proposed method can also be implemented for multiple-input multiple-output (MIMO) systems, where the multiplication of the two received signals will be the Hadamard product of the two received vectors.

IV. Simulation Results and Discussions

A. Simulation Results

It is obvious that in order to implement the proposed Doppler mitigation method, two receive antennas are necessary. That is, when two antennas are located on the train as shown in Figure 1, the proposed method can be adopted for both DL and UL. However, when only one antenna is located on the train as shown in Figure 2, the proposed method can be employed only for UL. Figure 6 shows the performance comparison of Doppler shift for the DL when two antennas are located on the train. We count the location 0 m as the position of head antenna passing over RU. The parameters setting is given in Table 1, which represents the typical parameters for trains in tunnel environment as an example. As aforementioned, the head antenna on the train performs handover to the next RU at the location of 0 m and 1000 m. As soon as the handover is done, the Doppler spread of the head antenna behaves as the maximum Doppler shift. The reason is that the tunnel is quite a space limited environment and all the reflected paths with relatively high power reaches the receiver with very small time difference which cannot be

TABLE 1. SYSTEM PARAMETERS

Parameter Setup	
Frequency	32 GHz
Antenna Configuration	1 Head Ant. + 1 Tail Ant. / Single Ant.
Antenna Height	6.5 m for RU, 3 m for TE
Antenna Setup	Directional / Omni-directional Ant.
Length of Train	200 m
Distance between RUs	1 km
Speed	100 m/s (360 km/h)

distinguished by the receiver. Therefore, the channel behaves like a one-tap channel. As the train is getting closer to the RU, the Doppler shift decreases rapidly until the antenna hands over to the next RU. However, we should notice that the Doppler decreasing period is as short as 50 m in the example. The similar situation happens to the tail antenna also, but the handover of the tail antenna is performed 200 m later than the head tail due to the length of train is assumed to be 200 m. In Figure 6, the maximum Doppler shift of the head antenna and tail antenna is 10.667 kHz and -10.667 kHz respectively, which value is too big for the receiver to process. By using the proposed method, the residual Doppler shift is mitigated to 0 Hz with the probability of 90% (900 m out of 1000 m distance between adjacent RUs). Only the Doppler shift of the remaining two peaks (when handover happens) cannot be reduced by the proposed method. The UL of one omni-directional antenna on the train case shows the same performance as in Figure 6.

At the mobile TE side, the TE on the train estimates the carrier frequency from the DL signal and transmits the UL signal by using the estimated carrier frequency. Recall that the DL signal $Y(t)$ after multiplication has the carrier frequency of $(2f_C+\Delta f_d)$, then after estimation, the carrier frequency used for UL transmission will be $(f_C+\Delta f_d/2)$, i.e., the residual frequency error for UL transmission due to Doppler effect can be further reduced by half. Figure 7 shows the residual Doppler shift for UL transmission. Without using the proposed method, the remaining maximum Doppler shift to be handled by the BS is 2×10.667 kHz for the forward link and -2×10.667 kHz for the backward link. When the proposed Doppler mitigation is employed for both DL and UL, the total residual Doppler shift at the BS side will be 0 Hz with the probability of 81% (90%×90%), ±0.5×10.667 kHz with the probability of 18% (90%×10%+90%×10%), and ±1.5×10.667 kHz with the probability of 1% (10%×10%).

B. Discussions

The advantages of the proposed Doppler mitigation method can be summarized as follows:

- Efficiently remove Doppler effect for most of the cases without the necessity of estimating Doppler spread
- Time-domain pilot density can be reduced since the residual Doppler shift is 0 Hz with high probability. Even though the peaks of residual Doppler shift exist, the handover should be performed at the exact time of peak residual Doppler, therefore the influence of peak residual Doppler shift to the data transmission and reception is limited.
- Reduce residual Doppler shift: especially for UL, residual Δf_d in DL can be reduced by half for UL transmission due to the doubled carrier frequency after multiplication of the two received signals (two antennas on the train)
- Robust to the time-varying mobility: since the head antenna and the tail antenna always have the same mobility with the opposite direction, the residual Doppler shift will be 0 Hz no matter how the mobility varies with the time.

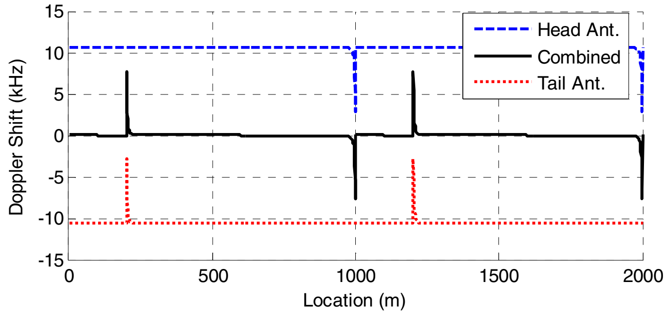

Figure 6. Performance comparison of Doppler shift for DL reception with constant maximum mobility

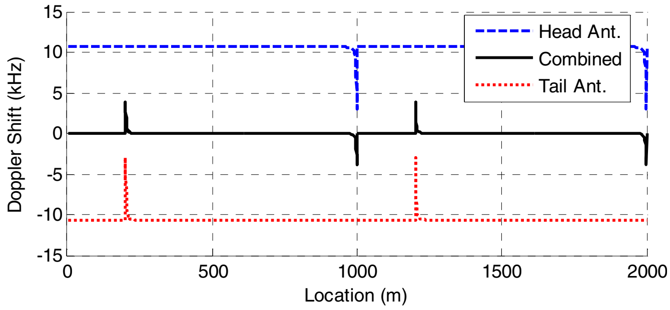

Figure 7. Residual Doppler shift after carrier frequency estimation for UL

For the practical implementation of the proposed Doppler mitigation method, five possible difficulties exist.

- Two receive antennas are necessary, which requests additional hardware cost.
- In order to implement the proposed method for Doppler shift mitigation in UL, the X2 interface (interface among DUs) is necessary to jointly process the two received signals by different RUs.
- Accurate time synchronization is necessary to guarantee that the received signals from different antennas can be multiplied without mismatch. This problem may be solved by employing the buffer memories to save the received signal for a while.
- A filter to generate the square root of the baseband transmitted signal $\sqrt{s(t)}$ is necessary.
- For very high carrier frequency case, IF converters are required at the receiver side to control the hardware cost.

V. CONCLUSIONS

A Doppler mitigation method for HSR communications was proposed in this paper. The proposed method shows the capability of efficiently removing Doppler effect for most of the cases without the necessity of estimating Doppler spread. The simulation results show that in most of the cases (90%), the residual Doppler shift Δf_d is 0 Hz. Furthermore, by employing the proposed method, time-domain pilot density can be reduced since the residual Doppler shift is 0 Hz with high probability. Particular, for the accumulated Doppler shift, the residual Δf_d in DL can be reduced by half for UL transmission due to the doubled carrier frequency after multiplication of the two received signals when two antennas are equipped on the train. The proposed method also shows the robustness to the time-varying mobility.

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