International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 17 (2018) pp. 13344-13348

Compensating Doppler Frequency Shift of High Speed Rail Communications

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Abstract

In High Speed Rail (HSR), the passengers's demand and transportation management networks require high-speed data communications services with reliable real- time connections. OFDM is a modulation method in the LTE wireless communication systems to provide broadband commmunications services, but it is very sensitive to the Doppler effect. When the speed of the train is becoming more and more faster, the Doppler frequency Shift is becoming more and more greater. In this paper, we propose a practical model to determine the Carrier Frequency Offset (CFO) without using the pilot in the data frame. The simulation results show that the BER performance has been improved significantly using the proposed practical system model.

Keywords: Carrier frequency offset, Doppler effect, HSR, OFDM

INTRODUCTION

In High Speed Railway (HSR), the integration of Artificial Intelligence (AI) into control systems and the growth of train speed lead to the requirements of automatic remote control and supervision technologies in which the broadband wireless communications act as the nervous system. The safety of train operation will be enhanced by using the broadband communication systems as onboard video surveillance and track monitoring, Closed Circuit Television (CCTV). Besides, the demands for high-speed data connections of passengers on board as Internet, video calls, online TV are also vital. But the Global System for Mobile Communications-Railway (GSM-R) based on GSM technology does not meet the increasing requirements of broadband communications for supervising, controlling the train operation and services for passengers [1].

Currently, there are a lot of multimodal systems supplying broadband communications for HSR. One of them is the global broadband multimodal radio system (MOWGLY) in Europe, which provides WiFi signal for passengers on board, the satellite signal for communications between train and the ground with 30 seconds delay. It also be used on Thalysand TGV East to supply broadcast internet [2]. With the speed of train is 300 kph, the maximum speed of data downlink and uplink are 4 Mbps and 2 Mbps, respectively [3]. Although current technologies temporarily meet the demands for HSR radio communications, they don't meet the requirements for the fastest speed trains, high-speed data, real-time and reliable communications. According to recent studies, the required data rate for a train in HSR is around 37.5 Mbps and over 0.5-5 Gbps in the near future [4]. Therefore, researches, applications about wireless communication systems for the HSR scenarios face many challenges and it attracts a lot of attention.

The 4G LTE standard has been set up for the train communication and the transmission of train control data by UIC (Internationla Union of Railway) [5] . The main modulation of 4G LTE standard is Orthogonal Frequency Division Multiplexing (OFDM). It provides high bandwidth efficiency and reliable signal transmission by dividing the available spectrum into group of closely spaced orthogonal sub-carriers, instead of transmitting a high data stream with a single carrier. Nevertheless, a series of difficulties caused by high movement speed such as over-frequent handover and high Doppler shift [6]. Particularly, when using OFDM based systems for HSR communications, the Doppler frequency Shifts must be considered due to the fact that the OFDM systems are easily vulnerable by the carrier frequency offset (CFO), which may introduce the inter-carrier interference (ICI). Therefore, CFO problem plays a crucial role in OFDM systems for HSR communications. There are a lot of researches on Doppler shift estimation methods as [7], [8], [9]. Authors in [7] presented a Doppler shift estimation based on channel estimation, however which is effective once users moving with low speed. In [8], this paper pre-compensates Doppler frequency Shift in LTE-R Systems but it is not reliable because of the delay of feedback from MRs to RRUs and the accuracy of Doppler frequency shift estimation. In [9], authors proposed the Doppler Shift Estimation for HSR Wireless Communication Systems. Although its Doppler shift estimation algorithm has high accuracy, it must use Large-Scale linear antennas with a phase rotation algorithm. Moreover, the train speed will be more and more increased leading to the requirements of estimating and compensating CFO accurately in a very short time. In this research, we propose a model to compensate CFO by determining the frequency shift without estimating CFO.

The rest of the paper is divided into four sections as follows. In section II, the system model for practical scenarios is introduced. The performance analysis of the proposed model is denoted in section III. The simulation results are shown and analyzed in section IV. A brief conclusion is given in section V.

SYSTEM MODEL

In public mobile communication systems, all mobile stations (MSs) connect directly to Base Stations (BSs). Due to the metal frame of the train, the signal will be attenuated much more than ordinary cases. With the large demands of passengers for broadband communication services at the same time, if the links are connected directly to the train moving at high speed, the MSs will take handover simultaneously, which impacts significantly to quality of services. So two ring structures are accepted in HSR communication [10]. The links between Base Station (E-NodeB) and Access Point (AP) on board serves as the repeater according to D2A model and the other link between AP and MSs (UE in LTE) operates as D2B Model. This paper focuses on the downlink from the E-Node B to APs.

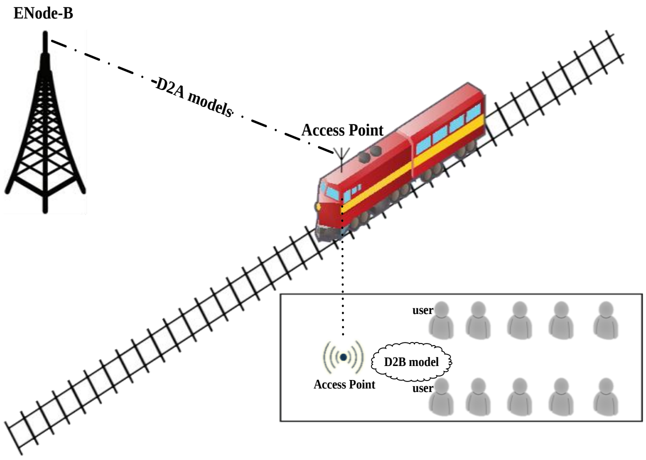

Figure 1. The system model of HSR

In HSR, when the train moves at the high speeds, the received signal at AP suffers from the Doppler effect that produces the Doppler frequency Shift. Our proposed model in Fig.2 can compensate it.

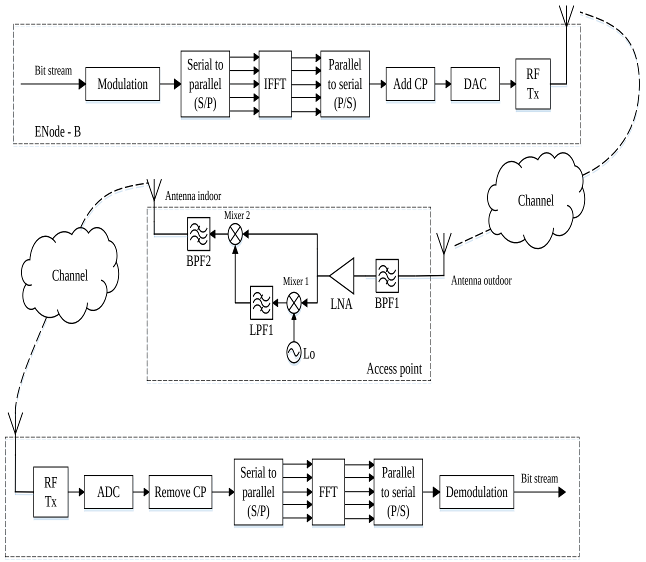

Figure 2. The proposed practical model system

Fig. 2 shows the proposed practical model system for compensating Doppler frequency Shift. At transmitter, data from Enode-B is turned into bit streams, modulated and gone to Serial to Parallel block. The output signals from IFFT block are inserted cycle prefix (CP) and fed to DAC block to generate OFDM signals. Because the distance between E-NodeB and AP is short and the train usualy runs in suburban area, the signal energy mainly focus on the light of sight (LOS) in HSR scenario. Therefore, the Ricean-fading channel is applied here according to D2a scenario of WINNER II [11]. The resultant signals are transmitted through multipath Rician channel with Additive white Gaussian noise (AWGN) to HSR. Doppler frequency shift is determined and compensated at the AP. This process is described as following. Firstly, the received signal at AP go through the Band Pass Filter (BPF1) and Low Noise Amplifier (LNA). Then, it divided into two paths.

Path 1: The received signal with frequency $f_c + f_d$ goes to input port of mixer 1 . A fixed carrier f_c generating by Local Oscillator (LO) also comes to input port of mixer 1. As an ideal mixer, the output signal frequencies are f_d and $f_c + 2f_d$ with constant waveform. Then output signals go through a Low Pass Filter (LPF), we have a desired signal at the frequency f_d.

Path 2: The received signal with frequency $f_c + f_d$ goes to input port of mixer 2. At this block, this signal will be mixed with signal at the frequency f_d from the path 1. So the output signal frequencies of mixer 2 are f_c, $f_c + 2f_d$. After using a Band Pass Filter 2 (BPF 2), the signal frequency f_c is passed over, the signal with frequency $f_c + 2f_d$ is omitted. Finally, the signal frequency f_c is transmitted to users by antenna indoor. This signal suffers from multipath fading channel and goes through an inverted process as in E-Node B in order to transform into initial data.

PERFORMANCE ANALYSIS

The Doppler frequency shifts are our main research objective, so the following assumptions are taken for analysing:

The system has been synchronized in time and oscillator frequency.

Input bits are random and independent.

One OFDM modulated signal of the baseband in frequency domain is given by

$$x[n] = \sum_{k=0}^{N-1} X[k].e^{j2\pi nk/N} \tag{1}$$

Where $X[k]$ is denoted the symbol transmitted by k-th subcarrier

The transmitted OFDM signal with carrier frequency f_c can be written as

$$s(t) = e^{j2\pi f_c t}.x[n] = e^{j2\pi f_c t}.\sum_{k=0}^{N-1} X[k].e^{\frac{j2\pi nk}{N}} \tag{2}$$

The received signal, after passing through multipath Rician channel and suffering AWGN, with Dopler frequency shift at the input of AP can be expressed by

$$r(t) = e^{j2\pi(f_c+f_d)t}.x[n] = e^{j2\pi(f_c+f_d)t}.\sum_{k=0}^{N-1} X[k].e^{j2\pi nk/N} \quad (3)$$

In the proposed model in Fig. 2, the received signal $r(t)$ containing the Doppler frequency Shift component at AP will pass through BPF1 and is amplified by using LNA and goes to Mixers. At the mixer 1, the signal will be mixed with oscillating frequency f_c generated by Local Oscillator (LO) block. The result of the mixed signal $r_1(t)$ as following:

$$r_1(t) = e^{-j2\pi f_c t}.r(t) = e^{j2\pi f_d t}.x[n] \quad (4)$$

After this signal passes through LPF1, the spectrum of the signal is f_d. It is mixed with the initial received signal $r(t)$ at the mixer 2 to eliminate the Doppler frequency shift. The result of the mixed signal $r_2(t)$ is determined as the following:

$$r_2(t) = e^{-j2\pi f_d t}.r(t) = e^{j2\pi f_c t}.x[n] \quad (5)$$

Doppler Frequency Shift in the signal $r_2(t)$ is completely canceled. The signal $r_2(t)$ is transmitted to users by an indoor antenna in HSR. At users, signal is demodulated at frequency f_c, removed cycle prefix and goes to FFT block. The signal before going FFT block can be given by:

$$y[n] = e^{-j2\pi f_c t}.r_2(t) = x[n] = \sum_{i=0}^{N-1} X[i].e^{j2\pi in/N} \quad (6)$$

The signal after passing through FFT block can be written as

$$Y[k] = \frac{1}{N}\sum_{n=0}^{N-1} y[n]e^{-j2\pi kn/N} = \frac{1}{N}\sum_{n=0}^{N-1}\left(\sum_{i=0}^{N-1} X[i]e^{j2\pi in/N}\right)e^{-j2\pi kn/N} = \frac{1}{N}\sum_{n=0}^{N-1}\sum_{i=0}^{N-1} X[i]e^{j2\pi(i-k)n/N} = X[k] \quad (7)$$

With the proposed model, the signal after going through FFT block does not affect by Doppler frequency shift so the Bit Erro Rate (BER) is significantly enhanced.

In conventional models, baseband signal with CFO from Doppler Frequency Shift can be written as:

$$y_d[n] = e^{j2\pi\varepsilon n/N}.x[n] \quad (8)$$

Through the inverse process at the users, the signal can be determined as the following:

$$Y_d[k] = \frac{1}{N}\sum_{n=0}^{N-1} y_d[n]e^{-j2\pi kn/N} = X[k-\varepsilon] \quad (9)$$

So the affect of Doppler frequency shift to signal constellations increases BER clearly.

SIMULATION RESULTS

Firstly, we create a simulated system model with parameters in Table 1. The sampling frequency f_s is 15.36 MHz with BPSK modulation and IFFT and FFT points are 1024. The Guard Interval length equals $\frac{1}{4}$ OFDM signal lengths.

Table 1: Specific Parameters for Simulation

Parameters	Values
Cell radius	1000 m
Veclocity of train	v=150 mps = 540 kph
Total number of subcarriers	N=1024
Modulation	BPSK
Subcarrier spacing	Δf=15 kHz
Bandwidth	10MHz
Sampling Frequency	15.36 MHz
Frequency	2.6 GHz
Guard Interval Ratio	¼
Doppler Frequency	1300 Hz
Transmissions Channel	AWGN, Multipath Rician channel (K=2, K=8)

When the speed of the train is v, the maximum value of Dopler frequency shift is calculated by

$$f_d = f_c.\frac{v}{c} \quad (10)$$

Since the simulated system model operates at baseband with subcarrier spacing is 15 kHz, the Carrier Frequency Offset (CFO) can be estimated as

$$\varepsilon = \frac{f_d}{\Delta f} = \frac{f_c v}{c\Delta f} \quad (11)$$

Figure 3, 4, 5 present the BER of the system using AWGN and Rician multipath fading channel with K=2 and K=8.

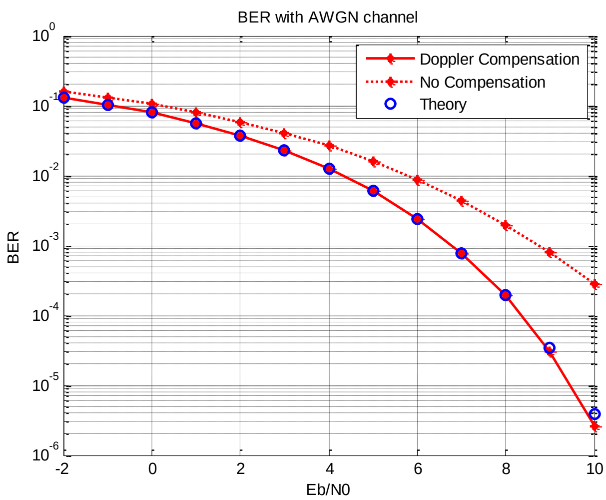

Figure 3. BER performance of system over AWGN channel

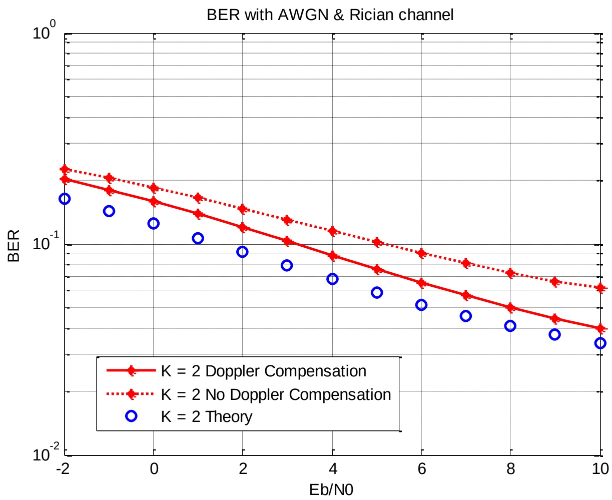

Figure 4. BER performance of system over AWGN and Rician channel with K=2

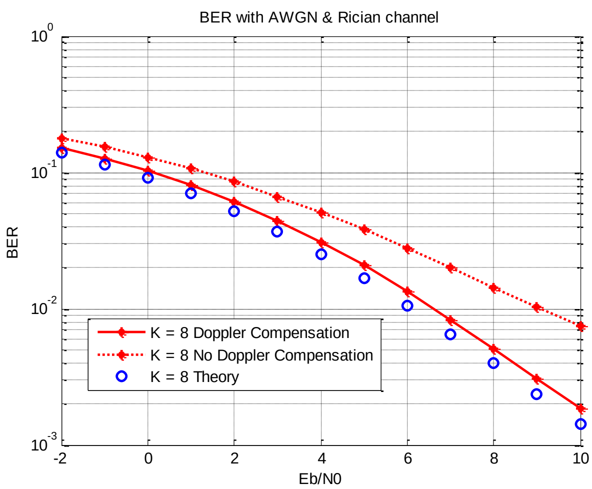

Figure 5. BER performance of system over AWGN and Rician channel with K=8

The affect of Doppler frequency shift to conventional communication systems can be considered as the the affect of CFO to baseband signals. In 4G-LTE systems, CFO coefficient equals 0.0867. The BER performance of the proposed system model has been significantly improved, especially when the paths of the Rician channel increase. The proposed method that compensates Doppler frequency shift at the received antenna outdoor in HSR has improved the quality of signal dramatically.

CONCLUSIONS

In this paper, we propose a practical model system to compensate Doppler frequency shift by adding a fixed carrier frequency f_c generated by Local Oscillator (LO) at AP without using the pilot in the data frame. The studied system is described and the numeric results have been presented. The BER values of signals, which go through multipath Rician channel and AWGN, are evaluated through simulation results. Compared to the no Doppler compensation signals, the BER perfomance of the simulated signal has been improved. With the advanced development of microwave engineering technology, the implementation of this model at AP can be performed. This model helps to compensate Doppler frequency shift, guarantees real-time connections and increases data-speed effectively in HSR.

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