Channel Transfer Function estimation based on Delay and Doppler Profiler for 5G System Receiver targeting 500km/h linear motor car

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Summary
A 500 km/h linear motor high speed terrestrial transportation service is planned to launch 2027 in Japan. In order to support 5G service in the train, the Sub-carrier spacing frequency of 30 kHz is planned to be used instead of common 15 kHz sub-carrier spacing to mitigate Doppler effect in such high-speed transportation. In addition, to increase the cell size of 5G mobile system, plural Base Station antenna will transmit the identical Down Link (DL) signal to form the expanded cell size along the train rail. In this situation, forward and backward antenna signals will be Doppler shifted by reverse direction respectively and the receiver in the train might suffer to estimate accurate Channel Transfer Function (CTF) for its demodulation.
In this paper, Delay and Doppler Profiler (DDP) based Channel Estimator is proposed and it is successfully implemented in signal processing simulation system. Then the simulated performances are compared with the conventional Time domain linear interpolated estimator. According to the simulation results, QPSK modulation can be used even under severe channel condition such as 500 km/h, 2 path reverse Doppler Shift condition, although QPSK modulation can be used less than 200 km/h with conventional Channel estimator.

Keywords:
5G, 5th Generation Mobile Communication System, Channel estimation

I. Introduction

A 500 km/h linear motor high speed terrestrial transportation service is planned to launch 2027 between Tokyo and Nagoya in Japan. The maximum speed of current high speed train Shinkansen is 300 km/h. However, the coming linear motor train's speed will be 500 km/h by using magnetic levitation mechanism. In order to support 5G service in the train, 5G will use some different configurations. First, increased sub-carrier spacing f_0 of 30 kHz is used instead of conventional 15 kHz to mitigate Doppler frequency shift. This change automatically shortens OFDM symbol length by half. Consequently, channel state change tracking performance will increase. Second, to increase mobile service cell size, plural Base Station antennas transmit the identical Down Link (DL) signal to form the expanded cell size along the train rail. In this situation, forward and backward antenna signals will be Doppler shifted by reverse directions respectively and the receiver in the train might suffer to estimate accurate Channel Transfer Function (CTF) for demodulation. Fig. 1 shows the situation of two Down Link (DL) reception in the car. Approaching TX1 antenna signal is $+f_d$ shifted and backward TX2 signal is $-f_d$ shifted.

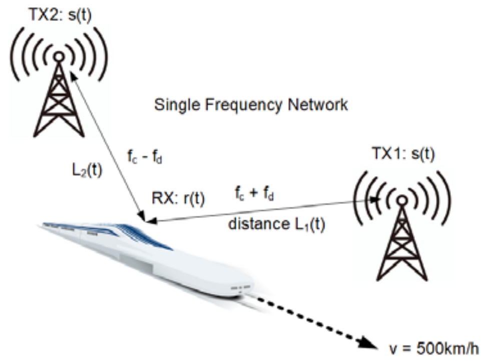

Fig. 1: Two Down Link receiving situation in the high-speed train

In this paper, in order to improve the receiver performance, Delay and Doppler Profiler (DDP) based estimation method of Channel Transfer Function (CTF), which varies along with the train movement, is applied. In section II, first, targeting 5G Mobile Communication System is briefly shown. Then the proposed DDP method is explained. Computer simulation results are shown in section III. Finally, in section IV, the conclusions will be given.

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Table 1: 5th Generation Mobile Communication System Parameters

Parameters	Value
System Band Width	100 MHz
Sub-carrier Spacing (f_0)	30 kHz
Pass Band Frequency	3.9 GHz
OFDM symbol length (T)	33.33 us (4096 points)
Number of Common Resource Blok (CRB)	273
Number of Sub-carriers	3276
Sampling Frequency (Fs)	122.88 Msps
FFT size	4096
CP length	352 or 288 points

II. 5G Mobile Communication System Architecture

5th Generation Mobile Communication System [1] is OFDM communication system standard developed as the successor to the 4G system with various enhancements. For example, the sub-carrier spacing was fixed as 15kHz in 4G but in 5G variable sub-carrier spacing is supported such as 15 / 30 / 60 / 120 / 240 kHz. For the application of the linear motor train, 30 kHz sub-carrier frequency will be used for RF Carrier of 3.9 GHz Band. Table I summaries the 5G system parameters for this application. To support eMBB (enhanced Mobile Broadband), 100MHz bandwidth is assumed with 3276 sub-carriers. Because of sub-carrier spacing f_0 of 30 kHz, OFDM symbol length T of 33.33us (4096 sampling points) is used.

Fig. 2 shows the 5G Frame structure for f_0 of 30 kHz. 10 ms Frame is divided into 20 Slots. In one Slot, 14 OFDM symbols are embedded. Cyclic prefix (CP) length is 288 sampling points for each 4096 points OFDM symbols except the 1st CP. The length of the 1st CP is a little expanded such as 352 points. In 5G system, Demodulation Reference Signals (DMRS) are inserted to

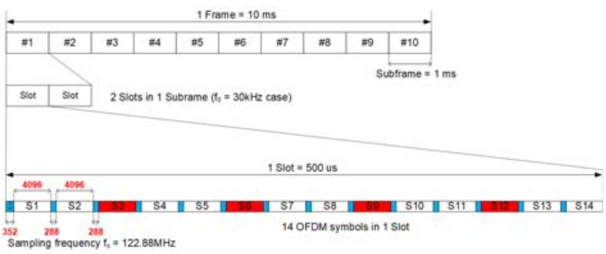


Fig. 2: 5G Frame structure

some Sub-carriers to measure Channel Transfer Function (CTF) and the DMRS can be placed with a high degree of freedom according to the system configuration. This time, DMRS is asserted in S3, S6, S9, S12 OFDM symbols to detect rapidly time-domain changing CTF [2].

Time-Frequency structure of this 5G system is shown in Fig. 3. Since 12 sub-carriers and 14 OFDM symbols constitute one Common Resource Block (CRB), the total 3276 sub-carriers correspond to 273 CRBs. The detail of sub-carrier arrangement in a CRB is also shown in the figure. For frequency direction (vertically), DMRS are placed every 2 sub-carriers as shown in the odd number places. Sub-carriers at the odd number in S3, S6, S9, S12 OFDM symbols are empty, although those empties might be used for MIMO configurations system with multiple antennas.

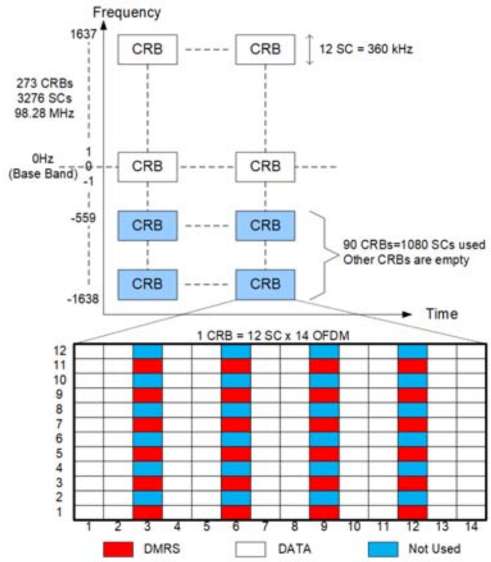


Fig. 3: Time-Frequency structure of System

A) *Physical layer of 5G communication system*

Fig. 4 shows the block diagram of the Physical Layer (PHY) for 5G SISO (Single Input Single Output) system. The upper side is the transmitter and the lower side is the receiver. The Bit Data, which are provided from the upper MAC, Protocol and Application layer, are digital modulated at Symbol mapper by QPSK / 16QAM / 64 QAM / 256 QAM. Then the modulated symbols and DMRS pilots signals configure Slots as shown in Fig. 3. Then Inverse 4096 points Fourier Transform (IFFT) is performed as OFDM modulation and Cyclic Prefix (CP)

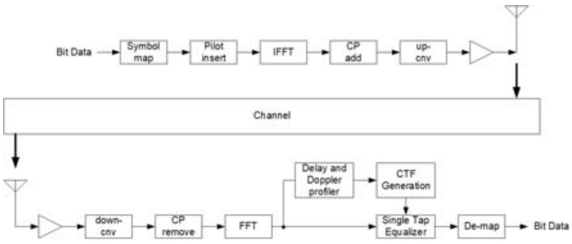


Fig. 4: Physical layer of 5G communication system

is appended. This signal is Baseband (BB) signal. By applying up-conversion to BB signal, path-band signal is generated then emitted through power amplifier and antenna.

The receiver side performs basically the reverse process of the transmitter. However, since the receiving signal is distorted through the propagation channel, Channel Transfer Function (CTF), which is a Frequency domain representation of Channel Impulse Response in Time domain, has to be estimated and the distortion has to be compensated at Equalizer using the estimated CTF. Then the accuracy of the CTF estimation greatly influence to the receiver error performance. In conventional 5G receiver, the measured CTF values at the DMRS position are interpolated in Frequency and Time domain to get all sub-carrier position CTF. In order to improve CTF estimation, this paper studies new method such as Delay and Doppler Profiler based all CTF estimation.

B) Improved Channel Transfer Function estimation based on Delay and Doppler Profile

References [3-5] describe detail methods of Delay and Doppler Profile (DDP) based CTF estimation using pilot signals embedded in OFDM sub-carriers. Fig. 5 is a

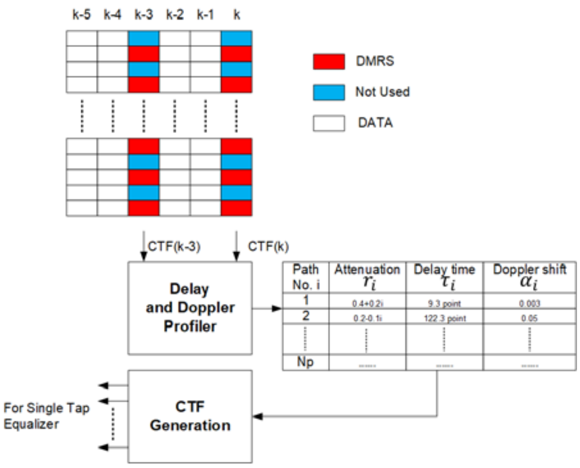


Fig. 5: Delay and Doppler Profiler based CTF estimator

block diagram of proposed DDP CTF generation. The upper side of the figure represents the Time-Frequency structure of sub-carriers with time-domain symbol index k. The DDP estimates each Np multipath component waves to receiving antenna. Each analyzed component can be characterized using three parameters such as Attenuation r_i, Propagation Delay time τ_i, and normalized Doppler shift α_i for wave component index i. Here the Attenuation r_i is complex value including amplitude attenuation and phase rotation and the normalized Doppler shift is normalized by sub-carrier spacing f_0 such as $\alpha_i = fd_i/f_0$. Using the symbol k measured CTF(k) and symbol k-3 measured CTF(k-3), the DDP detects Np sets of those three parameters. Using those parameters, all position CTF $h(k,l)$ can be calculated as Equation (1). Here, k is symbol number, l is sub-carrier index, N is the FFT size, N_p is the total number of delay paths, T_s is the sum of OFDM symbol length and CP length.

$$h(k,l) = \sum_{i=1}^{N_P} \frac{1}{N} \frac{\sin\{\pi(\alpha_i)\}}{\sin\frac{\pi(\alpha_i)}{N}} \times e^{j\frac{\pi(N-1)\alpha_i}{N}} \times e^{j2\pi\alpha_i f_0 T_s k} \times r_i e^{-j2\pi f_0 (l+\alpha_i)\tau_i} \quad \cdots (1)$$

Once Delay and Doppler profile parameters are known, by changing the symbol number k, CTF at different times can be generated.

The method of obtaining the parameters in each delay path by DDP is detailed in references [3-5], but now DMRS pilots are inserted at symbol numbers k and $k-3$. Consider the following estimated evaluation function $E(k)$. CTF is measured at DMRS pilots, h is the channel transfer function to estimate by minimizing $E(k)$. Summation range P corresponds sub-carrier indexes on DMRS positions.

$$E(k) = \sum_{l=P} |CTF(k,l) - h(k,l)|^2 + \sum_{l=P} |CTF(k-3,l) - h(k-3,l)|^2 \quad \cdots (2)$$

First, the maximum power delayed wave is detected by minimizing the following equation.

$$E_1(k) = \sum_{l=P} \left|CTF(k,l) - f(\alpha_1) r_1 e^{-j2\pi f_0 (l+\alpha_1)\tau_1}\right|^2 + \sum_{l=P} \left|CTF(k-3,l) - f(\alpha_1) e^{j2\pi\alpha_1 f_0 T_S(-3)} r_1 e^{-j2\pi f_0(l+\alpha_1)\tau_1}\right|^2 \quad \ldots (3)$$

where $f(\alpha_1)$is given by

$$f(\alpha_i) = \frac{1}{N}\frac{\sin\{\pi(\alpha_i)\}}{\sin\frac{\pi(\alpha_i)}{N}} \times e^{j\frac{\pi(N-1)\alpha_i}{N}} \times e^{j2\pi\alpha_i f_0 T_s k} \quad \ldots (4)$$

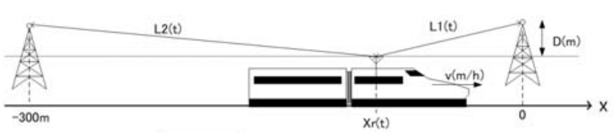
According to [3-5], r_1, τ_1, and α_1 can be obtained by minimizing $E_1(k)$. This yields the channel transfer function of the first pass (i=1) according to equation (1).

By subtracting the obtained channel transfer function of the first pass from the measured CTF, remaining CTF value can be obtained, and the same calculation is performed to obtain the parameters of the second pass. By repeating the above calculations N_p times, all parameters for each pass can be obtained. Once the parameters of all N_p paths are known, all CTF such as $h(k,l)$ according to equation (1) can be synthesized, and by varying the symbol number k, channel transfer functions corresponding to k from $k-5$ can be obtained.

III. Computer Simulations

Since the actual test environment is not yet available, computer simulations were used to simulate the environment. Fig. 6 shows a computer simulated running linear motor train situation. Nearby Base Station (gNB: g Node B in 5G notation) antennas are located from the train rail by D (m). In a Single Frequency Network (SFN), the same DL signal is transmitted from antennas in different each gNBs. Communication area is assumed then The distance of two antennas is 300 m between gNBs. Assuming the location of the reception antenna as Xr(t) of horizontal x-axis as shown in the figure. The distances between two antennas and the receiver antenna are L1(t) and L2(t) as shown in the figure (Fig. 6).

More detail of simulation parameters is listed in Table 2. Assumed Radio passband frequency is 3.9 GHz. In the simulation, moving train will start receiving 4 frames of DL signal with Xr(t=0) = -50 m. Path1 DL signal comes from forward antenna with varying length L1(t) with relative amplitude gain = 1.0. Path2 DL signal comes from backside with L2(t) distance with relative



$$L1(t) = \sqrt{D^2 + Xr(t)^2}$$

$$L2(t) = \sqrt{D^2 + (Xr(t) + 300)^2}$$

Fig. 6: Simulated vehicle moving situation

Table 2: Simulation Parameters

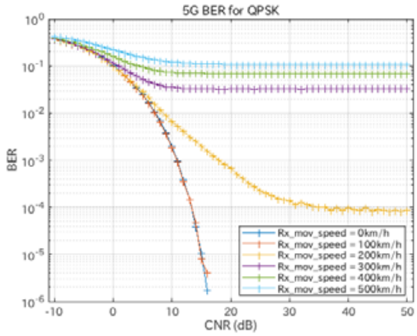
Parameters	Value
RF pass band frequency	3.9 GHz
Modulation	QPSK / 16QAM / 64QAM / 256QAM
RX moving speed	0 km/h ~ 500km/h, (100km/h step)
CNR	Add to AWGN -10 dB ~ 50 dB, (1 dB step)
Number of Frames	4 Frames (40 ms, 80 slots)
Used number of CRBs	90 CRBs (1080 Sub-carriers)
Channel	SISO, 2 Paths, Single Frequency Network
Path1 (L1(t))	Distance = ~50m Amp gain = 1.0
Path2 (L2(t))	Distance = ~250m Amp gain = 0.5
Antenna Distance (D)	D = 2 m

amplitude gain = 0.5. Bit Error Rate (BER) is measured in lower frequency 90 CRBs as shown in Fig. 3.

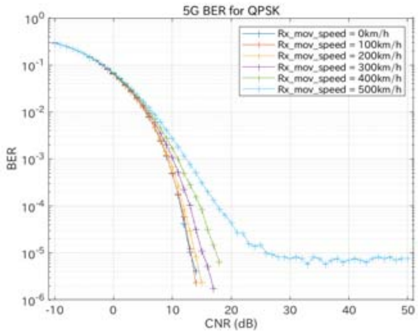
The Bit Error Rate (BER) was obtained by adding Additive White Gaussian Noise (AWGN) to the signal received as a composite wave of the 2gNB-derived Down Link (DL) signal, varying from -10 dB to 50 dB in 1 dB steps.

Simulated results for QPSK / 16QAM / 64QAM / 256QAM BER with Carrier to Noise Ratio (CNR) were shown in Figs. 7-10. In each figure, (a) corresponds to conventional linearly interpolated CTF estimation and (b) corresponds to proposed DDR based CTF estimation. Figs. 11-14 show BER vs train moving speed for QPSK with CNR=16dB, 16QAM with CNR=23dB, 64QAM with CNR=30dB and 256QAM with CNR=30dB.

Assuming BER below 1.0E-03 can be error correctable with associated error correction mechanism, QPSK modulation can be used even under severe channel condition such as 500 km/h with 2 path reverse Doppler Shift condition, although QPSK modulation with conventional Channel estimator can be used less than 200 km/h. For 16QAM modulation, roughly 150km/h limitation is extended to double speed of 300km/h. For 64QAM case, the limitation speed is improved from below 100km/h to 150km/h. For 256QAM modulation, only small improvement has been confirmed.

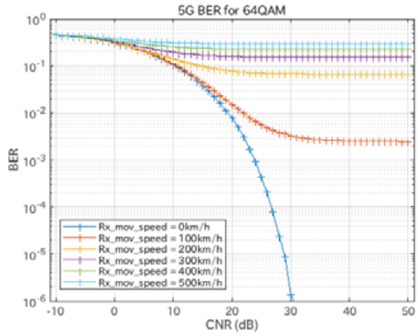


(a) Conventional CTF Linear Interpolator

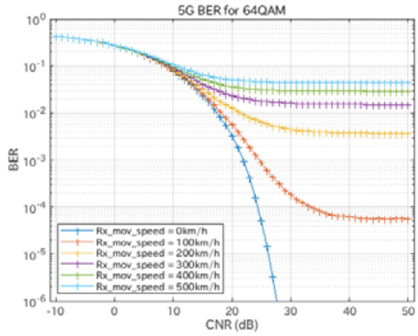


(b) Delay and Doppler Profiler based CTF

Fig. 7: BER vs CNR (dB) for QPSK modulation

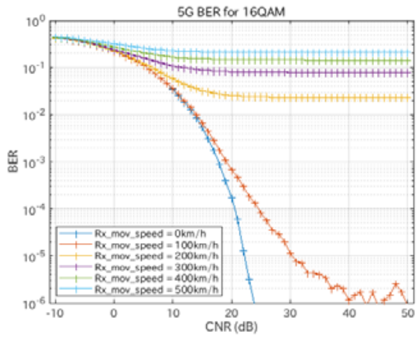


(a) Conventional CTF Linear Interpolator

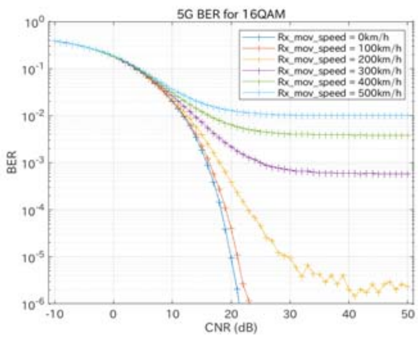


(b) Delay and Doppler Profiler based CTF

Fig. 9: BER vs CNR (dB) for 64QAM modulation

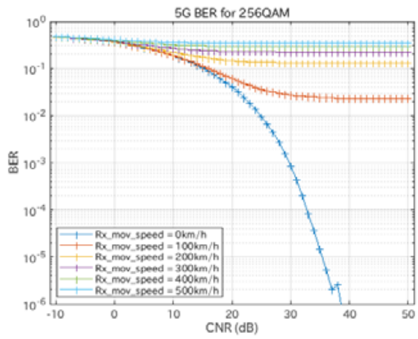


(a) Conventional CTF Linear Interpolator

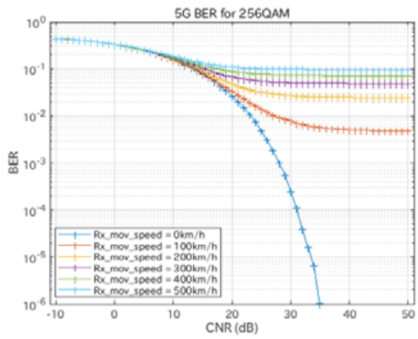


(b) Delay and Doppler Profiler based CTF

Fig. 8: BER vs CNR (dB) for 16QAM modulation



(a) Conventional CTF Linear Interpolator



(b) Delay and Doppler Profiler based CTF

Fig. 10: BER vs CNR (dB) for 256QAM modulation

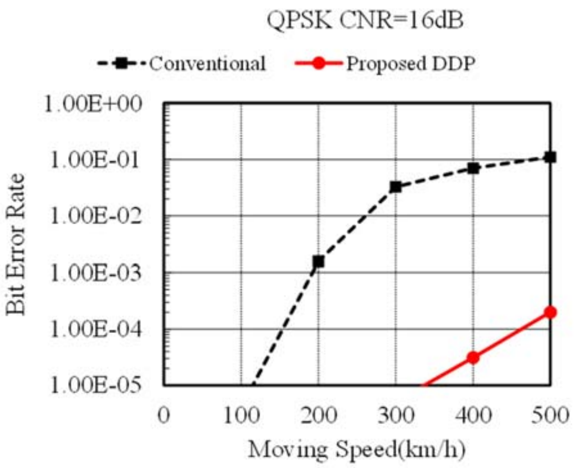


Fig. 11: BER vs Moving Speed for QPSK

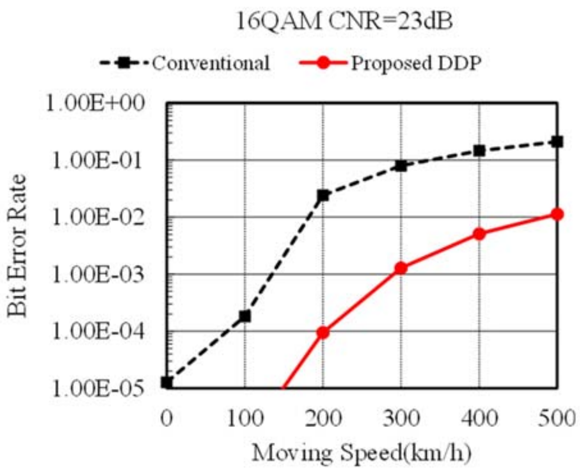


Fig. 12: BER vs Moving Speed for 16QAM

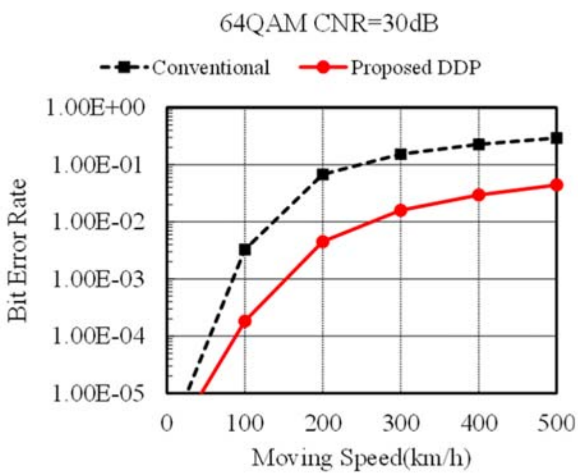


Fig. 13: BER vs Moving Speed for 64QAM

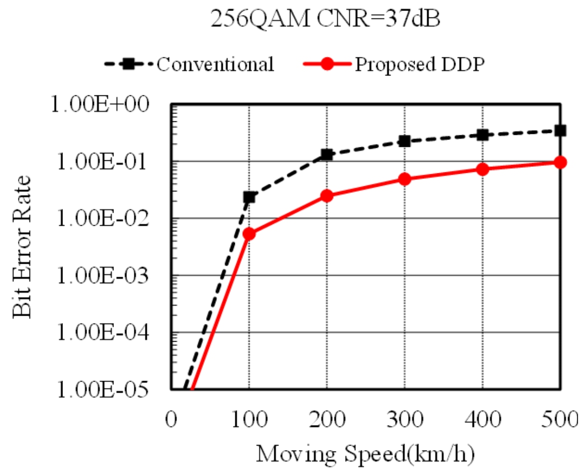


Fig. 14: BER vs Moving Speed for 256QAM

IV. Conclusion

Delay and Doppler Profiler (DDP) based Channel Estimator is proposed targeting 500km/h train support and it is successfully implemented in signal processing simulation system. Simulated performances are compared with the conventional Time domain linear interpolated estimator. According to the simulation results, QPSK modulation can be used even under severe channel condition such as 500 km/h, 2 path reverse Doppler Shift condition, although QPSK modulation can be used less than 200 km/h with conventional Channel estimator. For 16QAM modulation, roughly 150km/h limitation is extended to double speed of 300km/h. For 64QAM case, the limitation speed is improved from below 100km/h to 150km/h. For 256QAM modulation, only small improvement has been confirmed.

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