An ICI Canceling 5G System Receiver for 500km/h Linear Motor Car

Suguru Kuniyoshi[1], Rie Saotome[1], Shiho Oshiro[2] and Tomohisa Wada[3]

1) Magna Design Net Inc., 3-1-15 Maejima, Naha-shi, Okinawa, Japan
2) Information Technology Center, University of the Ryukyus, Okinawa, Japan
3) Dept. of Engineering, University of the Ryukyus, Senbaru 1, Nishihara, Okinawa, Japan

Summary
This paper proposed an Inter-Carrier-Interference (ICI) Canceling Orthogonal Frequency Division Multiplexing (OFDM) receiver for 5G mobile system to support 500 km/h linear motor high speed terrestrial transportation service. A receiver in such high-speed train sees the transmission channel which is composed of multiple Doppler-shifted propagation paths. Then, a loss of sub-carrier orthogonality due to Doppler-spread channels causes ICI. The ICI Canceler is realized by the following three steps. First, using the Demodulation Reference Symbol (DMRS) pilot signals, it analyzes three parameters such as attenuation, relative delay, and Doppler-shift of each multi-path component. Secondly, based on the sets of three parameters, Channel Transfer Function (CTF) of sender sub-carrier number $\boldsymbol{n}$ to receiver sub-carrier number $\boldsymbol{l}$ is generated. In case of $\boldsymbol{n \neq l}$, the CTF corresponds to ICI factor. Thirdly, since ICI factor is obtained, by applying ICI reverse operation by Multi-Tap Equalizer, ICI canceling can be realized. ICI canceling performance has been simulated assuming severe channel condition such as 500 km/h, 2 path reverse Doppler Shift for QPSK, 16QAM, 64QAM and 256QAM modulations. In particular, for modulation schemes below 16QAM, we confirmed that the difference between BER in a 2 path reverse Doppler shift environment and stationary environment at a moving speed of 500 km/h was very small when the number of taps in the multi-tap equalizer was set to 31 taps or more. We also confirmed that the BER performance in high-speed mobile communications for multi-level modulation schemes above 64QAM is dramatically improved by the use of a multi-tap equalizer.

Keywords:
5G, 5th Generation Mobile Communication System, Channel estimation, Delay and Doppler Profiler, Inter-Carrier-Interference

I. Introduction

A 500 km/h linear motor high speed terrestrial transportation service is planned to launch 2027 between Tokyo and Nagoya in Japan. In such a 5th Generation Mobile Communication System (5G) [1-2] environment on high-speed train, a proposal to adopt a different station design than usual is being discussed in the 3rd Generation Partnership Project (3GPP). By considering an area covered by multiple base stations having the same cell number as one control area, an environment can be configured in which handover does not occur. Such a configuration of communication areas is called a Single Frequency Network (SFN) scenario, where instead of eliminating the overhead of cell switching due to handover, the environment becomes one in which signals with positive and negative Doppler frequency shifts arriving at the same time are received. 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. 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. Then new CTF estimation based on Delay and Doppler profiler was proposed [3]. It has reduced BER at 500km/h condition for all modulation cases. However, the obtained BER performance was not enough for especially for 256QAM and 64QAM applications. To achieve the further reduction of BER, ICI caused by a loss of sub-carrier orthogonality due to Doppler-spread channels have to be mitigated.

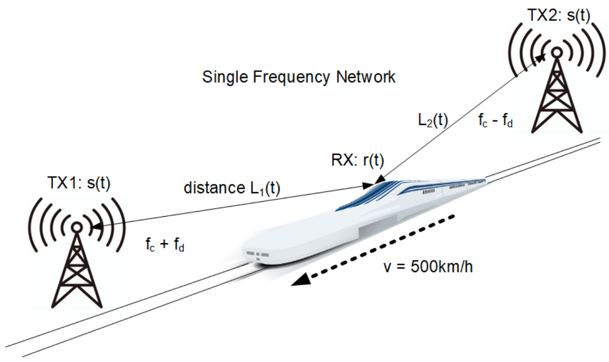

Fig. 1: Two Down Link receiving situation in the high-speed train

In this paper, in order to further improve the receiver performance, Delay and Doppler Profiler (DDP) based ICI canceler has been applied[4-6]. The ICI Canceler is realized by the following three steps. First, using the Demodulation Reference Symbol (DMRS) pilot signals, it analyzes three parameters such as attenuation, relative delay, and Doppler-shift of each multi-path component. Secondly, based on the sets of three parameters, CTF of sender sub-carrier number n to receiver sub-carrier number l is generated. In case of $n \neq l$, the CTF corresponds to ICI factor. Thirdly, since ICI

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factor is obtained, by applying ICI reverse operation by Multi-Tap Equalizer, ICI canceling can be realized. ICI canceling performance has been simulated assuming severe channel condition such as 500 km/h, 2 path reverse Doppler Shift for QPSK, 16QAM, 64QAM and 256QAM modulations.

In section II, first, targeting 5G Mobile Communication System is briefly shown. The proposed DDP based ICI canceler is explained. Computer simulation results are shown in section III. Finally, in section IV, the conclusions will be given.

II. 5G Mobile Communication System and DDP based ICI Canceler

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. In the previous paper [3], authors have simulated Delay and Doppler profiler based CTF interpolator performance without using ICI cancelation. In order to make fair comparison with the previous [3] and ICI canceler effectiveness, the same 5G configuration is assumed as shown in Table I, Fig. 2, and Fig. 3.

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 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 [1-2].

Time-Frequency structure of the 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.

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

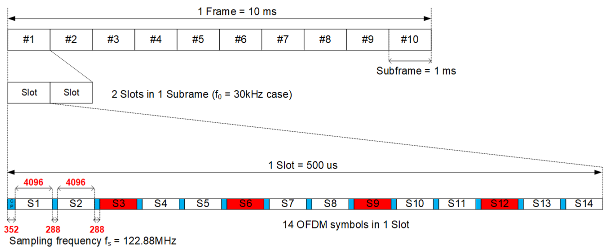


Fig. 2: 5G Frame structure

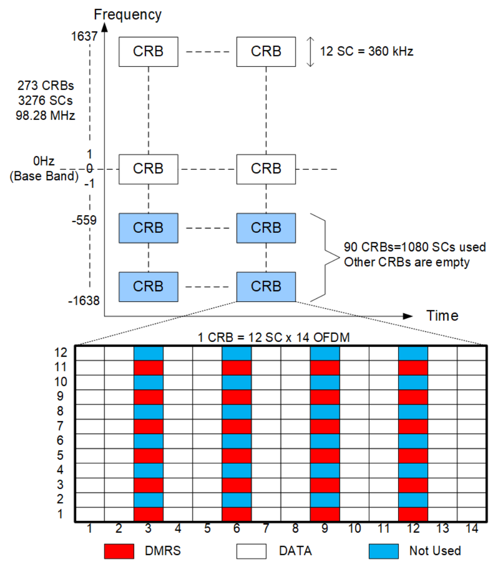


Fig. 3: Time-Frequency structure of System

A) Physical layer of the system with ICI canceling Equalizer

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 / 256QAM. Then the modulated symbols and DMRS pilots signals configure Slots as shown in Fig. 3. Then 4096 points Inverse Fast Fourier Transform (IFFT) is performed as OFDM modulation and Cyclic Prefix (CP) 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 and Inter-Carrier-Interference caused by Doppler spread channels, Channel Transfer Function (CTF), which is a Frequency domain representation of Channel Impulse Response in Time domain, has to be estimated and the distortion and the Interference has to be compensated at Equalizer.

B) ICI Cancellation based on Delay and Doppler Profiler

References [4-6] describe detail methods of Delay and Doppler Profile (DDP) based ICI Cancellation using pilot signals embedded in OFDM sub-carriers. Fig. 5 is a block diagram of proposed DDP and ICI Cancel Coefficients 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.

5G baseband transmitting signal $s_B(t)$ can be expressed as (1).

$$s_B(t) = \sum_{m=-\infty}^{\infty} g(t - mT_s) \cdot \sum_{n=0}^{N-1} d(m,n) e^{j2\pi n f_0 (t - mT_s)} \quad \cdots (1)$$

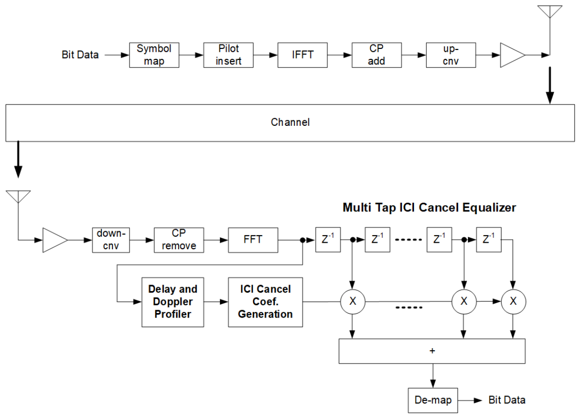


Fig. 4: Physical layer of 5G communication system with ICI Canceling Multi Tap Equalizer

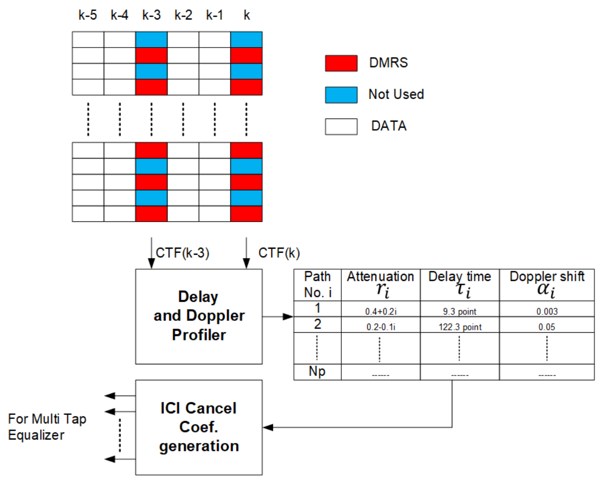


Fig. 5: ICI Canceling Coefficients generation by Delay and Doppler Profiler

$$T_s = \frac{1}{f_0} + T_g \quad \cdots (2)$$

$$g(t) = \begin{cases} 1 & -T_g \leqq t < 1/f_0 \\ 0 & otherwise \end{cases} \quad \cdots (3)$$

where, N is the number of sub-carriers, f_0 is the sub-carrier spacing, T_s is symbol length as defined in (2), $d(m,n)$ is data symbol of sub-carrier index n at the m^{th} OFDM symbol. By assuming the transmission channel has N_P delay paths, the received baseband signal can be written as (4).

$$r_B(t) = \sum_{p=1}^{N_P} r_p \, s_B(t - \tau_p) e^{j2\pi \Delta f_p (t - \tau_p)} \quad \cdots (4)$$

$$t = \frac{i}{Nf_0} + kT_s \quad \cdots (5)$$

where, r_p, τ_p and Δf_p are attenuation, relative delay and Doppler-shift of p^{th} path respectively. After sampling of $r_B(t)$ by using equation (5) with sampling index i and OFDM symbol number k, the block of samples is de-modulated by DFT to generate data symbol $\hat{d}(k,l)$ as expressed in (6).

$$\hat{d}(k,l) = h(k,l,l)d(k,l) + \sum_{\substack{n=0 \\ n \neq l}}^{N-1} h(k,l,n)d(k,n) + w(k,l) \quad \cdots (6)$$

where $w(k,l)$ is additive noise that corresponds to the l^{th} sub-carrier in the k^{th} OFDM symbol and $h(k,l,n)$ is the channel transfer function from symbol $d(k,n)$ to the l^{th} sub-carrier. If $n \neq l$, $h(k,l,n)$ represents the influence of ICI. $h(k,l,n)$ can be expressed as (7), (8a) and (8b).

$$h(k,l,n) = \sum_{p=1}^{N_P} h_p(k,l,n) \quad \cdots (7)$$

$$h_p(k,l,n) = \frac{sinc(A)}{sinc(\frac{A}{N})} \cdot e^{j\frac{\pi(N-1)A}{N}} \cdot r_p \cdot e^{-j\frac{2\pi(n+\alpha_p)\tau_p'}{N}} \cdot e^{j\frac{2\pi k(N+GI)\alpha_p}{N}} \quad \cdots (8a)$$

$$A = n - l + \alpha_p \quad \cdots (8b)$$

where $\alpha_p = \Delta f_p / f_0$ is normalized frequency offset of p^{th} path.

The parameters of channel transfer function $h(k,l,n)$ are estimated so as to minimize the mean square error shown in (9).

$$E(k) = \sum_{l=\boldsymbol{P}} \{|CTF(k,l) - h(k,l,l)|^2 + |CTF(k-3,l) - h(k-3,l,l)|^2\} \quad \cdots (9)$$

where $\Sigma_{l=\boldsymbol{P}}$ means that the summation is performed as long as l is DMRS pilot symbol.

In order to simplify the problem, it is supposed that the channel model contains one path at the first. In this case, criterion is rewritten as (10).

$$E_1(k) = \sum_{l=\boldsymbol{P}} \left\{ \left| CTF(k,l) - f(\alpha_1) r_1 \cdot e^{-j\frac{2\pi(l+\alpha_1)\tau_1'}{N}} \right|^2 + \left| CTF(k-3,l) - f(\alpha_1) r_1 \cdot e^{-j\frac{2\pi(l+\alpha_p)\tau_1'}{N}} \cdot e^{j\frac{-2\pi 3(N+GI)\alpha_1}{N}} \right|^2 \right\} \quad \cdots (10)$$

here, $f(\alpha_1)$ is written as (11).

$$f(\alpha_1) = \frac{sinc(\alpha_1)}{sinc\left(\frac{\alpha_1}{N}\right)} \cdot e^{j\frac{\pi(N-1)\alpha_1}{N}} \cdot e^{j\frac{2\pi k(N+GI)\alpha_1}{N}} \quad \cdots (11)$$

One of the necessary conditions to minimize $E_1(k)$ with regard to r_1, τ_1' (relative delay time in sampling points) and α_1 is that its partial derivative of r_1 has zero value. With this condition, r_1 can be shown as (12a) and (12b).

$$r_1 = \frac{S_k^* + e^{j\frac{2\pi 3(N+GI)\alpha_1}{N}} S_{k-3}^*}{2 \cdot f(\alpha_1) e^{-j\frac{2\pi\alpha_1\tau_1'}{N}}} \quad \cdots (12a)$$

here,

$$S_k = \sum_{l=\boldsymbol{P}} CTF^*(k,l)\, e^{-j\frac{2\pi l \tau_1'}{N}} \quad \cdots (12b)$$

By calculate more as shown in reference [4-6], α_1 is calculated from τ_1' as (13).

$$\alpha_1 = \frac{1}{\frac{2\pi 3(N+GI)}{N}} arctan\left[\frac{\Im(S_k^* \cdot S_{k-3})}{\Re(S_k^* \cdot S_{k-3})}\right] \quad \cdots (13)$$

Consequently, once τ_1' is determined, r_1 and α_1 are easily obtained from (12a) and (13), respectively. In this proposed method, τ_1' is changed by $1/(2Nf_0)$ (twice of sampling frequency) and rough estimation is first obtained. And this rough estimation is modified to more precise value using Newton method as described in references [4-6].

According to the computation above, $h_1(k,l,n)$ can be obtained using equations (8a) and (8b). Then, measured $CTF(k,l)$ and $CTF(k-3,l)$ are updated to $CTF(2,k,l)$ and $CTF(2,k-3,l)$ by subtracting $h_1(k,l,n)$ and $h_1(k-3,l,n)$ respectively. By removing the influence of the first estimated path from the cost function$E_1(k)$, the following criterion $E_2(k)$ can be obtained such as (14).

$$E_2(k) = \sum_{l=P}\left\{\left|CTF(2,k,l) - f(\alpha_1)r_1 \cdot e^{-j\frac{2\pi(l+\alpha_1)\tau_1'}{N}}\right|^2 + \left|CTF(2,k-3,l) - f(\alpha_1)r_1 \cdot e^{-j\frac{2\pi(l+\alpha_p)\tau_1'}{N}} \cdot e^{j\frac{-2\pi 3(N+GI)\alpha_1}{N}}\right|^2\right\} \cdots (14)$$

Since $E_2(k)$ contains the influence of other paths, the second path can be estimated using the same procedure in the previous section. By repeating this operation by the number of paths in the channel model, N_p sets of those three parameters can be obtained as shown in Fig. 5.

After all, complete channel transfer function $h(k,l,n)$ can be generated. Since most energy of ICI is concentrated in the neighborhood of sub-carrier index, the ICI terms which do not significantly affect $\hat{d}(k,l)$ in (6) can be neglected and it is assumed as (15).

$$h(k,l,n) = 0 \quad when \quad |l-n| > \frac{NumCOL - 1}{2} \quad \cdots (15)$$

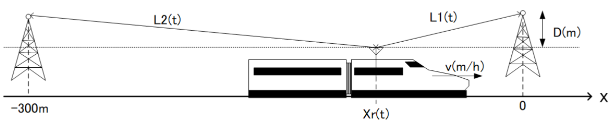
where, $NumCOL$ is the number of neighborhood sub-carrier taken into account against l^{th} sub-carrier. By considering the reverse operation of the ICI effect by $h(k,l,n)$, Multi Tap ICI Canceling Equalizer has been implemented as shown in Fig. 4. as a Fixed Impulse Response Filter.

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, (2 dB step)
Number of Frames	1 Frame (10 ms, 20 slots)
Used number of CRBs	90 CRBs (1080 Sub-carriers)
Channel	SISO, 2 Path, 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
Number of Fixed Impulse Response Filter Taps of ICI Canceling Equalizer (NumCOL)	8patterns (1, 3, 5, 7, 15, 31, 45, 63)

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).



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

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

Fig. 6: Simulated vehicle moving situation

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 1 frame 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 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 2 dB steps. For the Number of Fixed Impulse Response Filter Taps of ICI Canceling Equalizer (Hereinafter referred to as NumCOL), We used 8 patterns, where NumCOL=1 is equivalent to the condition when the number of neighbor subcarriers is not considered. We performed CNR vs BER data acquisition while varying the NumCOL coefficients for a total of 8 patterns, from NumCOL=1 to 63.

Simulated results for QPSK / 16QAM / 64QAM / 256QAM BER vs Carrier to Noise Ratio (CNR) with moving speed 500km/h were shown in Figs. 7-10. For the RF pass band frequency of 3.9 GHz, the Doppler frequency (f_d) at the moving speed of 500 km/h is approximately 1805.6 Hz. BER in a static environment with the number of taps in the multi-tap equalizer set to 1 was added to the graph as an indicator of the performance limits of the current algorithm.

The DDP scheme shown in [3] corresponds to NumCOL=1. Fig7-10 shows that the value of NumCOL improves the BER regardless of the modulation scheme. For modulation schemes below 16QAM, we confirmed that the difference between BER at a moving speed of 500 km/h and BER in a stationary environment becomes very small when the number of taps of the multi-tap equalizer is increased to 31 or more.

Assuming BER below 1.0E-03 can be error correctable with associated error correction mechanism. At a moving speed of 500 km/h, the bit error rate (BER) is less than 1.0E-03 with a DDP parameter of NumCOL of 15 or less for modulation schemes below 64QAM. In the case of 256 QAM, Fig.10 shows that the number of operations approaches 1.0E-03 when NumCOL is increased to about 63. However, 256QAM does not become error-free even when CNR is improved. This situation may be due to amplitude, phase, and frequency errors in the receive path estimation obtained by the DDP method, which leaves a constellation disturbance after demapping in the demodulator.

Figs. 11-14 show BER vs NumCOL for QPSK with CNR=16dB, 16QAM with CNR=24dB, 64QAM with CNR=32dB and 256QAM with CNR=40dB. Moving speeds of less than 100 km/h for 16QAM and 400 km/h for QPSK were not plotted in the graph because the BER was less than 1.0E-07. The results for 256 QAM show that by increasing the number of operations from NumCOL=1 (DDP method in [3]), the BER at a moving speed of 100 km/h with NumCOL=1 is equivalent to the BER at a moving speed of 500 km/h with NumCOL=32. In QPSK, the characteristic improvement by DDP is large, the effect of BER improvement by the number of NumCOLs is small.

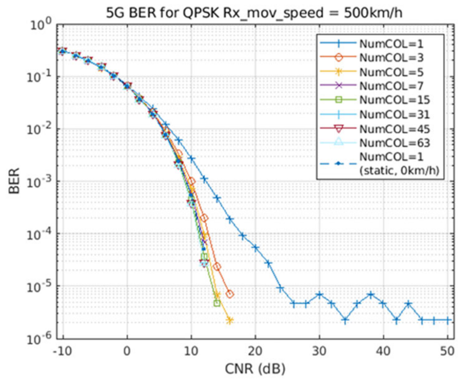


Fig. 7: BER vs CNR (dB) for QPSK modulation

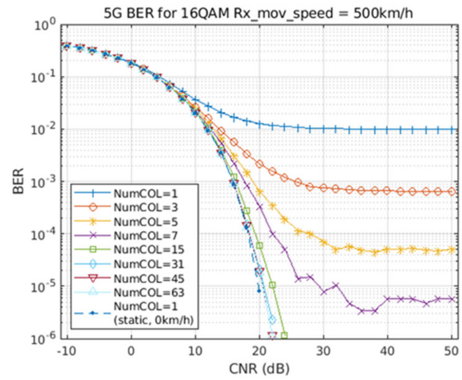


Fig. 8: BER vs CNR (dB) for 16QAM modulation

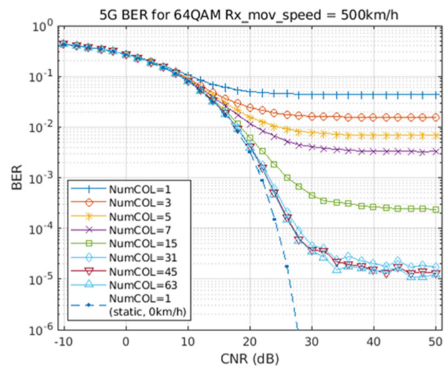


Fig. 9: BER vs CNR (dB) for 64QAM modulation

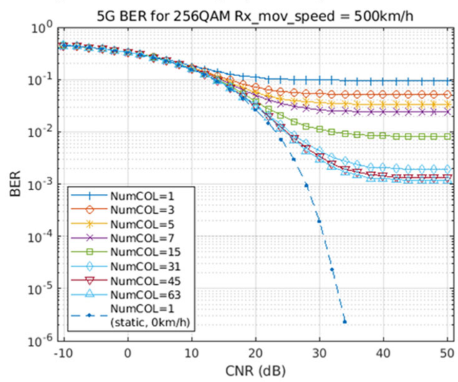


Fig. 10: BER vs CNR (dB) for 256QAM modulation

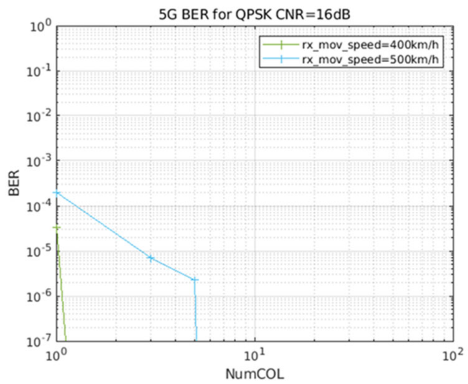


Fig. 11: BER vs NumCOL for QPSK

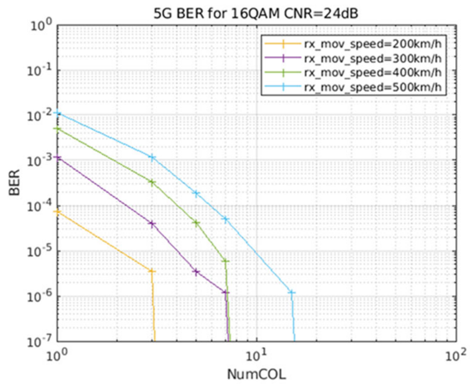


Fig. 12: BER vs NumCOL for 16QAM

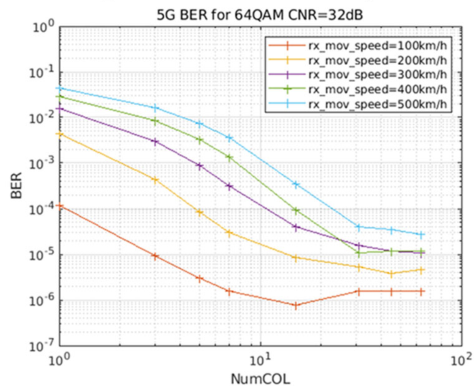


Fig. 13: BER vs NumCOL for 64QAM

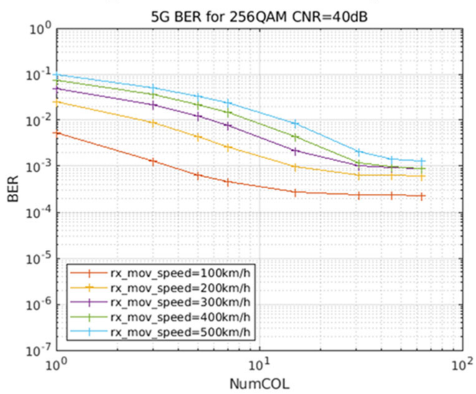


Fig. 14: BER vs NumCOL for 256QAM

Fig7-14 shows that the performance limit of the current algorithm is reached at a NumCOL value of about 31, and even if NumCOL is set to a value higher than 31, the improvement in BER characteristics is small. Therefore, the optimal number of NumCOL taps for the multi-tap equalizer scheme in this paper is considered to be 31 taps.

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. ICI cancellation with multi tap equalizer performance was simulated for QPSK, 16QAM, 64QAM, and 256QAM modulations under severe channel conditions such as 500 km/h and 2 path reverse Doppler shift. It was confirmed that increasing the number of taps in the multi-tap equalizer dramatically improves the BER performance.

The performance limit of the current algorithm is reached at the Number of Fixed Impulse Response Filter Taps of ICI Canceling Equalizer (NumCOL) value of about 31, the improvement in BER characteristics is small. Therefore, the optimal number of Fixed Impulse Response Filter taps for the multi-tap equalizer scheme in this paper is considered to be 31 taps.

For modulation schemes below 16QAM, we confirmed that the difference between BER in a 2 path reverse Doppler shift environment and stationary environment at a moving speed of 500 km/h was very small when the number of taps in the multi-tap equalizer was set to 31 taps or more.

Even if the number of taps of the Fixed Impulse Response Filter is increased to 63 to improve CNR, a noise floor still exists for 256QAM. This situation may be due to detection errors in Attenuation r_i, Propagation Delay time τ_i, and normalized Doppler shift α_i, which affect the received path estimation obtained by the DDP method and appear as disturbances that remain in the constellation after demapping in the demodulator. The performance improvement in 256QAM is a future issue.

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Suguru Kuniyoshi received the B.E. and M.E. degrees, from the University of the Ryukyus, Okinawa, Japan in 2004 and 2006, respectively. He joined Magna Design Net, Inc. in 2006 and has engaged with digital signal processing design of modulator and demodulator part for a Wireless LAN, WiMAX, 4G-LTE, 5G-NR, and Underwater Acoustic communication. Currently he is the Engineering Manager of the Development Department at Magna Design Net, Inc.

Rie Saotome received the B.E. and M.E. degree from Tokyo University of technology, Tokyo, Japan in 1999 and 2001, respectively. She received Dr. Eng. degree from University of the Ryukyus in 2016. From 2004 to 2016, she was a part-time lecturer at Univ. of the Ryukyus, Okinawa Univ., Meio Univ. and Okinawa Polytechnic College. She joined Magna Design Net, Inc. in 2016. Her research interest includes Wireless communications systems, 5G-NR, Underwater Acoustic communication, and Rain attenuation.

Shiho Oshiro received the B.E. and M.E. degrees, from the University of the Ryukyus, Okinawa, Japan in 2018 and 2020, respectively. She received the Dr. Eng. degree from University of the Ryukyus in 2023. She has been an assistant professor at University of the Ryukyus since 2023. She has experienced short-term study abroad at Madan Mohan Malaviya University of Technology (MMMUT) Gorakhpur and Atal Bihari Vajpayee-Indian Institute of Information Technology and Management (ABV-IIITM) Gwalior in India, Institute of Technology of Cambodia (ITC) in Cambodia, and National Taiwan University of Science and Technology (Taiwan Tech). Her research interest includes Underwater OFDM Acoustic communication systems, developed Underwater Acoustic OFDM wireless communication systems, Underwater Acoustic Positioning systems targeting for Underwater Drone controls, Flight Control for Underwater Drone automatically controls, and Autoencoder for OFDM communication system.

Tomohisa Wada received B.S. degree in electronic engineering from Osaka University, Osaka, Japan, in 1983, M.S.E.E. degree from Stanford University, Stanford CA, in 1992, and Ph.D. in electronic engineering from Osaka University in 1994. He joined the ULSI Laboratory, Mitsubishi Electric Corp. Japan in 1983 and engaged in the research and development of VLSI such as High-speed Static Random-access memories, Cache memories for Intel MPUs in 16 years. Since 2001, he has been a Professor at the Department of Information Engineering, the University of the Ryukyus, Okinawa, Japan. In 2001, He was the founding member of Magna Design Net, Inc., which is a fab-less LSI design Company for communication related digital signal processing such as OFDM. Currently, he is also the chief scientist of Magna Design Net, Inc. who is engaging in the research and development of a terrestrial video broadcasting receiver, a wireless LAN, WiMAX, 4G-LTE and 5G systems. After 2009, he also started Underwater OFDM Acoustic communication systems and developed Underwater Acoustic OFDM wireless communication systems and Underwater Acoustic Positioning systems targeting for Underwater Drone controls.