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Communication

A 2-Step Modified Delay and Doppler Profiler Based ICI Can-Celing OFDM Receiver for Underwater Multi-Path Channel

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Abstract: In 2023, we proposed the modified Delay and Doppler Profiler (mDDP) as an inter-carrier interference (ICI) countermeasure for underwater acoustic OFDM mobile communications in a multipath environment. However, the performance improvement in computer simulation and pool experiments was not significant. In a subsequent study, the accuracy of the Channel Transfer Function (CTF), which is the input for the mDDP channel parameter estimation, was considered insufficient. Then a 2-step mDDP was devised. This paper presents simulations of underwater OFDM communications using 1- to 3-step mDDPs. The simulation conditions are a two-wave multipath environment where the receiving transducer moves at a speed of 0.3 m/sec and is subjected to a Doppler shift in the opposite direction. As NumCOL, the number of taps in the multi-tap equalizer which removes ICI, was increased, Bit Error Rate (BER) of 0.016 at NumCOL = 1 was significantly reduced by a factor of approximately 40 to BER of 0.00041 at NumCOL = 41 for the 2-step mDDP.

Keywords: underwater acoustic communication; OFDM; channel estimation; modified delay and doppler profiler

1. Introduction

Underwater wireless communications are used in many applications to reduce cable costs and deployment time, such as harbor and shoreline monitoring, fish monitoring, and monitoring of drilling sites such as oil wells and trenches [1]. To increase data bandwidth, orthogonal frequency division multiplexing (OFDM)-based wireless communication systems have received widespread attention for their high transmission rates and high spectrum efficiency, even for underwater applications. Since Doppler shift occurs in underwater wireless communications due to the movement of equipment and vessels, signal processing is required to compensate for the Doppler shift. So far, our research team has proposed a time-domain signal processing algorithm for Doppler compensation of Desired propagation path [2–4].

In 2023, we proposed a modified delay and Doppler profiler (mDDP) as a frequency domain signal processing to combat inter-carrier interference (ICI) in underwater acoustic OFDM mobile communications in multipath environments [5,6]. However, the performance improvement in computer simulations and pool experiments was not remarkable. In a subsequent study, the accuracy of the Channel Transfer Function (CTF), which is the input for the mDDP channel parameter estimation, was considered insufficient. Then a 2-step mDDP was devised.

In this paper, the performance of underwater OFDM communications using 1- to 3-step mDDPs are compared by computer simulation, assuming a two-wave multipath environment subject to Doppler shift in the opposite direction as shown in Figure 1. Section II presents the details of the

proposed UWA OFDM communication system using multi-step mDDP. In Section III, computer simulation results are presented. Finally, in section IV, the conclusions will be given.

2. Multi-Step mDDP Based ICI Canceling UWA OFDM Communication System

In the two-wave multipath environment shown in Figure 1, Path #1 and Path #2 are affected by backward Doppler shift when the receiving device moves. Therefore, as shown in Figure 2, the received signal is expanded or shrunk in underwater acoustic communication. Then we have previously introduced resampling and de-rotation to OFDM receiver as shown in Figure 3 [3]. The performance in mobile reception is improved by detecting the Desired Path signal with high intensity and stretching the received signal in Resample and De-rotation processing. However, if the Doppler shift of the second wave is different from the first wave, as in this case, the second wave is affected by the Doppler shift and generates ICI. Figure 4 shows a proposed mDDP based OFDM receiver, which does not have resample and de-rotation. Although the 2-step configuration is the main focus, the figure shows 1- to 3-step mDDPs available for simulation comparison.

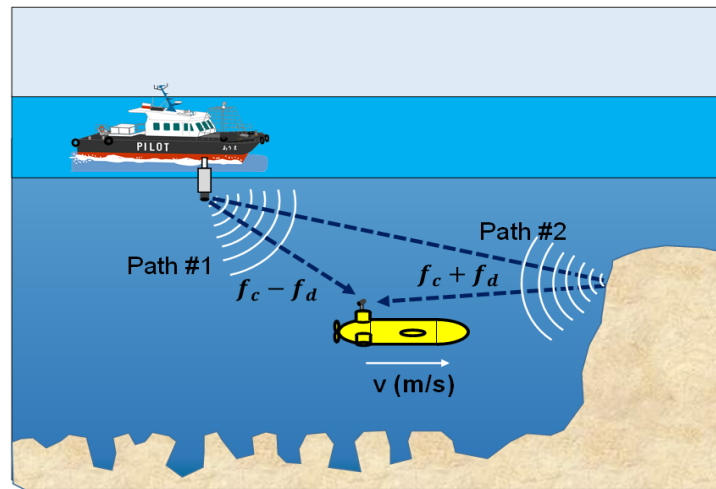


Figure 1. UWA communication under reverse direction.

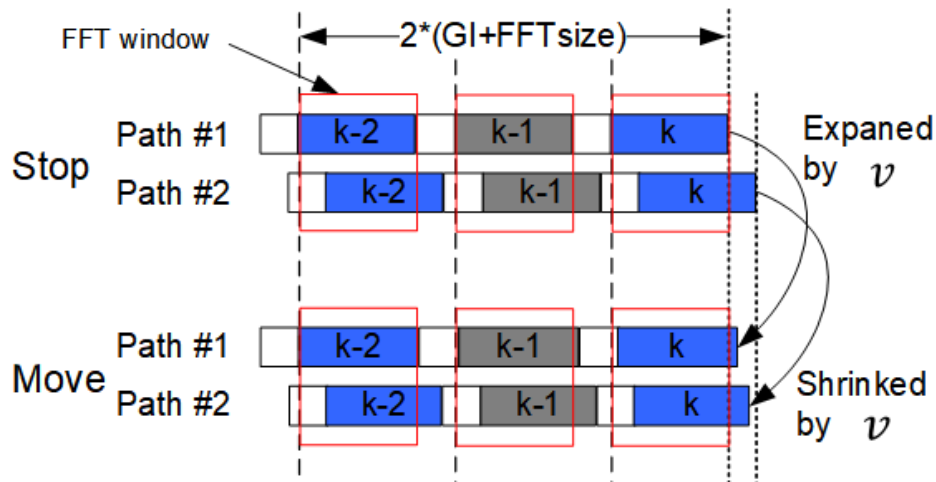


Figure 2. OFDM signal after the Shrink and Expansion processing.

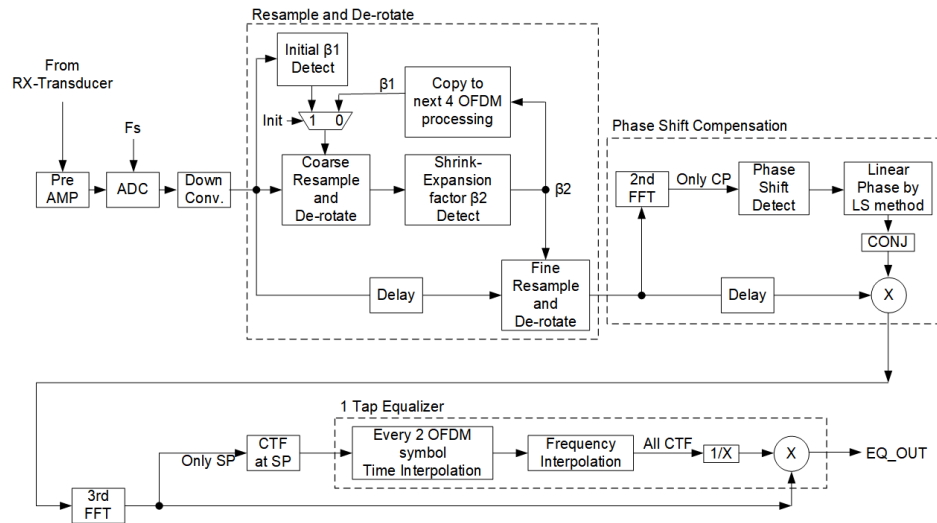


Figure 3. Block Diagram of Previous Receiver.

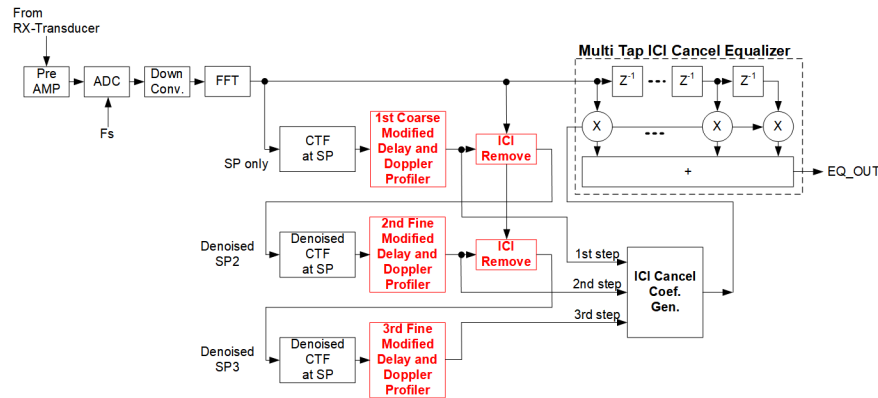


Figure 4. Block Diagram of Proposed multi-step mDDP Receiver.

Detail system parameters are listed in Table 1. The sub-carrier spacing of OFDM is 50Hz, then effective OFDM symbol duration is 20ms with 2048 points IFFT/FFT as modulation/demodulation. To estimate CTF, two kinds of pilot signals are inserted in Time-Frequency sub-carriers' arrangement as shown in Figure 5. The blue circles for CTF estimation are scattered pilots which is inserted every 2 row and every 2 columns. The other yellow circles are continuous pilots for tracking phase-change in time domain.

Table 1. UWA OFDM System Parameters.

Parameters	Value
Sampling Frequency F_s	102.4kHz
Band Width	8 kHz
Passband frequency	16 kHz
FFT size	2048
OFDM symbol length T	20.0 ms (2048 points)
Guard Interval length T_g	5.0 ms (512 points)
Sub-carrier spacing	50 Hz
Number of sub-carriers	161
Number of scattered pilots	81 every 2 OFDM symbols

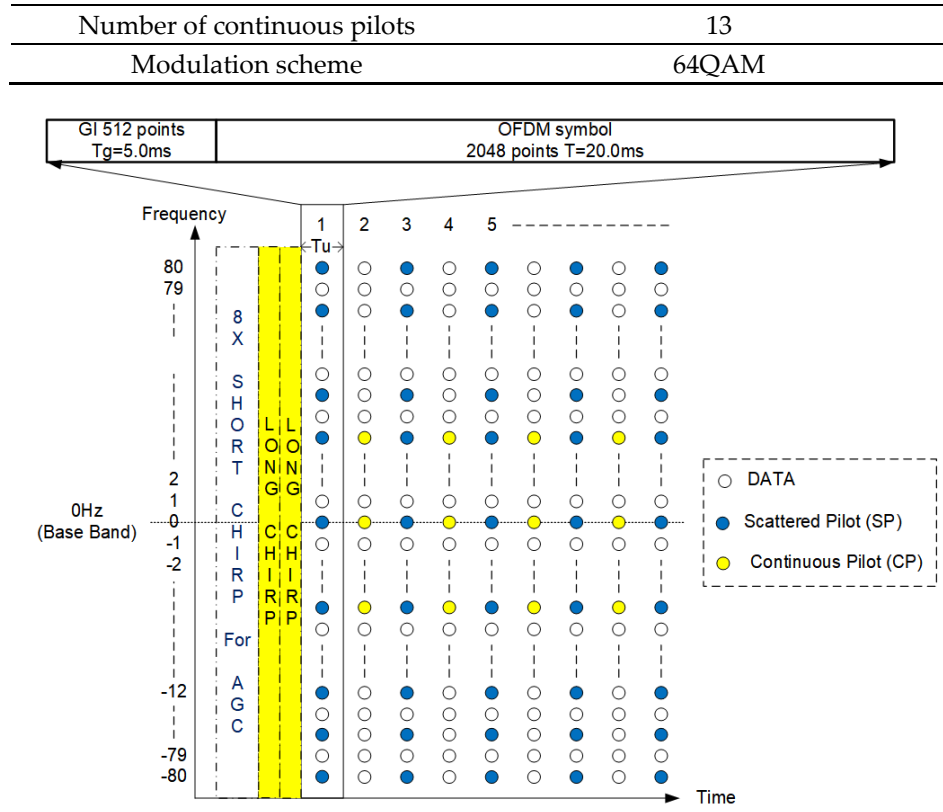


Figure 5. Time - Frequency representation of OFDM signal.

Modified Delay and Doppler Profiler (mDDP) estimates a combination of multiple Doppler-shifted propagation paths and their parameters such as attenuation, relative delay, Doppler-shift and sampling CLK error as shown in Figure 6. The FFT of the OFDM demodulation generates data symbol $\hat{d}(k, l)$ as expressed in Eq. (1) as shown in the original mDDP paper [5,6] and DDP papers [7–9].

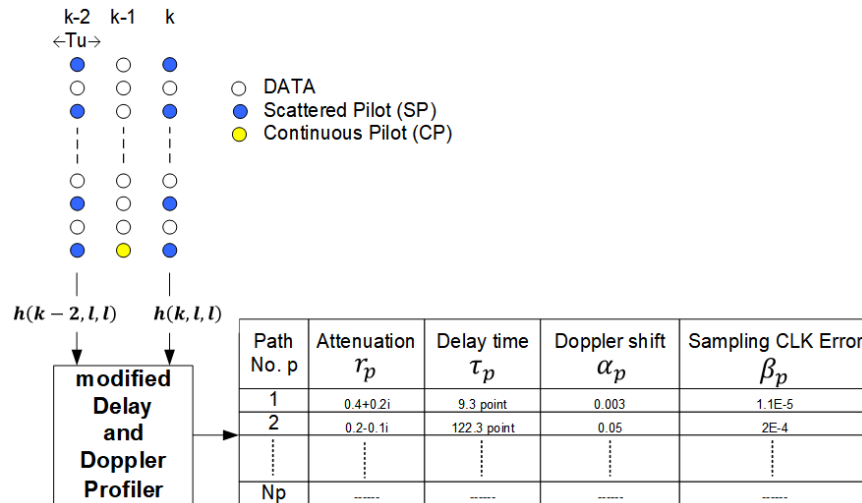


Figure 6. Modified Delay and Doppler Profiler.

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

where $d(k, n)$ is sending data symbol of sub-carrier index n at the k^{th} OFDM symbol, $w(k, l)$ is additive noise that corresponds to the l^{th} sub-carrier in the k^{th} OFDM symbol and $h(k, l, n)$ is the 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 Eqs. (2), (3a) and (3b).

$$h(k, l, n) = \sum_{p=1}^{N_p} h_p(k, l, n) , \quad (2)$$

$$h_p(k, l, n) = \frac{\text{sinc}(A)}{\text{sinc}(\frac{A}{N})} \cdot e^{j\frac{\pi(N-1)A}{N}} \cdot r_p \cdot e^{-j\frac{2\pi(n+\alpha_p)\tau_p'}{N}} \cdot e^{j\frac{2\pi k(N+GI)(\alpha_p+n\beta_p)}{N}} , \quad (3a)$$

$$\begin{aligned} A &= n - l + n\beta_p + \alpha_p(1 + \beta_p) \\ &\cong n - l + n\beta_p + \alpha_p , \end{aligned} \quad (3b)$$

where $\alpha_p = \Delta f_p / f_0$ is normalized frequency offset of p^{th} path. From Eq. (1), the inputs such as $h(k, l, l)$ and $h(k-2, l, l)$ of mDDP in Figure 6 can be approximated as Eqs. (4a) and (4b).

$$h(k, l, l) \cong \frac{\hat{d}(k, l)}{d(k, l)} , \quad (4a)$$

$$h(k-2, l, l) \cong \frac{\hat{d}(k-2, l)}{d(k-2, l)} . \quad (4b)$$

However, this approximation totally ignores the effect of ICI component. When the effect of ICI was large, there was a problem that the accuracy of mDDP parameter estimation deteriorated significantly. Therefore, after the second step mDDP, the inputs shown in Eqs. (5a) and (5b) are used.

$$h(k, l, l) \cong \frac{\hat{d}(k, l) - \sum_{n=0}^{N-1} h(k, l, n) d(k, n)}{d(k, l)} , \quad (5a)$$

$$h(k-2, l, l) \cong \frac{\hat{d}(k-2, l) - \sum_{n=0}^{N-1} h(k-2, l, n) d(k-2, n)}{d(k-2, l)} , \quad (5b)$$

where $h(k, l, n)$ can be calculated by Eqs. (2), (3a) and (3b) using the parameters from 1st mDDP; and $d(k, n)$ can be obtained by hard decision of multi-tap equalizer outputs. As explained above, the 2-step mDDP is expected to improve the accuracy of the mDDP estimation parameters by improving the accuracy of the input signal.

3. Computer Simulations

Figure 7 shows computer simulation model assuming non-reflection pool experiment. Two transmitting transducers TX1 and TX2, 3.5 meters apart, are used to model multi-path environment. A receiving transducer RX moves 1.0 meters from 0.5 meters from TX1 in the direction of TX2 with speed of 0.3 m/s. OFDM signal length is about 10.0 ms with 400 OFDM symbols. Calculated 1st to 2nd received wave delay time and Desired (1st wave) and Undesired (2nd wave) power Ratio (DUR) are shown in Figure 8. Applied Carrier to Noise Ratio (CNR) is 40 (dB). Figure 9(a) shows the time dependences of measured Bit Error Rate (BER) and the real value of 64 QAM constellation of conventional receiver and 2-step mDDP receiver with NumCOL=1, 5, 11 (the number of taps in the multi-tap equalizer). Figure 9(b) shows 64QAM constellations in the moving period for the same cases. As can be seen from these figures, in the 2-step mDDP, constellation disorder decreases and the BER value decreases dramatically as the value of NumCOL is increased.

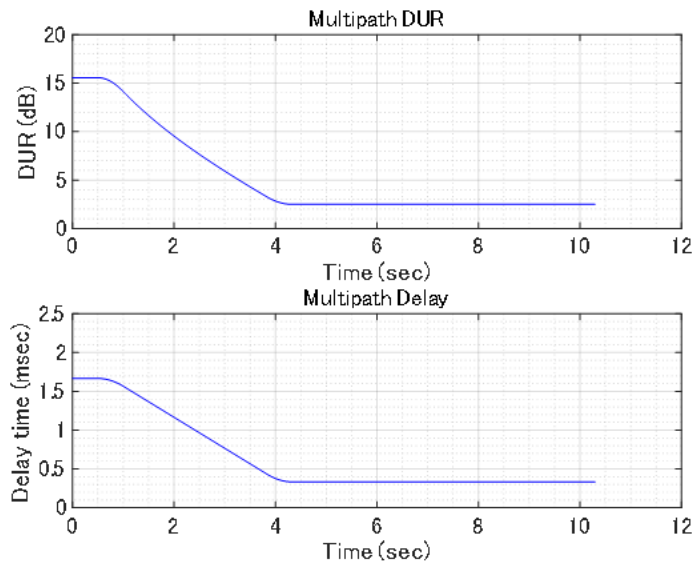


Figure 7. Delay time and DUR in simulation.

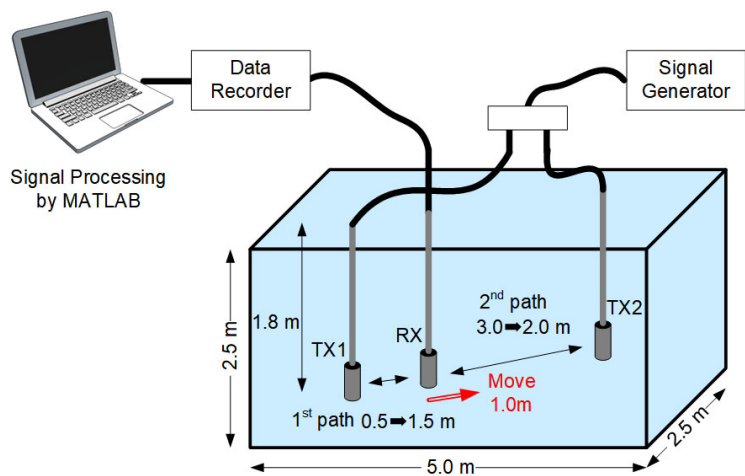


Figure 8. Computer simulation model assuming pool experiment.

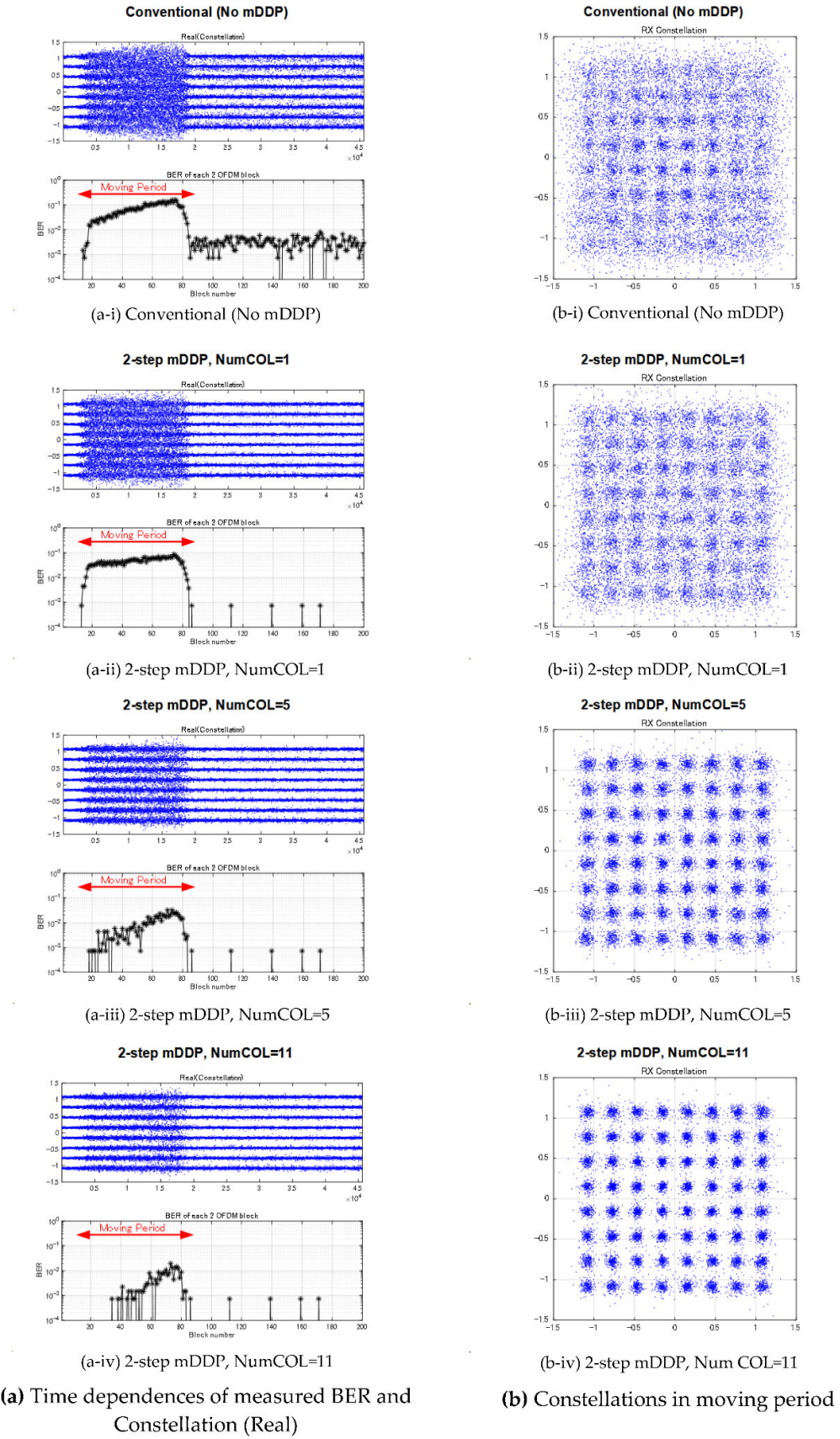


Figure 10 summarizes simulated BER with changes of NumCOL for conventional and 1- to 3-step mDDP. Increasing from 1- to 2-step dramatically reduces the BER value, but increasing to 3-step has no effect. There is a dependence of BER reduction on increasing NumCOL values, especially in 2-step. 2-step mDDP scheme reduces inter-carrier interference dramatically.

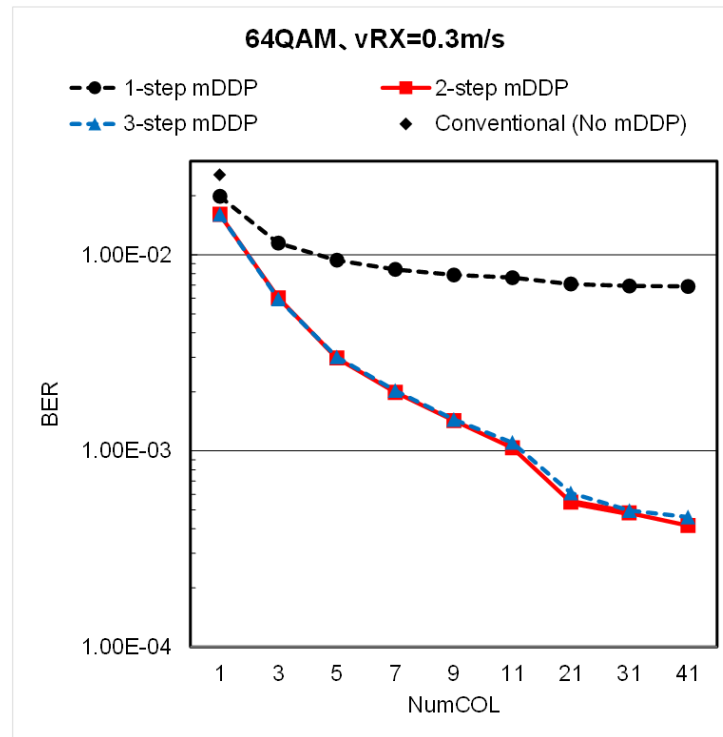


Figure 10. Comparison of Simulated BER.

4. Conclusions

Basically, modified Delay and Doppler Profiler (mDDP), which estimates not only attenuation, relative delay and Doppler shift but also sampling clock shift of each multi-path component, combined with ICI canceling multi-tap equalizer reduces inter-carrier interference between OFDM sub-carriers. With 1-step mDDP, the BER reduction was limited by the degradation of the estimation accuracy of those parameters, but with 2-step mDDP, dramatic ICI cancellation can be achieved.

In a simulation of a two-wave multipath environment where the receiving transducer moves at a speed of 0.3 m/sec and is subject to backward Doppler shift, increasing NumCOL, the number of taps in the multi-tap equalizer that removes ICI, the BER of 0.016 at NumCOL = 1 was reduced by 2-step mDDP, the BER at NumCOL = 41 was significantly reduced by about a factor of 40 to 0.00041.

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Conflicts of Interest: The authors declare no conflicts of interest.

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