Non-linear Doppler Scaling Correction in Underwater Acoustic Channels: Analysis and Simulation

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***Abstract*—This paper investigates the use of non-uniform fast Fourier transform (NUFFT) in detection of orthogonal frequency division multiplexing (OFDM) in underwater acoustic channels. We propose a new packet format and develop the necessary equations that show how NUFFT should be applied to this application and how the non-linear Doppler Scaling can be estimated and corrected in the received signal. We compare the performance of NUFFT with the traditional method of resampling through computer simulations and show how our method performs better in correcting the effect of non-linear Doppler Scaling.**

I. Introduction

Due to limitation of electromagnetic (EM) wave propagation in water, communications in underwater channels is established through acoustical waves. The far slower speed of the sound, as compared to EM waves, creates peculiar problems in underwater acoustic (UWA) channels that have no parallel in the EM medium. The particular problem that this paper aims to tackle is the impact of the mobility of the communicating vehicles on the UWA signals: *the time is scaled* by a factor equal to $1 + v(t)/c$, when the spacing between the vehicles is varied at a speed of $v(t)$ and c denotes the speed of the propagating waves. The time scaling is often referred to as *Doppler scaling*.

This point has been noted in some recent publications and active research [1], [2] and [3] are going on to solve this challenging problem. The Doppler scaling problem have been found more damaging in communication systems that use orthogonal frequency division multiplexing (OFDM) for signal modulation [3].

In [1], [2] and [3], the authors presented several methods that allow for the estimation of the Doppler scale $v(t)/c$. In general, these methods rely on: correlation in the preamble [1]; pilot aided [1]; time duration of a packet [2]; phase tracking [3]; or location of null-subcarriers [1]. After obtaining the estimated value of the Doppler scale, resampling operation is performed to fix the time scale or, equivalently, the rate of the samples. This requires signal interpolation to a much higher rate and down sampling the result to the desired rate. However, interpolation based methods have couple of serious problems that render their applicability in practice limited. Firstly, the Doppler scale $v(t)/c$ is assumed fixed within each OFDM block, while in the real world $v(t)$ may change significantly within each OFDM symbol. Secondly, the interpolation accuracy during the resampling process is limited by the interpolation factor which cannot be increased arbitrarily. This is because the complexity of the resampler increases with the interpolation factor. These clearly impose serious limitations and thus new approaches should be developed.

Based on the experimental results from ACOMM10 [5], an at-sea experiment that took place on the continental shelf off the coast of New Jersey, we found that the linear assumption of Doppler scaling factor may not be true. Vehicles may accelerate or deceleration, and in cases where two vehicles approach each other from opposite directions, the relative speed can change significantly in a short time period.

Unfortunately, the current packet format for ACOMM10 that we have chosen is too restrictive and does not allow easy estimation of acceleration. In this paper, we redesign a new packet format with a number of additional null subcarriers to allow us to estimate how much the subcarriers have moved due to non-linear Doppler scaling. This configuration allows us to detect the effect of non-linear Doppler scaling.

On the other hand, the traditional method of dealing with mobility in underwater acoustic channels was to resample the signal assuming linear Doppler shift. As noted, this may not hold in practice and those methods are not applicable in the case of non-linear Doppler scaling.

In the presence of non-linear Doppler scaling, when the received signal is sampled at the nominal rate, the samples will be seen as unevenly spaced within the domain of transmit signal. In [6], we introduced the

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use of non-uniform fast Fourier transform (NUFFT) in detection of OFDM in a situation where the received signal samples are unevenly spaced. We developed the necessary equations that show how NUFFT should be applied to this application. We also discussed a method of Doppler scaling estimation by using a number of null subcarriers that we assumed were inserted in the OFDM signal.

In this paper, we apply what we have developed using NUFFT in [6] to a new packet format that we introduce. In Sec. II, we go over the effect of Doppler scaling on an OFDM signal in an underwater acoustic channel. We discuss in details how NUFFT can be used to correct the Doppler scaling factor in the signal in Sec. III, and talk about how the NUFFT can be computed numerically in Sec. IV. In Sec. V, we propose a packet format that allows us to estimate the non-linear Doppler scaling factor in the received signal by optimizing a cost function. In Sec. VI, we simulate the transmitter, receiver and the underwater acoustic channel to test the performance of the new packet design. Non-linear Doppler scaling is considered and tested, in addition to the UWA sparse channel with exponentially distributed inter-arrival times and Rayleigh distributed average power. Using simulation, we show that the new packet design allows us to estimate both the relative velocity and acceleration between the transmitter and receiver, and that the NUFFT allows us to undo the effect of non-linear Doppler scaling without using the traditional method of resampling. Sec. VII concludes the paper.

II. OFDM Transceiver

In an OFDM block, the complex baseband signal in continuous time at the transmitter is

$$x(t) = \sum_{k=-N/2}^{N/2-1} s_k e^{j2\pi \frac{k}{T} t}, \tag{1}$$

where s_k is the data symbol being sent on the kth subcarrier channel and T is a predefined time duration that determines the subcarrier spacing. The baseband signal is then modulated into passband, resulting in the transmit signal

$$\begin{aligned} x_{\text{PB}}(t) &= Re\left\{x(t)e^{j2\pi f_c t}\right\} \\ &= Re\left\{\sum_{k=-N/2}^{N/2-1} s_k e^{j2\pi\left(\frac{k}{T}+f_c\right)t}\right\}, \end{aligned} \tag{2}$$

where $Re\{\cdot\}$ denotes the real part of its argument. When the signal is sent over an underwater channel, the received signal will, due to Doppler shift, experience a scaling effect in a way that the time variable at the receiver t' becomes

$$t' = \left[1 + \frac{v(t)}{c}\right] t. \tag{3}$$

Let $\alpha(t) = v(t)/c$. We call $(1+\alpha(t))$ the Doppler scaling factor, and the received waveform at the receiver will be

$$\begin{aligned} r_{\text{PB}}(t) &= x_{\text{PB}}\left(t'\right) \\ &= Re\left\{\sum_{k=-N/2}^{N/2-1} s_k e^{j2\pi\left(\frac{k}{T}+f_c\right)[1+\alpha(t)]t}\right\} \\ &= Re\left\{\sum_{k=-N/2}^{N/2-1} s_k e^{j2\pi\left[\frac{(1+\alpha(t))k}{T}+(1+\alpha(t))f_c\right]t}\right\}. \end{aligned} \tag{4}$$

We note that the presence of channel also introduces some additional (linear) distortion to the signal. We ignore such distortion, to keep the equations as simple as possible. Nevertheless, the results developed in this paper are readily applicable to the cases where channel introduces some linear distortion, and a cyclic prefix is added to each OFDM symbol to simplify channel equalization.

We can see that the Doppler scaling factor $(1+\alpha(t))$ has two effects on the received signal. The first effect is that it moves the center frequency from f_c to $(1+\alpha(t))f_c$, and the second effect is that the centers of the subcarriers will experience a frequency dependent shift from $\frac{k}{T}$ to $\frac{(1+\alpha(t))k}{T}$.

The first effect can be resolved relatively easily using existing frequency offset mitigation and tracking methods, but the second one can be harder because the shifts are different on different subcarriers. After demodulating the signal from passband to baseband and filtering, we have

$$r(t) = \sum_{k=-N/2}^{N/2-1} s_k e^{j2\pi \frac{(1+\alpha(t))k}{T} t}. \tag{5}$$

At the receiver, the received signal $r(t)$ is sampled at $t = nT/N$ for $n = 0, \cdots, N-1$ to obtain

$$r_n = \sum_{k=-N/2}^{N/2-1} s_k e^{j2\pi \frac{(1+\alpha_n)k}{N} n}, \tag{6}$$

where $\alpha_n = \alpha(nT/N)$. When $\alpha_n = 0$, for all n, applying an FFT to the sequence $[r_0, r_1, \cdots, r_{N-1}]$ delivers the symbol values s_k. This clearly does not work when the Doppler induced errors α_n are non-zero.

One may notice that (6) is equivalent to sampling $x(t)$ in (1) at $t = \frac{(1+\alpha_n)nT}{N}$. In other words, r_n can be considered as the result of sampling $x(t)$ non-uniformly, over the time grid $t_n = \frac{(1+\alpha_n)nT}{N}$. It turns out that a method called "non-uniform discrete Fourier transform" with "Fast Gaussian gridding", [8], allows one to extract the data symbols s_k through a clever processing of the non-uniformly sampled values of $r(t)$.

III. Non-uniform Discrete-Time Fourier Series through Fast Gaussian Gridding

In this section, for completeness of our presentation in this paper, we present a summary of NUFFT through construction of a periodic signal whose Fourier series coefficients are the desired samples of the non-uniform DFT. The following analysis is a modified version of the one in [8] so we can apply the technique to an OFDM signal with duration T.

Suppose that we are given $x[t_n]$, the samples of the function $x(t)$ at time indices $t = t_n$ where $t_n = \frac{(1+\alpha_n)nT}{N}$ (as defined at the end of Sec. II), and we define

$$\tilde{x}(t) = \sum_{n=0}^{N-1} x[t_n]\delta(t - t_n). \tag{7}$$

Let $g_\tau(t)$ be a T-periodic Gaussian function with variance $\sigma^2 = 2\tau$, i.e.

$$g_\tau(t) = \sum_{p=-\infty}^{\infty} e^{-\frac{(t-pT)^2}{4\tau}}. \tag{8}$$

Also, we define

$$\begin{aligned}\tilde{x}_\tau(t) &= \tilde{x}(t) \star g_\tau(t)\\ &= \sum_{n=0}^{N-1} x[t_n]\left[\sum_{p=-\infty}^{\infty} e^{-\frac{(t-t_n-pT)^2}{4\tau}}\right].\end{aligned} \tag{9}$$

The key point in the development of the NUFFT is the fact that when τ is chosen properly, $\tilde{x}_\tau(t)$, within the time interval $0 \le t \le T$, is a close approximation (within a scaling factor that is introduced below) to the original signal $x(t)$. Hence, its Fourier series coefficients gives us the transmitted symbols s_k.

The use of Gaussian pulse as an interpolator has two reasons. Firstly, the time-frequency isotropic property of the Gaussian pulse (i.e., the fact that the Fourier transform of a Gaussian pulse is Gaussian) is the key facilitator to the fast implement of the NUFFT. Secondly, the Gaussian pulse $g_\tau(t)$ with a coarse choice of τ is always a very good interpolator of all choices of $x(t)$, [9].

The Fourier series coefficients of the T-periodic signal $\tilde{x}_\tau(t)$ are

$$\tilde{X}_\tau[k] = \frac{1}{T}\int_0^T \tilde{x}_\tau(t)e^{-j2\pi kt/T}dt. \tag{10}$$

On the other hand, using $\boldsymbol{\mathcal{F}}\{\cdot\}$ to denote Fourier transform, we recall that

$$\boldsymbol{\mathcal{F}}\left\{e^{\frac{-t^2}{4\tau}}\right\} = 2\sqrt{\pi\tau}e^{-4\pi^2 f^2\tau}. \tag{11}$$

Hence, the Fourier coefficients of the T-periodic Gaussian function $g_\tau(t)$ are

$$G_\tau[k] = \frac{2\sqrt{\pi\tau}}{T}e^{-4\pi^2k^2\tau/T^2}. \tag{12}$$

We also note that (9) implies $\tilde{X}_\tau(f) = \tilde{X}(f)G_\tau(f)$, which in turn leads to

$$\tilde{X}[k] = \frac{\tilde{X}_\tau[k]}{G_\tau[k]}. \tag{13}$$

One can notice that as long as $\tilde{x}_\tau(t)$ is a well interpolated version of $x(t)$, then $\tilde{X}[k]$ will be close to the data symbol s_k and, thus, we have

$$\begin{aligned}s_k &= X[k]\\ &= \tilde{X}_\tau[k]/G_\tau[k]\\ &= \frac{Te^{4\pi^2k^2\tau/T^2}}{2\sqrt{\pi\tau}}\tilde{X}_\tau[k],\end{aligned} \tag{14}$$

in which $\tilde{X}_\tau[k]$ can be evaluated using (10). Now, the remaining task is to compute $\tilde{X}_\tau[k]$ using a numerically efficient method.

IV. Evaluating (10) using FFT: The NUFFT

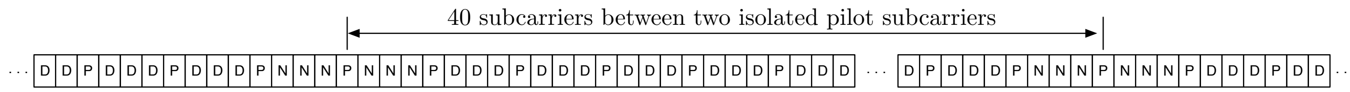
The evaluation of (10) can be performed using a numerical integration over an oversampled uniform grid.

Let M be the number of samples in the interval $0 \le t \le T$. It has been shown in [9] that $M = 2N$ gives a sufficient accuracy. Then we have

$$\begin{aligned}\tilde{X}_\tau[k] &= \frac{1}{T}\int_0^T \tilde{x}_\tau(t)e^{-j2\pi kt/T}\\ &\approx \frac{1}{M}\sum_{m=0}^{M-1}\tilde{x}_\tau\left(\frac{mT}{M}\right)e^{-j2\pi km/M}.\end{aligned} \tag{15}$$

This can be calculated by performing the M-point FFT on $\tilde{x}_\tau\left(\frac{mT}{M}\right)$ for $m = 0, \cdots, M-1$, where

$$\begin{aligned}\tilde{x}_\tau\left(\frac{mT}{M}\right) &= \sum_{n=0}^{N-1} x[t_n]\left[\sum_{p=-\infty}^{\infty} e^{-\frac{(mT/M-t_n-pT)^2}{4\tau}}\right]\\ &= \sum_{p=-\infty}^{\infty}\left[\sum_{n=0}^{N-1} x[t_n]e^{-\frac{t_n^2}{4\tau}+\frac{2mTt_n}{4M\tau}-\frac{2t_npT}{4\tau}}\right]\\ &\quad \times e^{-\frac{m^2T^2}{4M^2\tau}-\frac{p^2T^2}{4\tau}+\frac{2mpT^2}{4M\tau}},\end{aligned} \tag{16}$$



P: pilot subcarrier (96 in total, with 10 of them as isolated subcarriers)
D: data subcarrier (243 in total)
N: null subcarriers (60 in total)

Fig. 1: Subcarrier placement.

and, as defined earlier, $t_n = \frac{(1+\alpha_n)nT}{N}$. Note that in (16), the second exponential term does not depend on t_n. Thus, it can be pre-calculated and be stored in a table. Also, due to the rapid decay of the exponential function, we only need to compute the infinite sum using only the values of p that are close to zero, for example, in the experimental results we will present in Section VI, we have chosen $-6 \leq p \leq 6$.

In the literature there are algorithms that can evaluate (16) with low computation cost and processing time. Greengard *et al.* [8] presented an example of the fast gridding algorithm with low computation cost and high precision, which can be used for implementation. This is what has been referred to in the literature as NUFFT algorithm.

V. Doppler scaling factor acquisition and correction

Successful demodulation of a time-scaled ODFM signal depends heavily on our knowledge of the Doppler scaling factor $(1 + \alpha(t))$. The receiver must be able to estimate the non-linear Doppler scaling factor accurately in order to demodulate the received signal correctly.

As mentioned in Sec. II, the kth subcarriers will experience a frequency dependent shift from $\frac{k}{T}$ to $\frac{(1+\alpha(t))k}{T}$. In order to correct the Doppler scaling factor, we need to find a method to detect how much each subcarrier has shifted from its original location in frequency.

As null subcarriers are minimally affected by the channel, the locations and energy of the null subcarriers can be used in a cost function to estimate how much the frequency spectrum of the received signal has been stretched or shrunk along the frequency domain by the effect of non-linear Doppler scaling. We propose a packet format such that blocks of null subcarriers are inserted around selected pilot subcarriers. To estimate the non-linear Doppler scaling, we would design a cost function that calculates the energy of the received signal in the neighborhood of the null subcarriers. The packet format is a modified version of the one in [5]. Fig. 1 shows a portion of the placement of 399 subcarriers. Among these, 96 are pilot subcarriers. In addition, 10 of the pilot subcarriers are isolated and placed between two groups of two or three null subcarriers. Fig. 2 shows an isolated pilot and its surrounding null subcarriers

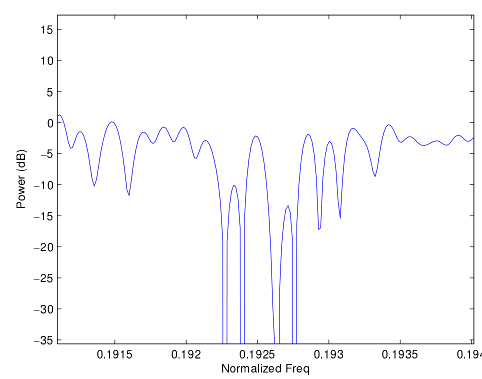


Fig. 2: An isolated pilot and the surrounding two groups of two null subcarriers in frequency domain.

Let $S_{\text{IP}} = \{$subcarrier indices of isolated pilots$\}$ and $S_{\text{null}} = \{$subcarrier indices of null subcarriers$\}$, and assume a non-linear Doppler scaling factor model with relative velocity $v(t) = v_0 + \gamma t$, which is the case of a constant acceleration or deceleration. It leads to non-linear Doppler scaling as the the Doppler scaling factor changes within one OFDM block. For each α_k, we have $\alpha_k = (v_0 + \gamma kT/N)/c$, which implies it is depends on the two parameters v_0 and and γ. We design a cost function $\xi(v_0, \gamma)$ that calculates the energy difference between the isolated pilots and the null subcarriers:

$$\xi(v_0, \gamma) = \sum_{k \in S_{\text{null}}} E\left[\left|\tilde{X}_\tau[k]\right|^2\right] - \sum_{k \in S_{\text{IP}}} E\left[\left|\tilde{X}_\tau[k]\right|^2\right] \tag{17}$$

To find the estimated values of v_0 and γ, we find

$$(\hat{v}_0, \hat{\gamma}) = \arg\min_{v_0, \gamma} \xi(v_0, \gamma) \tag{18}$$

using the method of steepest descent, that is,

$$\begin{aligned}&\hat{v}_0^{(n+1)}\\ =\;&\hat{v}_0^{(n)}-\frac{\mu_1}{2\epsilon_1}\left[\xi(\hat{v}_0^{(n)}+\epsilon_1,\hat{\gamma}^{(n)})-\xi(\hat{v}_0^{(n)}-\epsilon_1,\hat{\gamma}^{(n)})\right]\end{aligned} \tag{19}$$

$$\begin{aligned}&\hat{\gamma}^{(n+1)}\\ =\;&\hat{\gamma}^{(n)}-\frac{\mu_2}{2\epsilon_2}\left[\xi(\hat{v}_0^{(n)},\hat{\gamma}^{(n)}+\epsilon_2)-\xi(\hat{v}_0^{(n)},\hat{\gamma}^{(n)}-\epsilon_2)\right]\end{aligned} \tag{20}$$

with some selected values of $\mu_1, \mu_2, \epsilon_1, \epsilon_2$.

In practice we can further simplify the process of optimizing $\xi(v_0, \gamma)$ by noticing that the velocity function $v(t)$ is correlated to reduce the degree of freedom of the cost function. Consider the velocity at the middle of an OFDM block in time, $v_{\text{mid}} = v_0 + \gamma T/2$. Then we have $\alpha_k \approx v_{\text{mid}}/c$ and

$$\xi(v_{\text{mid}}) = \sum_{k\in S_{\text{null}}} E\left[\left|\tilde{X}_\tau[k]\right|^2\right] - \sum_{k\in S_{\text{IP}}} E\left[\left|\tilde{X}_\tau[k]\right|^2\right] \tag{21}$$

$$\hat{v}_{\text{mid}} = \arg\min_{v_{\text{mid}}} \xi(v_{\text{mid}}). \tag{22}$$

and, similarly, $\hat{v}_{\text{mid}}$ can be estimated using the method of steepest descent.

Let b be the block number in the OFDM packet, then we can estimate, for block b, the values of $v_{0,b}$ and γ_b using

$$\hat{v}_{0,b} \approx [\hat{v}_{\text{mid},b-1} + \hat{v}_{\text{mid},b}]/2 \tag{23}$$

$$\hat{\gamma}_b \approx [\hat{v}_{\text{mid},b} - \hat{v}_{\text{mid},b-1}]/T \tag{24}$$

In other words, we estimate only the velocity in the middle of each OFDM block and compute the initial velocity and the acceleration by linear interpolation. This works because the acceleration in the packet, while being non-zero, should not change too much from one OFDM block to the next OFDM block. In our experiment, which we will discuss in Sec. VI, we observed that this estimation of $\hat{v}_0$ can be off slightly due to the effect of the frequency dispersive channel, and we adjusted it using decision directed tracking methods.

The algorithm in (23) and (24) is performed along the OFDM packet. The timing phase and the duration of each OFDM block is calculated using the estimated information of $v(t)$. In each OFDM block, the values of $\hat{v}_0$ and $\hat{\gamma}$ are used to calculate $\hat{\alpha}_k = (\hat{v}_0 + \hat{\gamma}kT/N)/c$ for the input of NUFFT in Sec. IV, and thus we can obtain the data symbol s_k using (14).

VI. EXPERIMENTAL RESULTS

To evaluate the performance of non-linear Doppler scaling correction using NUFFT, we have performed simulations of an OFDM transceiver with non-linear Doppler scaling on two scenarios: (i) an AWGN channel, and (ii) a more realistic underwater acoustic channel with a number of multi-paths with Rayleigh distributed amplitudes, inter-arrival times of an exponential distribution, and Doppler spread due to the doubly dispersive channel. We compare the performance of the following three compensation methods:

- No Doppler scaling compensation.
- Traditional linear Doppler scaling compensation [7] by resampling the received signal $y(t)$ using

$$z(t) = y\left(\frac{1+\alpha}{1+\hat{\alpha}}t\right) \tag{25}$$

- Non-linear Doppler scaling compensation using NUFFT.

In the first scenario, for comparison purposes, we use an AWGN channel with non-linear Doppler scaling to better see the impact of the proposed NUFFT compensation of non-linear Doppler scaling factor. The relative velocity and acceleration of the vehicles used are 10 m/s and 2 m/s^2, respectively. Fig. 3 shows the eye diagram of the received data symbols in one OFDM block using the three different compensation methods. As seen, with no compensation the detected symbols are badly scrambled, hence correct detection of the transmitted data symbols is unlikely. The eye pattern significantly improves and open eye is seen when a constant speed is assumed with linear Doppler scaling and compensated for. Further significant improvement is observed when the the acceleration, i.e., the first derivative of $v(t)$, is also detected and compensated for using non-linear Doppler scaling compensation with NUFFT.

In the second scenario, we use a channel model for underwater acoustic channel similar to the one used in [7]. The channel is modeled to have 10 different multi-paths. The inter-arrival times are generated using the exponential random variable with mean of 1 milliseconds. The amplitudes of the paths are Rayleigh distributed, with an average power profile that decays exponentially from 0 dB to -20 dB. The maximum Doppler spread is selected to be $\sqrt{3}\sigma_v f_c/c$ where $\sigma_v = 0.25$ m/s is the velocity standard deviation, $f_c = 20$ kHz is the carrier frequency, and c is the speed of sound which is at 1484 m/s. Additive Gaussian noise is also added with SNR $= 30$ dB. The relative velocity ranges from 10 m/s to -10 m/s, and the deceleration of the vehicles used is 4 m/s^2.

We have simulated 12 OFDM packets, each with 43 blocks of OFDM symbols (with 262 usable data subcarriers), which give us 516 OFDM blocks and a little bit over 135,000 QPSK symbols. We used what we described in

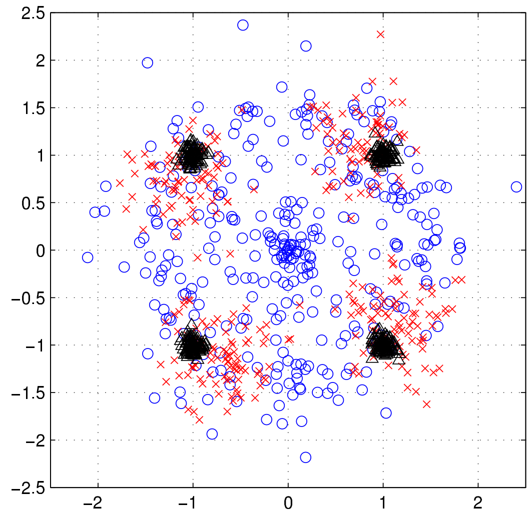


Fig. 3: Eye diagram at the receiver with SNR = 30 dB. Compensation method: blue, none; red, linear Doppler scaling compensation through resampling (velocity only); black, non-linear Doppler scaling compensation using NUFFT (velocity and acceleration).

Sec. V to perform Doppler scaling factor detection and compensation with NUFFT, as well as the traditional resampling method assuming linear Doppler scaling. Afterwards, we use the 96 pilot subcarriers to perform least square estimation of the channel, and equalized it using MMSE equalization. Fig. 4 shows an example of the channel in time domain for a sample OFDM block. Channel equalization is done in the frequency domain using the conventional single-tap per subcarrier method for OFDM.

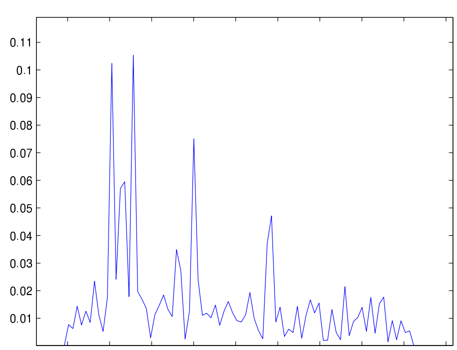


Fig. 4: An example of the channel we obtained using least square estimation, with the noise variance measured at the pilots.

TABLE I: Mean square error of the received data symbols after Doppler compensation and equalization.

Packet	Traditional (linear)	NUFFT (non-linear)
1	0.9901	0.5499
2	1.0029	0.5292
3	1.0251	0.4814
4	0.9482	0.5630
5	0.8594	0.4998
6	1.1369	0.5737
7	1.0005	0.5968
8	1.0461	0.5826
9	0.9031	0.5408
10	1.0596	0.6106
11	0.9859	0.6067
12	1.0374	0.5579
mean	0.9996	0.5577

The comparison of the mean square error for the 12 packets are summarized in Table. I. We can observed that with non-linear Doppler scaling correction, the mean square error of the received data symbols are lower than the one using traditional compensation method (≈ 44.2 % improvement). Of the 270384 bits transmitted, we get 26165 bit errors for the traditional method and 13064 bit errors for the NUFFT method ($\approx 50.1\%$ improvement). Fig. 5 shows the eye diagram.

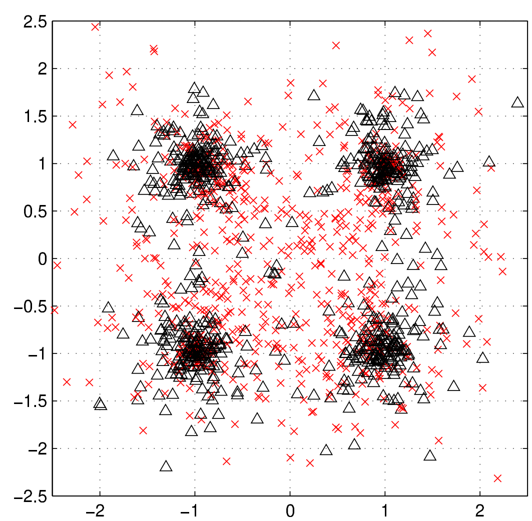


Fig. 5: Eye diagram at the receiver with the channel and SNR = 30 dB. Compensation method: red, linear Doppler scaling compensation through resampling (velocity only); black, non-linear Doppler scaling compensation using NUFFT (velocity and acceleration). Mean square error: red, 0.9996; black, 0.5577.

VII. Conclusions

In this paper, we furthered our study in [6], where we had introduced non-uniform fast Fourier transform (NUFFT) for Doppler scaling correction in underwater acoustic channels when OFDM is for data transmission. We introduced a new packet format that facilitates Doppler scaling parameters estimation. Mathematical equations where also developed to estimate the average speed as well as acceleration between the communicating vehicles. The effectiveness of the proposed packet format for estimating the Doppler scaling parameters and their compensation through NUFFT were demonstrated through numerical examples.

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