

Doppler Estimation and Correction in Underwater Industrial Internet of Things

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Abstract – Emerging industrial applications in underwater settings (e.g. oil & gas, fisheries) are usually based on acoustic signals which suffer significant Doppler effect distortions. Indeed, waves, currents, and tides may cause unintentional transmitter/receiver motion (drifting) as well as changes in the physical properties and spatial variations of the channel itself.

In this paper, we study how to correct Doppler effects in JANUS transmissions, a widely used standard for underwater IIoT. In particular, we exploit the JANUS preamble, composed of an m-sequence of 32 pseudo-random symbols, to estimate and compensate the Doppler effect, without requiring any modification to the standard. The proposed method is validated using Watermark simulator.

I. INTRODUCTION

In recent years, many new wireless communication technologies have been developed for the Industrial Internet of Things (IIoT), mostly based on Radio Frequency (RF) transceivers. However, in underwater environments, common RF technologies can not be used because of the extreme attenuation of the medium. Thus, emerging industrial applications (such as submarine oil & gas and fishing industries) have pushed the development of new underwater communication systems, to provide connectivity between subsea sensors, actuators and smart objects interconnected with each other and with the outside world.

These smart devices form an Underwater-IIoT (UW-IIoT), which mainly consist of static and mobile nodes deployed at different depths to perform cooperative monitoring, operation and data collection tasks. In current underwater communication systems, acoustic waves are widely used, having the advantage of undergoing significantly lower absorption at low frequencies (of the order tens of kHz), compared for example to optical communications. On the other hand, this fact allows to cover greater distances albeit with low bitrate (order of tens kbit/s).

However, as reported in [1], underwater acoustic communication suffers from frequency-dependent attenuation, reflections, as well as random local displacements. This last phenomena is peculiar in underwater channels be-

cause, apart from intentional transmitter/receiver motion (i.e. node displacements), changes in the physical properties and spatial variations of the channel itself can introduce severe Doppler effects. Indeed, waves, currents, and tides may cause unintentional transmitter/receiver motion (drifting) in some cases at comparable velocities of mobile nodes. Moreover, since the speed of acoustic waves in water is relatively low (approximately 1540 m/s, much lower, for example, to the speed of electromagnetic waves in air), the Doppler effect introduces significant distortions in propagated signals. In other words, there is always some motion present in the underwater environment, causing a Doppler effect which has to be taking into account and compensated in order to realize robust communication systems. In the literature, two approaches are the often used: the cross-ambiguity function (CAF) or the single-branch autocorrelation (SBA) [2]. The CAF method results in accurate estimations but with a high complexity, whereas the SBA is less complicated but also less accurate.

In this paper, we study how to estimate and correct Doppler effects in underwater communications. In particular, we propose a simplified CAF method that can be used in real-time applications and we apply it to JANUS [6], a promising standard for UW-IIoT. We exploit the JANUS preamble, composed of an m-sequence of 32 pseudo-random symbols, to estimate and compensate the Doppler effect without requiring any modification to the standard. Using Watermark [3], a realistic underwater channel simulator, we demonstrate the effectiveness of the proposed method.

II. ESTIMATING THE DOPPLER EFFECT

Consider the case of a source transmitting a sine wave at frequency f_T and moving at constant speed v towards a fixed receiver. The Doppler effect will alter the wavelength perceived by the receiver: the sine wavelength as seen by the receiver will be decreased by the space covered by the source in a period or, in terms of frequency, the receiver will observe a greater number of wave fronts in the unit of time, i.e. the received frequency f_R will be greater than the transmitted frequency. If by convention we use a positive velocity v to indicate the direction of an approaching source and a negative velocity $-v$ to indicate the direction

of a departing source, then we can express the frequency perceived by the receiver as: $f_R = \gamma f_T$ where

$$\gamma = \frac{c}{c - v} \quad (1)$$

and c is the speed of sound in water, approximately equal to 1540 m/s.

Generally, Doppler estimation is accomplished by inserting special waveforms known to the receiver during the data transmission. Such known waveforms, like linear-frequency-modulated (LFM) waveforms, hyperbolic-frequency modulated (HFM) waveforms, or m-sequences, are inserted as a preamble prior to the data symbols to estimate the frequency shift [4] or as preamble and postamble around each data burst to estimate the time difference between their arrivals (later transformed into the time-compression factor [5]). Also, it is possible to alternate known waveforms and data symbols, both in the time or frequency domain, such as in OFDM transmissions with the use of the pilot carriers. Finally, in demodulation, the receiver employs signal processing techniques to correct the Doppler distortion.

One of the most used technique is the cross-ambiguity function (CAF). The CAF represents the output of a matched filter to an input signal that is shifted in terms of delay and frequency (Doppler effect) [5], [7]. In practice, the CAF can be computed employing a bank of correlators, each of which is used to correlate the input signal with a Doppler-scaled replica of itself. This operation leads to a delay-Doppler scale grid in which the maximum of the CAF magnitude is searched. More specifically, through the position of the peak of the CAF along the doppler scale, it is possible to extract the Doppler estimate, while through the position of the peak of the CAF along the delay scale it is possible to extract the time delay estimation, used for timing synchronization.

Clearly, the receiver must know and compute in advance the Doppler-scaled replicas of the transmitted signal and the accuracy of the estimate will depend on the size of the correlator bank used. The number of correlators, as well as the scaled Doppler versions of the transmitted signal, depends on the expected range of the Doppler effect and the acceptable quantization error. Let M be the number of correlators and $s_0(t)$ the transmitted signal not distorted by Doppler effects. By sampling the signal at frequency f_s , we obtain:

$$s_0(n) = s_0(t) \cdot \sum_{n=0}^{N_{s_0}-1} \delta(t - nT_s)$$

where $T_s = 1/f_s$ is the sampling period and N_{s_0} is the number of samples required to cover the entire signal. Then, we can express the generic Doppler-scaled version $s_{v_i}(n)$ of the reference preamble as:

$$\begin{aligned} s_{v_i}(n) &= s_0(t) \cdot \sum_{n=0}^{N_{s_{v_i}}-1} \delta(t - n\gamma_{v_i}T_s) \\ &= \sum_{n=0}^{N_{s_{v_i}}-1} s(n\gamma_{v_i}T_s) \cdot \delta(t - n\gamma_{v_i}T_s) \end{aligned}$$

where the subscript v_i represents the relative speed of the signal affected by Doppler and N_{s_i} the number of samples of this same signal, which is equal to:

$$N_{s_{v_i}} = \frac{N_{s_0}}{\gamma_{v_i}} \quad i = 0, 1, \dots, M - 1$$

To compute the CAF, the received signal $r(t)$ is sampled, converted to baseband and filtered to obtain $r(n)$. Then, $r(n)$ is correlated with all the Doppler-scaled versions of the reference signal $s_0(n)$. Finally, considering the squared module of each correlation, the CAF is obtained from the output of all the correlators.

Since in this work we are interested in the impact of relative motion between transmitter and receiver, we will express the Doppler range in terms of speed (measured in m/s) and we will estimate the Doppler scale factor via equation 1. Differently from [10], where special waveforms are applied to JANUS packets, we exploit the standard JANUS preamble to compute the CAF and improve JANUS communications affected by Doppler.

III. DOPPLER ESTIMATION IN JANUS

In the literature, a plethora of underwater acoustic modems exist, developed to meet the need of different applications (see [8] and citations therein). However, the absence of a common standard for underwater communications has led to the development of several manufacturer-specific devices, generally employing proprietary modulation schemes. To overcome this lack of interoperability the NATO Centre for Maritime Research and Experimentation (CMRE) has developed and established in March 2017 a first standard for underwater communications, named JANUS [6]. The proposed protocol is not intended to be limited only to NATO military use, but also for civilian and NON-NATO maritime assets, because it has been designed both to ensure communication interoperability between heterogeneous assets and to minimize the changes required to bring existing underwater communications equipment into compliance. Indeed, in [9] JANUS is proposed as a second "language" to be implemented in manufacturer-specific devices in parallel with their proprietary digital coding schemes: JANUS could be used to establish the first contact, notifying the presence of an asset in the area and its capabilities to negotiate communication parameters. After, the devices can switch to a suitable modulation

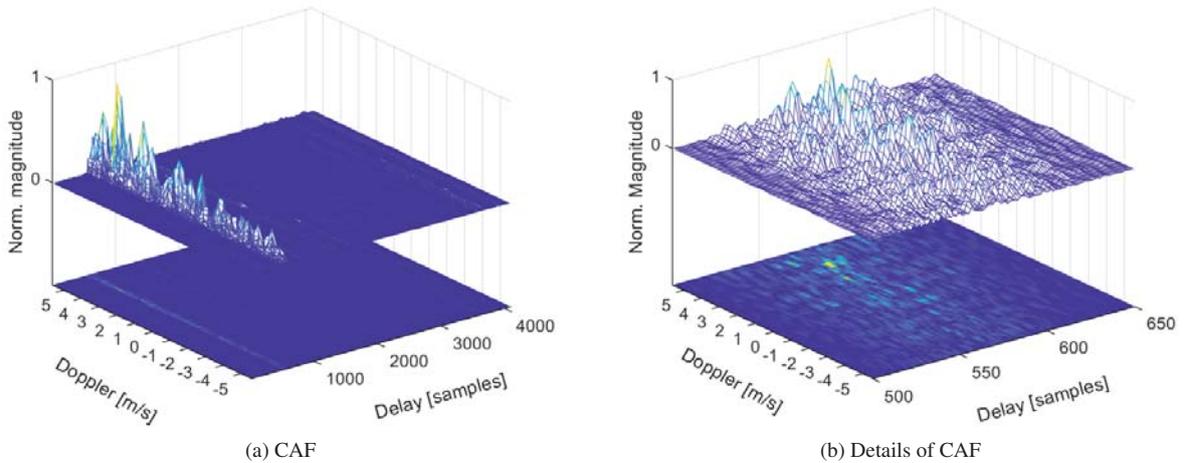


Fig. 1. Example of CAF using the JANUS preamble. Watermark NOF1 channel, simulated motion 4 m/s.

scheme supported by all, or a subset of, the devices in the area.

JANUS uses a simple Frequency-Hopped Binary FSK (FH-BFSK) scheme in which binary data is mapped to 13 evenly-spaced tone pairs spanning the bandwidth of the passband transmission. The JANUS packet starts with a fixed preamble of 32 chips, 32 frequency-hopped symbols which value is set to a pseudo-random 31-bit m-sequence. This preamble is followed by a "baseline JANUS Packet" encoding 64 bits of information. Optionally, a "Cargo" packet of arbitrary length can be added at the end. We exploit the JANUS preamble to perform the estimate of the Doppler effect and to compensate this type of distortion.

The proposed algorithm is implemented at the receiver, where the CAF method is applied: we use a correlators bank in which the received signal is correlated with the known waveforms (the 32-chips of the JANUS preamble), prescaled by different Doppler scaling factors. For this purpose, M doppler-scaled versions of the JANUS preamble must be generated, each of these corresponding to a different relative speed v_i between transmitter and receiver. Without loss of generality, in this work the CAF is designed to estimate and correct distortions caused by relative movement up to $\pm 5m/s$ and with resolution step of $\Delta v = 0.25m/s$. Thus, the total number of correlators M required is computed as the ratio between the speed range $[v_{min}, v_{max}]$ and the resolution plus 1:

$$M = \frac{v_{max} - v_{min}}{\Delta v} + 1$$

while the relative speed v_i , corresponding to each correlator i is:

$$v_i = \left(i - \frac{M-1}{2} \right) \cdot \Delta v \quad i = 0, 1, \dots, M-1 \quad (2)$$

Table 1. Watermark channels characteristics.

Channel	Mean Delay spread (ms)	Mean Doppler spread (Hz)	Maximum Delay spread (ms)	Maximum Doppler spread (Hz)
NOF1	13	1	18	1
NCS1	9	4	9	4
BCH1	13	1	18	1
KAU1	19	1	37	2
KAU2	27	1	28	1

The estimated Doppler will correspond to the highest value shown by the CAF, obtaining the relative speed \hat{v} . Although this is out of the scope of this paper, the CAF peak is also used to extract the time delay $\hat{\tau}$, used for time synchronization:

$$[\hat{v}, \hat{\tau}] = \arg \max_{v, \tau} |A(v, \tau)| \quad (3)$$

Since the CAF time and Doppler scales are quantized, searching for the CAF maximum value means finding the index of a matrix representing respectively the approximated values \tilde{v} of the relative motion and the time delay $\tilde{\tau}$. For example, figure 1 shows the CAF obtained when the JANUS preamble is received through Watermark NOF1 channel (more details in section iv.), with a simulated motion of 4 m/s. Note that the node's movement sums up with the watermark channel characteristics, which are summarized in Table 1 in terms of Delay spread and Doppler spread. From the figure, the maximum of the CAF is clearly distinguishable from other minor peaks, despite the fact that the JANUS preamble is generally not used for this purpose. Exploiting the JANUS preamble to compute

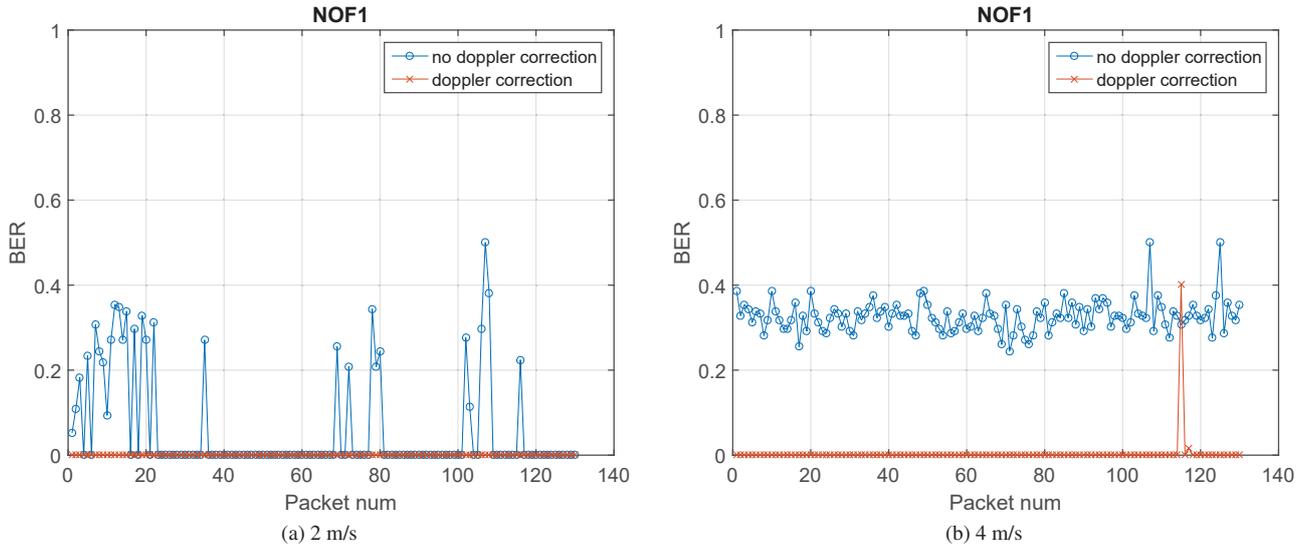


Fig. 2. Results obtained on Watermark NOF1 channel.

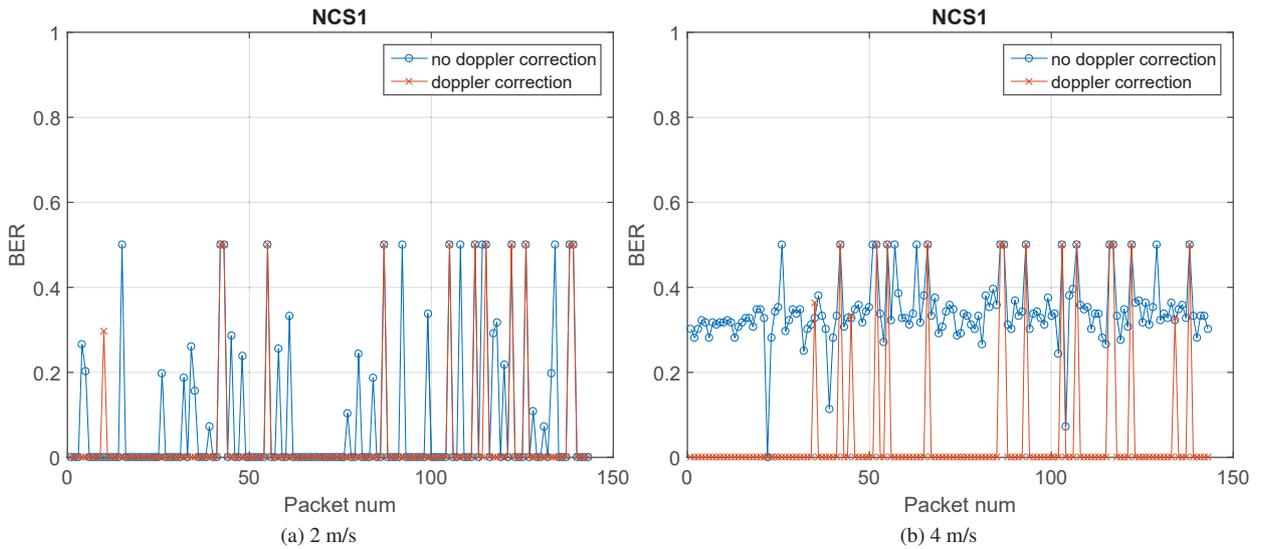


Fig. 3. Results obtained on Watermark NCS1 channel.

the CAF is a clear difference from the work in [10], where other out-of-the-standard waveforms are applied to JANUS packets.

IV. EXPERIMENTAL RESULTS

We tested the proposed mechanism using Watermark [3], a realistic underwater simulator which convolves user signals with at-sea measurements of the time-varying impulse response. This allows us to combine real channels and reproducible conditions: indeed, Watermark is issued with a library of sea channels measured in Norway (two sites), France, and Hawaii, offering three frequency bands (4-8, 10-18, and 32.5-37.5 kHz), single-hydrophone and

array receivers, and play times varying from 33 s to 33 min. In our experiments, we used the available SISO channels (NOF1 and NCS1) since most acoustic modems use a single receiver. These channels have frequency bands of 10-18 kHz, while JANUS usually has center frequency of $f_c = 11520$ Hz and band between 9440–13600 Hz. Thus, in our experiments we shifted the JANUS signal to a center frequency of 14 kHz, sampled at 48 kHz.

In the experiments, we set the size of the JANUS Cargo to be 8, 16, 32 and 64 Bytes and we repeat the test with different relative speeds, from -5 to 5 m/s with steps of 1 m/s. Depending on the size of the Cargo, the JANUS packet is transmitted many times to fill the Watermark trace (almost 300 packets with 8 Bytes Cargo). For the sake of

simplicity, we report only a subset of the results, with a JANUS Cargo of 16 Bytes.

Figure 2 shows the results obtained on the Watermark NOF1 channel, with node's relative speed of 2 and 4 m/s respectively. From the figure, it is clear that with our Doppler correction the packets are received without errors in almost all of the experiments. Instead, without Doppler correction, the BER becomes quickly unacceptable – over 30% for speeds of 4 m/s. We repeated the same experiments with Watermark NCS1 channel which is the most challenging trace available. Figure 3 summarizes the results obtained in this scenario, with node motion of 2 and 4 m/s respectively. With the NCS1 trace, errors appear also when employing the proposed Doppler correction. Nevertheless, using our method, packets are correctly received in over 90% of the cases, even with speeds as high as 4 m/s.

Table 2 summarizes the results obtained for the entire range of speeds (from -5 m/s to 5 m/s) on both the NOF1 and NCS1 channels in terms of average BER with or without Doppler correction. As we expected, if no Doppler correction is applied, the mean BER increases as the absolute relative speed increases, reaching average values of 42% and 46% for NOF1 and NCS1 channels respectively. Instead, employing the proposed Doppler correction, the mean BER is very low, with a maximum of the 3,2% for NOF1 channel and 18% for the challenging NCS1 channel. However, it turns out that the BER increase is probably due to synchronization problems in the JANUS implementation: indeed, as observable in figure 3, errors on NCS1 traces are mostly due to packets with BER at 0.5 which represent unsynchronized packets (i.e. lost packets). Instead, the rest of the packets, if correctly detected and synchronized, are received with almost no errors thanks to the proposed Doppler estimation (BER < 5% on average). Therefore, the mean BER could be further reduced by improving detection method, which is left as future work.

V. CONCLUSIONS

Underwater communications are significantly affected by Doppler distortions. In this paper, we study how to correct Doppler effects in JANUS transmissions, a widely used standard for underwater IIoT. In particular, we exploit the JANUS preamble to compute the CAF and compensate Doppler distortions up to $\pm 5m/s$ without requiring any modification to the standard. Validated through realistic simulations, the proposed method is able to correctly receive over 90% of the packets even under severe Doppler, demonstrating the effectiveness of our technique.

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Table 2. Mean BER obtained with and without Doppler correction on both NOF1 and NCS1 channel.

Relative speed (m/s)	NOF1 w/o Doppler correction	NOF1 w/ Doppler correction	NCS1 w/o Doppler correction	NCS1 w/ Doppler correction
-5	0.344	0.032	0.416	0.078
-4	0.328	0.003	0.338	0.052
-3	0.259	0	0.246	0.044
-2	0.058	0	0.087	0.038
-1	0.008	0	0.044	0.024
0	0	0	0.007	0
1	0.026	0	0.134	0.028
2	0.007	0	0.281	0.033
3	0.314	0	0.362	0.04
4	0.321	0	0.397	0.049
5	0.417	0.012	0.463	0.184

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