Underwater Distance Estimation Using the JANUS Communication Standard

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Abstract

Distance estimation is an integral part of localization in Euclidean space and the first step of any localization algorithm. In the underwater domain the distance is estimated by measuring the propagation delay of a pressure wave in the acoustic frequency range. In the process a known waveform is correlated with a received signal in order to determine the time instance of the wave incident at a receiver, thus the correlation properties of the known waveform are of upmost importance.

This paper evaluates the suitability of the communication standard called JANUS for the generation of waveforms for distance estimation while still adhering to the standard. Additionally the correlation properties of the resulting waveforms are compared to slight adaptations to the JANUS standard and less restricted FH-FSK waveforms commonly used in continuous wave sonar and radar systems.

Introduction

JANUS is an open underwater signaling standard designed by the NATO Centre for Maritime Research and Experimentation (CMRE)[1]. The usage of FH-BFSK as the physical layer coding scheme together with a convolutional encoder of rate $r = 0.5$ allows for robust communication even in harsh channel environments in spite the usage of rather simple signaling methods[2]. The simplicity of a JANUS transmitter and receiver allows it to serve as a interoperable and robust means of communication between increasingly heterogeneous maritime assets with modems from different manufacturers.

The JANUS standard specifies a physical layer coding scheme, channel coding and default MAC mechanisms while allowing for some flexibility regarding the used bandwidth, carrier frequency and other parameters. Figure 1 depicts a time-frequency plot of a baseline JANUS transmission with optional wake-up tones and a pause at the beginning of the transmission. Following the optional wake-up tones comes a preamble of 32 modulated binary symbols spanning a time of $32 \cdot C_d$ where C_d denotes a single chip duration. The instantaneous frequency of each symbol remains constant during the chip duration and depends on the symbol itself and a hopping pattern which is derived from Galois Field arithmetic and described in the standard[3]. The actual encoded information bits trail the preamble and are modulated using the continuation of the hopping pattern.

JANUS packets can be used to estimate the propagation time between two communication nodes implicitly inferring to a distance estimate between the nodes if the propagation velocity can be estimated. Since the JANUS standard does not impose a receiver implementation, the quality of the propagation time estimate depends on the actual receiver implementation which is described in a following section. Distance estimation waveform which are predominantly used in continuous-wave radars serve as a comparison and have the same receiver complexity to allow for a fair comparison between the propagation time estimates.

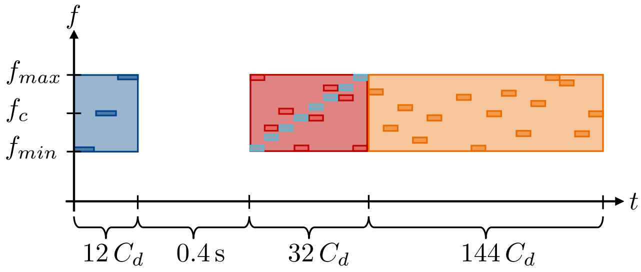

Figure 1: Time-frequency plot of a JANUS transmission. The standard conform preamble is in red, frequency hopped linear frequency modulated up-chirp replaces the preamble and is depicted in turquoise.

Distance Estimation Principles

Various different methods could in theory be used to obtain distance estimations, though the boundary conditions of a practical underwater sensor network restrict the available distance estimation methods. Using the received signal strength (RSS) for distance estimation necessitates the transmission of the transmit power in a heterogeneous communication network. Additionally an accurate path loss exponent estimation and knowledge about the channel model is needed for precise distance estimations which are both varying in time and location and are difficult to obtain in the underwater domain.

Time-of-Arrival (ToA) methods require locally synchronized clocks necessitating ideally atomic clocks which are more expensive and consume more power than quartz clocks. Regularly synchronizing less accurate quartz clocks congests the communication network and requires additional power, thus neither RSS nor ToA methods are well suited for heterogeneous, power constraint underwater networks.

Two-Way Ranging

Two-Way Ranging (TWR) is a ranging method which measures the round-trip time between two communication nodes and does not require prior clock synchronization. Since the propagation velocity is reciprocal in water the distance between two nodes can be calculated as long as the delay T_d between reception and transmission is either predetermined and known or contained in the contents of the message. When both nodes require a distance estimation double-sided two-way ranging (DS-TWR) can be used in order to reduce the amount of transmissions[4]. This procedure is depicted in figure 2 where the locally measured round-trip time for node N_1 amounts to $T^1_{rtt} = t^{(1)}_3 - t^{(1)}_0$ and are thus only measured using the local clock $t^{(1)}$.

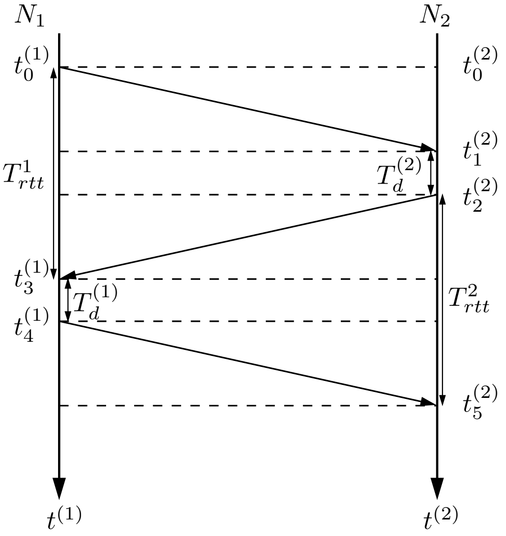

Figure 2: Time diagram of double-sided two-way ranging (DS-TWR). Both communication nodes are able to measure the round-trip time without prior clock synchronization.

Accurately measuring the receive time $t^{(1)}_3$ depends on the characteristics of the transmitted waveform. The standard deviation of the time measurement depends primarily on the effective signal bandwidth B and the signal-to-noise ratio $\frac{E_s}{N_0}$ while the ability to detect a given signal in an environment with strong multipath propagation depends on correlation properties of the signal and the receiver implementation[5]. The next section analyzes the correlation properties of the JANUS preamble and introduces some adaptations to the JANUS standard. This section is followed by a description of the receiver implementation which is compatible with the standard and the adaptations thus the complexity remains constant in the comparison.

Waveform properties and adaptations

The bandwidth, frequency spacing and symbols duration are parameters which are not dictated by the JANUS standard but they are related to the used carrier frequency of the transmission. Using the *initial JANUS acoustic frequency band* which is described in the standard documentation[3] results in the configuration shown in table 1.

The theoretical accuracy of time measurements is expressed in equation (1) where σ_t stands for the standard deviation of the time measurement, $\frac{E_s}{N}$ is the signal-to-noise ratio and B_{eff} stands for the effective bandwidth of the signal which can be calculated according to equation (2). For signals with a flat spectrum like a continuous up-chirp which is commonly used in radar and sonar applications B_{eff} can be approximated with $B_{eff} = \frac{B_w \cdot \pi}{\sqrt{3}}$[5]. Using the simplification for the effective bandwidth and the configuration of the initial JANUS acoustic frequency band from table 1, a lower bound for the standard deviation of the time measurement is determined in $\sigma_t \approx 9.37 \cdot 10^{-5}$ at a signal-to-noise ratio of 0 dB. Assuming a propagation velocity of $v_c = 1\,500\,\mathrm{m/s}$ an accuracy of approximately 14.6 cm can be achieved, which would be acceptable for many underwater localization and navigation scenarios. In practice the typical signal-to-noise ratio during transmissions using JANUS is at least 6 dB, thus further increasing the theoretically achievable accuracy.

Table 1: Parameter of the initial JANUS acoustic frequency band.

Parameter	Value
f_c	11 520 Hz
B_w	4 160 Hz
F_s	160 Hz
T_s	160^{-1} s

$$\sigma_t = \frac{1}{B_{eff} \cdot \sqrt{2 \cdot \frac{E_s}{N_0}}} \tag{1}$$

$$B_{eff} = \frac{1}{E_s} \cdot \int_{-\infty}^{\infty} (2\pi f)^2 \, |S(f)|^2 \, df \tag{2}$$

Changing the bits of the preamble or the hopping pattern of the standard conform JANUS transmission which is depicted in figure 1 does change the transmitted waveform and thus also the effective bandwidth, though as long the complete range of the usable frequencies is used the changes in the spectrum and thus the changes in effective bandwidth is minimal. Adhering to the JANUS standard the 32 binary symbols of the preamble are determined from a m-sequence of length 31 concatenated with a '0'. The hopping pattern provides good orthogonality properties and its purpose is to reject inter-symbol interference[6]. It is derived from Galois Field arithmentic. Both the hopping pattern as well as m-sequences have good auto-correlation properties by themselves and combining them in order to modulate a JANUS signal leads to the red auto-correlation function depicted in figure 3. Since the preamble bits change the instantaneous transmitted frequency only by a small amount compared to the hopping pattern its influence on the auto-correlation function is demonstrated in the orange curve. Here the preamble is set to a constant stream of 32 zeros which by itself would result in poor auto-correlation properties but the combination with the hopping pattern yields a similar curve to the standard waveform.

Continuous wave sonar and radar research of the past has shown that different waveforms design offer trade-offs on typical sonar and radar requirements like accuracy, resolution and target ambiguity[7]. Linear frequency modulated (LFM) chirp signals allow for both distance and velocity estimation with moderate signal

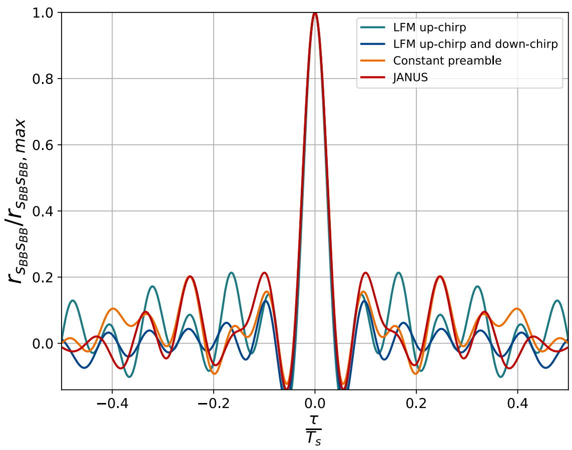

Figure 3: Autocorrelation function of the preamble waveforms around the peak.

processing overhead and are thus commonly used. Additionally the auto-correlation function of linear frequency modulated chirp signals have low side peaks. Adapting the hopping pattern and the preamble of the JANUS communication standard, linear frequency hopped chirp signals can be generated and used in place of the standard preamble which results in the turquoise frequencies of the time-frequency plot in figure 1. Both the hopping patter and the preamble can also be adapted to resemble a LFM up-chirp followed by an immediate down-chirp. The auto-correlation functions of all three adaptations to the standard JANUS waveform are plotted in figure 3. The widths of the peak is inversely related to the effective bandwidth which is practically the same for all four waveforms. Significant differences occur when the heights of the secondary peaks are compared. Evidently all adaptations to the JANUS standard have lower secondary peaks which could indicate a higher detectability rate of receivers with no or weak channel estimation or channel equalization.

Receiver implementation

Since the time estimation performance depends on the receiver implementation this section describes the implementation of the receiver with which the results in the last section are generated. The implementation is cross-tested to a reference implementation which can be found in the *JANUS Wiki*[8] and is an adaptation to it.

The received signal is continuously down-converted to the baseband in overlapping frames for which the spectrum is computed after windowing them with a Hamming window by using the Discrete Fourier Transform (DFT). The energies of the spectral bins corresponding to the frequencies of the modulated preamble waveform are added together after shifting each frame to correspond to the order in which the spectral component occurs in the preamble[9]. With the modulated signal consisting of ideally only complex exponentials and the DFT computing the cross-correlation of the input signal with N complex oscillations, the resulting signal processing chain is equivalent to a matched filter bank of these N frequencies. The signal detection is done using the resulting correlation values and a GO-FAR detector[10] well known from radar detection problems[11]. The GO-FAR detector is identical to the detector in the reference JANUS implementation.

Performance Evaluation

For the performance evaluation the JANUS transmission is sent over two simplistic channel impulse responses

$$h_1(t) = \delta(t - t_{d,1}) \tag{3}$$

$$h_2(t) = \frac{1}{\sqrt{1^2 + 0.8^2}} \cdot (\delta(t - t_{d,1}) + 0.8\delta(t - t_{d,2})) \tag{4}$$

which simulate a direct line-of-sight (LOS) scenario in equation (3) and a multipath scenario in equation (4). The delay of the secondary signal path is chosen to be $t_{d,2} = 0.1\,\mathrm{s}$ and thus roughly coincides with secondary peak of the auto-correlation function. Furthermore seeded additive white Gaussian noise is added to the signal for each simulation so that the different waveforms can be compared fairly.

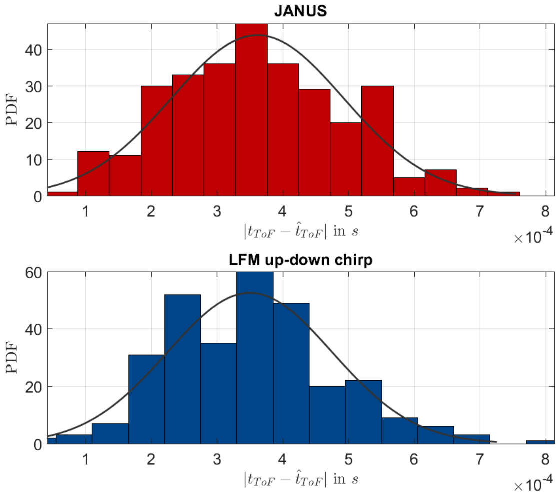

Figure 4: Absolute error of the receive time estimate $|t_{ToF} - \hat{t}_{ToF}|$ histogram for the LOS channel at a SNR of 0 dB and 300 transmissions.

Figure 4 shows two histograms of the absolute error of the receive time estimations of the JANUS standard preamble waveform and the LFM up- and down-chirp in the LOS scenario. As the used effective bandwidth of both waveforms are practically identical, the receive time estimation accuracy is equivalent. Table 2 summarizes the results of the receive time estimations for the remaining waveforms for which the same argumentation holds. A noteworthy results is that the standard deviation of LFM up-chirp is significantly higher than the comparison waveform for both channel scenarios. Additionally it can be seen that the effect of the preamble itself is almost negligible when the hopping pattern is not adapted simultaneously since the waveform generated with a constant preamble of 32 zeros performs almost identically to the JANUS standard conform waveform. A absolute time estimation error of 0.35 µs would lead to an range estimate error of 0.525 m which is acceptable for underwater localization purposes in typical operation ranges.

Table 2: Mean absolute error $\mu_{\hat{t}}$ and standard deviation $\sigma_{\hat{t}}$ of the receive time estimation for all four waveform variations at a SNR of 0 dB.

Param. Config.	$\mu_{\hat{t}}$ [µs]	$\sigma_{\hat{t}}$ [µs]	$\mu_{\hat{t}}$ [µs]	$\sigma_{\hat{t}}$ [µs]
Channel	$h_1(t)$		$h_2(t)$	
JANUS	0.361	0.131	0.362	0.136
Const. preamble	0.370	0.124	0.369	0.131
LFM up-chirp	0.401	0.176	0.412	0.192
LFM up-down-chirp	0.350	0.125	0.359	0.140

Table 3 contains simulation results of the same scenarios generated with a SNR of -4 dB. It can be observed that the receive time estimation accuracy is still equivalent between the standard JANUS waveform and two of the three adaptations. Similar to the previous result table 2 the LFM up-chirp yields a significantly weaker accuracy and a larger standard deviation. The results validate the original assumption formulated in equation (1) which relates the effective bandwidth and the signal-to-noise ratio to the standard deviation of the receive time estimation.

Three of the four waveform simulations are marked with a '$*$' which indicates that not all attempted transmissions could be successfully detected and subsequently decoded. For the here showed scenarios the detection rate of the standard JANUS transmission and the JANUS hopping pattern with a constant preamble of 32 zeros is about 0.97 while the LFM up-chirp detection rate is 0.91. Only the LFM up- and down-chirp could successfully detect all transmission attempts. The archived SNR gain the adapted waveform yields for detection depends on the channel impulse response. Since $h_2(t)$ is specifically constructed to be a simple but bad case scenario with a strong delayed propagation path exactly timed to arrive at the secondary peak of the auto-correlation function the detection gain is not computed.

Table 3: Mean absolute error $\mu_{\hat{t}}$ and standard deviation $\sigma_{\hat{t}}$ of the receive time estimation for all four waveform variations at a SNR of -4 dB. Configurations marked with a '$*$' have a detection rate < 1 for the scenario using the channel impulse response $h_2(t)$.

Param. Config.	$\mu_{\hat{t}}$ [µs]	$\sigma_{\hat{t}}$ [µs]	$\mu_{\hat{t}}$ [µs]	$\sigma_{\hat{t}}$ [µs]
Channel	$h_1(t)$		$h_2(t)$	
JANUS*	0.515	0.193	0.519	0.199
Const. preamble*	0.520	0.180	0.522	0.187
LFM up-chirp*	0.613	0.235	0.568	0.250
LFM up-down-chirp	0.498	0.180	0.537	0.199

Conclusion

This paper has shown that the JANUS communication standard can be used to measure receive times precisely and thus estimate the distance between two communication nodes just as accurate as waveforms known from sonar and radar applications. Adaptations to the JANUS standard to resemble LFM chirp signals could improve the detection rate marginally, though underwater measurements or simulations with more realistic channel impulse responses are needed for a more accurate assessment. Additionally the preamble is not exclusively used for receive time estimation but also for channel and Doppler shift estimation which are both disregarded in this analysis. Taking into account that typically transmissions in practice assume a signal-to-noise ratio of ≥ 6 dB it can be concluded that an adaptation to the standard is not necessary.

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