Short Paper: Low complexity multipath and Doppler-shift correction algorithm for reliable underwater coherent-FSK acoustic modems

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ABSTRACT
This paper presents an innovative algorithm for Doppler-shift and multipath correction in a coherent-FSK modem, which is optimized for acoustic communications in shallow water underwater networks.

The final modem will be used in the ANDREA project, whose goal is to deploy a reliable network in a fish farm in Mediterranean shallow waters with both fixed and mobile nodes. As we will discuss in this scenario both multipath and Doppler-shift are critical.

On the one hand, multipath distortion is produced by echoes from the sea-bottom, the surface or submerged structures -e.g. fish farm structure. On the other hand, Doppler-shift is also very important in this case attending to the proposed scenario. Doppler-shift is produced as an effect of the relative movement between transmitter and receiver, e.g. Autonomous Underwater Vehicles (AUV); but it also can be produced by sound speed changes. All these aspects must be addressed in our system to deploy a reliable network.

Since sensor networks are formed by a large number of nodes, sensor nodes must be low cost. Moreover, as underwater system maintenance is very expensive, node battery lifetime must be extended. Thus, an optimal solution should run reliable but still low complexity algorithms in low power architectures. With this purpose a new coherent FSK modem was released last year but, unfortunately, neither optimal multipath nor Doppler-shift correction algorithms have been found for coherent-FSK modulation in the literature so far.

The aim of this paper is to find a balance between speed and complexity, as well as to reduce power consumption, but still having a reliable modem for using multi-node networks in shallow water environments. The implementation is simple and needs very low extra resources. An additional adaptive filter is needed for multipath correction and the already present FSK demodulator is reused for Doppler-shift correction. The design has been simulated in a bellhop model and experimentally tested. Results are presented in the paper.

Categories and Subject Descriptors
B.4.1 [Input/Output and Data Communication]: Data Communication Devices

General Terms
Design, Experimentation

Keywords
Underwater networks, wireless sensor networks, acoustic modem, Doppler-shift, multipath correction

1. INTRODUCTION & RELATED WORK
As underwater communications systems are getting more popular they are starting to get specialized. There is a number of applications in which requirements are for short-range, long-life, low-cost underwater communications systems, such as water pollution monitors, offshore fish farms, autonomous underwater vehicle guidance, coastal surveillance applications, etc. Generally speaking, these applications may require one or more of the following characteristics: short range underwater communications between collaborative devices; short/medium range communications between sea bottom and surface; and longer range communications between the site and land.

Examples of important research projects on wireless sensor networks in marine environments are [6][5], and for relevant ecosystems [11][3]. These point to the need for specific systems for environmental monitoring of water parameters in lakes, bays, ports, seas, and oceans. The work described in this paper falls within the ANDREA project (Automated iNspection anD Remote pErformance of mArine fish farms), in which an underwater wireless network is to be used for both water parameters monitoring and AUV navigation around a fish farm structure.

Acoustic modems have proved to be the most reliable solution to deploy underwater sensor networks, rather than optics or radio wave solutions [9]. Since acoustic propagation speed is much lower than electromagnetic waves propagation speed, multipath and Doppler-shift effects interfere.
in the acoustic signal [9][7], and should be tackled to provide reliable acoustic links.

Shallow water environment imposes many limitations to the design. The fish farm is deployed in shallow waters so the acoustic signal will be received with many echoes, and multipath correction is necessary. Also, as the acoustic signal will be used for navigation, AUV speed will induce a considerable Doppler shift that must be corrected.

Current difficulties in finding an adequate underwater acoustic modem prompted us to design an ultra-low power and low-cost modem: the ITACA modem [12]. It provides 1 kbps transmission with an 85 kHz carrier frequency using coherent-FSK for the first time. The modem only requires 11 µW on stand-by and 24 mW in data reception mode, that is the lowest power requirement reported in the literature. The presented modem showed that coherent FSK significantly improves low-power non-coherent OOK or FSK [7] modems data rate, while modem complexity, and therefore, power consumption [9] is not compromised.

Unfortunately this modem does not implement neither Doppler-shift nor multipath correction algorithms. Modems based in non-coherent modulation insert some gaps during signal transmission to avoid interferences [14] and data-rate decreases. However, coherent modulation communications -e.g. QPSK, OFDM, BPSK- need complex correction algorithms and power consumption is higher since complex DSPs and FPGAs must be used [14][1].

Since this ITACA modem is the first coherent FSK solution presented so far, there are no efficient correction algorithms designed. Thus, a new algorithm for both Doppler-shift and multipath corrections for coherent FSK modems is presented. This algorithm must be optimized to be run in low resources and low power modem architectures. The final result is a reliable modem to deploy underwater networks in scenarios as described in the ANDREA project, but still keeping the ITACA modem as a good compromise between data rate, complexity and power consumption.

This paper is organized as follows. Section 2 describes the environment set and shows this simulation results. Experimental testbed as well as the experimental results are detailed in Section 4. Finally, Section 5 concludes the paper.

2. CORRECTION ALGORITHMS

Fig. 1 shows the presented algorithm block diagram. It is based in a closed feedback loop instead of block-based Doppler-shift estimators [13]. As a general overview, the existing FSK decoder is reused and included in a feedback loop that compensates both Multipath and Doppler effects with an initial training step.

2.1 Doppler-shift correction

Doppler-shift correction is straightforward in FSK modems. In this section this assumption is presented. As described in [13], Doppler-shift can be seen as either a frequency shift or a time scaling (expansion/compression) of the signal waveform. These effects are shown in (1), where \( s(t) \) and \( r(t) \) are the source and the received signal respectively.

\[
r(t) = s((1 + \Delta) t)
\]

These effects are reflected in a frequency shift of the received signal following (2). If a FSK receiver able to actually detect incoming frequency signal is used, bit decision threshold could be adjusted to correct this frequency deviation.

This is the case of the FSK receiver presented in the first ITACA modem [12]. It is based in a Phased-Locked Loop (PLL), that is able to decode coherent FSK signals and, additionally, to calculate received signal current frequency. This block is shown in Fig. 1.

\[
f_r = (1 + \Delta)f_s
\]  

During the algorithm training state, the PLL frequency range is enlarged in order to lock the loop even when the frequency deviation produced by Doppler-shift effect is maximum. If average frequency of the source training signal is equal to its theoretical centre frequency, difference between received average frequency and theoretical centre frequency is \((\Delta \cdot f)\). This \(\Delta\) modifies received signal as shown in equations (1) and (2).

When Doppler-shift is mainly produced by relative movement between source and receiver, this relative speed can be calculated using (3) and the frequency deviation calculated using the PLL.

\[
\Delta = \frac{v_{s,r}}{c}
\]

Once the algorithm is trained, the PLL receiver centre frequency can be tuned to adapt it to the shifted received signal. PLL frequency deviation can also be reconfigured to the original ITACA modem values to increase PLL accuracy to its maximum.

It should be remarked that the symbol length also changes following (2). Thus, the bit synchronization algorithm must be informed of the new bit length. Moreover, frequency
2.2 Multipath compensation

An adaptive filter is applied on the input signal. The parameters of this filter are trained using a suitable training sequence.

As shown in Fig. 2, coefficients of the filter \( h(n) \) are iteratively calculated according to a Minimum Mean Squared Error (MMSE) Filter algorithm described in Equation (4). Once trained, error \( e(n) \) between the incoming filtered signal \( y(n) \) and a reference training pattern \( d(n) \) is minimal.

\[
h(n + 1) = h(n) + \mu u(n) e(n)
\]

The training stage finishes when the correlation between the filtered signal and the reference signal stored in the lookup table is above a pre-established threshold.

As already mentioned, Doppler-shift can produce either compression or expansion of the received signal and, consequently, affects the training sequence. To correct this effect, literature proposals are based in input signal re-sampling to reconstruct original signal based on the calculated frequency deviation. State-of-the-art implementations [13] include an interpolator to tackle this issue.

Since computational power of the ITACA platform is restricted, in this paper a new approach is explored. As proposed in the literature, some training sequence is added to the chirp in order to train the adaptive filter for multipath correction.

This proposal, no chirp tone is needed because the training sequence can also be used for Doppler shift estimation.

In this algorithm, training signal average frequency must be equal to the centre frequency to train Doppler estimator suitably. In digital binary FSK signals this condition is fulfilled with binary 50 % probability symbols condition.

In order to optimize LMS training statement, good correlation training signals are preferred. The training signal must present the autocorrelation properties shown in (5), not being correlated with itself time-shifted.

\[
\theta_{x}(l) = \begin{cases} 
N, & l = 0 \\
0, & l \in [1, N-1] 
\end{cases}
\]

This sequence can be obtained using primitive polynomials to generate Pseudo Noise (PN) sequences. The resulting training sequence fulfills characteristics for both multipath and Doppler algorithm training. The training sequence is based on a 5 bit primitive polynomials algorithm [2] with 31 states, as we will show in experimental results.

Finally, this code is FS-Keyed and Doppler shifted off-line and written in the lookup table used in the receiver training algorithm.

The rest of the frame sequence is structured as follows: bit synchronization block, start byte, length, data, CRC and stop byte. Since this frame format definition is out of the scope of this work, we will not go into further details.

In a final implementation FEC (Forward Error Correction) algorithms should be added. Nevertheless, it is also out of scope of this work.

3. ALGORITHM SIMULATION

To evaluate algorithm design and performance in early design states, ITACA modem [12] has been modelled using MATLAB.

The underwater acoustic channel is simulated using bellhop [10]. Bellhop’s ray tracing requires the solution of the ray equations to determine the ray coordinates of the acoustic signal propagation [8] and returns amplitude and acoustic pressure results for each point. Additionally, the Algarve University has improved channel response description including relative source/receiver mobility. Received signal is dopplerized according to relative receiver speed in both vertical (depth) and horizontal (distance) axis.

The model assumes an infinite signal-to-noise ratio. This assumption let us focus on Doppler and multipath compensation.

Final experimental scenario has been modelled as a 3 meter depth and 200 meter length bellhop simulation environment to obtain realistic simulation results.
The Doppler-shift and multipath correction algorithms have been also modelled in Matlab according to the descriptions of this paper.

The acoustic attenuation map calculated for this scenario is shown in Fig. 4a. Modems have been placed in six different positions. Each simulation is run ranging from -5 to +5 m/s relative receiver speed.

Fig. 4b shows the results of error probability Vs. relative speed. There are three lines: with no correction, with multipath correction and with Doppler correction. There is no line in the graphic for both corrections as the error probability in the simulations was negligible.

The Doppler correction algorithm is able to correct most of the errors. FSK receiver without Doppler correction fails on symbol decision as received frequency is shifted. However, multipath correction is still needed for some cases, specially in very short-range communications. Upper-left graphic in Fig. 4b shows that in case of 1 meter depth and 50 meter distance multipath correction it is mandatory to correct the errors due to channel response.

4. EXPERIMENTAL RESULTS

An experimental testbed has been deployed in a small craft marina. The hardware platform block diagram is shown in Fig. 5. Underwater frames are sent from one PC to another, where it is sampled and stored in a labelled file. These files can be later processed off-line using the same algorithms as designed for the simulation environment.

Generated frame electric signal generation and receiving signal acquisition is run by a ST STM32F407 ARM Cortex-M4 microcontroller connected to the PCs. To suitably generate and receive the acoustic signal, a power amplifier, a receiving analog pre-amplifier and piezoelectric transducers used in ITACA modem [12] and modelled for simulation tests have been used.

Frames are sent to a 10 meter distance with a relative movement ranging from -1 to +1 m/s. The frames received are demodulated both with and without corrections and results compared.

Messages can be decoded using the correction algorithms designed and the results are shown in Table 1. As expected from simulation, the more positive the speed is, the higher error probability is obtained.

Algorithm convergence is also analysed. Central frequency estimation and LMS algorithm error are displayed in Fig. 6. On one hand, Fig. 6a shows that the Doppler correction algorithm converges with 25 symbols - @ 1kbps - in the worst case. This effect is mainly produced by the fact that symbols 0 and 1 already have the same probability. On the other hand, LMS converges in only 4 symbols as shown in 6b even in a multipath scenario as severe as the worst case shown in simulation. To conclude, and described in Section 2.3, 31 bit PN training sequence is enough to train the receiver.

5. CONCLUSIONS AND FUTURE WORK

This paper has presented a novel algorithm for multipath and Doppler-shift effects correction in coherent-FSK acoustic modems. The main advantage of this algorithm is its low complexity, that enables its applicability in a low power
microcontroller to build long life underwater networks.

The algorithms proposed have been simulated using a bell-hop model of the underwater environment. Besides, some experimental tests have been conducted using an innovative testbed that can be used as future modem. The results show that the algorithm is feasible.

Doppler and multipath correction algorithms have been validated with signals with a high SNR (signal to noise ratio), what is a realistic scenario when emitter and receiver are within a short distance. With this assumption Doppler and multi-path have been corrected independently to other effects. The next step is to assess these algorithms in worst case scenarios, such as noisy environments in both simulation and real testbed.

The proposed correction algorithm should be run whenever channel conditions change. Currently it is run before every transmission. In future work we intend to dynamically estimate the optimum algorithm refresh rate to reduce overhead as much as possible.

6. ACKNOWLEDGMENTS

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7. REFERENCES


