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Original Research

NEAR–OPTIMUM DETECTION OF SIGNALS IN UNDERWATER ACOUSTIC NOISE USING LOCALLY OPTIMAL DETECTOR IN TIGERS RIVER

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Abstract: Signal detection has been considered important in underwater signal processing and digital communications, and depending upon noise statistics' knowledge, near-optimum signal detections in the under-water acoustic noises (UWANs) may be realised more effectively. The theory of the normal (i.e. Gaussian) noise permits using matched filter (MF) detectors; for that reason, a locally optimal (LO) detector has been designed in the present work for improving the probability of the detection (P_D) based upon knowing the probability density function (PDF) of noise. Under-water noise that has been utilized for the validation represents the real data that had been gathered from the sea with the use of the broad-band hydrophones at Abo Dali district -Kazem Al Ali Village-Tigris Beaches-Baghdad-Iraq. The LO detector performance is compared after that to conventional matched filter detectors and those have been assessed based on their P_D values. For time-varying signals, the probability of false alarms has been identified as 0.010, and a P_D of 90%, energy-to-noise ratios (ENRs) of LO are more efficient compared to the ones of Matched Filter by 4.1dB and for the signals with a fixed frequency, LO is more efficient compared to matched filter by 4.7dB.

Keywords: *Underwater acoustic noise; detection theory; student's t-distribution; non-Gaussian signal detection*

1. Introduction

Detecting signals in the existence of noise is an important issue arising in a variety of applications of signal processing, which include sonar as well as radar systems. Earlier research related to detection has considered that the signals have been included within the additive white Gaussian noise and that the receivers have been therefore modelled. On the other hand, a variety of practical noise sources, like the atmospheric noise that has been detected with the radar systems as well as the underwater acoustic noise (UWAN) that has been found with the sonar systems, are non-Gaussian and they exhibit very impulsive properties. Where those noise statistics are known, matched filter detectors are considered the optimal detector in the case where it's Gaussian noise [1, 2]. MF detector turns less than optimal in the case where noise is non-Gaussian, nonetheless, due to the degradation in the efficiency [3]. Despite this problem, and due to its simple implementations and absence of complete statistical data concerning underwater

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noise, matched filter detector is still commonly utilized for signal detection in which the noise doesn't follow the Gauss probability density function. The UWAN in the low water with the biological noise is non-Gaussian distributed, and the characteristics presented impulsive behaviour [4-6]. This is why, bub-optimum MF detector performances in the UWAN has created the considerable potential for the enhancement of the performances in underwater condition [2, 7]. Gaussian noise injection detector proposed by [8, 9]to improve the detection in underwater media using differenttime–frequency de-noising methods.

In the present work, an experimental noise model in acoustic underwater channels has been developed on the basis of the measurements of field data, and via the Monte Carlo simulation, LO detector performances in the UWAN have been compared to the conventional matched filter detectors. This study has been organized as follows. Section2 presents summarized signal model introduction and in addition to data collection and analysis approaches that are utilized for defining UWAN characteristics. Section 3 includes the description of signal detection in the t-distribution noise with the use of the LO. Section4 provides results, and Section5 present a brief discussion of conclusions.

2. Signal Detection Problem

In the present section, a common issue in the digital communications utilizing sonar and radar systems has been provided, where known signal must be found in non-Gauss additive noise channels.

2.1 Signal Model

The signals that have been utilized represent linear frequency modulated (LFM) signal and fixed frequency sinusoidal signal. Those have been utilized for representing time-varying signals and single frequency signals which might be stumbled upon in practical cases. A random sinusoidal signal might be characterized by the equation below:

$$s(n) = Acos(\theta(n)) \quad 0 \le n \le N-1 \qquad (1)$$
$$= 0 \quad \text{otherwise}$$

N represents the duration of the signal in samples, A represents the amplitude of the signal, and $\theta(n)$ represents the instantaneous phase. For the signal of fixed-frequency, instantaneous phase can be expressed as

$$\theta(n) = 2\pi f_m n T_s \qquad (1)$$

f_m represents frequency of the signal and T_s represents the period of sampling. The instantaneous phase for LFM signal can be expressed as

$$\theta(n) = 2\pi(f_m + \frac{\varphi}{2} nT_s)nT_s \qquad (2)$$

φ represents the frequency, which is characterized as $\varphi = f_{BW}/NT_s$, where f_{BW} represents signal band-width. The signal that has been received is expressed as:

$$x(n) = s(n) + v(n) \qquad (4)$$

$s(n)$ represents signal of interest and $v(n)$ represents UWAN.

The main concept of the detection is determination of existence of signal in under-water noise. Taken under consideration a vector of observation x and many hypotheses, Hi, the objective is discovering collection of the data matching a hypothesis. Even though the number of the hypotheses might be arbitrary, a case of having 2 types of hypothesis, Ho and Hl, has been viewed to be valid for the majority of the radar, sonar and communication systems [1]. As a result, the hypothesis-testing can be represented as:

H0 (Null hypothesis): $y(n) = v(n)$ (5)

$n = 0, 1, \ldots, N - 1$

H1 (Alternative hypothesis) : (6)

$y(n) = s(n) + v(n)$

$n = 0, 1, \ldots, N - 1$

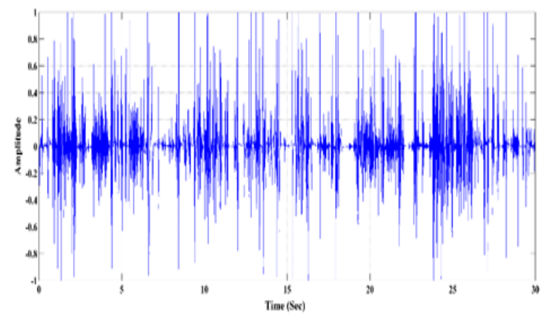
Bayesian and Neyman–Pearson (NP) approaches have been utilized fundamentally for the testing of the hypothesis. The selection of the approach is dependent upon prior probability availability, as even though the pattern recognition and digital communication systems utilize the Bayes risk [10], NP criterion has been utilized for the sonar and radar systems. In addition to that, the optimum detectors' derivation is dependent upon an assumptions that has been made concerning noise [1]. Taken under consideration that the UWAN depends upon frequencies, AWGN assumption isn't valid, and the UWAN has been modelled more properly as colored noise [5, 6, 11].

3. Collection of Data and Non-Gaussian Noise Model

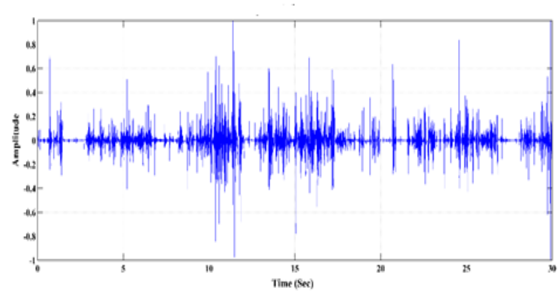
River variable measurements have been carried out in Abo Dali district -Kazim Al Ali Village-Tigris Beaches-Baghdad-Iraq. (longitude: 44. 3052168oE; Latitude: 33.5223301oN) on Nov. 1st 2020. As can be seen from in Fig. (1). Velocity of wind has been nearly 8knots, T has been 34oC, 6m deep, S = 0.4944ppt, and pH = 6.90. based on empirical formula, the obtained speed of the sound has been 1519m/s.

Figure 1. Experiment test in Abu Dali district.

Figure2 depicts time representation of obtained data at depth levels of 3m and 5m, and impulsive noise nature may be clearly noticed.



(a) Time representation at 3 meters depth.



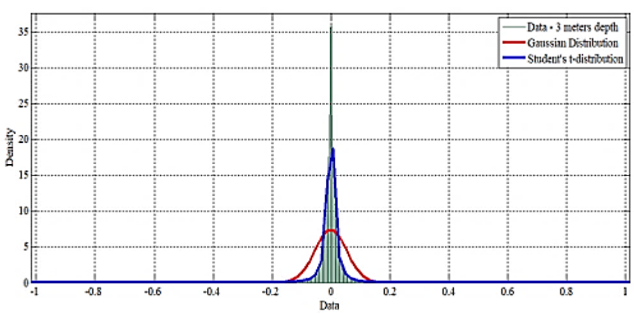
(b) Time representation at 5 meters depth.

Figure 2. Time representation of the UWAN at depths of 3 meters and 5 meters.

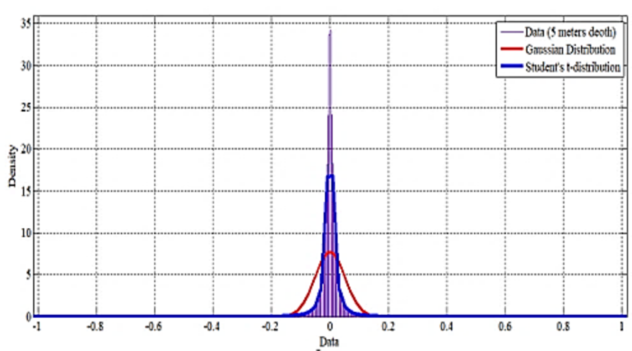
The distributions of the amplitude that have been found from collected data have been compared to Student's Gauss distribution and t distribution by the use of the tool of distribution fitting in MATLAB. As can be seen from Figure3, the results of the comparison have shown that the underwater noise pdf in general, follows Student's t distribution. Which is why, UWAN doesn't validate Gauss distribution assumption, and, obviously, distribution of noise pdf has to be fitted by t distribution. Student's t PDFs can be obtained based on [12]

$$\rho_{v,d}(v,d) = \frac{\Gamma\left[{(d+1)}/{2}\right]}{\sqrt{\pi v}\,\Gamma({d}/{2})}\left(1 + \frac{v^2}{d}\right)^{-{(d+1)}/{2}} \quad (7)$$

$\Gamma(\cdot)$ represents gamma function and d represents freedom degree controlling the distribution dispersion. The pdf that has been represented by eq. (7) has a 0 average value and variance that equals ${d}/{(d-2)}$ for $d \geq 2$.



(a) 3 meters depth.



(b) 7 meters depth.

Figure 3. Comparison of the amplitude distribution of the UWAN with the Gaussian distribution and t-distribution.

Table1 lists freedom degrees for various depth levels. UWAN may be considered as stationary [15, 16] for a brief time period, approximately few seconds.

Table 1. Degree of freedom for different depth

Depth (m)	**Analysis period (Sec)**	**Degree of freedom (v)**
3	1.15	2.38
5	1.35	2.36

From Table1, the freedom degree is approximately 3. UWAN analysis has shown that its properties aren't identical to the ones for AWGN. UWAN pdf succeeds the Student's t distribution, unlike assumption of the Gauss pdf that has been suggested in an earlier research [13].

4. Signal Detection in Non-Gaussian Distribution Noise

For the optimal detector and the near-optimal detections in the non-Gauss noise distribution, the non-linear detectors have to be utilized. A locally optimal (LO) detector has been therefore designed for the purpose of obtaining such performances, and it has been compared to the conventional matched filter.

4.1 Matched Filter

In existence of Gauss noise, matched filter detector has been considered optimum for the detection of some known signal. Which is why, several of the communication systems utilize that detector as MF. Test statistics for MF can be specified as [1]

$$T(x) = \sum_{n=0}^{N-1} x[n]s[n] \quad (8)$$

$s\,(n)$ represents reference signal and $x\,(n)$ represents observed data. Projected value ($E\{T; H_i\}$ for i=0, 1) and test statistics' variance (Var $\{T; H_i\}$ for i=0, 1) are

$$T(x) = \begin{cases} N(0\,, \sigma_v^2 . E_s) & under\ H_0 \\ N(E_s\,, \sigma_v^2 . E_s) & under\ H_1 \end{cases} \quad (9)$$

E_s represents energy of the signal and $var(v)$ represents variance of noise following t distribution as it has been presented by Eq7. The probability of the false alarm (P_{FA}) can be found based on:

$$P_{FA} = P(H_1; H_0) = P_r\{x[0] > \gamma; H_0\} = Q\left(\frac{\gamma}{(\sigma_v^2 . E_s)^{1/2}}\right) \quad (10)$$

γ represents threshold for a certain P_{FA}, and such threshold value is specified with the use of the following equation:

$$\gamma = Q^{-1}(P_{FA}).(\sigma_v^2 . E_s\,)^{1/2} \quad (11)$$

Detection probability (P_D) can be given as:

$$P_D = P(H_1; H_1) = P_r\{x[0] > \gamma; H_1\} = Q\left(\frac{\gamma - E_s}{(\sigma_v^2 . E_s\,)^{1/2}}\right) \quad (12)$$

With the use if eq. (9) and eq. (11) in eq. (12), the results becomes the equation below [1]:

$$P_D = Q\left[Q^{-1}(P_{FA}) - \sqrt{\frac{E_S}{\sigma_v^2}}\right] \quad (13)$$

4.2. Locally Optimal Detector (LO)

LO detector has been utilized for the detection of the signal in the existence of the non-Gauss noise [15 ,14] . The LO detector may be utilized for the detections of the weak signals [16,17] with the use of non-linear transfer function (NLTF) before MF detector as it has been shown in Figure4.

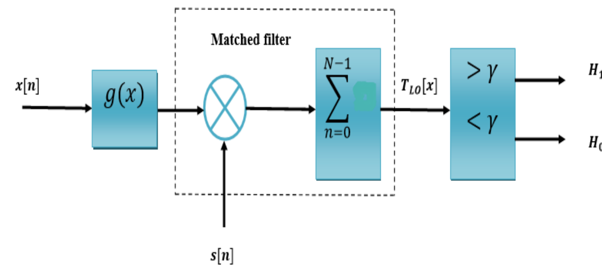


Figure 4. Schematic diagram of the LO detector for a known signal in non-Gaussian noise.

The statistic of the test for locally optimal detector has been assumed based on [1-3, 7]

$$T(x) = \sum_{n=0}^{N-1} g(x[n])s[n] \quad (14)$$

$g(x[n])$ represents NLTF which is computed from pdf of noise. Which is why,

$$g(x) = -\frac{1}{\rho(x)}\frac{d\rho(x)}{dx} \quad (15)$$

$\rho(x)$ represents pdf of the student's t-distribution as it has been characterized by Eq. (7). The function of transfer can be represented as:

$$g(x) = \frac{(d+1)x}{(d+x^2)} \quad (16)$$

for $d = 2.50$:

$$g(x) = \frac{3.5x}{(2.5+x^2)} \quad (17)$$

Characteristic transfer function has been depicted by Figure5.

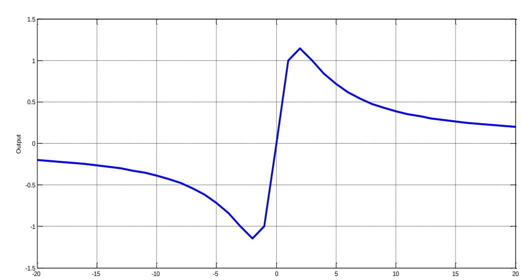


Figure 5. Nonlinear transfer function for a locally optimal detector in t-distribution noise with $\boldsymbol{d = 2.5}$.

The average and variance of $T(x)$ under H_i are [1, 7]

$$T(x) = \begin{cases} N(0, IE_s) & under\ H_0 \\ N(I\,E_s, IE_s) & under\ H_1 \end{cases} \qquad (18)$$

I is [1]

$$I = \int_{-\infty}^{\infty} \frac{\left(\frac{d\rho(x)}{dx}\right)^2}{\rho(x)} dx \qquad (19)$$

Value of I specified in eq18 has been mathematically calculated. For $d = 2.5$,

$$I = 0.2841 \int_{-\infty}^{\infty} v^2.\left(1 + \frac{v^2}{3}\right)^{-4} dv \qquad (20)$$

$$I = 0.6362 \qquad (21)$$

For any certain P_{FA}, the P_D of locally optimal detector may be represented as [7]

$$P_D = Q\left(Q^{-1}(P_{FA}) - \sqrt{I.E_s}\right) = \left(Q^{-1}(P_{FA}) - \sqrt{0.63627E_s}\right) \qquad (22)$$

5. Results

LO detector performance in detections of signal in the additive UWAN has been tested then compared to MF detection performance with the use of Monte Carlo simulations with 10000 repetitions for every one of the ENR. Over every one of repetitions, signals have been defined by Eq1 to Eq4 have been added to under-water noise for the two signal types, time-invariant and time-varying. Those signals have been utilized in the simulation, in the following way:

1. LFM signal with 400Hz starting and 1500Hz ending frequencies
2. Signal of fixed frequency with 500Hz frequency

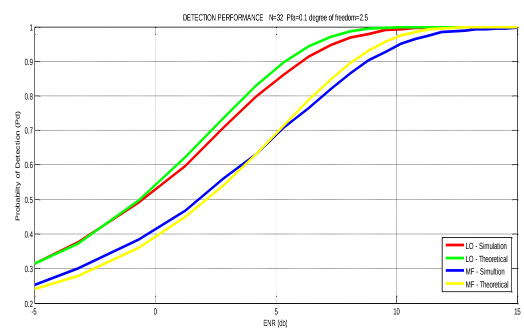
For various ENR values, simulations have been repeated through the change of signal energy whereas maintaining constant of noise power. Generally, ENR can be characterized as:

$$ENR(db) = 10\log_{10}\left(\frac{\mathrm{NA}^2}{2\sigma_v^2}\right) \qquad (23)$$

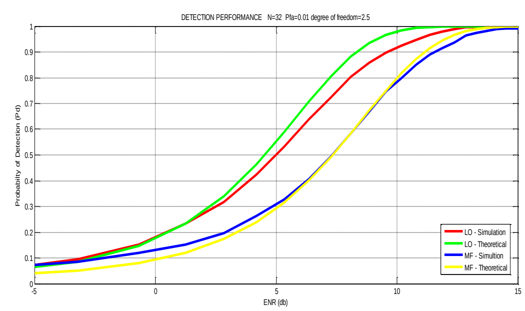
Figure6 depicts both detector performances through ENRs' range of -5dB to 15dB for signal with fixed frequency value of 500Hz with P_{FA} of 10^{-1} and 10^{-2} [7, 13]. Results have shown that locally optimal detectors are evidently more sufficient compared to MF detectors. ENRs of both detection approaches utilized and P_{FA} given a P_D of 90% have been listed in table2. Obviously, ENR of locally optimal detector is more sufficient compared to that of MF, by 4.7dB.

Table 2. The ENRs for different approaches of detection given P_D of 90% for one tone signal with 400Hz frequency.

P_{FA}	LO	MF
0.1	5.5dB	8.3dB
0.01	7.2dB	11.8dB



$(a)P_{FA} = 0.1$



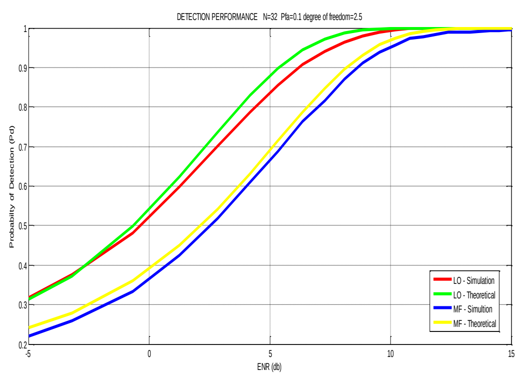
$(b)P_{FA} = 0.01$

Figure 6. Performances of the LO and MF detectors for the single-tone signal with 500 Hz frequency. $(a)P_{FA} = 0.1$. $(b)P_{FA} = 0.01$.

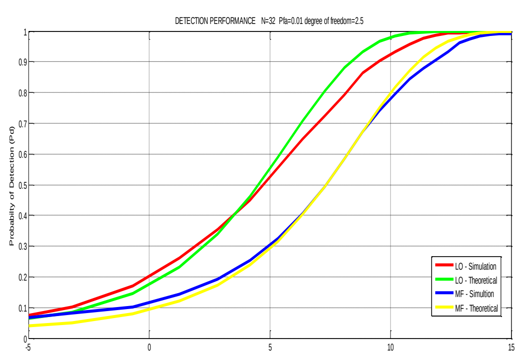
Figure7 depicts performances of the two detectors within ENR range between -5dB and 15dB for LFM signal at fixed 500Hz frequency with P_{FA} of 10^{-1} & 10^{-2} [7, 13]. Results have shown that locally optimal detectors are evidently better compared to MF detectors. ENRs of both approaches of detection utilized and P_{FA} considering P_D of 90% have been listed in table3. Evidently, ENR of locally optimal detector is superior to than that of MF, by 4.1dB.

Table 3. ENR values for different approaches of detection given P_D of 90% for the LFM signal

P_{FA}	LO	MF
0.1	5.1dB	8.1dB
0.01	8.2dB	12.5dB



$(a)P_{FA} = 0.1$



$(b)P_{FA} = 0.01$

Figure 7. The performance of the LO and MF detectors for the LFM signal.

$(a)P_{FA} = 0.1$. $(b)P_{FA} = 0.01$.

6. Conclusion

In the tropical shallow waters, UWAN emphasise the impulsive behaviour, which is why, it doesn't track normal distributions. Field data measurement analyses show that PDF of noise fits Student's t distributions successfully with 3 freedom degrees. Noise statistics knowledge, which is assisted in designing and improving proper locally optimal detector that had performed more sufficiently compared to traditional matched filter detector, as it has been presumed by probability of detection (P_D). For the time-varying signals, the specification of the probability of the false alarm of 0.01 and 90%P_D value, ENR of locally optimal detector have been superior to matched filter by 4.1dB, and for the signals of fixed frequency, locally optimal detector has been superior to matched filter by 4.7dB. Almost ideal locally optimal detector's performance has made it one of the most attractive tools for the sonar and under-water digital communications.

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Conflict of interest

The authors confirm that there is no conflict of interest.

Author Contribution Statement

All authors contributed in writing and editing this manuscript.

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