Short Data Record Filtering for Adaptive Underwater Acoustic Communications

Adam Gannon[1], Sarankumar Balakrishnan[1], George Sklivanitis[2], Dimitris A. Pados[2], and Stella N. Batalama[3]

[1]State University of New York at Buffalo, Dept. of Electrical Engineering

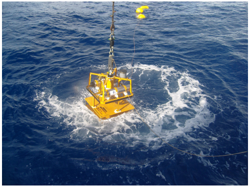
[2]I-SENSE and Dept. of Computer and Electrical Engineering & Computer Science,
Florida Atlantic University

[3]College of Engineering and Computer Science, Florida Atlantic University

9 July 2018

Motivation: Networking The Oceans

Potential impacts of underwater acoustic (UW-A) networking for sensor networks and autonomous systems are significant.



(a) Tsunami early-warning instrument deployment in South China Sea[1]

(b) Toxic algae bloom in Lake Erie which left 500,000 without drinking water in 2014[2]

(c) Autonomous underwater vehicle (AUV) for search and rescue, security, and scienfic uses[3]

---

[1] Image Credit: Van.takacs, Wikimedia

[2] Image Credit: NASA/NOAA

[3] Image Credit: Bluefin Robotics

Challenges of the UW-A Environment

UW-A presents a challenging dynamic environment:

- Significant path loss and propagation delay
- Time-varying multipath
- Large frequency and time spread

Spread spectrum signaling offers significant robustness over the multipath UW-A channel. However, static spreading code length limits achievable link data rate in favorable channel conditions.

Favorable Channel Conditions	Poor Channel Conditions
Short Spreading Length	Long Spreading Length
Maximize Data Rate	Maintain Connectivity

This work: leverage the short-data record performance of auxiliary-vector (AV) filtering, adaptively optimize code lengths.

System Model

K multiplexed users transmit unit-energy information symbols spreaded with a code sequence of length L to a common receiver over a time-varying frequency-selective UW-A channel with M resolvable paths. Received signal after downconversion and sampling

$$\mathbf{r}[i] = b_0[i]\mathbf{H}_0\mathbf{s}_0 + \sum_{k=1}^{K-1} b_k[i]\mathbf{H}_k\mathbf{s}_k + \mathbf{j} + \mathbf{n} \in \mathbb{C}^{L_M} \tag{1}$$

- $\mathbf{R} \triangleq \mathrm{E}\{\mathbf{r}[i]\mathbf{r}[i]^H\}$: input autocorrelation matrix
- $b_k[i] \in \mathcal{A}$: k-th user's information symbol from constellation $\mathcal{A}$
- $\mathbf{H}_k \in \mathbb{C}^{L_M \times L}$ $(L_M = L + M - 1)$: multipath fading matrix
- $\mathbf{s}_k \in \left\{\pm 1/\sqrt{L}\right\}^L$: binary antipodal spreading code of length L
- $\mathbf{j} \in \mathbb{C}^{L_M}$: multipath-induced inter-symbol interference
- $\mathbf{n} \in \mathbb{C}^{L_M}$: additive colored Gaussian ambient noise

Ambient Noise Model

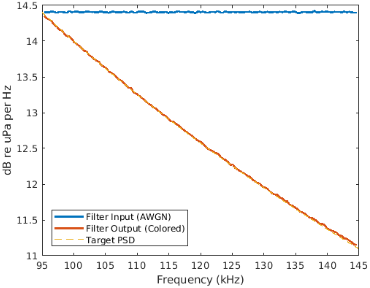
Sources of ambient underwater acoustic noise:

- Thermal Noise
- Turbulence
- Ship Traffic
- Wave Action

A good approximation noise PSD in dB re μPa/Hz

$$N_{\mathrm{AVG}}(f) = 50 - 18\log(f) \qquad (2)$$

Generated in simulation by filtering white noise.



Adaptive MVDR Filtering

Symbols recovered by applying a normalized linear filter $\hat{b}_0[i] = \underset{b \in \mathcal{A}}{\operatorname{argmin}} \left| \mathbf{w}_0^H \mathbf{r}[i] - b \right|^2$

- RAKE-matched filter (MF)

$$\mathbf{w}_0^{\|\mathrm{MF}\|} = \frac{\mathbf{H}_0 \mathbf{s}_0}{\|\mathbf{H}_0 \mathbf{s}_0\|^2}. \tag{3}$$

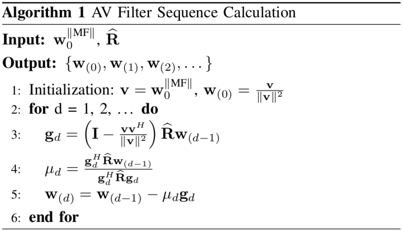
- RAKE sample matrix inversion (SMI): an unbiased estimator of the minimum variance distortionless receiver (MVDR)

$$\mathbf{w}_0^{\|\mathrm{SMI}\|} = \frac{\widehat{\mathbf{R}}^{-1} \mathbf{H}_0 \mathbf{s}_0}{\mathbf{s}_0^T \mathbf{H}_0^H \widehat{\mathbf{R}}^{-1} \mathbf{H}_0 \mathbf{s}_0}. \tag{4}$$

With the estimated autocorrelation matrix $\widehat{\mathbf{R}} = \frac{1}{N} \sum_{n=1}^{N} \mathbf{r}[n] \mathbf{r}^H[n]$ calculated by sample averaging over $N >> L_M$ signal snapshots.

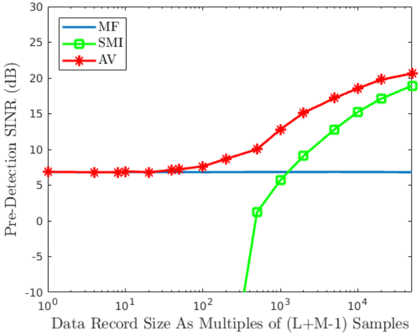
Short Data Record AV Filtering

Auxiliary-vector (AV) filter $\mathbf{w}_0^{\|\mathrm{AV}\|} = \frac{\mathbf{w}_{(\hat{d})}}{\|\mathbf{H}_0\mathbf{s}_0\|^2}$ outperforms SMI implementation of the MVDR filter for limited sample support.



Algorithm 1 AV Filter Sequence Calculation

```
Input: $\mathbf{w}_0^{\|\mathrm{MF}\|}$, $\widehat{\mathbf{R}}$
Output: $\{\mathbf{w}_{(0)}, \mathbf{w}_{(1)}, \mathbf{w}_{(2)}, \dots\}$
Initialization: $\mathbf{v} = \mathbf{w}_0^{\|\mathrm{MF}\|}$, $\mathbf{w}_{(0)} = \frac{\mathbf{v}}{\|\mathbf{v}\|^2}$
for d = 1, 2, ... do
    $\mathbf{g}_d = \left(\mathbf{I} - \frac{\mathbf{v}\mathbf{v}^H}{\|\mathbf{v}\|^2}\right)\widehat{\mathbf{R}}\mathbf{w}_{(d-1)}$
    $\mu_d = \frac{\mathbf{g}_d^H\widehat{\mathbf{R}}\mathbf{w}_{(d-1)}}{\mathbf{g}_d^H\widehat{\mathbf{R}}\mathbf{g}_d}$
    $\mathbf{w}_{(d)} = \mathbf{w}_{(d-1)} - \mu_d\mathbf{g}_d$
end for
```

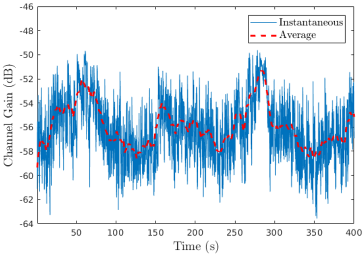


Code Length Adaptation

Goal: adaptively optimize the code length L of the user of interest to maximize link data rate, while satisfying a pre-defined BER constraint

$$\begin{aligned} \underset{L}{\text{maximize}} \quad & R(L) \\ \text{subject to} \quad & BER(L) \leq BER_{max} \\ & L_{min} \leq L \leq L_{max} \end{aligned} \tag{5}$$

with $R(L) \triangleq 1/(LT_c)$ for chip duration T_c.

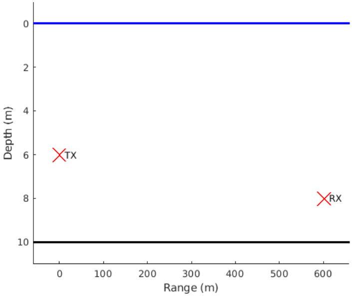


Simulations use time-varying channel realizations generated by an UW-A channel simulator.[4]

---

[4] http://millitsa.coe.neu.edu/?q=research/simulator

Feedback Considerations



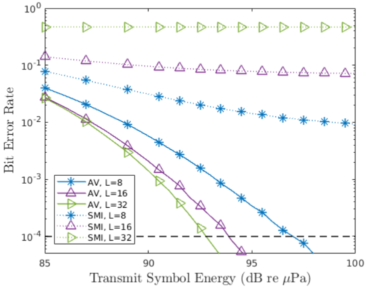
Parameter	*Value*
Bandwidth	50 kHz
Center Frequency	120 kHz
Coherence Time	1.0 s
Frame Duration	200 ms

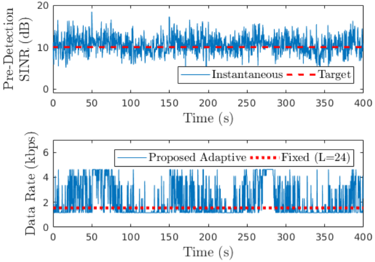
Frame duration $T_f = L \cdot N \cdot T_c$ such that round-trip time (RTT) of a data frame and its associated feedback frame does not exceed the channel coherence time $\mathrm{RTT} = 2T_{prop} + T_f + T_{feedback}$.

For a transmitter-receiver distance of d meters and $c \approx 1500\,\mathrm{m/s}$, the speed of sound in water

$$T_f \leq T_{coh} - \frac{2d}{c}. \qquad (6)$$

Performance Evaluation





- Target BER of 10^{-4} which, for our noise and channel conditions, will be satisfied with a pre-detection SINR of 10 dB.
- Estimate channel gain and select the shortest code length that satisfies target SINR of 10 dB plus a small margin (1.5 dB) for uncertainty.
- Consider a discrete set of code lengths $L \in \{8, 9, 10, 11, 12, 16, 20, 24, 28, 32\}$ and compare to static ($L = 24$).

In Summary

We run simulations of $4,000$ frames and average results over a dozen independent channel realizations. Although the average BER of both the static and adaptive schemes satisfy (within 10%) the target BER of 10^{-4}, the static scheme achieves an average throughput of 1.54 kbps and the adaptive scheme an average of 2.01 kbps, an improvement of 30.5%.

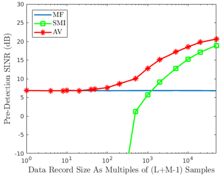
In summary

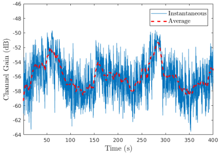
- Short data record AV filtering outperforms SMI and MF.
- Leverage AV filtering performance benefits to implement adaptive spreading code length optimization with short frames.
- Simulations[5] show adaptive spreading code length optimization can maximize data rate under pre-defined BER constraints in time varying UW-A channels.

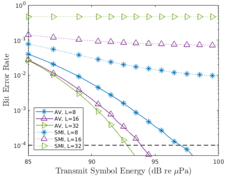
---

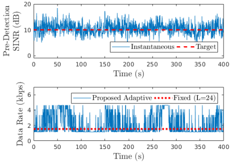
[5] Code Available: https://github.com/adamgann/av-uwa

Thank You.


MF
SMI
AV
Pre-Detection SINR (dB)
30
25
20
15
10
5
0
-5
-10
10^0
10^1
10^2
10^3
10^4
Data Record Size As Multiples of (L+M-1) Samples


Instantaneous
Average
Channel Gain (dB)
-46
-48
-50
-52
-54
-56
-58
-60
-62
-64
50
100
150
200
250
300
350
400
Time (s)


Bit Error Rate
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
AV, L=8
AV, L=16
AV, L=32
SMI, L=8
SMI, L=16
SMI, L=32
85
90
95
100
Transmit Symbol Energy (dB re μPa)


Pre-Detection SINR (dB)
20
10
0
Instantaneous
Target
0
50
100
150
200
250
300
350
400
Time (s)
Data Rate (kbps)
6
4
2
0
Proposed Adaptive
Fixed (L=24)
Time (s)