A Comparative Study of Differential and Noncoherent Direct Sequence Spread Spectrum over Underwater Acoustic Channels with Multiuser Interference

Sean Mason\textsuperscript{1}, Shengli Zhou\textsuperscript{1}, Wen-Bin Yang\textsuperscript{2}, and Paul Gendron\textsuperscript{3}

\textsuperscript{1}Dept. of Elec. and Comp. Engr., University of Connecticut, Storrs, CT
\textsuperscript{2}National Institute of Standards and Technology, Gaithersburg, MD
\textsuperscript{3}Naval Research Laboratory, Washington D.C.

September 18, 2008
Spread Spectrum Signals in UWA Communications

Two reasons for studying spread spectrum for UWA Communications

- Multi-user scenarios;
  - under water sensor networks (UWSNs)
  - underwater autonomous vehicle (UAV) networks
- Low SNR communication

We compare two variants of direct sequence spread spectrum (DSSS)

- Commonly used in UWA modems
- Favored for simplicity
- Robust to wide ranges of channel conditions
DSSS System

- Each user, $u$, assigned a pseudonoise (PN) sequence of $N_c$ chips defined as $c_u[n]$, $n = [0, 1, \ldots, N_c - 1]$:
  - $c_u[n]$ is the $n^{th}$ chip
  - elements of $c_u$ are $\pm 1$
  - the system is sampled at the chip rate

- A transmission is represented as
  \[
  x_u[n] = s_u[i]c_u[n\{\text{mod}N_c\}], \tag{1}
  \]
  where $s_u[i]$ is the $i^{th}$ information bearing symbol, lasting for $N_c$ chips (the rate of $n$ (chip rate) is $N_c$ times the rate of $i$ (data rate)).

- The signal, in the presence of noise and interference, is received as
  \[
  r[n] = \sum_u \sqrt{P_u} \sum_l h_{u}[n - \tau_u, l]x_u[n - \tau_u - l] + w[n] \tag{2}
  \]
  where
  - $h_{u}[n, l]$ is user $u$’s channel
  - $\tau_u$ is the (integer) delay of user $u$
  - $w[n]$ is additive noise
Data from UNET’06 experiment at St. Margarets Bay, Nova Scotia in May 2006

Parameters:
- bandwidth, $B = 4\text{kHz}$
- $N_c = 511$
- center frequency, $f_c = 17\text{kHz}$
- symbol duration = 127.75ms
- water depth: 60m
- transmitter/receiver distance: 3.1km
Each symbol is encoded relative to the previous symbol

The $i^{th}$ data symbol: $s_u[i] = e^{j\phi_u[i]}s_u[i - 1]$

$\phi_u[i] \in [0, \frac{2\pi}{M}, \ldots, \frac{2\pi(M-1)}{M}]$ for $M$-ary phase shift keying (PSK).

The receiver first despreads (matched filters with its own copy of $c_u[n]$):

$$y_u[n] = \sum_{k=1}^{N_c} c_u[k]r[n + \tau_u + k], \quad (3)$$

then forms the decision statistic as (using $L + 1$ channel taps)

$$z_u[i] = \sum_{l=0}^{L} y_u[iN_c + l] \cdot y_u^*((i - 1)N_c + l). \quad (4)$$

A rapidly changing channel hurts the effective SNR of the result
Each user is assigned a group of orthogonal user sequences, \( c_{g_u} \)
- \( g_u \) has \( M \) choices
- all sequences are orthogonal (including sequences from different users)

User \( u \)'s transmits the user sequence that corresponds to the current symbol:

\[
x_u[n] = c_{g_u[i]}[n\{\text{mod}N_c\}]
\] (5)

The receiver despreads as in (3), but with each of its \( M \) usercodes
- This produces \([y_{u,0}[n], ..., y_{u,M-1}[n]]\)
- The symbol decision determines which result has the most energy

\[
\hat{g}_u[i] = \arg\max_g \left\{ \sum_{n=iN_c}^{iN_c+L} |y_{u,g}[n]|^2 \right\}.
\] (6)
Bit error rate (BER) performance is compared for both systems

Given transmissions from users, \( u = \{ u, u' \} \), received in zero mean AWGN w/ variance \( \sigma^2 \)

- User \( u \) is the user you want to hear
- Users \( u' \) are interferers

BER is a function of:

- \( \text{SNR} = \frac{P_u}{\sigma^2} \) where \( P_u \) is the energy of user \( u \)'s signal at the receiver
- Signal to interference ratio: \( \text{SIR} = \frac{P_u}{\sum_{u'} P_{u'}} \)
- The level of channel coherence, \( \rho \), which is considered at the chip level
Experimental BER Results

- Solid lines: SIR = 10dB
- Dotted lines: SIR = 0dB
- No line: SIR = −5dB

- Differential has poor performance in low SIR cases
- 4-ary differential has a very high error floor

Presenter: Sean Mason
The channel model for user $u$, sampled at the chip level is $h_u[n, l]$, is a collection of impulses with random complex valued path gains.

The channel coherence coefficient, $\rho \in [0, 1]$ relates $h_u[n, l]$ to itself in an autoregressive manner:

$$h_u[n, l] = \rho h_u[n - 1, l] + v_u[n, l], \forall l$$

where $v_u[n, l]$ is noise that conserves energy.

Jakes’ model is often used to relate $\rho$ to path velocity, $v$.

$$\rho(v) = J_0(2\pi f_c v c \tau), \text{ where } \tau, \text{ in this case, is the chip duration.}$$

- $J_0$ is a zero order Bessel function of the first kind
- $c$ is the propagation speed
Case 1: No Interference/Perfect Channel Coherence

- Solid line: 2-ary
- Dotted line: 4-ary

3dB gain in performance for differential in the 2-ary case

even more gain for 4-ary
Case 2: Adding Interference/Perfect Channel Coherence

- **Solid line:**
  \[ \text{SIR} = 10 \text{dB} \]

- **Dotted line:**
  \[ \text{SIR} = 0 \text{dB} \]

- **No line:**
  \[ \text{SIR} = -10 \text{dB} \]

In 2-ary, noncoherent is a better choice for high interference cases.
Case 3: No Interference/Channel Coherence Loss

- Solid line: $\rho = 0.9988$
- Dotted line: $\rho = 0.9980$
- No line: $\rho = 0.9972$

- At about $\rho = 0.9986$, both systems have similar performance in 2-ary
- Corresponds to a velocity of 4.2m/s in a Jakes’ model
Case 4: With Interference and Channel Coherence Loss

- Solid lines: $\text{SIR} = 10\text{dB}$
- Dotted lines: $\text{SIR} = 0\text{dB}$
- No line: $\text{SIR} = -10\text{dB}$

$\rho$ is fixed at 0.9986

Interference has a worse effect on differential than noncoherent.
The differential scheme is favorable when the channel coherence is high and the multiuser interference is light.

The noncoherent scheme is favorable when the channel coherence is low and/or when the multiuser interference is severe.

Noncoherent tends to be more robust