Narrowband Interference Cancellation for Index-Modulated TDS-OFDM in Underwater Acoustic Communications

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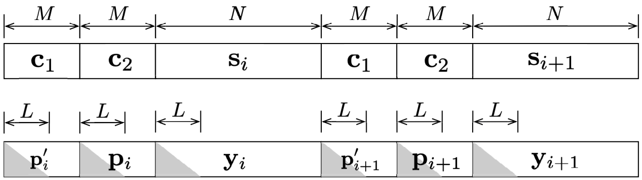
Introduction

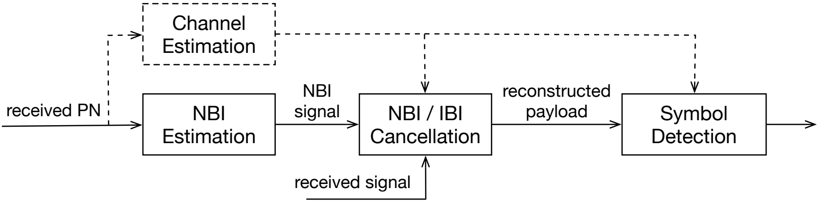
- Narrowband interference
  - Neutral and hostile interference in environment
  - Affect OFDM subcarriers
- TDS-OFDM
  - PN sequence as guard interval, high SE with no pilot in data block
  - PN sequence used for channel estimation [1] and NBI estimation [2]
- IM-OFDM
  - Information on both QAM symbols and **active subcarrier indices**
  - Proposed in UAC for improved spectral efficiency [3]
  - Could be more susceptible to NBI and demand cancellation
- Our work
  - Propose CS-based NBI estimation algorithm for dual-PN-padded TDS-OFDM system in underwater acoustic communication.
  - Derive the NBI and IBI cancellation process for payload reconstruction.
  - Evaluate NBI cancellation performance for IM-OFDM scheme.

System Diagram

- Dual-PN-padded TDS-OFDM frame structure



- Receiver structure

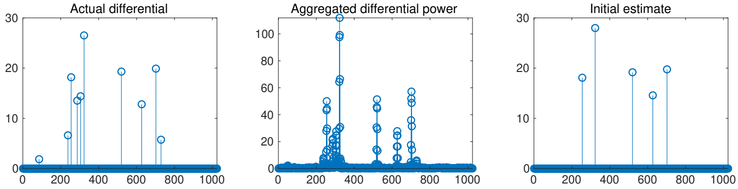


NBI Model

- Frequency domain NBI signal: $\tilde{\mathbf{e}}_i = [\tilde{e}_{i,0}\ \tilde{e}_{i,1}\ \dots\ \tilde{e}_{i,N-1}]^{\mathrm{T}}$
- Support set of K NBI sources:
  $\Omega_i = \{k | e_{i,k} \neq 0, k = 0, 1, \dots, N-1\},\ |\Omega_i| = K,\ K \leq 5\%N$
- Time-domain correlation property: Fixed support and amplitude across several frames, as NBI usually changes much more slowly.
  $\tilde{e}_{i+1,k} = \tilde{e}_{i,k} \exp(j2\pi k \Delta L / N), k = 0, 1, \dots, N-1$
- No IBI in second PN when $L < M$: $\mathbf{p}_i = \mathbf{\Phi}_{\mathrm{M}} \mathbf{h}_i + \mathbf{F}_M \tilde{\mathbf{e}}_i + \mathbf{w}_i$
- Time-domain differential of two consecutive frames:
  $\Delta \mathbf{p}_i = \mathbf{F}_M \Delta \tilde{\mathbf{e}}_i + \Delta \mathbf{w}_i$,
  where $\Delta \tilde{e}_{i,k} = \tilde{e}_{i,k}(1 - \exp(j2\pi k \Delta L / N)), k = 0, 1, \dots, N-1$
- Estimation problem to be solved by CS:
  $\Delta \hat{\mathbf{e}}_i = \min_{\Delta \tilde{\mathbf{e}}_i \in \mathbb{C}^N} ||\Delta \tilde{\mathbf{e}}_i||_1,\ \mathrm{s.t.} ||\Delta \mathbf{p}_i - \mathbf{F}_M \Delta \tilde{\mathbf{e}}_i||_2 \leq \epsilon.$

Initialization-enhanced Sparsity-adaptive Subspace Pursuit

- Sparsity K is unknown, yet trial from $K = 0$ is too complex.
  $\rightarrow$ Support Initialization + Sparsity Adaptation
- Fourier transform: $\Delta\tilde{\mathbf{p}}_i = \mathcal{F}(\Delta\mathbf{p}_i) = \mathbf{F}_N^* \Delta\mathbf{p}_i$
- Aggregate D consecutive frames: $\Delta\bar{p}_k = \sum_{j=i}^{i+D-1} |\Delta\tilde{p}_{j,k}|^2$
  Inference-to-noise ratio is enhanced.
- Search for local maxima, locate K_0 peaks, and form initial support.



Initialization-enhanced Sparsity-adaptive Subspace Pursuit

- Outer loop for sparsity adaption, inner loop [4] for iterative estimation.
- Ensure decreasing residue and terminate iteration promptly.

Input:
PN differential $\Delta\mathbf{p}_i$, observation matrix $\boldsymbol{\Psi} = \mathbf{F}_M$, initial support set $\Omega^{(0)}$ with sparsity K_0, and sparsity increase step length δ
Initialization:
$\Delta\hat{\mathbf{e}}_i^{(0)}\Big|_{\Omega^{(0)}} \leftarrow \boldsymbol{\Psi}^{\dagger}_{\Omega^{(0)}}\Delta\mathbf{p}_i$
$\mathbf{r} \leftarrow \Delta\mathbf{p}_i - \boldsymbol{\Psi}\Delta\hat{\mathbf{e}}_i$
Iteration:
for $j = 1$ to $j_{\max}$ **do**
  $T = K_0 + j\delta$
  for $k = 1$ to $k_{\max}$ **do**
    $S_k \leftarrow \max(\boldsymbol{\Psi}^{\mathrm{H}}\mathbf{r}^{(k-1)}, \delta)$
    $C_k \leftarrow \Omega \cup S_k$
    $\Omega_t \leftarrow \max(\boldsymbol{\Psi}^{\dagger}_{C_k}\Delta\mathbf{p}_i, T)$
    $\Delta\hat{\mathbf{e}}_i\Big|_{\Omega_t} \leftarrow \boldsymbol{\Psi}^{\dagger}_{\Omega_t}\Delta\mathbf{p}_i$
    $\Delta\hat{\mathbf{e}}_i\Big|_{\Omega_t^{\mathrm{c}}} \leftarrow \mathbf{0}$
    $\mathbf{r}' \leftarrow \Delta\mathbf{p}_i - \boldsymbol{\Psi}_{\Omega_t}\Delta\hat{\mathbf{e}}_i$
    if $\|\mathbf{r}'\|_2 \geq \|\mathbf{r}\|_2$ **then**
      break
    else
      $\Omega \leftarrow \Omega_t$
      $\mathbf{r} \leftarrow \mathbf{r}'$
    end if
  end for
  if $k = 1$ **then**
    break
  end if
end for
Output:
Support set Ω and reconstructed NBI differential $\Delta\hat{\mathbf{e}}_i$

NBI/IBI Cancellation

- Received signals with IBI

$$\mathbf{y}_i = \left(\begin{bmatrix} \mathcal{S}_{\mathrm{L}} \\ \mathcal{S} \end{bmatrix} + \begin{bmatrix} \mathcal{C}_{\mathrm{U}} \\ \mathbf{0} \end{bmatrix} \right) \mathbf{h} + \mathbf{F}_N \tilde{\mathbf{e}}_i'' + \mathbf{n}_i$$

$$\mathbf{p}_{i+1}' = \left(\begin{bmatrix} \mathcal{C}_{\mathrm{L}} \\ \mathcal{C} \end{bmatrix} + \begin{bmatrix} \mathcal{S}_{\mathrm{U}} \\ \mathbf{0} \end{bmatrix} \right) \mathbf{h} + \mathbf{F}_M \tilde{\mathbf{e}}_{i+1}' + \mathbf{w}_{i+1}'.$$

- Zero-padding and addition/subtraction

$$\mathbf{y}_i + \begin{bmatrix} \mathbf{p}_{i+1}' \\ \mathbf{0} \end{bmatrix} = \mathbf{H}_{N\times N} \cdot \mathbf{s} + \begin{bmatrix} \mathbf{H}_{M\times M} \cdot \mathbf{c} \\ \mathbf{0} \end{bmatrix}$$

$$+ \mathbf{F}_N \tilde{\mathbf{e}}_i'' + \begin{bmatrix} \mathbf{F}_M \tilde{\mathbf{e}}_{i+1}' \\ \mathbf{0} \end{bmatrix} + \mathbf{n}_i + \begin{bmatrix} \mathbf{w}_{i+1}' \\ \mathbf{0} \end{bmatrix}$$

$$\mathbf{y}_i + \begin{bmatrix} \mathbf{p}_{i+1}' - \mathbf{H}_{M\times M} \cdot \mathbf{c} \\ \mathbf{0} \end{bmatrix} = \mathbf{H}_{N\times N} \cdot \mathbf{s}$$

$$+ \mathbf{F}_N \tilde{\mathbf{e}}_i'' + \begin{bmatrix} \mathbf{F}_M \tilde{\mathbf{e}}_{i+1}' \\ \mathbf{0} \end{bmatrix} + \mathbf{n}_i + \begin{bmatrix} \mathbf{w}_{i+1}' \\ \mathbf{0} \end{bmatrix}$$

- Reconstructed signals

$$\mathbf{y} = \mathbf{y}_i + \begin{bmatrix} \mathbf{p}_{i+1}' - \mathbf{H}_{M\times M} \cdot \mathbf{c} \\ \mathbf{0} \end{bmatrix}$$

$$\mathbf{e} = \mathbf{F}_N \tilde{\mathbf{e}}_i'' + \begin{bmatrix} \mathbf{F}_M \tilde{\mathbf{e}}_{i+1}' \\ \mathbf{0} \end{bmatrix}$$

$$\mathbf{n} = \mathbf{n}_i + \begin{bmatrix} \mathbf{w}_{i+1}' \\ \mathbf{0} \end{bmatrix}$$

- NBI Cancellation and frequency-domain conversion

$$\mathbf{y} = \mathbf{Hs} + \mathbf{e} + \mathbf{n}$$

$$\hat{\mathbf{y}} = \mathbf{y} - \hat{\mathbf{e}} = \mathbf{Hs} + \mathbf{n}$$

$$\mathbf{F}_N^* \hat{\mathbf{y}} = \mathbf{F}_N^* \mathbf{H} \mathbf{F}_N \mathbf{F}_N^* \mathbf{s} + \mathbf{F}_N^* \mathbf{n}$$

$$\tilde{\mathbf{y}} = \tilde{\mathbf{H}} \mathbf{S} + \tilde{\mathbf{n}}$$

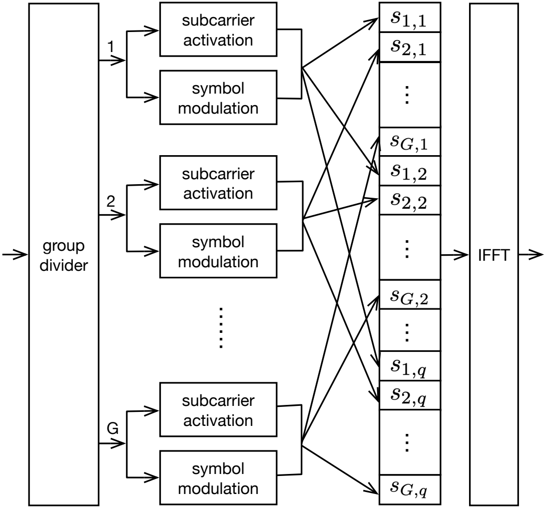
Symbol Detection

- Plain OFDM
  - ML detection

$$\hat{\mathbf{S}} = \min_{s \in \mathcal{S}_{\mathrm{QAM}}} \left\| \tilde{\mathbf{y}} - \tilde{\mathbf{H}}\mathbf{S} \right\|_2$$

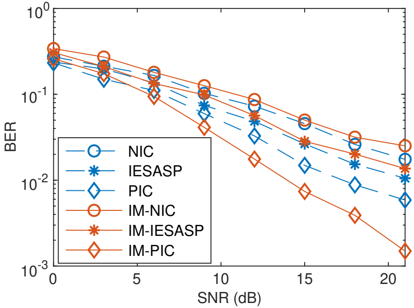
- IM-OFDM
  - Group interleaving [3]
  - ML detection of subcarrier and symbol combination

$$(\hat{\mathbf{a}},\ \hat{\mathbf{S}}_a) = \min_{\substack{\mathbf{a}_g \in \mathcal{A}_{\mathrm{IM}} \\ s \in \mathcal{S}_{\mathrm{QAM}}}} \left\| \tilde{\mathbf{y}} - \tilde{\mathbf{H}}\mathbf{S} \right\|_2$$



Simulations

- Questions
  - Is IM-OFDM more susceptible to NBI?
  - Is NBI cancellation more effective for IM-OFDM?
- Simulations
  - $N = 1024$, $M = 199$, QPSK
  - Sparse channel $L = 100$, 5 to 10 paths
  - $K = 10$, INR level $\gamma = 30$ dB



- Results: for IM-OFDM,
  - Greater gap between no cancellation and perfect cancellation.
  - Greater enhancement between NIC and proposed method.

References

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[3] M. Wen, X. Cheng, L. Yang, Y. Li, X. Cheng, and F. Ji, "Index modulated OFDM for underwater acoustic communications," *IEEE Communications Magazine*, vol. 54, no. 5, pp. 132–137, 2016.

[4] W. Dai and O. Milenkovic, "Subspace pursuit for compressive sensing signal reconstruction," *IEEE Transactions on Information Theory*, vol. 55, no. 5, pp. 2230–2249, mar 2009.

Summary

- The NBI cancellation problem is formulated for dual-PN-padded TDS-OFDM signal in underwater acoustic communication.
- The IESASP algorithm is proposed to estimate the NBI differential.
- the NBI/IBI cancellation process is derived.
- Simulation results show that proposed NBI cancellation method is more effective for IM-OFDM than for plain OFDM.

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