Transmission des mesures d’un réseau de capteurs environnementaux en bande ISM. Une approche semi-logicielle

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Context and Objectives

✓ **Context**
  - Need from the French public institution involved in the Earth Science field
    - Automatic Water quality monitoring

✓ **Current application limitations**
  - Data loggers requiring manual downloading
  - No « real time » sampling (e.g. monthly)

✓ **Objectives**
  - Design of a remote sensor network:
    - Autonomous low cost sensors
    - Central receiver in a urban area (radio frequency interference)
    - Emitter/Receiver range >10 km
    - Daily sampling
    - free Band (no fees)

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Sensor network characteristics

RF transmission
- BPSK (ISM band at 433MHz, baud rate=1200 bit/s)
- TDMA

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RFI monitoring in the 433MHz band

**Results**

- High RFI occupancy
- 95% RFI < 1s
- Average duration $\Delta T$: 30 ms
- Average bandwidth $\Delta F$: ~1.3 kHz
- Low activity during the night
Our approach: selective acquisition and off-line processing

**Specifications**
- Short data frame (<100ms)
- Daily transmission
- Don’t need a continuous reception

**Concept**
- Selective acquisition by detecting sensor transmission
- Data waveform storage
- Antenna array for spatial processing

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Antenna array model

**Hypothesis**

<table>
<thead>
<tr>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s(t)e^{i(2\pi f_0t+\varphi_0)}$</td>
</tr>
<tr>
<td>$u_k(t) = s(t - k\tau)e^{i(2\pi f_0(t-k\tau)+\varphi_0)}$</td>
</tr>
<tr>
<td>$u_k(t) = s(t)e^{-i2\pi f_0k\tau+i\varphi_0}e^{i2\pi f_0t}$</td>
</tr>
</tbody>
</table>

**Antenna output**

$z_k(t) = g_k e^{-i2\pi f_0k\tau+i\varphi_0} s(t) + n_k(t)$

**Antenna array model**

$z(t) = \begin{bmatrix} a_{s0} \\ \vdots \\ a_{sM-1} \end{bmatrix} s(t) + a_r r(t) + n(t)$

1 source $s(t)$
1 RFI $r(t)$

Far field range $> 1$km
Narrow band $\frac{\Delta f_0}{f_0} << 1$
Cyclostationary detector (1)

Cyclic autocorrelation:

\[ R_{x,x^*}^\alpha(\tau) = E\left\{ x(t + \frac{\tau}{2})x^*(t - \frac{\tau}{2})e^{-i2\pi\alpha t} \right\} \]

- **Different cyclic signatures**
  - **Source (BPSK)**
    - Baud rate \(1/T_{\text{sym}}\)
    - \(\alpha_s = \frac{k}{T_{\text{sym}}} \implies R_{s,s^*}^\alpha \neq 0\)
  - **Noise = stationary**
    - \(R_{n,n^*}^\alpha = 0\)
  - **RFI**
    - \(\alpha_r \neq \alpha_s \implies R_{r,r^*}^\alpha = 0\)

- **Multidimensional case**

\[ R_{z,z^*}^\alpha = E\left\{ z(t)z^H(t)e^{-i2\pi\alpha t} \right\} = \left( \begin{array}{c} s^H \\ a^H \\ r^H \\ n^H \end{array} \right) \left( \begin{array}{c} R_{s,s^*}^\alpha \\ R_{s,s^*}^\alpha \\ R_{r,r^*}^\alpha \\ R_{r,r^*}^\alpha \end{array} \right) \left( \begin{array}{c} s \\ a \\ r \\ n \end{array} \right) \]

\[ R_{z,z^*}^\alpha = a_s a_s^H R_{s,s^*}^\alpha \]

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Cyclostationary detector (2)

Detector criteria

- Singular value decomposition

\[ R_\alpha^{z,z^*} = \begin{bmatrix} r_{ij} \end{bmatrix} = U_c \Lambda_c V_c^H \]

- With \( \alpha = \alpha_s \), asymptotically:

\[ \Lambda_c = \begin{bmatrix} \lambda_s & 0 \\ 0 & 0 \end{bmatrix} \]

\[ \lambda_{\text{max}} \leq \text{threshold} \]

- Frobenius norm

\[ \left\| R_\alpha^{z,z^*} \right\|_F^2 = \sum_{i=1}^M \sum_{j=1}^M r_{ij}^2 = \sum_{k=1}^M |\lambda_k|^2 \]

- With \( \alpha = \alpha_s \), asymptotically:

\[ \left\| R_\alpha^{z,z^*} \right\|_F^2 = |\lambda_s|^2 \]

\[ \left\| R_\alpha^{z,z^*} \right\|_F^2 \leq \text{threshold} \]

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Simulations (1)

Detector performance evaluation

- Hypothesis
  - No transmission: $H_0 \rightarrow z(t) = \sqrt{\rho} a_r r(t) + \sqrt{1-\rho} n(t)$
  - Transmission: $H_1 \rightarrow z(t) = \sigma_s a_s s(t) + \sqrt{\rho} a_r r(t) + \sqrt{1-\rho} n(t)$

- 4 detector criteria:

- $SNR = \sigma_s^2$

- Performance criterion: Fisher criteria

$$F = \frac{(E_{H_1}[T(z)] - E_{H_0}[T(z)])^2}{Var_{H_1}[T(z)] + Var_{H_0}[T(z)]}$$

<table>
<thead>
<tr>
<th>$T(z)$</th>
<th>$R^{0}_{z,z^*}$</th>
<th>$R^{\alpha_s}_{z,z^*}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_\lambda$</td>
<td>$T_\lambda$</td>
<td>Dominant singular value</td>
</tr>
<tr>
<td>$T_F$</td>
<td>$T_F$</td>
<td>Frobenius Norm</td>
</tr>
</tbody>
</table>

Classic cyclic

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Simulations (2)

Scenario 1: 1 RFI + calibrated noise
Scenario 2: no RFI + uncalibrated noise

✓ conclusions
  - In practice, $T_F < T_\lambda$
  - Cyclostationary detectors are robust

$\mathbf{R}_{\alpha}^{\alpha_{\text{z,z}}} = \frac{1}{M} \sum_{k=1}^{M} \lambda_{N,k}^2$
Filtrage spatial

Objectifs
- Focaliser le réseau
- Annuler les brouilleurs

Méthode de Capon
- Puissance reçue
  \[ y(t) = w^H z(t) \]
  \[ P = \langle |y(t)|^2 \rangle = w^H R w \]
- Critère de Capon
  \[ \min_w \ w^H R w \]
  avec \( w^H a_s = 1 \)
- Solution
  \[ w_o = \frac{R^{-1} a_s}{a_s^H R^{-1} a_s} \]

Simulations
8 antennes, rapport signal sur brouilleur initial (en dB)

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Cyclic approach is robust against RFI and uncalibrated array

Sensor emitter and relay station have been designed

Practical tests with simple receiver (no spatial processing) have shown that long range transmission are very difficult due to RFI

Next step: implementation of the proposed approach

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Mastère Spécialisé Capteurs & Géosciences

Le sol intelligent au service de l'intelligence du sol

% de la thématique dans le MS

Milieux physiques → Capteurs → Acquisition Transmission → Analyse → Modélisation Management

En partenariat avec :

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