Pilot-Aided and Blind Equalization in FBMC Modulation for PMR Networks

Séminaire SCEE
CentraleSupélec, Campus de Rennes

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Vincent Savaux
• PMR Networks

• FBMC Modulation Scheme
  • OFDM/OQAM

• Pilot-Aided Estimation/Equalization

• Blind Equalization
What is the PROFIL project?

**PROFIL**: Evolution de la PROFessional Mobile Radio large bande basée sur la modulation FILter Bank MultiCarrier

Evolution of the Wideband PROFessional Mobile Radio Based on the FILter Bank MultiCarrier Modulation

- **ANR Project** with Cassidian, CEA-Leti, TeamCast and CentraleSupélec
- CentraleSupélec’s part: **Blind equalization in FBMC for PMR Networks**
PMR Networks

PMR : Professional Mobile Radio

- Emergency Networks for police, firefighters, ambulances …

Currently:

- Transmission of 2G-like data

<table>
<thead>
<tr>
<th>radio</th>
<th>TV</th>
<th>GSM</th>
<th>WiFi</th>
</tr>
</thead>
<tbody>
<tr>
<td>380 - 395 MHz</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Standard TETRA - TETRAPOL
PMR Networks

- Specificities

- Mobility
- Narrowband channels

UL - Uplink
DL - Downlink
P to P - Point-to-Point
Goal: transmission of broadband signal in the 380 – 395 MHz band
FBMC Modulation Scheme

- OFDM/OQAM Modem

\[ y_{m,n} = H_{m,n}x_{m,n} + j \sum_{(p,q) \in \Omega} H_{p,q} x_{p,q} < g >_{p,q}^{m,n} + w_{m,n}, \]

\[ I_{m,n} \]
FBMC Modulation Scheme

Bellanger’s filter frequency response [1]:

\[
G(f) = \sum_{k=-(K-1)}^{K-1} G_k \frac{\sin(\pi(f - \frac{k}{L_f})L_f)}{L_f \sin(\pi(f - \frac{k}{L_f}))},
\]

The subcarriers are orthogonal only in the real field.
The channel induces complex interferences from neighboring subcarriers and symbols
### FBMC Modulation Scheme

Comparison with OFDM:

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>• No cyclic prefix</td>
<td>• Modem more complex</td>
</tr>
<tr>
<td>➔ higher spectral efficiency</td>
<td>• Intrinsic interferences</td>
</tr>
<tr>
<td>• Low out-of-band interferences</td>
<td>• Specific processes at receiver</td>
</tr>
<tr>
<td>➔ better coexistence properties</td>
<td></td>
</tr>
</tbody>
</table>
**Reminder**: Channel equalization in OFDM/OQAM

\[ z = F y, \quad \Rightarrow \quad a = \Re(F y), \]

Transmitted signal \( x \)

Received signal \( y \)

Equalized signal \( a \)

**Equalizer** \( F \)
First solution: pilots are multiplexed in the data stream (1/2)

Loss of spectral efficiency

Transmitted data known at the receiver

BUT

Simple Equalization process
First solution: pilots are multiplexed in the data stream (2/2)

2 steps:
1) The channel $H$ is estimated on pilot tones
2) The signal is equalized with a one-tap per-carrier channel inversion $F = 1/\hat{H}$
Different pilot allocation methods in OFDM/OQAM [2], [3], [4] (1/4)

**POP**

- Simple implementation
- Pair of pilots (POP) [3]
- Weak performance [c1]

\[
\hat{H}_{m,n} = j \frac{\text{Im} \left\{ y_{m,n} y_{m,n+1}^* \right\}}{(-1)^m y_{m,n+1}^*}
\]

\[
MSE_{POP,2} = \frac{1}{2} \left( \sigma_H^2 + \sigma_I^2 + \sigma^2 - \frac{\alpha}{\sigma_{I,1}^2 + \sigma^2} \right)
\]

- Simple implementation
- Good spectral efficiency (same as OFDM)

- channel variance
- interference variance
- noise variance
Pilot-Aided Equalization

Different pilot allocation methods in OFDM/OQAM [2], [3], [4] (2/4)

**AP**

- **n**
- **m**
- **p**
- **a**

Auxiliary pilot (AP) [4]

Good spectral efficiency

Cancellation of the interference (elegantly)

High complexity at transmitter

\[ a = - \sum_{(p,q) \in \Omega} x_{p,q} \cdot g_{p,q}^{m,n} \]

\[ y_{m,n} = H_{m,n} x_{m,n} + j \sum_{(p,q) \in \Omega} H_{p,q} x_{p,q} \cdot g_{p,q}^{m,n} + w_{m,n} \]

\[ \hat{H}_{m,n} = \frac{y_{m,n}}{x_{m,n}} = H_{m,n} + \frac{w_{m,n}}{x_{m,n}} \]
Different pilot allocation methods in OFDM/OQAM [2], [3], [4] (3/4)

**IAM**

$\begin{array}{c}
\text{I}\text{AM-R} [2]: p^- = \pm 1, p = \pm 1, p^+ = -p^- \text{ and } a = 0, b = 0.
\end{array}$

\[ y_{m,n} = H_{m,n} x_{m,n} + j \sum_{(p,q) \in \Omega} H_{p,q} x_{p,q} < g >_{p,q}^m + w_{m,n}, \]

\[ y_{m,n} \approx H_{m,n} (x_{m,n} + jC'_{m,n}) + I_{m,n} + w_{m,n}, \]

\[ \hat{H}_{m,n} = \frac{y_{m,n}}{x_{m,n} + jC'_{m,n}} = H_{m,n} + \frac{w_{m,n}}{x_{m,n} + jC'_{m,n}} \]
Different pilot allocation methods in OFDM/OQAM [2], [3], [4] (4/4)

**IAM**

- Reduction of the noise and interference energy
- Simple implementation
- Loss of spectral efficiency
- Good performance [c1]

\[
\hat{H}_{m,n} = \frac{y_{m,n}}{x_{m,n} + jC'_{m,n}} = H_{m,n} + \frac{w_{m,n}}{x_{m,n} + jC'_{m,n}}
\]
LMMSE in OFDM/OQAM [c2], [c3]

\[ J_{MMSE} = E\{\|H_n - \theta y_n\|_F^2\} \]

\[ \hat{H}_n^{LMMSE} = (R_{HH} + x_n^{-1} R_{IH} (x_n^H)^{-1}) (R_{HH} + x_n^{-1} R_{II} (x_n^H)^{-1})^{-1} \]

\[ + R_{HI} (x_n^H)^{-1} + x_n^{-1} R_{IH} + (x_n x_n^H)^{-1} \sigma^2 I_p \]

\[ \times (H_n + x_n^{-1} I_n + x_n^{-1} w_n). \]

\[ \hat{H}_n^{LMMSE} = R_{HH} \left( R_{HH} + \sigma^2 (d_n d_n^H)^{-1} \right)^{-1} \hat{H}_n \]

OFDM-like
Pilot-Aided Equalization

Some results: Typical urban (TU) channel, 3 km.h$^{-1}$, no channel coding
Application to PMR band: some changes in the LTE PHY parameters [c4] (1/3)

From LTE parameters ...

<table>
<thead>
<tr>
<th>Transmission bandwidth</th>
<th>1.4 MHz</th>
<th>3 MHz</th>
<th>5 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT size</td>
<td>128</td>
<td>256</td>
<td>512</td>
</tr>
<tr>
<td>Useful subcarriers</td>
<td>72</td>
<td>180</td>
<td>300</td>
</tr>
<tr>
<td>Resource blocks</td>
<td>6</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Effective bandwidth</td>
<td>1.080 MHz</td>
<td>2.700 MHz</td>
<td>4.500 MHz</td>
</tr>
</tbody>
</table>

... to proposed LTE-like parameters

<table>
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<th>Transmission bandwidth</th>
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<th>3 MHz</th>
<th>5 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT size</td>
<td>512</td>
<td>1024</td>
<td>2048</td>
</tr>
<tr>
<td>Useful subcarriers</td>
<td>217</td>
<td>541</td>
<td>901</td>
</tr>
<tr>
<td>Resource blocks</td>
<td>18</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>Effective bandwidth</td>
<td>1.085 MHz</td>
<td>2.705 MHz</td>
<td>4.505 MHz</td>
</tr>
</tbody>
</table>

More flexibility
Pilot-Aided Equalization

Application to PMR band: some changes in the LTE PHY parameters [c4] (2/3)

1. LTE pilot distribution
2. Proposed rectangular distribution

- 1 RB in LTE
- 1 RB in proposed scheme
- 15 KHz
- 5 KHz
-added subcarrier

a. LTE pilot distribution
b. Proposed rectangular distribution
Pilot-Aided Equalization

Application to PMR band: some changes in the LTE PHY parameters [c4] (3/3)

- Channel estimation along the whole band
- More flexibility
- Good channel estimation over each sub-band
Pilot-Aided Equalization

Some results (1/2): achieved bit rate

- 4-QAM symbols, 3 MHz bandwidth
- reference in OFDM in LTE: 4.8 Mbits.s⁻¹

- Proposed scheme:

<table>
<thead>
<tr>
<th>AP</th>
<th>$N_τ$</th>
<th>IAM</th>
<th>$N_τ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>$N_f$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4.49</td>
<td>5.08</td>
<td>5.14</td>
</tr>
<tr>
<td>4</td>
<td>4.95</td>
<td>5.25</td>
<td>5.27</td>
</tr>
<tr>
<td>6</td>
<td>5.1</td>
<td>5.32</td>
<td>5.32</td>
</tr>
<tr>
<td>$N_f$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4.19</td>
<td>4.8</td>
<td>4.91</td>
</tr>
<tr>
<td>4</td>
<td>4.65</td>
<td>5.02</td>
<td>5.09</td>
</tr>
<tr>
<td>6</td>
<td>4.9</td>
<td>5.15</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Similar to LTE

Enable high bit rate applications, as video streaming
Some results (1/2): achieved BER
- 4-QAM, no channel coding
Second solution: **blind equalization**

→ Iterative processus, without pilot

- Goal: achieve $H.F = 1$
- Constraint: limited knowledge of the signal feature
Second solution: **blind equalization**

- **Iteration 0**: Initial state
- **Transient state**
- **Steady state**

- Gain in terms of bit rate
- Requires a convergence delay
Blind Equalization

Basics (1/2), [5], [6], [7]:

- Goal: Solve the optimization problem

\[ F_{opt} = \min_{F} J(a) \]

- How? Use the stochastic gradient

\[ F_{m,n+1} = F_{m,n} - \mu \phi(a_{m,n}) \]

with

\[ \phi(a_{m,n}) = \frac{\partial J(a_{m,n})}{\partial F_{m,n}} \]

- \( \mu \) is the step-size parameter
- \( J \) a given cost function

[2 degrees of freedom]
Blind Equalization

Basics (2/2), [5], [6], [7]:

Cost function: Constant modulus algorithm [5], [6]

\[ F_{m,n+1} = F_{m,n} - \mu p y_m^* a_m,n |a_m,n|^p \gamma (|a_m,n|^p - \gamma) \]

with \( p \): another degree of freedom

Transient state = 1000 OFDM/OQAM symbols!
Some results: blind equalization in mobile environment (1/2)

\[ \text{MSE} = (1/M).\sum(|x|-|a|)^2 \]

\[ \text{SNR} = 20 \text{ dB} \]

Fast increase
Some results: blind equalization in mobile environment (2/2)

Blind equalization does not track the channel variations
Any solutions? … Yes!

Several ways are investigated:

\[ F_{m,n+1} = F_{m,n} - \mu \phi(a_{m,n}) \]  
Can be reconsidered [c5]

\[ F_{m,n+1} = F_{m,n} - \mu p y_{m,n}^* a_{m,n} |a_{m,n}|^{p-2} |a_{m,n}|^p - \gamma \]  
Can be adapted to OFDM/OQAM [c6], [c7]

New blind receiver design
Contributions:

[c1] V. Savaux, F. Bader, “Mean Square Error Analysis and LMMSE Application for Preamble-Based Channel Estimation in OFDM/OQAM Systems,”
Thanks for your attention!

Merci de votre attention!

Des questions?