Study on channel equalization for OFDM/OQAM

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Introduction

- Multi-carrier modulation: OFDM (the reference) => Wifi, DVB-T, ADSL . . . .

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- Multi-carrier modulation: OFDM/OQAM.
- Problem: multipath channels.
- Equalization: counteract the channel effects.

Outline

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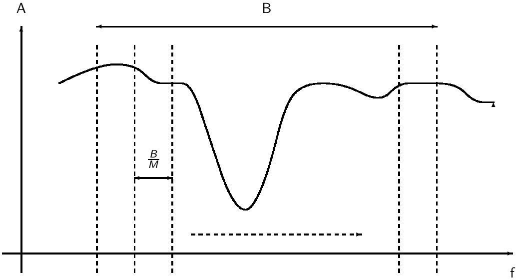
1. Multi-carrier modulation
   - Principle
   - Modulation OFDM
   - Modulation OFDM/OQAM
2. Problem statement
3. Equalization method
4. Results

Multi-carrier modulation: principle

- Parallel data transmission.
- Low data rate in each subchannel.
- Well-suited for frequency selective channels.

Frequency selective channel



B: bandwidth, A: attenuation and M: carrier number.

OFDM/QAM

Baseband signal:

$$s(t) = \frac{1}{\sqrt{T_0}} \sum_{m=0}^{M-1} \sum_{n=-\infty}^{+\infty} c_{m,n} \Pi(t - nT_0) e^{j2\pi m F_0 t}$$

with $\Pi(t) = \begin{cases} 1 & si \;\; -\frac{T_0}{2} \leq t < \frac{T_0}{2}, \\ 0 & sinon. \end{cases}$

$c_{m,n}$: complex symbols (M-QAM).

$F_0 = \frac{1}{T_0}$: subcarrier spacing.

T_0: duration of complex symbols.

Modulation CP-OFDM

Problem: multipath channel => intersymbol interference.

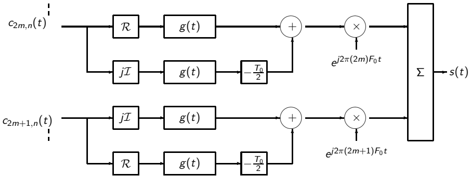
Solution: insertion of a guard interval => CP-OFDM (Cyclic Prefix).

Drawback: loss of spectral efficiency.

OFDM/OQAM

- OFDM/OQAM: another choice.
- Pulse shape: well-localized in time-frequency.
- No guard interval.
- No loss of spectral efficiency.
- Transmission of real valued symbols.

Modulation



$c_{m,n}$: complex symbols (M-QAM).

T_0: duration of complex symbols.

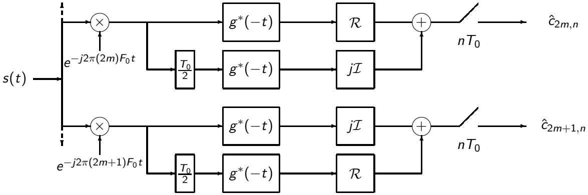
F_0: subcarrier spacing.

$g(t)$: pulse shape.

The baseband continous-time OFDM/OQAM signal:

$$s(t) = \sum_{m=0}^{N-1} \sum_{n} \left(c^{\mathcal{R}}_{2m,n} g(t - nT_0) + jc^{\mathcal{I}}_{2m,n} g(t - (nT_0 + \frac{T_0}{2})) \right) e^{j2\pi(2m)F_0t}$$
$$+ \left(c^{\mathcal{R}}_{2m+1,n} g(t - (nT_0 + n\frac{T_0}{2})) + jc^{\mathcal{I}}_{2m+1,n} g(t - nT_0) \right) e^{j2\pi(2m+1)F_0t}$$

Demodulation



$$\hat{c}^{\mathcal{R}}_{2m,n} = \mathcal{R}e\left\{\int_{-\infty}^{+\infty} s(t) \times g^*(t - nT_0)e^{-j2\pi(2m)F_0 t}dt\right\}$$

$$\hat{c}^{\mathcal{I}}_{2m,n} = \mathcal{I}m\left\{\int_{-\infty}^{+\infty} s(t) \times g^*(t - (nT_0 + \frac{T_0}{2}))e^{-j2\pi(2m)F_0 t}dt\right\}$$

OFDM/OQAM: general expression

The baseband continous-time OFDM/OQAM signal:

$$s(t) = \sum_{m=0}^{M-1} \sum_{n \in \mathbf{Z}} a_{m,n} \underbrace{g(t - n\tau_0) e^{j2\pi m F_0 t}}_{g_{m,n}(t)} e^{j\phi_{m,n}}$$

with,

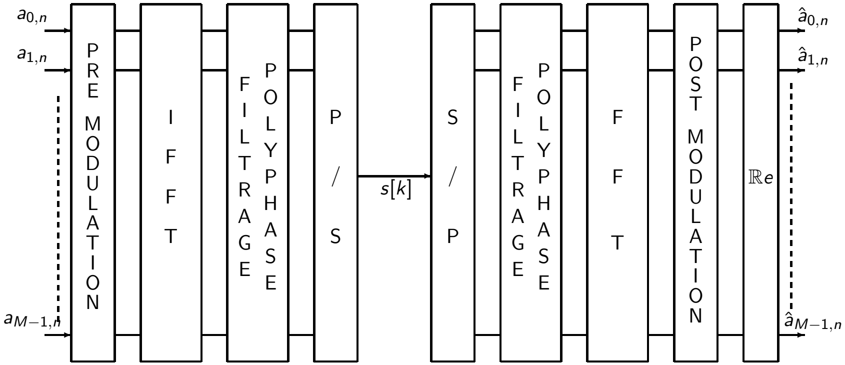
- $a_{m,n}$: real symbols being transmitted = real or imaginary part of QAM constellation symbols.
- $\tau_0 = \frac{T_0}{2}$.
- Phase term: $\Phi_{m,n} = \Phi_0 + \frac{\pi}{2}(m+n)$ with Φ_0 arbitrarily chosen.
- g: prototype filter.

Demodulated symbols:

$$\hat{a}_{m,n} = < s, g_{m,n} >_{\mathcal{R}}$$

Discret-time OFDM/OQAM: modem

Digital modem OFDM/OQAM



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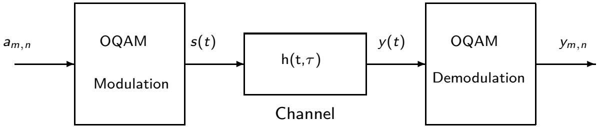
2. Problem statement
3. Equalization method
4. Results

Multipath channel



Received signal : $y(t) = (h \otimes s)(t)$.

Demodulated symbol y_{m_0,n_0} at the (m_0, n_0) position:

$$
\begin{aligned}
y_{m_0,n_0} &= \int_{\mathbb{R}} y(t) g^*_{m_0,n_0} dt \\
&= \sum_m \sum_n a_{m,n} e^{j(\Phi_{m,n} - \Phi_{m_0,n_0})} \int_{\mathbb{R}} \int_0^{\Delta} g(t - n\tau_0 - \tau) g(t - n_0\tau)^* \\
&\quad \times e^{j2\pi(m-m_0)F_0 t} h(t,\tau) e^{j2\pi m F_0 \tau} d\tau dt
\end{aligned}
$$

Problems & solutions

Problems:

- Intersymbol interferences.
- Intercarrier interferences.

Solutions: channel equalization

- Zero forcing (ZF).
- Interferences cancellation: EIC method [1] (Equalization with Interference Cancellation).

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   - Zero forcing (ZF)
   - Equalization with Interference cancellation
   - Equalization with Interference cancellation: computational complexity
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ZF equalization (1/2)

Assumptions:

- A flat fading happens over each sub-carrier.
- $g(t - \tau - n\tau_0) \approx g(t - n\tau_0)$ sur $\tau \in [0, \Delta]$.

Demodulated signal y_{m_0,n_0} at the (m_0, n_0) position:

$$y_{m_0,n_0} = H_{m_0} a_{m_0,n_0} + \underbrace{\sum_{(m,n)\neq(m_0,n_0)} a_{m,n} H_m < g_{m_0,n_0}, g_{m,n} >}_{I_{m_0,n_0}}$$

ZF equalization (2/2)

Equalized signal y_{m_0,n_0} at the (m_0, n_0) position:

$$\frac{y_{m_0,n_0}}{H_{m_0}} = a_{m_0,n_0} + \sum_{(m,n)\neq(m_0,n_0)} a_{m,n}\frac{H_m}{H_{m_0}} < g_{m_0,n_0}, g_{m,n} >$$

Estimated symbol:

$$\hat{a}_{m_0,n_0} = a_{m_0,n_0} + \mathcal{R}e\{I_{m_0,n_0}\}$$

If the prototype filter is well-localized [2]: $\mathcal{R}e\{I_{m_0,n_0}\} \approx 0$

Equalization with Interference cancellation (EIC)

The approximations are no longer satisfied when :

- Large delay spread.
- Large QAM constellation.

=>Equalization with Interference cancellation developed by Hao LIN [1].

Now, we take into account:

- $g(t-\tau-n\tau_0) \neq g(t-n\tau_0)$
- $\mathcal{R}e\{I_{m_0,n_0}\} \neq 0.$

Demodulated signal

The demodulated signal:

$$y_{m_0,n_0} = a_{m_0,n_0} \int_0^{\Delta} h(\tau) e^{-j2\pi m_0 F_0 \tau} A_g(-\tau, 0) d\tau + J_{m_0,n_0}$$

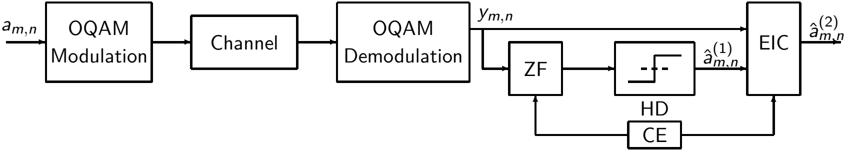
with J_{m_0,n_0} the interference term:

$$\begin{aligned} J_{m_0,n_0} &= \sum_{(m,n)\neq(m_0,n_0)} a_{m,n} e^{j(\Phi_{m,n}-\Phi_{m_0,n_0})} e^{j\frac{\pi}{2}(m-m_0)(m_0+n)} \\ &\times \int_0^{\Delta} h(\tau) e^{-j\pi(m_0+m)F_0\tau} A_g[(n_0-n)\tau_0 - \tau, (m-m_0)F_0] d\tau \end{aligned}$$

where A_g is the ambiguity function:

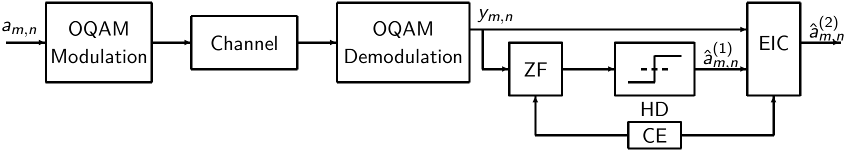
$$A_g[\tau, \mu] = \int_{\mathbb{R}} g(t+\frac{\tau}{2}) g(t-\frac{\tau}{2}) e^{j2\pi\mu t} dt$$

Step 1



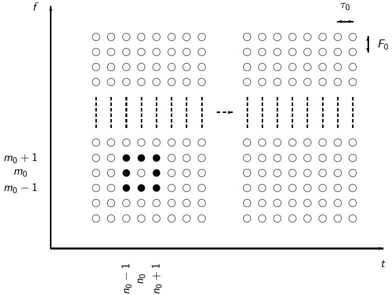
$$\hat{a}^{(1)}_{m,n} = HD\left[\mathcal{R}e\left\{\frac{y_{m_0,n_0}}{\hat{H}_{m_0}}\right\}\right]$$

Step 2



$$\hat{a}^{(2)}_{m_0,n_0} = \mathcal{R}e\left\{\frac{y_{m_0,n_0} - \hat{J}_{m_0,n_0}}{\int_0^{\Delta}\hat{h}(\tau)e^{-j2\pi m_0 F_0 \tau}A_g(-\tau,0)d\tau}\right\}$$

Interference term: calculation



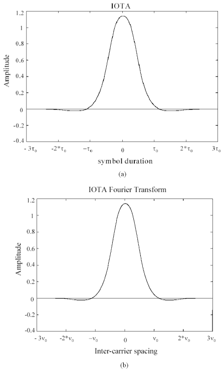
$$\hat{J}_{m_0,n_0} = \sum_{(p,q)\in\Omega^*_{(1,1)}} \hat{a}^{(1)}_{m_0+p,n_0+q} e^{j\frac{\pi}{2}(p+q)} \times e^{j\frac{\pi}{2}p(2n_0+q)}$$

$$\times \int_0^{\Delta} \hat{h}(\tau) e^{-j\pi(2m_0+p)F_0\tau} \times A_g[-q\tau_0-\tau, pF_0] d\tau$$

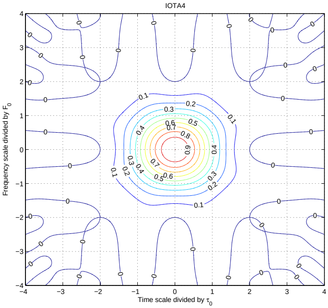
Example IOTA4

IOTA (Isotropic Orthogonal Transform Algorithm) prototype filter of length $4T_o$.

Time/frequency response:



Ambiguity function:



Computational complexity

- A reduced neighborhood around (m_0, n_0) position.
- A_g computed off-line.
- Interference term computed with FFT algorithm.
- Complexity for 1-tap neighborhood $\Omega^*_{(1,1)}$:
  - On-line: $O(M)$.
  - Off-line: $\frac{9}{2}M \times log_2(L_h)$.

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   - Over PLC channel
   - Over test channel

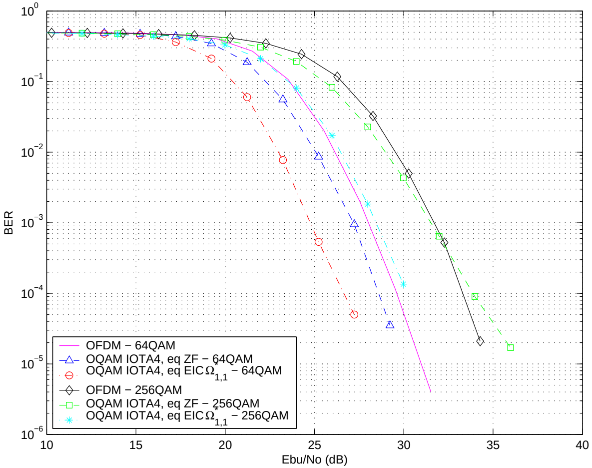
Simulations parameters

Parameters	Values
Sampling frequency	$10 \ Mhz$
FFT size	$M = 128$
Symbol duration	$T_0 = 12.8 \ \mu s$
Frame length	$20 \ T_0$
Prototype function	IOTA4.
Real estimation	IAM2 [2]
Convolutional coding	$rate = 1/2; \ K = 7; \ (133, 177)_o$
CP-OFDM	$GI = 9 \ samples \ (0,9 \ \mu s)$

Zimmermann channel [3] (4 paths):

- Delays (μs): 0;0,4;0,6;0,7.
- Power profile (linear): 0,2;0,1;0.02;0.01.

BER: CP-OFDM & OFDM/OQAM over PLC channel



Simulation parameters

Parameters	Values
Central frequency	1 *Ghz*
Bandwidth	10 *Mhz*
Sampling frequency	10 *Mhz*
FFT size	$M = 128$
Symbol duration	$T_0 = 12.8\ \mu s$
Frame length	20 T_0
Prototype filter	IOTA4.
Estimation	perfect.
Constellation	64 QAM.
Convolutional coding	$rate = 1/2;\ K = 7;\ (133, 177)_o$

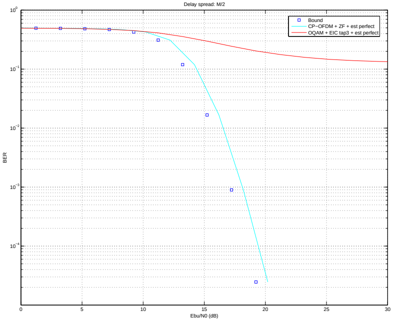
BER results (1/2)

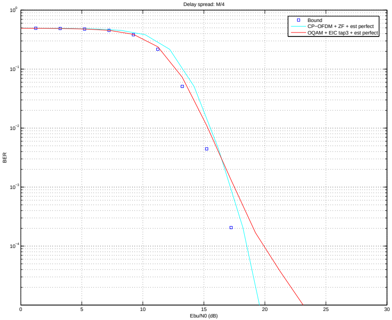
Delay spread M/2

- Delays (μs): 0;1,6.
- Power profile (in dB): -4;-15.

Delay spread M/4

- Delays(μs): 0;2,2.
- Power profile (in dB): -4;-15.

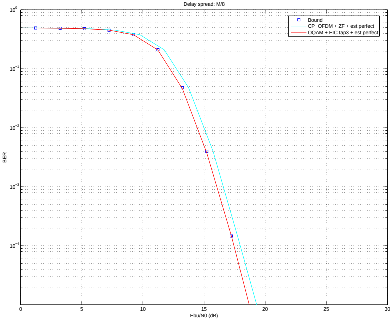




BER results (2/2)

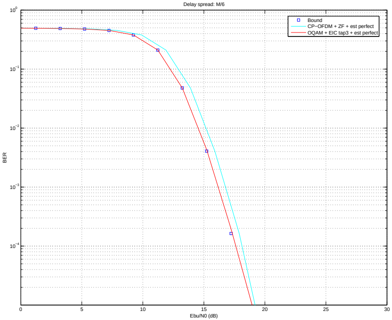
Delay spread M/8

- Delays(μs): 0;6,4.
- Power profile (in dB): -4;-15.



Delay spread M/6

- Delays(μs): 0;3,2.
- Power profile(in dB): -4;-15.



Conclusion

=> We have checked the efficiency of an equalization procedure with interference cancellation (EIC).

- Good efficiency of EIC over PLC channel with large constellations (64 QAM, 256QAM).
- EIC uses fast algorithm (FFT).

=> A comparison between OFDM/OQAM with EIC and CP-OFDM with ZF has been made.

- EIC removes totally the interference like CP-OFDM
- No loss of spectral efficiency.

Questions ?

Référence

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[3] M. Zimmermann and K. Dostert
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