Why Looking for Beyond OFDM in 5G Wireless Network Systems?

CentraleSupélec

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What drives 5G ?

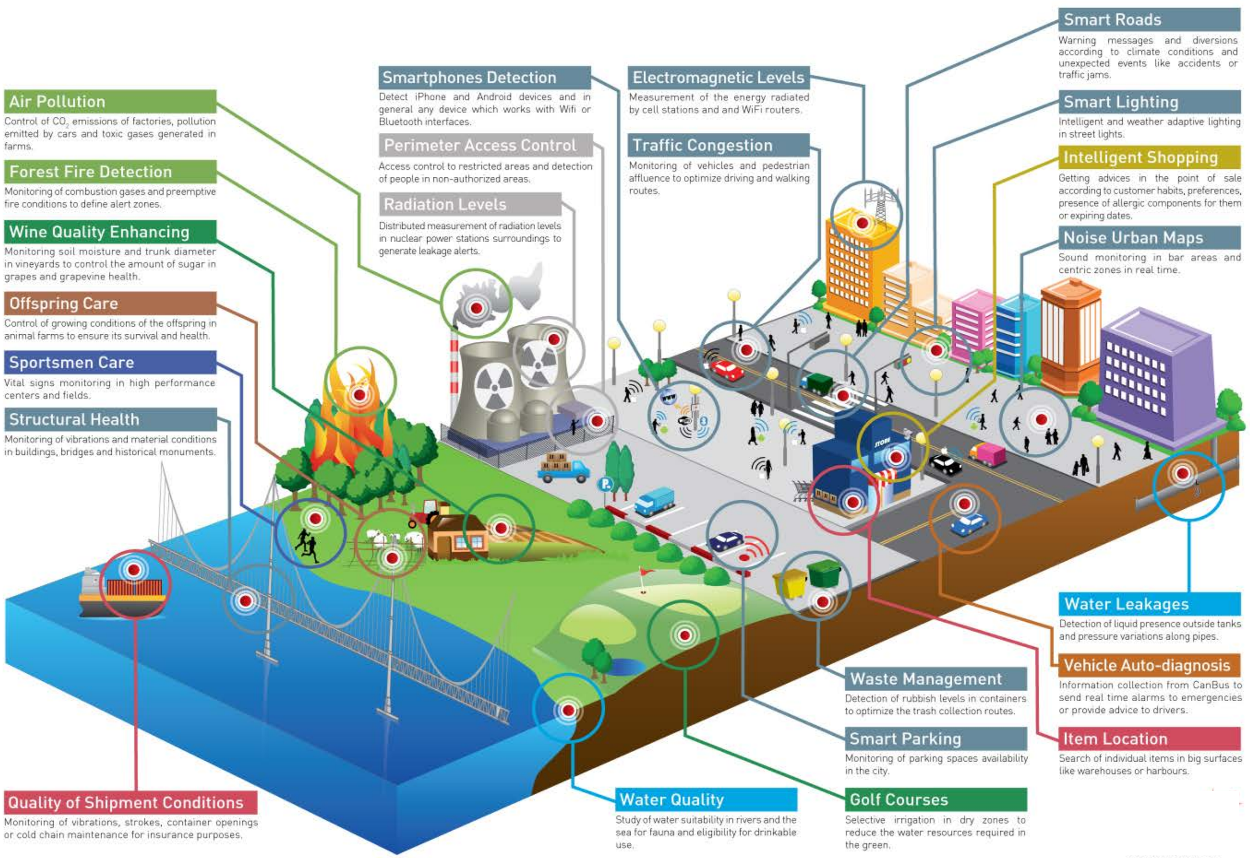
Gigabit Wireless Connectivity

- Examples: 3D video streaming, large crowd gatherings

2002

2013

Internet of Things (IoT)



Source: Libelium

Internet of Things (IoT)

- Connecting the things of every day life, scalable connectivity for billions of devices

Cost below 10$

Coverage (deep indoor)

Battery (10 years)

„Plug&secure“, human in the loop

Tactile Internet (TI)

100ms

10ms

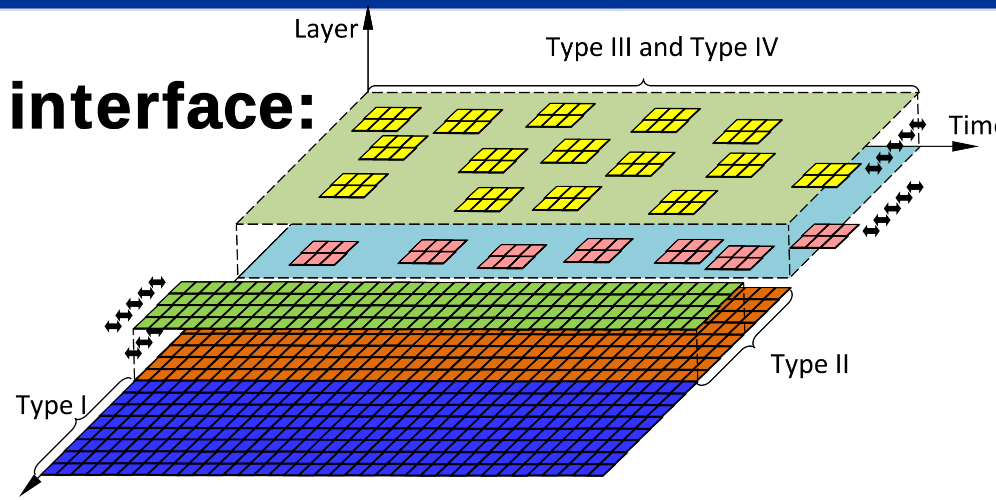
1ms

100 µs latency on physical layer!

Future integrated air interface

Future (5G) integrated air interface:

Efficiently combine various types of service and performance classes within a radio frame (from small packet service to high rate ‘bit-pipe’)



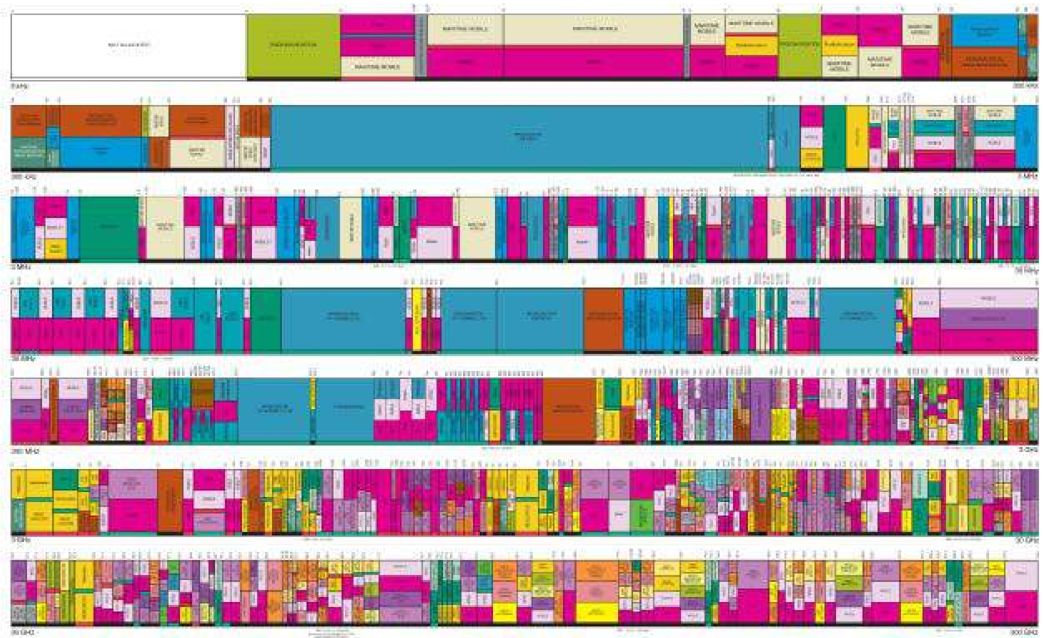
Traffic Type	Synch?	Access Type	Properties
I	closed-loop	scheduled	classical high volume data services
II	open-loop	scheduled	HetNet and/or cell edge multi-layered high data traffic
III	open-loop	sporadic, contention-based	few bits, supporting low latency, *e.g. smartphone apps*
IV	open-loop/none*	contention-based	energy-efficient, high latency, few bits

***: none for maximal energy savings at Tx, open-loop for reduced complexity at Rx**

*Source: Gehard Wunder/5GNOW

Fragmented Spectrum

- ***Spectrum paradox***: spectrum scarce and expensive but underutilized!
- EC Digital Agenda forces the systems to deal with fragmented spectrum and white spaces communication



Application Challenges

Wireless Access:

- Flexible
- Scalable
- Fast
- Robust
- Reliable
- Efficient (energy, spectrum)

MC techniques

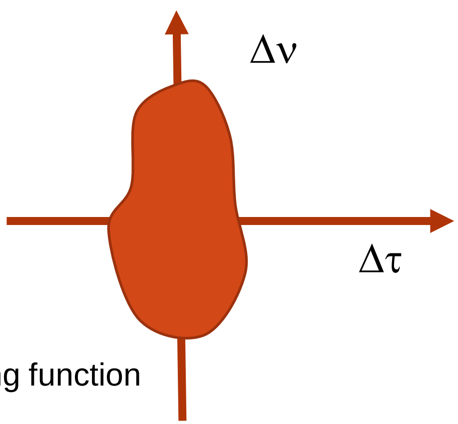
- Multicarrier Communications (MC) are promising techniques in Cognitive Radio CR
- Moreover, MC based systems can meet the spectrum shape requirements by deactivating (i.e. nulling) the subcarriers where the PU is currently transmitting or the subcarriers that can potentially interfere with other users.
- The multicarrier systems offers very flexible multiple access and spectral allocation of the available spectrum which can be performed by a secondary system without any extra hardware complexity (really ?).
- Several parameters can be adjusted in the system like subcarrier spacing, subcarrier number, modulation, coding and powers.

Pulse/Carrier Shaping

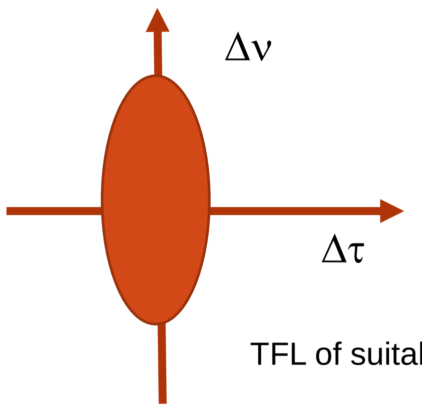
A good signal waveform should be compactly supported and well localized in time and in frequency with the same time-frequency scale as the channel itself:

$$\frac{\tau_0}{\Delta\tau} = \frac{\nu_0}{\Delta\nu}$$

where $\Delta\tau$ and $\Delta\nu$ is the rms (root-mean-square) delay spread and frequency (Doppler) spread of the wireless channel, respectively



Channel scattering function



TFL of suitable pulse shape

Rectangular Function

The rectangular prototype function is a possible choice and can be a benchmark for comparison. A time shift has to be applied to ensure the even function property, as shown in

$$g(t) = \begin{cases} \frac{1}{\sqrt{\tau_0}}, |t| \leq \frac{\tau_0}{2} \\ 0, \quad elsewhere \end{cases}$$

By interchanging time and frequency axes, the dual of the rectangular function becomes a natural extension, which is defined in the frequency domain as follows

$$G(f) = \begin{cases} \frac{1}{\sqrt{\nu_0}}, |f| \leq \frac{\nu_0}{2} \\ 0, \quad elsewhere \end{cases}$$

with its inverse Fourier transform $\longrightarrow$ $g(t) = \frac{sin(\pi\nu_0\, t)}{\pi t\sqrt{\nu_0}}$

a longer duration in the time domain, the implementation and equalization complexity is considerable even after proper truncation.

Pulse Shaping, II

Half Cosine Function

A conventional prototype function in OFDM/OQAM system is the half cosine function which is defined by

$$g(t) = \begin{cases} \frac{1}{\sqrt{\tau_0}} cos \frac{\pi t}{2\tau_0}, |t| \leq \tau_0 \\ 0, \quad elsewhere \end{cases}$$

Dual form defined by its Fourier Transform

$$G(f) = \begin{cases} \frac{1}{\sqrt{\nu_0}} cos \frac{\pi f}{2\nu_0}, |f| \leq \nu_0 \\ 0, \quad elsewhere \end{cases}$$

Could be extended to any real even function whose *G(f)* satisfies

$$\begin{cases} |G(f)|^2 + |G(f-\nu_0)|^2 = {}^1/_{\nu_0}, & |f| \leq \nu_0 \\ G(f), & otherwise \end{cases}$$

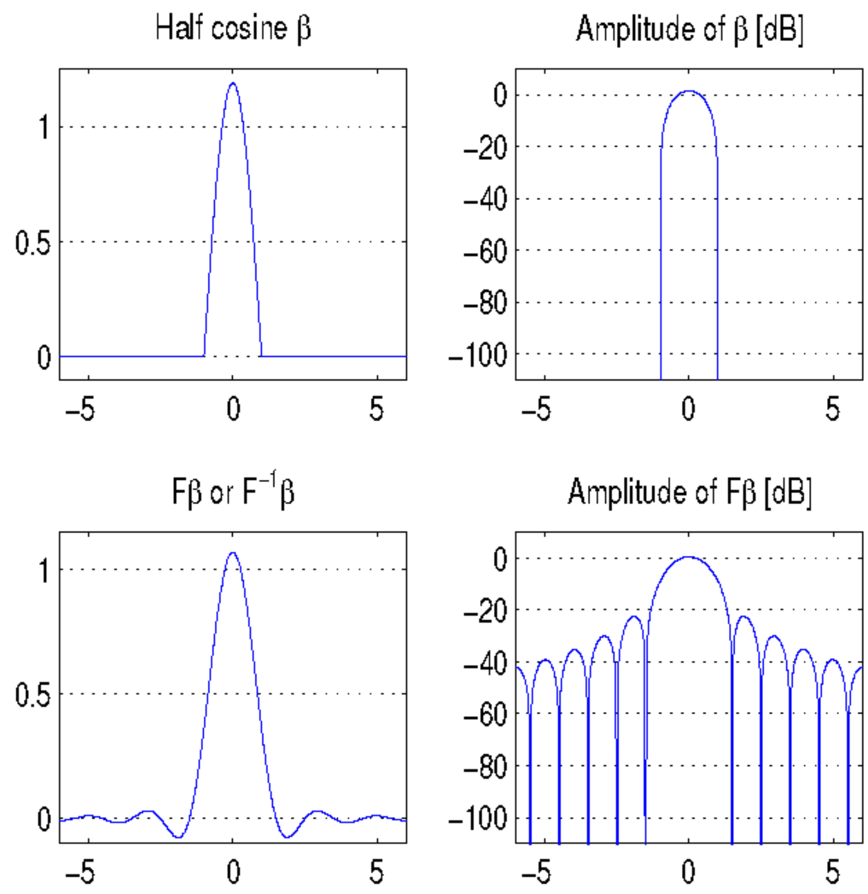


Figure: Half cosine function and its Fourier transform

Gaussian Function

Gaussian function is very famous for its Fourier transform that maintains the same shape as itself except for an axis scaling factor. For a Gaussian function

$$g_\alpha(t) = (2\alpha)^{1/4} e^{-\pi\alpha t^2}, \alpha > 0$$

Its Fourier transform is

$$\mathcal{F}_{g_\alpha}(t) = (2\alpha)^{1/4} \int_{-\infty}^{\infty} e^{-\pi\alpha t^2} e^{-j2\pi f t}\, dt$$

$$= \left(\frac{2}{\alpha}\right)^{1/4} e^{-\pi\frac{f^2}{\alpha}} = g_{1/\alpha}(t)$$

The basis generated by Gaussian prototype function is in no way orthogonal as $g(t) > 0$ holds on the whole real axis.

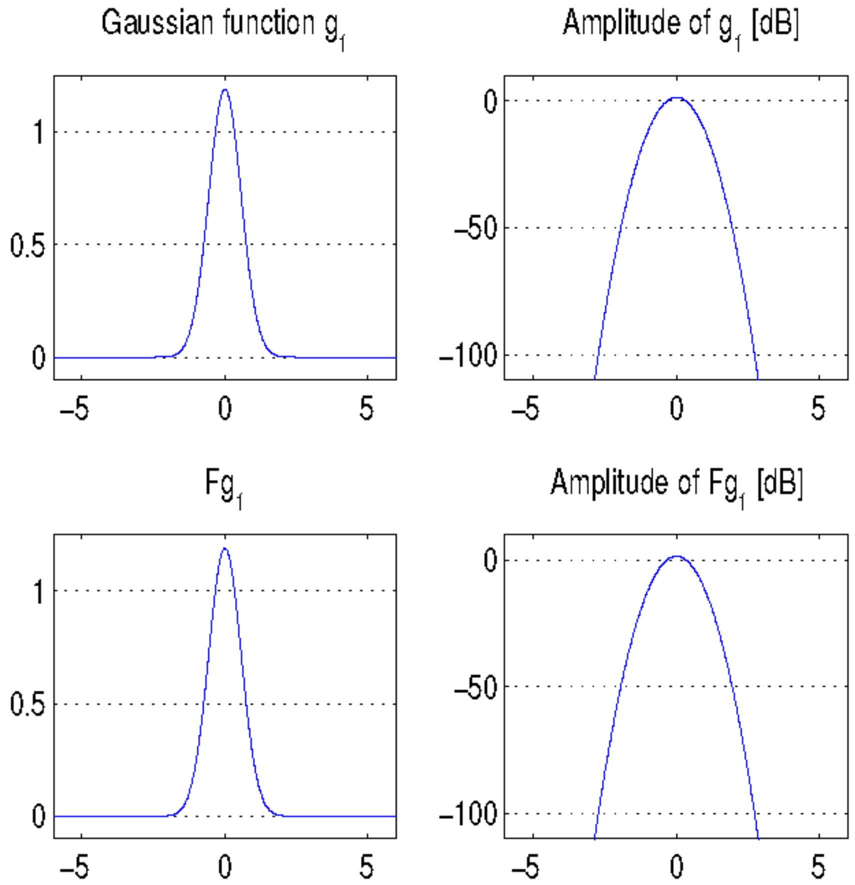


Figure: Gaussian function with $\alpha = 1$ and its Fourier transform.

Pulse Shaping, IV

Isotropic Orthogonal Transform Algorithm (IOTA) Function

Define O_a as the orthogonalization operator on function $x(t)$ according to the following relation $\mathrm{O}_a = \frac{x(t)}{\sqrt{a \sum_{k=-\infty}^{\infty} |x(t-ka)|^2}}, a > 0$

The effect of the operator O_a is to orthogonalize the function $x(t)$ along the frequency axis, which can be seen directly on the ambiguity function

The resulting function $\mathrm{O}_a x(t) = y(t)$ and its frequency shifted versions construct an orthonormal set of functions.

$$A_y\left(0, \frac{m}{a}\right) = 0, \forall m \neq 0 \text{ and } A_y(0,0) = 1$$

Similarly, in order to orthogonalize $x(t)$ along the time axis,

$$y(t) = \mathcal{F}^{-1}\, \mathrm{O}_a \mathcal{F}\, x(t)$$

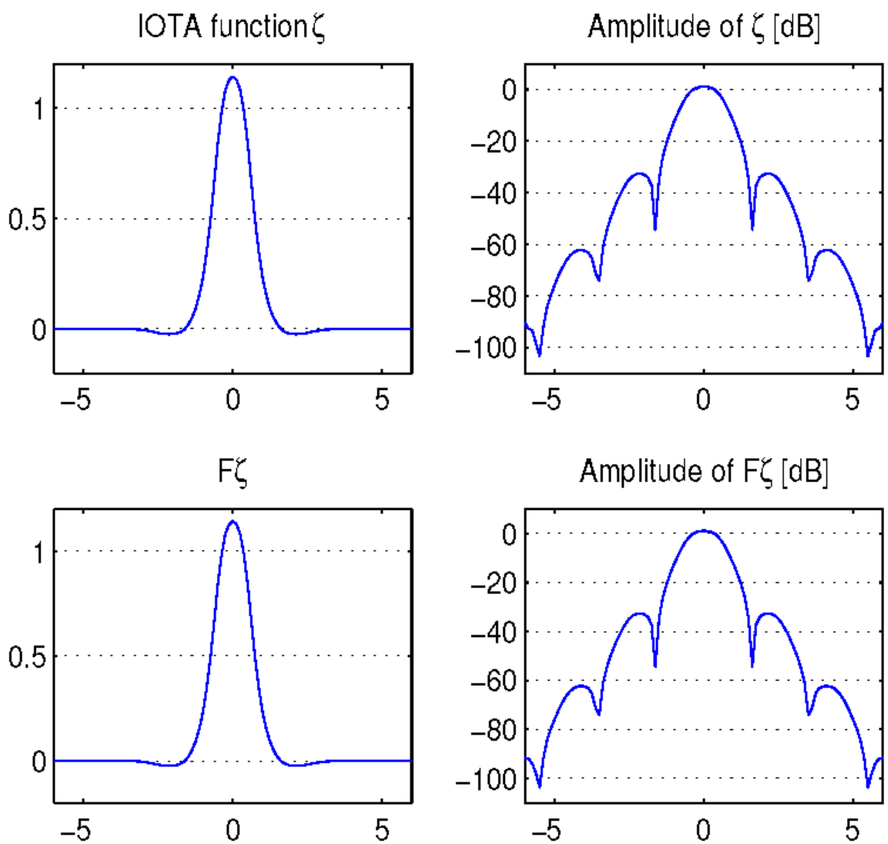


Figure: IOTA function and its Fourier transform

Pulse Shaping, V

Starting from the Gaussian function $g_\alpha(t) = (2\alpha)^{1/4} e^{-\pi\alpha t^2}, \alpha > 0$ by applying O_{τ_0} we get $y_\alpha(t) = O_{\tau_0} g_\alpha(t)$ and

$$A_y\left(0, \frac{m}{\tau_0}\right) = 0, \forall m \neq 0 \; and \; A_y(0,0) = 1$$

$y_\alpha(t)$ is orthogonal to its frequency shifted copies at multiple of m/τ_0

→ Then we apply $\mathcal{F}^{-1} O_\nu \mathcal{F}$ to $y_\alpha(t)$, we get

$$z_{\alpha,\nu_0,\tau_0} = \mathcal{F}^{-1} O_{\nu_0} \mathcal{F}\, y_\alpha(t) = \mathcal{F}^{-1} O_{\nu_0} \mathcal{F}\, O_{\tau_0} g_\alpha(t) = O_{\tau_0} \mathcal{F}^{-1} O_{\nu_0} \mathcal{F} g_\alpha(t)$$

and $$A_z\left(\frac{n}{\nu_0}, \frac{m}{\tau_0}\right) = A_z(2n\tau_0, 2m\nu_0) = 0, \forall (m,n) \neq (0,0)$$

where the first equality comes from the fact that $\tau_0\nu_0 = 1/2$ and the second equality is the straightforward result of time and frequency orthogonalization

$$\mathcal{F} z_{\alpha,\nu_0,\tau_0} = \mathcal{F}\mathcal{F}^{-1} O_{\nu_0} \mathcal{F}\, y_\alpha(t) = O_{\nu_0} \mathcal{F}\, y_\alpha(t) = O_{\nu_0} \mathcal{F}^{-1}\, y_\alpha(t)$$

$$= O_{\nu_0} \mathcal{F}^{-1} O_{\tau_0} g_\alpha(t) = O_{\nu_0} \mathcal{F}^{-1} O_{\tau_0} \mathcal{F} g_{1/\alpha}(t) = z_{1/\alpha,\nu_0,\tau_0}$$

$\alpha = 1, \tau_0 = \nu_0 = \frac{1}{\sqrt{2}}$, we define $\zeta(t) = z_{1,\frac{1}{\sqrt{2}},\frac{1}{\sqrt{2}}}$ then we have $\mathcal{F}\zeta = \mathcal{F} z_{1,\frac{1}{\sqrt{2}},\frac{1}{\sqrt{2}}} = \zeta$

M. Alard, C. Roche, and P. Siohan, "A New family of function with a nearly optimal time-frequency localization " Technical report of the RNRT Project *Modyr*, 1999.

MC: comparative features

CP-OFDM:

$$\Phi_{\text{OFDM}}(f) = T_{\text{OFDM}} \left(\frac{sin(\pi f T_{\text{OFDM}})}{\pi f T_{\text{OFDM}}} \right)^2$$

Where: $T_{OFDM} = T + \Delta$

PHYDYAS:

$$\Phi_{\text{PHYDYAS}}(f) = \sum_{k=-(K-1)}^{k=(K-1)} G_k^2 \frac{\sin\left(\pi\left(f - \frac{k}{NK}\right)NK\right)}{NK\sin\left(f - \frac{k}{NK}\right)}$$

Where: K is the overlapping factor and the coefficients G_k depends on K. When $K = 4$, G_k are given by:

$$G_0 = 1, G_1 = 0.971960, G_2 = 1/\sqrt{2}$$

$$G_3 = \sqrt{1 - G_1^2}, G_k = 0; 4 < k < L - 1$$

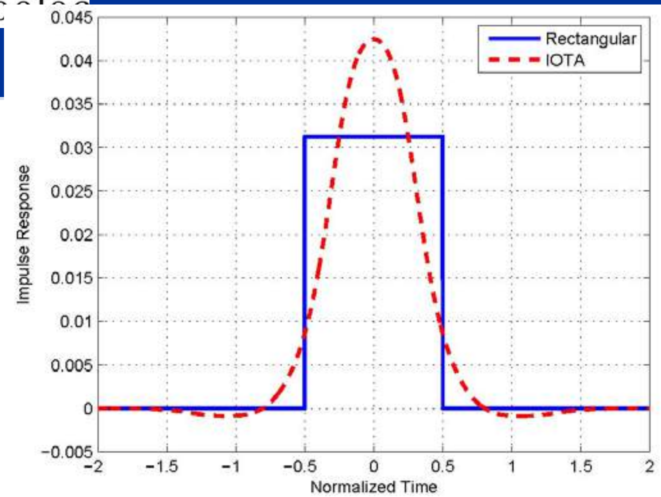
IOTA:

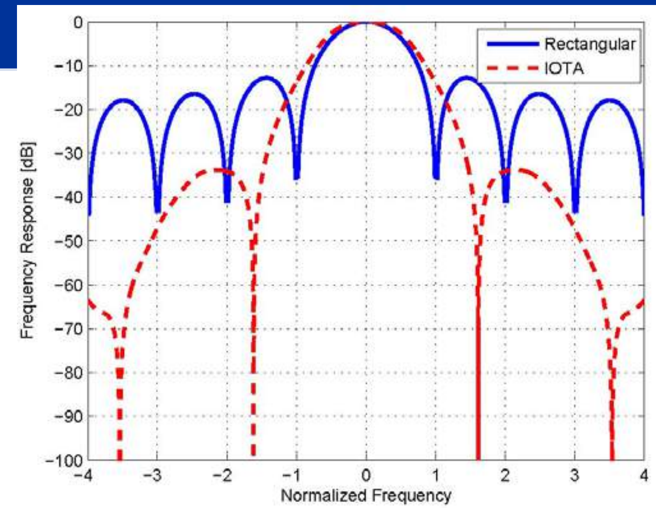
$$\Phi_{\text{IOTA}}(f) = g^2_{1,\sqrt{2}/2,\sqrt{2}/2}(t)$$

We recall that $g_{1,\frac{\sqrt{2}}{2},\frac{\sqrt{2}}{2}}(t)$ is the IOTA impulse response.

MC: comparative features

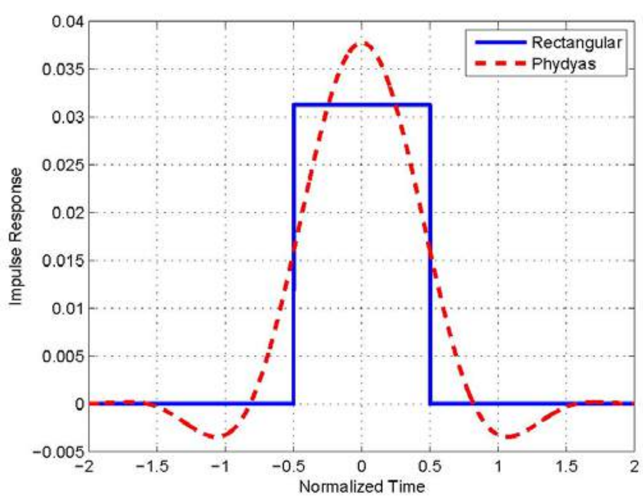
Extended Gaussian Function (**EGF**)

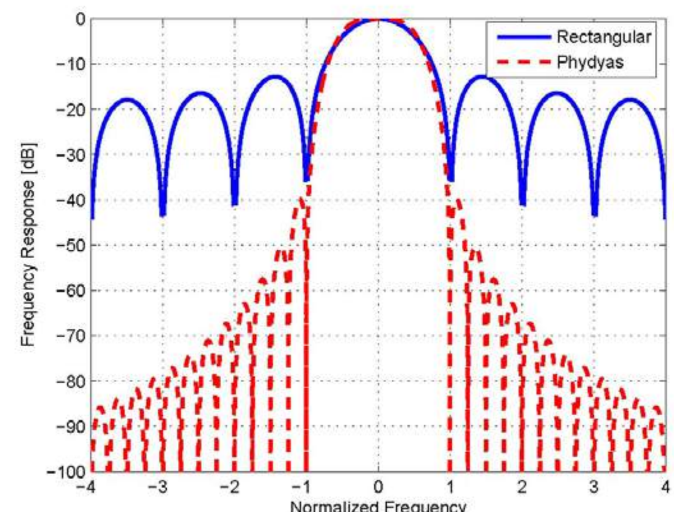




P. Siohan and C. Roche, "*Cosine-Modulated Filterbanks based on Extended Gaussian Functions*," IEEE Trans. Signal Processing, vol. 48, no. 11, pp. 3052 – 3061, Nov. 2000.

PHYDYAS Prototype Filter





M.G. Bellanger, "*Specification and Design of a Prototype Filter for Filter Bank based Multicarrier Transmission*," in IEEE Int. Conf. on Acoustics, Speech, and Signal Processing, 2001. Proceedings. (ICASSP '01)., May 2001, vol. 4, pp. 2417 –2420.

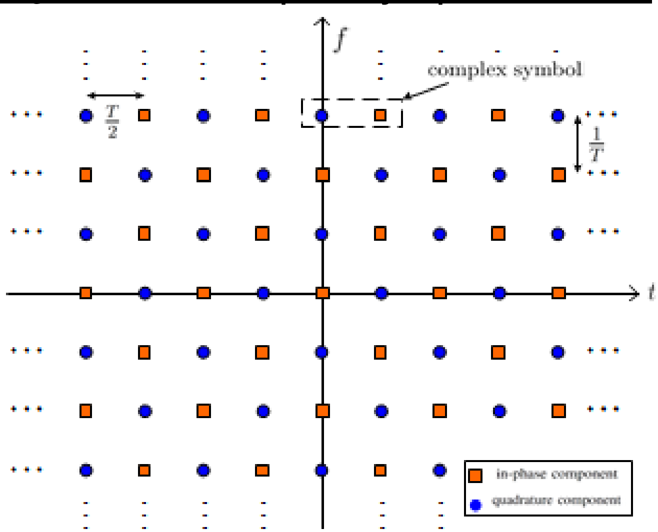
Filter Bank Multicarrier-FBMC/OQAM

- Balian-Low theorem: It is not possible to get a prototype function being well-localized in time and frequency, and satisfying in the meantime the orthogonality condition and a symbol density of one.

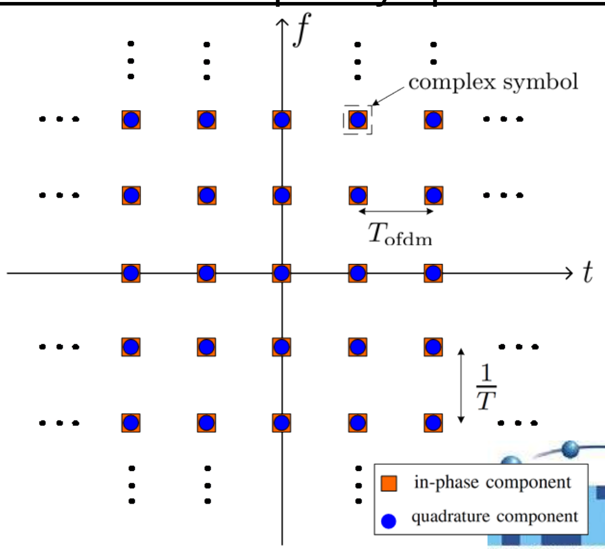
- OQAM: Saltzberg showed that by choosing a root-Nyquist filter with symmetric impulse response and by <u>introducing a half symbol period delay between the in-phase and quadrature components of QAM symbols</u>, it is possible to achieve baud-rate spacing between adjacent subcarriers and still recover the information symbols, free of ISI and ICI.

orthogonality in the real domaine

<u>OQAM time/frequency space lattice</u>



<u>CP-OFDM time/frequency space lattice</u>



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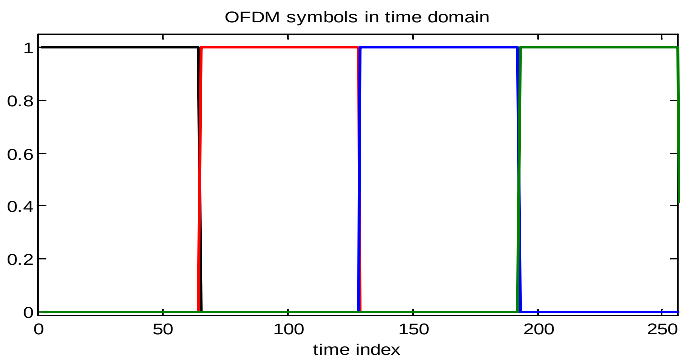
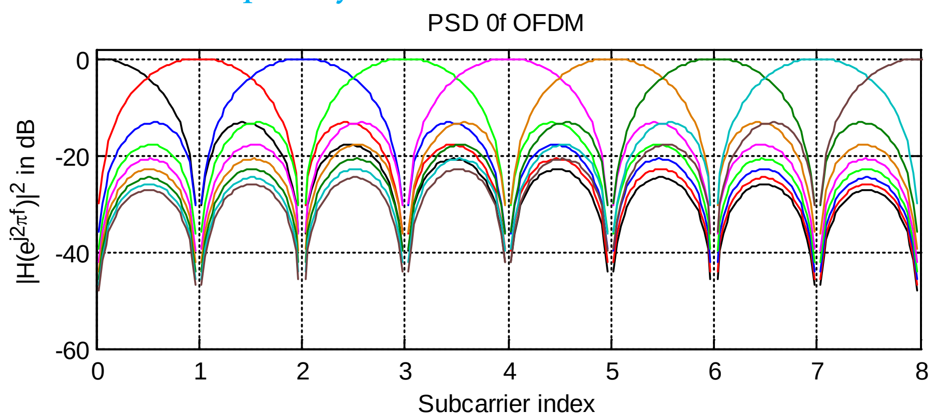
OFDM vs. OFDM-OQAM

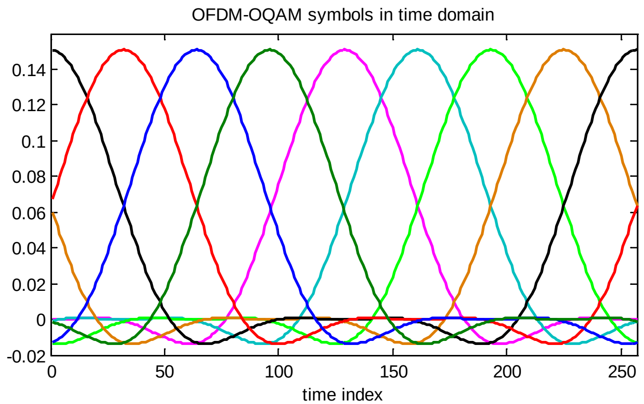
OFDM in time domain



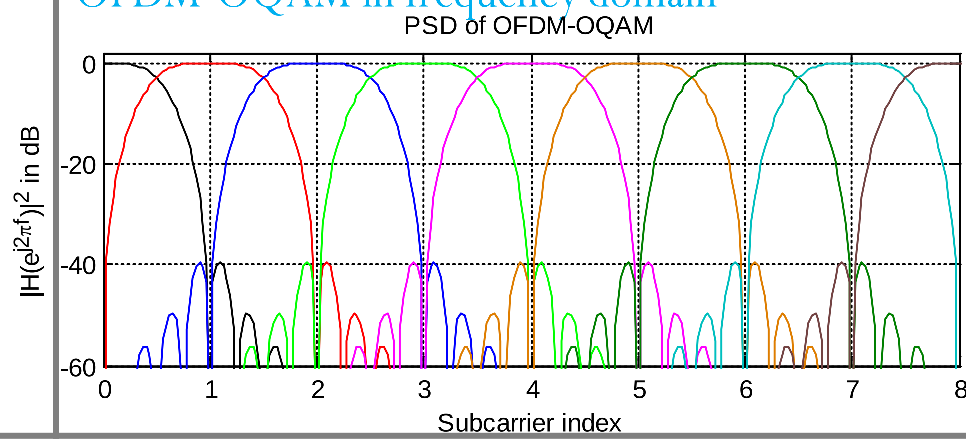
OFDM in frequency domain



OFDM-OQAM in time domain



OFDM-OQAM in frequency domain



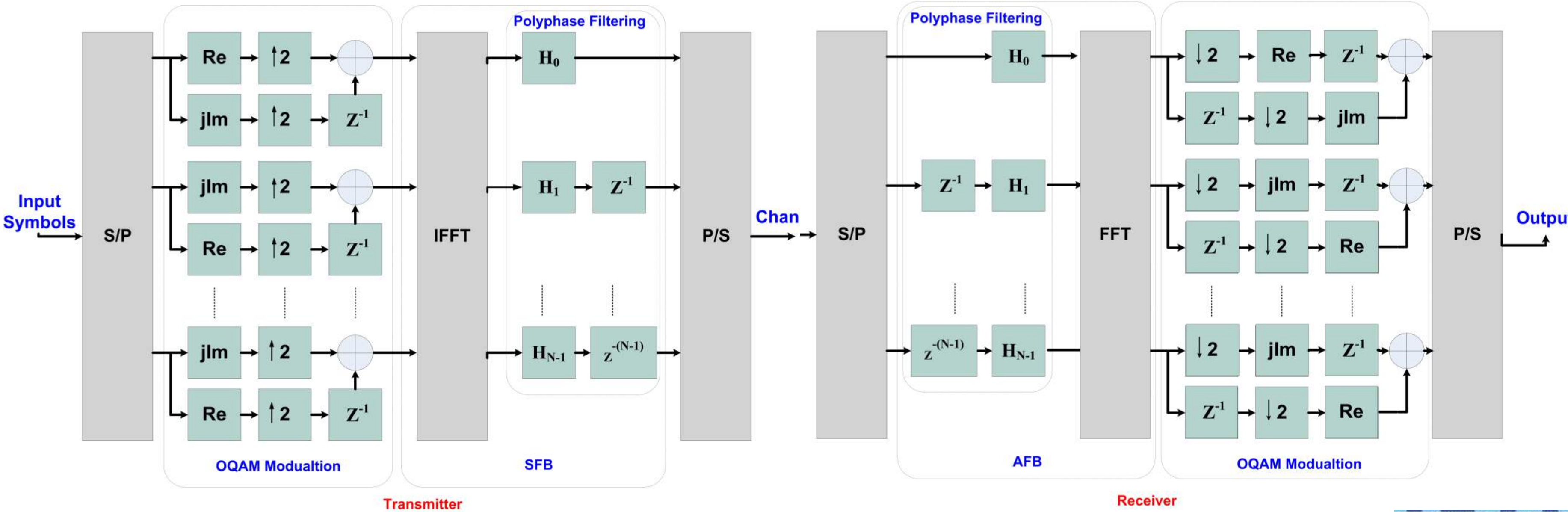
- **OFDM:** No overlapping in time using rectangular pulse, which has large sidelobes.
- **OFDM-OQAM:** Allowing overlapping in time using well designed pulse to reduce sidelobes, as well as to minimize ISI and ICI. There is no cyclic prefix

Source: Erdem Bala (InterDigital, USA)

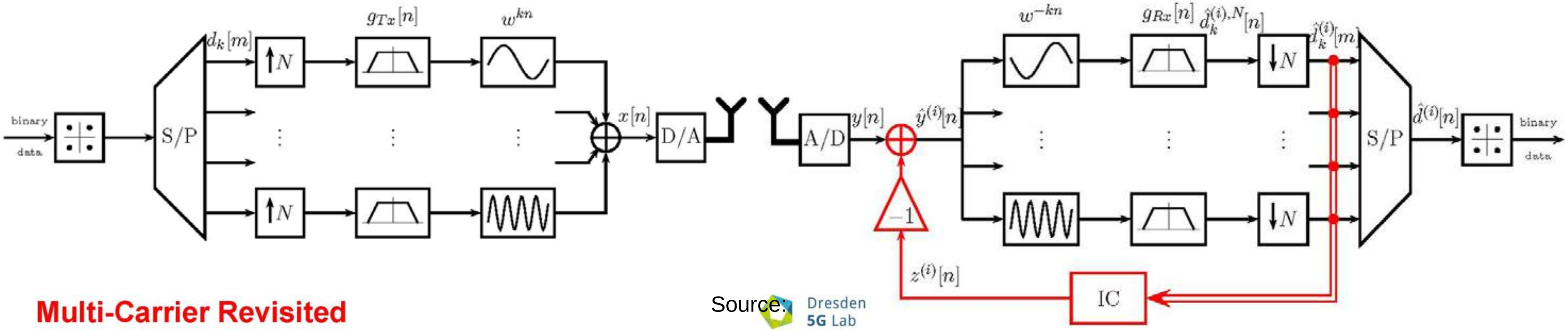
Filter Bank Multicarrier

❑ Filter Based MC scheme:

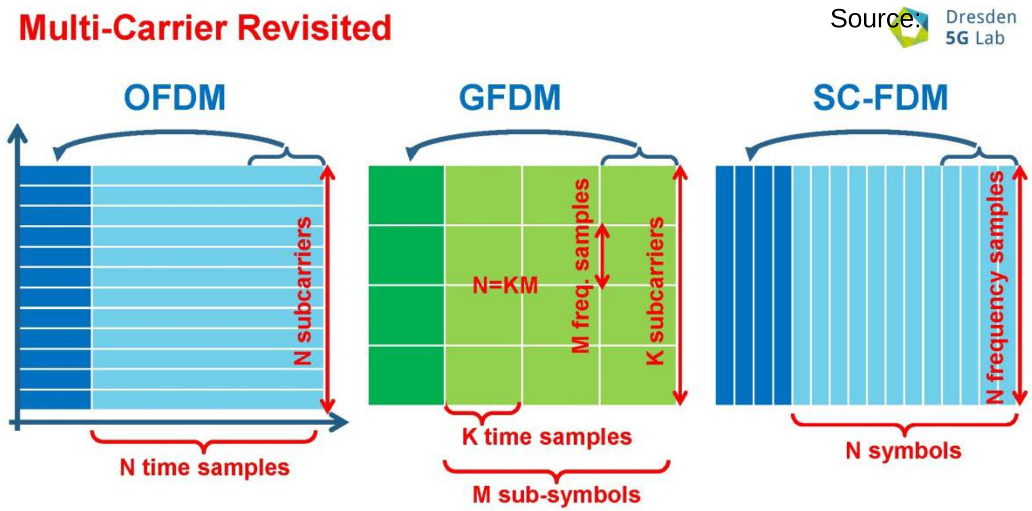
Filter bank can be defined generally as an array of N filters that processes N (different or equal) input signals to produce N outputs. If the inputs of these N filters are connected together, the system -in analogous manner- can be seen as analyser to the input signal based on each filter characteristics. Therefore, this type of filter bank is called analysis filter bank (**AFB**).



Generalized Frequency Division Multiplexing (GFDM)



Source: Dresden 5G Lab

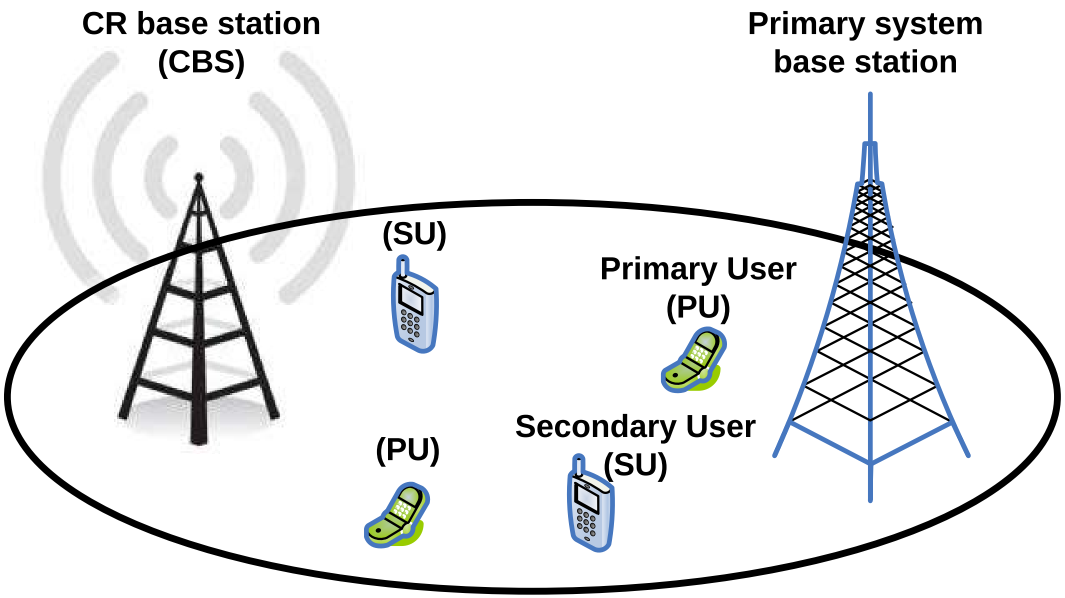


N. Michailow, R. Datta, S. Krone, M. Lentmaier and G. Fettweis “**Generalized Frequency Division Multiplexing: A Flexible Multi-Carrier Modulation Scheme for 5th Generation Cellular Networks**” in *Proceedings of the German Microwave Conference (GeMiC'12)*, Ilmenau, Germany, 12.3. - 14.3.2012- invited paper

N. Michailow, M. Matthé, I. S. Gaspar, A. N. Caldevilla, L. L. Mendes, A. Festag and G. Fettweis **"Generalized Frequency Division Multiplexing for 5th Generation Cellular Networks"**. IEEE Transaction on Communications. Vol. 62 , Issue: 9, Sept. 2014, pp. 3045 -3061.

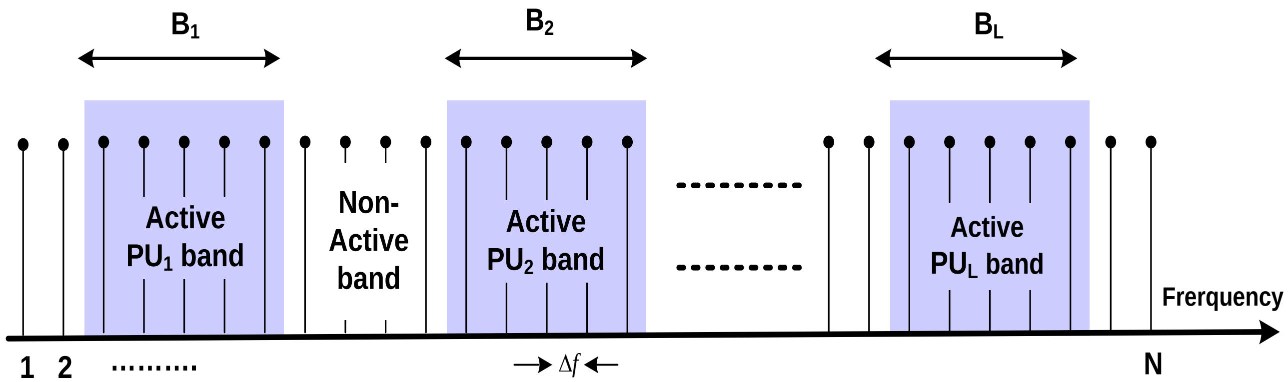
Resource Allocation for Spectrum Sharing/Coexistence
-OFDM vs. FBMC capabilities-

System Model



- The CR system coexist with the PU's radio in the same geographical location.
- The downlink scenario will be considered.
- Each of the two system causes interference to each other.

System Model



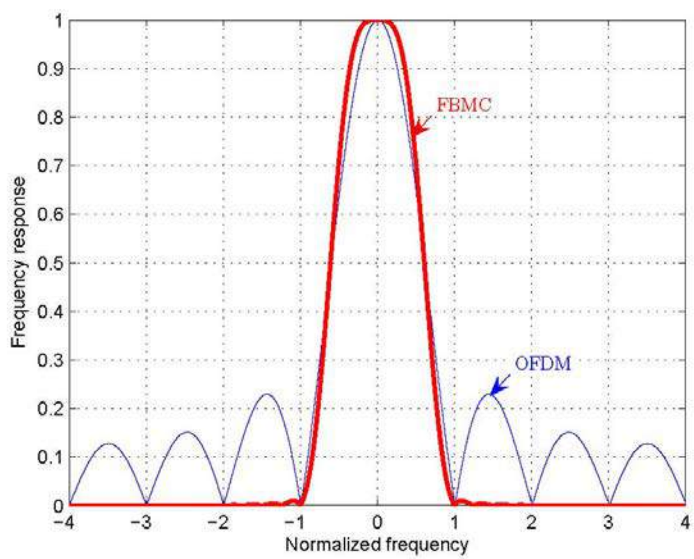
- The SU and PU band are exist side by side.
- Mutual interference is a limiting factor affect the performance of both systems.
- The SU can use active and non-active bands.
- The introduced interference to l^{th} band should be below $I_{th}^{l} = T_{th}^{l} B_l$ where T_{th}^{l} is the interference temperature limit.

System Model

- The interference introduced by the i^{th} subcarrier to l^{th} PU band is the integration of the PSD of the i^{th} subcarrier across the PU band

$$I_i\left(d_i, P_i\right) = \int_{di-B/2}^{di+B/2} \left|g_i\right|^2 \Phi_i\left(f\right) df = P_i \Omega_i$$

- The PSD expression depends on the use multicarrier technique.



Problem Formulation

- The objective is to maximize the total capacity of the SU system subject to the interference introduced to the PU's and total power constraints.

$$P1:\max_{P_i}\sum_{m=1}^{M}\sum_{i=1}^{N}\upsilon_{i,m}\log_2\left(1+\frac{P_{i,m}\left|h_{i,m}\right|^2}{\sigma_i^2}\right)$$

$$Subject\quad to$$

$$\upsilon_{i,m}\in\{0,1\},\ \forall i,m$$

$$\sum_{m=1}^{M}\upsilon_{i,m}\le 1,\ \forall i$$

$$\sum_{m=1}^{M}\sum_{i=1}^{N}\upsilon_{i,m}P_{i,m}\le P_T$$

$$P_i\ge 0,\forall i\in\{1,2,\cdots,N\}$$

$$\sum_{m=1}^{M}\sum_{i=1}^{N}\upsilon_{i,m}P_i\Omega_i\le I_{th}$$

System Model, Cont.

- The problem is combinatorial optimization problem.
- The complexity grows with the input size
- The problem is solved in two steps by many of suboptimal algorithm
  a) Subcarriers are assigned to the users.
  b) Power allocated to the different subcarriers (virtually as single user multicarrier system)
- Its proofed that the maximum data rate in downlink can be obtained if the subcarriers are assigned to the user with the best channel.

$$P_2 : \max_{P_i} \sum_{i=1}^{N} \log_2 \left(1 + \frac{P_i \left| h_i \right|^2}{\sigma^2} \right)$$

subject to

$$\sum_{i=1}^{N} P_i \Omega_i \le I_{th}$$

$$\sum_{i=1}^{N} P_i \le P_T, \quad P_i \ge 0, \forall i \in \{1, 2, ..., N\}$$

Problem Formulation, Cont.

- The problem is convex , by using the Lagrange optimization we can get

$$P_i^* = \left[\frac{1}{\alpha \Omega_i + \beta} - \frac{\sigma^2}{|h_i|^2} \right]^+$$

- Solving more than one Langrangian multipliers is computational complex.

- Ellipsoid or interior point methods can be used with complexity $O(N^3)$

- Computationally efficient algorithm is needed for practical applications.

Proposed Algorithm, Cont.

- For any set of subcarriers,

1. Optimal solution of the optimization subject to total power constraint only is waterfilling.

2. Optimal solution of the optimization problem subject to interference only can be solved by means of Langrangian and given by

$$P_i^{'(Int)} = \left[\frac{1}{\alpha_l^{(Int)} \Omega_i} - \frac{\sigma^2}{|h_i|^2} \right]^+$$

$$\alpha_l^{(Int)} = \frac{|N_l|}{I_{th} + \sum_{i \in N_l} \frac{\sigma^2 \Omega_i}{|h_i|^2}}$$

Computational Complexity

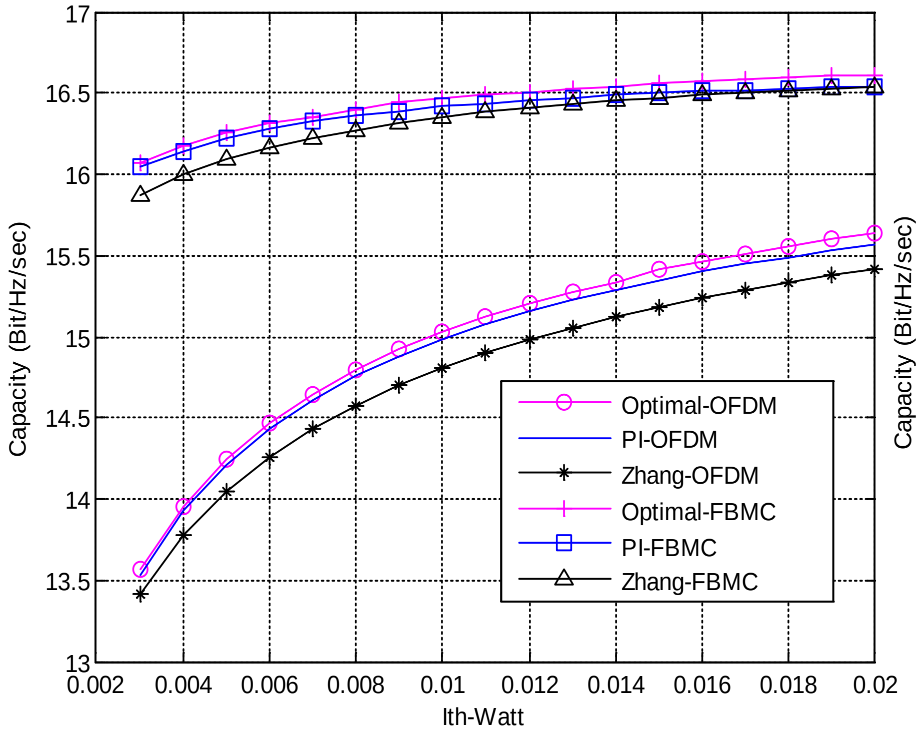
- The overall complexity of the proposed algorithm is lower than

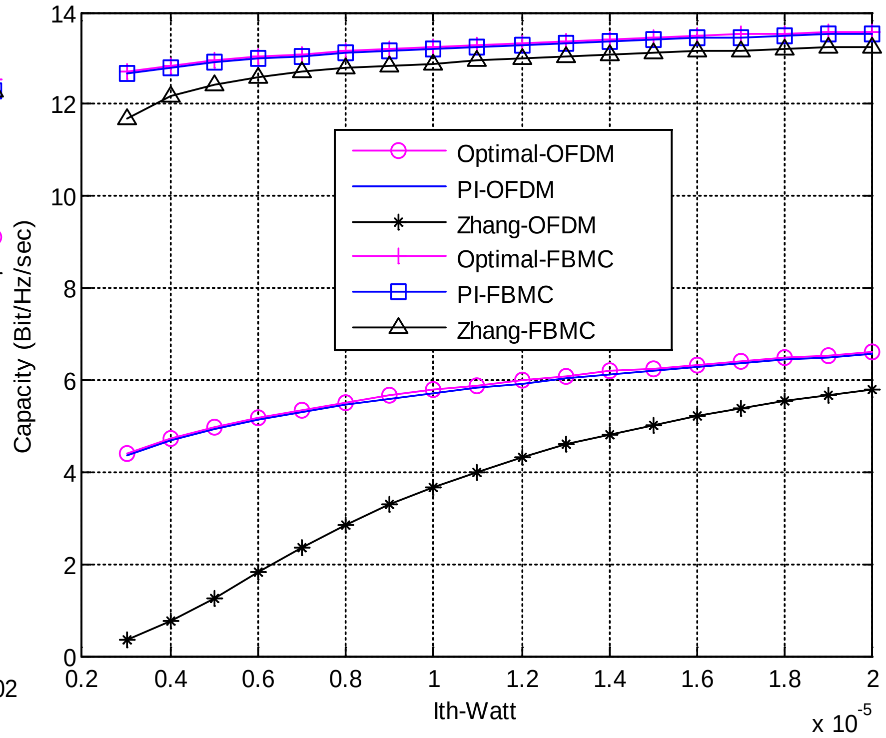
$$O\left(N\log N+\eta N\right)+O\left(L\right)$$

- Where $\eta \le N$ is the number of waterfilling iterations.
- η is estimated via simulations
- Average $\eta_{average}=2.953$
- Maximum $\eta_{\max}=5, \quad \text{i.e.} \quad \eta\in\left[0,5\right]$

Results comparison

- N=32 subcarriers, M=3 SU's; N1=N2=16, PT=1 watt, L=2 PU's.





Low Interference

Y. Zhang, "Resource allocation for OFDM-Based cognitive radio systems," Ph.D. dissertation, Univ. of British Columbia, Vancouver, December 2008.

Musbah Shaat, "Resource Management in Multicarrier Based Cognitive Radio Systems", PhD. dissertation , Universitat Politècnica de Catalunya-UPC, Barcelona-Spain-2013

Future broadband Professional Mobile Radio (PMR)/(PPDR) systems:
Spectrum Coexistence Capabilities

Future broadband PMR/(PPDR) systems

❑ PMR R
bands a
❑ Standar
systems.
BW). Near
❑ Need t
services…
future PMI
Constrain
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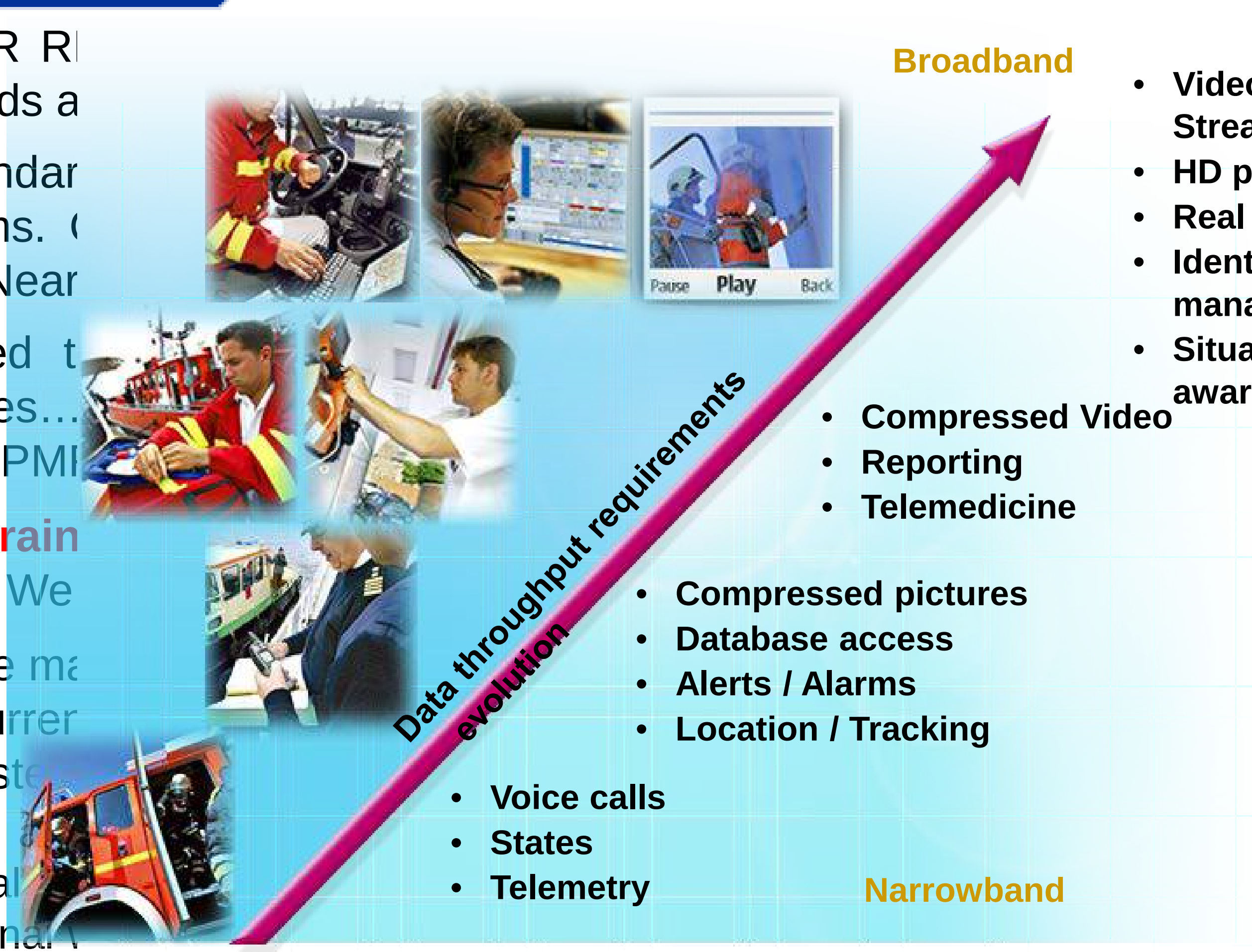
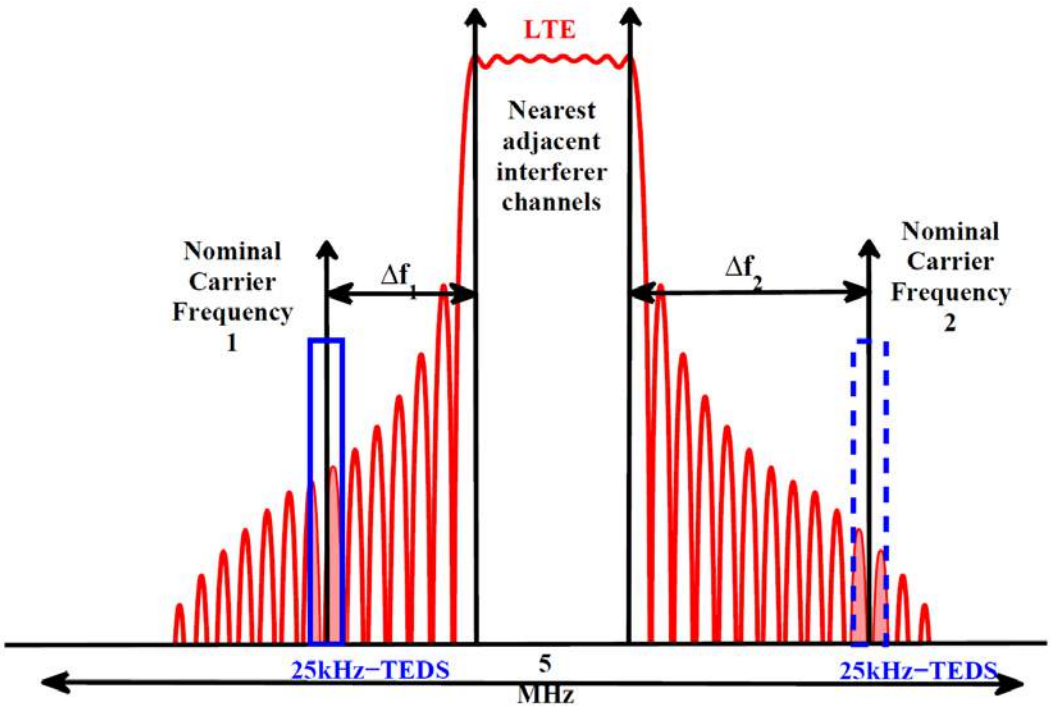
Frequency



Coexistence and PMR requirements..

Scenario:



LTE broadband in coexistence with narrowband PMR systems

Coexistence and PMR requirements..

Table 1: LTE Main Parameters:

Transmission bandwidth	1.4 MHz	3 MHz	5 MHz
Subcarrier spacing	15 kHz		
FFT size	128	256	512
Useful subcarriers	72	180	300
Effective bandwidth	1.08 MHz	2.7 MHz	4.5 MHz

Multicarrier Techniques: CP-OFDM using the rectangular pulse shape, and FBMC using the PHYDYAS prototype filter, and GFDM with different filters.

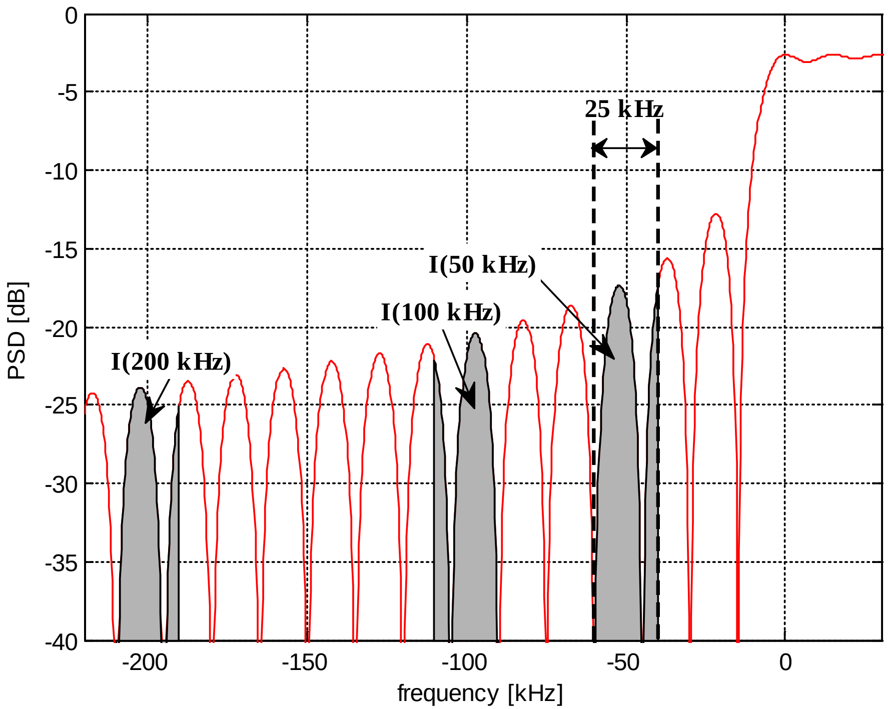
Table 2: TEDS Reception Mask: Blocking levels of the 25 kHz (8 subchannels) QAM receiver

Offset from nominal Rx frequency [kHz]	Level of interfering signal [dBm]
50 to 100	-40
100 to 200	-35
200 to 500	-30
> 500	-25

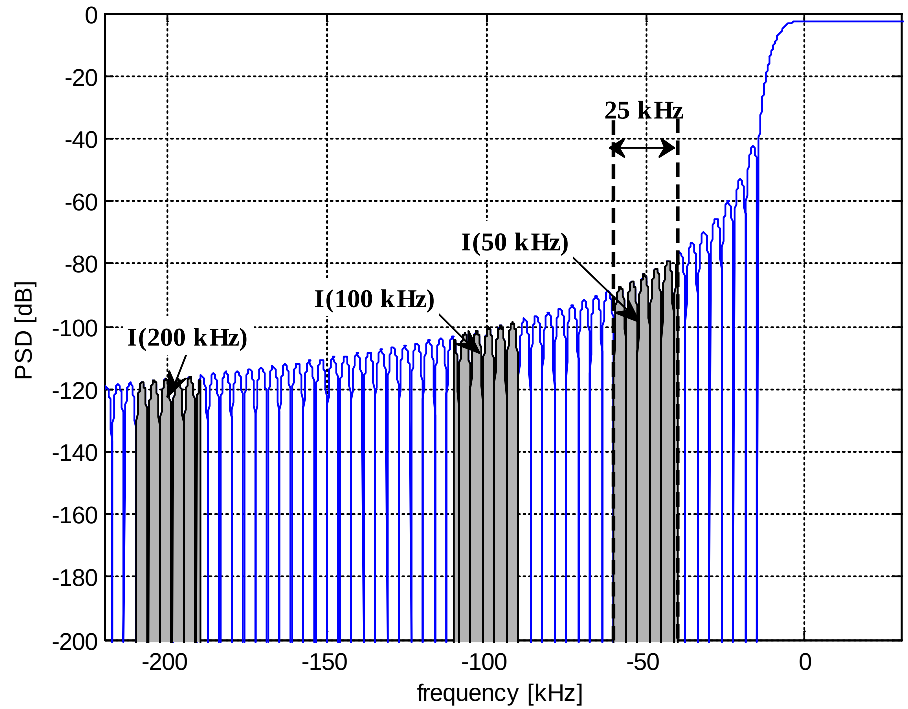
These power levels have been computed in the corresponding TEDS frequency band (25 kHz in this case) considering different offsets.

Interference Analysis 1.

LTE effective interference levels:



OFDM case



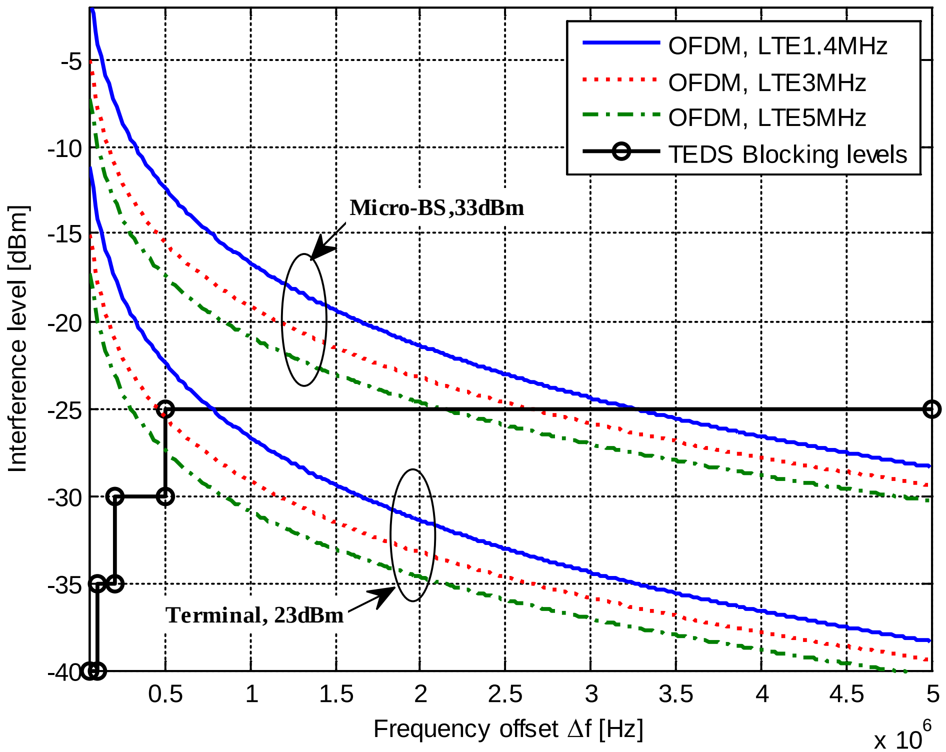
FBMC case

Effective interference levels of 1.4 MHz-LTE in 25 kHz-TEDS band

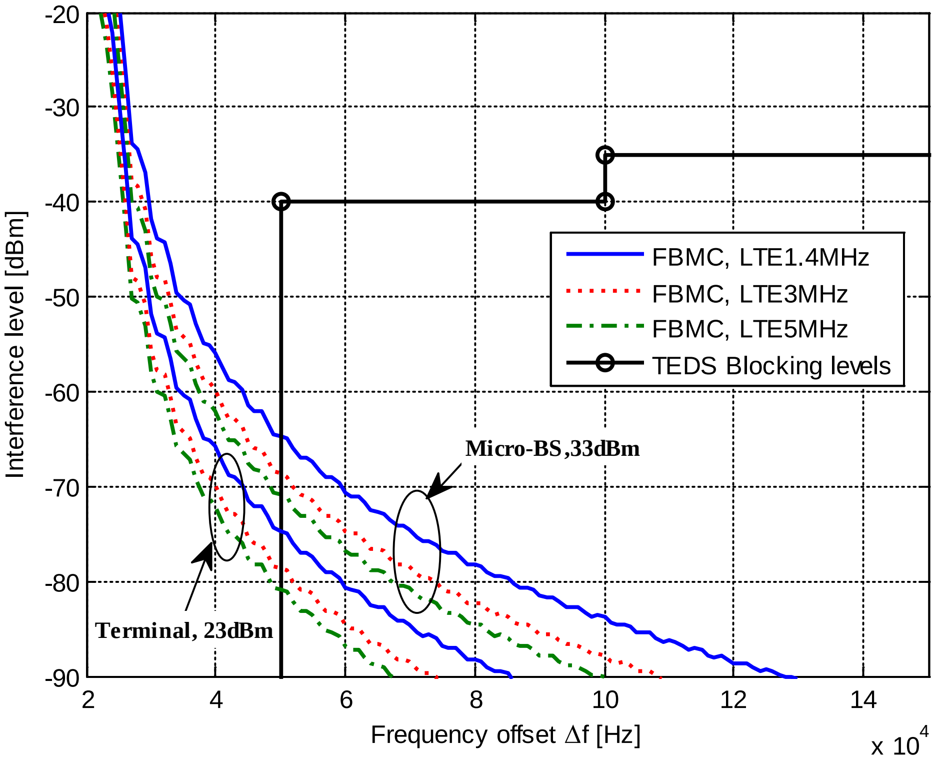
We assume that the PMR base station and the LTE system are co-located (i.e. the PMR transmitter and the LTE one are at equal distances from the PMR-receiver).

Interference Analysis 2.

LTE effective interference levels vs. TEDS/LTE spectral distance:



OFDM case

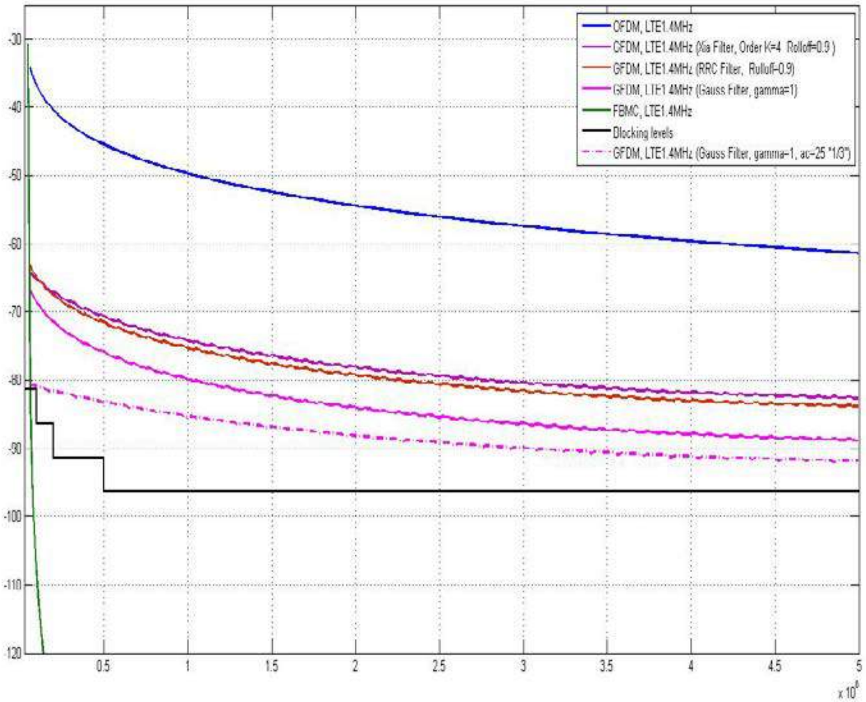


FBMC case

Effective interference powers [dBm] caused by LTE Micro-BS (Ptot = 33dBm) and Terminal (Ptot = 23dBm)

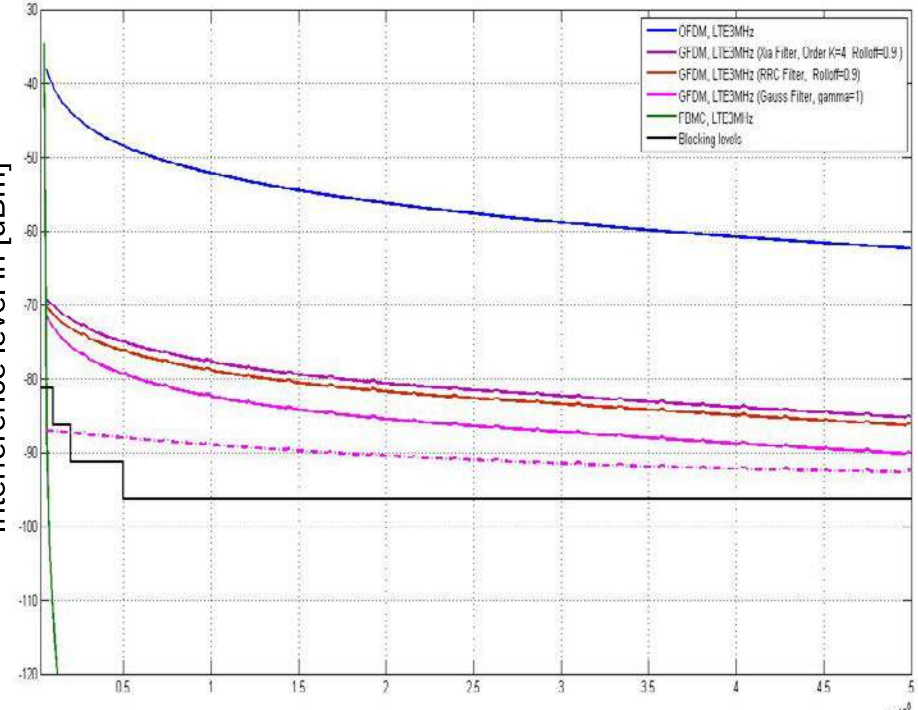
Yahia Medjahdi, Didier le Ruyet, Faouzi Bader, and Laurent Martinod, **Integrating LTE Broadband System in PMR Band: OFDM vs. FBMC Coexistence Capabilities and Performances**, accepted at the 11th International Symposium on Wireless Communication Systems (ISWCS'2014). Barcelona, Spain. August 2014.

Interference Analysis 3.



Interference level in [dBm]

Frequency offset Δf [Hz]



Interference level in [dBm]

Frequency offset Δf [Hz]

Compared systems: OFDM

GFDM with ≠ filters : Gaussian, Xia, and RRC

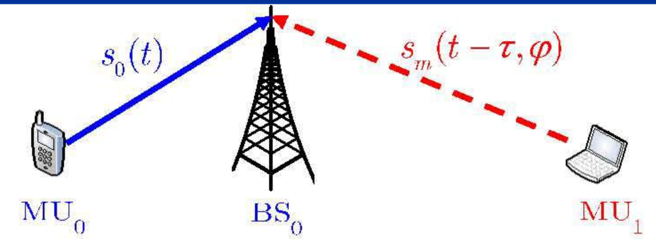
FBMC (PHYDYAS's filter)

Analysis of an Instantaneous Interference in Asynchronous Wireless Communication Systems

-OFDM and FBMC-

OFDM Instantaneous Interference

Context:



Asynchronous interference in multicarrier systems

- We refer to a receiver BS_0 which suffers from the interference coming from an asynchronous transmitter MU_1. BS_0 is assumed to be perfectly synchronized with its corresponding transmitter MU_1.
- We will be interested in the impact of the interfering signal $s(t-\tau,\varphi)$ on the reference receiver.

OFDM interfering signal (subchannel *m*):

$$s_m(t-\tau,\varphi) = \sum_{n=-\infty}^{n=+\infty} x_{m,n} f_T(t-n(T+\Delta)-\tau) e^{j\left[\frac{2\pi}{T}m(t-n(T+\Delta)-\tau)+\varphi\right]}$$

The m_0-th output of the victim receiver :

$$y_{m_0,n_0}(\tau,\varphi) = \int_{-\infty}^{+\infty} s_m(t-\tau,\varphi) f_R(t-n_0(T+\Delta)) e^{-j\frac{2\pi}{T}m_0(t-n_0(T+\Delta))} dt$$

$$f_T(t) = \begin{cases} \frac{1}{\sqrt{T}} & t\in[0,T+\Delta] \\ 0 & elsewhere \end{cases} \qquad f_R(t) = \begin{cases} \frac{1}{\sqrt{T}} & t\in[\Delta,T+\Delta] \\ 0 & elsewhere \end{cases}$$

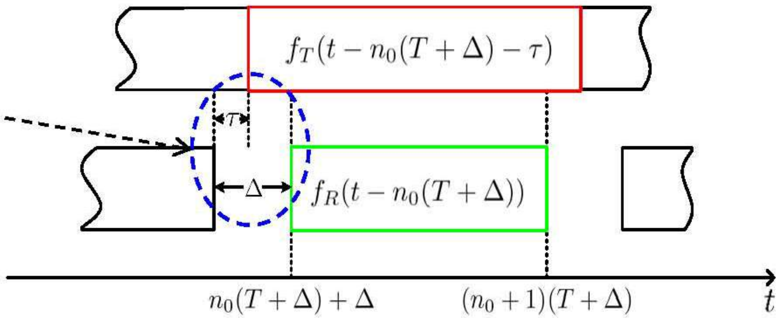
OFDM Instantaneous Interference

$$y_{m_0,n_0}(\tau,\varphi) = \sum_{n=-\infty}^{+\infty} x_{m,n} e^{-j\left[\frac{2\pi}{T}m\tau-\varphi\right]} \int_{-\infty}^{+\infty} f_T(t-n(T+\Delta)-\tau) f_R(t-n_0(T+\Delta)) e^{j\frac{2\pi}{T}m(t-n(T+\Delta))} e^{-j\frac{2\pi}{T}m_0(t-n_0(T+\Delta))} dt$$

The product $f_T(t-n(T+\Delta)-\tau) f_R\big(t-n_0(T+\Delta)\big)$ and the choice of τ determine the limits of the integral.

Case 1 ($0 < \tau < \Delta$):

The timing offset τ is absorbed by the cyclic prefix Δ.



Respective positions of transmit and receiver pulses

$$y_{m_0,n_0}(\tau,\varphi) = \begin{cases} \boxed{x_{m_0,n_0} e^{-j\left[\frac{2\pi}{T}m_0\tau-\varphi\right]} \qquad m = m_0} \\ 0 \qquad otherwise \end{cases}$$

- Orthogonality between subcarriers is maintained.

- There is only co-channel interference

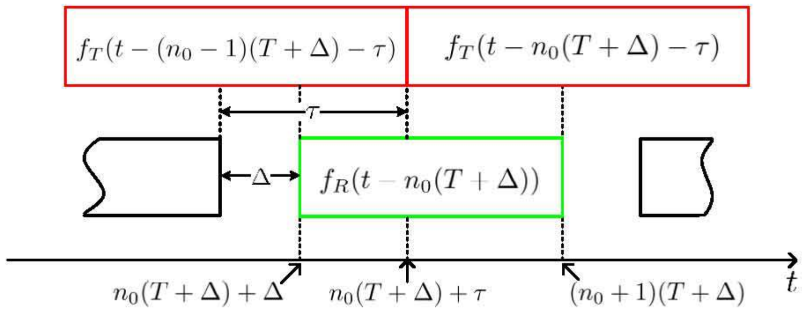
OFDM Instantaneous Interference

$$y_{m_0,n_0}(\tau,\varphi)=\sum_{n=-\infty}^{+\infty} x_{m,n} e^{-j\left[\frac{2\pi}{T}m\tau-\varphi\right]}\int_{-\infty}^{+\infty} f_T(t-n(T+\Delta)-\tau)f_R(t-n_0(T+\Delta))e^{j\frac{2\pi}{T}m(t-n(T+\Delta))}e^{-j\frac{2\pi}{T}m_0(t-n_0(T+\Delta))}dt$$

The product $f_T(t-n(T+\Delta)-\tau)f_R\big(t-n_0(T+\Delta)\big)$ and the choice of τ determine the limits of the integral.

Case 2 ($\Delta < \tau < T+\Delta$):

- Orthogonality between subcarriers is no longer maintained.
- The resulting interference is the sum of the contribution of two successive blocs (n_0-1, n_0)



Respective positions of transmit and receiver pulses

$$y_{m_0,n_0}(\tau,\varphi)=e^{-j\left[\frac{2\pi}{T}m\tau-\varphi\right]}\times\left\{\frac{\boxed{x_{m,n_0-1}}}{\pi(m-m_0)}e^{-j\frac{2\pi}{T}m(T+\Delta)}e^{j\frac{\pi}{T}(m-m_0)(\tau+\Delta)}\sin\left[\pi(m-m_0)(\tau-\Delta)/T\right]\right.$$
$$\left.+\frac{\boxed{x_{m,n_0}}}{\pi(m-m_0)}e^{j\frac{\pi}{T}(m-m_0)(T+\Delta+\tau)}\sin\left[\pi(m-m_0)(T+\Delta-\tau)/T\right]\right\}$$

FBMC Instantaneous Interference

FBMC interfering signal (subchannel *m*):

$$s_m(t-\tau,\varphi) = \sum_{n=-\infty}^{+\infty} a_{m,n} f\ \ t - nT/2 - \tau\ \ e^{j\frac{2\pi}{T}m(t-\tau)} e^{j(\varphi_{m,n}+\varphi)}$$

The m_0-th output of the victim receiver :

$$y_{m_0,n_0}(\tau,\varphi) = \sum_{n=-\infty}^{+\infty} a_{m,n} e^{j(\varphi+\varphi_{m,n}-\varphi_{m_0,n_0})} e^{-j\frac{2\pi}{T}m\tau} \times \int_{-\infty}^{+\infty} f(t-nT/2-\tau) f(t-n_0T/2) e^{j\frac{2\pi}{T}(m-m_0)t} dt$$

where $f(t)f(t-\tau) \neq 0, \quad \tau \in [-KT, +KT]$

Yahia Medjahdi, ''**Interference modeling and performance analysis of asynchronous OFDM and FBMC wireless communication systems**",, PhD. Dissertation, Conservatoire National des Arts et Métiers- CNAM, Paris France, 2012.

FBMC Instantaneous Interference (2)

Similarly to OFDM, the limits of the integral depend on the choice of the timing offset τ and the product $f\left(t-\frac{nT}{2}-\tau\right)f(t-\frac{n_0T}{2})$.

Case 1 ($(n_0-n)T/2<\tau$):

$$y_{m_0,n_0}(\tau,\varphi)=\sum_{n=\left\lfloor\frac{-\tau}{T/2}\right\rfloor+n_0+1}^{2K+n_0-1} a_{m,n}e^{j(\varphi+\varphi_{m,n}-\varphi_{m_0,n_0})}e^{-j\frac{2\pi}{T}m\tau}\Psi(t,\tau,l)\Big|_{l=\tau}^{KT+(n_0-n)\frac{T}{2}}$$

where $\lfloor\alpha\rfloor$ denotes the floor function (the largest integer less than or equal to α).

Case 2($\tau<(n_0-n)T/2$):

$$y_{m_0,n_0}(\tau,\varphi)=\sum_{n=-2K+n_0+1}^{n_0+\left\lceil\frac{-\tau}{T/2}\right\rceil-1} a_{m,n}e^{j(\varphi+\varphi_{m,n}-\varphi_{m_0,n_0})}e^{-j\frac{2\pi}{T}m\tau}\Psi(t,\tau,l)\Big|_{t=(n_0-n)\frac{T}{2}}^{KT+\tau}$$

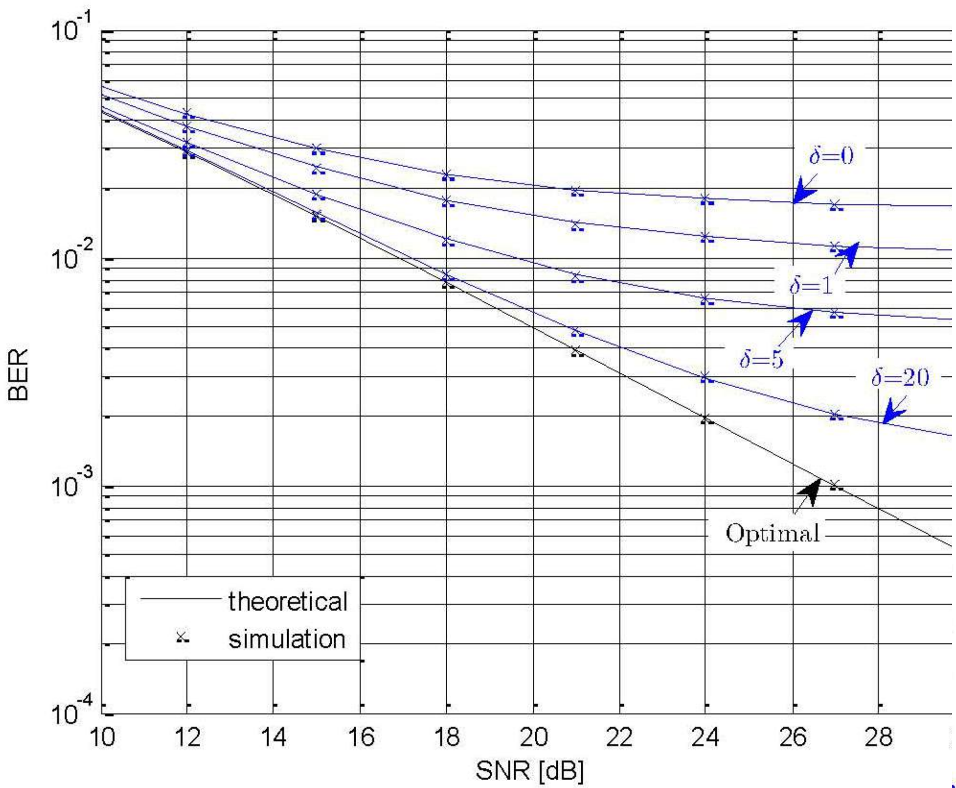
- where $\lceil\alpha\rceil$ is the ceil function (the smallest integer greater than or equal to α).
- After the OQAM decision, we can write the total complex symbol $y_{tot}(\tau,\varphi)$ as follows:

$$y_{tot}(\tau,\varphi)=\mathrm{Re}\left\{y_{m_0,n_0}(\tau,\varphi)\right\}+j\mathrm{Re}\left\{y_{m_0,n_0+1}(\tau,\varphi)\right\}$$

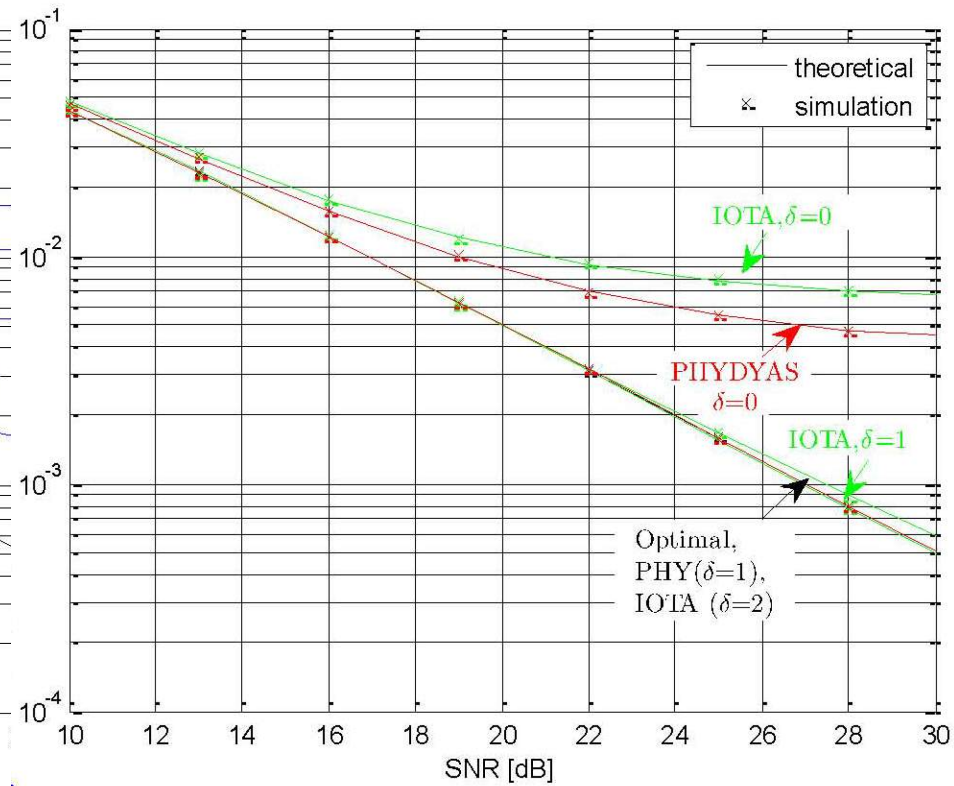
- Consequently, the corresponding interference power table $I(\tau,l)$ is given by:

$$I(\tau,l)=\mathbb{E}_{a_{m,n},\varphi}\left[\left|y_{tot}(\tau,\varphi)\right|^2\right]$$

Under Asynchronous Scenarios



OFDM average BER vs. SNR for different guard-band sizes $\delta = 0, 1, 5, 20$ with $\tau \in [0,T]$



FBMC average BER vs. SNR for different guard-band sizes $\delta = 0, 1, 2$ with $\tau \in [0,T]$

Yahia Medjahdi, ''**Interference modeling and performance analysis of asynchronous OFDM and FBMC wireless communication systems**",, PhD. Dissertation, Conservatoire National des Arts et Métiers- CNAM, Paris France, 2012.

Faouzi Bader, Musbah Shaat, and Yahia Medjahdi, ***New Opportunities for Spectrum Coexistence Using Advanced Multicarrier Scheme***, in Proc. of Military Communications and Information Systems Conference MCC'2013 **(Invited paper)**. Saint Malo, France, October 2013..

CONCLUSION !

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