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EcoSys Lab

What's Next on Filter Bank Modulation?

from FMT to Concatenated FMT to Cyclic Block FMT

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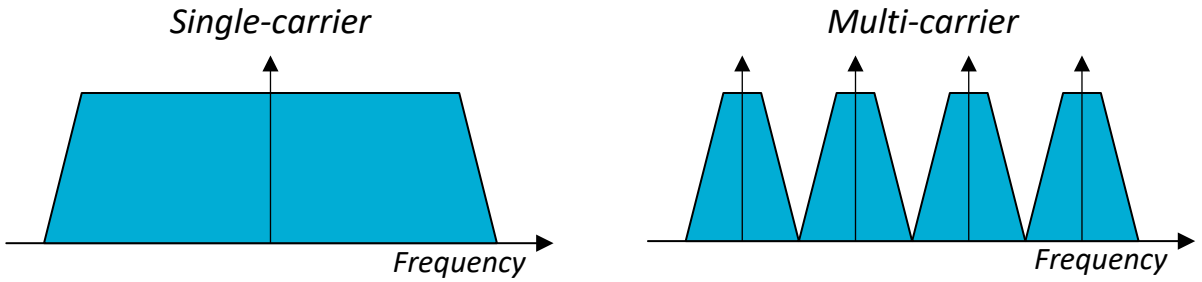
Contribution

- Multicarrier modulation (MCM) seen as a filter bank modulation (FBM) scheme
- Show that Filtered Multitone Modulation (FMT) is a general scheme that embeds *all* forms of linear MCM (exponentially modulated linear filter banks)
- Show that Cyclic Block Filtered Multitone Modulation (CBFMT) is a general scheme that embeds *all* forms of cyclic MCM (exponentially modulated cyclic filter banks)
- Describe some new schemes, analogies, differences, and motivations:
  - Adaptive FMT
  - Concatenated DMT-FMT
  - Cyclic Block FMT

Why Filter Bank Modulation ?

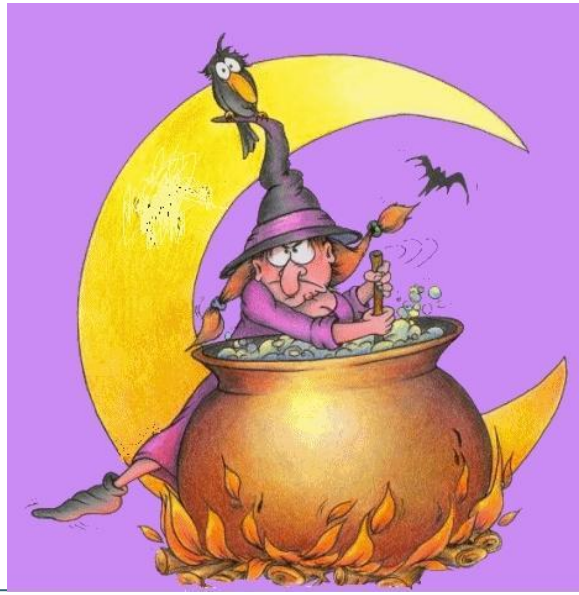
- Some motivations for FBM
  - Robustness to channel frequency selectivity
  - Robustness to channel time variations
  - Potentially lower transmission delay
  - Flexibility: power/bit loading, parameters adaptation, user multiplexing

  ➡ Flexible spectrum usage and notching capability



History

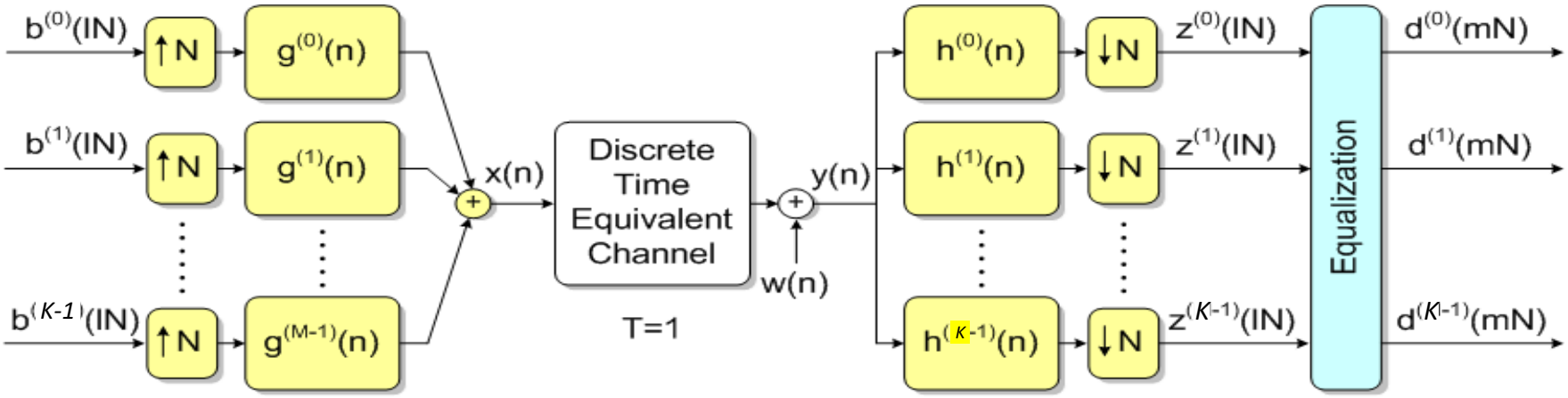
- Multi-carrier modulation dates back 1957 (*Doelz et al*)
- Over 50 years of research about it



Goals and Challenges

- Main challenge: try to improve OFDM
  - spectrum selectivity, flexibility/agility, robustness to impairments, spectral efficiency and energy efficiency (with complexity constraints)
- Starting point: interpret MCM as a filter bank
  - We will focus on the filtered multitone modulation (FMT) philosophy and derive improved schemes that meet certain goals

Baseline FBM Scheme



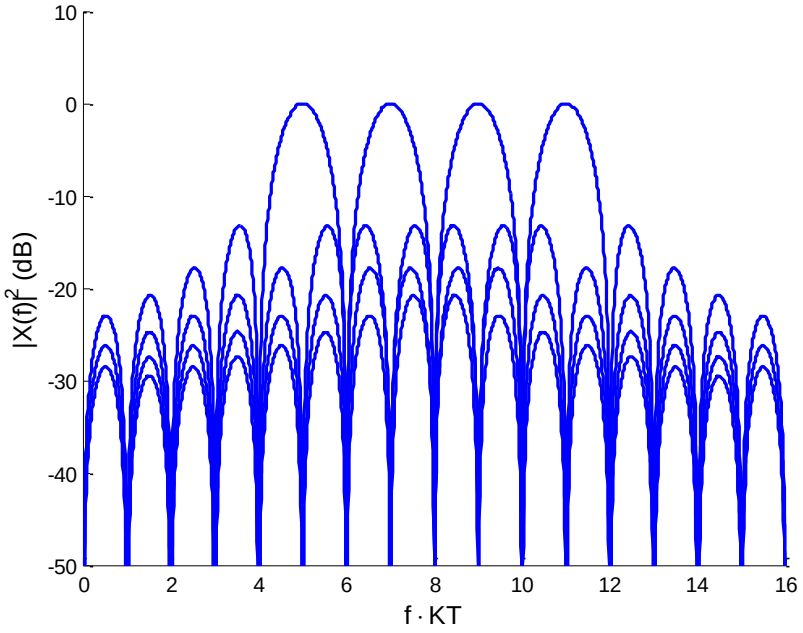
- $b^{(k)}(IN)$: QAM data symbols
- $g^{(k)}(n)$: Sub-channel pulses, obtained from the modulation of a prototype pulse
- N: Interpolation factor $N \geq K$ number of sub-channels

Almost all MCM systems can be described with the FB architecture

The difference is in the sub-channel waveform !

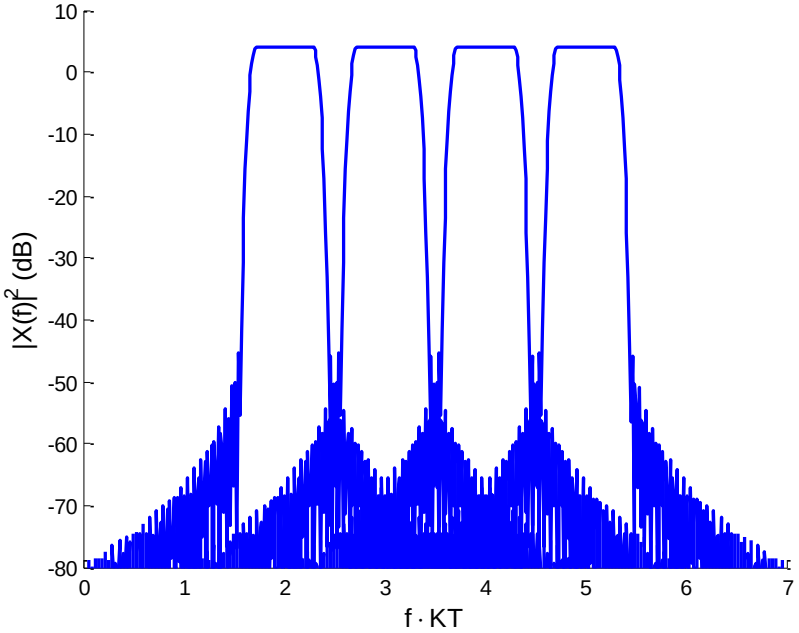
OFDM and FMT: dual approaches

OFDM



- Most popular multi-carrier scheme
- **Prototype pulse confined in time domain**
- Efficient implementation (FFT based)
- Poor frequency selectivity (notching capability), sensitive to synchronization errors, affected by time variant channels

FMT



- Filtered Multitone (FMT)
- **Prototype pulse confined in freq. domain**
- Out-of-band interference reduced
- High notching selectivity
- Robust to asynchronism and channel time selectivity

Other Filter Bank Schemes

- OQAM-OFDM: Offset QAM OFDM
  - Proposed for 5G
  - Orthogonal critically sampled system

1967 B. Saltberg, "Performance of an efficient parallel data transmission system," IEEE TCTC 1967

- DWMT: Discrete wavelet multitoned (and DCT-OFDM)
  - Adopted in IEEE 1901 PLC standard
  - DCT modulated filter bank

1995 S. Sandberg, M. Tzannes, "Overlapped discrete multitone modulation for high sped copper wire communications," IEEE JSAC 1995

- PS-OFDM: Pulse shaped OFDM (and windowed OFDM)
  - Adopted in PLC standards, e.g., IEEE 1901
  - Similar to OFDM with the use of a non rectangular window

1999 F. Sjoberg, R. Nilsson, M. Iasaksson, P. Ödling, P. Borjesson, «Asynchronous zipper," IEEE ICC 1999.

Goal: compete with OFDM in complexity

FMT Design and Implementation

Efficient Realization

- ***Basic idea:*** FMT can be implemented with a DFT polyphase FB
- There exist 3 main realizations described in the (*broad*) literature:
  - **Method A** (*Cvetkovic, Vetterli 1998, and recently, Siclet, Siohan, Pinchon 2006*)

    Polyphase decomposition of the pulse with factor $M_1 = l.c.m.(M,N)$
  - **Method B** (*Weiss, Stewart 2000*)

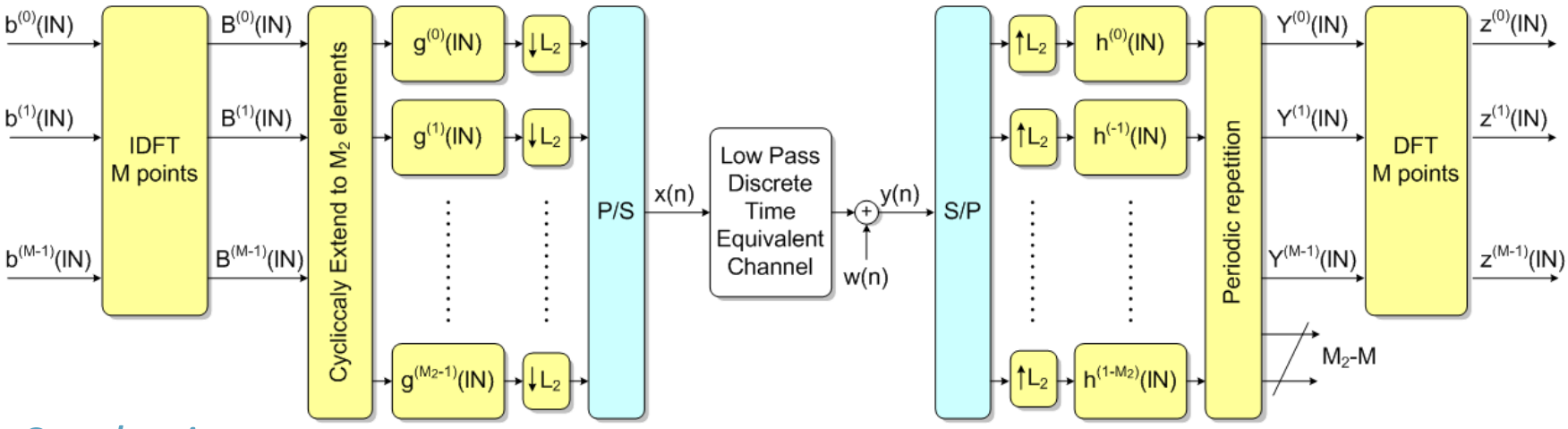
    Polyphase decomposition of the pulse with factor L_f = pulse length
  - **Method C** (*Tonello 2006*)

    Polyphase decomposition of the tx/rx signals with factor $M_1 = l.c.m.(M,N)$
- **4-th Method** (*Cherubini, Eleftheriou, Olcer 2002*) is based on a DFT FB with cyclically time variant sub-channel pulses.

REF. A. Tonello, "**Time Domain and Frequency Domain Implementations of FMT Modulation Architectures**", *Proc.* ***IEEE ICASSP 2006***

REF. N. Moret, A. Tonello, "**Design of Orthogonal Filtered Multitone Modulation Systems and Comparison among Efficient Realizations**", *Eurasip JASP 2010*

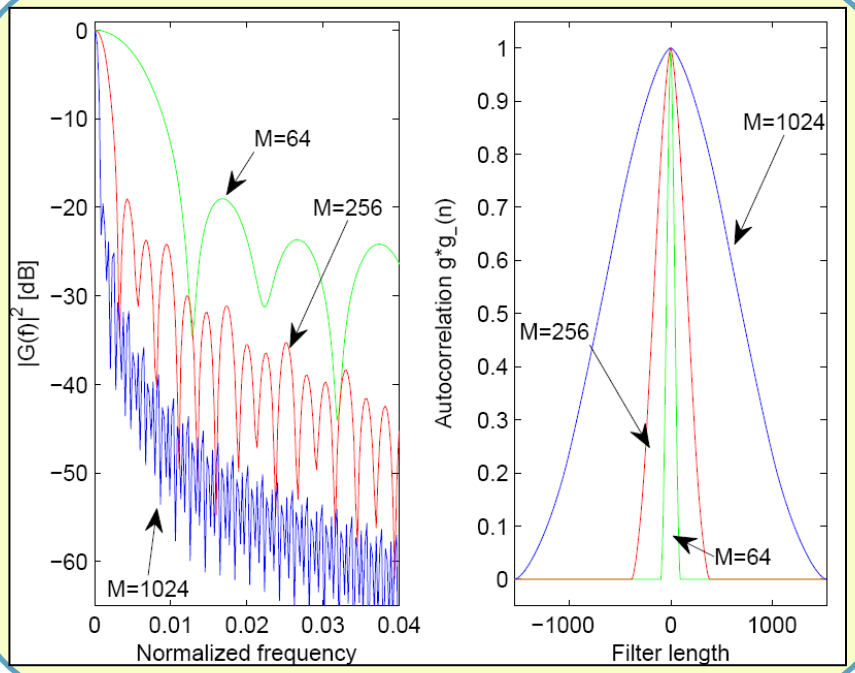
Efficient Realization (Method C)

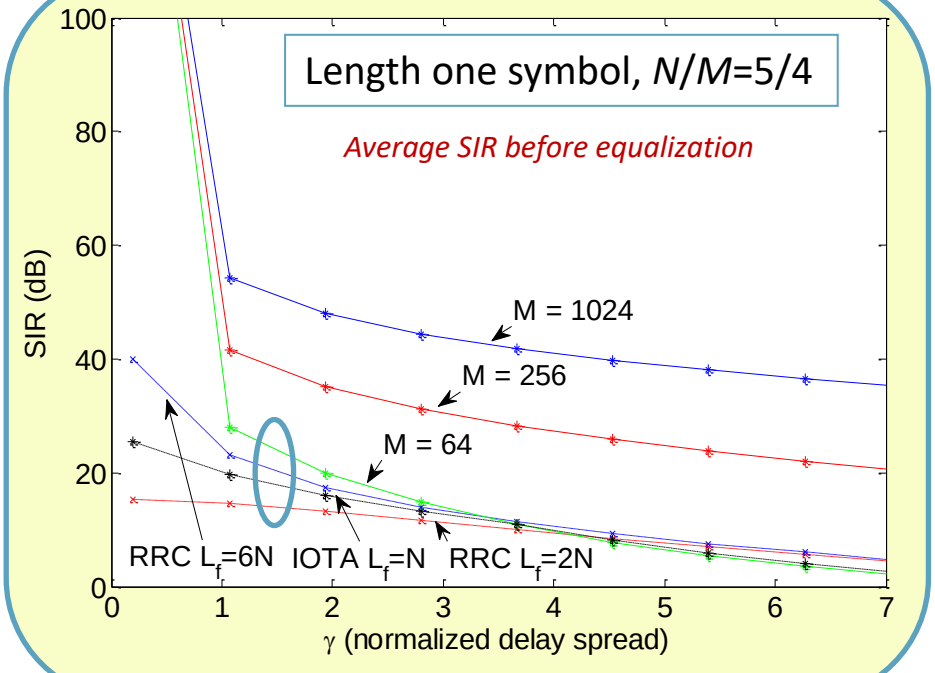


- *Synthesis*
  - M point IDFT and cyclic extension to $M_2 = l.c.m.(M,N) = L_1 M = L_2 N$
  - **Pulses**: PP components of order N, i.e., $g^{(i)}(nN) = g(i+nN) \quad i = 0,\ldots,N-1$
  - Sample with period L_2
- *Analysis*
  - Dual operations
- *Complexity:* $(M\log_2 M + L_{g,h})/N$ operations/sample ($L_{g,h}$: pulse length)

Orthogonal FMT: optimal pulse design

- From the efficient realization scheme we can derive the orthogonality conditions
- Parameterize the pulse coefficients via trigonometric functions of angles. Search for pulses that fulfill the orthogonal relations and maximize the in-band energy





REF. N. Moret, A. Tonello, "**Design of Orthogonal Filtered Multitone Modulation Systems and Comparison among Efficient Realizations**", *Eurasip JASP 2010*

Goal: introduce flexibility

Hybrid FMT

Hybrid FMT: the idea

- Realize a **flexible filter bank**
  - We can adapt the pulse shape
  - We can adapt the overhead (or interpolation) factor **β = *N-M***

- The objective is to maximize the "capacity"

$$C(\beta, pulse) = \frac{1}{(M+\beta)T} \sum_{k} log_2(1 + SINR^{(k)}(\beta, pulse))$$

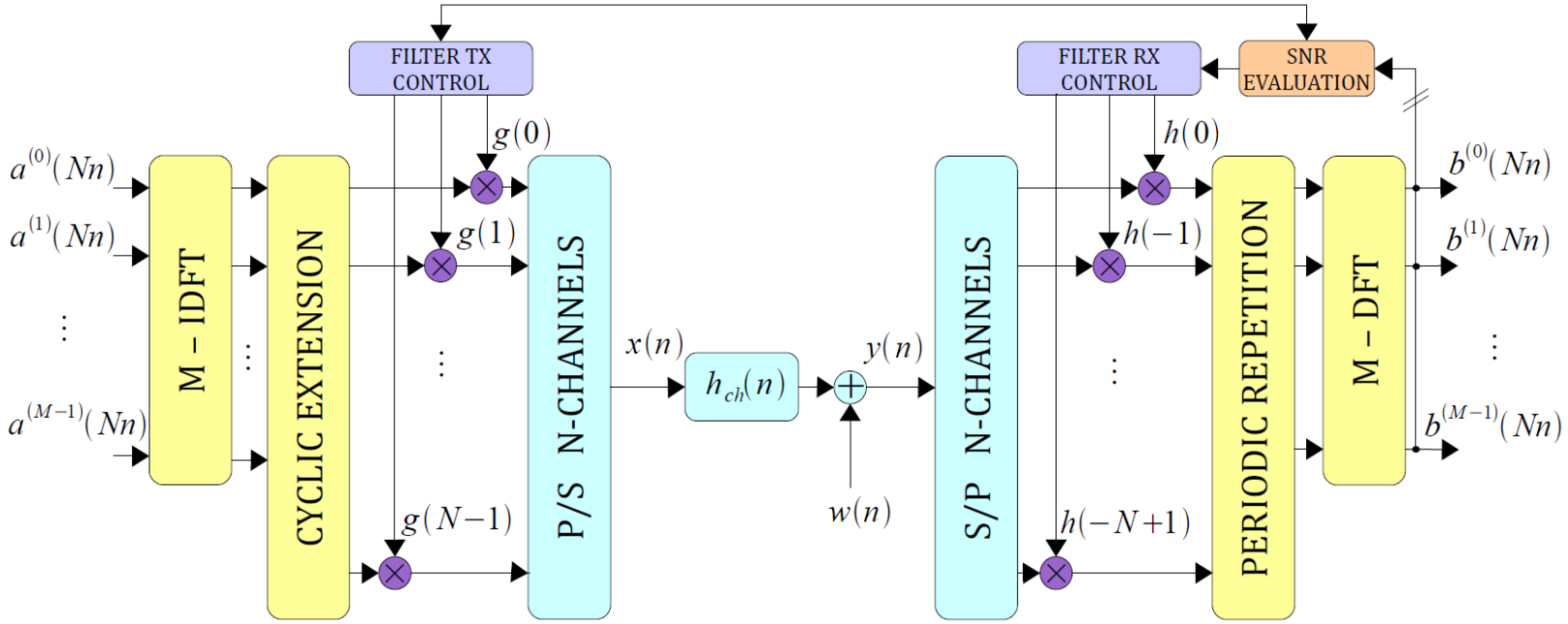
↓ convex function of β (*not strictly, though*)

↓ It depends on β and the pulse

- *Example 1:* OFDM with adaptive CP
- *Example 2:* FMT with r.r.c. pulse with variable roll-off
- *Example 3:* adapt between OFDM and FMT (Hybrid FMT)

REF. A. Tonello, S. D'Alessandro, L. Lampe, "**Cyclic Prefix Design and Allocation in Bit-Loaded OFDM over Power Line Communication Channels**", *IEEE TCOM 2010*.

Hybrid FMT: Realization



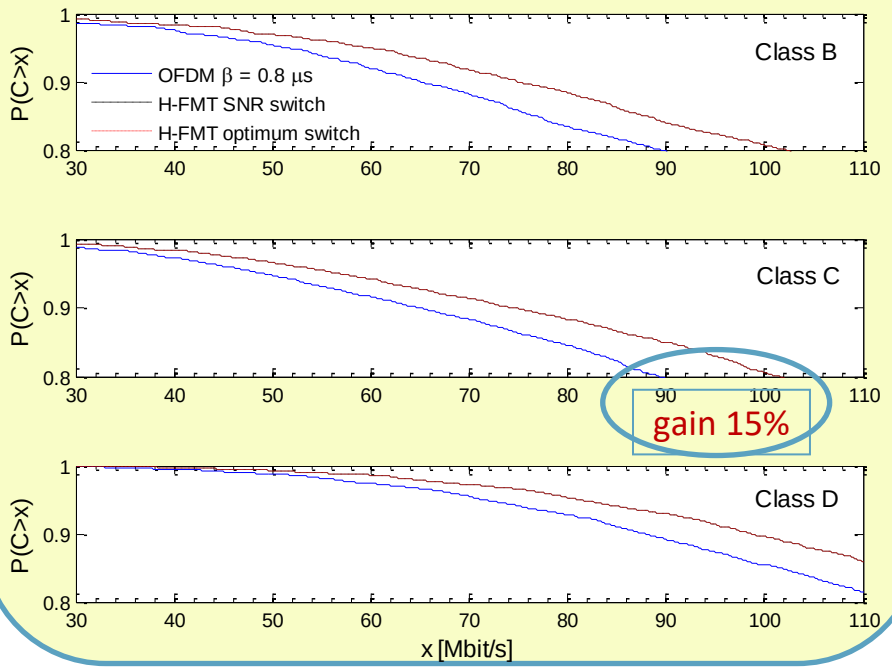
- Adaptation between OFDM and FMT (pulse) is done by simply changing:
  - cyclic extension length M_2 and coefficients of pulse **g**
- Simple adaptation metric exploits the measured SNR
  - if SNR below a certain threshold then use FMT, otherwise use OFDM

REF. S. D'Alessandro, A. Tonello, "**Rate Improvements and Power Saving with a Hybrid Filtered Multitone Scheme**" *Eurasip JWCN 2013.*

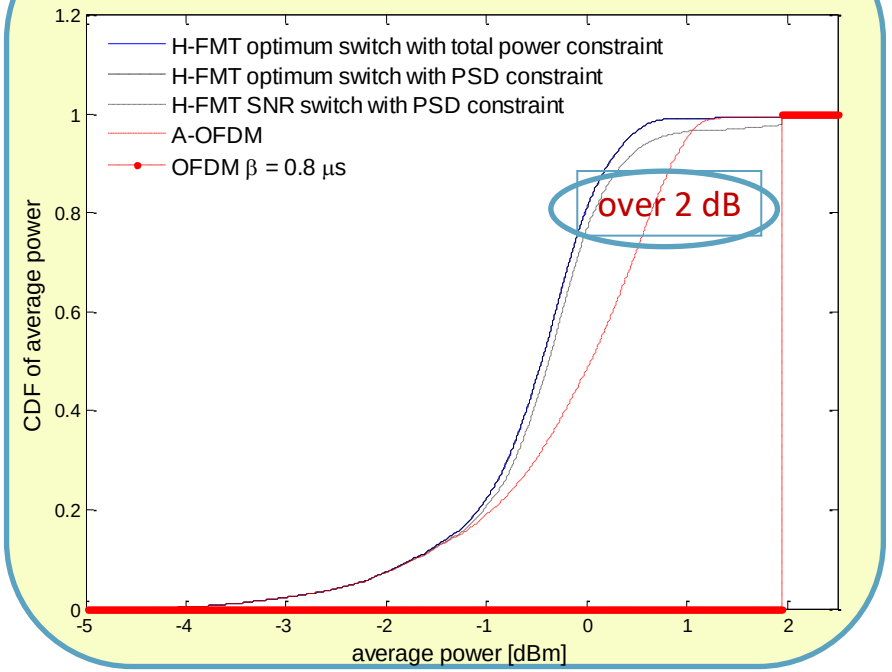
Hybrid FMT: Performance

- OFDM performs better in the high SNR regime where the interference may limit performance
- FMT with orthogonal short pulses performs better in the low SNR regime

Rate improvement in WLAN channels



Power saving in WLAN channels

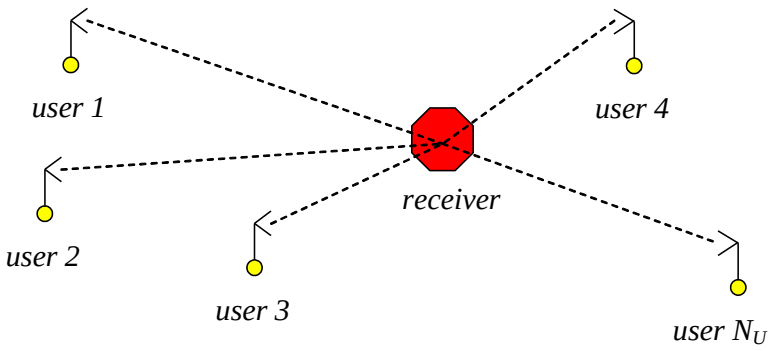


REF. S. D'Alessandro, A. Tonello, "**Rate Improvements and Power Saving with a Hybrid Filtered Multitone Scheme**" *Eurasip JWCN 2013.*

Goal: orthogonalize the uplink channel

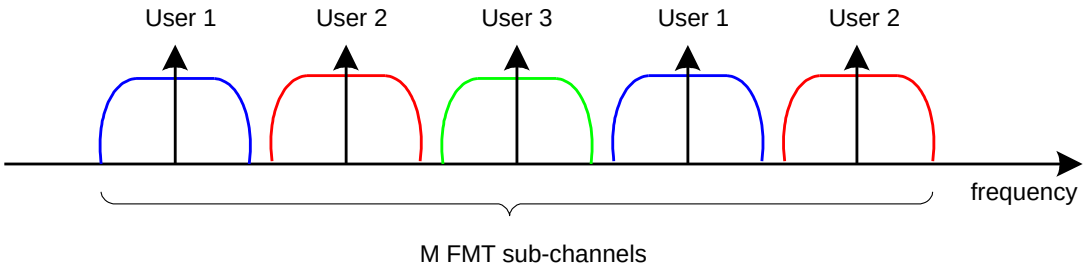
Concatenated OFDM-FMT

Multiuser Uplink



- **Users are asynchronous**
- **Time offsets** between users (*propagation delays*)
- **Carrier frequency offsets** between users (*oscillators, Doppler*)

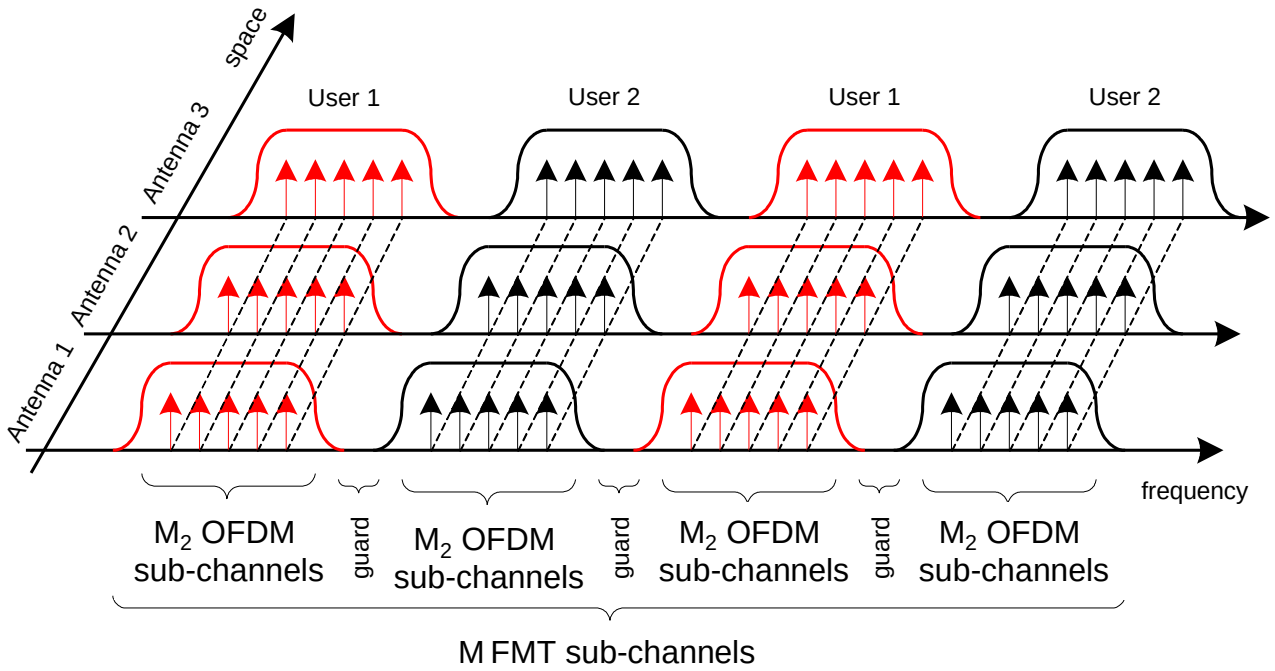
- FB modulation allows implementing a form of **FDMA** by partitioning the sub-channels among the users



- The sub-channel spectral containment of FMT makes it more robust to time and carrier frequency offsets than OFDM !

REF. A. Tonello, "**Asynchronous Multicarrier Multiple Access: Optimal and Sub-optimal Detection and Decoding**", *BLTJ 2003*

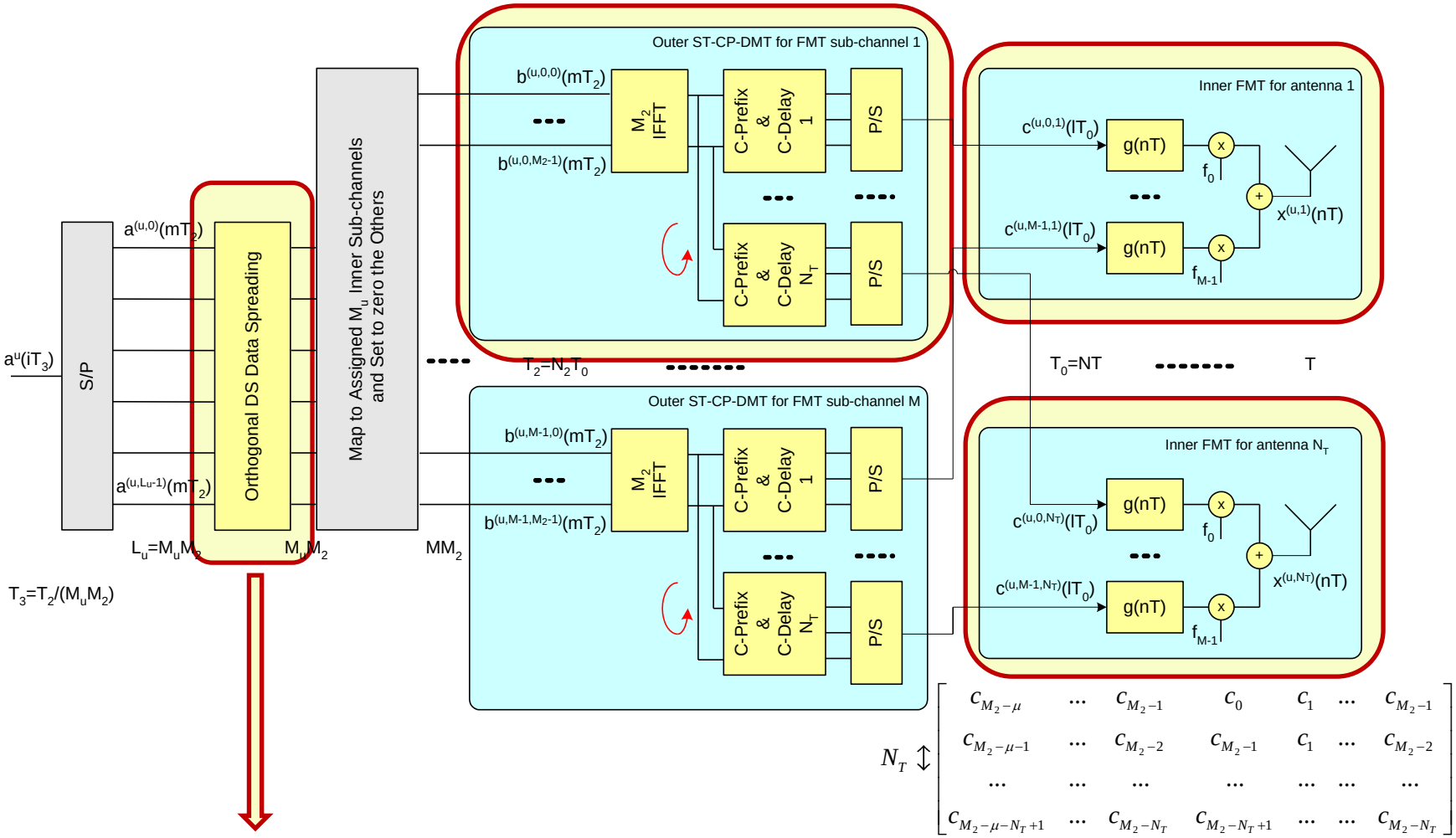
Basics of Concatenated OFDM-FMT



- Inner FMT to multiplex the users (by partitioning FMT tones)
- Outer CP-OFDM to remove the sub-channel ISI
- Cyclic TX Diversity combined with Walsh Spreading to gain spatial diversity over all the M_2 x M (OFDM x FMT) sub-channels

REF. A. Tonello, "**A Concatenated Multitone Multiple Antenna Air-interface for the Asynchronous Multiple Access Channel**", *IEEE JSAC 2006*

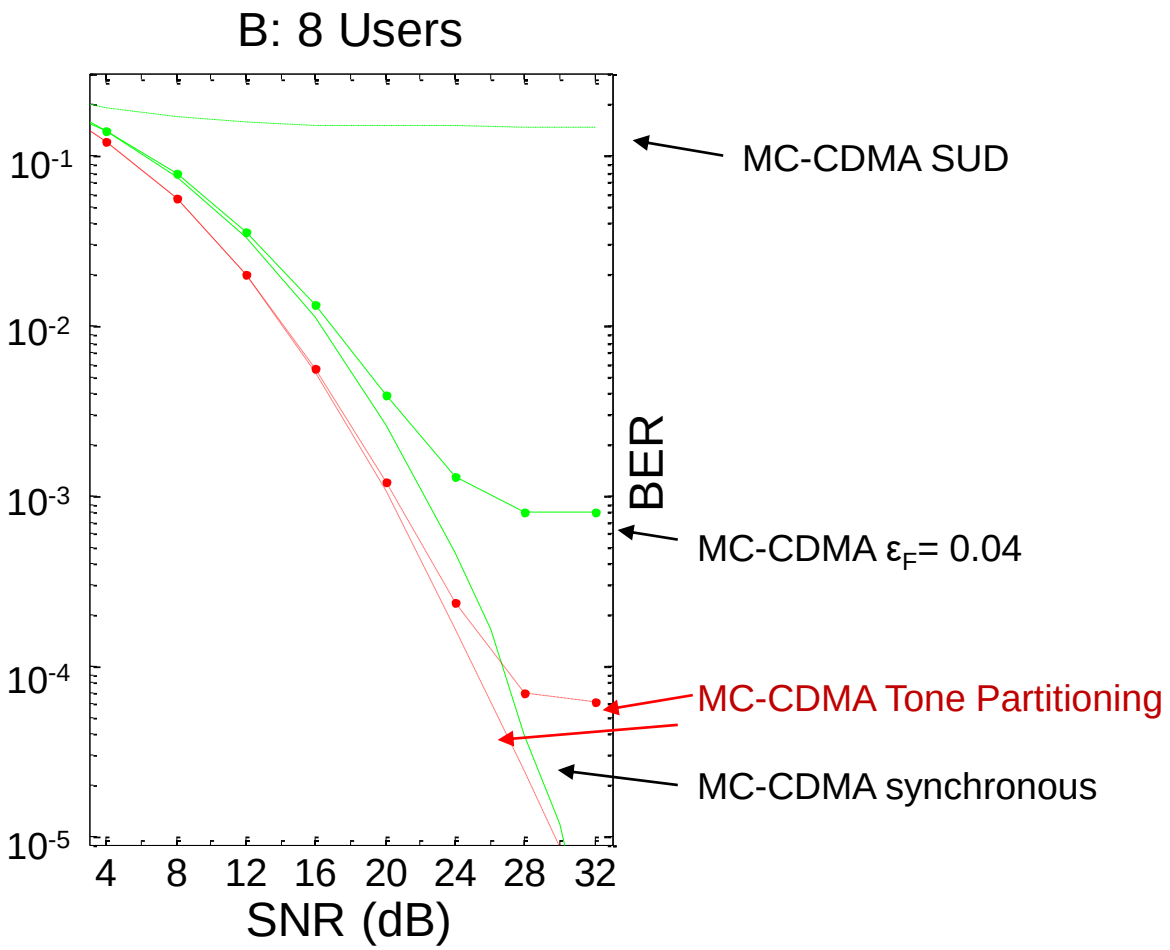
Realization of Concatenated DMT-FMT



Orthogonal Data Spreading + Cyclic TX Diversity to increase spatial diversity

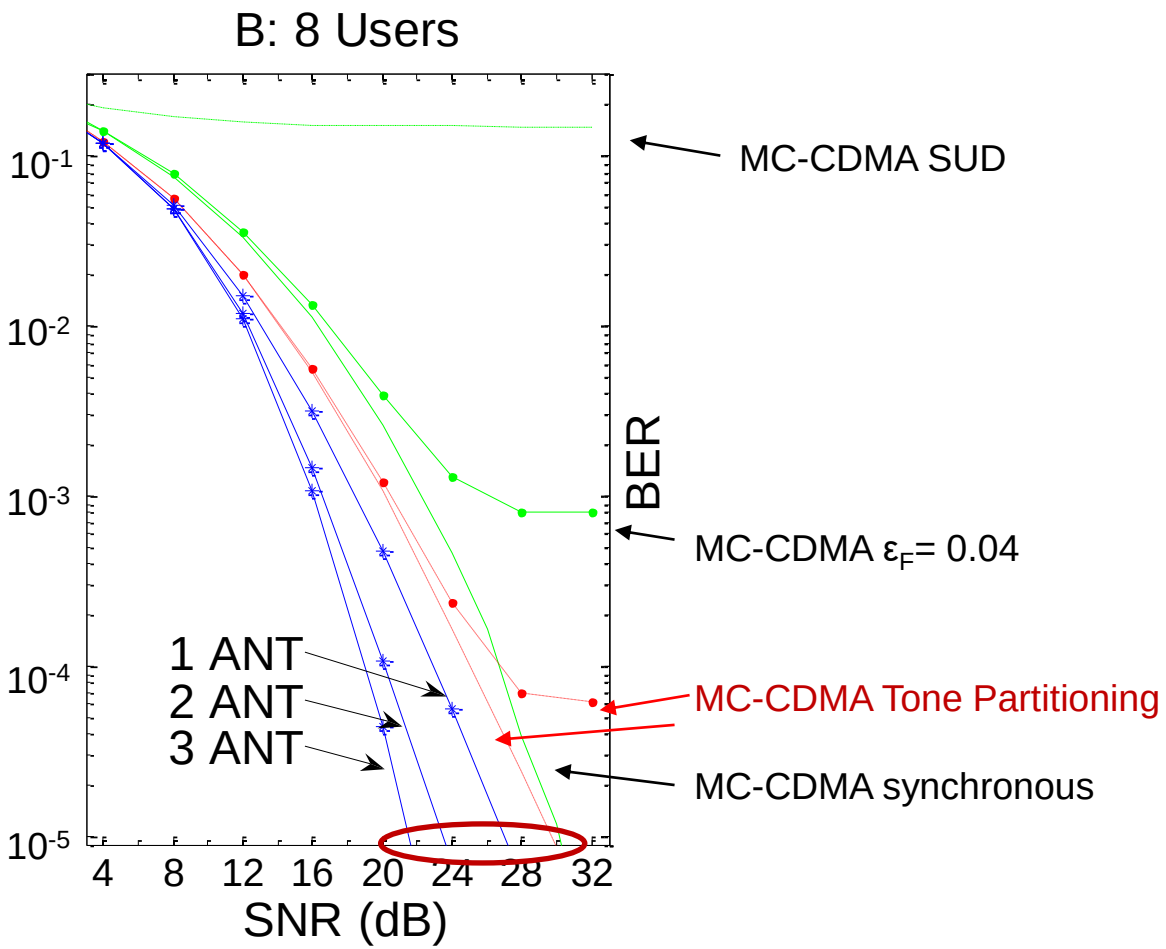
REF. A. Tonello, M. Bellin, "**Low-Complexity Realization of a Concatenated DMT-FMT Multiuser Uplink System with Transmit Diversity**", *IEEE TVT 2009*

Concatenated OFDM-FMT vs. MC-CDMA in asynchronous uplink



- MC-CDMA with 128 Tones and with Walsh Codes Length 128

Concatenated OFDM-FMT vs. MC-CDMA



- FMT with 32 Tones, OFDM with 32 Tones, and Walsh Codes Length 128
- **Concatenated DMT-FMT performs significantly better than MC-CDMA in the uplink !**

Goal: do better than FMT

Cyclic Block FMT Modulation

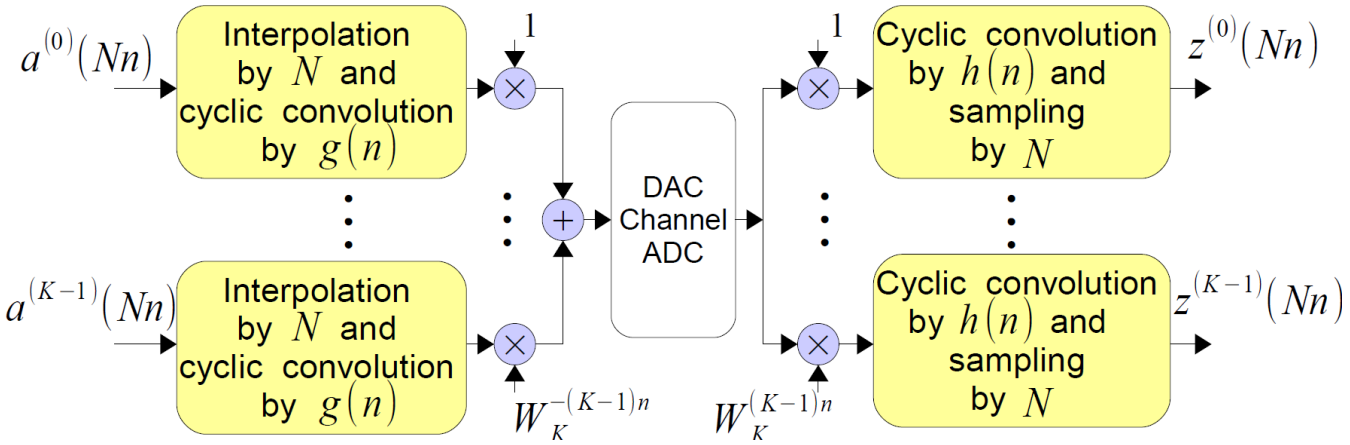
What is CB-FMT about ?

- **Combine, possibly, the positive aspects of OFDM and FMT:**
  - Block transmission (OFDM)
  - Orthogonality (OFDM)
  - Efficient implementation (OFDM)
  - Sub-channel frequency selectivity (FMT)
  - Robustness to time/frequency impairments (FMT)
  - Better peak-to-average power ratio (FMT)

Cyclic Block FMT: modulation scheme based on the filter bank concept

CB-FMT: the Idea

- Replace the linear convolutions with circular convolutions !
  - Sub-channel sequences are grouped in blocks of length L
- CB-FMT is a cyclic filter bank



2008 A. Tonello, **"Method and Apparatus for Filtered Multitone Modulation using Circular Convolution"** , Patent WO2009135886A1

2013 A. Tonello, "**Novel Multi-carrier Scheme: Cyclic Block Filtered Multitone Modulation**", Proc. IEEE ICC 2013

2014 A. Tonello, M. Girotto, "**Cyclic Block Filtered Multitone Modulation**," EURASIP J. Adv. Signal Proc., 2014

2016 M. Girotto, A. M. Tonello, "**Orthogonal Design of Cyclic Block Filtered Multitone Modulation**," IEEE Trans. Comm., Nov. 2016

Others Cyclic Filter Bank Schemes (all particular examples of CB-FMT)

SC-FDMA: Single-Carrier FDMA

- Adopted in LTE uplink
- Similar to CB-FMT with rectangular pulse in frequency domain

2006 H.G.Myung, J. Lim; D. Goodman, "**Single carrier FDMA for uplink wireless transmission**," IEEE VT Magazine, Sept. 2006

GFDM: Generalized Frequency Division Multiplexing

- Proposed for 5G
- Non-orthogonal system

2009 G. Fettweis, M. Krondorf, S. Bittner, "**GFDM - Generalized frequency division multiplexing**," IEEE VTC 2009

C-OQAM/OFDM: Cyclic Offset-QAM OFDM

- Cyclic filter bank version of Offset QAM / OFDM

2014 H. Lin, P. Siohan. "**Multi-carrier modulation analysis and WCP-COQAM proposal.**" EURASIP J. Adv.Signal Proc. 2014

Implementation and Equalization of CB-FMT

Digital Implementation

- Let us compute the M_2-point DFT of x(n) (transmitted signal). Then, we obtain

$$X(i) = \sum_{k=0}^{K-1} A^{(k)}(i - kQ)G(i - kQ)$$

L-point DFT of data symbol block $\mathbf{a}^{(k)}$ — M_2-point DFT of pulse g(n)

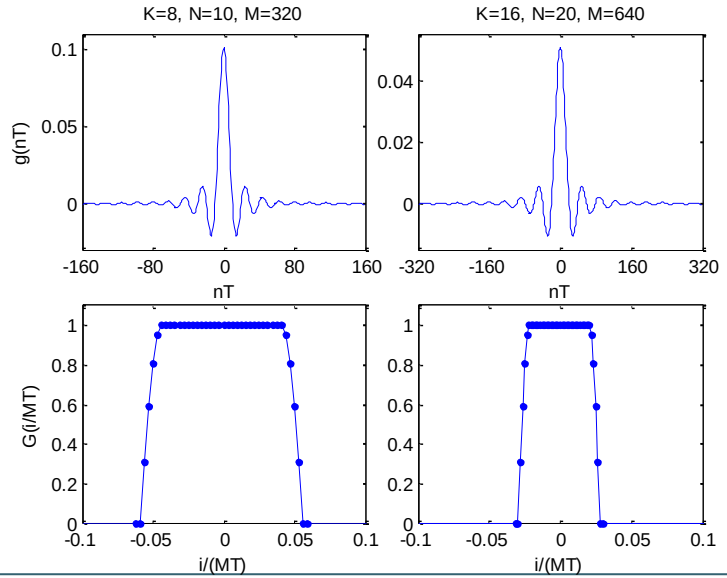
with M_2=LN=QK

- If $G(i)$ has only Q non zero coefficients, we will obtain

$$X(i) = A^{(k)}(i - kQ)G(i - kQ)$$
$$k = 0,\ldots,K-1$$
$$i = kQ,\ldots,(k+1)Q-1$$

Baseline Prototype Pulse Design

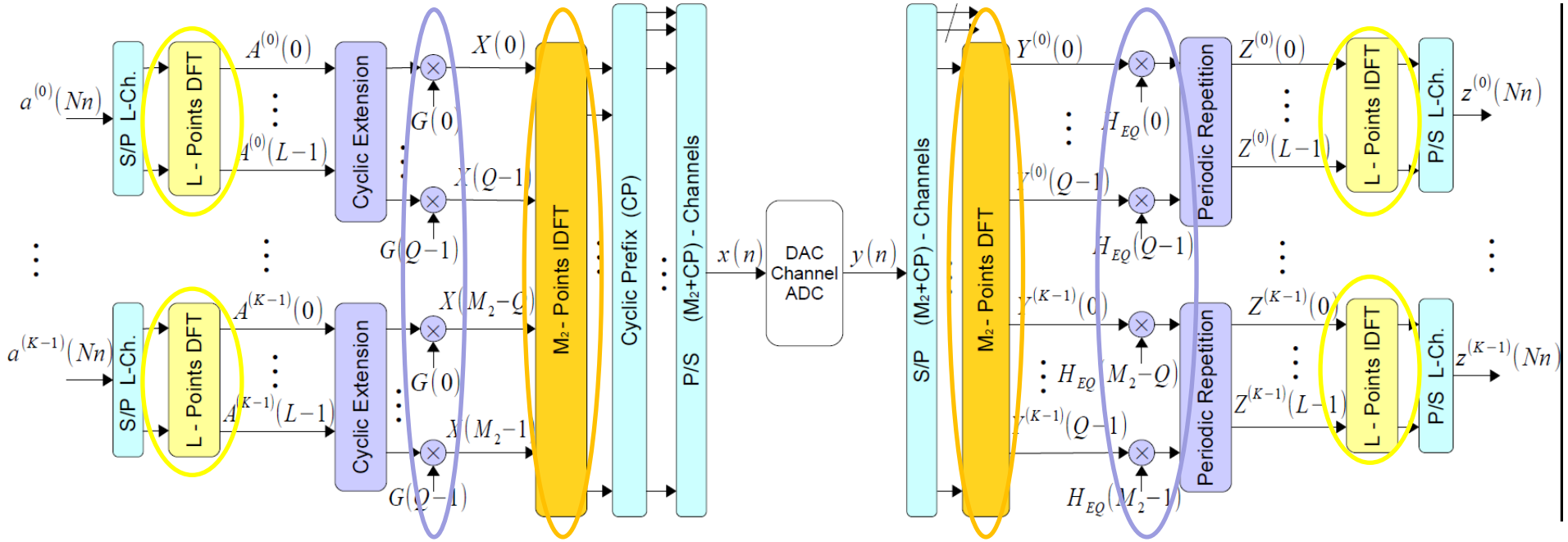
- Pulse modeled as a causal M_2-points FIR filter
  - $M_2=LN$, N is the interpolation factor, L is the block size
- Pulse at the receiver matched to transmission pulse: $g(n)=h^*(-n)$
- Orthogonality criterion
  - Choose a pulse with only Q non zero frequency coefficients
  - The pulse must be orthogonal to its cyclic translations of multiples of N
- Simple design procedure in the frequency domain
  - Sample in the FD a root-raised cosine pulse obtaining Q coefficients



Rate

$$R=\frac{K}{NT}\ symb/s$$

CB-FMT: Example of Realization Scheme



- CB-FMT can be efficiently implemented in the frequency domain
  - Orthogonal pulse design can be done in the FD[1]
- A cyclic prefix can be inserted in each transmitted block to cope with channel dispersion (not mandatory)
- A simple one-tap FD equalizer can be used (MMSE or ZF) whose coefficients are $H_{EQ}(i)$

[1] Frequency domain pulse design is possible also for FMT but no orthogonality, see A. M. Tonello, F. Pecile, "**Efficient Architectures for Multiuser FMT Systems and Application to Power Line Communications**", *IEEE TCOM 2009*.

Cyclic Filter Bank Orthogonal Design: Orthogonal CB-FMT

Orthogonality Conditions

- Easy to manipulate in frequency domain
  - Extension of bi-dimensional Nyquist criterion to a cyclic filter bank
  - Conditions are imposed on the *M*-points DFT of the prototype pulse

No ISI Condition

$$R^{(k,k)}(q) = \frac{1}{N}\sum_{s=0}^{N-1}\left|G\left(q+sL+kQ\right)\right|^2 = 1$$

No ICI Condition

$$R^{(k,h)}(q) = \frac{1}{N}\sum_{s=0}^{N-1}G\left(q+sL+kQ\right)G^*\left(q+sL+hQ\right) = 0$$

$$\forall q \in \{0,\dots L-1\}, \forall k,h \in \{0,\dots K-1\}, k \neq h$$

Parameters

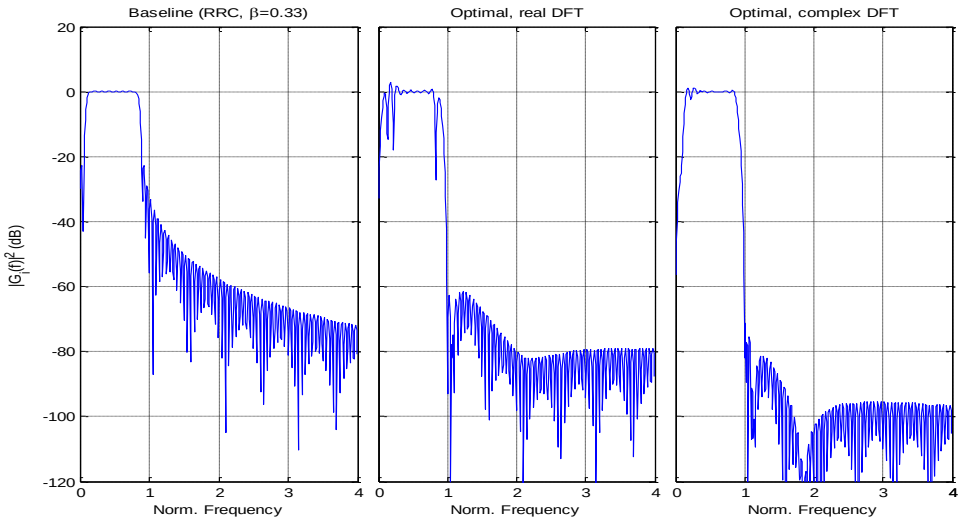
M: filter length
K: sub-channels
N: interpolation factor
L: block size
Q: M/K

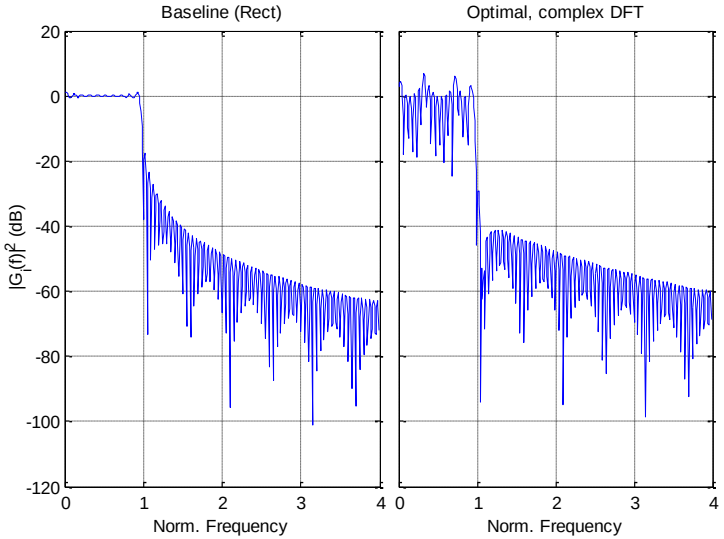
- For a certain *k*, this is a system of *KL* equations in *M* unknowns

M. Girotto, A. M. Tonello, "**Orthogonal Design of Cyclic Block Filtered Multitone Modulation**," IEEE Trans. Comm., Nov. 2016

Angular Solutions

- Efficient search of orthogonal pulses with optimal spectral efficiency
  - Parameterize pulses with angles, segment the system of equations into sub-systems, solve iteratively

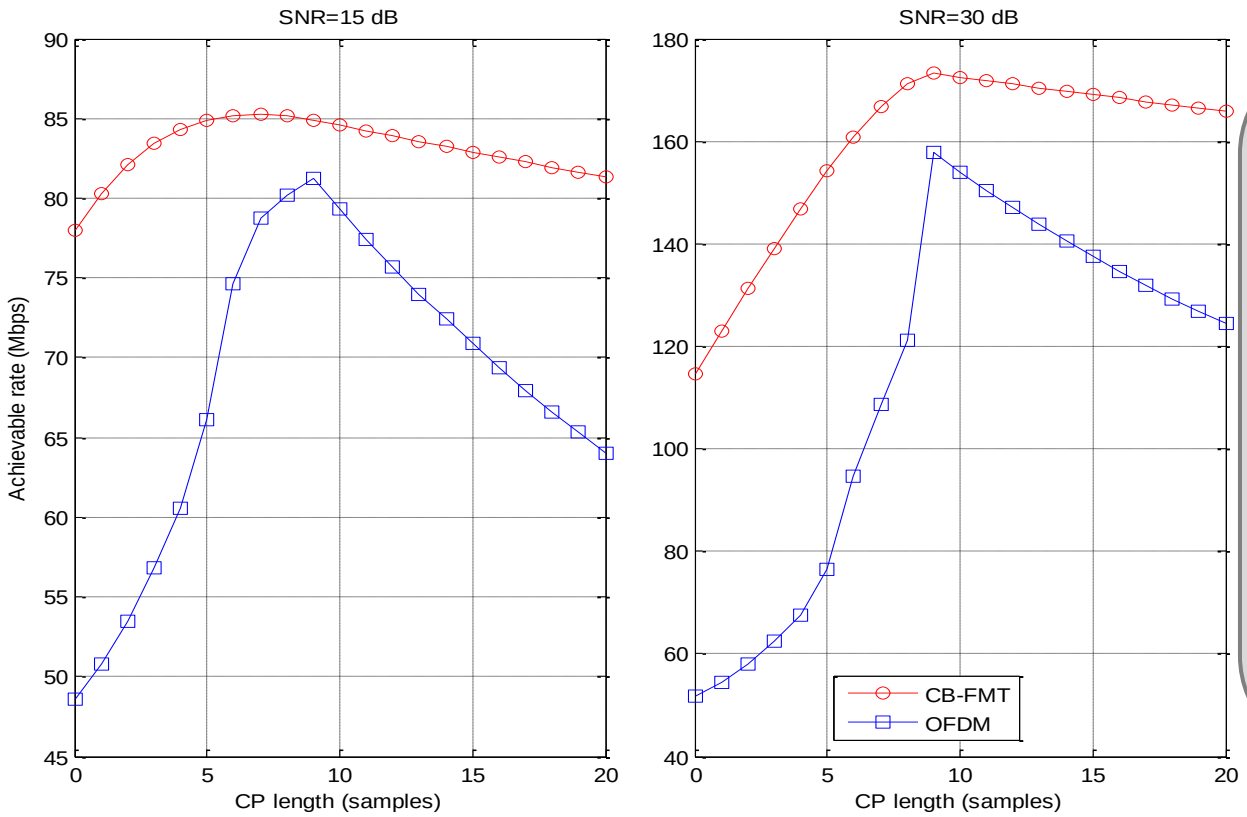




- Frequency response of the prototype pulse
  - Baseline pulse: root-raised-cosine
  - K=12, N=16, M=240

- Frequency response of the prototype pulse
  - Baseline pulse: rect pulse in FD
  - K=12, N=12, M=240

Mean Capacity as a Function of the CP Length



CB-FMT:
K=24, N=24, M=240

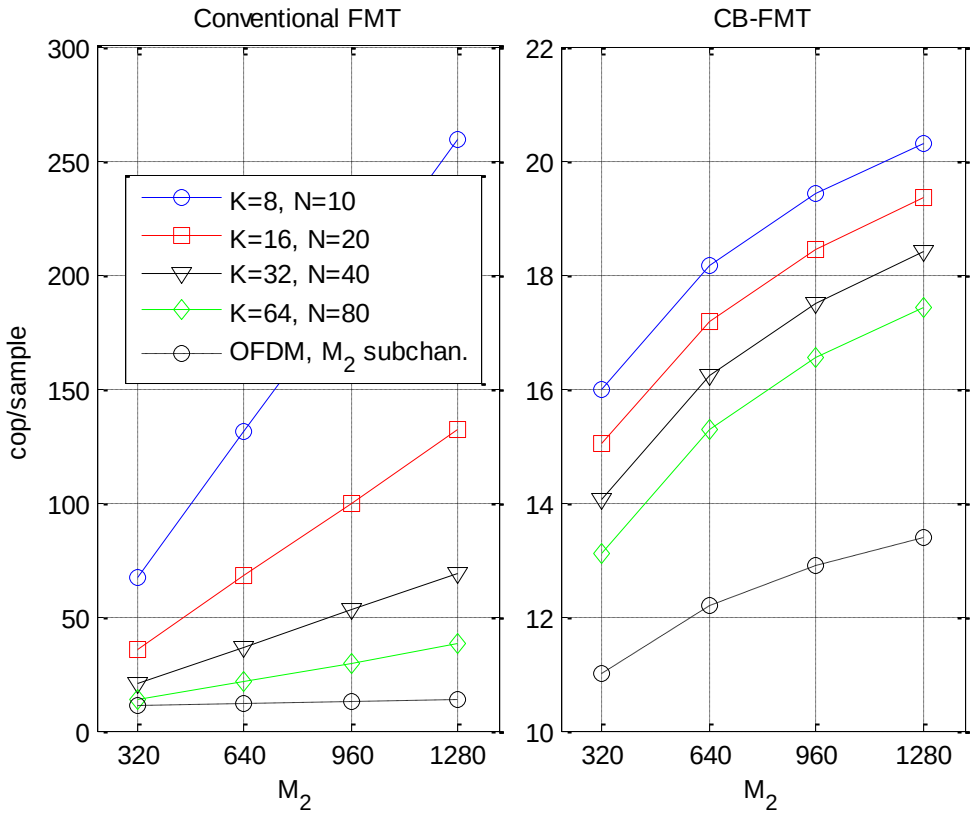
OFDM: K=32

Channel:
Rayleigh fading model,
delay spread of 0.15 us

- CB-FMT is capable to exploit the sub-channel frequency diversity
- CB-FMT requires a shorter CP than OFDM

Complexity of CB-FMT

Complexity

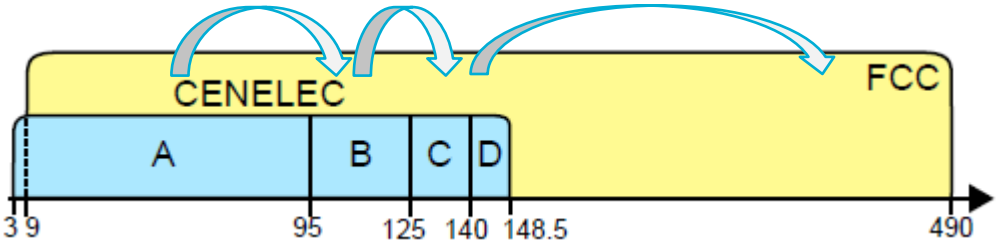


- **Conventional FMT:** 3-12 times more complex than CB-FMT with the same pulse length M_2 and the same number of sub-channels
- **OFDM:** less complex by a factor 1.1-1.6 than CB-FMT

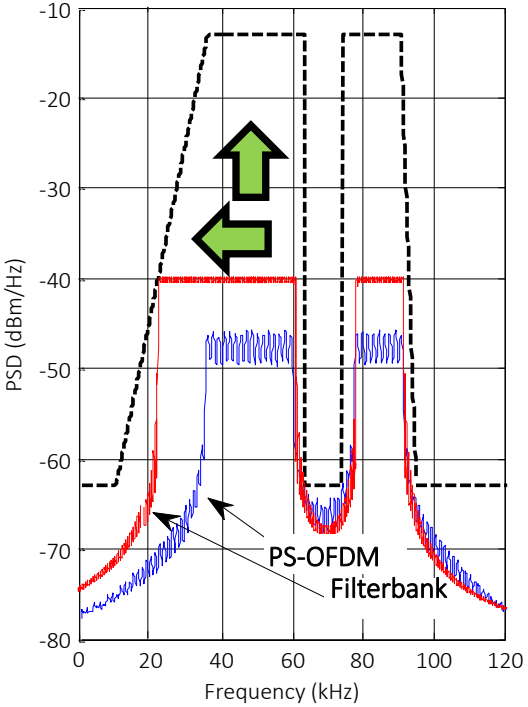
PSD related aspects in CB-FMT

Flexible spectrum usage and EMC enhancements

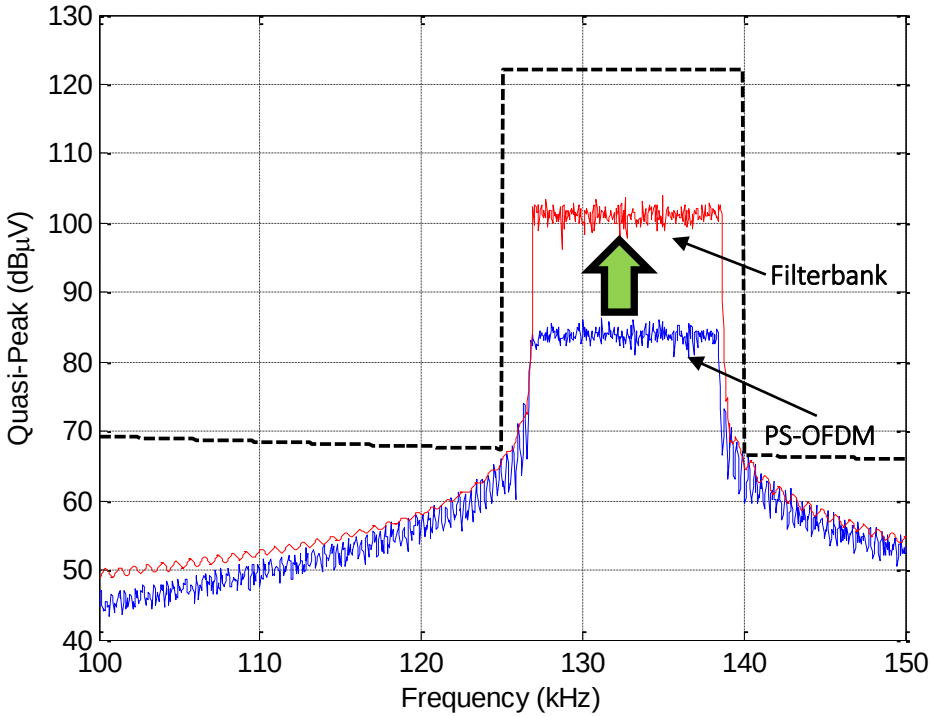
- PLC example



CENELEC A - G3-PLC SPECTRAL MASK



CENELEC C - EN50065 SPECTRAL MASK

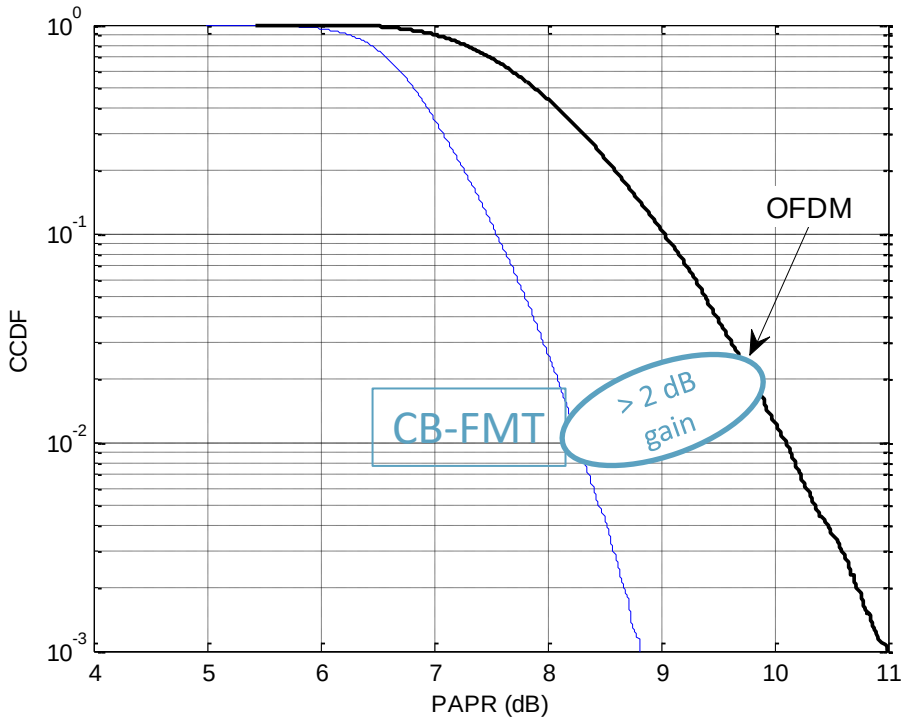


- **Filterbank modulation** allows better usage of the spectrum still respecting regulation masks
- Higher throughput and lower latency is achievable w.r.t. OFDM solutions defined in standards

REF. M. Girotto, A. Tonello, "**Improved Spectrum Agility in Narrow-Band PLC with Cyclic Block FMT Modulation**," *IEEE GLOBECOM 2014*

Peak-to-Average Power Ratio

- The high PAPR is a known drawback of OFDM
- FB modulation may alleviate such a problem especially if we use a lower number of sub-channels
- CB-FMT has lower PAPR depending on the choice of the parameters

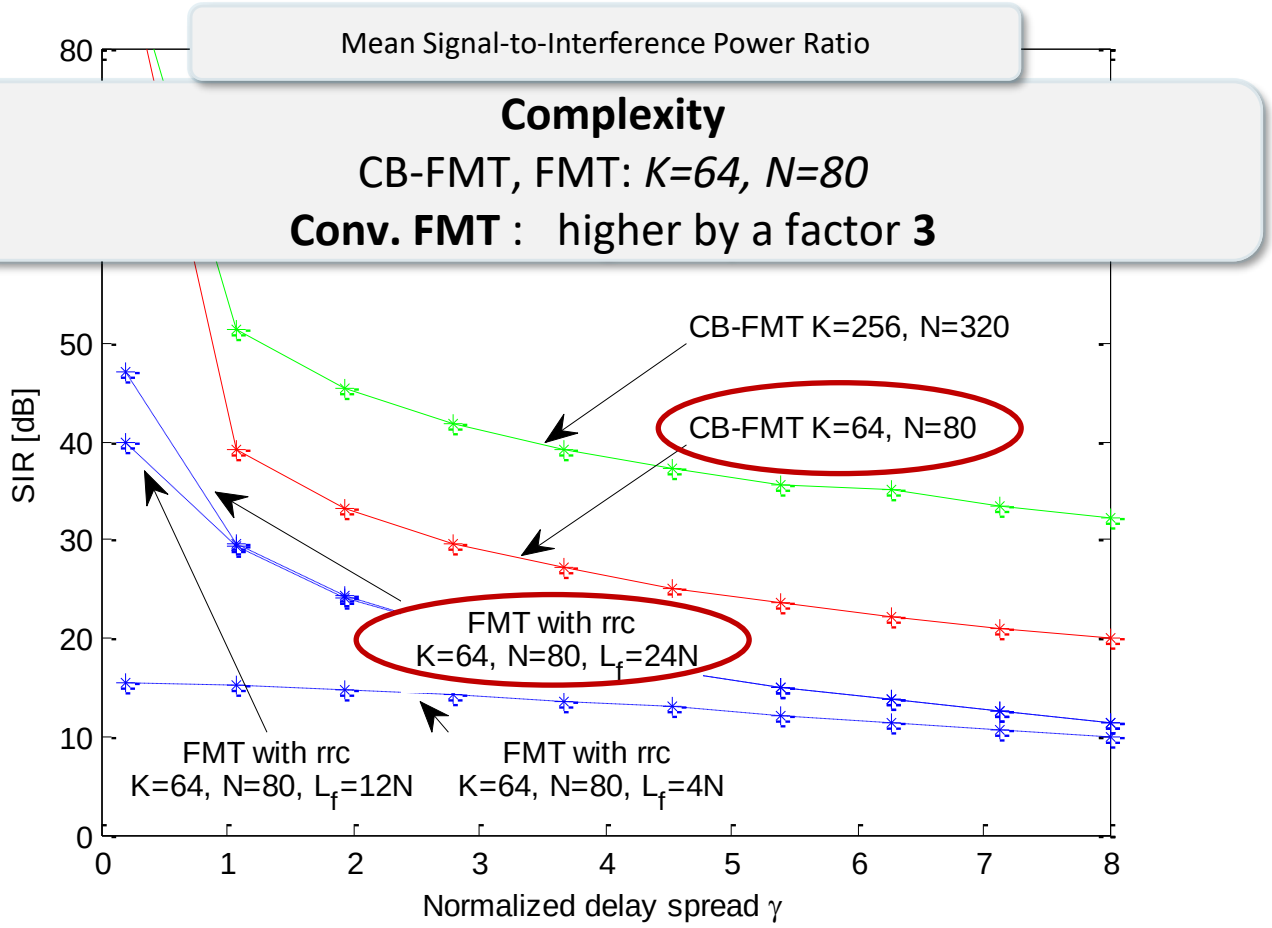


M_2=1024 for both OFDM and CB-FMT

Performance in Fading Channels of CB-FMT

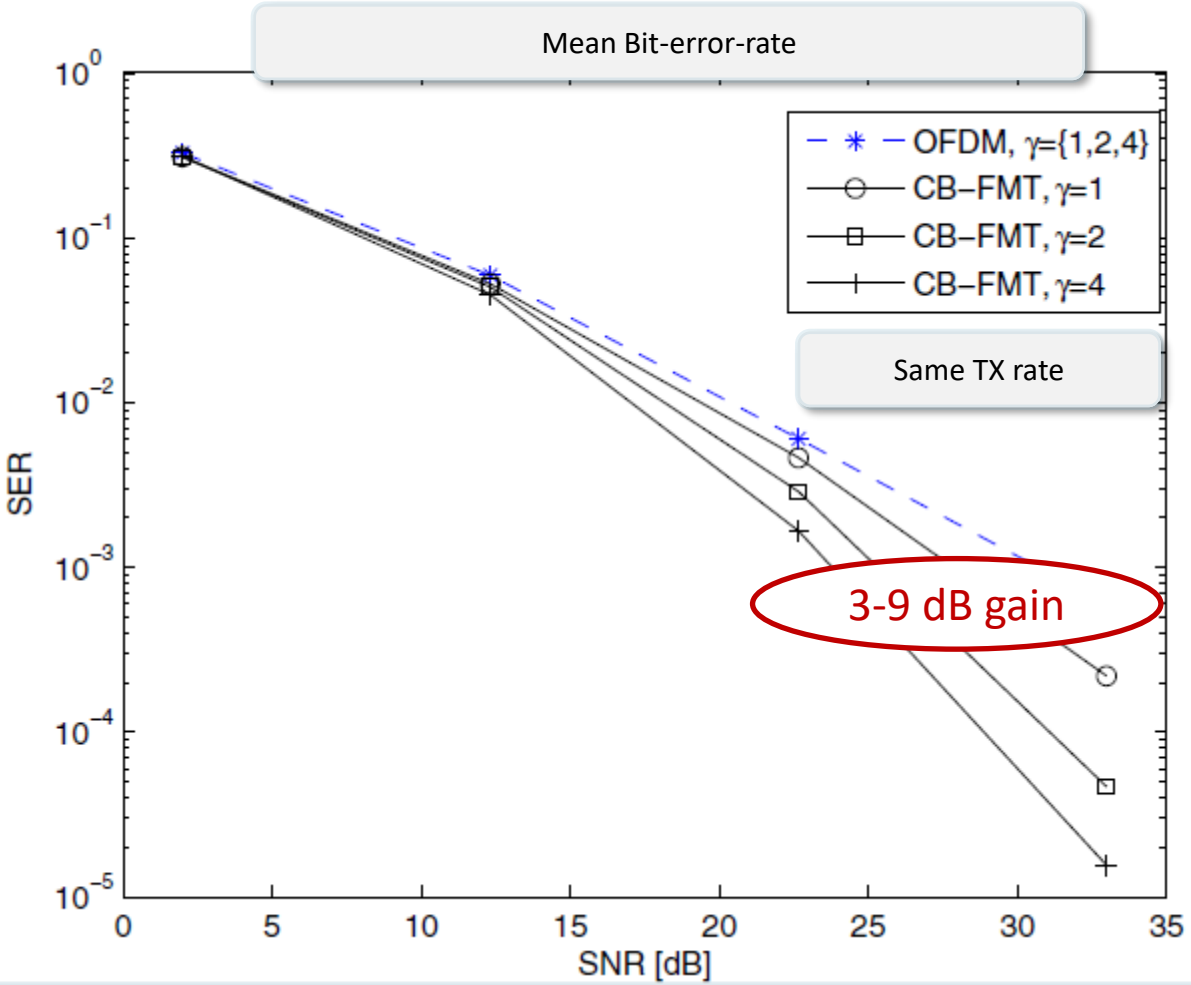
SIR: CB-FMT vs. FMT

- Rayleigh fading channel with exponential power decay profile with delay spread γ



- No cyclic prefix is used when we evaluate the SIR
- CB-FMT is significantly more robust to delay spread and significantly less complex than FMT

BER: CB-FMT vs. OFDM



Complexity compared to OFDM

CB-FMT: higher by a factor 1.6 with the specific choice of parameters

Other Aspects Not Discussed about FMT Modulation

Other Areas Where FMT has a Role

- Power line communication channels: notching capability and SNR gain [R1]
- Doubly selective fading channels: FMT can be interpreted as a diversity transform and it provides time/frequency diversity gains [R2]
- Hardware impairments: robustness to phase noise and asynchronism (time-frequency offsets)[R3]
- MIMO: multiple antenna transmission and precoding [R4]
- Multiple user channels: synchronization, channel estimation and MU detection [R5]-[R7]
- Variations of CB-FMT: zero padded CB-FMT [8], pulse shaped CB-FMT [9].

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Conclusions

- Shown that linear and cyclic filter banks can represent “any” exponentially modulated multicarrier modulation scheme
- The FMT and CB-FMT architectures encapsulate almost all other schemes. The difference exists only in the choice of the pulse
- Presented:
  - FMT
  - Adaptive FMT
  - Concatenated DMT-FMT
  - Cyclic FMT: CB-FMT

It is the time to deploy filter bank modulation

PLC standards have included it

Let’s see what will happen in wireless !

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Thank you !

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