Courses of the 24th Jyväskylä Summer School , August 2014. Finland

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Course on: Beyond OFDM Radio Interfaces Facilitating Spectrum Coexistence and Secondary Access

Supélec

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Outline of the course

- PART 1 (**Flexible MC waveforms**)
  1. Introduction/motivations
  2. Introduction to multicarrier signal
     - Overview of MC techniques (OFDM and its variations)
     - Other multicarrier schemes: features summary
       i. OFDM/OFDMA
       ii. DMT
       iii. FB Based MC (FMT, CMT)
       iv. FBMC/OQAM
       v. Polyphase decomposition
       vi. Comparative features
- PART 2 (**Exemplary results: OFDM vs. FBMC**)
  1. Resource allocation for spectrum sharing in CR environment
  2. DF Multi-relay in CR scenario

Outline of the course

3. Power loading: An Analysis with Mercury-filling
4. Analysis of Asynchronous OFDM/FBMC Wireless Comm.
5. Comparison of MIMO OFDM/FBMC for IA in CR

- PART 3 (**Projects and Practical Applications**)
  1. Previous and actually running EU funded projects focusing on filter based Multicarrier waveforms
  2. Application of flexible multicarrier waveforms
     - In TV white spaces
     - Machine to Machine
     - Future broadband Professional MobileRadio (PMR)/(PPDR) systems
- PART 4 (**5G Wireless Communication Concept Eco-System**)
  - Beyond LTE (5G) Communication Systems
  - EC H2020 5G Infrastructure PPP

Outline of the course

- PART 5 (**FBMC Implementation and Link level Simulations**)
  1. FBMC implementation challenges and extensions:
     - Channel estimation in FBMC systems
     - Equalization and CFO compensation
     - Fast Convolution (FC) Filter Banks
     - Non-uniform FBs
     - Generalized FDM (GFDM)
  2. Simulations for MC systems
     - Introduction to Simulations
     - Link-level simulations of FBMC system
     - Link to System interface for MC systems
     - System level simulations and NS3 simulator

Part I: Flexible MC waveforms

Introduction/motivations

Why Flexible Multicarrier Waveforms?

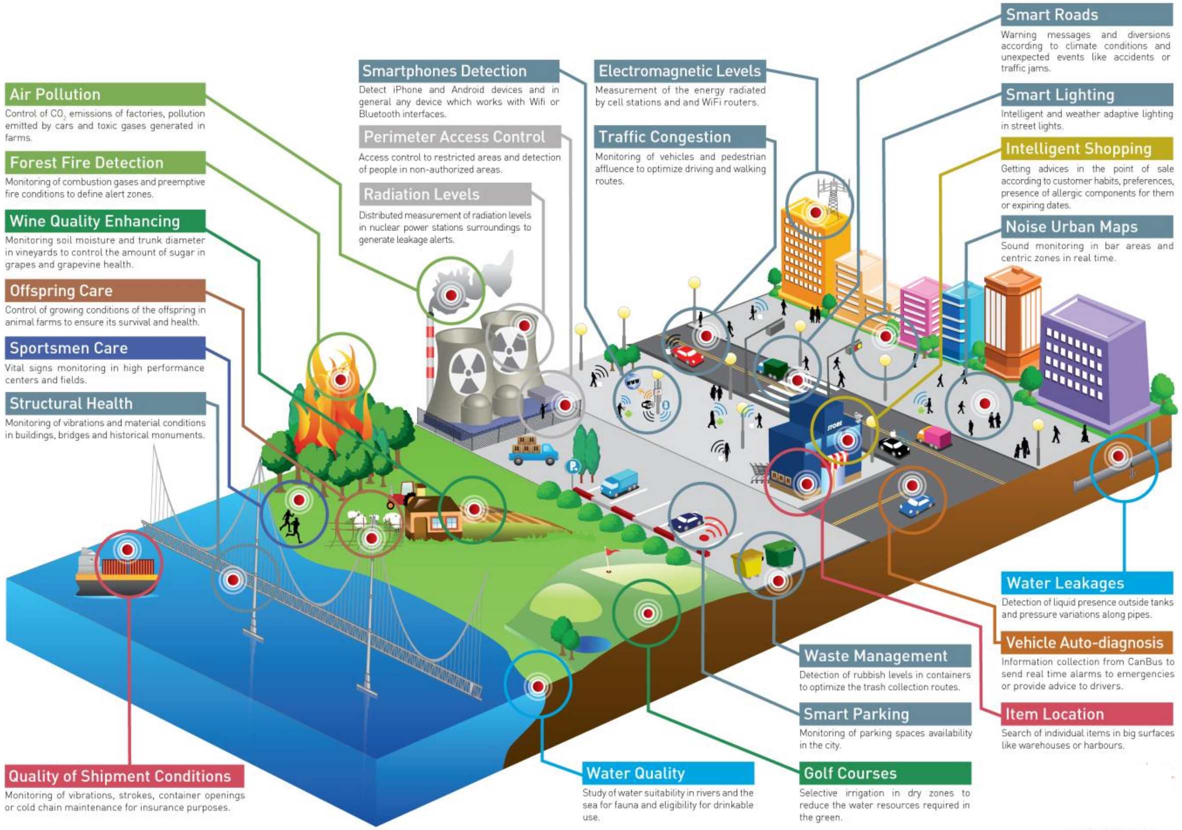
Gigabit Wireless Connectivity

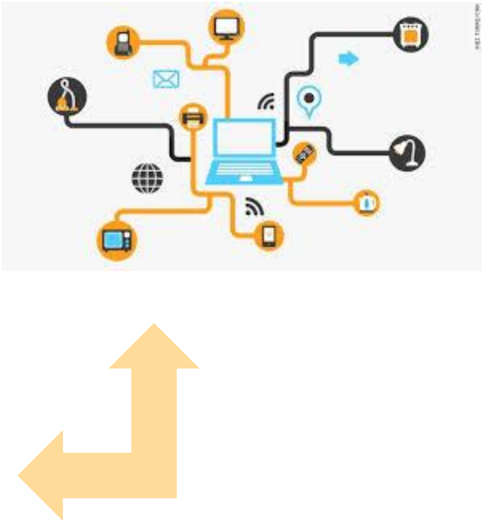
- Examples: 3D video streaming, large crowd gatherings

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

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 (PAPR, 100x better localization)

Tactile Internet (TI)

100ms

10ms

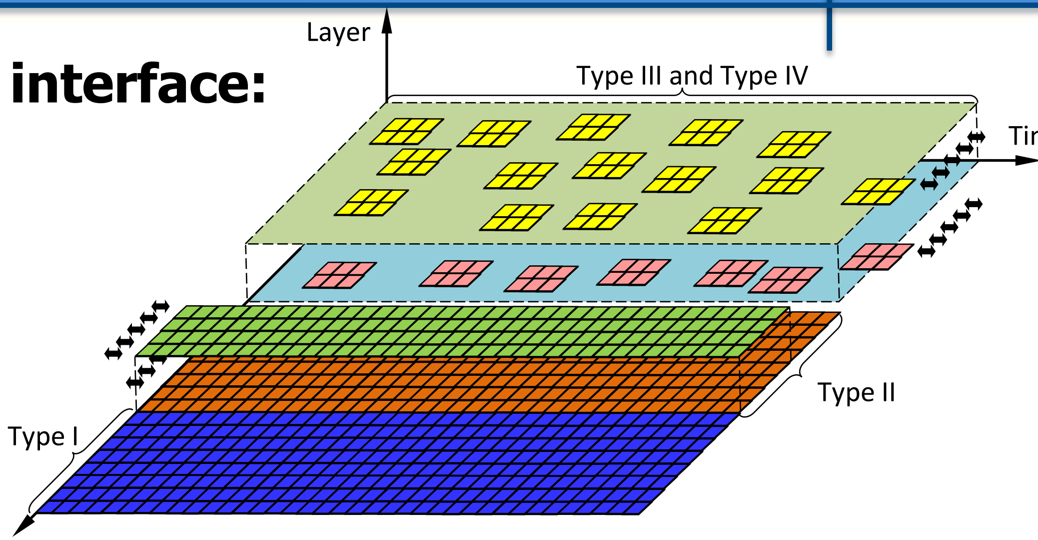
1ms

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')



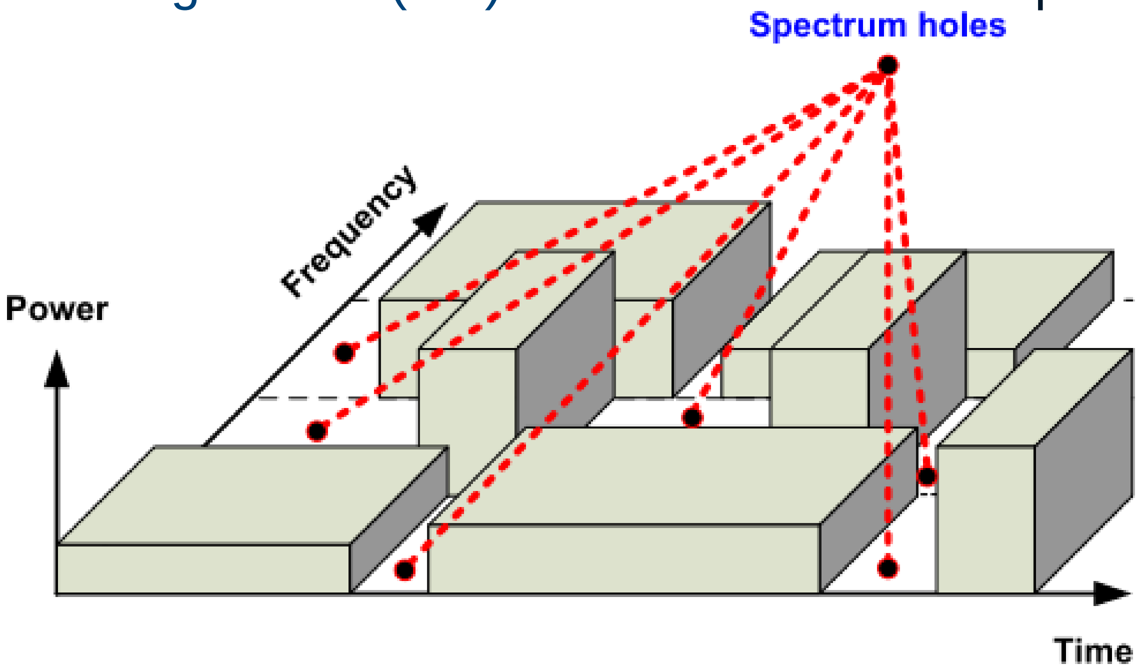
Traffic Type	Synch?	Access Type	Properties
I	closed-loop	scheduled	classical high volume data services
II	open-loop	scheduled	HetNet and/or cell edge multi-layered high data traffic
III	open-loop	sporadic, contention-based	few bits, supporting low latency, *e.g. smartphone apps*
IV	open-loop/none*	contention-based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

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

Source: Gehard Wunder/5GNOW

Targets.....

- The spectrum scarcity is considered as one of the serious problem.
- Cognitive radio/algorithms (CR) aims to increase the spectrum utilizatior
- Multicarri ... ıte for cognitive
  1. Oper
  2. Flexi
  3. FBM
- Combinir ... ıe achievab



Application Challenges

Wireless Access:

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

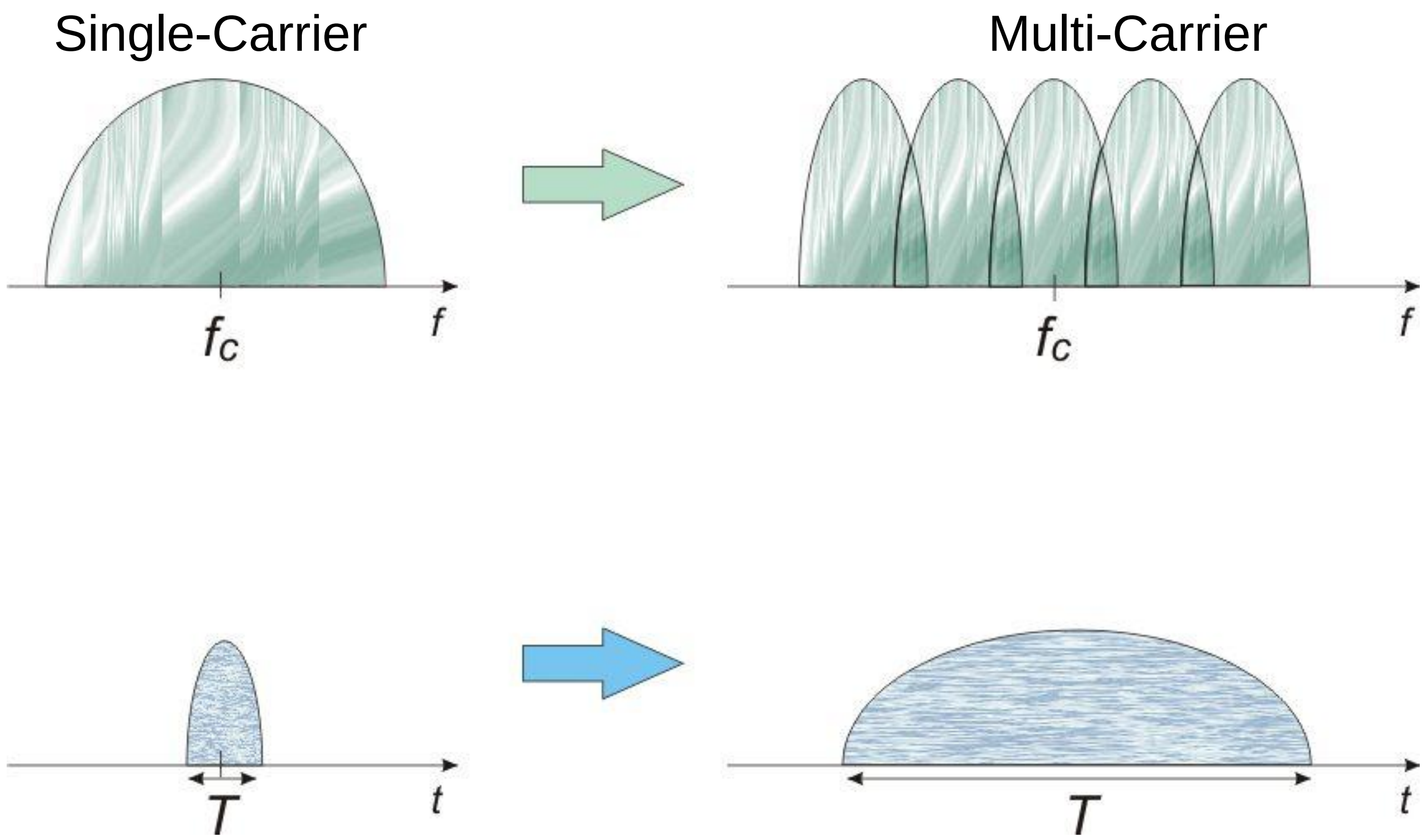
Requirements

- Flexibility: Cyclic prefixes reduce spectral efficiency and prohibit flexible handling of frame formats
- Scalable: Spectral localization is too bad, e.g. in narrowband setting up to 4-6 subcarrier gain by different waveforms
- Robust and Reliable: OFDM is very sensitive both in time and frequency domain due to FFT
- Fast: Very difficult to support short symbols with given channel delay spread
- Efficient (energy, spectrum): OFDM is not robust under incomplete channel state information

Part I : Flexible MC waveforms

Introduction to multicarrier signal

Single Carrier and Multi Carrier



Single Carrier and Multi Carrier

Single Carrier

- Short pulse duration (wide in frequency domain)
- Robust to frequency synchronization errors
- Sensitive to fading in frequency domain
- Low variation of the signal amplitude in time domain

Multi Carrier

- Longer time duration of the transmit pulse
- Sensitive to frequency synchronization errors
- Effective and simple estimators can be applied
- High variation of the signal amplitude in time domain

Overview of MC techniques I.

- Multicarrier Communications (MC) are promising techniques in Cognitive Radio CR
- Moreover, MC based CR 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 in the CR system without any extra hardware complexity (really ?).
- Several parameters can be adjusted in the system like subcarrier spacing, subcarrier number, modulation, coding and powers.

Overview of MC techniques II.

- **OFDM is the most common MC technique.**

It is widely used in many of the current and coming wireless and wireline standards, e.g., VDSL, DAB, DVB-T, WLAN (IEEE 802.11a/g), WiMAX (IEEE 802.16), 3G LTE and others as well as the 4G wireless standard, since next generation wireless systems will be fully or partially OFDM-based.

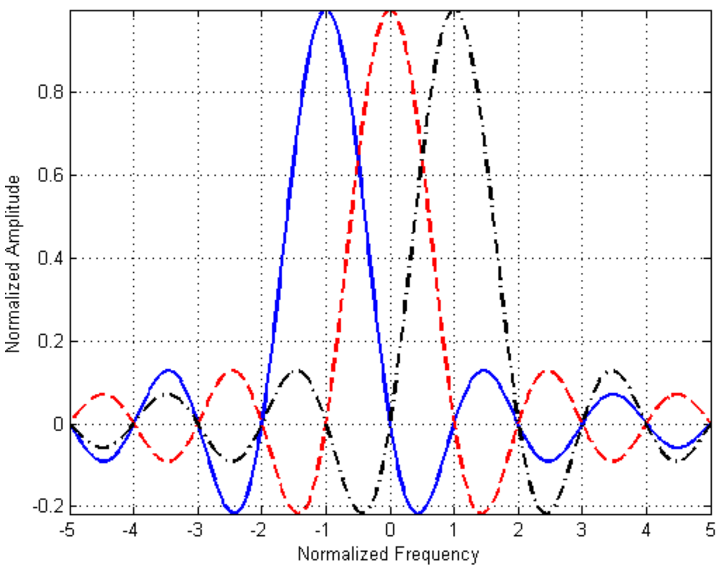
OFDM employing baseband quadrature amplitude modulation and rectangular pulse shape (OFDM/QAM).

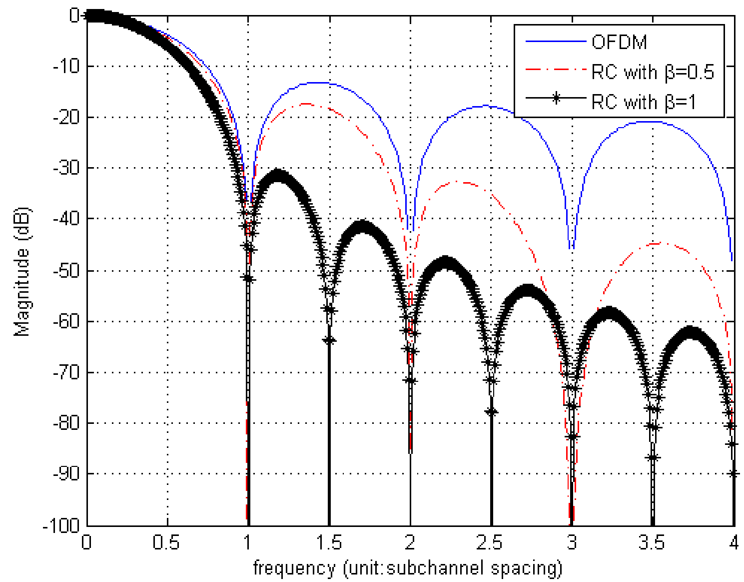
In an ideal channel where no frequency offset is induced, inter-carrier interference (ICI) can be fully removed by orthogonality between sub-carriers.

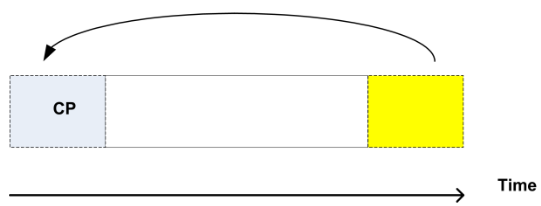
Inter-symbol interference (ISI), which is caused by multipath propagation, can also be eliminated by adding a guard interval (i.e., a cyclic prex. after OFDM modulation1)

Overview of MC techniques III.

- OFDM is the most common MC technique.







WLAN, WMAN, etc.

IEEE 802.22

Large side lobes, and use Cyclic Prefix (CP) !

costs a loss of spectral efficiency and increases power consumption

Overview of MC techniques III.

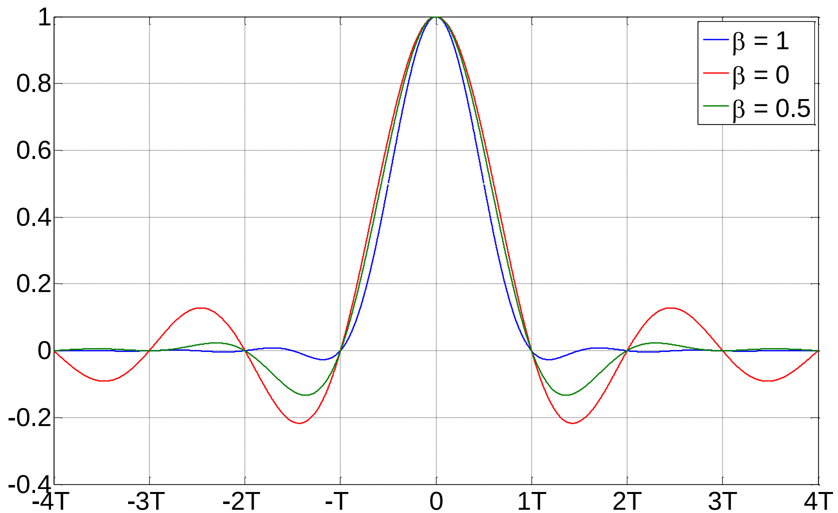
- In order to reduce the Inter Symbol Interference (root)-raised-cosine filter is used

Raised cosine

$$h(t) = \mathrm{sinc}\left(\frac{\mathrm{t}}{\mathrm{T}}\right)\frac{\cos\left(\frac{\pi\beta t}{T}\right)}{1-\frac{4\beta^2 t^2}{T^2}}$$

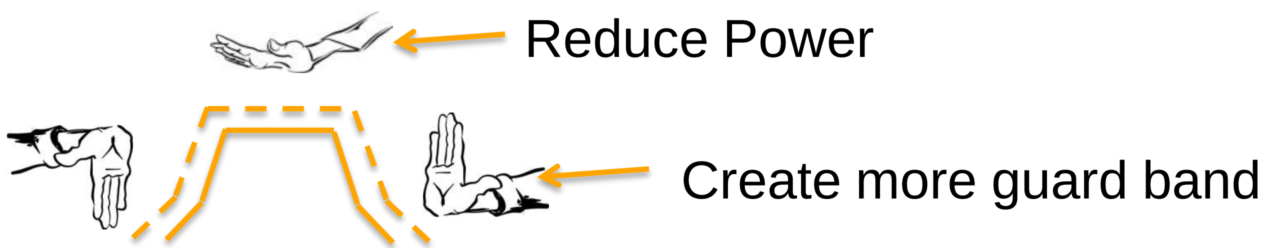
$$H(f) = \begin{cases} \mathrm{T} & \text{for} \quad |f| \le \frac{1-\beta}{2T} \\ \frac{T}{2}\left[1+\cos\left(\frac{\pi\beta}{T}\left(|f|-\frac{1-\beta}{2T}\right)\right)\right] & \text{for} \quad \frac{1-\beta}{2T} < |f| < \frac{1+\beta}{2T} \\ 0 & \text{otherwise} \end{cases}$$

$$\beta = 2T\Delta f$$



OFDM and its Variations

- OFDM is the most popular multicarrier modulation technique
- It is well recognized that large side lobes of OFDM waveform is a critical issue for it to be a viable waveform for future spectral agile networks
- Simple Solution



Low spectrum usage & Low coverage;

Source: Erdem Bala (InterDigital, USA)

- Other Advanced Solutions

Time Domain Filtering	**Domain Windowing/ Pulse**	**Frequency Domain Precoding**	**N-Continuous**

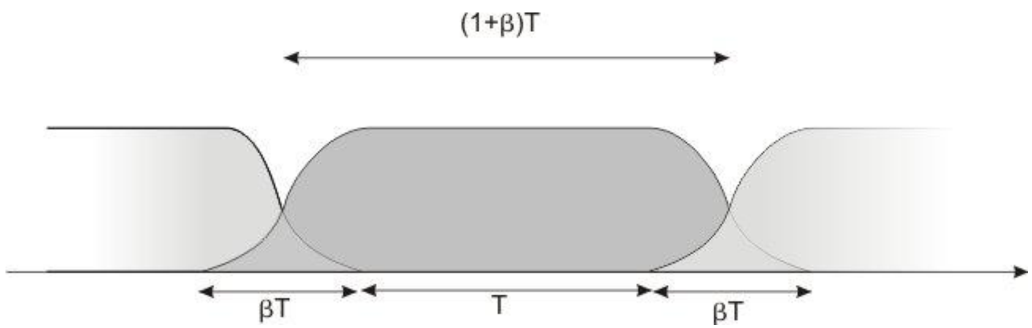
Time domain filtering

- Time domain filtering allow us to reduce the out-of-band radiation
- Filtering in time domain is equivalent to multiplication in frequency domain, thus OOB can be limited

Time Domain Filtering | Domain Windowing/ Pulse | Frequency Domain Precoding | N-Continuous

Windowing

- Rectangular pulse leads to high spectrum sidelobes
- By application of different pulse (windowing in time domain) the OOB can be reduced
- The concept here is to eliminate the "steepness" of the edges between the consecutive OFDM symbols



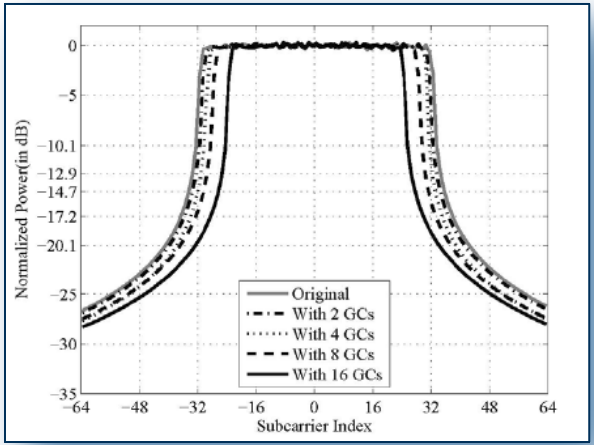
Time Domain Filtering

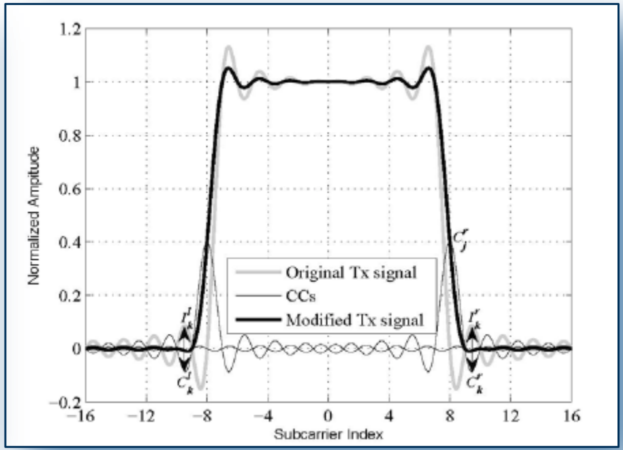
Domain Windowing/ Pulse

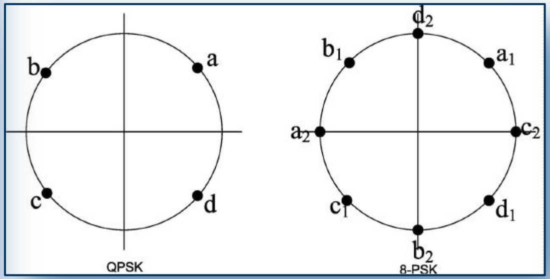
Frequency Domain Precoding

N-Continuous

- Guard bands, Cancellation Carriers, Constellation Extension







Source: "Cognitive Radio Communications and Networks: Principles and Practice"
By A. M. Wyglinski, M. Nekovee, Y. T. Hou (Elsevier, December 2009)

Time Domain Filtering | Domain Windowing/ Pulse | **Frequency Domain Processing** | N-Continuous

N-continuous OFDM

- Specifically, the proposed construction will render the transmitted signal *s(t) and its first N derivatives continuous by satisfying*

$$\frac{d^n}{dt^n} s_i(t)\Big|_{t=-T_g} = \frac{d^n}{dt^n} s_{i-1}(t)\Big|_{t=T_s},$$

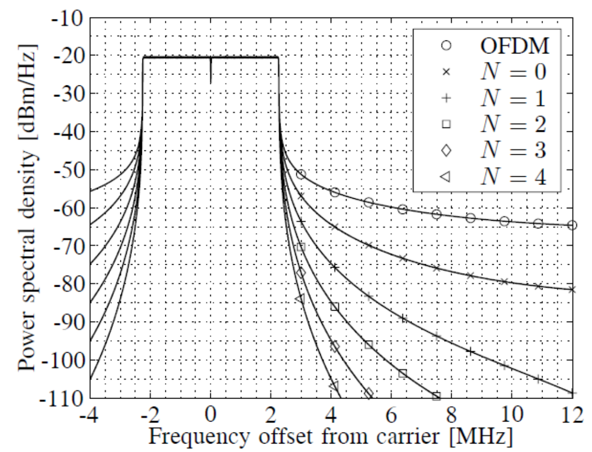


Fig. 3. Power spectral density of conventional and N-continuous OFDM signals.

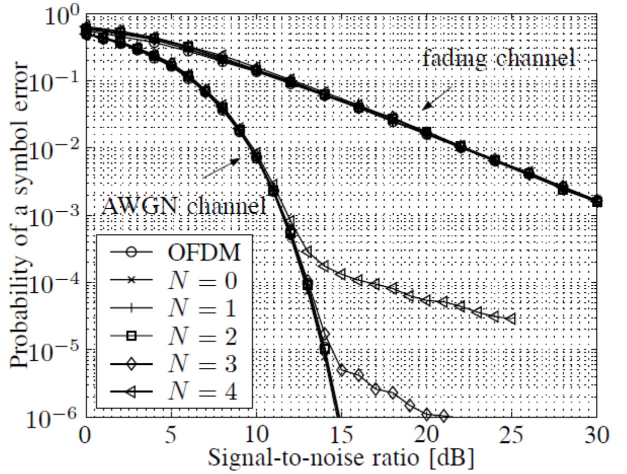


Fig. 5. 16-QAM symbol-error rate performance of conventional OFDM and N-continuous OFDM in AWGN and flat fading channel.

Time Domain Filtering | Domain Windowing/ Pulse | Frequency Domain Precoding | **N-Continuous**

Source: J. van de Beek; F. Berggren, "N-continuous OFDM," Communications Letters, IEEE , vol.13, no.1, pp.1,3, January 2009
Peng W.; Lilin D.; Yue X.; Shaoqian L., "A low-complexity time-domain signal processing algorithm for N-continuous OFDM," , ICC,pp.5754,5758,June 2013

OFDM and its Variations

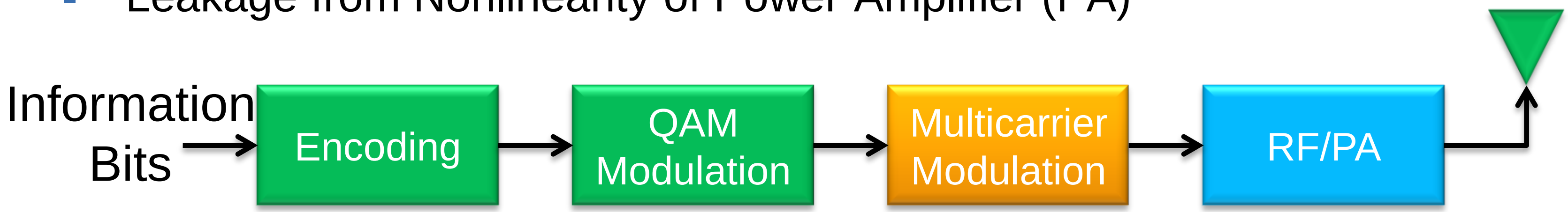
However, OFDM has a number of drawbacks

- a prefix is needed to cope with the channel impulse response, resulting in a loss of capacity and radiated power that can reach 25 %. Also, in the initialization phase, the data-aided procedures are slowed down due to the reduction in symbol rate,
- the frequency selectivity is poor, resulting in high sensitivity to jammers and losses in the exploitation of spectral masks,
- it requires block processing to maintain orthogonality among all the sub-carriers. This is a major limitation to scalability. In particular, it is impossible to introduce, in a block of carriers, one or several signals that are not synchronous with the rest of the block. As a consequence, for example, the scheme can be used for downlink in a radio connection, but not for uplink, unless severe constraints are imposed on time, frequency and power alignments,
- the leakage among frequency sub-bands has a serious impact on the performance of the spectrum sensing in cognitive radio.

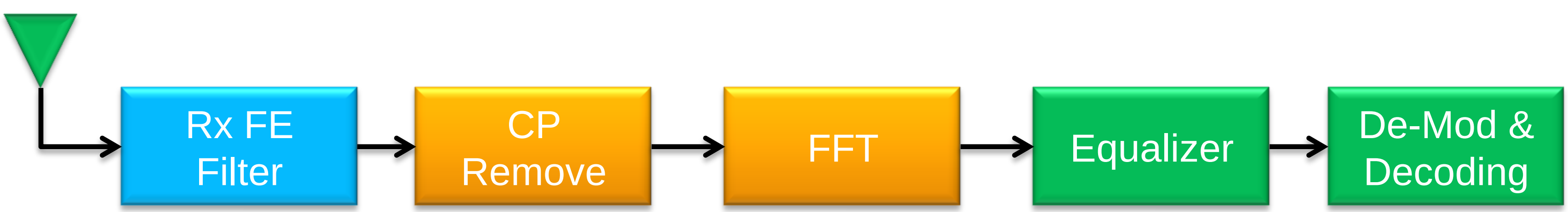
Sources of Adjacent Channel Interference (ACI)

Source: Erdem Bala (InterDigital, USA)

- Transmitter Side
  - Out of band leakage
    - Sidelobes of Baseband (BB) Waveform
    - Leakage from Nonlinearity of Power Amplifier (PA)



- Receiver Side
  - Insufficient filtering
  - Signal distortion

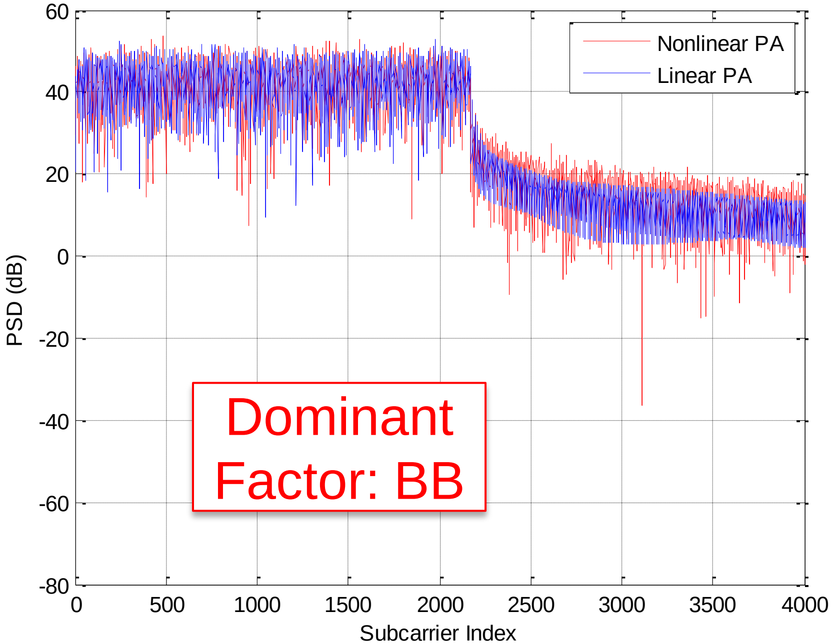


Sources of Out of Band Leakage

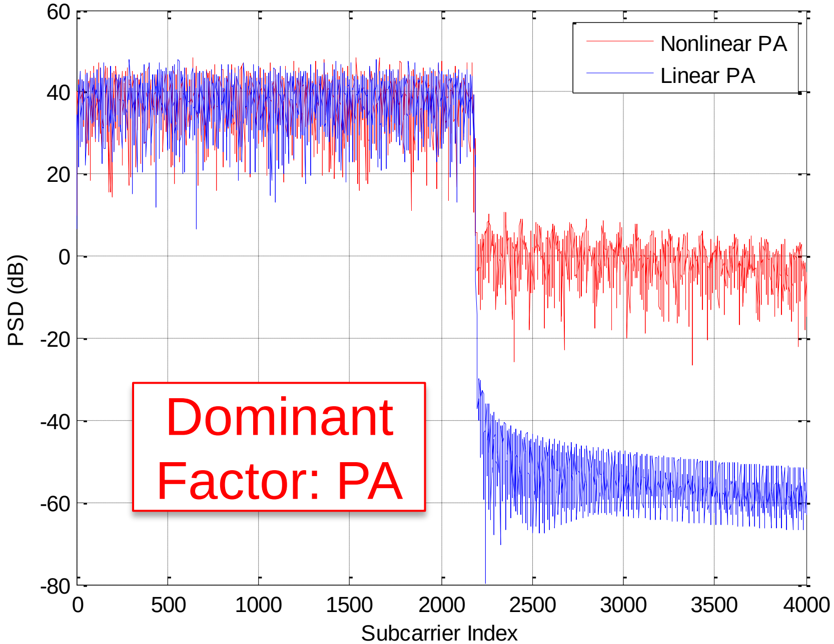
- Two main contributors
  - Sidelobes of Baseband (BB) Waveform
  - Leakage from Nonlinearity of Power Amplifier (PA)
- Examples

Source: Erdem Bala (InterDigital, USA)

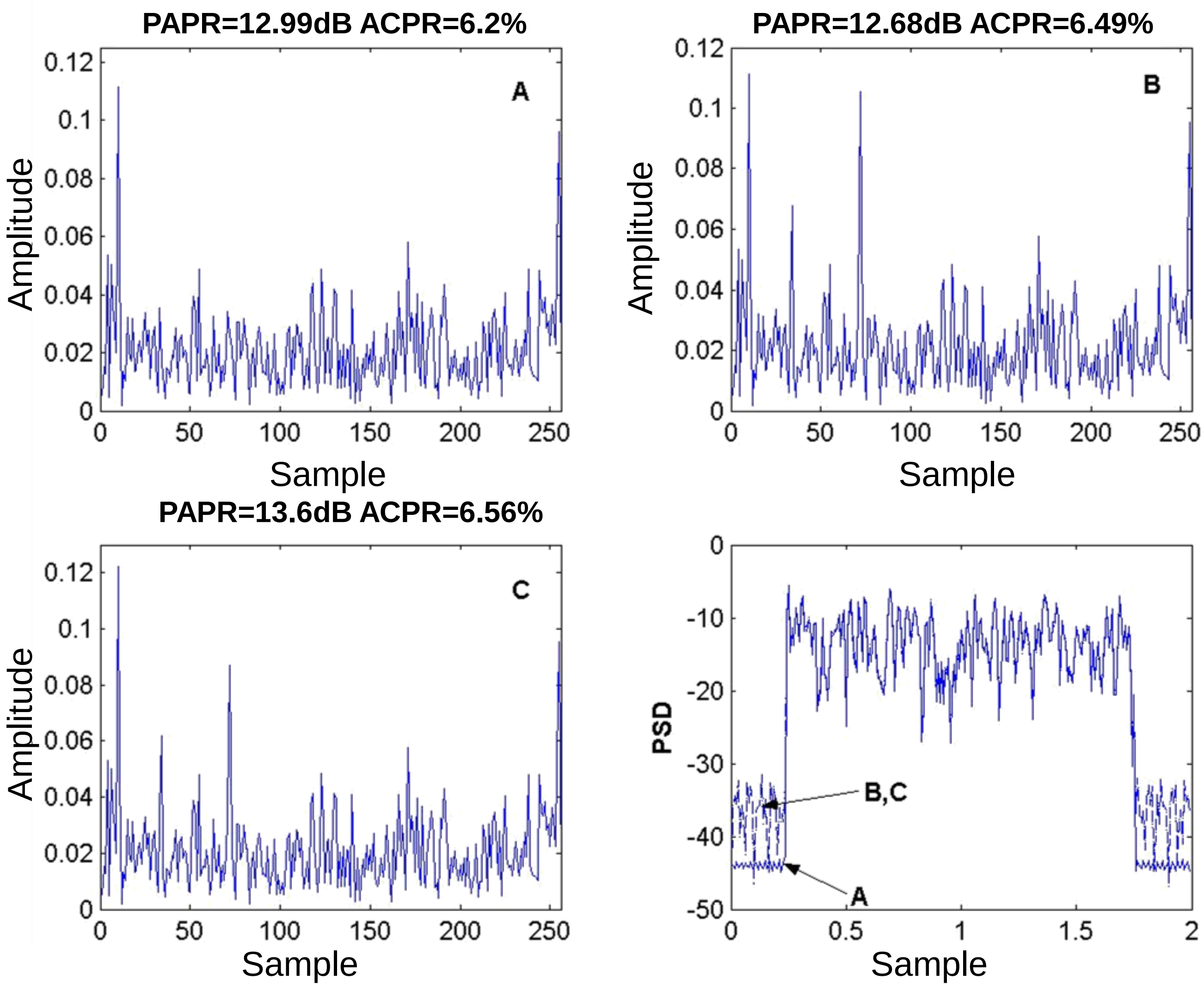
Power Spectrum Density of OFDM



Power Spectrum Density of FBMC



Sources of Out of Band Leakage



ACPR – Adjacent Channel Power Ratio

$$ACPR = \frac{P_{out\_band}}{P_{OFDM}}$$

Part I : Flexible MC waveforms

Other multicarrier schemes: features summary

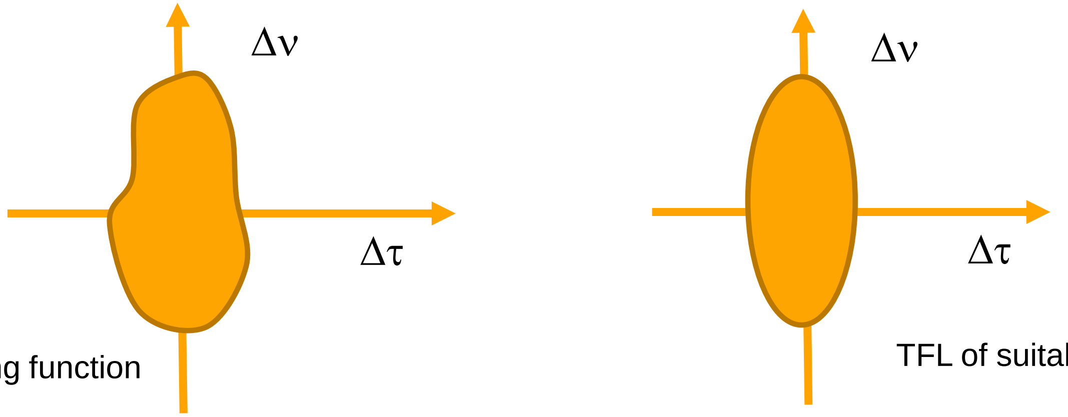
-OFDM/OFDMA
-DMT
-FB Based MC (FMT, CMT)
-FBMC/OQAM, UFMC
-Polyphase decomposition
- Comparative features

Pulse 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

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

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

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

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

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

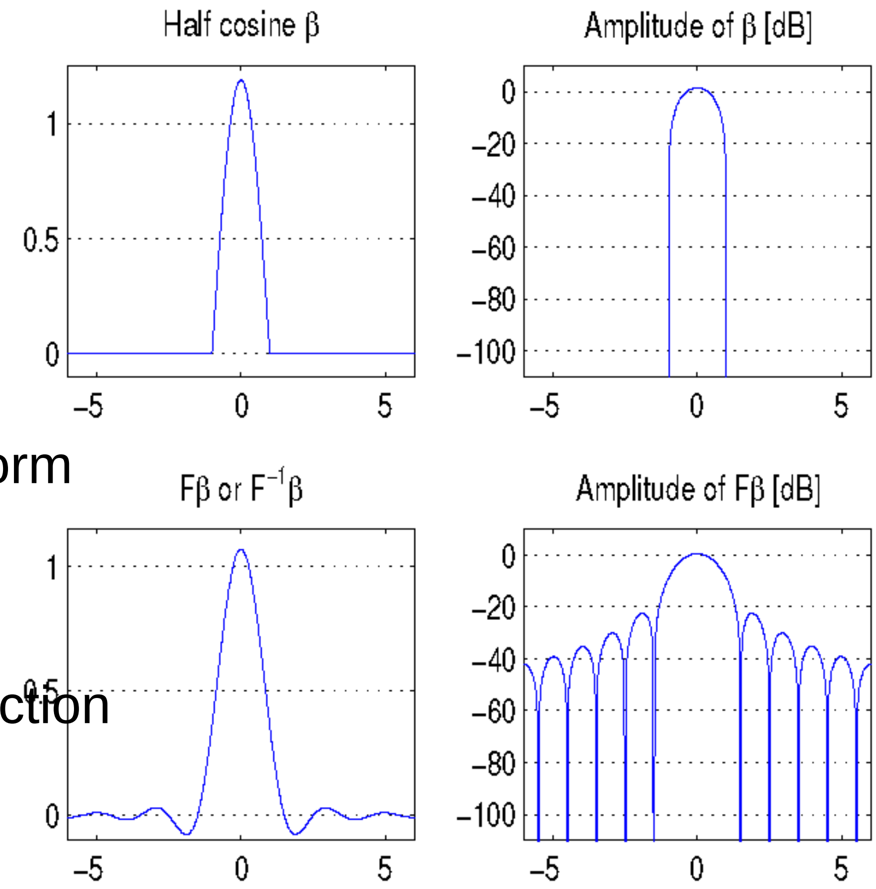


Figure: Half cosine function and its Fourier transform

Pulse Shaping, III

Gaussian Function

Gaussian function is very famous for that its Fourier transform has 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 function generated by Gaussian prototype function is in no way orthogonal as *g(t)* > 0 holds on the whole real axis.

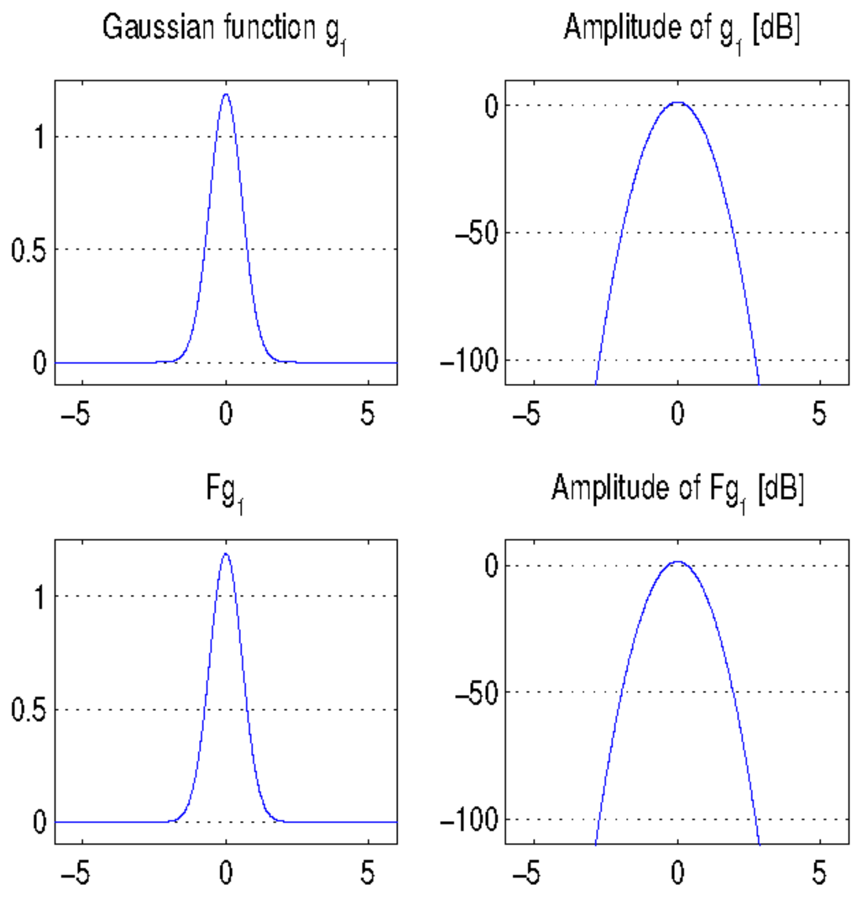


Figure: Gaussian function with $\alpha = 1$ and its Fourier transform.

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,

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

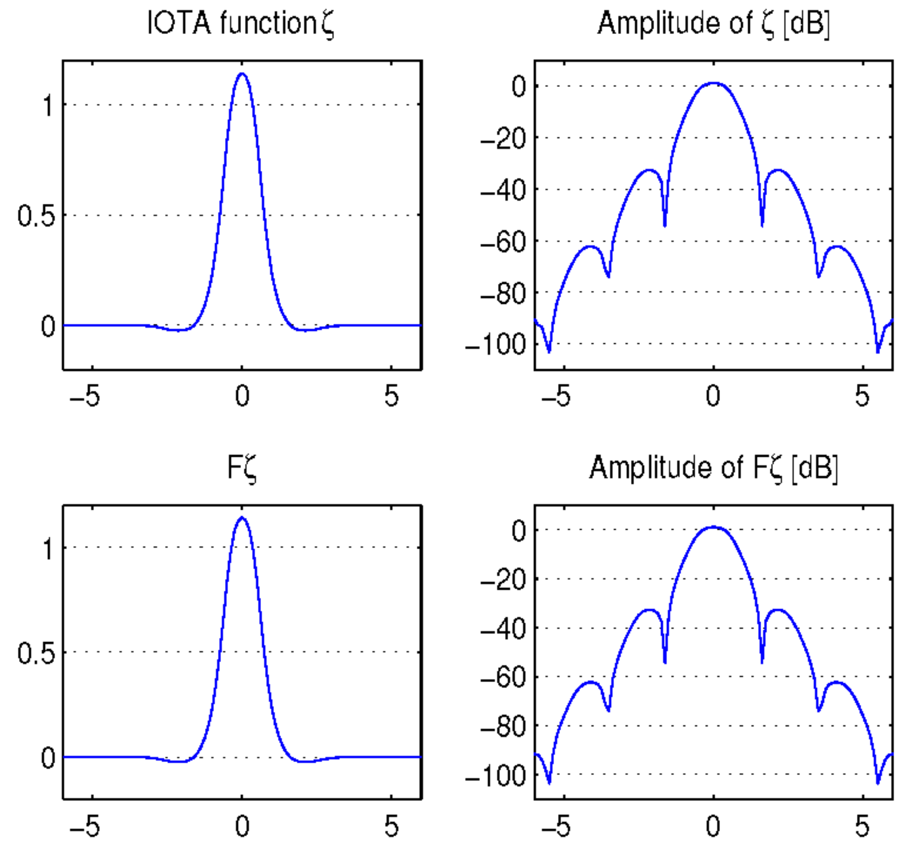


Figure: IOTA function and its Fourier transform

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 $y_\alpha(t) = \mathrm{O}_{\tau_0} g_\alpha(t)$ and

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

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

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

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

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

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

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

$\alpha=1, \tau_0=\nu_0=\frac{1}{\sqrt{2}}$, 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.

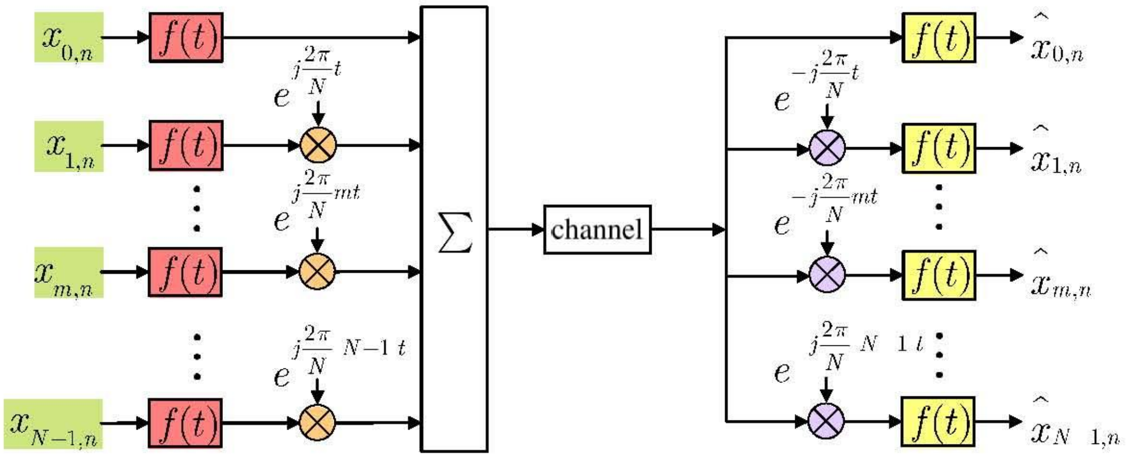
IOTA/OQAM

The goal behind the development of the Isotropic Orthogonal Transform Algorithm (IOTA) function was to design an orthogonal set of pulses that are well localized in the TF plane, i.e. the energy of the pulse is concentrated on the possibly small area.

OFDM Multicarrier System

Multicarrier techniques:

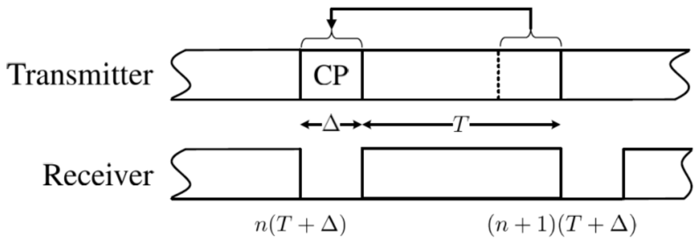
- consist of splitting up a wide band signal at a high symbol rate into several lower rate signals, each one occupying a narrower band.
- System performance improves because subcarriers experience flat fading channels and are orthogonal thus minimizing the threat of interference caused by multipath effects of the propagation channels.
- Orthogonal Frequency Division Multiplexing (OFDM) is the most widespread multicarrier technique. It is used in a large range of applications: WiFi, WiMax, LTE downlink, DSL, …

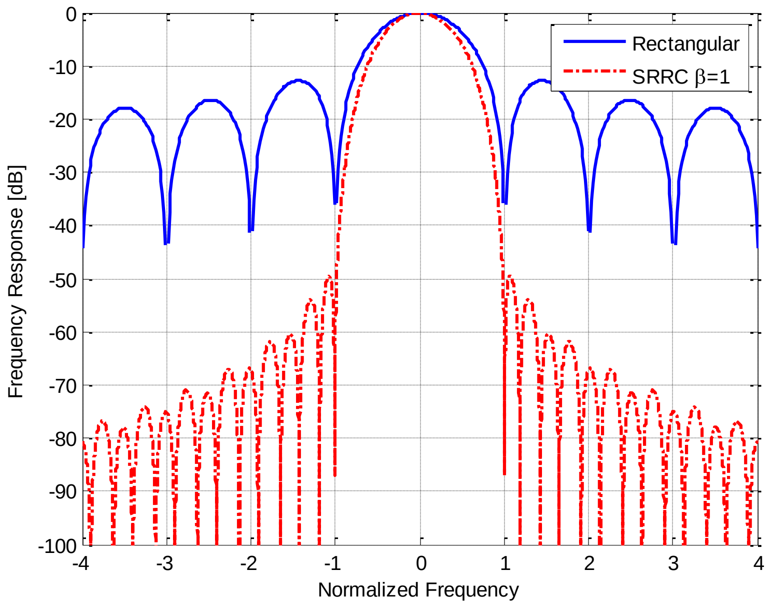


OFDM Multicarrier System

Pros & Cons:

- efficient FFT-based implementation
- robustness to multi-path effects by adding a cyclic prefix
- equalization with a single complex coefficient per subcarrier
- rectangular pulse shape leading to large sidelobes of OFDM spectrum





OFDM Multicarrier System

– The large sidelobes of the OFDM signal frequency response cause high interference to the adjacent unsynchronized subcarriers and are considered as the major shortcoming of the OFDM system.

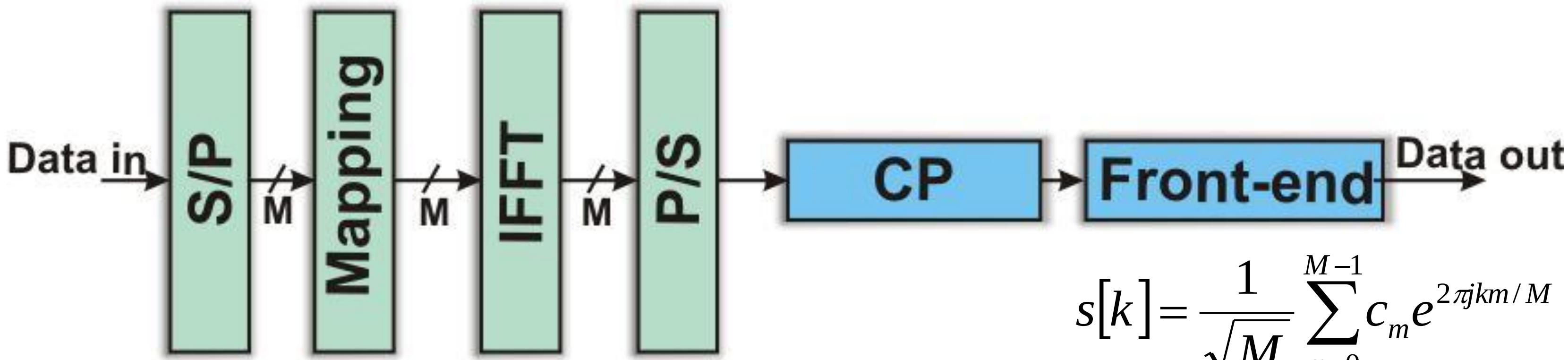
– First Solution: adding guard bands by nulling the subcarriers in the boundaries of the adjacent unsynchronized bands

– Sidelobes reduction in OFDM refers to methods for reducing spectral leakage outside the active OFDM subcarriers, thus reducing interferences in non-contiguous use of OFDM subcarriers needed in case of fragmented spectrum usage

– Several techniques have been developed for this purpose including :
  - Windowing techniques
  - Edge windowing
  - Subcarrier weighting
  - Adaptive Symbol Transition (AST)
  - Active Interference Cancellation (AIC)
  - Multiple Choice, Constellation adjustement, Precoding, …

- I. Cosovic, S. Brandes and M. Schnell, "**Subcarrier weighting : a method for sidelobe suppression in OFDM systems**, Comm. Letters, juin 2006
- H. A. Mahmoud et H. Arslan, "**sidelobe suppression in OFDM-based spectrum sharing systems using adaptive symbol transition**", Comm. Letters, feb. 2008
- Yamaguchi, "**active interference cancellation technique for MB-OFDM cognitive radio**, in Proc. 34th IEEE Eur. Microw. Conf., vol. 2, oct. 2004
- D. Qu and Z. Wang, **"Extended active interference cancellation for sidelobe suppression in cognitive radio OFDM systems with cyclic pre**fix," IEEE Trans. Veh. Technol., pp. 1689–1695, May 2010

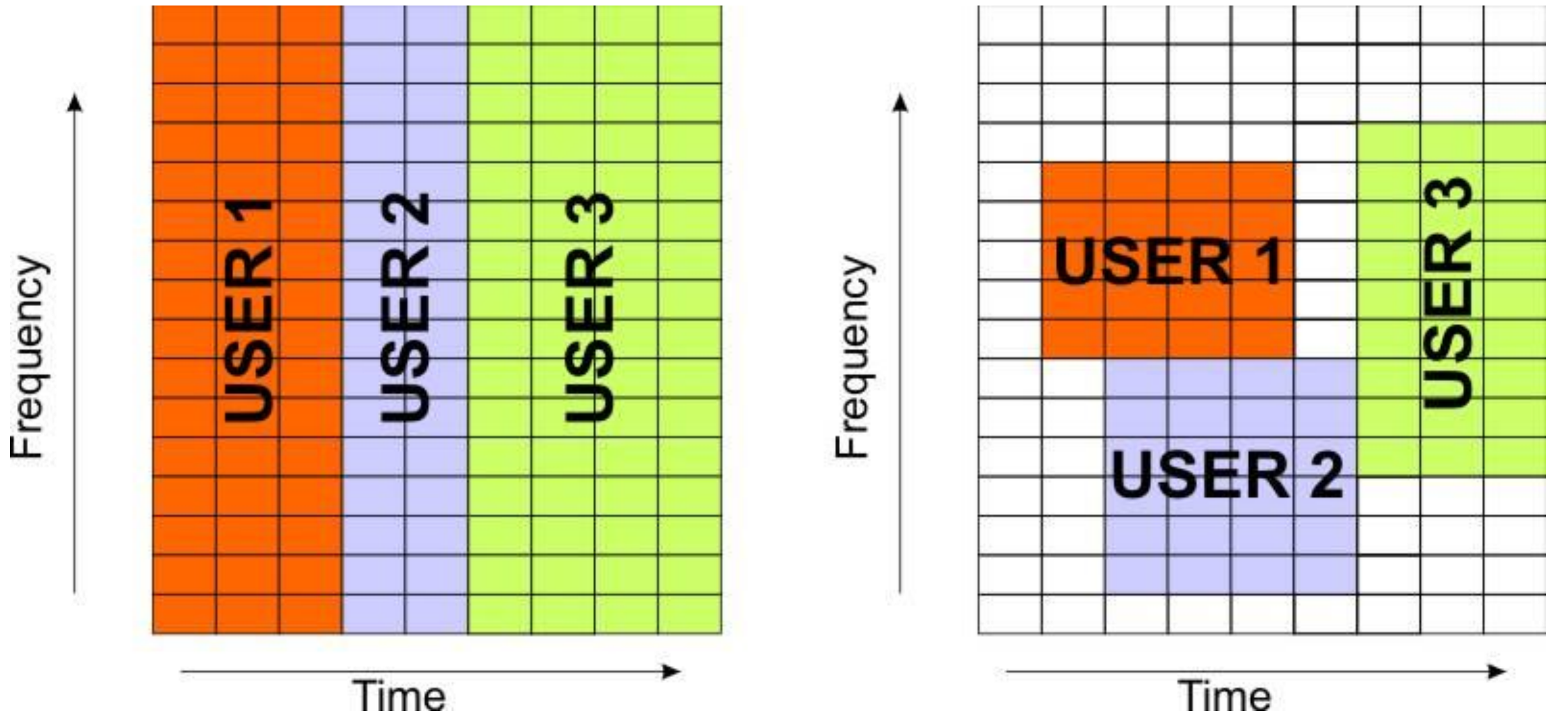
OFDM - overview



$$s[k] = \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} c_m e^{2\pi jkm/M}$$

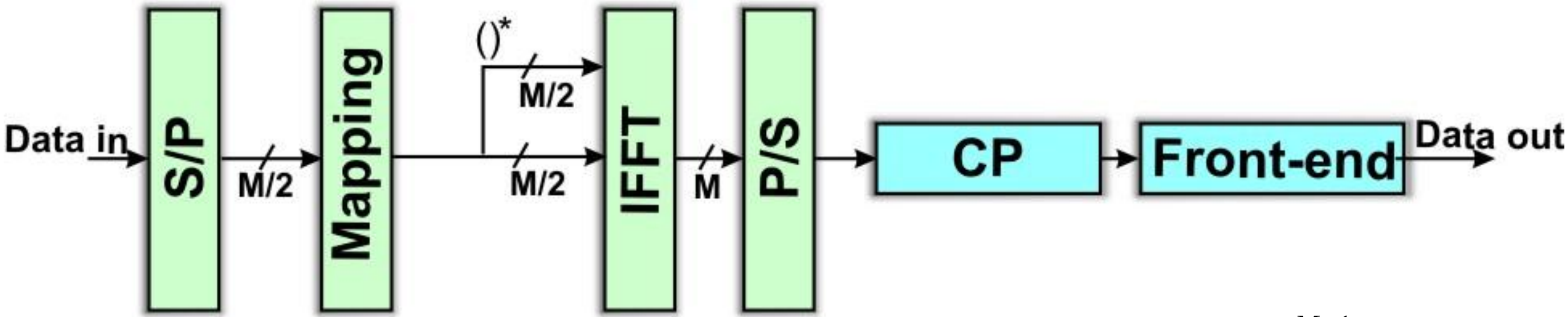
Number of sub-carriers	OFDM symbol duration	cp-OFDM symbol duration	Subcarrier spacing	Pulse shape in time/ frequency domain	Efficiency of uncoded system and BPSK mod.	Overlapping in time/ frequency
M	T [*sec*]/ M [*samples*]	$T + T_{CP}$ [*sec*]/ $M + L_{CP}$ [*samples*]	$\Delta f = 1/T$	rect. / sinc	≤1	no/no

OFDMA



- Due to the orthogonality property, the time-frequency plane can be utilized in a more efficient way (like in LTE-A/ IMT-A)

DMT - overview



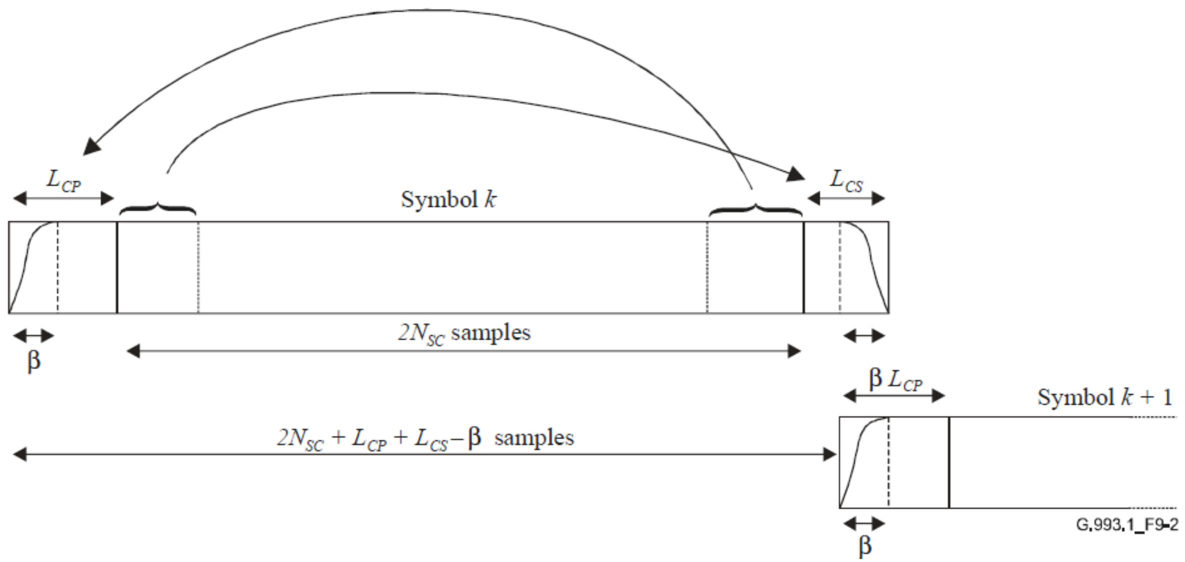
$$c_m^{(i)} = c_{M-m}^{(i)} \qquad c_m^{(q)} = -c_{M-m}^{(q)}$$

$$s[k] = \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} c_m e^{2\pi jkm/M}$$

Number of sub-carriers	DMT symbol duration	cp-DMT symbol duration	Subcarrier spacing	Pulse shape in time/ frequency domain	Efficiency of uncoded system and BPSK mod.	Overlapping in time/ frequency
$M/2$	T [sec]/ M [samples]	$T + T_{CP}$ [sec]/ $M + L_{CP}$ [samples]	$\Delta f=1/T$	rect. / sinc	≤1	no/no

DMT - overview

- ✓ DMT is applicable rather in wired systems (VDSL, ADSL), i.e. baseband signal is considered contrarily to the OFDM where the passband transmission is often assumed
- ✓ Real data are transmitted
- ✓ DMT has the same pros and cons as OFDM/OFDMA;
- ✓ Cyclic Extension (CE) is added



VDSL DMT symbol – $2N_{SC}=M$, Figure from ITU-T Rec. G.993.1

Filter bank based schemes I.

- The FBMC systems are classified into three main methods:

1. Offset quadrature amplitude modulated OFDM (OQAM-OFDM) by [Chang], [Siohan]
2. Cosine-modulated multitune (CMT)
3. Filtered multitune (FMT).

-The isotropic orthogonal transfer algorithm (IOTA) has been presented developed [Siohan] in order to adapt the FBMC system to match the channel time and frequency dispersion.

-CMT is considered by the under-development IEEE P1901 standard for power line communication (PLC) systems.

Different from OQAM-OFDM and CMT systems, FMT does not allow the subcarrier overlapping [Amini].

[Chang] RW Chang, “High-speed multichannel data transmission with bandlimited orthogonal signals,” *Bell sys. Tech. J*, vol. 45, pp. 1775–1796, 1966.

[Siohan] P. Siohan and C. Roche, “Cosine-modulated Filterbanks based on extended Gaussian Functions,” IEEE Transactions on Signal Processing, vol. 48, no. 11, pp. 3052–3061, 2000.

[Amini] A. Amini, R. Kempter, and B. Farhang-Boroujeny, “A comparison of alternative filterbank multicarrier methods in cognitive radios,” in 2006 Software Defined Radio Technical Conference and Product Exhibition (SDR’06), Orlando-Florida, Nov. 2006.

Filtered MultiTone FMT - overview

$$s[k] = \sum_{n} \sum_{m=0}^{M-1} c_{n,m} g[k - nN] \exp\left(\frac{j2\pi mk(1+\alpha)}{N}\right)$$

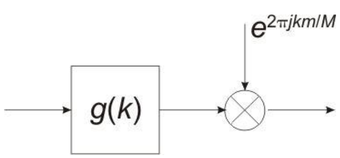
Number of sub-carriers	FMT symbol duration	Subcarrier spacing	Pulse shape in frequency domain	Efficiency of uncoded system and BPSK mod.	Overlapping in time/ frequency
M	*T* [sec]/ *M* [samples]	*Δf=1/T* *Can be parametricaly defined*	*SRRC/ any orthogonal*	≤1 *Usually higher than in OFDM*	*Defined by the pulse-shape*

Exemplary Nyquist SRRC Applied in DVB-DCT ETSI EN 301 958:

$$g(t) = \frac{\sin\left[\frac{\pi t}{T}(1-\alpha)\right] + \frac{4\alpha t}{T}\cos\left[\frac{\pi t}{T}(1+\alpha)\right]}{\frac{\pi t}{T}\left[1-(\frac{4\alpha t}{T})^2\right]} \quad \text{for } t \in \{-4T \;\; .4T\}$$

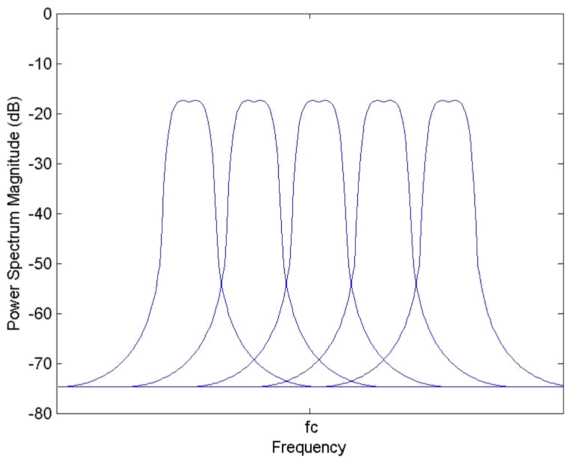
Excess bandwidth parameter (roll-off) $\alpha = 0.25$

In FMT systems we ensure the orthogonality between the adjacent subchannels by developing of proper filters with non-overlapping frequency domain filters characteristic (contrarily to the OFDM case where *sinc* functions are used). The usage of the cyclic prefix is not required due to the linear transmission that does not destroy the orthogonality between the pulses guaranteed in the mentioned way.



frequency shifted (modulated) version of the used prototype filter $g(k)$

FMT



Filter Bank based Multicarrier (FBMC)

History: Chang in 1960s has presented the conditions required for signalling a parallel set of pulse amplitude modulated (PAM) symbols sequences through a bank of overlapping vestigial side-band (VSB) modulated filters

Implementation: Efficient digital implementation through polyphase networks was introduced by Bellanger

FBMC main classes:

- Filtered multitone (FMT)
- Cosine modulated multitone (CMT)
- FBMC-OQAM (also called SMT, Staggered MultiTone)

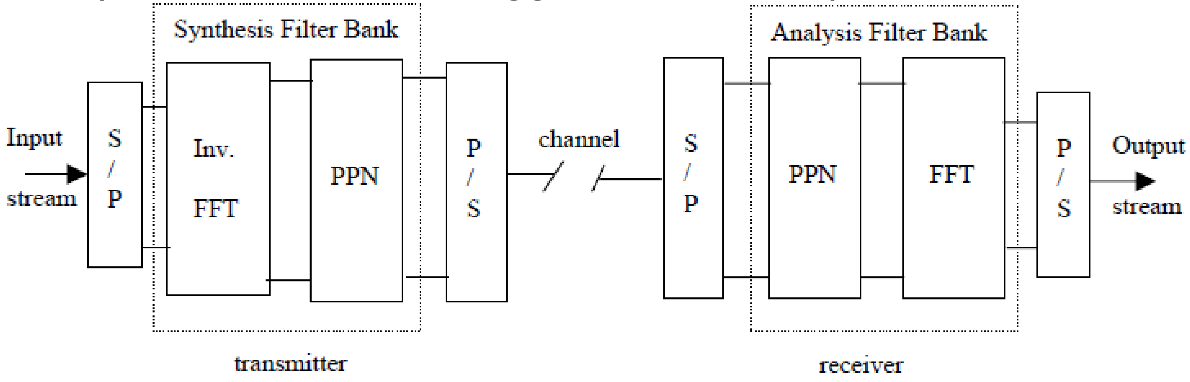
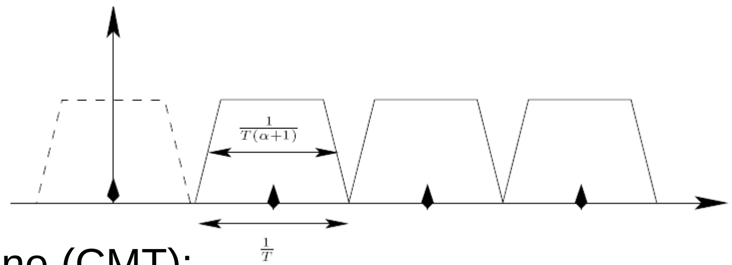


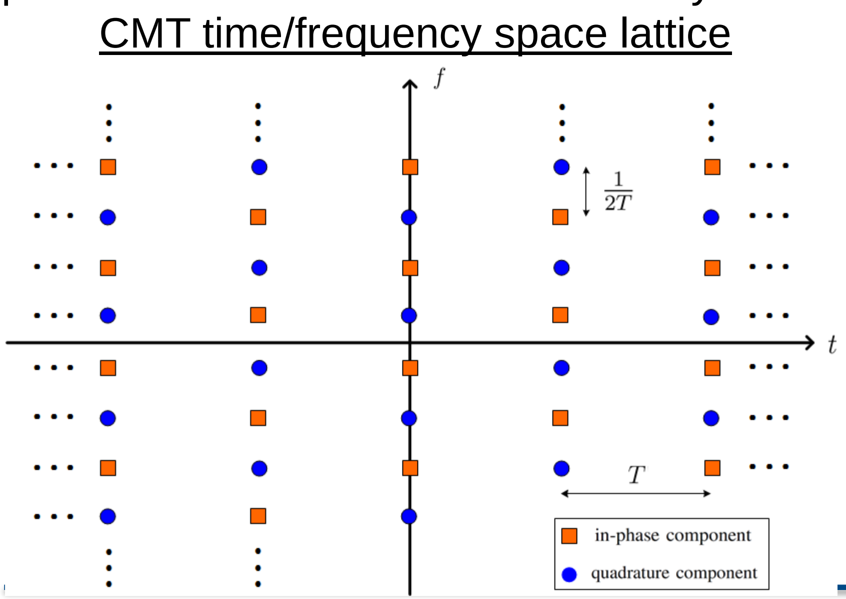
Fig. 1. Filter Bank-based Multicarrier (FBMC) system

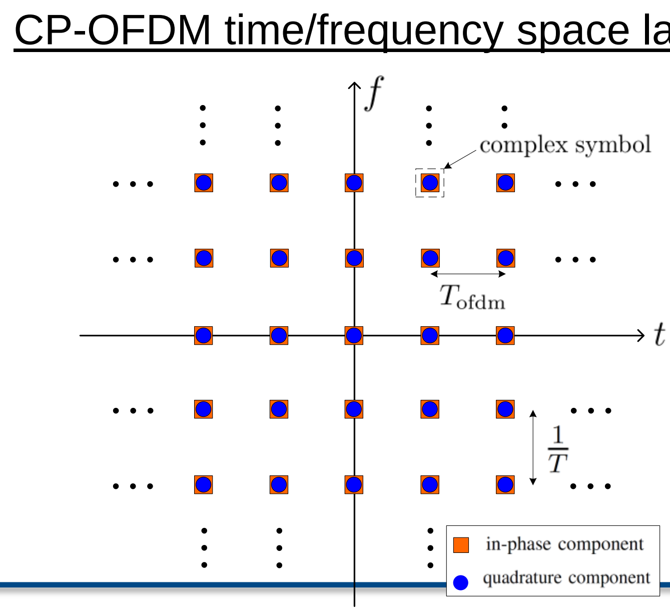
- R. W. Chang, "**High-Speed Multichannel Data Transmission with Bandlimited Orthogonal Signals**," Bell Syst. Tech. J., vol. 15, no. 6, pp. 1775–1796, Dec. 1966
- B. Farhang-Boroujeny, "**OFDM Versus Filter Bank Multicarrier**," IEEE Signal Processing Mag., vol. 28, no. 3, pp. 92 –112, May 2011.

Filtered MultiTone (FMT):
The subcarrier bands do not overlap and a complex symbol is transmitted every T seconds



Cosine modulated MultiTone (CMT):
In order to transmit *N* complex symbols on each multicarrier symbol, a system with 2*N* subcarrier is
implemented where each carrier conveys a real symbol



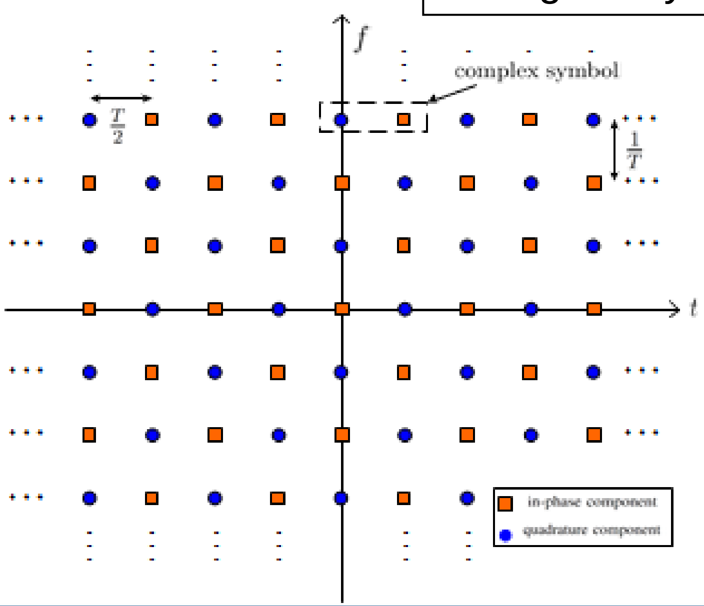


FBMC/OQAM

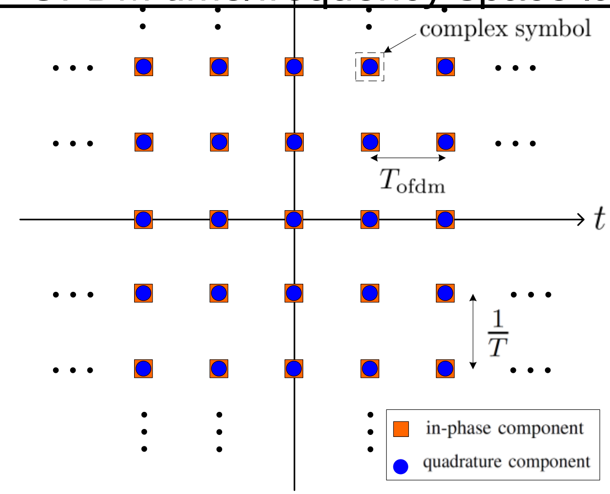
- Balian-Low theorem: It is not possible to get a prototype function being well-localized in time and frequency, and satisfying in the meantime the orthogonality condition and a symbol density of one.

- 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



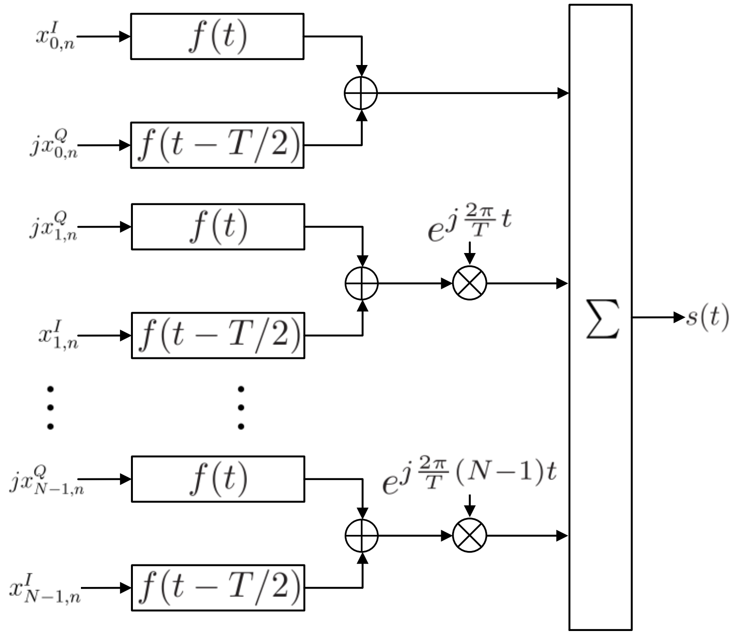
CP-OFDM time/frequency space lattice



FBMC/OQAM

- FBMC/OQAM signal: The second specificity is that considering two successive subcarriers, the time delay *T/2* is introduced into the imaginary part of the QAM symbols on one of the subcarriers, whereas it is introduced into the real part of the symbols on the other one.

$$s(t) = \sum_{m=0}^{M-1} \sum_{n=-\infty}^{+\infty} (x^I_{2m,n} f(t-nT) + j x^Q_{2m,n} f(t-nT-T/2)) e^{j\frac{2\pi}{T}(2m)t}$$
$$+ (x^I_{2m+1,n} f(t-nT-T/2) + j x^Q_{2m+1,n} f(t-nT)) e^{j\frac{2\pi}{T}(2m+1)t}$$



FBMC/OQAM

- FBMC/OQAM signal:

$$s(t) = \sum_{m=0}^{M-1} \sum_{n=-\infty}^{+\infty} (x^I_{2m,n} f(t-nT) + j x^Q_{2m,n} f(t-nT-T/2)) e^{j\frac{2\pi}{T}(2m)t}$$
$$+ (x^I_{2m+1,n} f(t-nT-T/2) + j x^Q_{2m+1,n} f(t-nT)) e^{j\frac{2\pi}{T}(2m+1)t}$$

notations:

$$a_{2m,2n} = x^I_{2m,n}, \qquad a_{2m,2n+1} = x^Q_{2m,n}$$
$$a_{2m+1,2n} = x^Q_{2m+1,n}, \quad a_{2m+1,2n+1} = x^I_{2m+1,n}$$

Consequently:

$$s(t) = \sum_{m=0}^{N-1} \sum_{n=-\infty}^{+\infty} a_{m,n} f(t-nT/2) e^{j\frac{2\pi}{T}mt} e^{j\varphi_{m,n}}$$
$$= \sum_{m=0}^{N-1} \sum_{n=-\infty}^{+\infty} a_{m,n} \gamma_{m,n}(t)$$

Modulation basis (Gabor family): modulation and translation of the prototype filter.

Polyphase Decomposition

Consider a finite impulse response (FIR) filter *F*(*z*) of *L* = *KN* coefficients:

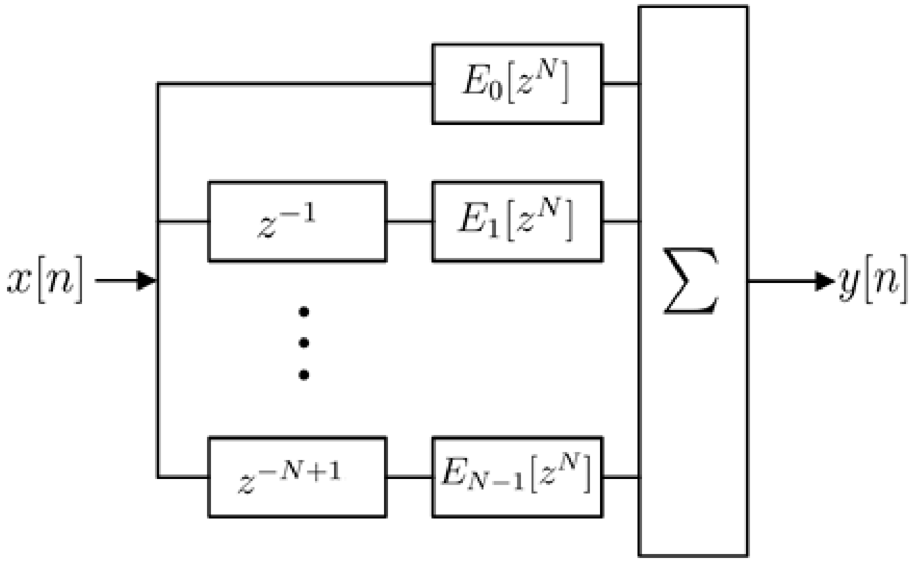
$$F(z) = \sum_{l=0}^{L-1} f[l] z^{-l}$$

This filter can be decomposed into *N* elementary filters, in the following way,

$$F(z) = \sum_{l=0}^{L-1} f[l] z^{-l} = \sum_{n=0}^{N-1} \sum_{k=0}^{K-1} f[kN+n] z^{-(kN+n)}$$

$$= \sum_{n=0}^{N-1} \boxed{\left[\sum_{k=0}^{K-1} f[kN+n] z^{-kN} \right]} z^{-n}$$

$E_n[z^N]$: Polyphase component

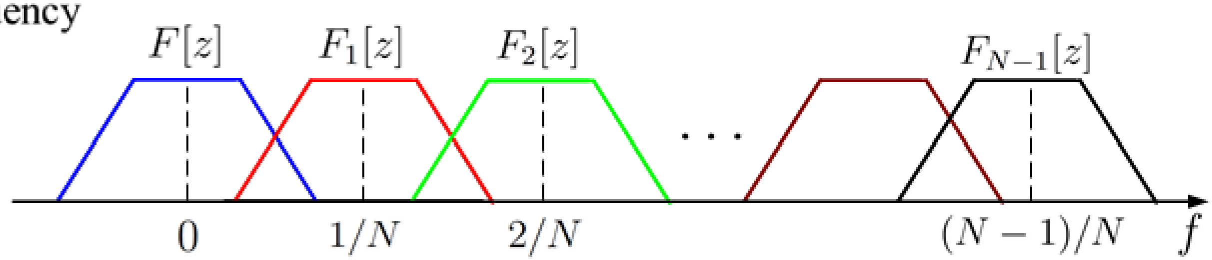


The polyphase network (PPN) of the filter *F*[*z*]

- M. Bellanger and J. Daguet, "**TDM-FDM Transmultiplexer: Digital Polyphase and FFT**," IEEE Trans. Commun., vol. 22, no. 9, pp. 1199 – 1205, Sep. 1974.

Polyphase Decomposition

We wish to build a filter bank of N filters uniformly spaced in the frequency range $[0, f_s]$ where f_s is the sampling frequency



<u>Frequency response of the modulation basis</u>

Now, let $F_i(z)$ be a replica of the filter $F(z)$ shifted by i/N in the frequency domain,

$$F_i(z) = \sum_{l=0}^{L-1} f[l] e^{j\frac{2\pi}{N}il} z^{-l}$$

Using the polyphase representation, $F_i(z)$ becomes,

$$F_i(z) = \sum_{n=0}^{N-1}\sum_{k=0}^{K-1} f[kN+n] e^{j\frac{2\pi}{N}i(kN+n)} z^{-(KN+n)}$$

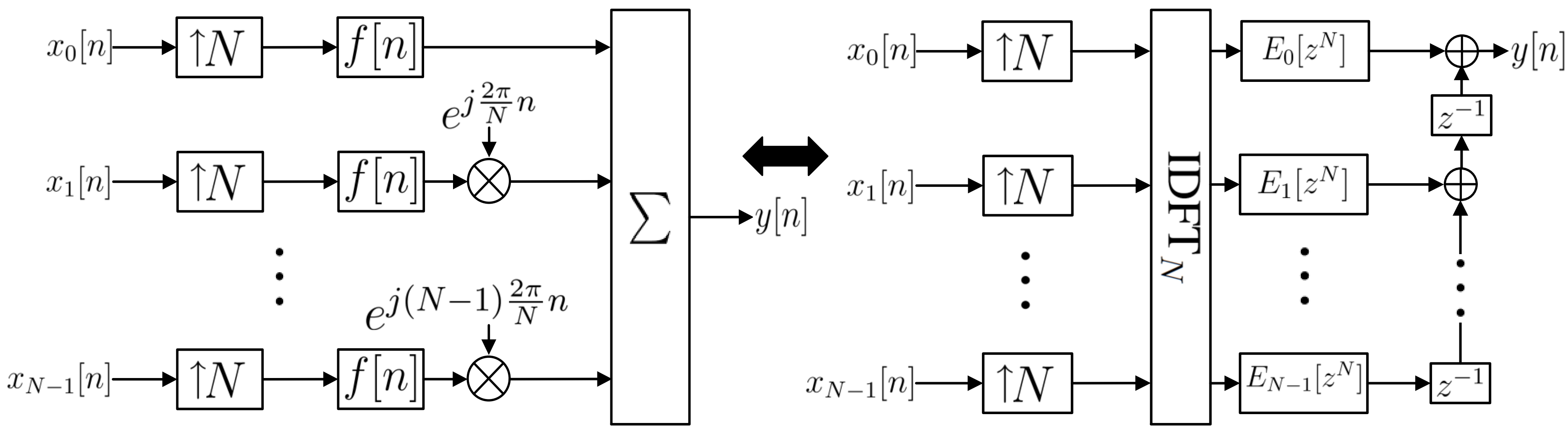
$$= \sum_{n=0}^{N-1} e^{j\frac{2\pi}{N}ni} E_n[z^N] z^{-n}$$

Polyphase Decomposition

Considering all shifts multiples of 1/*N* of the prototype filter *F(z),* we can write

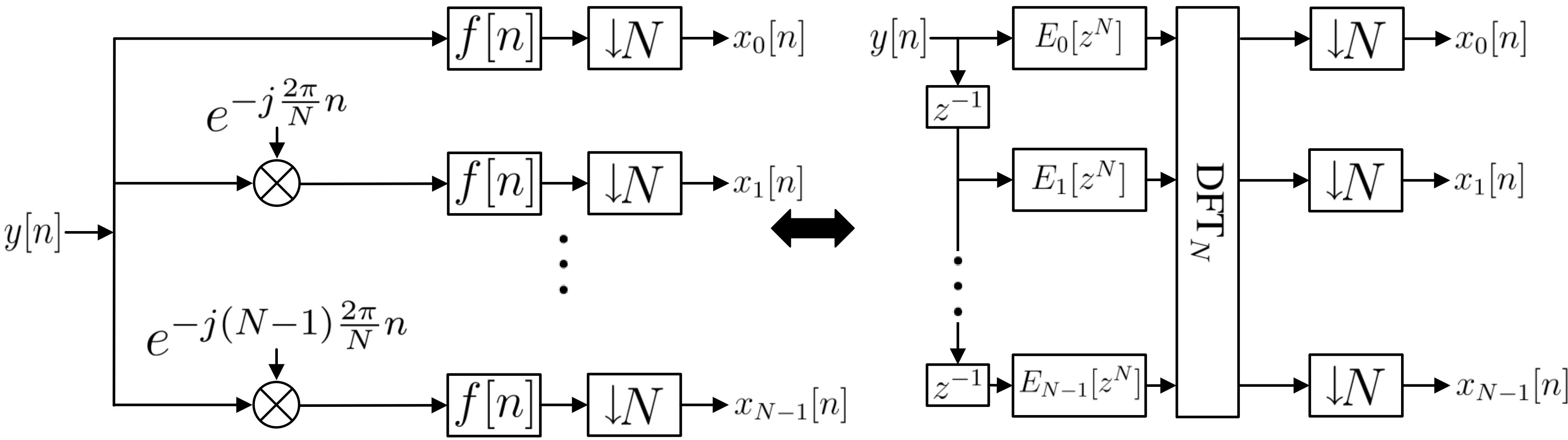
$$\begin{bmatrix} F_0(z) \\ F_1(z) \\ \vdots \\ F_{N-1}(z) \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & w^{-1} & \cdots & w^{-(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & w^{-(N-1)} & \cdots & w^{-(N-1)^2} \end{bmatrix}}_{IDFT_N} \underbrace{\begin{bmatrix} E_0[z^N] \\ z^{-1}E_1[z^N] \\ \vdots \\ z^{-(N-1)}E_{N-1}[z^N] \end{bmatrix}}_{PPN} \quad \text{where } w = e^{-j\frac{2\pi}{N}}$$

Consequently, the SFB (the transmitter) can be implemented as follows,



Block diagram of a synthesis filter bank (SFB)

The analysis filter bank (the receiver): as indicated by its name, performs a frequency decomposition of the input signal. The polyphase implementation of the AFB represents a structure which is the dual of the previously considered synthesis filter bank, and is derived in a similar manner.



Block diagram of an Analysis filter bank (AFB)

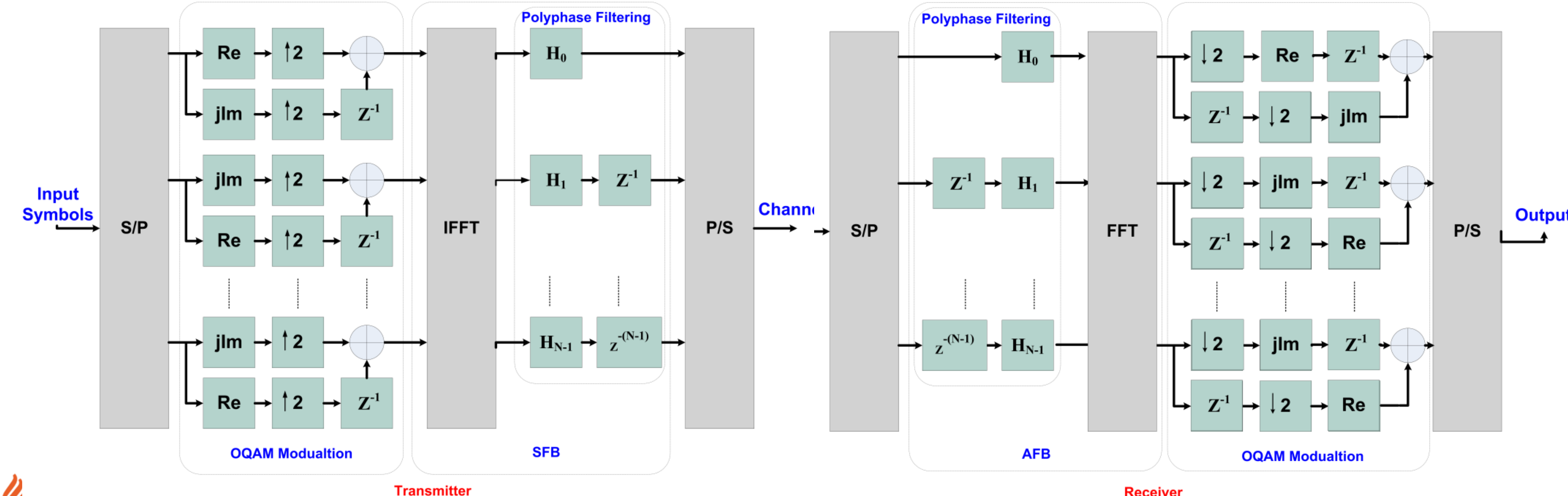
M. Bellanger and J. Daguet, "TDM-FDM Transmultiplexer: Digital Polyphase and FFT," IEEE Trans. Commun., vol. 22, no. 9, pp. 1199 – 1205, Sep. 1974.

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).

On the other hand, by adding the outputs of the filter array, a new signal is



FBMC System

- In order to restore the orthogonality or to eliminate intrinsic interference, we use OQAM modulation
- A real PAM symbol is transmitted every half period $T/2$

PHYDYAS

	n-3	n-2	n-1	n	n-+1	n+2	n+3
k-1	R	I	R	I	R	I	R
k	I	R	I	R	I	R	I
k+1	R	I	R	I	R	I	R

t

f

IOTA

	n-3	n-2	n-1	n	n-+1	n+2	n+3
k-2	I	R	I	R	I	R	I
k-1	R	I	R	I	R	I	R
k	I	R	I	R	I	R	I
k+1	R	I	R	I	R	I	R
k+2	I	R	I	R	I	R	I

FBMC System

- The impulse response of the FBMC system (transmitter and receiver connected back to back) is given for PHYDYAS and IOTA waveforms, respectively.

- Row *k* is the subchannel response that satisfies the Nyquist criteria.

- The other rows correspond to the impulse responses of the interference filters due to the overlapping of the neighboring subchannels.

$T/2$; t ; f

PHYDYAS

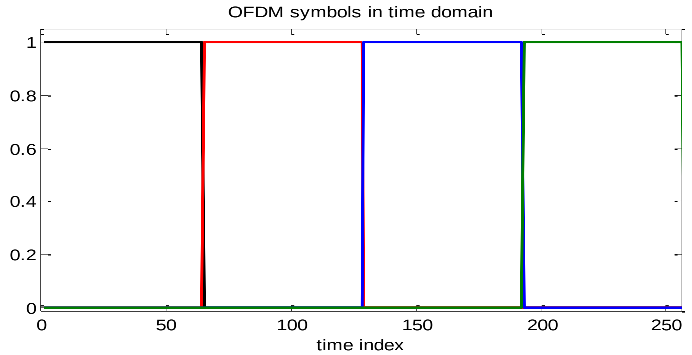
	n-3	n-2	n-1	n	n-+1	n+2	n+3
k-1	0.043j	-0.125	-0.206j	0.239	0.206j	-0.125	-0.043j
k	0.067	0	0.564	1	0.564	0	0.067
k+1	-0.043j	-0.125	0.206j	0.239	-0.206j	-0.125	0.043j

IOTA

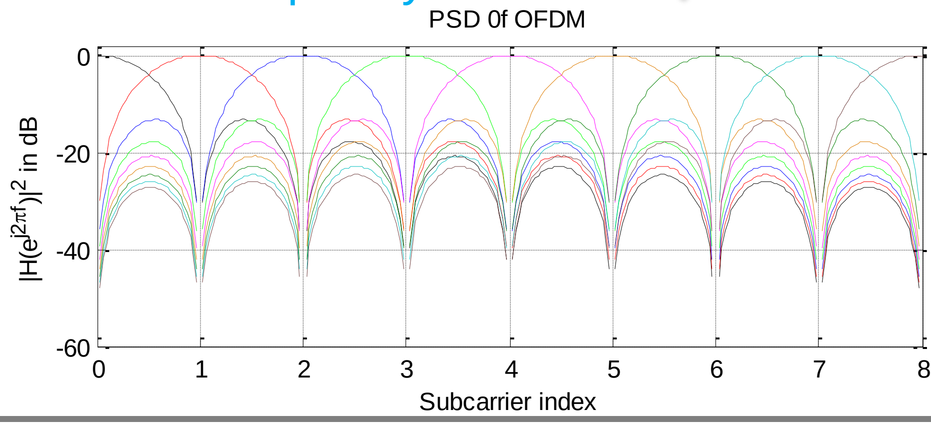
	n-3	n-2	n-1	n	n-+1	n+2	n+3
k-2	0.001	0	-0.038	0	-0.038	0	0.001
k-1	-0.01j	-0.038	0.228j	0.441	0.228j	-0.038	-0.01j
k	-0.018	0	0.441	1	0.441	0	-0.018
k+1	-0.01j	-0.038	0.228j	0.441	0.228j	-0.038	-0.01j
k+2	0.001	0	-0.038	0	-0.038	0	0.001

OFDM vs. OFDM-OQAM

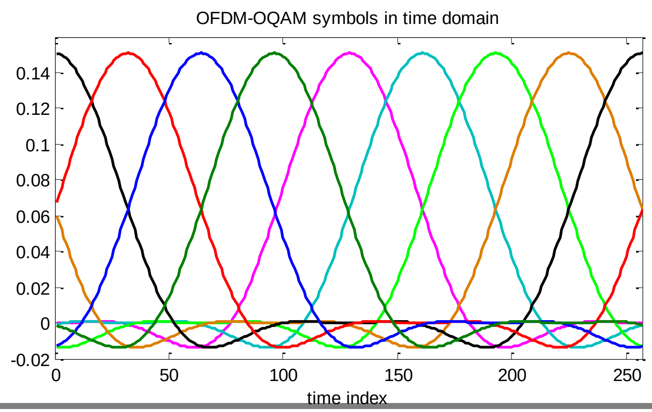
OFDM in time domain



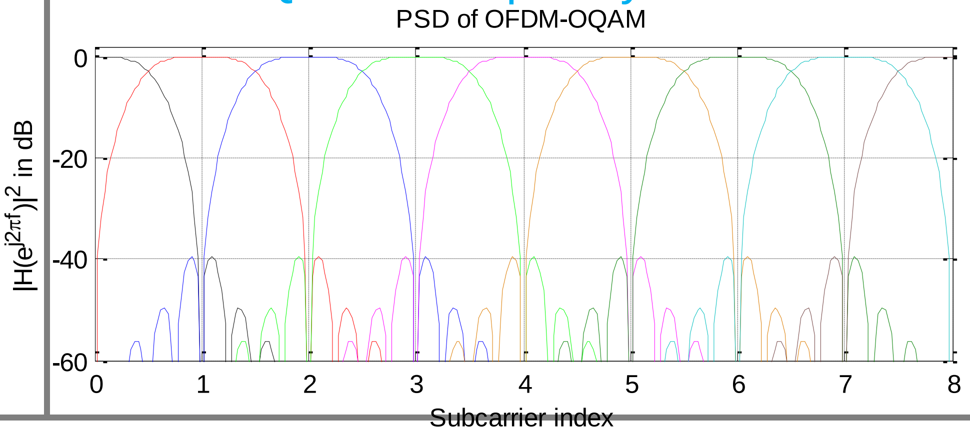
OFDM in frequency domain



OFDM-OQAM in time domain



OFDM-OQAM in frequency domain

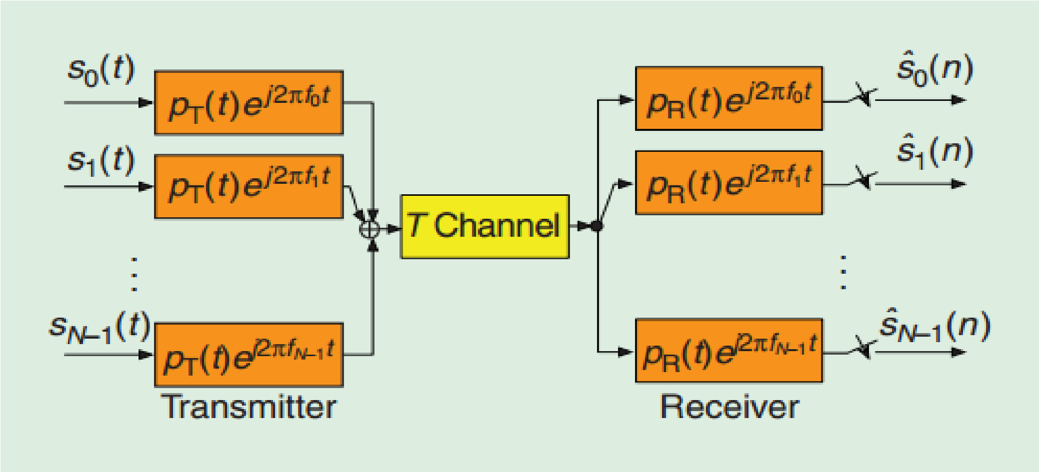


- **OFDM:** No overlapping in time using rectangular pulse, which has large sidelobes.
- **OFDM-OQAM:** Allowing overlapping in time using well designed pulse to reduce sidelobes, as well as to minimize ISI and ICI. There is no cyclic prefix

Source: Erdem Bala (InterDigital, USA)

Filter Bank Multicarrier (FBMC) (II)

- FBMC
  - Applying filtering for each subcarrier
  - Very effective to achieve spectral containment



Source: Erdem Bala (InterDigital, USA)

- OFDM-OQAM
  - A popular implementation of the FBMC
  - Can be designed to (almost) remove inter-symbol and inter-carrier interferences

MC: comparative features

CP-OFDM:

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

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

PHYDYAS:

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

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

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

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

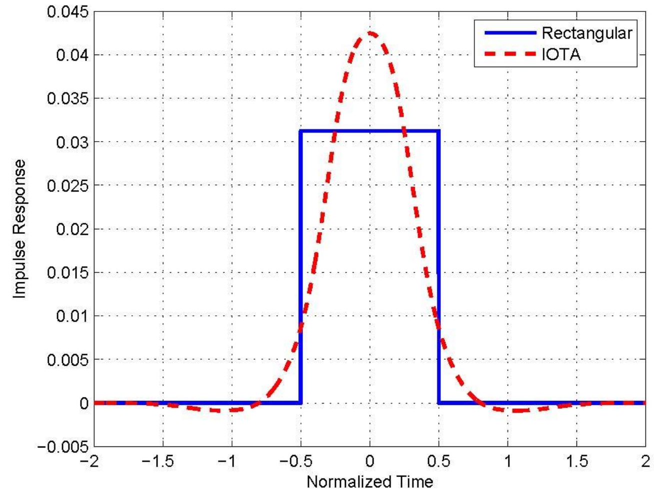
IOTA:

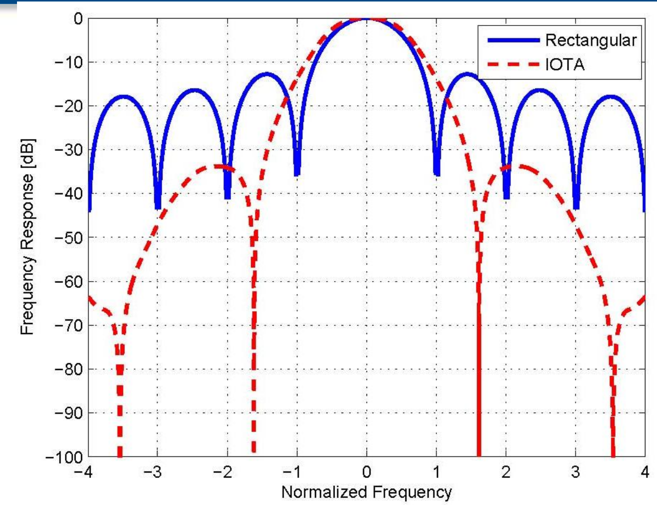
$$\Phi_{\mathrm{IOTA}}(f) = g^2_{1,\sqrt{2}/2,\sqrt{2}/2}(t)$$

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

MC: comparative features

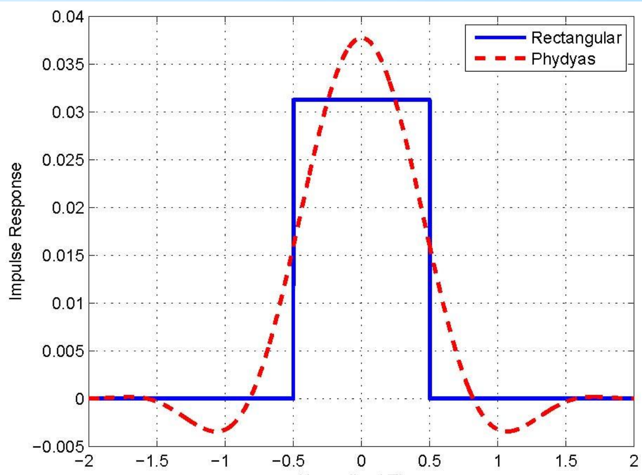
Extended Gaussian Function (**EGF**)

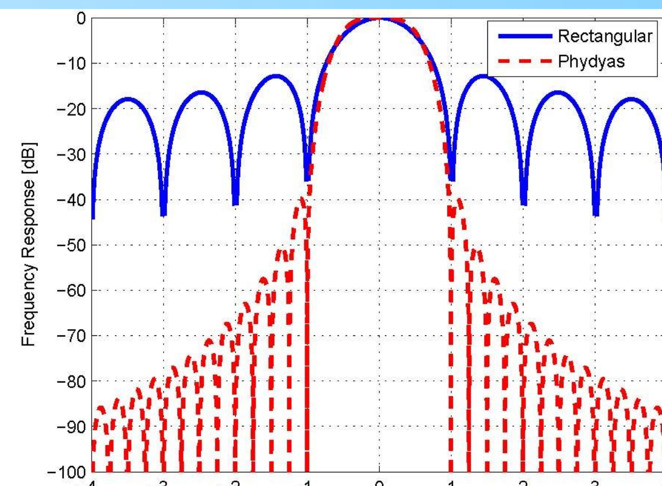




P. Siohan and C. Roche, "*Cosine-Modulated Filterbanks based on Extended Gaussian Functions*," IEEE Trans. Signal Processing, vol. 48, no. 11, pp. 3052 –3061, Nov. 2000.

PHYDYAS Prototype Filter





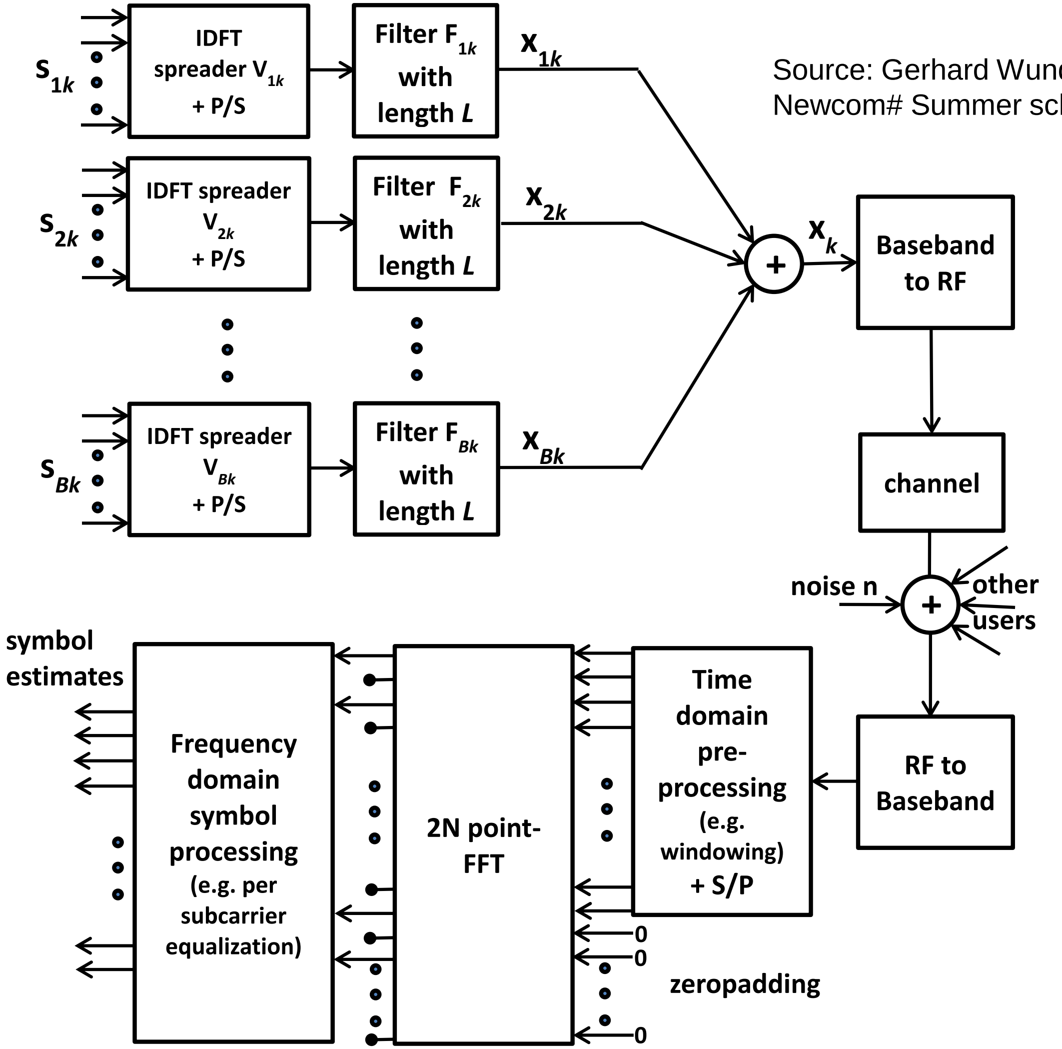
M.G. Bellanger, "*Specification and Design of a Prototype Filter for Filter Bank based Multicarrier Transmission*," in IEEE Int. Conf. on Acoustics, Speech, and Signal Processing, 2001. Proceedings. (ICASSP '01)., May 2001, vol. 4, pp. 2417 –2420.

FBMC vs. OFDM

OFDM	FBMC
• Carriers are orthogonal • Symbols do not overlap • Presence of cyclic prefix (suffix) limiting spectral efficiency • High OOB • Complexity issues are negligible • Other issues	• Carriers overlap • Symbols overlap • No need for cyclic prefix, but spectral efficiency depends on the filter shape • OOB is low • Complexity of the algorithms can play a role • Other issues

Universal Filtered MC Transceiver

(UFMC a.k.a. UF-OFDM)



Source: Gerhard Wunder
Newcom# Summer school 2014

Time domain transmit samples

Sub-band FIR filter

IDFT matrix

Data symb.

$$\underset{[(N+L-1)\times 1]}{\mathbf{x}_k} = \sum_{i=1}^{B} \underset{[(N+L-1)\times N]}{\mathbf{F}_{ik}} \; \underset{[N\times n_i]}{\mathbf{V}_{ik}} \; \underset{[n_i\times 1]}{\mathbf{s}_{ik}}$$

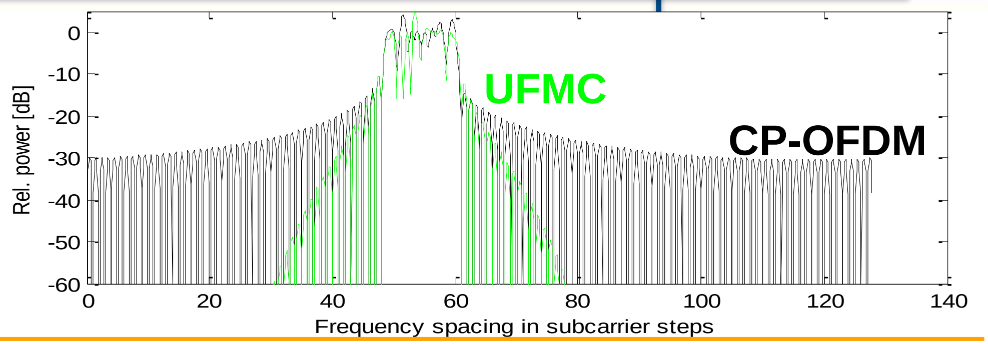
FFT-length N, filter length L, B sub-bands

- UFMC complexity similar to OFDM
- Huge knowledge base of OFDM processing can be re-applied to UFMC

UFMC – Temporal and Spectral Properties

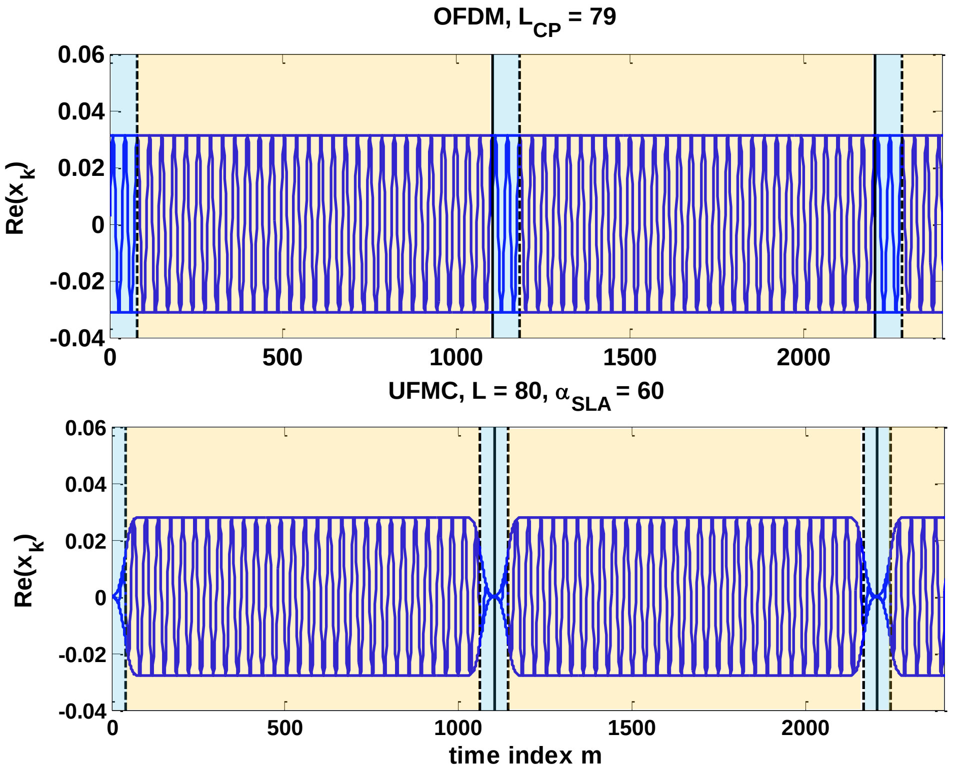
Spectral properties

- UFMC applies per sub-band filters
- Within sub-bands: CP-OFDM-like behaviour
- Between sub-bands: strong decay



Temporal properties

- Time domain overhead (~ 8%) used for filter ramps instead of cyclic extension
  - CP-OFDM design geared towards time domain protection
  - FBMC design (not depicted) geared towards frequency domain protection (between sub-carriers)
  - UFMC (also known as UF-OFDM) design geared towards frequency domain protection (between sub-bands) with keeping soft-protection in time domain



Source: Gerhard Wunder
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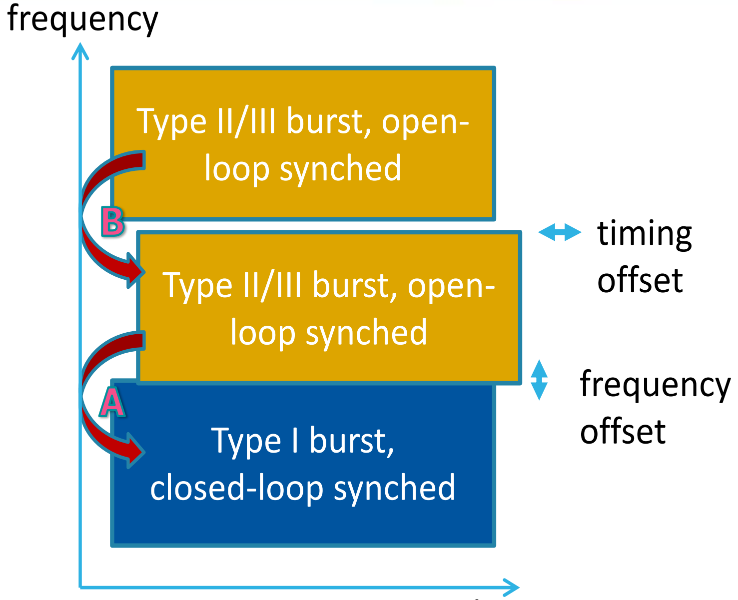
UFMC Suitability for Relaxed Synchronicity



Source: Gerhard Wunder
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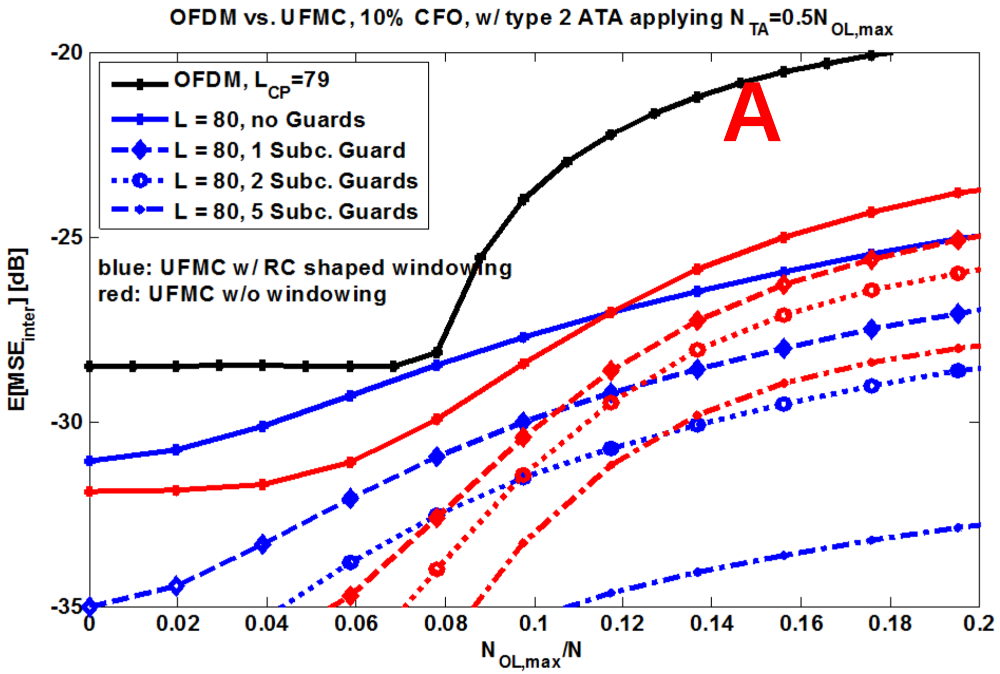
A: Inter-traffic interference: distortions from type II/III transmissions to type I transmissions

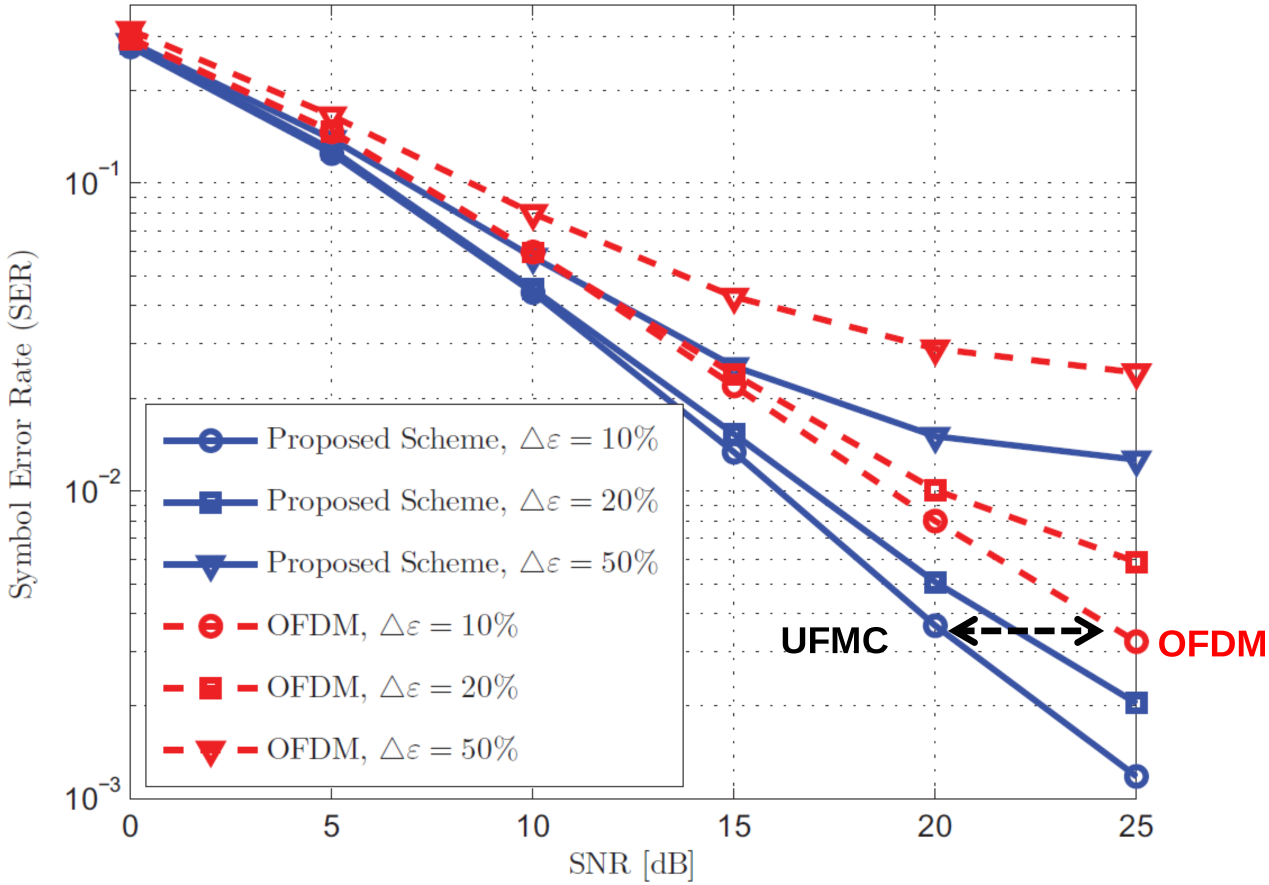
B: Intra-traffic interference: distortions between type II/III transmissions



- UFMC is able to support both closed-loop and open-loop synchronized traffic within a single frame
- more efficient than OFDM with negligible distortions
- enabling a highly scalable system.

Uplink CoMP/ UFMC vs OFDM

- UFMC adds increased robustness in CoMP against time-frequency misalignments



- CFO is estimated and compensated.
- CFO estimation error Δε

Parameters

- CFO 10% of subcarrier spacing
- QPSK
- FFT size 128
- 12 subc. per PRB
- 6 PRBs allocated
- Filter length / CP length 16
- UFMC: Dolph-Chebychev filters with 120 dB att.
- Frequency-selective fading channel (16 taps)

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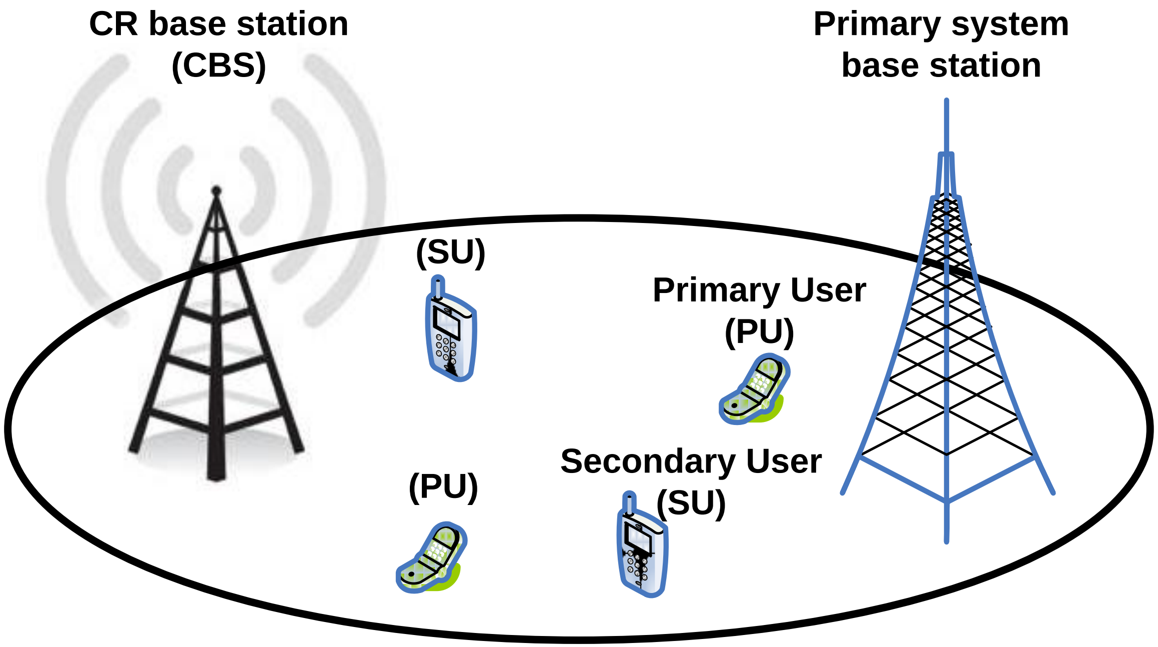
Part II : Comparison of FBMC and OFDM

Exemplary results

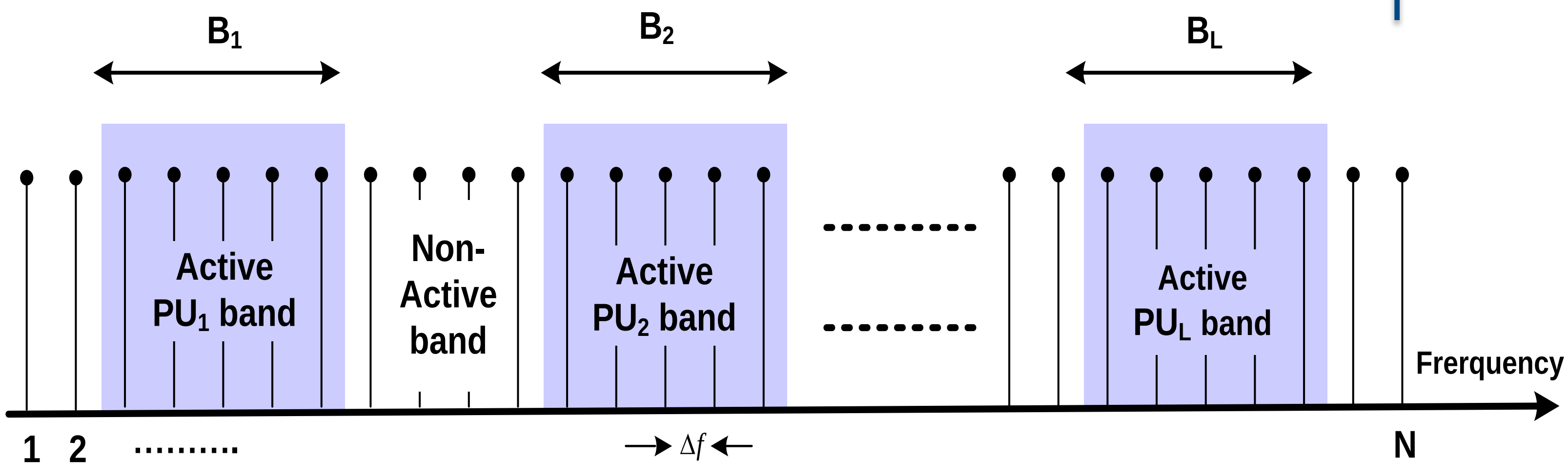
Resource Allocation for Spectrum Sharing in CR Environement: OFDM vs. FBMC capabilities

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



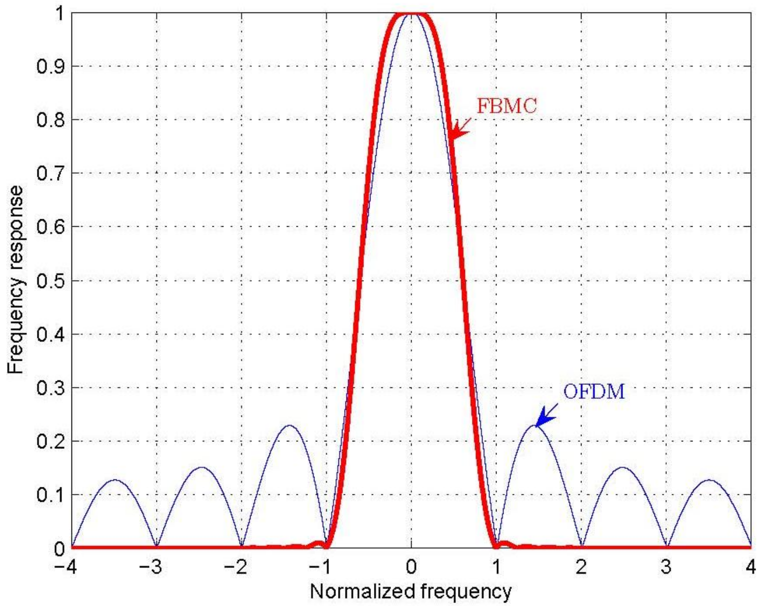
- The SU and PU band are exist side by side.
- Mutual interference is a limiting factor affect the performance of both systems.
- The CR can use active and non-active bands.
- The introduced interference to l^{th} band should be below $I_{th}^{l} = T_{th}^{l} B_{l}$ where T_{th}^{l} is the interference 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 CR 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
  1. Subcarriers are assigned to the users.
  2. 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

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

$$\sum_{i=1}^{N} P_i \leq P_T, \quad P_i \geq 0, \forall i \in \{1, 2, \ldots, N\}$$

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 $O\left(N^3\right)$ complexity
- Computationally efficient algorithm is needed for practical applications.

Proposed Algorithm, Cont.

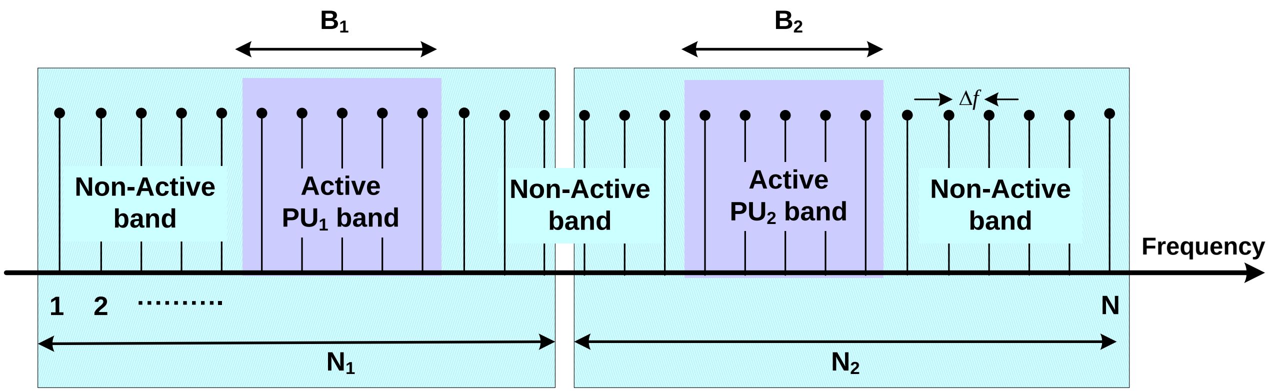
- For any set of subcarriers,
  - Optimal solution of the optimization subject to total power constraint only is waterfilling.
  - Optimal solution of the optimization problem subject to interference only can be solved by means of Langrangian and given by

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

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

Proposed Algorithm, Cont.

- Assume that each subcarrier is belonging to the closest PU band and only introducing interference to it.



Proposed Algorithm, Cont.

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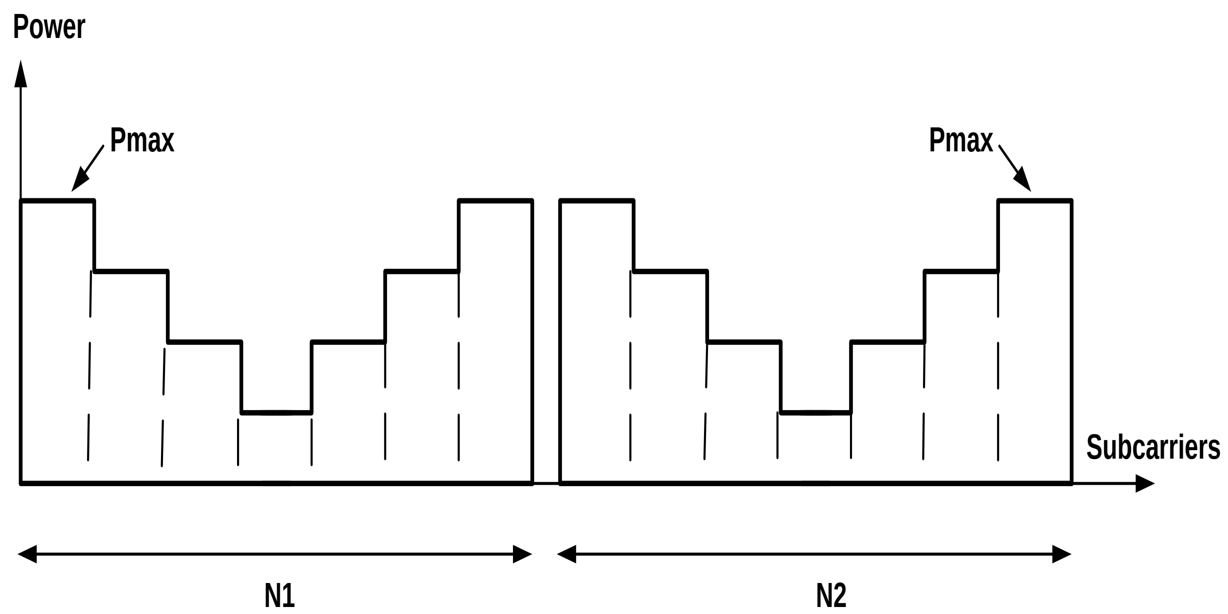
$$P_i^{'(Int)} = \left[\frac{1}{\alpha_l^{(Int)} \Omega_i} - \frac{\sigma^2}{|h_i|^2} \right]^+$$

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

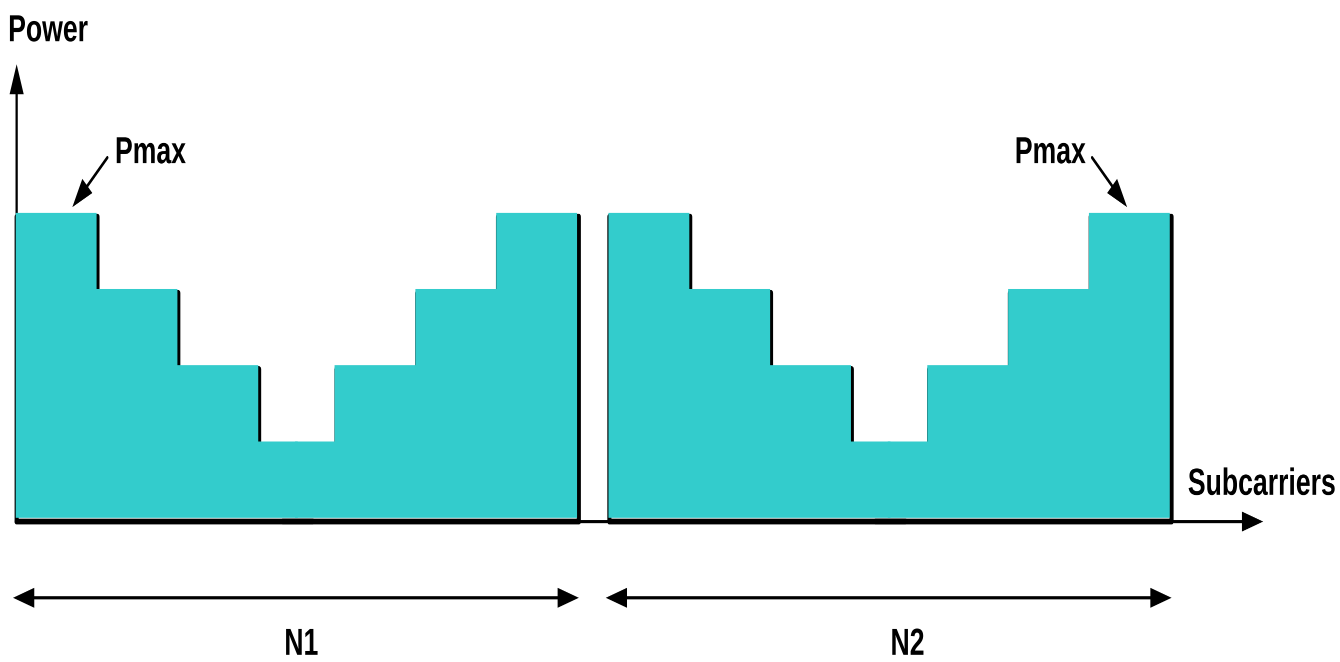
Proposed Algorithm, Cont.

- Assign the maximum power that can be allocated to each subcarrier by optimization subject to interference constraint only



Proposed Algorithm, Cont.

- Test the total power constraint, if it is satisfied the solution is found else continuo.



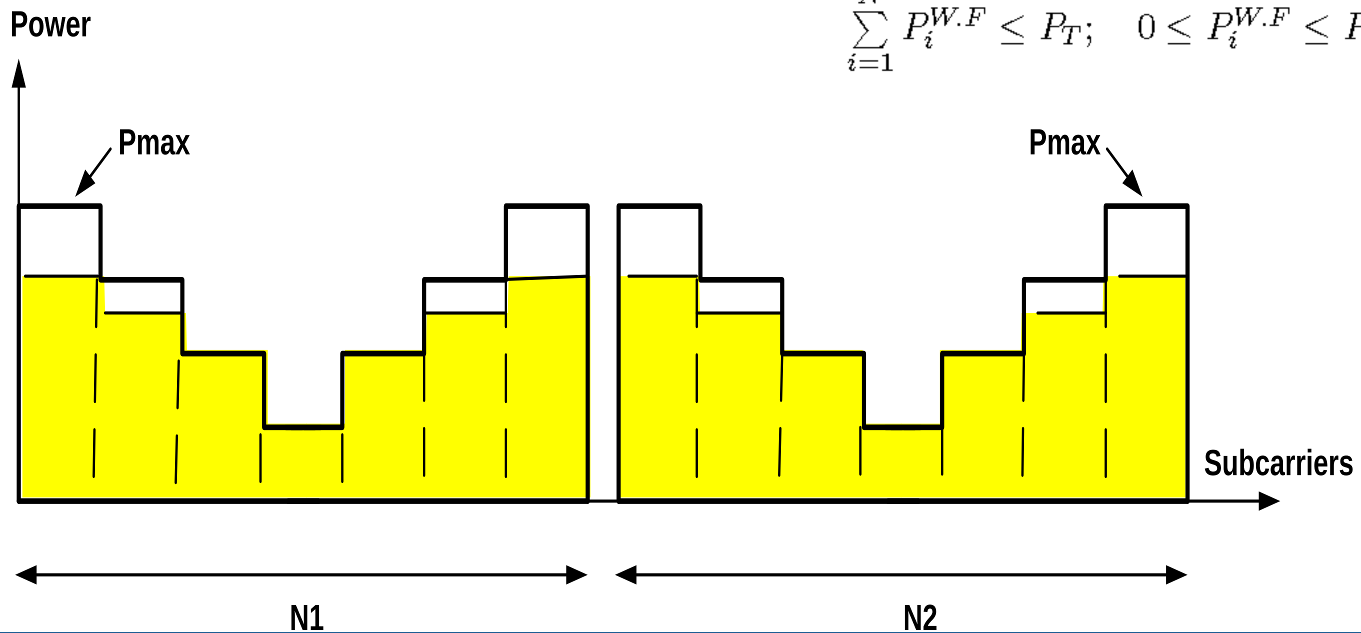
Proposed Algorithm, Cont.

- Distribute the available power according to the water-filling
- with the constraint that the power allocated to each subcarrier never exceeds P_i^{max}.

$$P3: \quad \max_{P_i^{W.F}} \sum_{i=1}^{N} \log_2\left(1 + \frac{P_i^{W.F}|h_i|^2}{\sigma^2}\right)$$

Subjet to

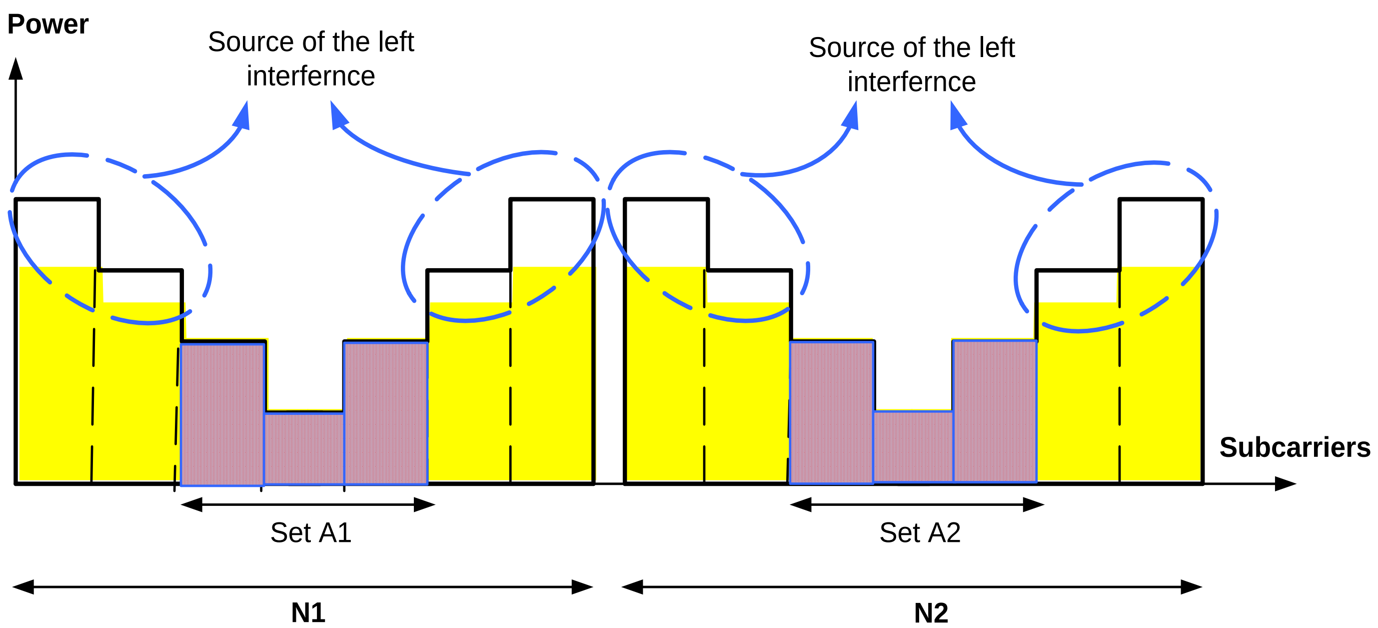
$$\sum_{i=1}^{N} P_i^{W.F} \leq P_T; \quad 0 \leq P_i^{W.F} \leq P_i^{Max}$$



Proposed Algorithm, Cont.

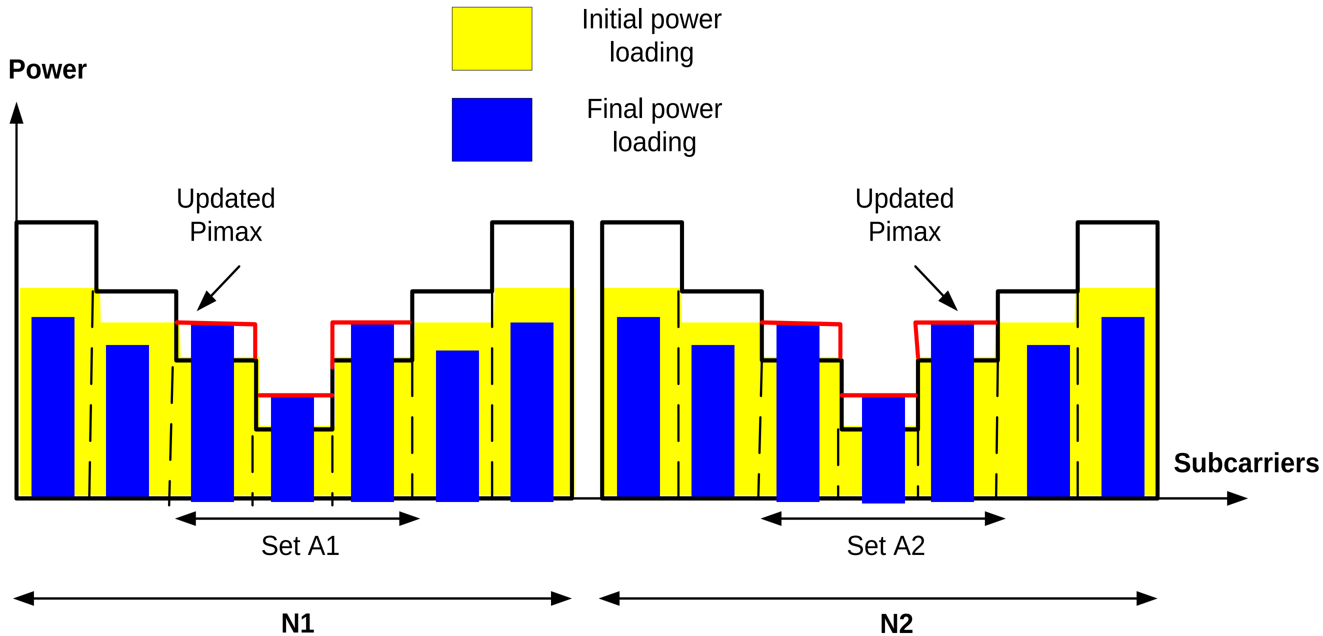
- The power constraint is satisfied with equality, which is not the case for the interference constraint.
- Determine the left available interference and the set A_l of the subcarriers that reach the maximum.

$$I^l_{Left} = I^l_{th} - \sum_{i \in N_l} P_i^{W.F} \Omega_i$$



Proposed Algorithm, Cont.

- Update the values of Pi_{max} in the set A_l according to the left interference and perform the waterfilling again.
- The power and interference constraints are approximately satisfied with equality.



Computational Complexity

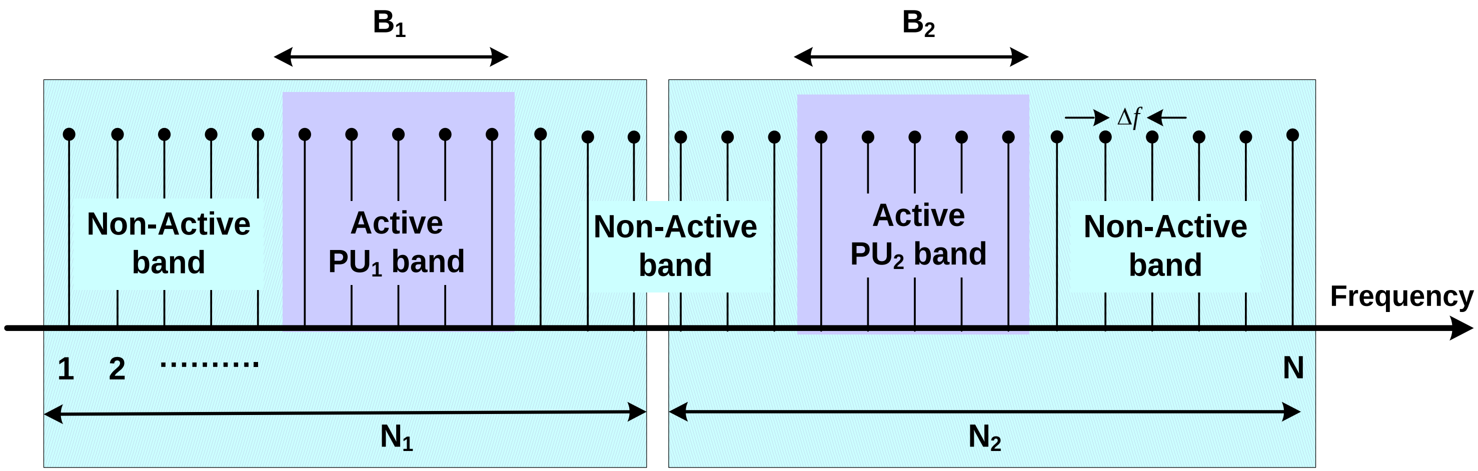
- The overall complexity of the algorithm is lower than

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

- Where $\eta \leq N$ 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.



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

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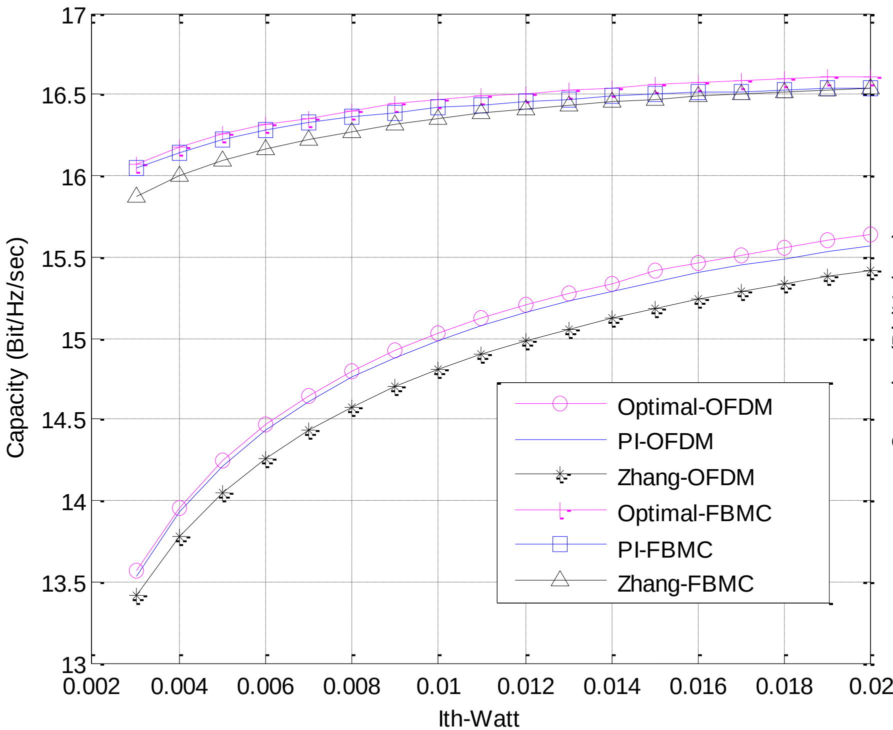
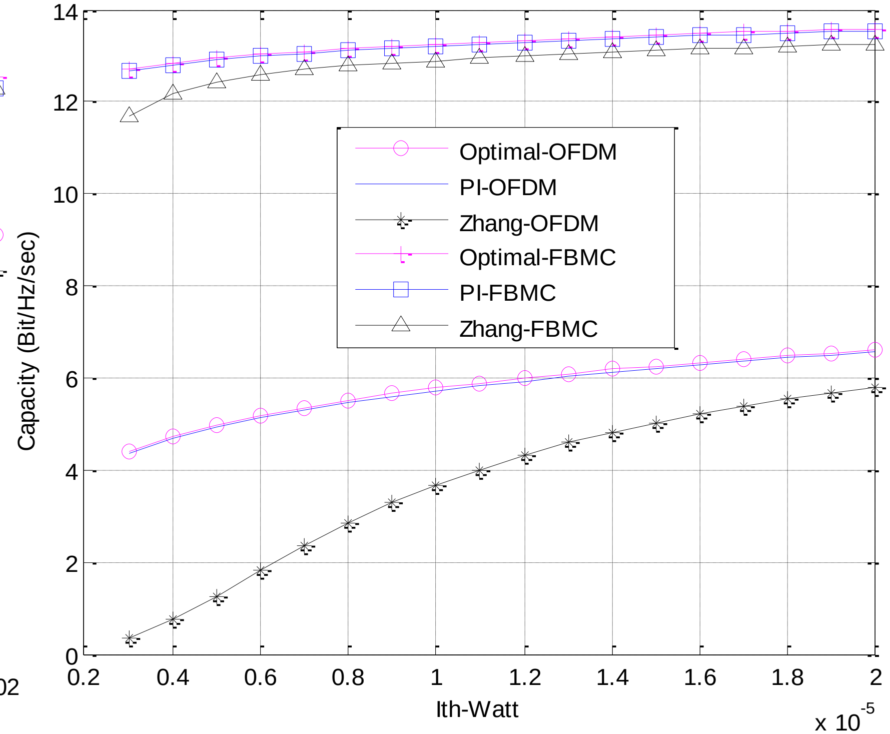


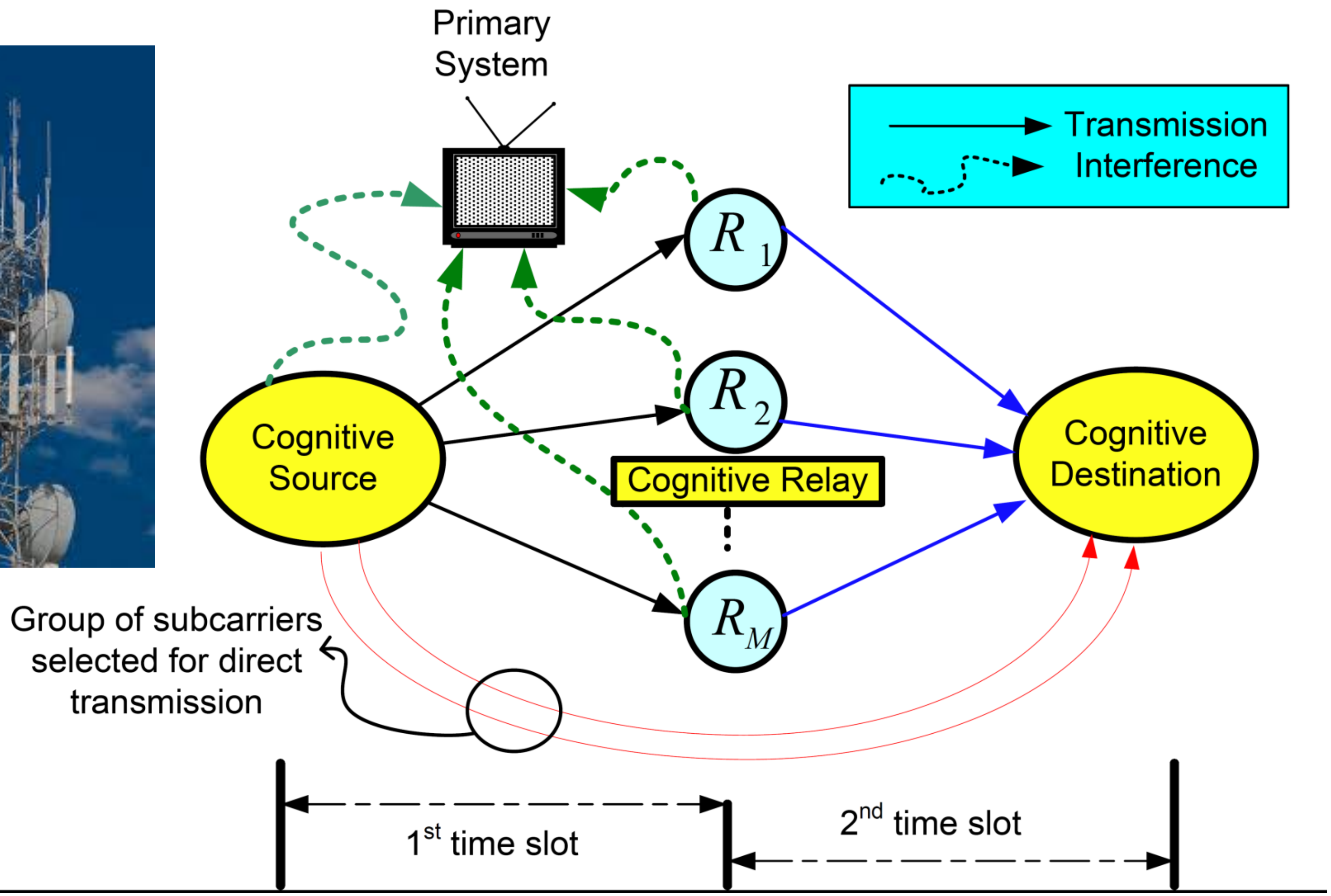


Low Interference

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

DF Multi-Relay in CR scenario: OFDM vs. FBMC Performance

System Model



System Model, Cont.

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

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

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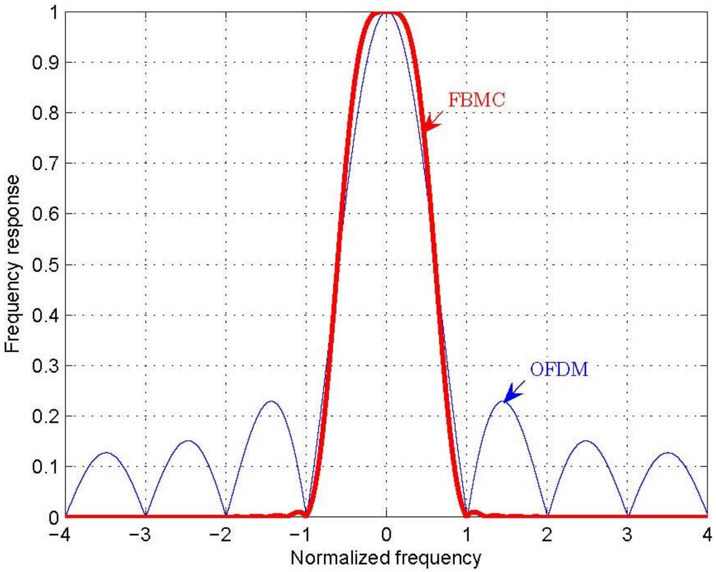
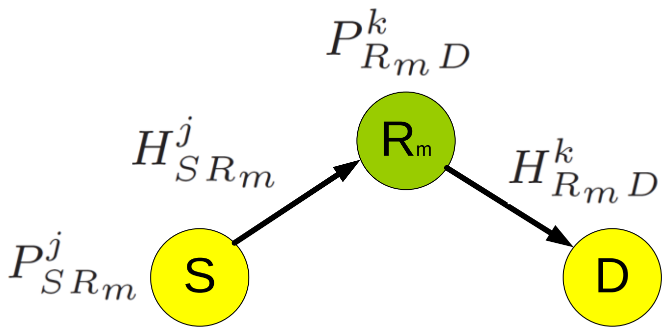


Problem Formulation



$$Rate_{m,(j,k)} = \frac{1}{2} \min \left\{ \begin{array}{l} \log_2 \left(1 + \dfrac{P^j_{S R_m} H^j_{S R_m}}{\sigma^2_{j,m}} \right) \\ \log_2 \left(1 + \dfrac{P^k_{R_m D} H^k_{R_m D}}{\sigma^2_{k,m}} \right) \end{array} \right.$$

$$R_{Direct}(j) = \frac{1}{2} \log_2 \left(1 + \frac{P^j_S H^j_{SD}}{\sigma^2_{j,D}} \right)$$

Problem Formulation

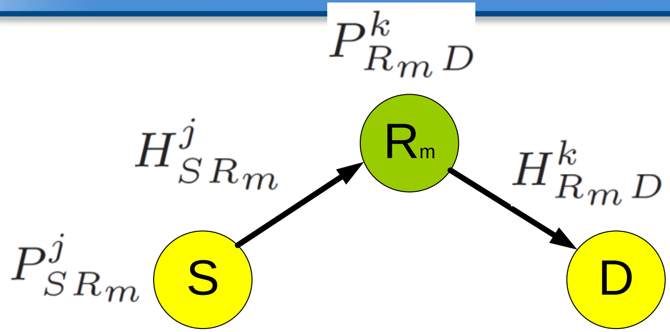
- $$\max_{P_S^j \geq 0, P_{R_mD}^k \geq 0, \alpha_j, \pi_{j,k}^m, t_{j,k}} \mathcal{R}$$

  $s.t.$

  - (C1: Source power constraint): $\sum_{j=1}^{N} P_S^j \leq P_S$
  - (C2: Relays individual power constraints): $\sum_{k=1}^{N} P_{R_mD}^k \leq P_{R_m}, \quad \forall m$
  - (C3: Interference at the first time slot): $\sum_{j=1}^{N} P_S^j \Omega_j \leq I_{th}$
  - (C4: Interference at the second time slot): $\sum_{m=1}^{M} \sum_{k=1}^{N} P_{R_mD}^k \Omega_{k,m} \leq I_{th}$
  - (C5: Relayed/Direct transmission constraint): $\alpha_j \in \{0, 1\}, \quad \forall j$
  - (C6: Subcarrier pairing constraint): $\sum_{k=1}^{N} t_{j,k} \leq 1, \forall j; \sum_{j=1}^{N} t_{j,k} \leq 1, \quad \forall k$
  - (C7: Relay Assignment constraint): $\sum_{m=1}^{M} \pi_{j,k}^m = 1 \quad \forall j, k$

where $\mathcal{R} \triangleq \left[\sum_{m=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{N} \frac{1}{2} \alpha_j \pi_{j,k}^m t_{j,k} R_{Relayed}(j, k, m) + \sum_{j=1}^{N} \frac{1}{2} \left(1 - \alpha_j\right) R_{Direct}(j) \right]$

Problem Formulation



$$Rate_{m,(j,k)} = \frac{1}{2}\min\left\{\begin{array}{l} \log_2\left(1+\dfrac{P^{j}_{S R_m} H^{j}_{S R_m}}{\sigma^2_{j,m}}\right) \\ \log_2\left(1+\dfrac{P^{k}_{R_m D} H^{k}_{R_m D}}{\sigma^2_{k,m}}\right) \end{array}\right.$$

$$P^{j}_{S R_m} H^{j}_{S R_m} = P^{k}_{R_m D} H^{k}_{R_m D}$$

$$P^{k}_{R_m D} = \frac{P^{j}_{S R_m} H^{j}_{S R_m}}{H^{k}_{R_m D}}$$

$$R_{Direct}(j) = \frac{1}{2}\log_2\left(1+\frac{P^{j}_{S} H^{j}_{SD}}{\sigma^2_{j,D}}\right)$$

Problem Formulation

$$\max_{P_S^j \geq 0, P_{R_m D}^k \geq 0, \alpha_j, \pi_{j,k}^m, t_{j,k}} \quad \mathcal{R}$$

$s.t.$

- (C1: Source power constraint): $\sum_{j=1}^{N} P_S^j \leq P_S$
- (C2: Relays individual power constraints): $\sum_{j=1}^{N} \sum_{k=1}^{N} \alpha_j \pi_{j,k}^m t_{j,k} \frac{P_S^j H_{SR}^j}{H_{RD}^k} \leq P_{R_m}; \quad \forall m$
- (C3: Interference at the first time slot): $\sum_{j=1}^{N} P_S^j \Omega_j \leq I_{th}$
- (C4: Interference at the second time slot): $\sum_{m=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{N} \alpha_j \pi_{j,k}^m t_{j,k} \frac{P_S^j H_{SR}^j}{H_{RD}^k} \Omega_{k,m} \leq I_{th}$
- (C5: Relayed/Direct transmission constraint): $\alpha_j \in \{0, 1\}, \quad \forall j$
- (C6: Subcarrier pairing constraint): $\sum_{k=1}^{N} t_{j,k} \leq 1, \forall j; \sum_{j=1}^{N} t_{j,k} \leq 1, \quad \forall k$
- (C7: Relay Assignment constraint): $\sum_{m=1}^{M} \pi_{j,k}^m = 1 \quad \forall j, k$

Optimal solution

- The problem is mixed binary integer optimization problem.
- Large number of subcarrier matching and relay assignment possibilities specially with large number of subcarrier (High Complexity).
- The problem is satisfying the time sharing condition.
- The duality gap of the problem is negligible as the number of subcarrier is sufficiently large (more than 8) regardless of the convexity of the problem.
- The solution obtained by the dual method is asymptotically optimal.

Wei Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," IEEE Transactions on Communications, vol. 54, no. 7, pp. 1310 1322, 2006.

M. Shaat and F. Bader, Joint Resource Optimization in Decode and Forward Multi-Relay Cognitive Network with Direct Link, accepted at the IEEE Wireless Communications and Networking Conference (IEEE WCNC'2012). Paris, France. April 2012.

Optimal solution

- The dual decomposition approach has high computational complexity.

$$\mathcal{O}\left(T(MN) + M(N!) + 2N + N^3\right)$$

where "T" is the number of iteration required to converge which is usually large.

- To reduce the computational complexity, a suboptimal algorithm is proposed to jointly optimize the different system resources.

Sub-Optimal solution

The assigning procedures of a particular subcarrier j

- Determine the power in the source side $P_S^j = \min(P_j^{uni}, P_j^{max})$.
- For every relay m, evaluate the rate $R_{j,m}^{Source}$ achieved by allocating the subcarrier $j \rightarrow m^{th}$ relay.
- Compute the required power $P_{j,k,m}^{\text{rate}}$ to achieve a rate in the $R \rightarrow D$ link equal to that in the $S \rightarrow R$ link.
- Determine the power in the destination side $Power_{j,k,m} = \min\left(P_{j,k,m}^{\text{rate}}, P_{k,m}^{uni}, P_{k,m}^{max}\right)$.
- Find k^* and m^* satisfying $(k^*, m^*) = \arg\max_{k,m}\left(Power_{j,k,m} H_{R_m D}^k\right)$.
- Choose the direct link if $P_S^j H_{SD}^j > Power_{j,k^*,m^*} H_{R_{m^*} D}^k$. Otherwise, update the subcarrier/relay indicators and the m^{th} relay power budget.
- Repeat the steps until the assignment of the all subcarriers.

Musbah Shaat and Faouzi Bader, "***Asymptotically Optimal Resource Allocation in OFDM-Based Cognitive Networks with Multiple Relays***", IEEE Transactions on Wireless Communications, Vol. 11, NO.3, March 2012.

Complexity Comparison

Algorithm	Complexity
Asymptotically Optimal	$\mathcal{O}\left(T(MN^2 + M(N!) + 2N + N^3)\right)$
Proposed suboptimal	$\mathcal{O}(MN + MN^2)$

- Simulation Parameters

Parameter	Value
No. Subcarrier	$N = 64$
No. Relays	$M = 5$
Power	$P_S = P_R = 0$ and $P_S = P_R = 20$ dBm

- Optimal: Dual decomposition technique.
- Suboptimal: Proposed Algorithm.
- SNR: Subcarrier and users are assigned based on their SNR values.
- Random: Subcarrier and users are assigned randomly.
- For SNR and Random, Powers are evaluated by solving the optimization problem with known $t_{j,k}$ and $\pi_{m(j,k)}$

Performances, Cont.

OFDM vs. FBMC

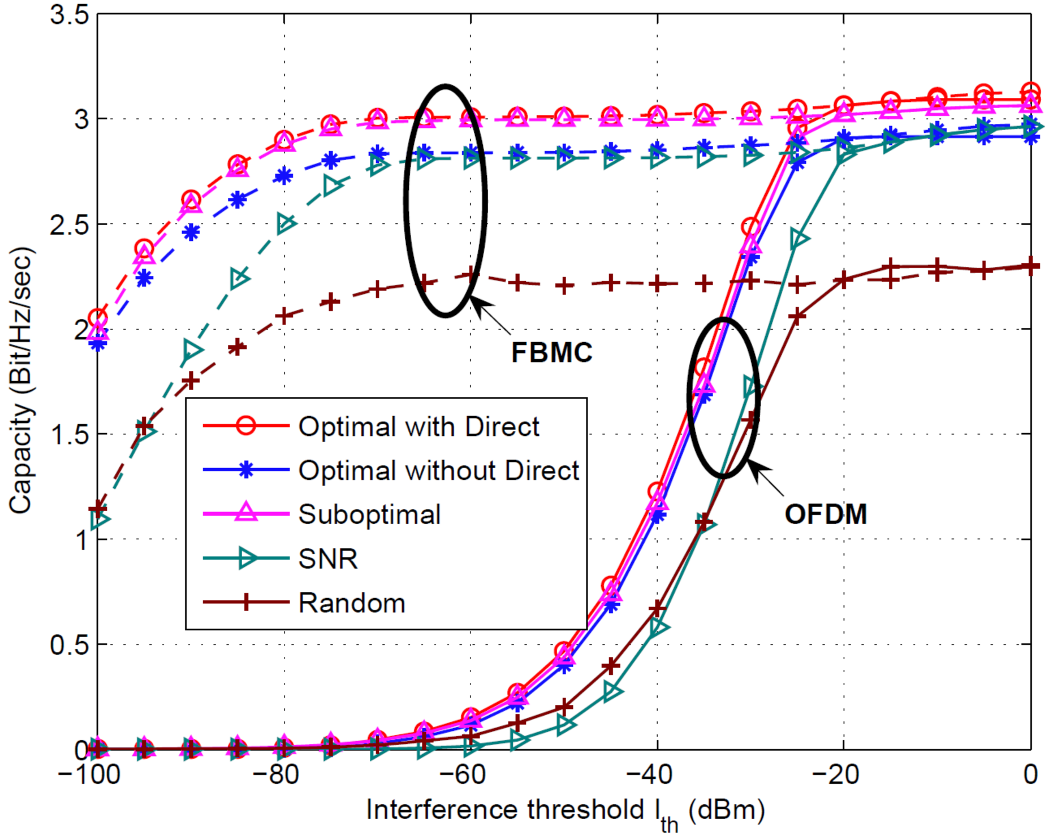


Figure 3: Achieved capacity vs. interference threshold with P_s=P_{Rm} = 0 dBm. OFDM is plotted in solid lines, and FBMC is plotted in dashed lines.

M. Shaat and F. Bader, **Comparison of OFDM and FBMC Performance in Multi-Relay Cognitive Radio Network,** in Proc. of the ninth IEEE International Symposium in Wireless Communication Systems (ISWCS'2012), on 29 August 2012, at Paris, France.

Performances, Cont.

OFDM vs. FBMC

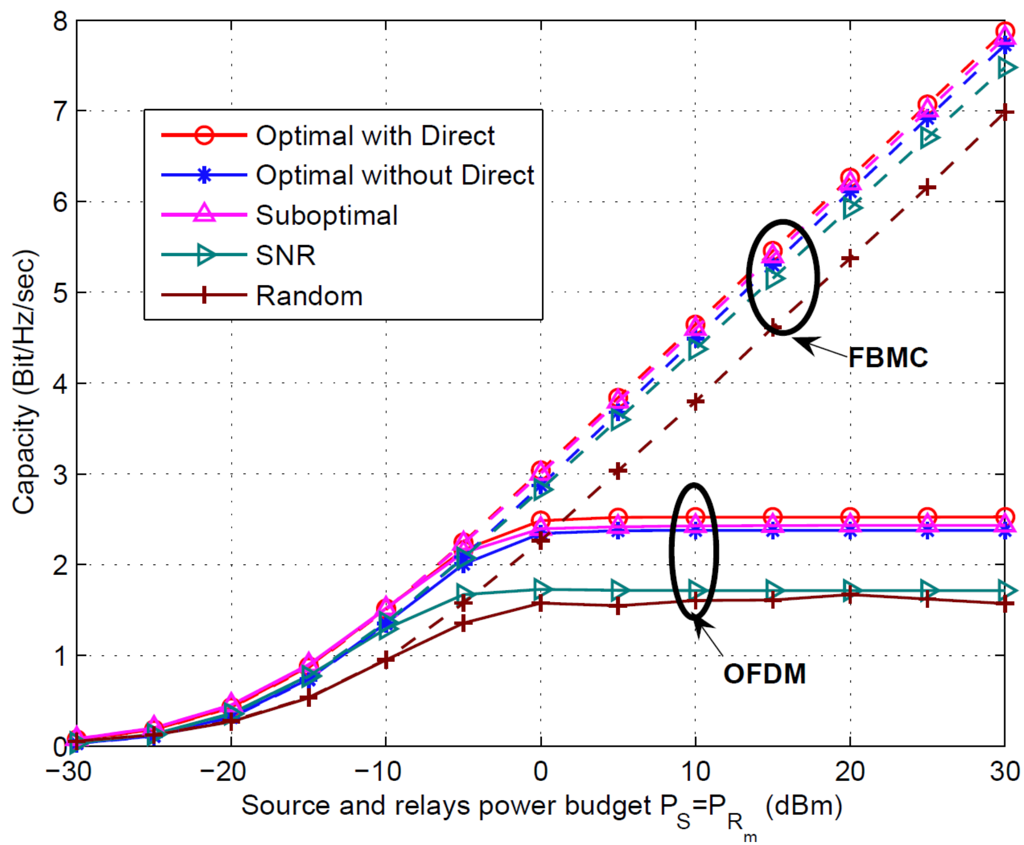
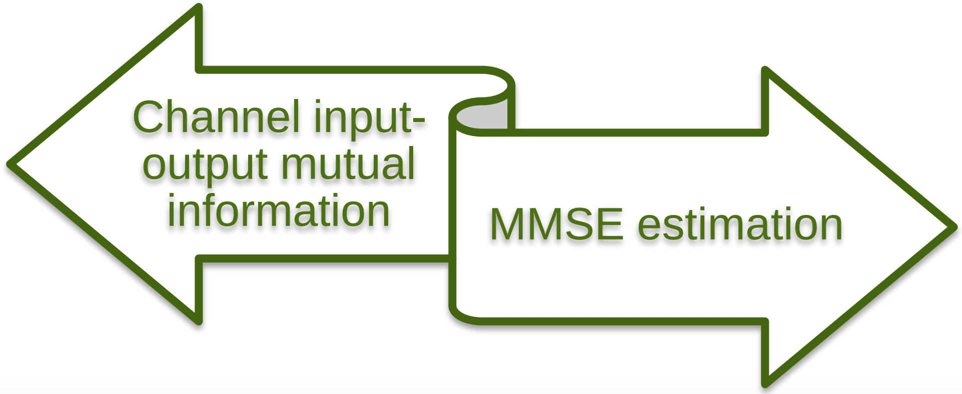


Figure 3: Achieved capacity vs. interference threshold with $P_s=P_{Rm}$ when $P_{Ith.}$ = -30 dBm. OFDM system is plotted in solid lines, FBMC is plotted in dashed lines.

M. Shaat and F. Bader, **Comparison of OFDM and FBMC Performance in Multi-Relay Cognitive Radio Network,** in Proc. of the ninth IEEE International Symposium in Wireless Communication Systems (ISWCS'2012), on 29 August 2012, at Paris, France.

Power Loading for FBMC Systems: An Analysis with Mercury-filling Approach

Mercuryfilling principle

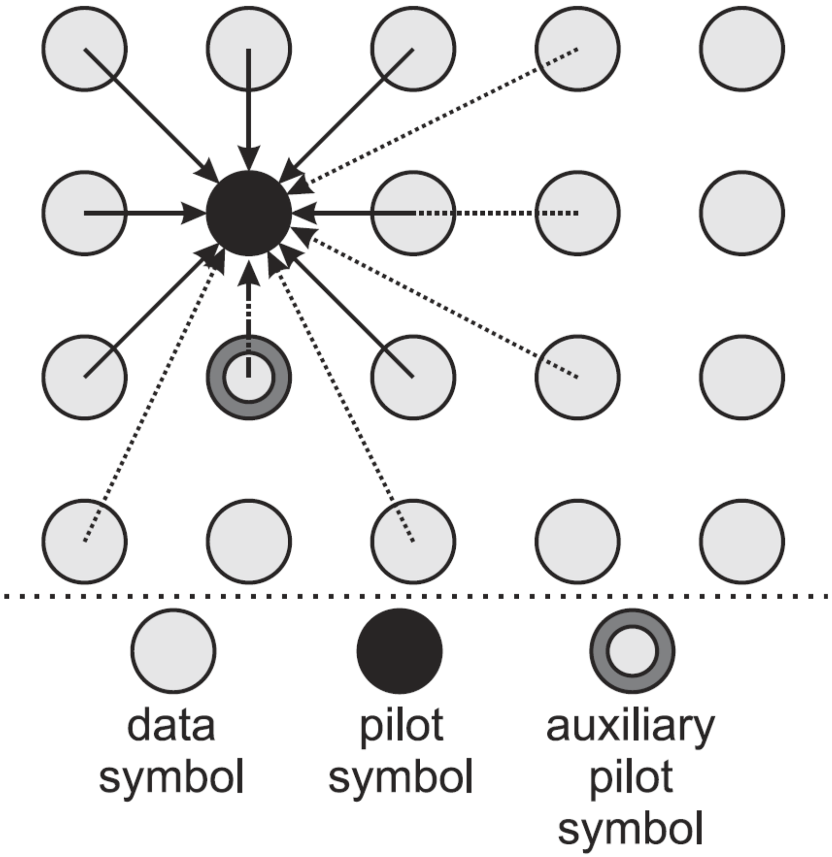


„The input–output mutual information is an indicator of how much coded information can be pumped through a channel reliably given a certain input signaling, whereas the MMSE measures how accurately each individual input sample can be recovered using the channel output."

$$\frac{d}{d\gamma} I_{l,m}(\gamma) = \frac{1}{2} \mathrm{MMSE}_{l,m}(\gamma);$$

D. Guo, S. Shamai (Shitz), S. Verdú, Mutual Information and Minimum Mean-Square Error in Gaussian Channels, IEEE TRANSACTIONS ON INFORMATION THEORY, VOL. 51, NO. 4, APRIL 2005, pp. 1261-1282

Auxiliary pilot concept



Mercuryfilling principle

Optimum power allocation for non-gaussian inputs

$$\begin{aligned} p^*_{l,m} &= 0 \quad \text{for} \quad \gamma_{l,m} < \zeta \\ \gamma_{l,m} \cdot \mathrm{MMSE}_{l,m}(p^*_{l,m}\gamma_{l,m}) &= \zeta \quad \text{for} \quad \gamma_{l,m} \geq \zeta \end{aligned}$$

2-step algorithm

$$\mathrm{MMSE}(\gamma_{a,b}) = 1 + \ddot{I}(0)\gamma_{a,b} + O(\gamma^2_{a,b})$$

Generic formula for MMSE calculation

$$\begin{aligned} \mathrm{MMSE}(\rho) &= \int \sum_{\ell=1}^{m} \left| s_\ell - \hat{S}(y,\rho) \right|^2 \frac{e^{-|y-\sqrt{\rho}\, s_\ell|^2}}{m\pi} dy \\ &= 1 - \frac{1}{m\pi} \int \frac{\left| \sum_{\ell=1}^{m} s_\ell\, e^{-|y-\sqrt{\rho}\, s_\ell|^2} \right|^2}{\sum_{\ell=1}^{m} e^{-|y-\sqrt{\rho}\, s_\ell|^2}} dy \end{aligned}$$

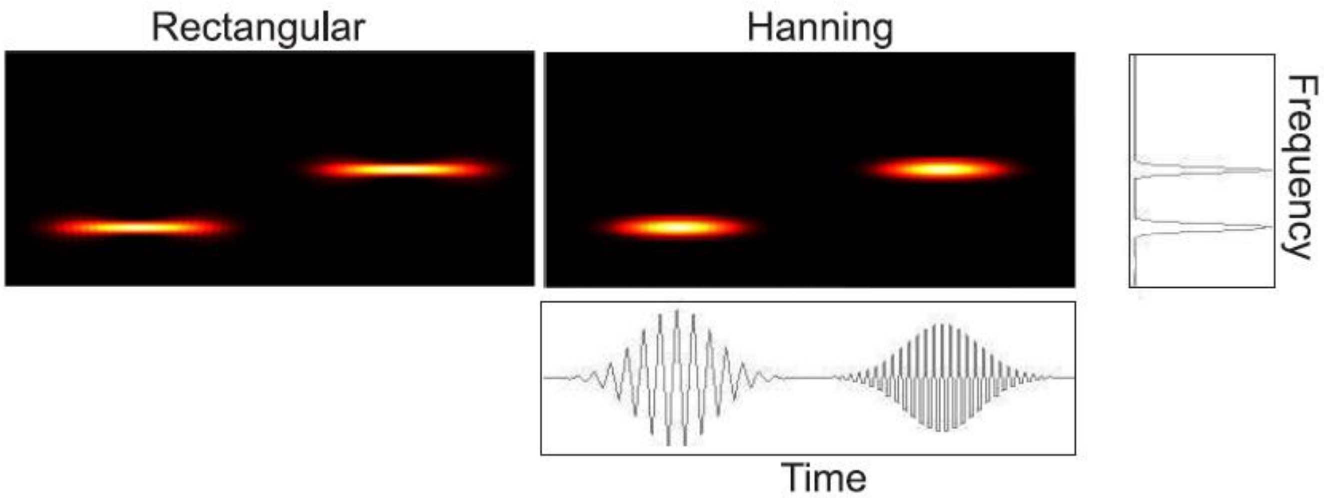
Application of the MFP

First approach:

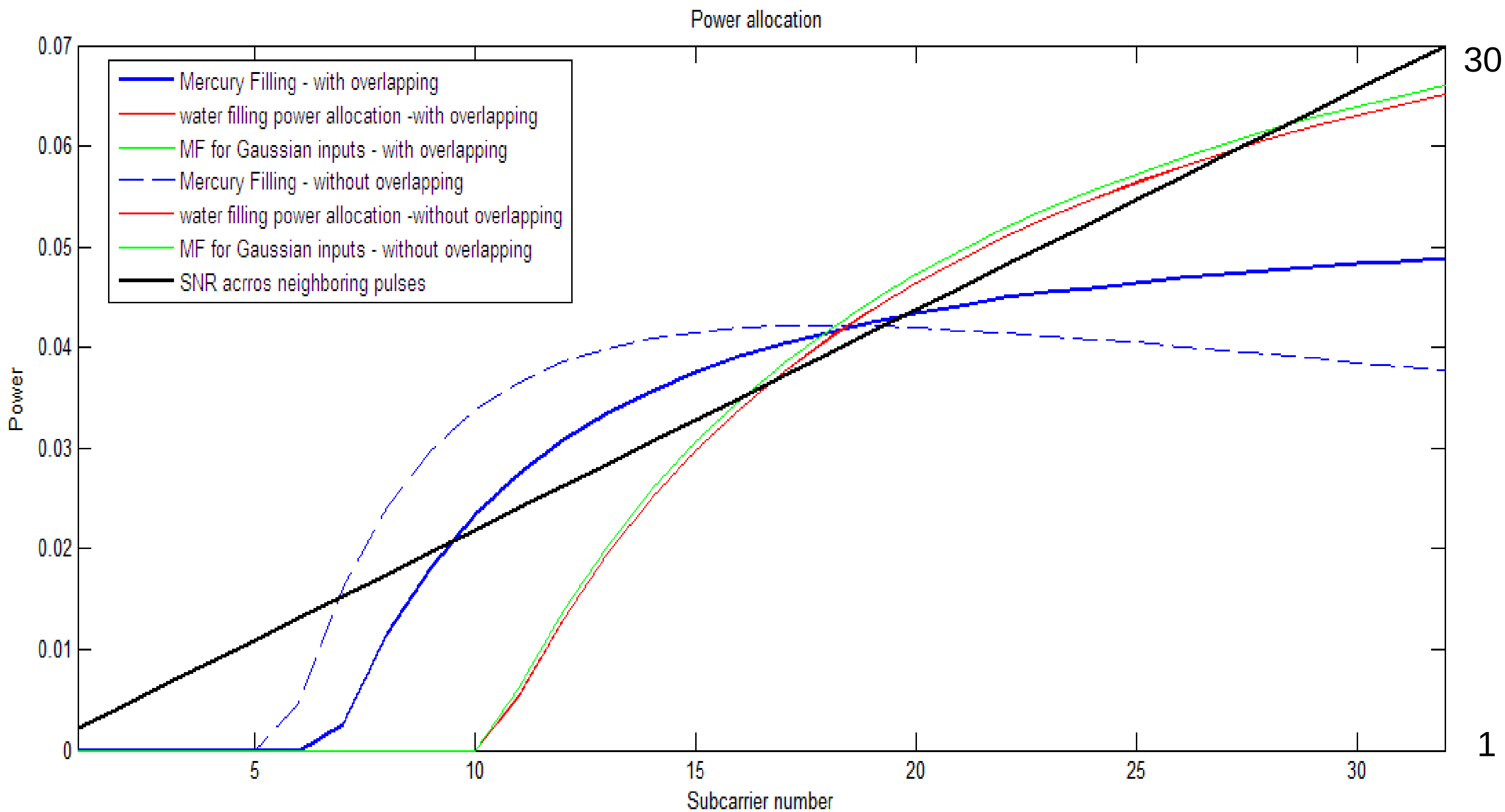
$$\gamma_{l,m} = \frac{|h_{l,m}|^2 \; p_{l,m} |\Delta\epsilon_{l,m}^{(l,m)}|^2}{\sum_{(l',m')\neq(l,m)} |h_{l',m'}|^2 p_{l',m'} |\Delta\epsilon_{l',m'}^{(l,m)}|^2 + \sigma^2 |\Delta\epsilon_{l,m}^{(l,m)}|^2}$$

Problem of calculation of the power distrubution on time-frequency plane:

- Heisenberg uncertainity rule
- Application of STFT (current solution)

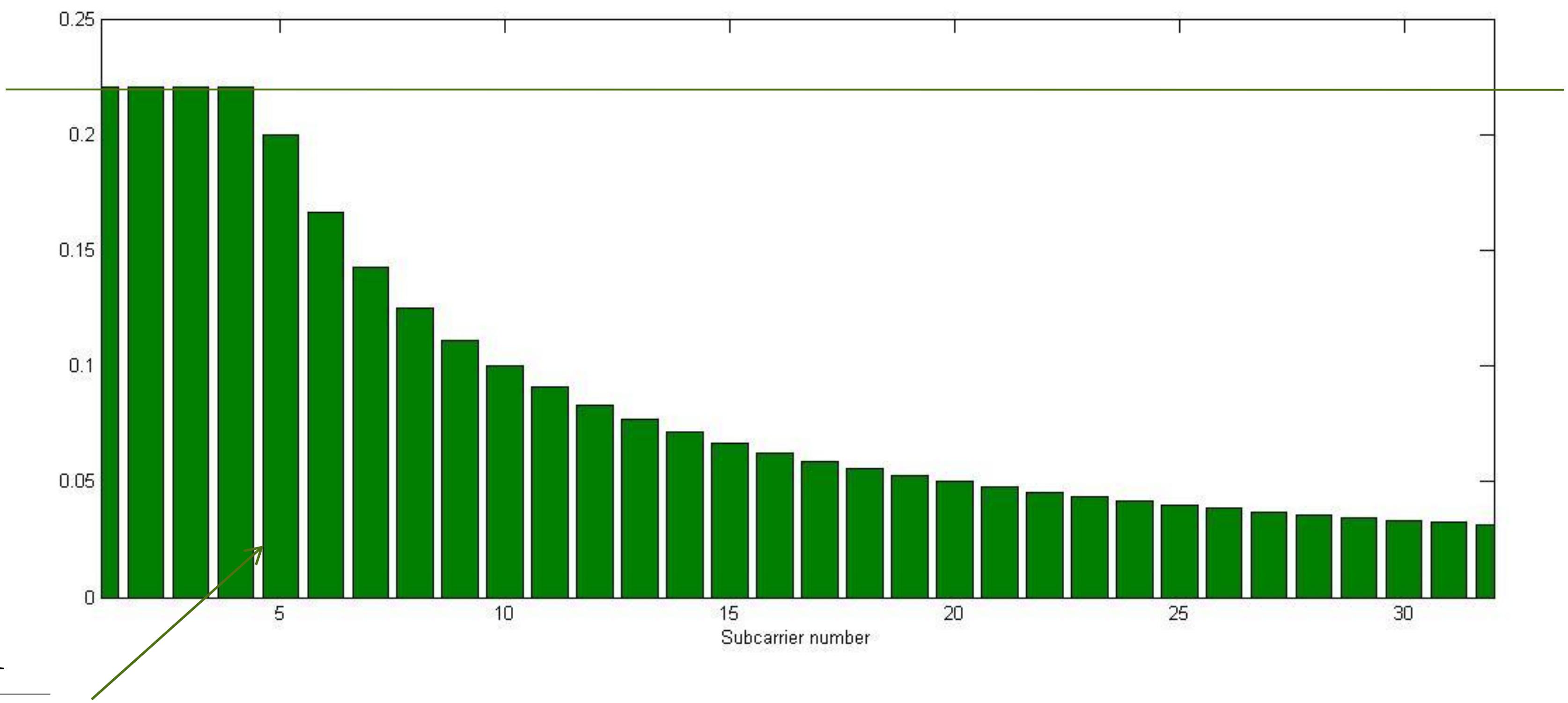


Application of the MFP



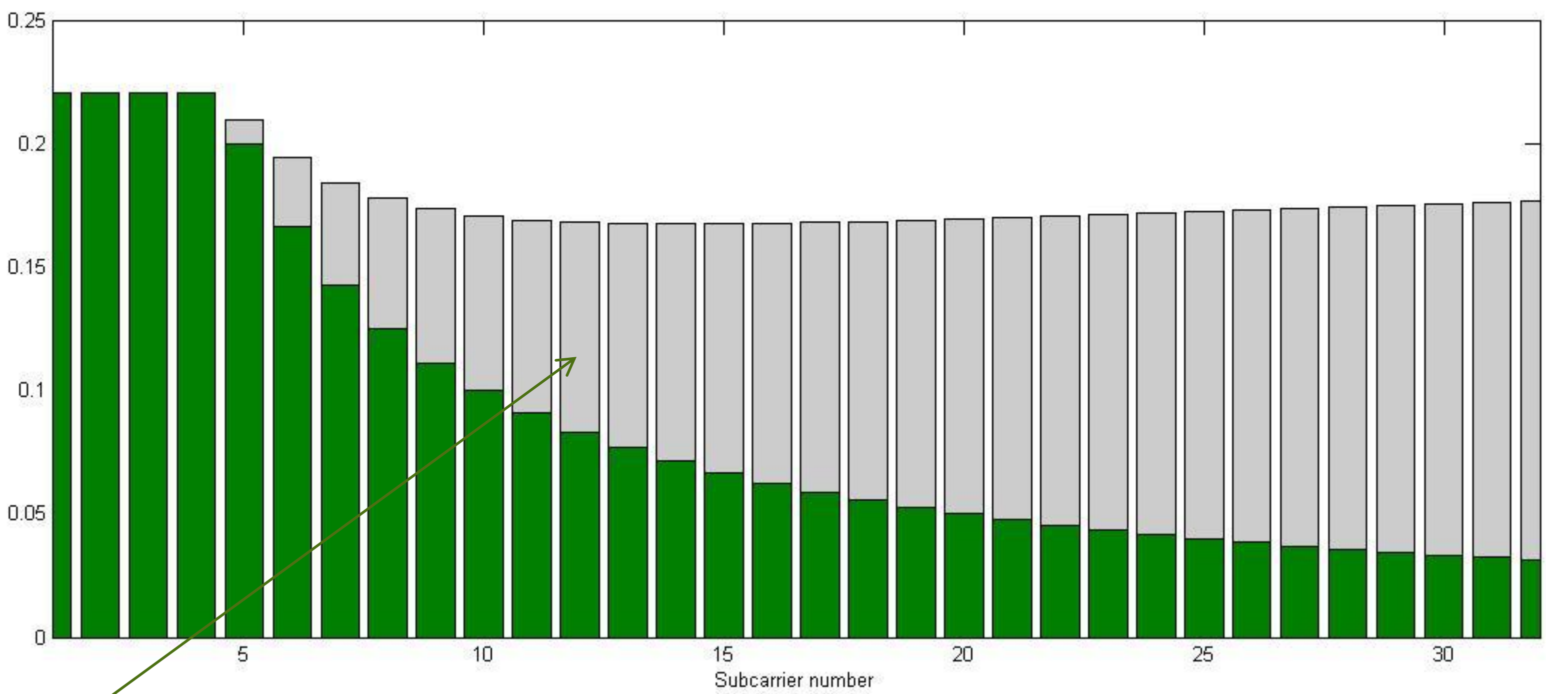
Mercury/Waterfilling- no overlapping

$\frac{1}{\zeta}$



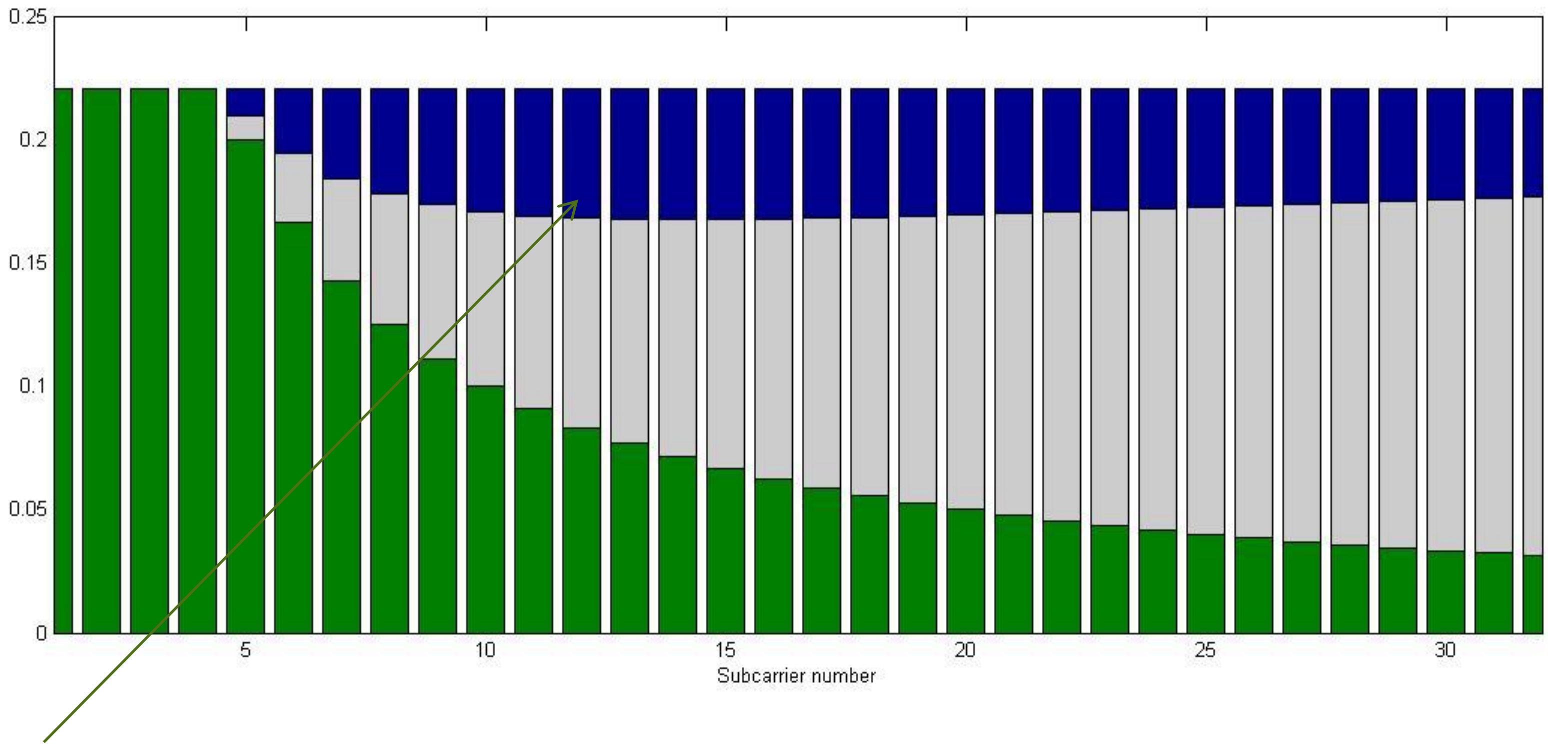
$\frac{1}{\gamma_{l,m}}$

Mercury/Waterfilling- no overlapping



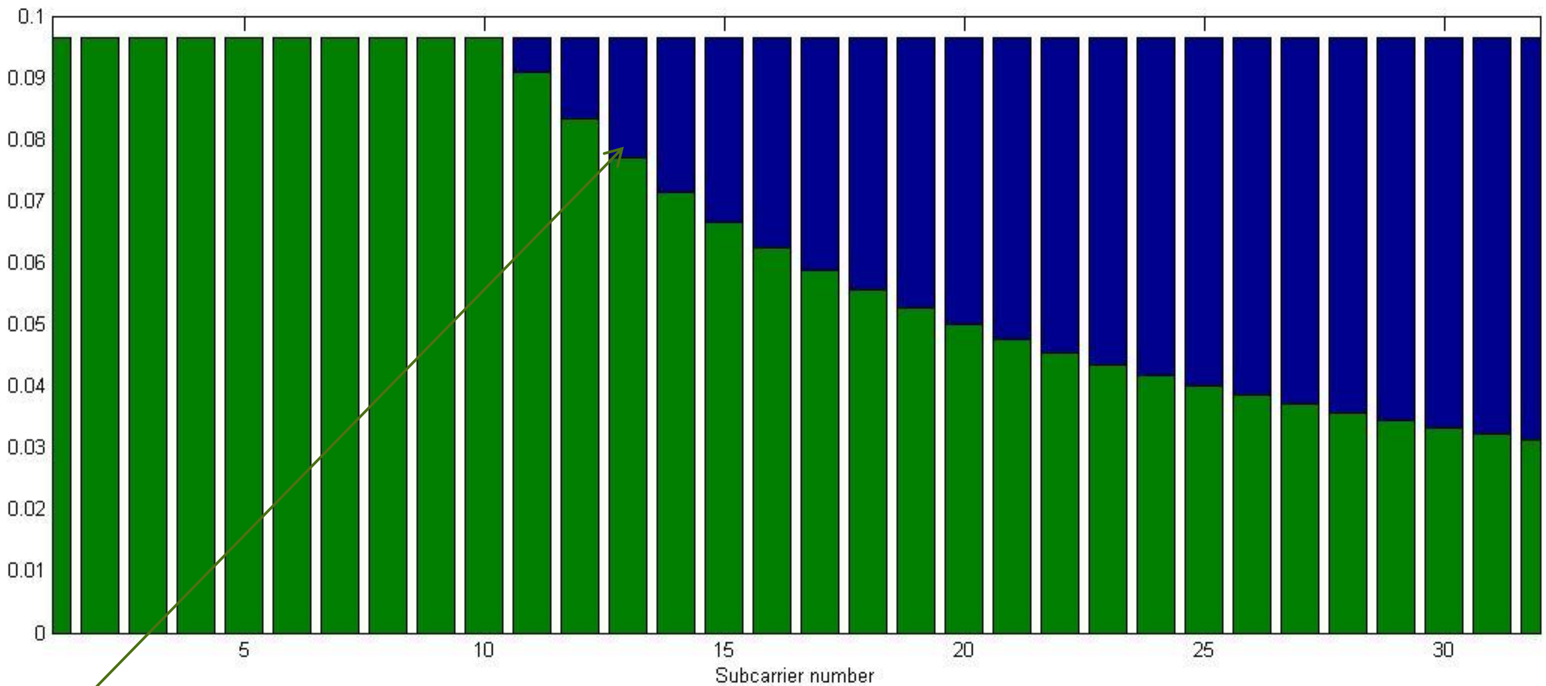
Fill with mercury up to the level $\frac{1}{\zeta} - \frac{1}{\gamma_{l,m}} MMSE^{-1}\left(\frac{\zeta}{\gamma_{l,m}}\right)$

Mercury/Waterfilling- no overlapping



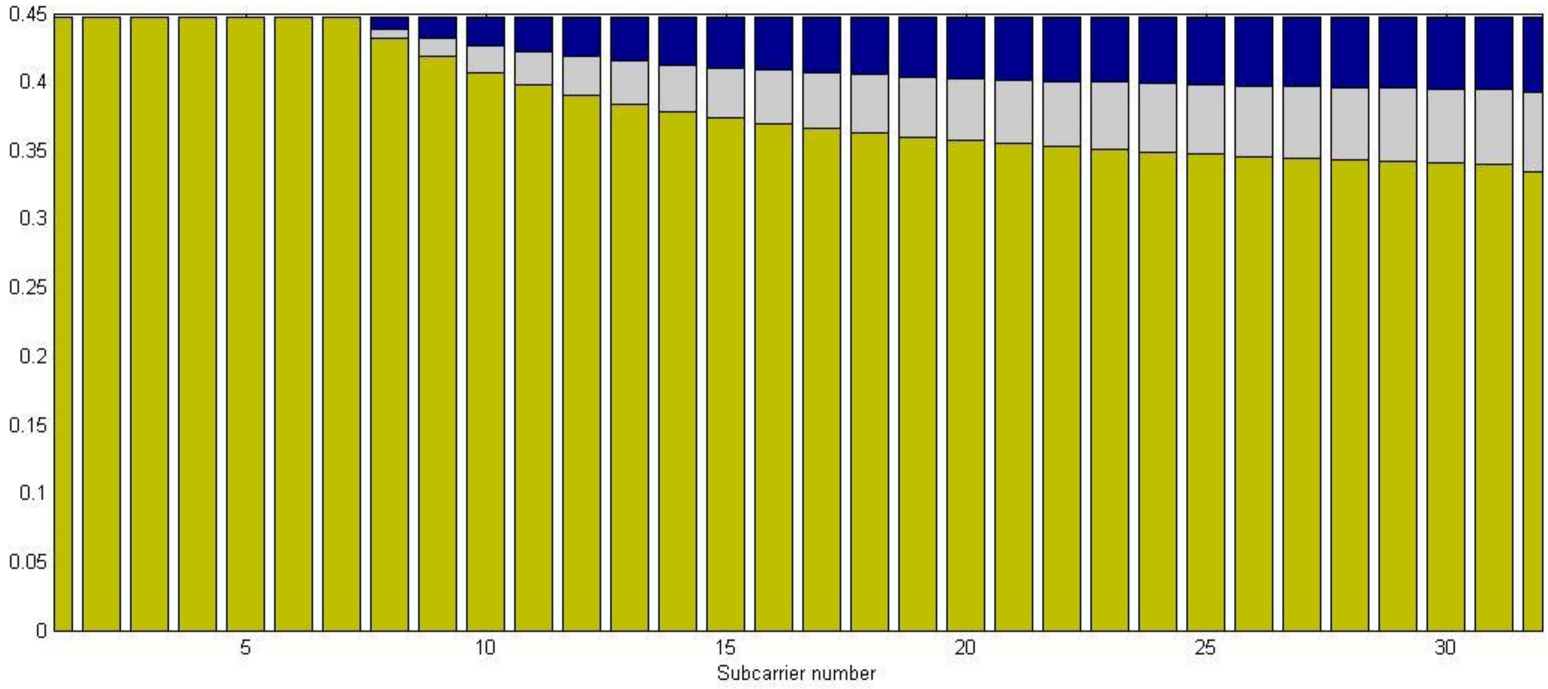
Fill with water – what corresponds to the allocated power

Pure waterfilling – no overlapping

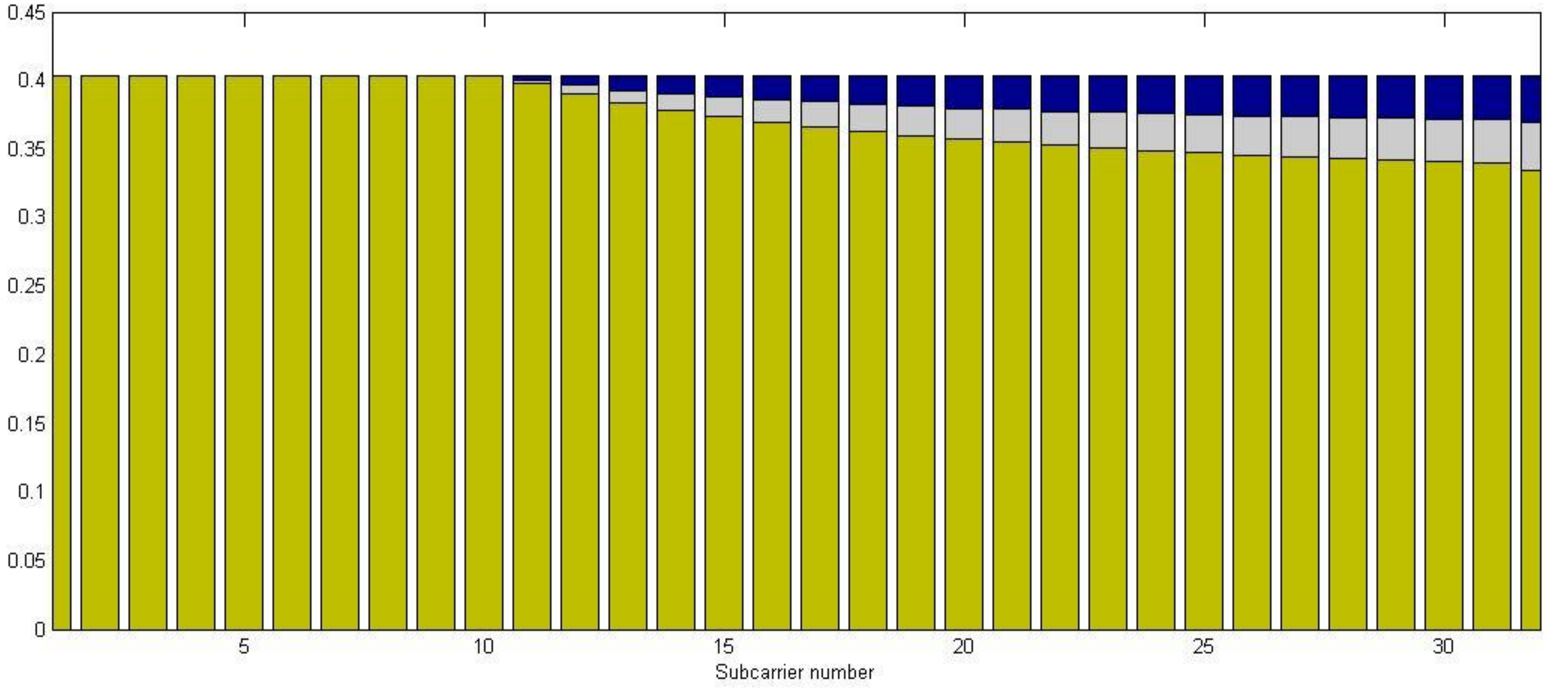


Fill with water – what corresponds to the allocated power

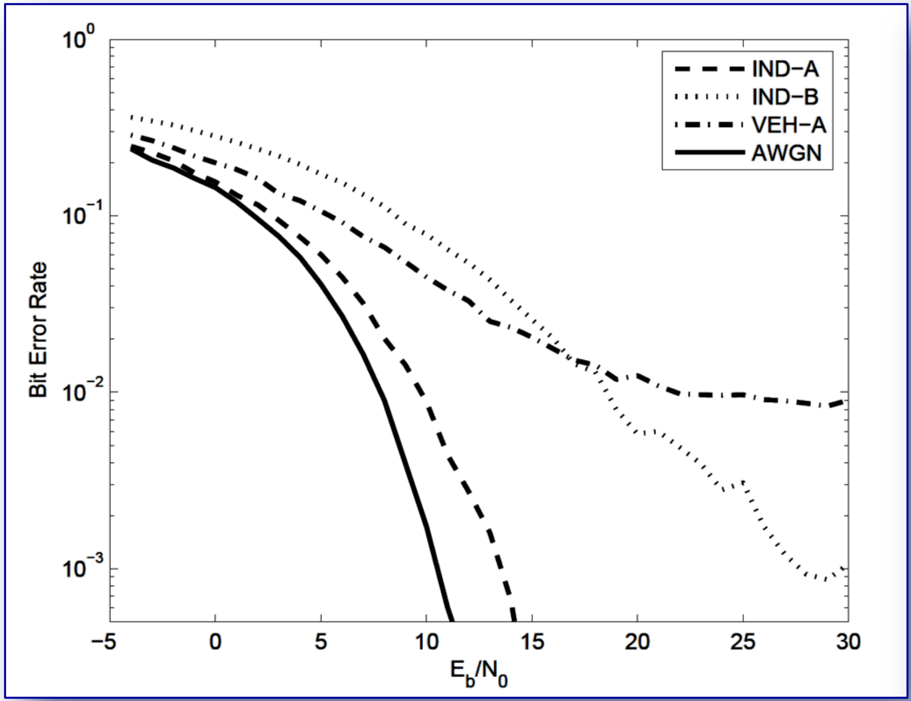
Mercury/waterfilling – with overlapping

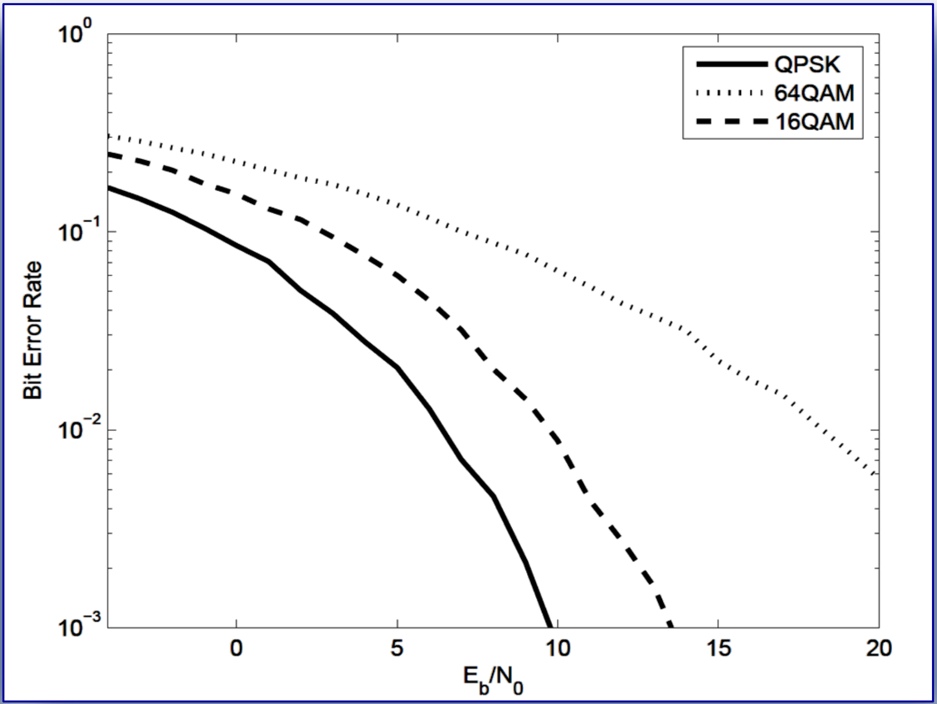


Pure waterfilling – with overlapping



Simulation results





Adrian Kliks, Faouzi Bader, **Bit and Power loading for FBMC systems: an analysis with Mercury-filling Approach,** Submitted to the SS on: *Cognitive Radio for Energy Efficient Next Generation Networks,* accepted at the 20th IEEE International Conference on Telecommunications (IEEE ICT 2013) May 6-8, 2013 in Casablanca, Morocco.

Analysis of Asynchronous OFDM and FBMC Wireless Communication Systems

Source: Yahia Medjahdi, PhD dissertation, CNAM, Paris 2012.

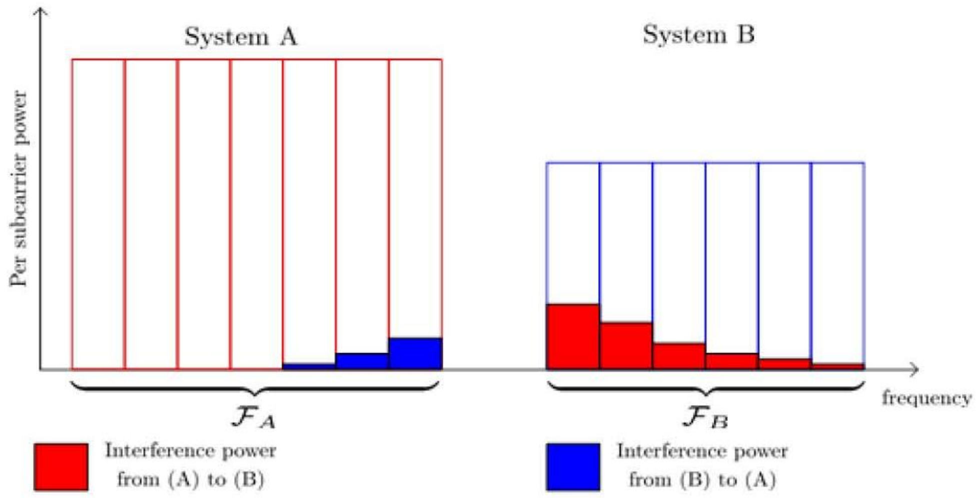
Concept of Interference Tables

- Let us consider two asynchronous systems (A) and (B) that coexist in the same geographical area.

- We assume that both systems share a given frequency band. let F_A and F_B be the frequency sub-bands occupied by systems (A) and (B), respectively.

- Due to the non-orthogonality between their respective transmit signals, some amount of the power is spilled from a system to the other.

- Our aim is to quantify the interference power caused by all subcarriers of a system on a given subcarrier of the other system. The estimation of this interference will constitute the so-called "**Interference Table**"



Mutual interference between systems (A) and (B)

Concept of Interference Tables

- In the literature, the power spectrum density (PSD) is generally used to evaluate the mutual interference between both systems.

- In general, the mutual interference between the co-located systems is defined as:

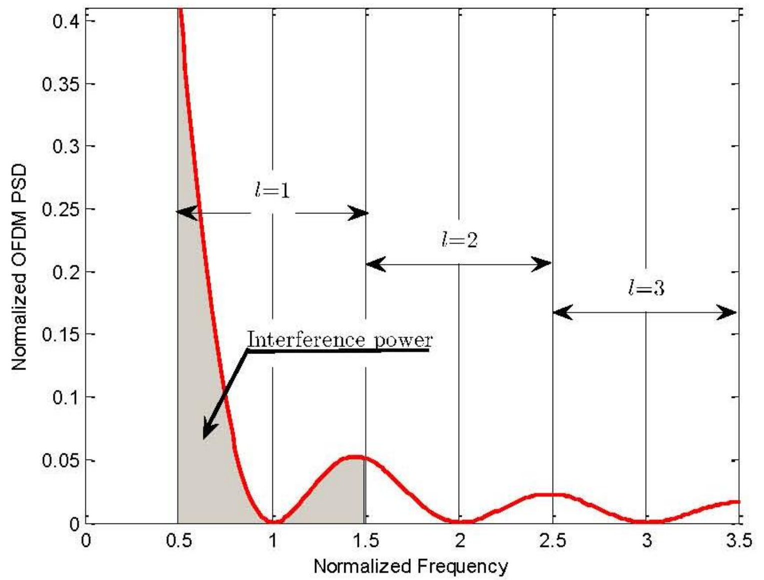
$$I(l) = \int_{(l-1/2)\Delta f}^{(l+1/2)\Delta f} \Phi(f)df$$

Where:

- l is the spectral distance between the interfering subcarrier and the victim one,

- Δf is the subcarrier spacing,

- $\Phi(f)$ is the PSD which depends on the considered multicarrier technique.

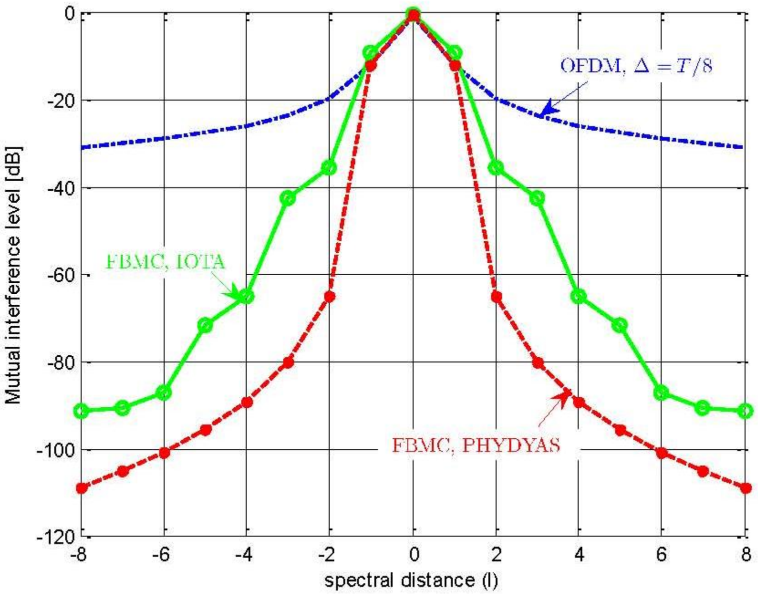


PSD of a single OFDM modulated carrier

T. Weiss et al., “**Mutual interference in OFDM-based spectrum pooling systems** ,” in VTC’ 04, May 2004.
H. Zhang et al., “**Spectral Efficiency Comparison between OFDM/OQAM and OFDM based CR Networks**,” in Wiley, Nov. 2009

Concept of Interference Tables

- Based on the previous analysis, we can construct a table of mutual interference as a function of the spectral distance l .
- OFDM interference level is higher than FBMC one, whatever the waveform.
- The interference remains the same for any timing misalignment between the transmitted signals of both systems, since the signals are considered to be non-orthogonal.



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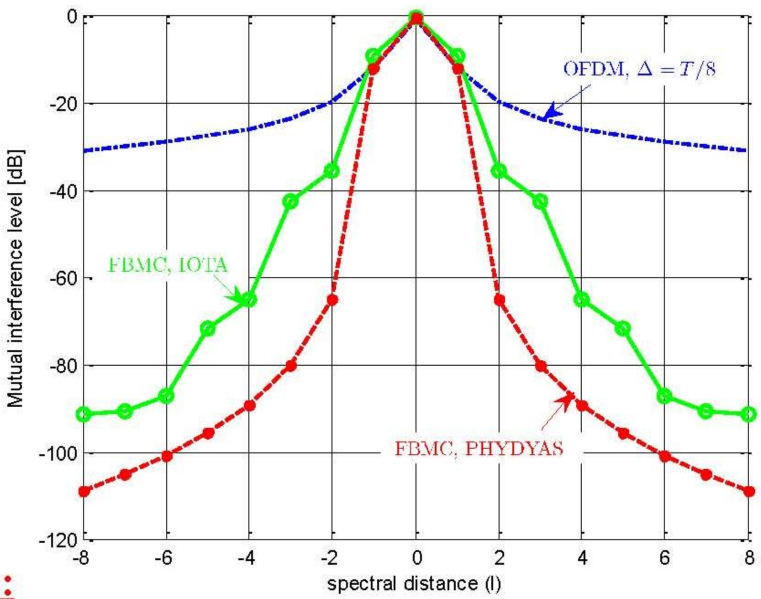

Problem:

- However in CP-OFDM systems, the orthogonality between the different transmit signals is maintained as long as the timing misalignment does not exceed the cyclic prefix duration Δ.

- In fact, the real **asynchronous interference is always a function of the timing offset** between the considered asynchronous systems that is not taken into account in the PSD- based interference tables generation.

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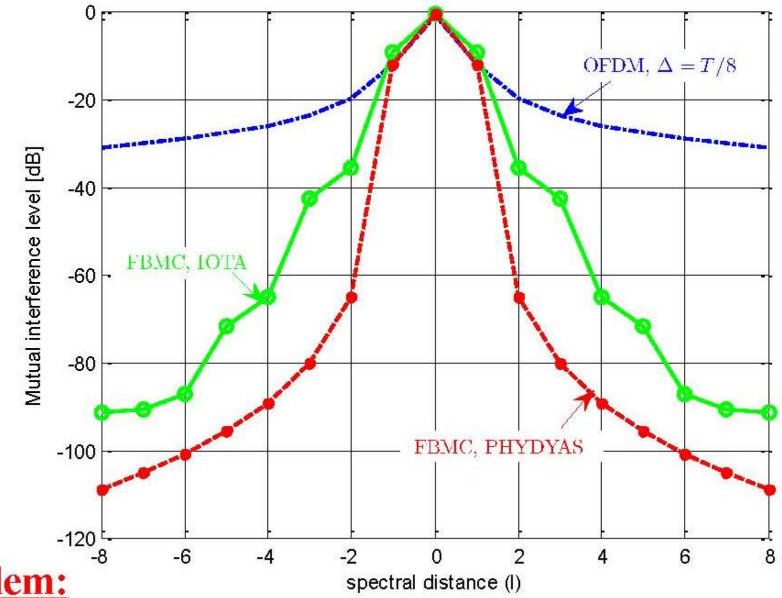

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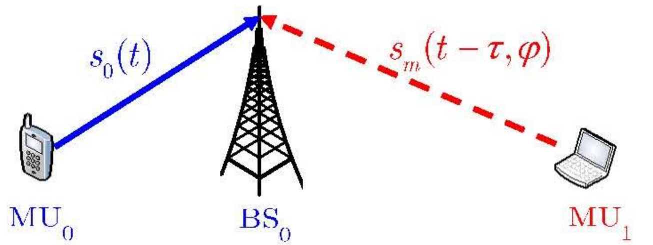
Proposed Solution:

- "**Instantaneous Interference Tables**" that take into account the timing offset in addition to the spectral distance.

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 :

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

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

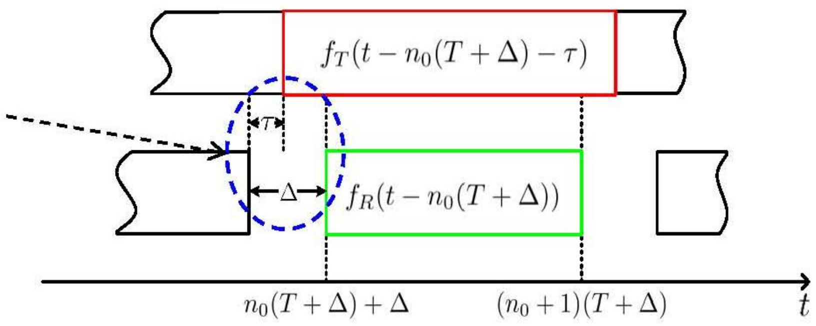
OFDM Instantaneous Interference

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

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

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

- Orthogonality between subcarriers is maintained.
- There is only co-channel interference

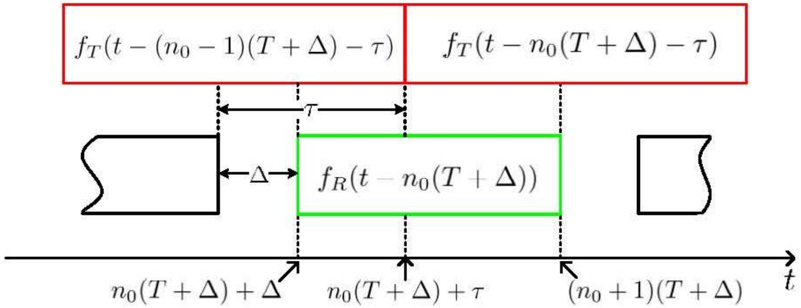
OFDM Instantaneous Interference (2)

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

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

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

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

OFDM Instantaneous Interference (3)

Assuming that $\mathbb{E}\left[|x_{m,n}|^2\right] = 1$, The instantaneous interference power is given by:

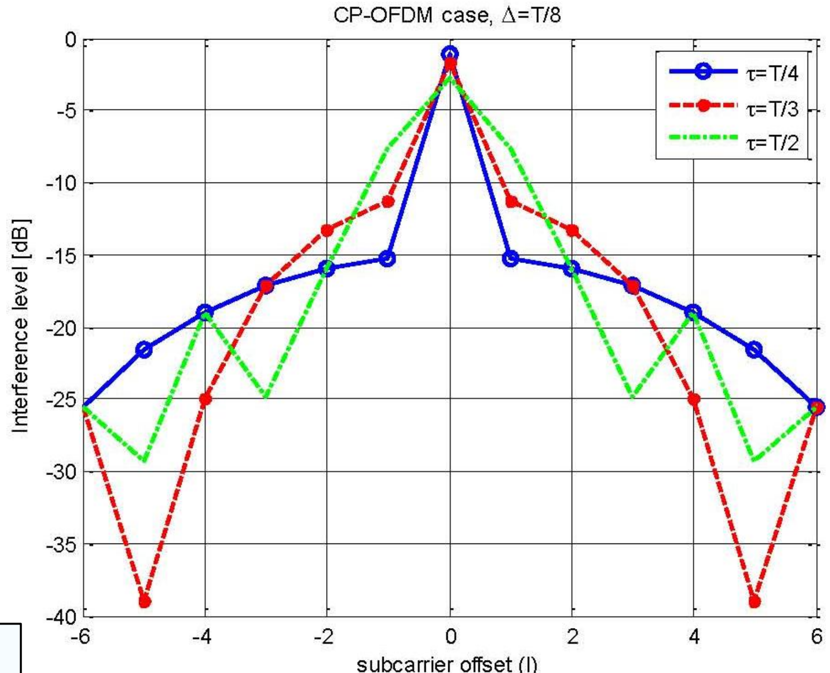
$$I(\tau,l) = \mathbb{E}_x\left[|y_{m_0,n_0}(\tau,\varphi)|^2\right]$$

$$= \begin{cases} \delta(l) & \tau \in [0,\Delta] \\ \left[(T+\Delta-\tau)^2 + (\tau-\Delta)^2\right]/T^2 & \tau \in [\Delta, T+\Delta], l=0 \\ \left|\frac{\sin(\pi l(T+\Delta-\tau)/T)}{\pi l}\right|^2 + \left|\frac{\sin(\pi l(\tau-\Delta)/T)}{\pi l}\right|^2 & \tau \in [\Delta, T+\Delta], l \neq 0 \end{cases}$$

In contrast to the PSD-based model, we can see that the asynchronous interference depends on both:

- the spectral distance l

- the timing misalignment between the interfering transmitter and the victim receiver

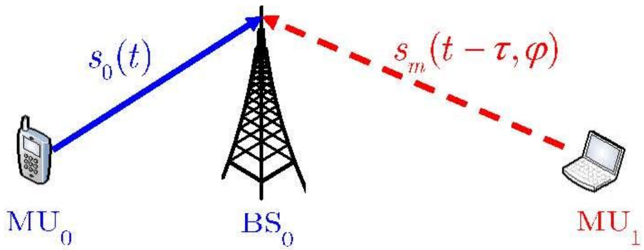


OFDM instantaneous interference tables

Y. Medjahdi, et al., "Inter-Cell Interference Analysis for OFDM/ FBMC Systems", SPAWC 2009

FBMC 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.

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

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

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

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

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

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

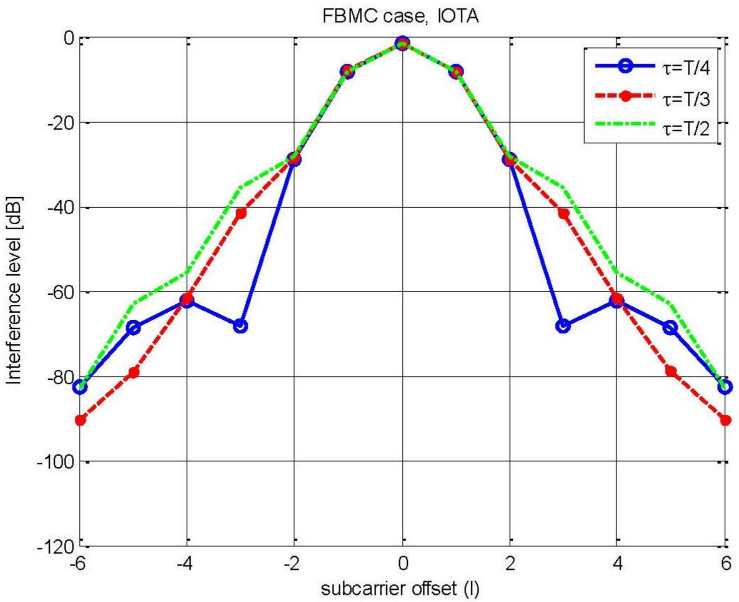
- where $\lceil\alpha\rceil$ is the ceil function (the smallest integer greater than or equal to α).
- After the OQAM decision, we can write the total complex symbol $y_{tot}(\tau,\varphi)$ as follows:

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

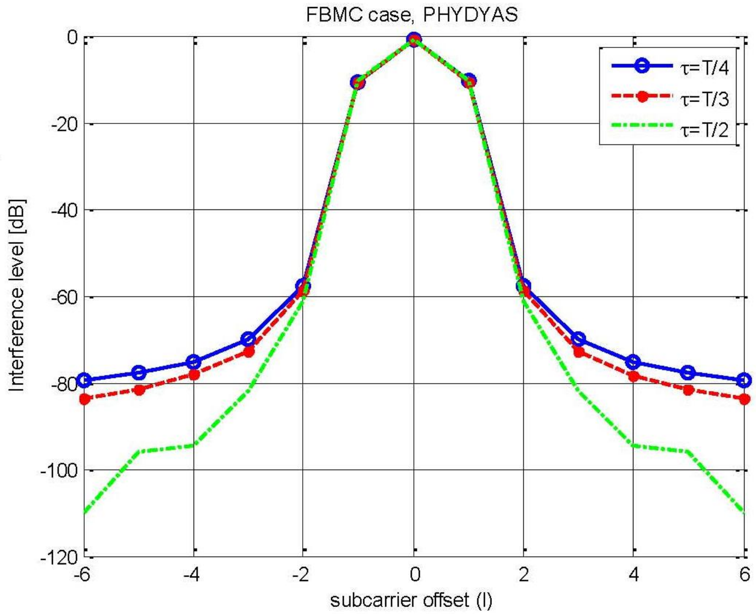
- Consequently, the corresponding interference power table $I(\tau,l)$ is given by:

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

FBMC vs. IOTA Instantaneous Interference



FBMC/IOTA instantaneous interference tables



FBMC/PHYDYAS instantaneous interference tables

- In IOTA case, the interference also varies with respect to the timing offset τ and the spectral distance l

- From l=3 subcarriers, the asynchronous IOTA interference level is very low.

- When l<3, the interference is less sensitive to the timing offset.

- The same behavior can be noticed in PHYDYAS case.

- However in contrast to IOTA, the PHYDYAS interference becomes negligible from l=2 subcarriers.

Simulations

- Uplink OFDM/FBMC transmission

- MU_0 and MU_1 are communicating with BS_0 and BS_1, respectively

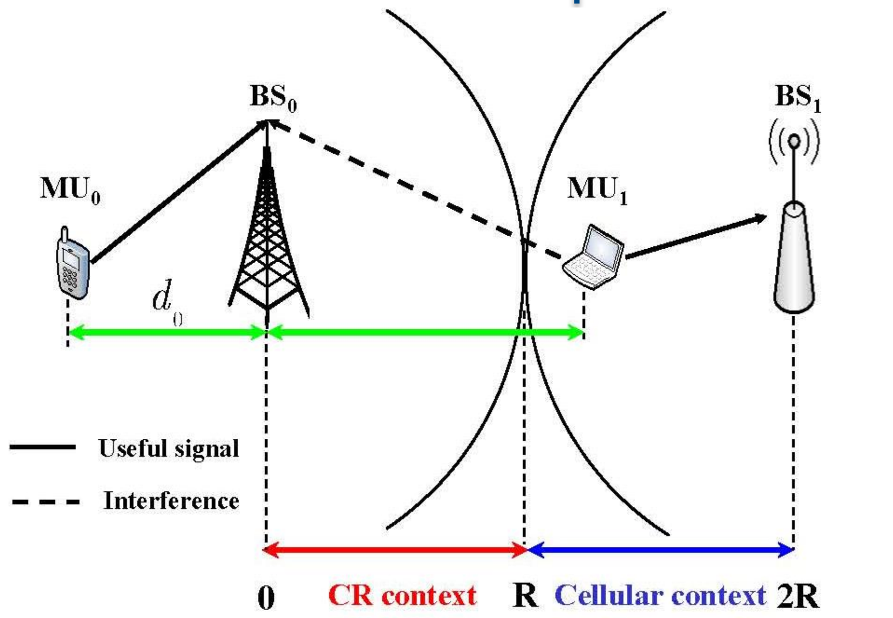
- All signals propagate through different multipath channels using the Pedestrian-A model.

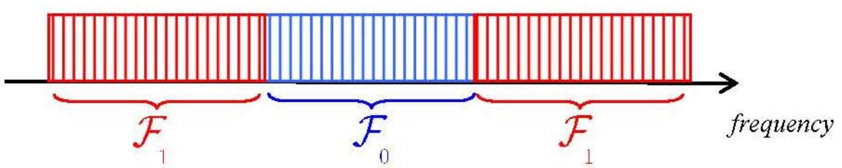
- The path-loss of a received signal at a distance d :

$$\Gamma_{loss} = 128.1 + 37.6 \log_{10}(d[km]) \ \ [dB]$$

- System parameters:

  - $N_{FFT} = 1024$ subcarriers
  - $f_{sampling} = 10MHz$
  - Thermal noise density: $N_0 = -174dB/Hz$
  - Subcarrier block size: 18 subcarriers
  - SNR target (must guaranteed by each user) is 20 dB





Simulations

- Each user is assumed to be perfectly synchronized with its corresponding BS but it is not synchronized with the other BS

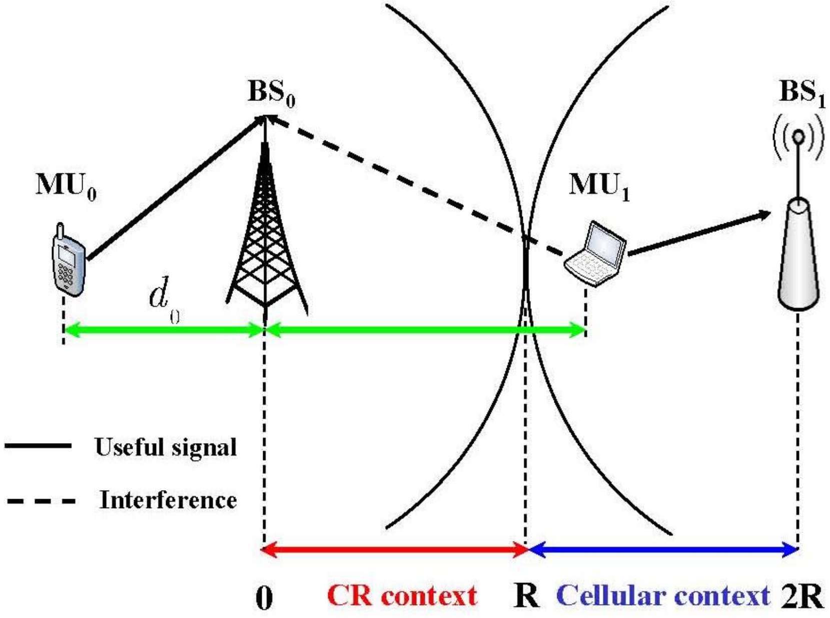
- Because of the timing misalignment between BS_0 and MU_1, the signal arriving from this latter appears **non-orthogonal** to the desired signal coming from MU_0.

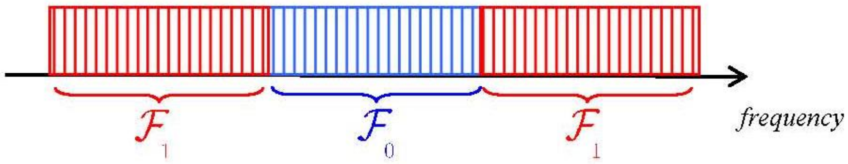
- This non-orthogonality generates interference and degrades the SINR:

$$SINR(m) = \frac{d_0^{-\beta} P_{trans}(m)|H_0(m)|^2}{\sum_{m' \in F_1} d^{-\beta} P_{trans}(m') I(\tau, |m'-m|) + N_0 \Delta f}$$

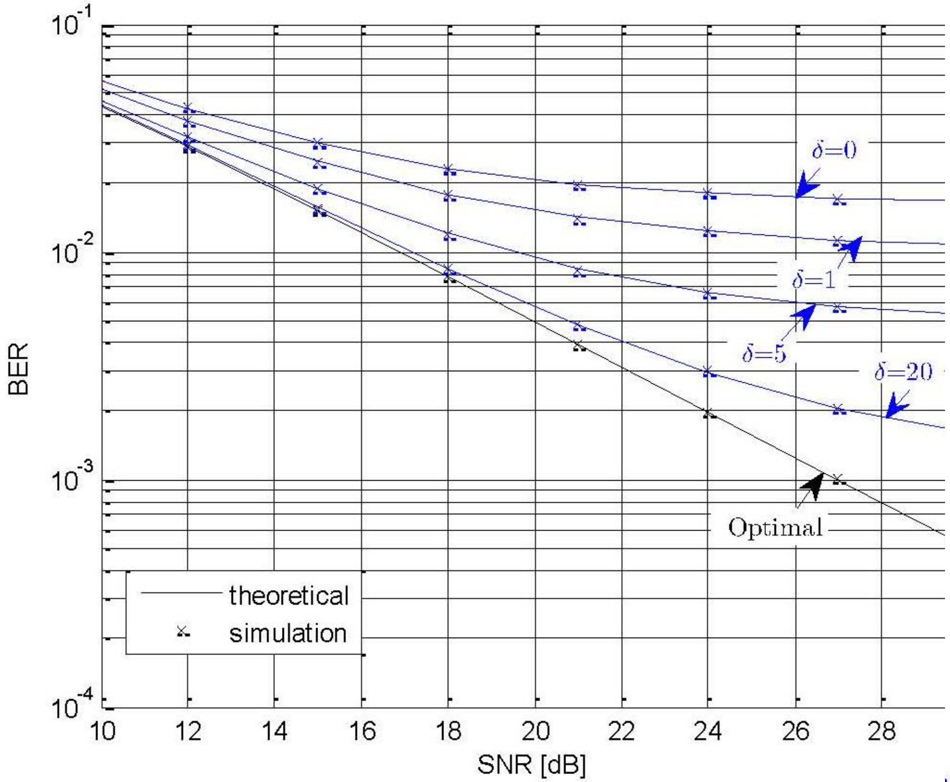
- Objectives:
  - $SINR_{average}(m) = \mathbb{E}[SINR(m)]$
  - $C_{average}(m) = \mathbb{E}[\log_2(1 + SINR(m))]$

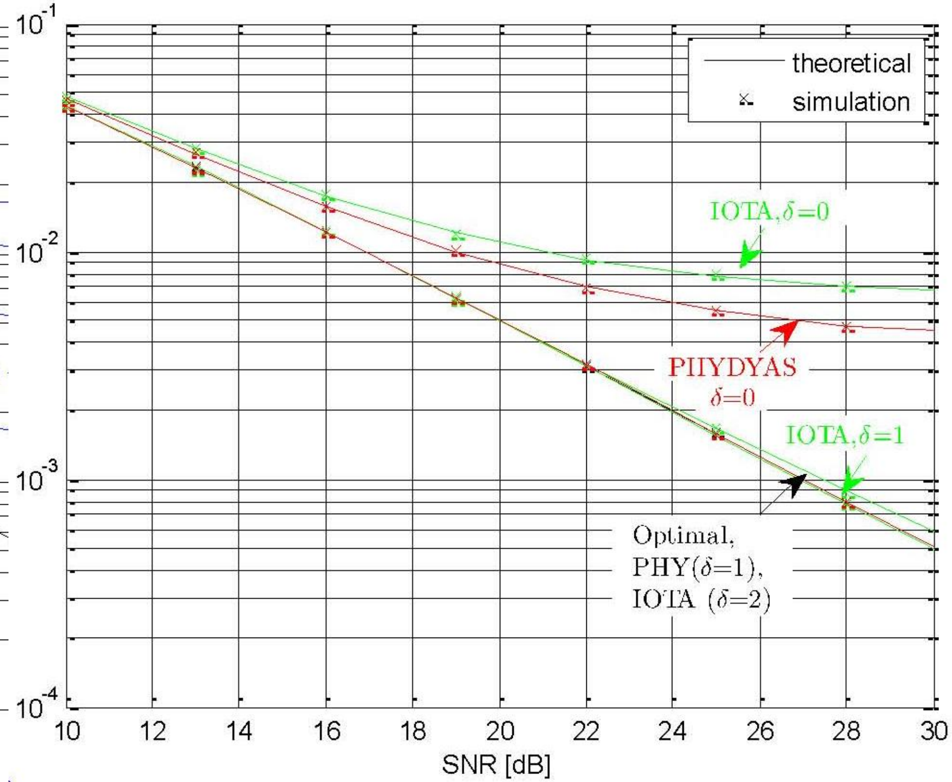
- Methods:
  - PSD-based model
  - Instantaneous Interference Tables
  - Numerical evaluation





Under Asynchronous Scenarios !

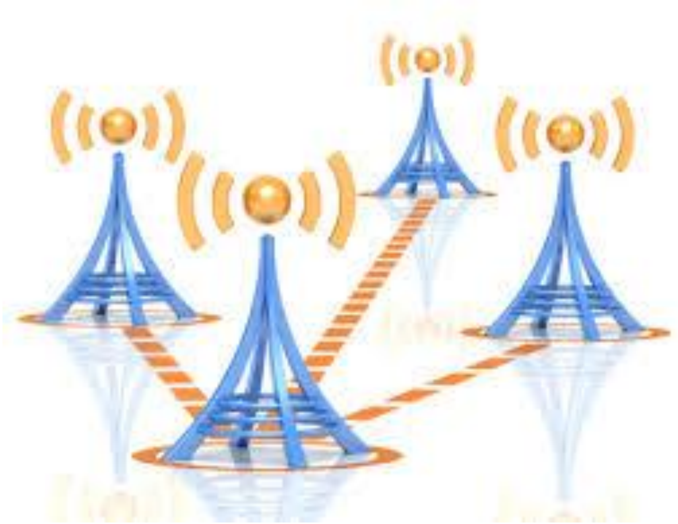




OFDM average BER vs. SNR for different guard-band sizes $\delta = 0, 1, 5, 20$ with $\tau \in [0,T]$

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

Source: Yahia Medjahdi, "Interference Modeling and Performance Analysis of Asynchronous OFDM and FBMC Wireless Communication Systems". PhD dissertation, CNAM-Paris (France) 2012



Comparison of MIMO OFDM/FBMC for Interference Alignment Based CR Systems

- Interference Alignment (IA) has been considered in order to improve the spectral efficiency

- MIMO IA is a powerful tool that use manage interference for multi-user wireless communications.

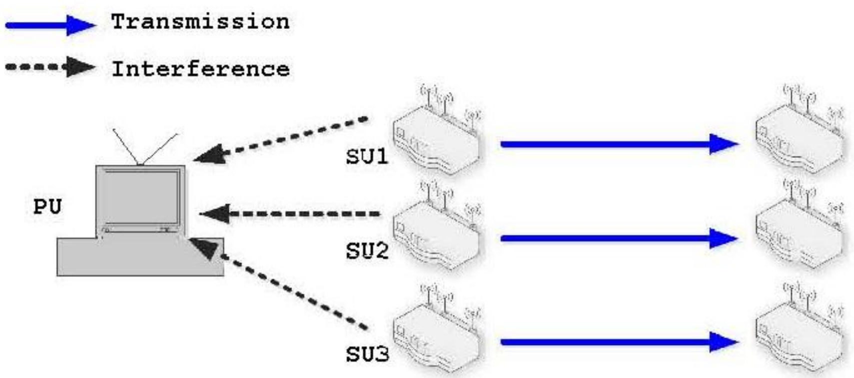
- The basic idea of MIMO IA in managing interference is based on the subspace separation; half of the available subspace is set to interference and the other half is set for the desired signal.

- In this scenario, MIMO employment at the PU provides extra degrees of freedom to null the interference at the PU receiver and to exclude interference constraints from the optimization problem.

System Model

- SU nodes with MIMO employment is assumed while each PU is assumed to have a single antenna, which means that the spatial degree-of-freedoms are not available anymore at PU side.

- Working with a single antenna at PU system increases the problem complexity as several interference constraints should be added to the optimization problem



Cognitive radio system.

K pairs of SU pairs of secondary transmitters and receivers with M_T and M_R

The CR system coexist with the PU's radio in the same geographical location.

The available spectrum is divided into *N* sub-carriers with a Δf separation, where L active primary bands (W_1,W_2, ...,W_L) have been occupied by the PUs.

The CR system is allowed to use the active and non-active bands under a condition that the total induced interference to the l_{th} PU active band is below the interference limit, I^l_{th}.

Problem Formulation

Mostly, frequency division multiple access (FDMA) technique is used to manage the transmission between the SUs in CR network, in which the transmission over each subcarrier is restricted to one SU at a given time.

MIMO IA passes over this limitation → giving the opportunity for a number of SUs to share a given subcarrier at the same time.

designing precoding matrices for the SUs in a way that the desired data is aligned at its own receiver in an interference free subspace while the interference signals from other SU transmitters are aligned at the interference subspace

$$\mathbf{y}_k^n = \mathbf{u}_k^{n\mathrm{H}} \mathbf{H}_k^n \mathbf{v}_k^n \mathbf{x}_k^n + \sum_{j=1, j \neq k}^{K} \mathbf{u}_k^{n\mathrm{H}} \mathbf{H}_{kj}^n \mathbf{v}_j^n \mathbf{x}_j^n + \mathbf{u}_k^{n\mathrm{H}} \mathbf{z}_k^n,$$

Interference is completely eliminated at each SU receiver.

$$\mathbf{y}_k^n = \mathbf{u}_k^{n\mathrm{H}} \mathbf{H}_k^n \mathbf{v}_k^n \mathbf{x}_k^n + \mathbf{u}_k^{n\mathrm{H}} \mathbf{z}_k^n$$

$\mathbf{H}_{kj}^n$: denotes the channel frequency response between j^{th} SU transmitter and k^{th} SU receiver

$\mathbf{u}_\mathbf{k}^\mathbf{n}$: is an orthonormal linear interference suppression matrix applied at the k^{th} SU receiver

$\mathbf{v}_k^n$: the IA precoder matrix

Optimal solution

The sum-rate of the SUs over the n^{th} subcarrier is

$$R^n = \sum_{k=1}^{K} \log \left| 1 + \frac{P_k^n \mathbf{u}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n \mathbf{v}_k^n \mathbf{v}_k^{n\mathrm{H}} \mathbf{H}_{kk}^{n\ \mathrm{H}} \mathbf{u}_k^n}{\sigma_{\mathrm{AWGN}}^2 + \sum_{l=1}^{L} J_{l,k}^n} \right|.$$

the transmitted power by the k^{th} SU user over the n^{th} subcarrier

is the total interference introduced by the l^{th} PU transmitter in the n^{th} subcarrier to the k^{th} *CR* user

the interference introduced by the k^{th} SU transmitter over the n^{th} CR subcarrier transmission to the l^{th} PU receiver should be considered

$$I_{l,k}^n \left(D_n, P_k^n\right) = \mathrm{Tr}\left(P_k^n \Omega_l^n \mathbf{G}_{k,l}^n \mathbf{V}_k^n \mathbf{V}_k^{n\mathrm{H}} \mathbf{G}_{k,l}^{n\ \mathrm{H}}\right)$$

$$P1: \max_{P_k^n} \sum_{n=1}^{N} \sum_{k=1}^{K} \log\left(1 + \frac{P_k^n \mathbf{u}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n \mathbf{v}_k^n \mathbf{v}_k^{n\mathrm{H}} \mathbf{H}_{kk}^{n\ \mathrm{H}} \mathbf{u}_k^n}{\sigma_k^{n2}}\right)$$

$$\text{s.t.}: \sum_{n=1}^{N} P_k^n \leq P_k \quad \forall k$$

$$P_k^n \geq 0, \qquad \forall n \ \text{ and } \ \forall k$$

$$\sum_{n=1}^{N} \sum_{k=1}^{K} P_k^n \Omega_l^n \mathrm{Tr}\left(\mathbf{G}_{k,l}^n \mathbf{V}_k^n \mathbf{V}_k^{n\mathrm{H}} \mathbf{G}_{k,l}^{n\ \mathrm{H}}\right) \qquad , \ \forall l,$$

can be solved using the Lagrangian theory.

Optimal solution

Can be solved using the Lagrangian theory.

$$
\begin{aligned}
G = &-\sum_{n=1}^{N}\sum_{k=1}^{K}\log\left(1+\frac{P_k^n {\mathbf{u}_k^n}^{\mathrm{H}} \mathbf{H}_{kk}^n \mathbf{v}_k^n \mathbf{v} \qquad {}_k{}^{\mathrm{H}} \mathbf{u}_k^n}{{\sigma_k^n}^2}\right) \\
&+\sum_{l=1}^{L}\alpha^l\left(\sum_{n=1}^{N}\sum_{k=1}^{K}\Omega_l^n P_k^n \mathrm{Tr}\left(\mathbf{G}_{k,l}^n \mathbf{V}_k^n {\mathbf{V}_k^n}^{\mathrm{H}} {\mathbf{G}_{k,l}^n}^{\mathrm{H}}\right)-I_{th}^l\right) \\
&+\sum_{k=1}^{K}\beta_k\left(\sum_{n=1}^{N}P_k^n-P_k\right)-\sum_{n=1}^{N}\sum_{k=1}^{K}P_k^n\mu_k^n,
\end{aligned}
$$

$$
P_k^n = \left[\frac{1}{\sum_{l=1}^{L}\alpha^l\Omega_l^n \mathrm{Tr}\left(\mathbf{G}_{k,l}^n \mathbf{V}_k^n {\mathbf{V}_k^n}^{\mathrm{H}} {\mathbf{G}_{k,l}^n}^{\mathrm{H}}\right)+\sum_{k=1}^{K}\beta_k} - \frac{{\sigma_k^n}^2}{{\mathbf{u}_k^n}^{\mathrm{H}} \mathbf{H}_{kk}^n \mathbf{v}_k^n {\mathbf{v}_k^n}^{\mathrm{H}} {\mathbf{H}_{kk}^n}^{\mathrm{H}} \mathbf{u}_k^n}\right]^+
$$

The optimization problem $P1$ has a high computational complexity which is generally prohibitive specially with high number of subcarriers.

Optimal solution

To solve the resource allocation problem *P1* efficiently with low computational complexity, a sub-optimal power loading algorithm is proposed. In our sub-optimal method, we start by finding the solution for the problem *P1* after ignoring the per-SU power constraints. Thus, the optimization problem becomes

$$P2: \max_{\widehat{P}_k^n} \sum_{n=1}^{N} \sum_{k=1}^{K} \log\left(1 + \frac{\widehat{P}_k^n \mathbf{u}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n \mathbf{v}_k^n \mathbf{v}_k^{n\mathrm{H}} \mathbf{H}_{kk}^{n\ \mathrm{H}} \mathbf{u}_k^n}{\sigma_k^{n\,2}}\right)$$

$$\text{s.t.}: \sum_{n=1}^{N} \sum_{k=1}^{K} \Omega_l^n \widehat{P}_k^n \mathrm{Tr}\left(\mathbf{G}_{k,l}^n \mathbf{V}_k^n \mathbf{V}_k^{n\mathrm{H}} \mathbf{G}_{k,l}^{n\ \mathrm{H}}\right) \leq I_{th}^l,$$

$$\widehat{P}_k^n \geq 0, \qquad \forall n \text{ and } \forall k,$$

where (^) indicates the variables that are optimized under the interference constraint only. By solving *P2*, we get

Optimal solution

$$\widehat{P}_k^n(l) = \left[\frac{1}{\widehat{\alpha}^l \Omega_l^n \mathrm{Tr}\left(\mathbf{G}_{k,l}^n \mathbf{V}_k^n \mathbf{V}_k^{n\mathrm{H}} \mathbf{G}_{k,l}^n{}^{\mathrm{H}}\right)} - \frac{\sigma_k^{n\,2}}{\mathbf{u}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n \mathbf{v}_k^n \mathbf{v}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n{}^{\mathrm{H}} \mathbf{u}_k^n}\right]^+$$

where the Lagrange multiplier α^l is evaluated

$$\alpha^l = \frac{|N\,K|}{I_{th}^l + \sum_{n=1}^{N} \sum_{k=1}^{K} \frac{\Omega_l^n \sigma_k^{n\,2} \mathrm{Tr}\left(\mathbf{G}_{k,l}^n \mathbf{V}_k^n \mathbf{V}_k^{n\mathrm{H}} \mathbf{G}_{k,l}^n{}^{\mathrm{H}}\right)}{\mathbf{u}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n \mathbf{v}_k^n \mathbf{v}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n{}^{\mathrm{H}} \mathbf{u}_k^n}}.$$

We assume that the maximum power $P_k^{n\max}$ that can be loaded for the *k-th* SU over the *n-th* subcarrier can be obtained from the solution of problem *P2* as follows

$$P_k^{n\max} = \min\left\{\widehat{P}_k^n(l)\right\}_{l=1}^{L}.$$

Ok ! With P1

Optimal solution

Otherwise, we move to the second step, in which the power budget for each SU P_k is distributed among all the subcarriers subject to be lower or equal to the upper-bound of the power of each user at every subcarrier $P_k^{n\max}$ The problem can be described as a caplimited waterfilli

$$P3: \max_{\widetilde{P}_k^n} \sum_{n=1}^{N} \sum_{k=1}^{K} \log\left(1 + \frac{\widetilde{P}_k^n \mathbf{u}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n \mathbf{v}_k^n \mathbf{v}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n{}^{\mathrm{H}} \mathbf{u}_k^n}{\sigma_k^{n\,2}}\right)$$

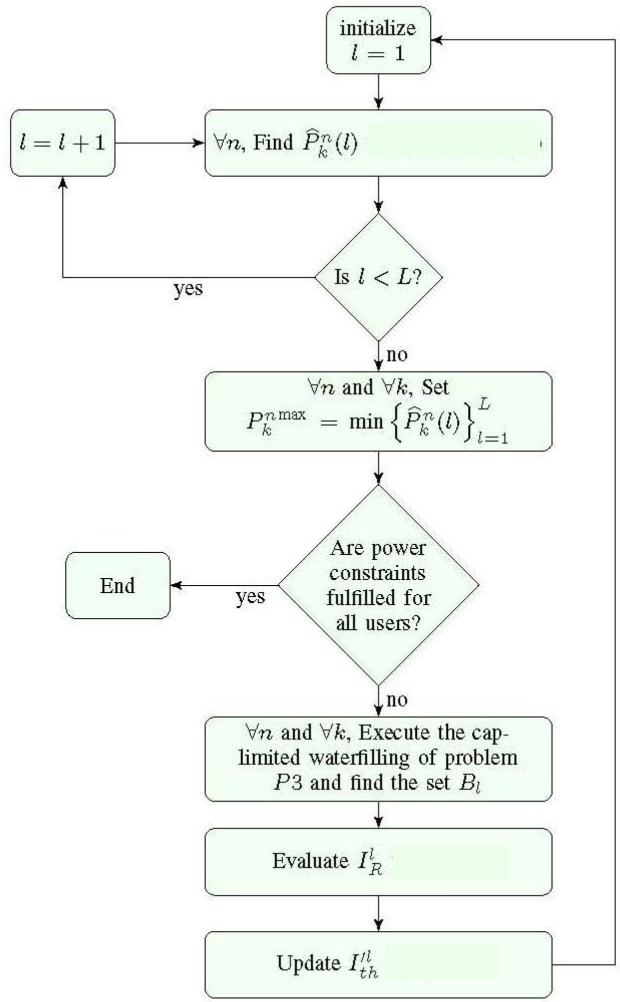
$$\text{s.t.}: \quad \sum_{n=1}^{N} \widetilde{P}_k^n \leq P_k$$

$$0 \leq \widetilde{P}_k^n \leq P_k^{n\max},$$

where $\widetilde{P}_k^n$ is the solution of problem *P3*. This problem is solved using the conventional waterfilling, where the waterfilling solution is found as

$$P_{k,WF}^n = \left[\lambda - \frac{\sigma_k^{n\,2}}{\mathbf{u}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n \mathbf{v}_k^n \mathbf{v}_k^{n\mathrm{H}} \mathbf{H}_{kk}^n{}^{\mathrm{H}} \mathbf{u}_k^n}\right]^+,$$

Sub-Optimal solution



Mohammed El-Absi, Musbah Shaat, Faouzi Bader, Thomas Kaiser, **Interference Alignment Based Resource in MIMO in Cognitive Radio System,** in Proc. of the European Wireless (EW'2014), Barcelona-Spain. May 2014.

Simulation parameters

K = 3 SUs with $M_T = M_R = 2$ is assumed, the values of N=64, Δf= 0.3125 MHz, L=2 PU bands each with 10 MHz bandwidth.

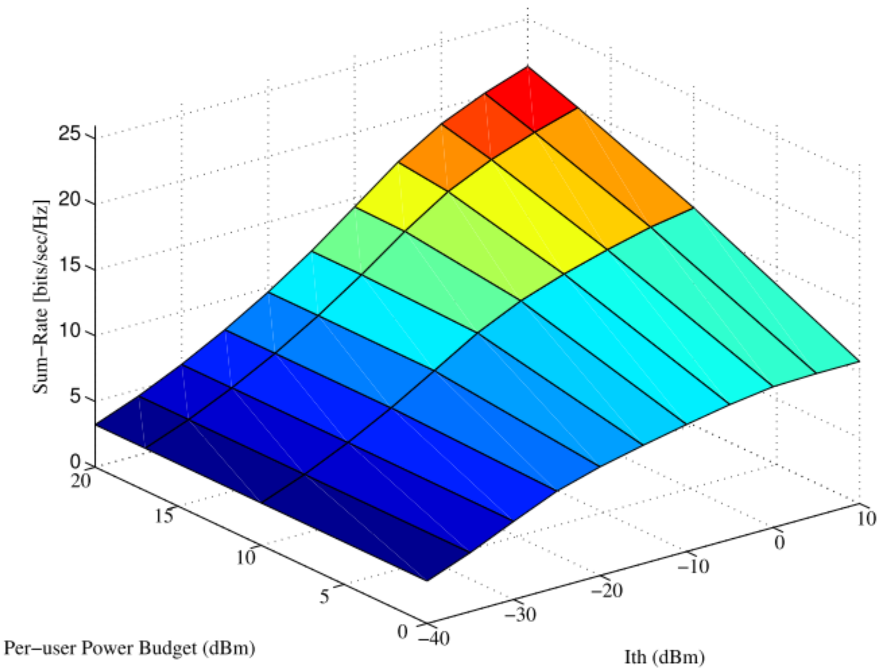
It is assumed that the channel realizations have been drawn from independent and identically distributed Gaussian distribution with zero mean and unit variance. The results are averaged over 1000 channel realizations.

For the purpose of performance comparison, the following algorithms are considered in the simulation:
1) **Optimal IA: find the optimal power loading solution** using problem $P1$ with either OFDM or FBMC physical layer.
2) **Optimal FDMA: allocate the power optimally considering** a FDMA system as in [1] with either OFDM or FBMC physical layer.
3) **Suboptimal IA: perform the power loading based on the proposed** with either OFDM or FBMC physical layer.

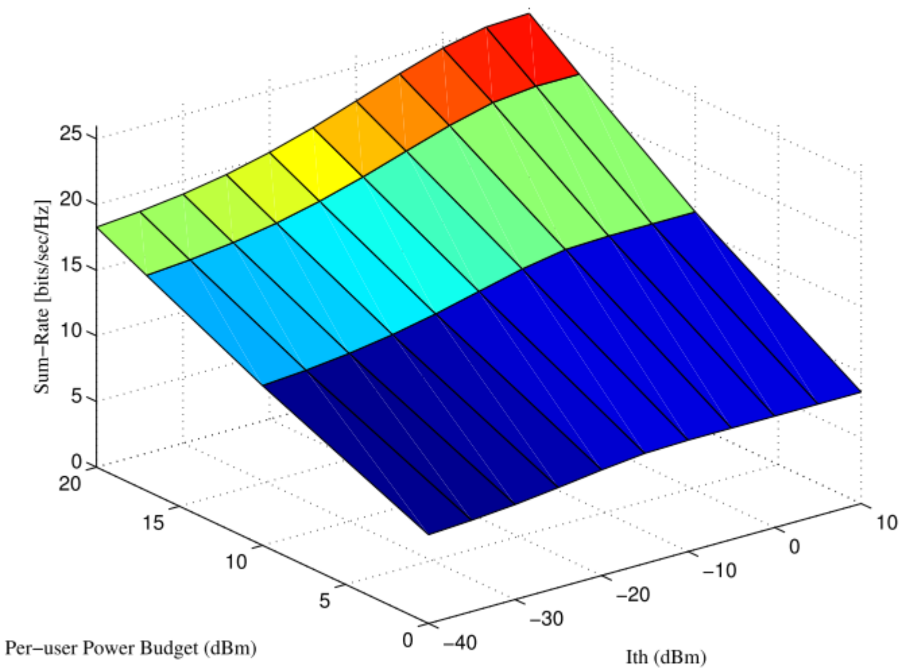
[1] R. Zhang and Y.-C. Liang, "**Exploiting multi-antennas for opportunistic spectrum sharing in cognitive radio networks**," *Selected Topics in Signal Processing, IEEE Journal of, vol. 2, no. 1, pp. 88–102, 2008.*

Performances, Cont.

OFDM



FBMC

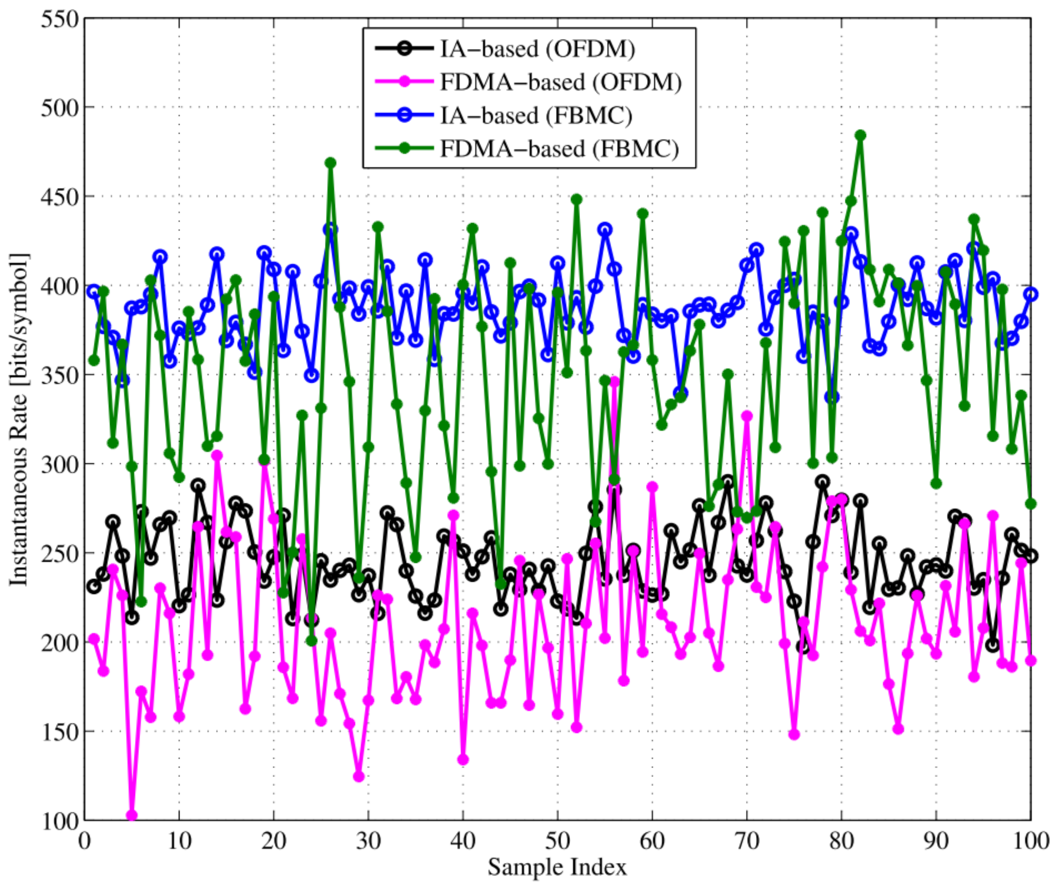


- For 3-SUs: 2 TX & 2 RX antennas, 64 OFDM subcarriers

Mohammed El-Absi, Musbah Shaat, Faouzi Bader, Thomas Kaiser, **Interference Alignment Based Resource in MIMO in Cognitive Radio System,** in Proc. of the European Wireless (EW'2014), Barcelona-Spain. May 2014.

Performances, Cont.

- For 3-SUs: 2 TX & 2 RX antennas.
- 64 subcarriers
- SUs power= 15 dBm
- I_{th} = -20 dBm



Mohammed El-Absi, Thomas Kaiser, **Optimal Resource Allocation Based on Interference Alignment for OFDM and FBMC MIMO Cognitive Radio Systems,** in Proc. of the European Conference on Networks and Communications (EuCNC'2014), Bologna, Italy. June 2014.

Performances, Cont.

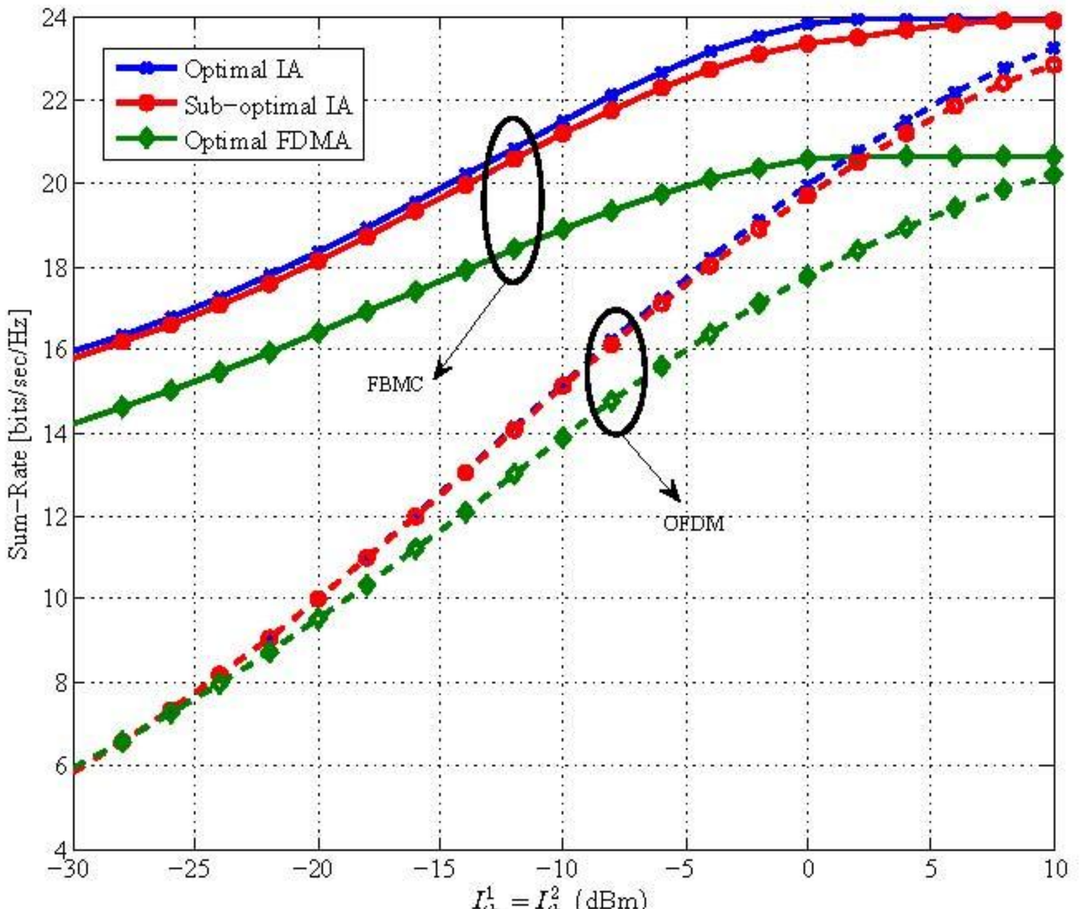


Figure 1: Sum-rate performance vs. allowed interference limit. P_k= 15 dBm

Mohammed El-Absi, Musbah Shaat, Faouzi Bader, Thomas Kaiser, **Power Loading and Spectral Efficiency Comparison of MIMO OFDM/FBMC for Interference Alignment Based Cognitive radio System**, Proc. ISWCS'2014, Barcelona, Spain. August 2014.

Performances, Cont.

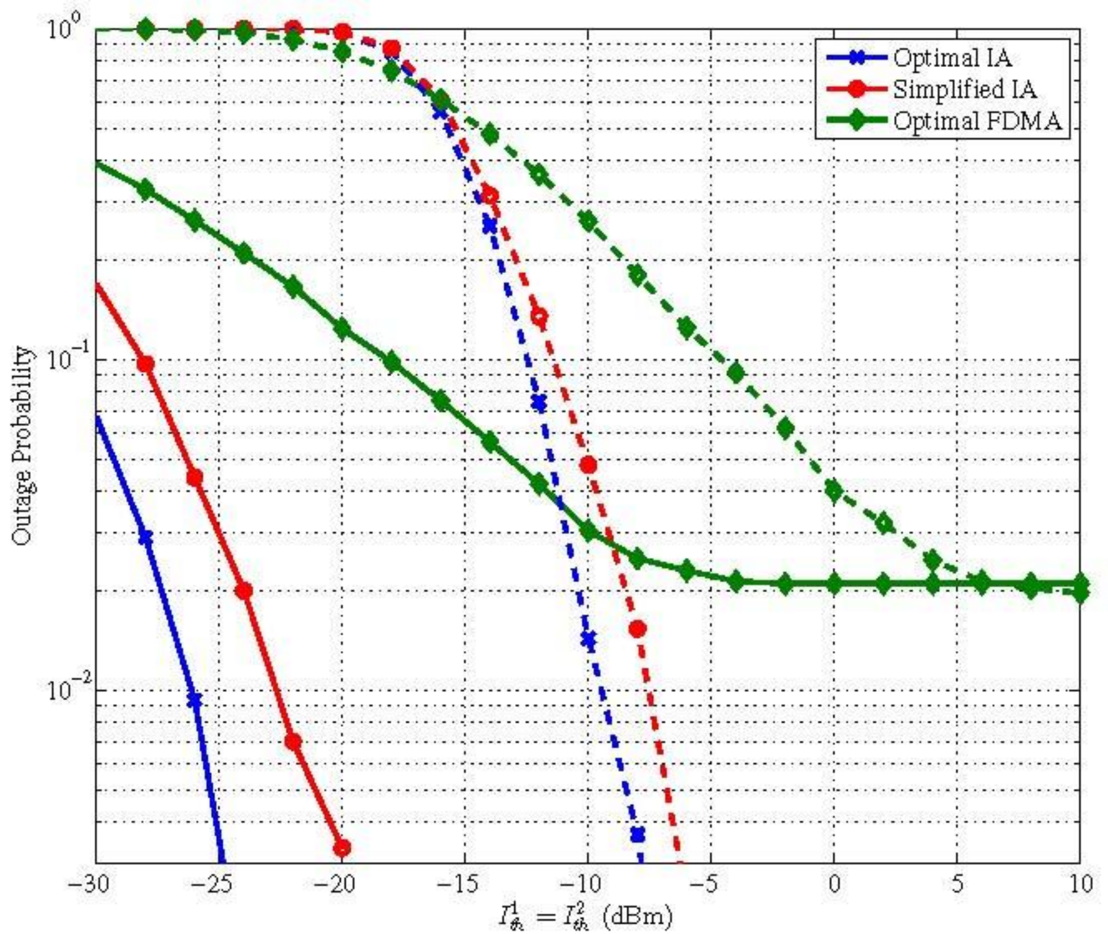


Figure 2: Outage probability vs. interference limit, Rmin = 60Mbits/sec.

Mohammed El-Absi, Musbah Shaat, Faouzi Bader, Thomas Kaiser, **Power Loading and Spectral Efficiency Comparison of MIMO OFDM/FBMC for Interference Alignment Based Cognitive radio System**, in Proc. of the ISWCS'2014, Barcelona, Spain. August 2014.

Part III : Practical Applications and Projects

A-Previous and actually running EC funded projects focusing on filter based Multicarrier Waveforms

PHYDYAS project

Physical layer for Dynamic spectrum Access and Cognitive Radio

The objective is to **propose a physical layer for future radio systems that is more efficient than the present OFDM** (Orthogonal Frequency Division Multiplexing) physical layer and better suited to the new concepts of DASM (Dynamic Access Spectrum Management) and cognitive radio.

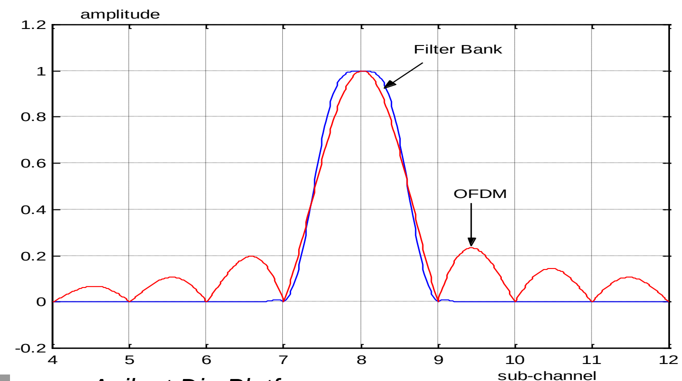
So far (2009-2012) , some attempts have been made to introduce FBMC in the radio communications arena, through proprietary schemes, in particular the IOTA technique (see: TIA-902.BBAB, " Wideband air interface Isotropic Orthogonal Transform Algorithm (IOTA) physical layer specification ", document of the Telecommunications Industry Association , 2003 , and, 3GPP TSG-RAN WG1. TR25.892, " Feasibility study of OFDM for UTRAN enhancement. V1.1.0, June 2004). **However, the full exploitation of FBMC** techniques and their optimization in the context of radio evolution, such as dynamic access, as well as their combination with MIMO techniques, have not been considered.

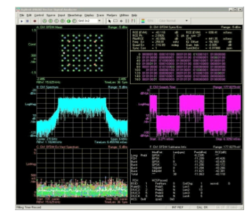
PHYDYAS project

http://www.ict-phydyas.org/

$$h_i = 1 - 1.94392\cos(\pi i/512) + \sqrt{2}\cos(\pi i/256) - 0.470294\cos(\pi 3i/512)\ ;\ 1 \le i \le 1023$$

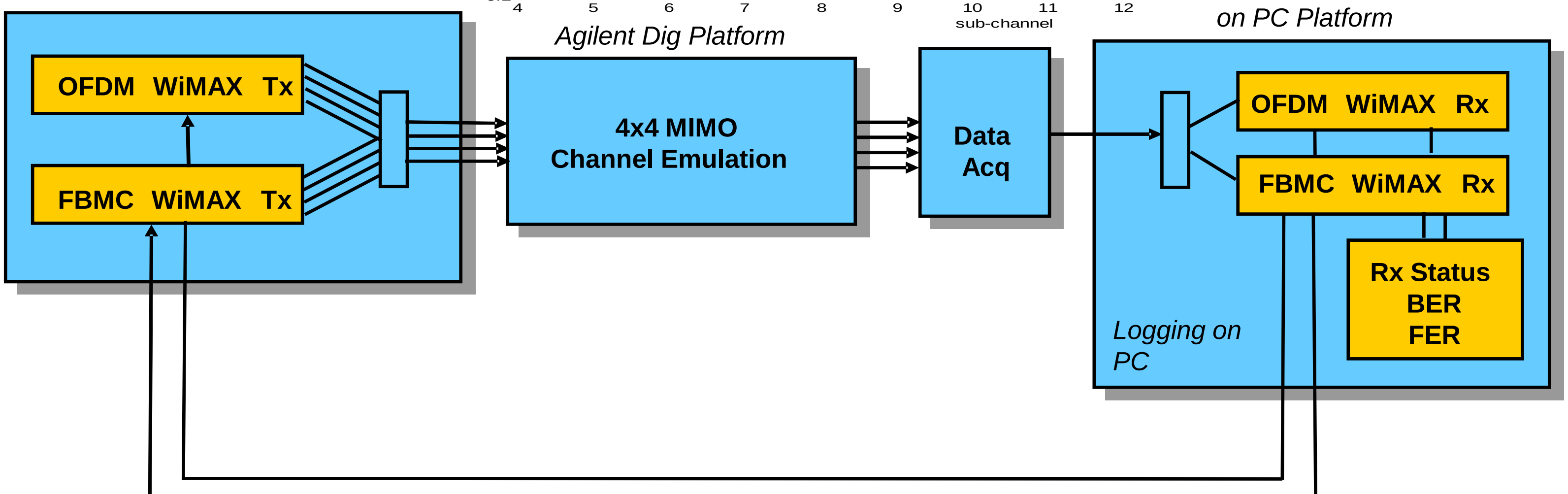
Dual Baseband Tx
on FPGA Platform





Dual Baseband Rx
on PC Platform

Agilent Dig Platform



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.

QoSMOS

Quality Of Service and MObility driven cognitive radio Systems

- Quality of Service and MObility driven cognitive radio Systems

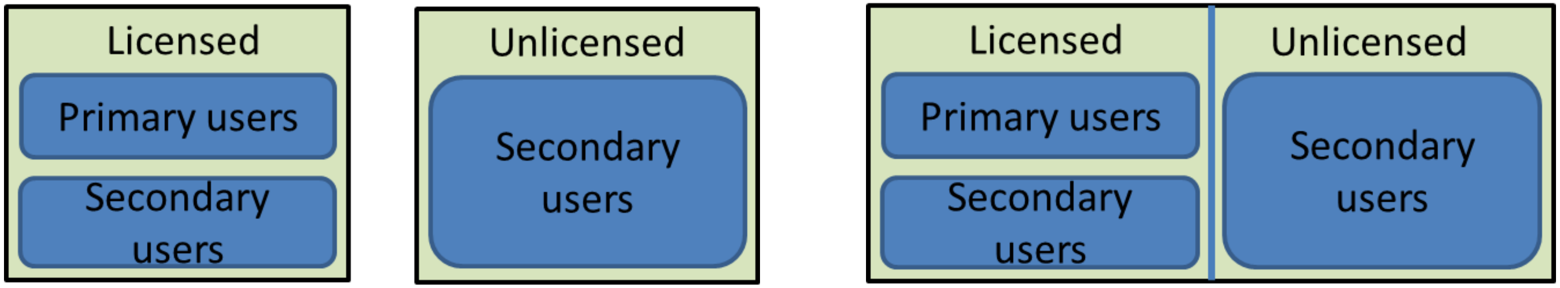
http://www.ict-qosmos.eu/

- Spectrum sharing
  - Enabling technologies: Spectrum management and PHY/ MAC layer
  - Architecture: Reference models
  - Value chain: Business case modelling for spectrum trading and various use-cases
- Impact
  - Regulation now more uniform across Europe
  - Contribution to standards: ETSI, IEEE, IETF
- Make-up
  - 15 partners across Europe
  - External Advisory Board made up of 14 representatives from broadcasters, regulators, industry and standards

Licensed, unlicensed, primary and secondary

Licensed and unlicensed in separate spectrum

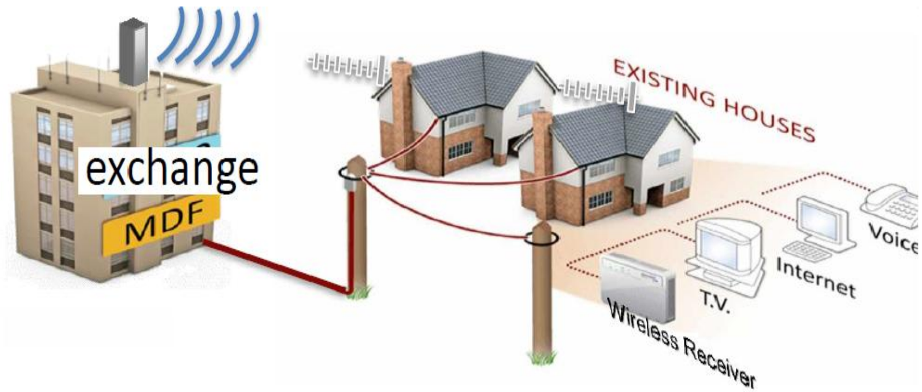
Licensed and unlicensed sharing the same spectrum

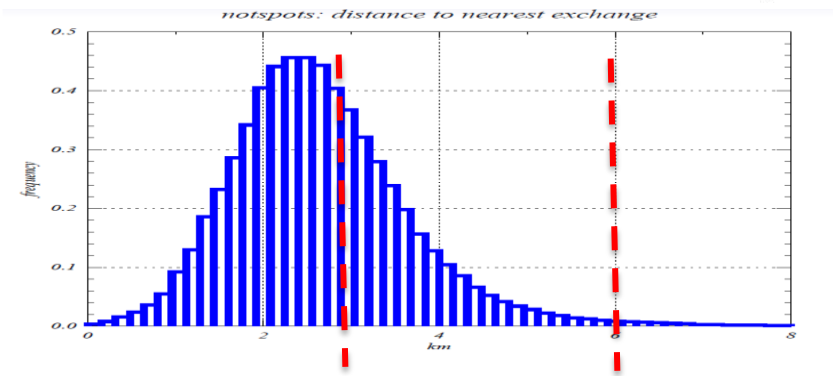


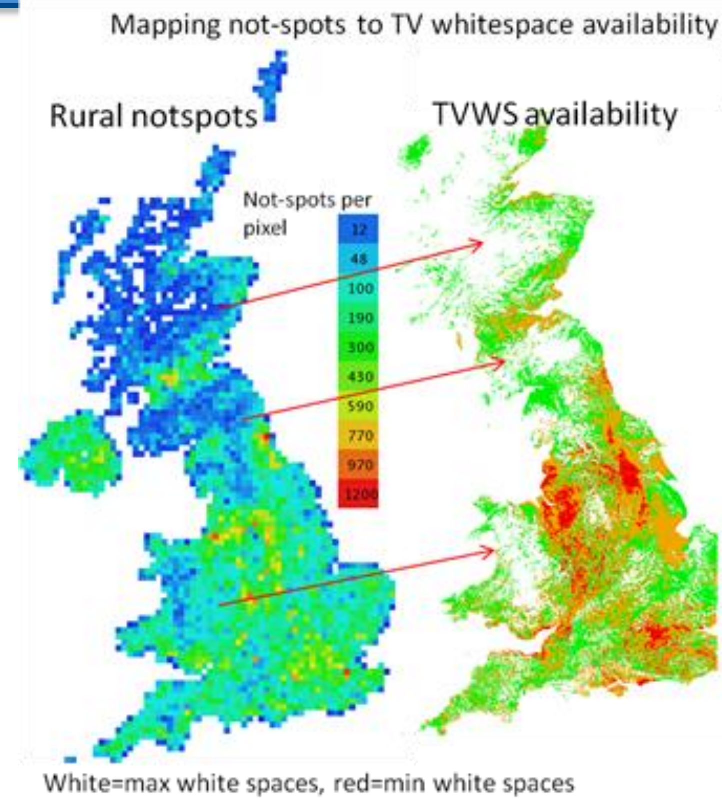
The order of access priority is Licensed Primary, Licensed Secondary, Unlicensed Secondary.

QoSMOS is focussing on spectrum sharing of secondary users, both licensed and unlicensed. TVWS is an early example of unlicensed.

Fixed line operator using TVWS for wireless broadband in Rural areas







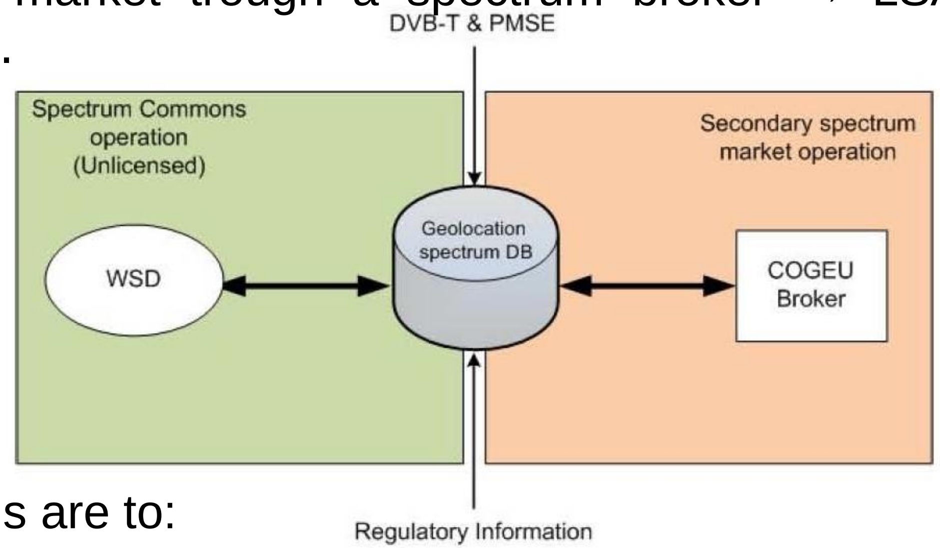
Number of TVWS base stations required

% of rural not-spots covered	20%	40%	60%	80%	100%
No of TVWS Base stations needed	1900	3800	5700	7500	9500

Assumptions
Guarantee simultaneous data-rate of 100Kb/s service (20:1 contention ratio for a 2MB/s EoC), 3 sectors per BS, LTE-TDD technology 15 MHz D/L, Tx antenna height 12m, Rx antenna height 5m, Uniform user distribution, Other standard link budget, propagation models

In COGEU-"**Cognitive radio systems for efficient sharing of TV white spaces in European context**" model, the regulatory bodies assign TVWS for licence-exempt (free access) in given areas. The remaining TVWS can be traded in a secondary spectrum market trough a spectrum broker → LSA (licensed shared access approach).

www.ict-cogeu.eu



At the **technical level** the mail goals are to:

Design, implement and demonstrate enabling technologies based on cognitive radio to support mobile applications over TVWS for spectrum sharing business models.

Quantify the impact of TVWS devices on DVB-T receivers and define methodologies for TVWS equipment certifications and compliance in the European regulatory context.

CogEU

COGEU has established a complete framework online and public available to educate stakeholders in the shared used of TV white spaces:

- Geo-location database for Munich, Bratislava and Banska Bystrica →inventory established by the RSPP
- Show white spaces tool
- Regulatory enforcement tool
- Wireless microphone booking system
- TV White Spaces repository
- Coverage maps for TVWS base stations
- Online spectrum broker ("ebay" for a local spectrum market)
- Implementation of a draft-PAWS (IETF)
- Key information can be downloaded from the tool without having to search in the Deliverables

ACROPOLIS-NoE

"Advanced coexistence technologies for radio optimisation in licensed and unlicensed spectrum "

- A "Network of Excellence" EU Research Project
  - "Integration" workpackages
  - "Research" workpackages
  - "Spreading of Excellence" workpackages
- Such a project aims to bring the best EU researchers on a particular topic together, in order to share ideas, "integrate" their research and achieve far more than would otherwise be possible with the entities working separately
  - Analyses current situation and fills the gaps in terms of what is missing in the EU research repertoire
  - Aims to maximise the impact of the research through contributions to standards, regulators and other long-term impacts
- Also aims to promote the prospects for the technology in question, by educating future researchers in the area, and organizing events, etc.

http://www.ict-acropolis.eu/

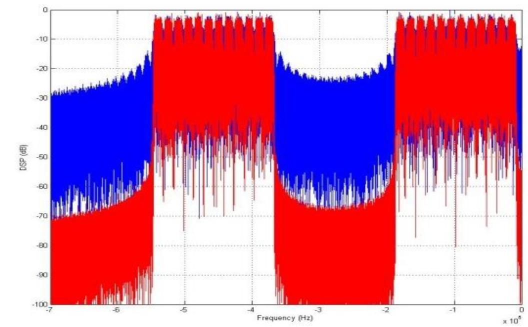
Reconfigurability and Flexible Radio Systems

Study measures for and tradeoffs of flexibility against highly optimised, but less configurable, technologies. Different reference architectures are considered in ACROPOLIS, but at least one of the key baseline architectures will be OFDM based flexible radio architecture, in this context we will be also consider **Filter Banks Multicarrier systems (FBMC) as a basis for flexible modem**.

Various aspects of the possible applications of the GMC/FBMC systems have been analyzed focusing on the application of the mercuryfilling principle to that systems (example previously presented).

Project objectives/solutions (http://www.ict-emphatic.eu)

- Develop **Innovative technological** solution allowing **increased data throughput for Public Safety radio-communication** systems,

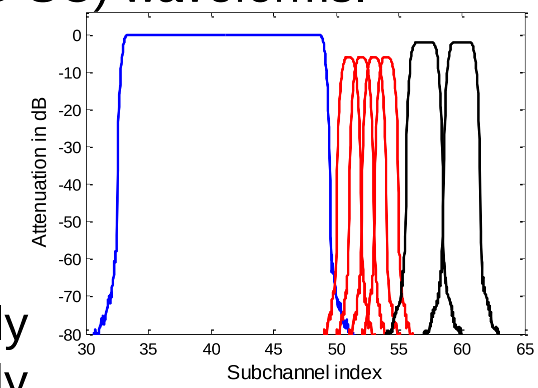


- **Cohabitation with existing networks** in the same Frequency bands

- Facilitate a **smooth migration towards broadband system** and to increase **spectrum use efficiency** ".

Solutions: The focus is on extension of uniform FB-MC arrangements (ICT-PHYDYAS) towards non-uniform and multimode combinations of filterbank based multicarrier (FBMC/OQAM, FMT, etc) and single-carrier (FB-SC) waveforms.

- Flexible, multimode, variable filterbank
- LTE compatibility and coexistence in PMR band
- Highly adjustable multirate digital filters based on fast convolution approach.



Develop a platform able to process simultaneously alternative filterbank based waveforms, with highly adjustable characteristics (SDR-model).

Future broadband PMR/ (PPDR) systems

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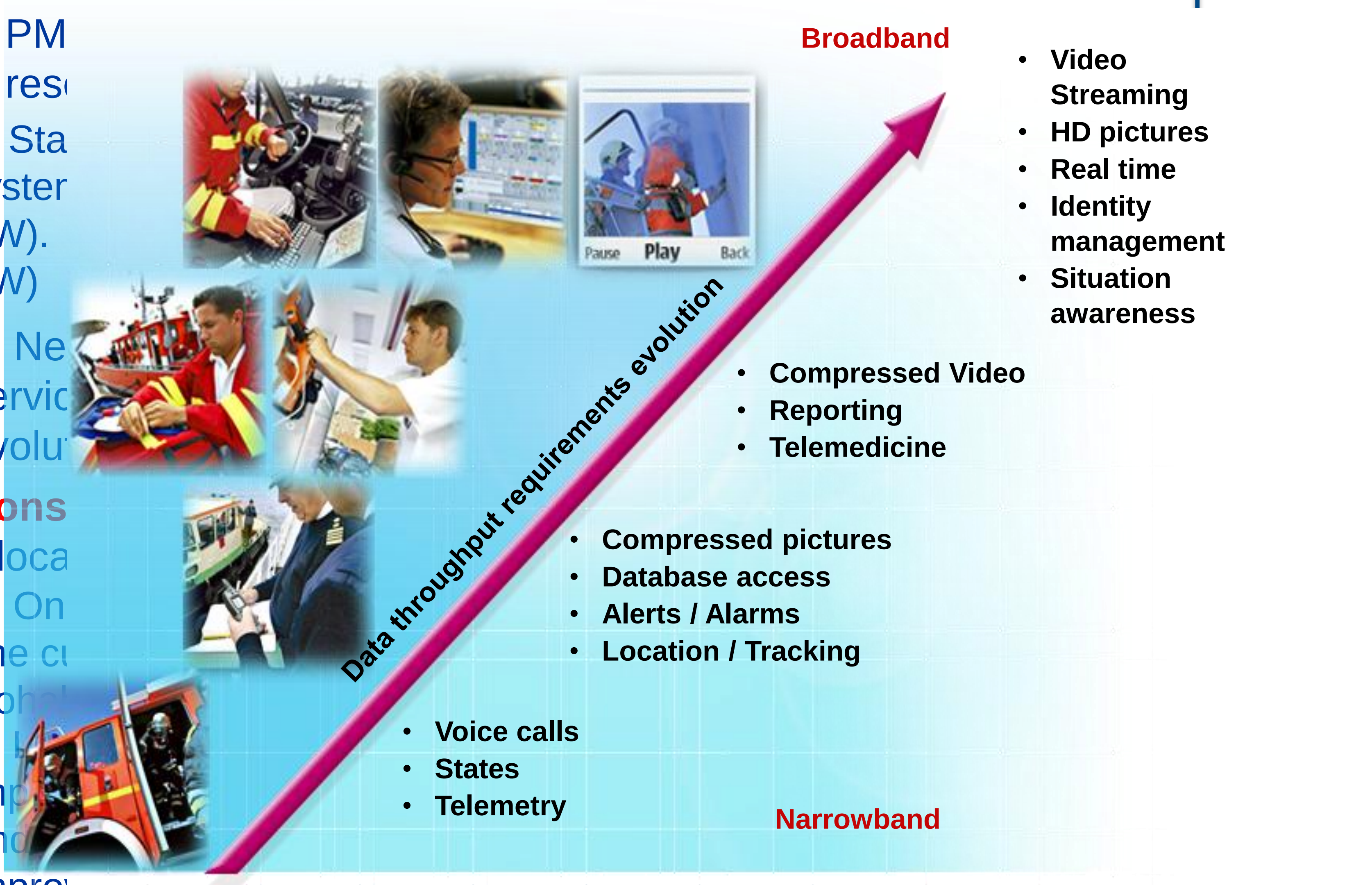

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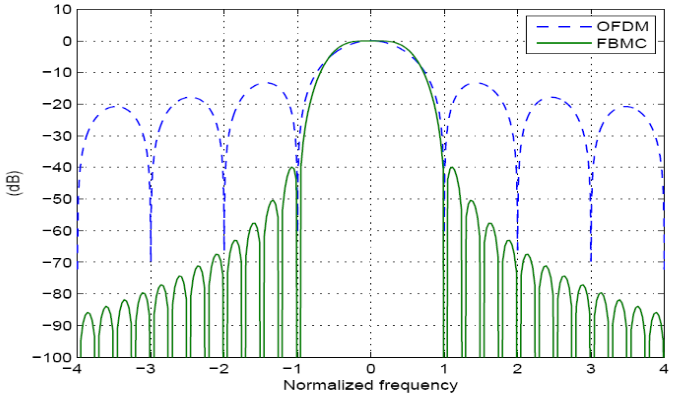
EMPhAtiC-General objective

"Develop **Innovative technological** solution allowing **increased data throughputs for Public Safety radio-communication** systems, in order to satisfy emerging new data service needs **in cohabitation with existing networks** in the same frequency bands, to facilitate a **smooth migration towards broadband systems** and to increase **spectrum efficiency** ".

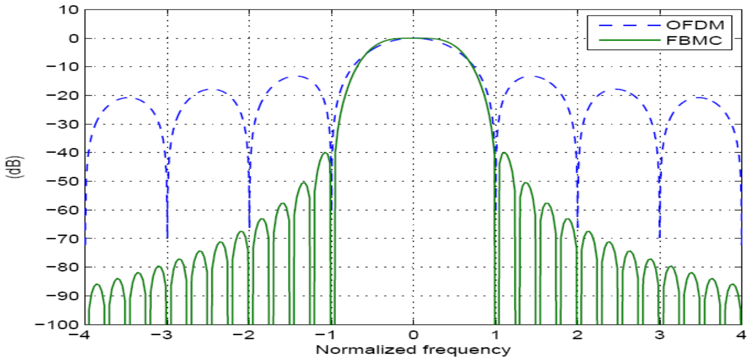
- New concepts on multimodal, multi-access flexible spectrum (DSA Dynamic Spectrum allocation) access require new functionalities:
  - fast accurate spectrum analysis
  - reliable channel state information
  - high flexibility/variability and scalability
  - coexistence with narrow bands
  - quality of service



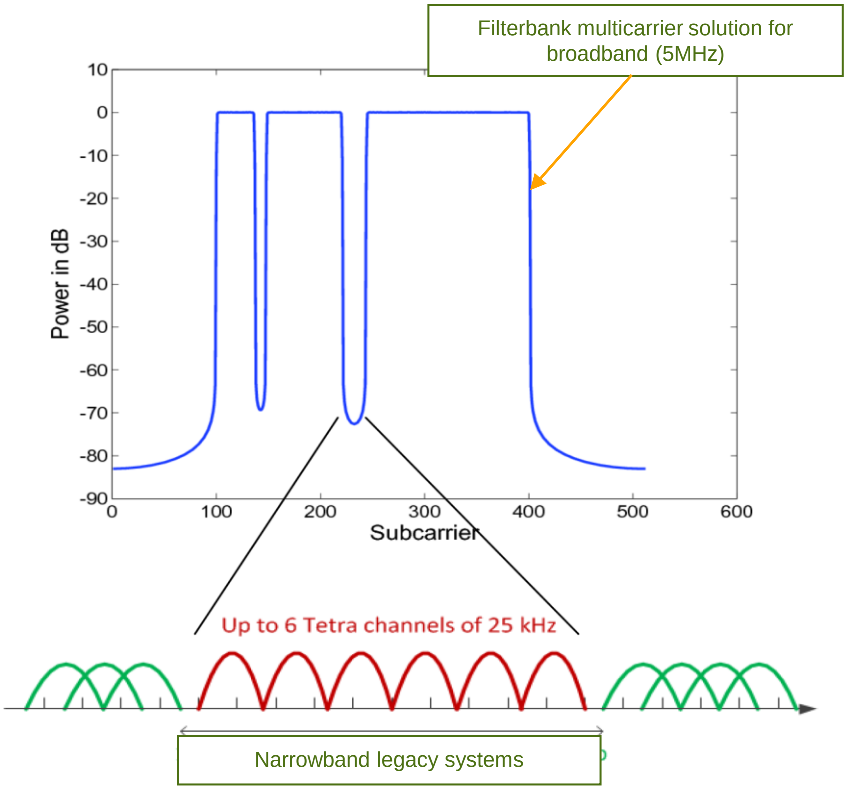
- a new PHY layer able to support these functionalities is needed
- FB-MC (Filterbank Based multicarrier)/enhanced OFDM scheme can support DSA and CR better than OFDM.
- The best techniques and algorithms available must be picked up, developed further, integrated and demonstrated.

EMPhAtiC-Approach

- The physical layer of LTE poses severe problems in order to guarantee cohabitation with legacy narrowband systems, especially due to the **poor spectral containment** of the CP-OFDM subcarriers.
- **Filter bank multicarrier modulations (FBMC)** are a natural approach to address this:
  - A non-rectangular pulse shape is used
    - → Better spectral containment
  - The presence of a cyclic prefix is avoided
    - → Improved spectral efficiency



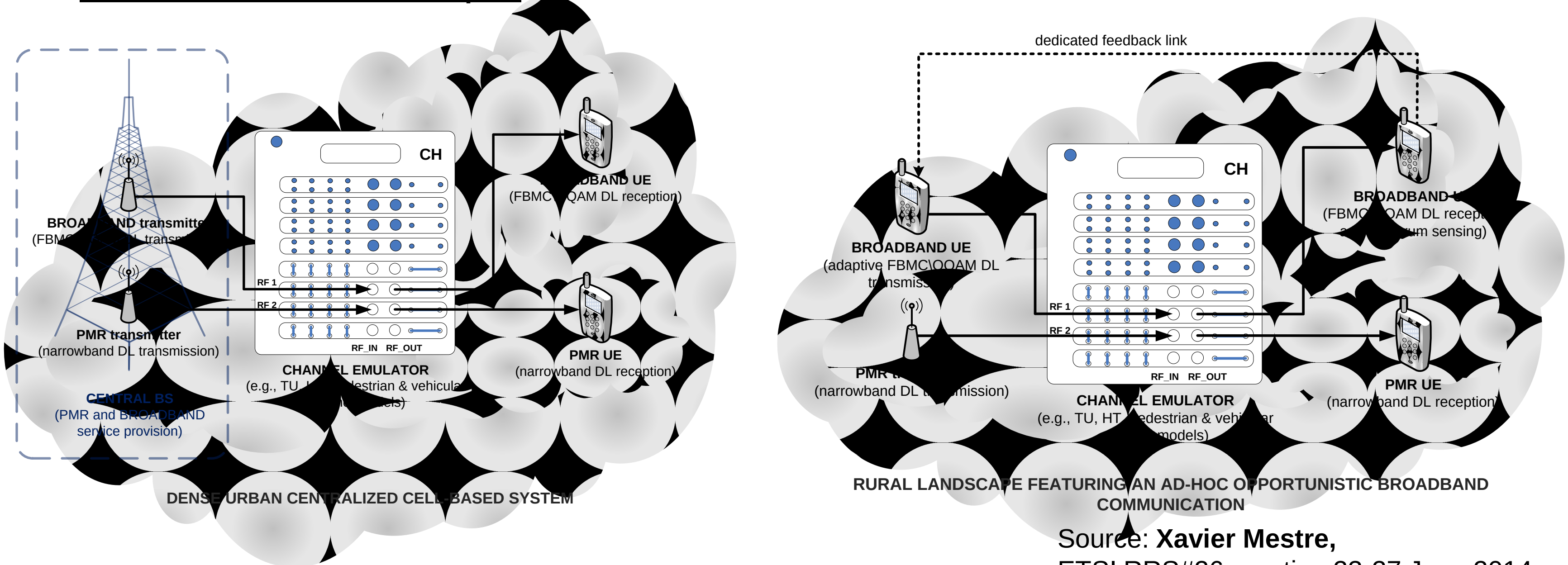
Source: **Xavier Mestre,**
ETSI RRS#26 meeting 23-27 June 2014



- Additionally, high flexibility is needed to utilize effectively the variable spectral gaps between different narrowband users: we propose a flexible **fast convolution filter bank** implementation.

Scenarios

- Two different scenarios are considered and demonstrated in the project: **cell-based (centralized) and ad-hoc (decentralized) scenarios**.
- Two demonstration set-ups are therefore considered:

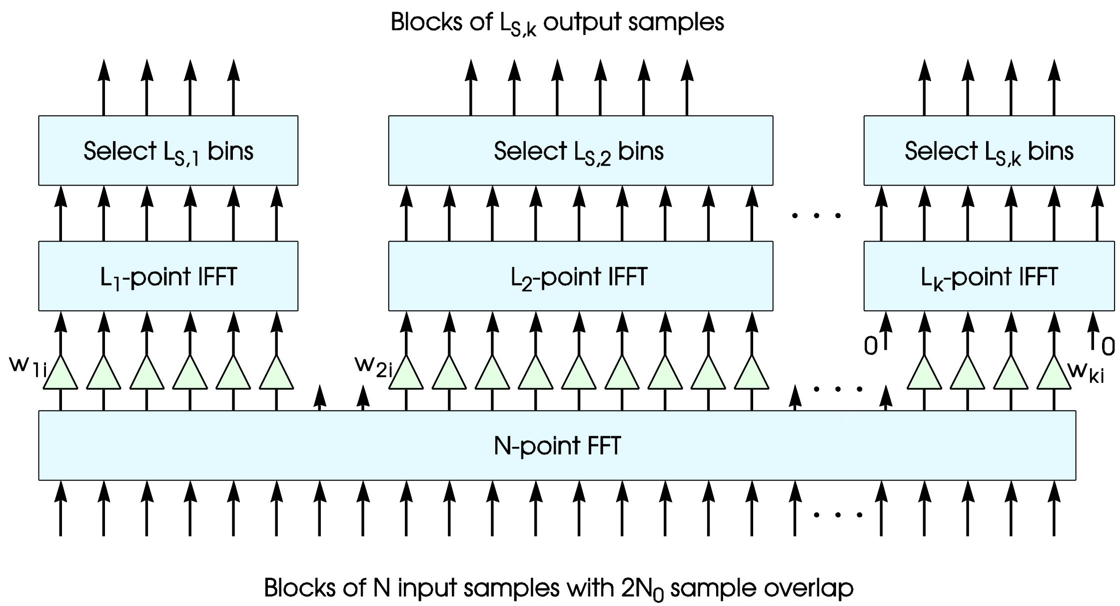


Source: **Xavier Mestre,**
ETSI RRS#26 meeting 23-27 June 2014

- In the cell-based scenario, broadband and narrowband (legacy) PMR coexist in a centralized fashion.
- In the ad-hoc mode, the two systems coexist without prior coordination. Both **spectrum sensing** and **cognitive radio** are used. The legacy narrowband PMR system is the primary user, whereas the wideband becomes the incumbent one.

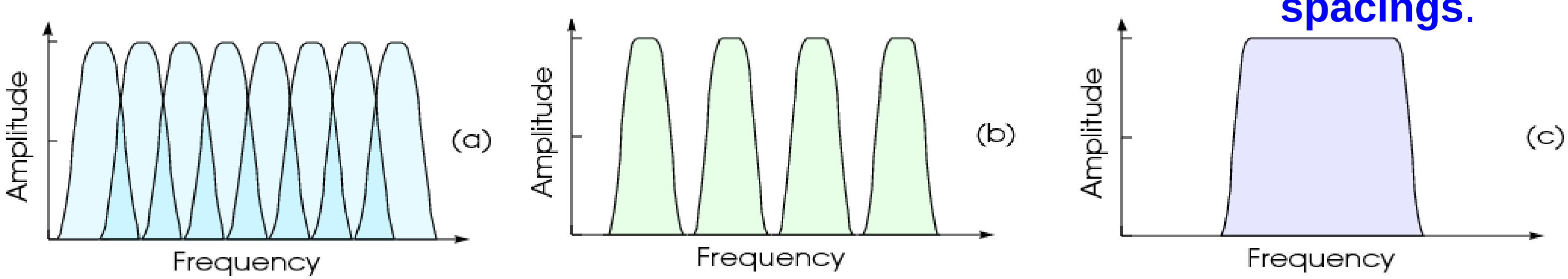
Intermediate achievements: waveform design

- A flexible filterbank structure has been proposed based on **fast convolution**, that can process and synthesize multiple modulations while adapting the transmission to the scenario:



Completely **flexible** filterbank architecture:

- With **tunable bandwidths** and center frequencies
- **Different waveforms** simultaneously in different subchannels.
- Also seamless combinations of FBMC/OQAM multiplexes with **different subcarrier spacings**.



FBMC/OQAM FMT single carrier

5GNOW in a Nutshell

The obedience of LTE and LTE-Advanced to strict synchronism and orthogonality will be challenged.

At the core of this paradigm change it will introduce non-orthogonal waveforms that carry the data on the physical layer:

1) Abandon synchronism and orthogonality altogether, thereby admitting some crosstalk or interference, and to
2) control these impairments by a suitable, most likely, more complex transceiver structure and transmission technique with a boost from Moore's law.
3) Reality check and proof-of-concept with hardware demonstrator
4) 5GNOW will contribute to upcoming 5G standardization.

Wireless transmission networks will be better prepared

1) to meet the manifoldness of services, device classes (like in smart cities),
2) to integrate MTC systems, e.g. sensor networks.
3) The per-user experience will be more uniform and satisfying.

http://www.5gnow.eu/

5GNOW Objectives:

MTC

- Let MTC nodes transmit their message right away only coarsly synchronized!
- Design of non-orthogonal PHY layer Random Access Channel (RACH)

Supplementary RACH design on MAC layer

- Application of modern sparse signal processing at the base station

CoMP/HetNet

- Creation of non-orthogonal MIMO PHY layer and related transceiver design in the presence of relaxed time/frequency constraints and imperfect channnel state information
- Identification PHY/MAC related asynchronisms; robust and adaptive heterogeneous network architecture

Fragmented spectrum

- Non-orthogonal, asynchronous waveforms with improved localization properties and relaxed (or completely omitted) synchronization requirements

METIS project

https://www.metis2020.com/

The overall technical objective of the METIS project is to develop a concept for the future mobile and wireless communications system that supports the connected information society by combining the results of the following technical objectives.

METIS will provide fundamentally new solutions which fit the needs beyond 2020. Research will be conducted on network topologies, radio links, multi-node, and spectrum usage techniques.

Horizontal topics are used to integrate the research results into a system concept that provides the necessary flexibility, versatility and scalability at a low cost.

METIS project

- To develop a concept for the future mobile and wireless communications system that supports the connected information society.
- To provide a system concept that supports
  - 1000 times higher mobile data volume per area
  - 10 times to 100 times higher number of connected devices
  - 10 times to 100 times higher typical user data rate
  - 10 times longer battery life for low power MMC
  - 5 times reduced End-to-End latency
- The system concept should be
  - efficient
  - versatile, and
  - scalable.
- and achieve these objectives at
  - similar cost and
  - energy consumption as today's networks.

Source: Hugo Tullberg, Ericsson
METIS | RAS meeting | 2013-02-27

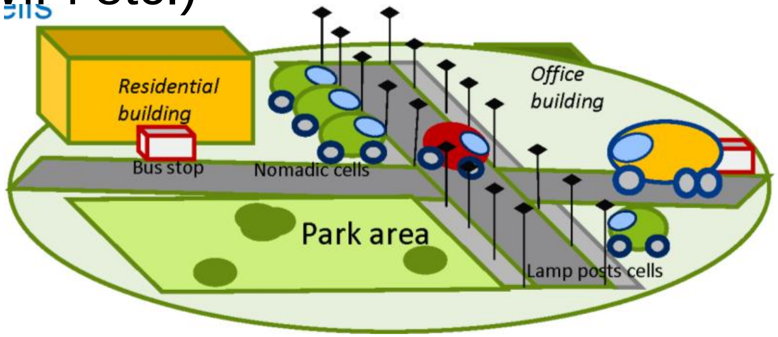
Ultra Dense Networks

Comprises dense deployments of BSs of different properties:

different transmit powers, leading to macro, micro, pico or femto cells of different size

connected to different RATs (2G-5G, WiFi etc.)

static or moving / nomadic cells



Motivation

An increase in capacity per area, and user QoE, to response for traffic avalanche. In the long term, this project will be facing fairly uncontrollable, dense and 3-dimensional constellations of APs connected in very different ways to the cloud

Source: Hugo Tullberg, Ericsson
METIS | RAS meeting | 2013-02-27

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Part III : Practical Applications and Projects

B- Application of Flexible multicarrier waveforms

-In TV white spaces
-Machine to Machine
-Future Broadband Professional Mobile Radio (PMR)/(PPDR) systems

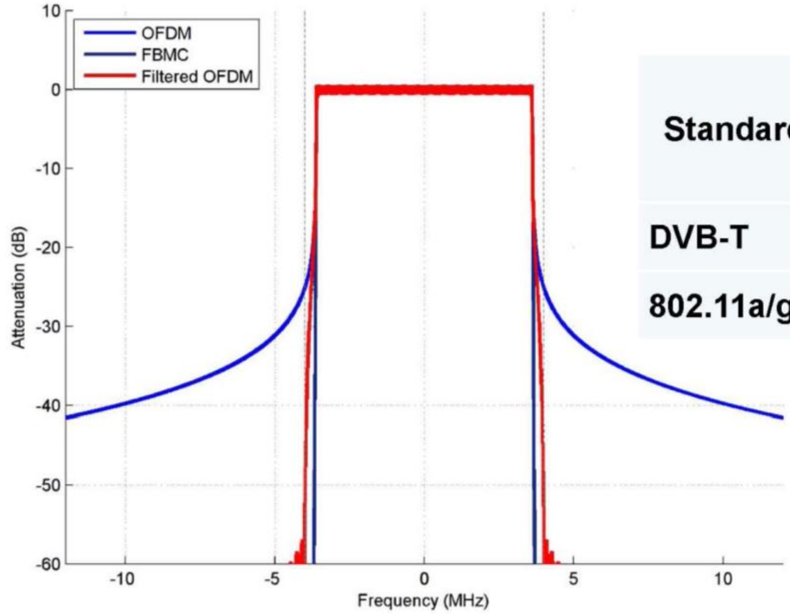
TV White Space Context

TVWS:
OFDM vs. FBMC Capabilities

Spectrum efficiency comparison

- Regulators require high rejection for adjacent incumbent protection in TVWS - e.g., 55dB requires by the FCC -→ **Low adjacent channel leakage**
- Maximizing spectrum usage implies the use of non contiguous spectrum

FBMC in the TVWS context



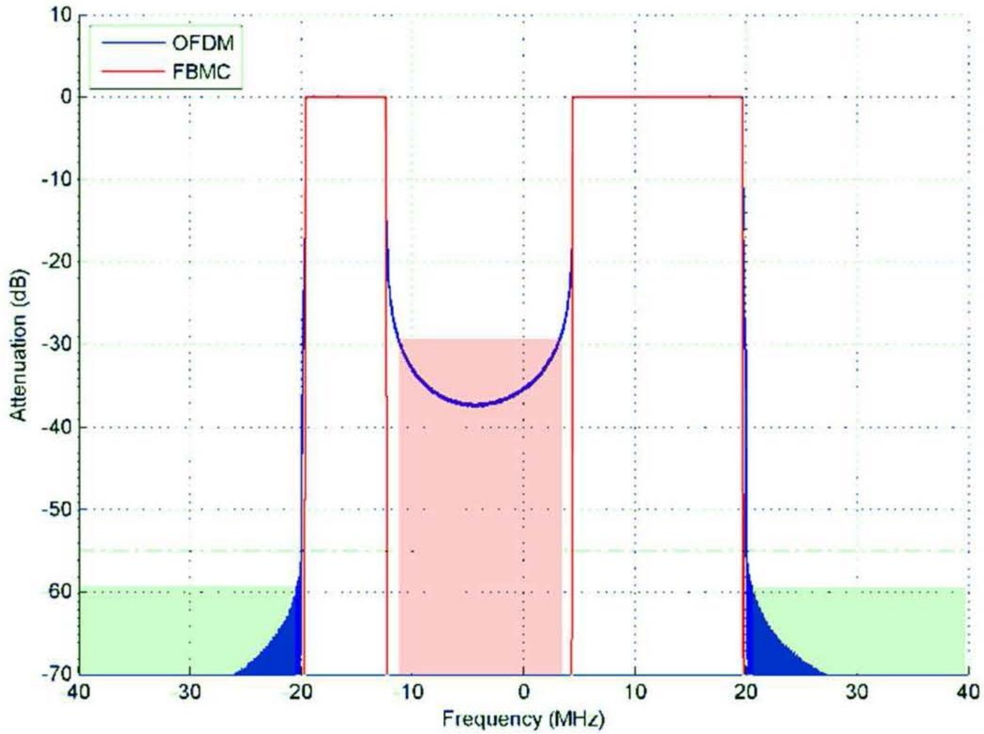
Standard	Spectral Efficiency Gain relative to filtered OFDM		
	Frequency Domain	Time Domain	Total Gain
DVB-T	10 %	3 %	13 %
802.11a/g	3.8 %	15.8 %	19.6 %

Source: "FBMC a flexible and low interference radio technology for TVWS" by Dominique NOGUET- ICT-QoSMOS

Spectrum pooling with FBMC

The benefit of filtering on top of OFDM mitigates interference on both sides of the overall band . It does not reject the signal inside the notch channels

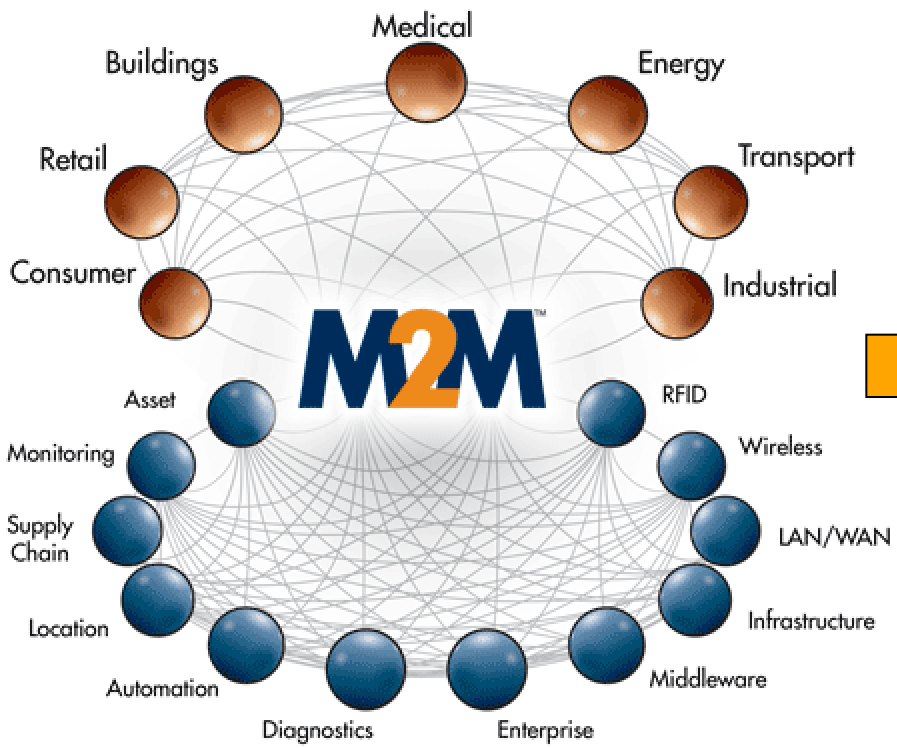
Source: “FBMC a flexible and low interference radio technology for TVWS” by Dominique NOGUET-ICT-QoSMOS



With FBMC, ACLR requirement is met both on adjacent and in the notch

Adrian Kliks, Hanna Bogucka, **Faouzi Bader**, Musbah Shaat, Oliver Holland, **FBMC and GMC Capabilities for TV White Space and Cognitive Radio,** IEEE 1900.7 Working Group Meeting, Osaka, Japan, 26-29 March 2012.

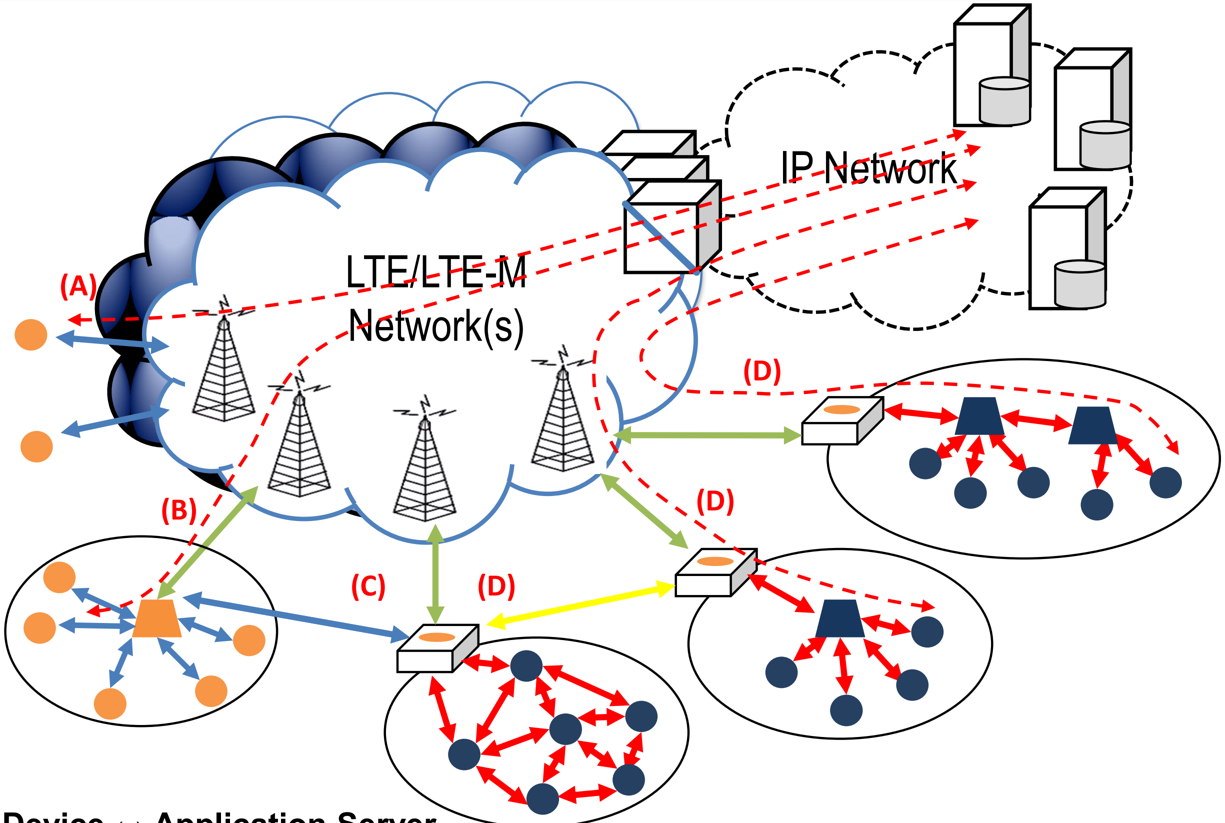
Machine-to-Machine context



coexists with LTE in the same spectrum

M2M basic communication scenarios (i.e)

Communication of devices with application servers



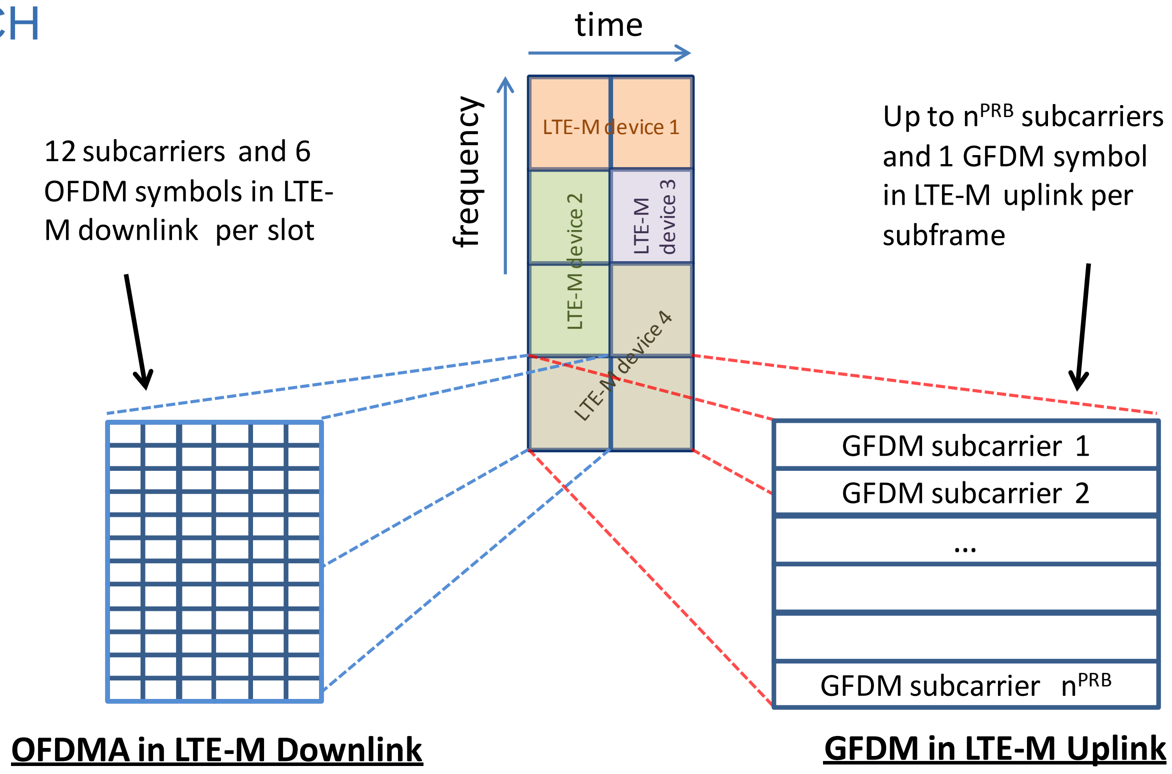
Source: with courtesy of ICT-EXALUTED project partners

(A) LTE -M Device ↔ Application Server
(B) LTE-M Device ↔ LTE-M Relay ↔ Application Server
(C) M2M Gateway ↔ Application Server
(D) M2M Gateway ↔ Application Server
(E) Non-LTE-M Device Group ↔ Application Server

UL and DL resource multiplex

- Radio resources assigned to LTE-M devices are multiplexed in time and frequency:
  - Uplink: Generalized Frequency Division Multiplex (GFDM) on PMUSCH
  - Downlink: Orthogonal Frequency Division Multiple Access (OFDMA) on PMDSCH

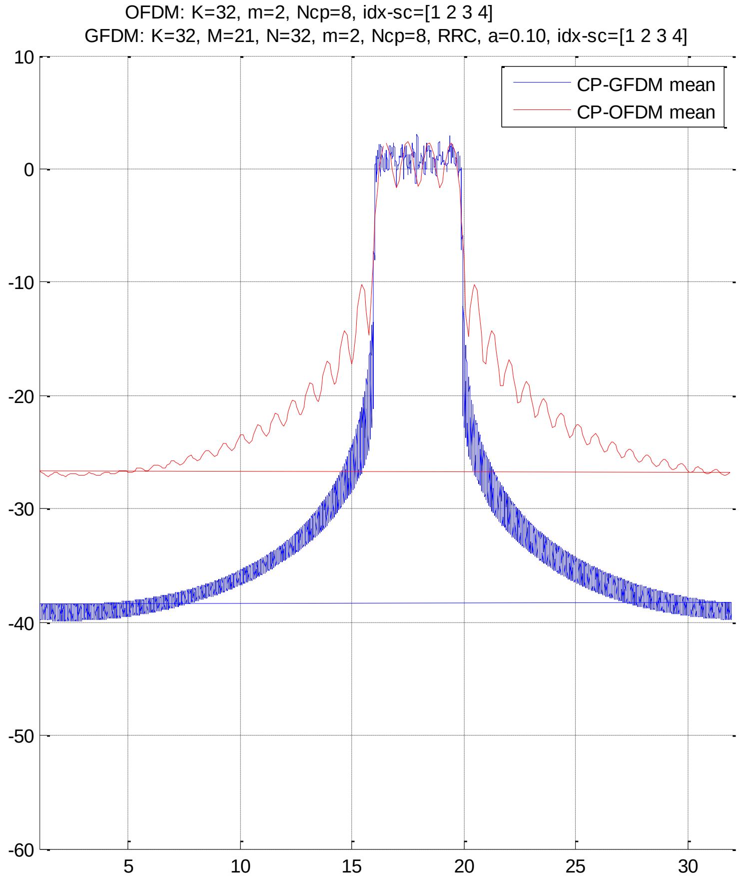
Source: with courtesy of ICT-EXALUTED project partners

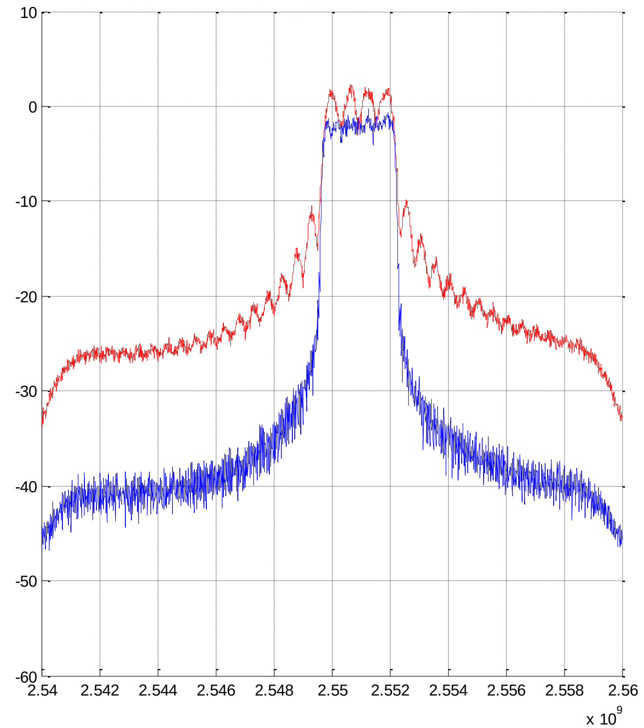


Preliminary results for GFDM

Source: with courtesy of ICT-EXALUTED project partners

- Setup: 4/32 subcarrier, BPSK, 2.55GHz carrier
- Simulated — Measured



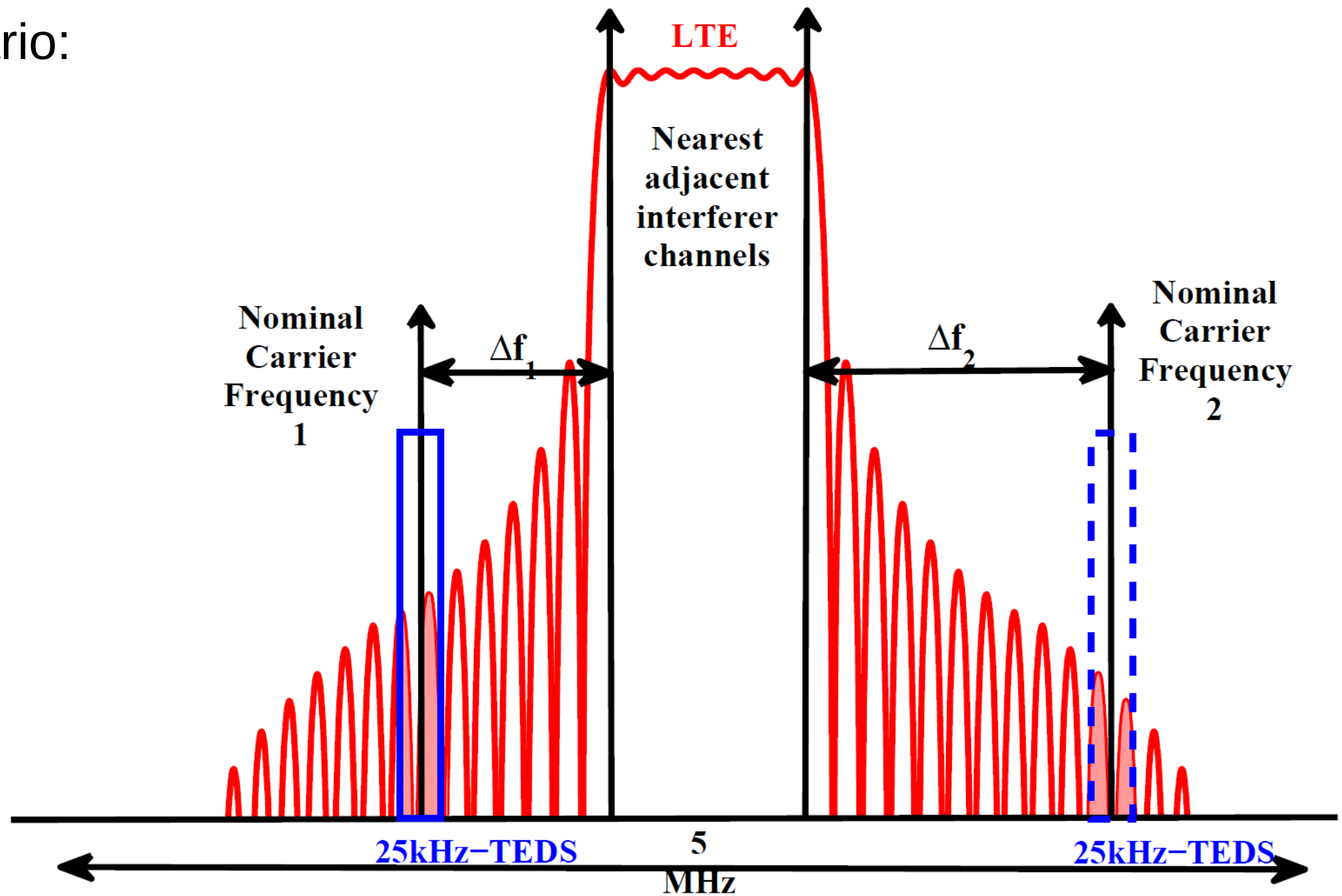


Future broadband Professional MobileRadio (PMR)/(PPDR) systems:

OFDM vs. FBMC Spectrum Coexistence Capabilities

Coexistence and PMR requirements..

Scenario:



LTE broadband in coexistence with narrowband PMR systems

Coexistence and PMR requirements..

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

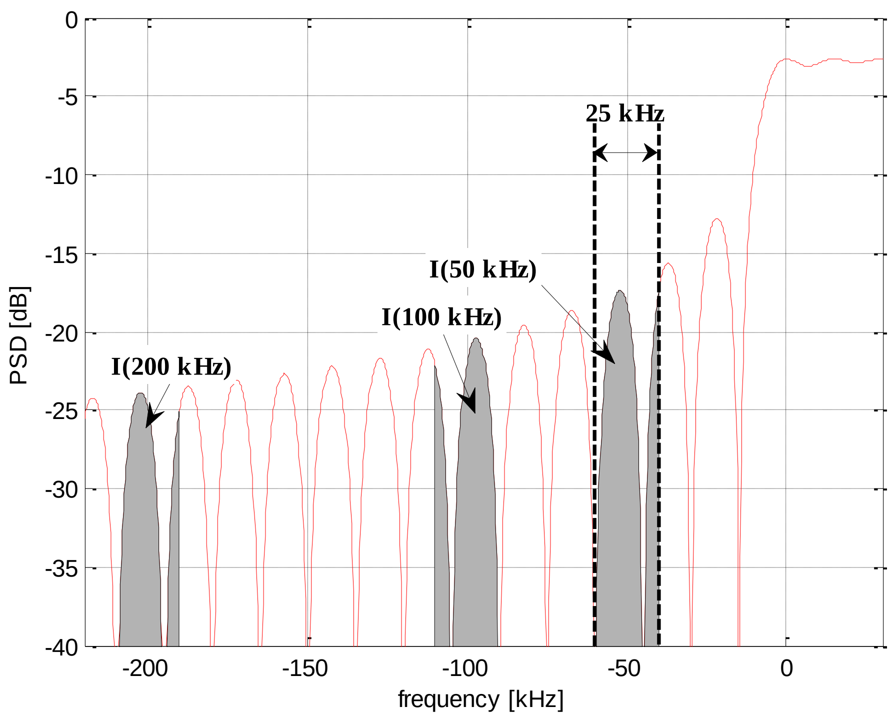
Multicarrier Techniques: CP-OFDM using the rectangular pulse shape, and FBMC using the PHYDYAS prototype filter

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

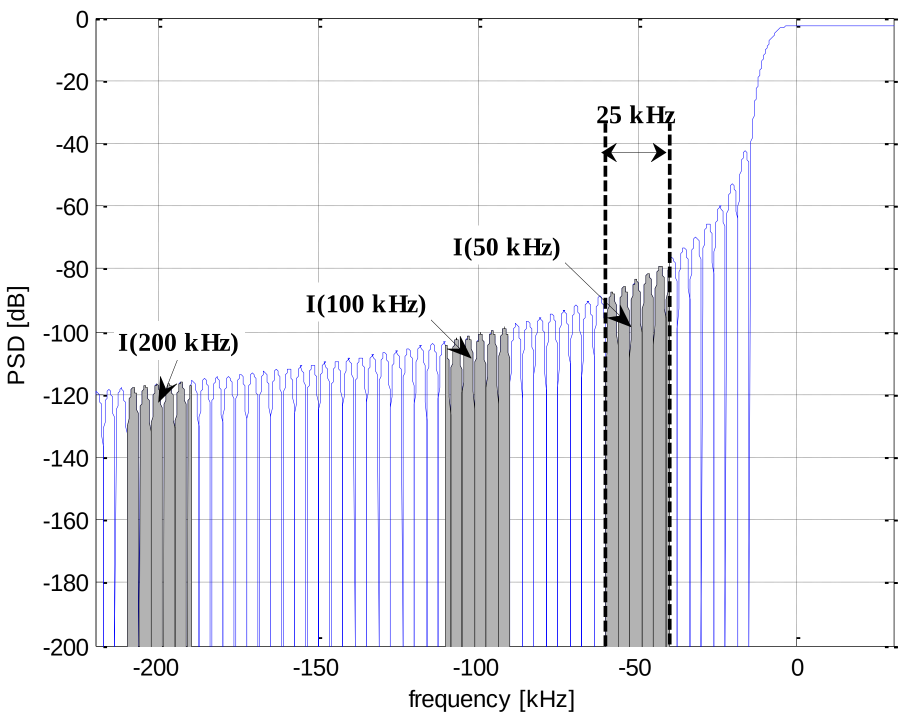
Offset from nominal Rx frequency [kHz]	Level of interfering signal [dBm]
50 to 100	-40
100 to 200	-35
200 to 500	-30
> 500	-25

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

LTE effective interference levels:



OFDM case



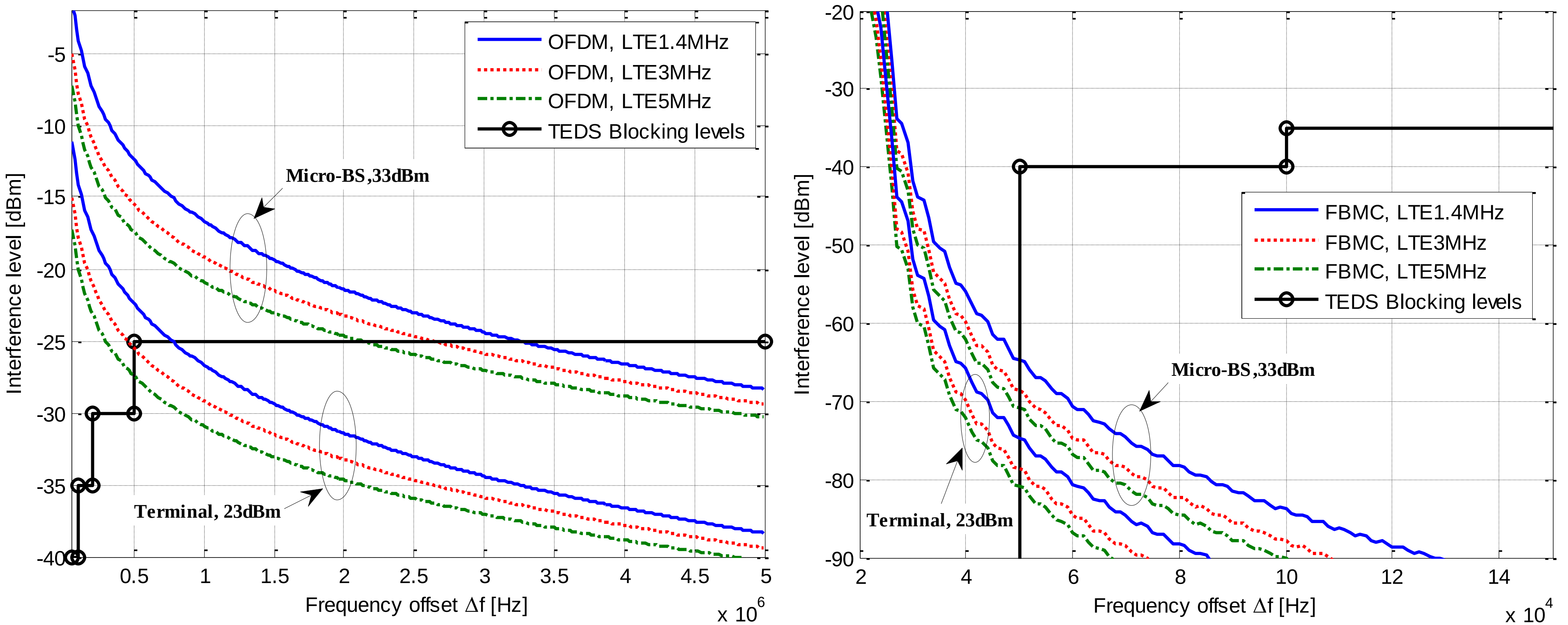
FBMC case

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

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)

Courses of the 24th Jyväskylä Summer School , August 2014. Finland

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Part IV: 5G Wireless Communication Concept Eco-System

A- Beyond LTE (5G) communication syst.

Beyond LTE (5G) communication syst.

4G Status

However, emerging trends reveal major pitfalls:

- **MTC communications**: bulky procedures to ensure strict synchronism
- **Collaborative schemes**: tremendous efforts to collect gains under the premise of strict synchronism and orthogonality
- **Digital Agenda/Carrier aggregation**: forces systems to deal with fragmented spectrum
- **Localized Communication**: communication sources and sinks might be in proximity → direct comm or meshed comm w/o fixed infrastructure
- **Special Application Requirements**: reliability, latency, event triggering delay might be outside of standard cellular requirements
- **Heterogeniouty**: in Network Arcitectures, Deployments and Applications
- **Wireless for Everything**: Access, Backhaul, Fronthaul, Direct Comm

OFDM might be not always the suitable waveform !

5G Wireless Vision

Holistic Approach for Heterogeneous Wireless Infrastuctures, Systems and Applications

MTC

Enable asynchroneous MTC traffic with drastically reduced signalling

CoMP/ HetNet

Provision of asynchronous CoMP/HetNet concepts

Fragmented & new Spectrum parts

Asynchroneous carrier aggregation & High Carrier Frequency Signal Processing

Wireless Communication (Context, Content, Location aware - Autonomy vs. Controlled)

PHY, MAC and Network Layer Design

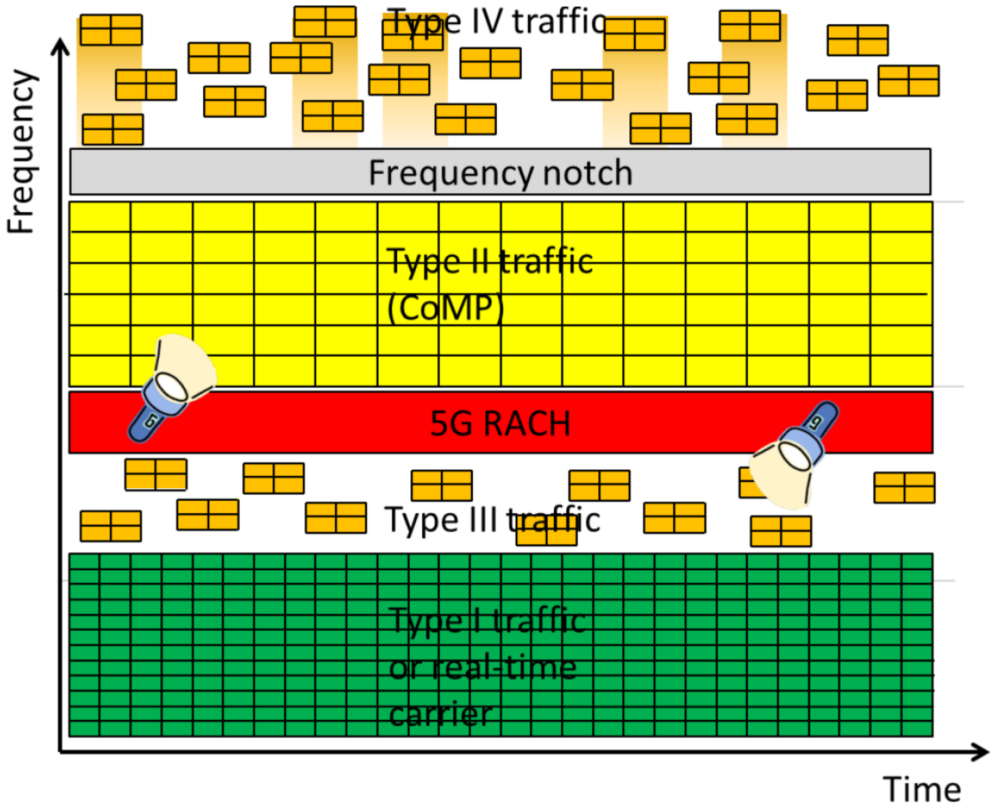
Spectrum Access Rules and Guidelines

Source: Thomas Haustein, Fraunhofer HHI Berlin , ISWCS 2013

Vision lower part of <6 GHz

Source: Thomas Haustein, Fraunhofer HHI Berlin , ISWCS 2013

- Classical “bit pipe” traffic (**type I**) with high-end spectral efficiency exploits orthogonality and synchronicity, wherever it is possible, e.g. when serving **cell-centre users**.
- Vertical layering at common time-frequency resources generates a non-orthogonal signal format supporting **interference limited transmissions** more efficiently (heterogeneous cell structures and cell edge). For high-volume data applications in those cell areas (**type II**), a multi-cell, multi-user transceiver concept is required.
- **Machine-Type Communication** (MTC) is expected to be one dominant application of 5G systems. For this sporadic traffic type (**type III**), a contention based-access technique is attractive, saving overhead by dropping the strict synchronicity requirement.
- **Sensor-type traffic** (**type IV**), the open weightless standard [3] has shown that, from an energy-efficiency perspective, it is beneficial to stretch the transmissions in time by spreading.



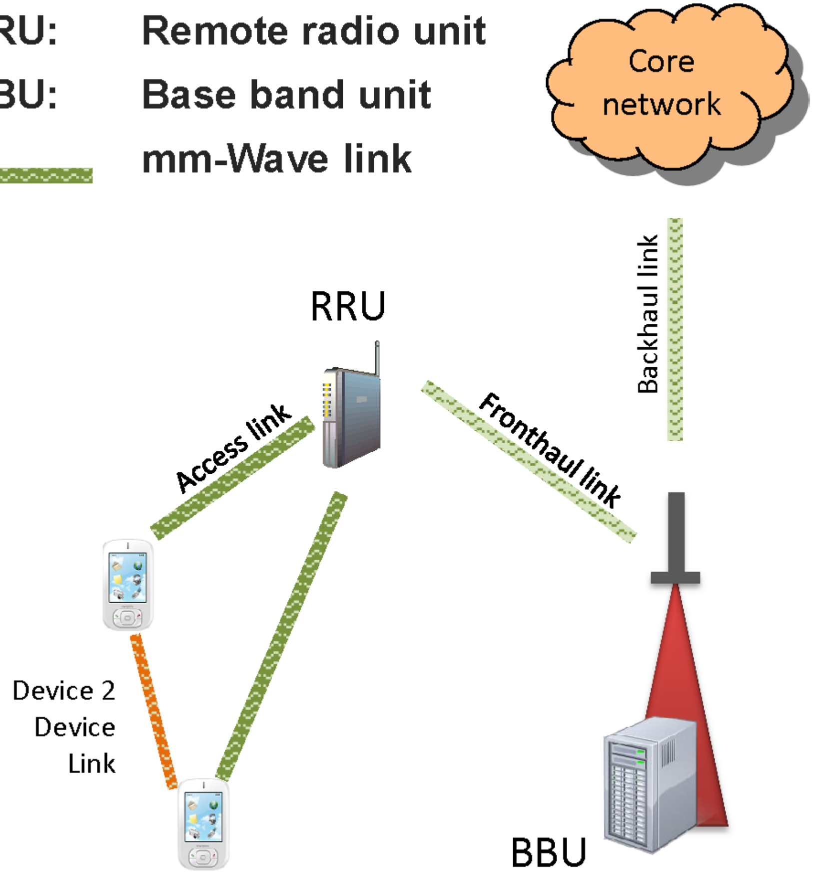
High Data Rate at > 10 GHz

- Use the **mm-wave bands**
  - Access link
  - Fronthaul link
  - Backhaul link
  - Device to device links
- Establish an overlay network where and when high capacity / data rate is needed
  - Seamless integration into 3GPP standards
  - Full indoor & outdoor mobility support
- Cost & energy reduction

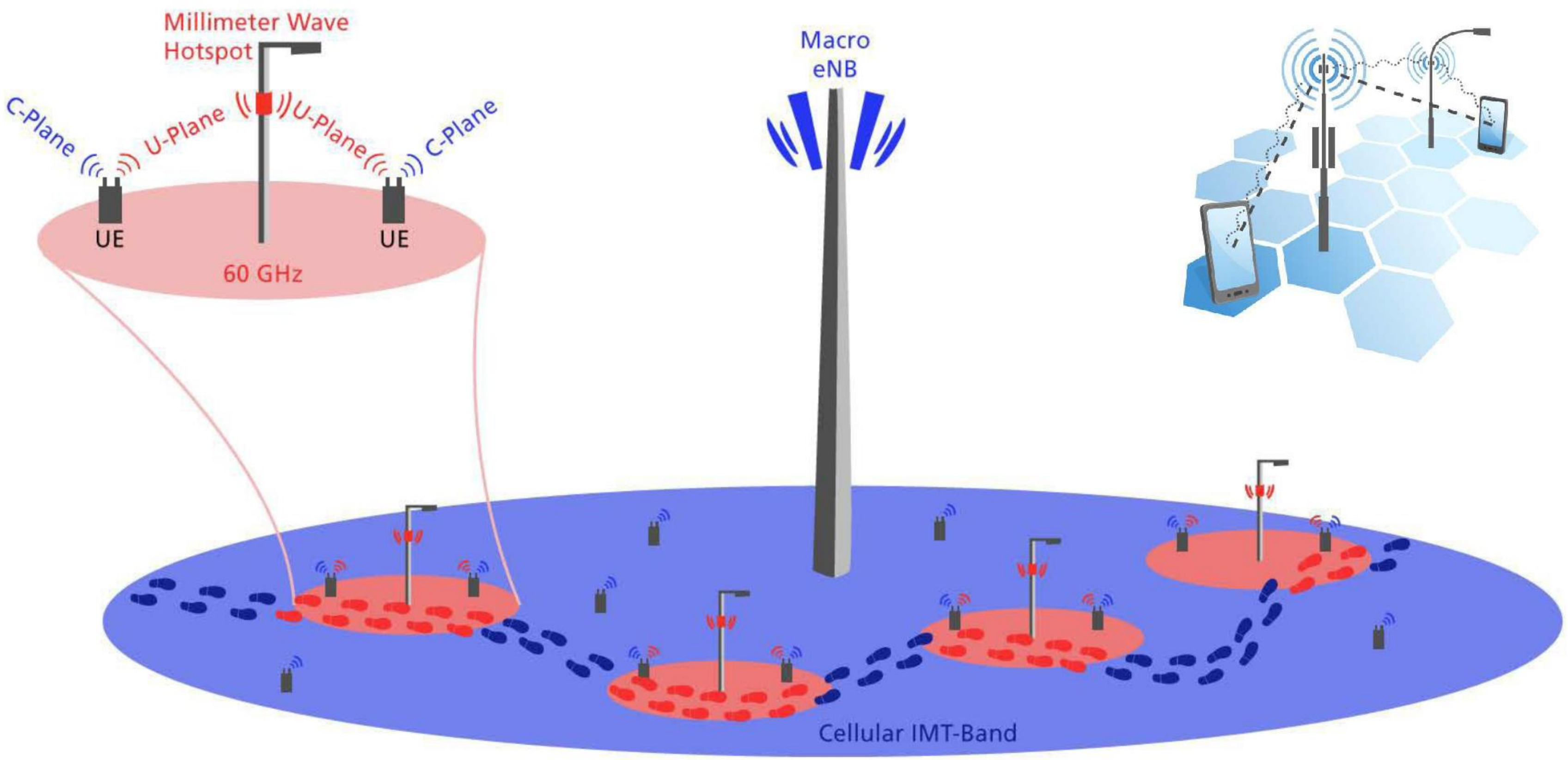
RRU: **Remote radio unit**

BBU: **Base band unit**

mm-Wave link



Millimetre Wave/Cellular Overlay Concepts

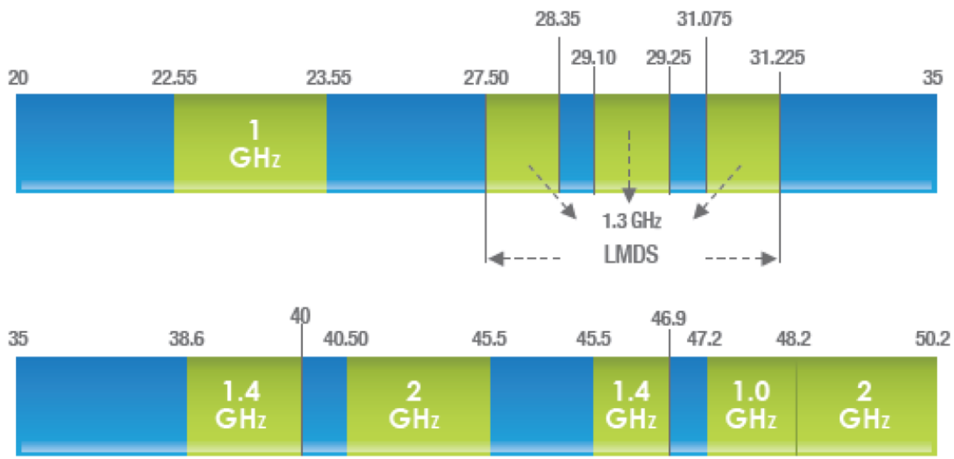


Source: Thomas Haustein,
Fraunhofer HHI Berlin ,
ISWCS 2013

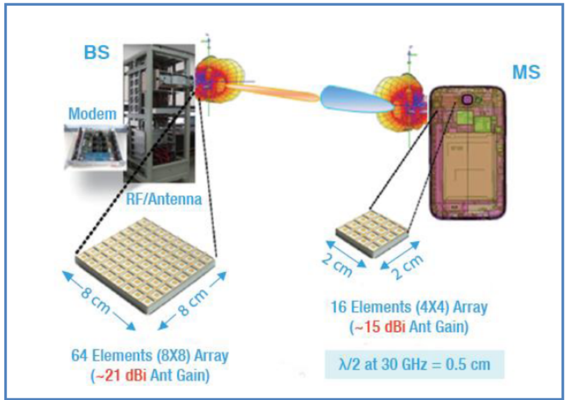
mm-Wave spectrum for 5G

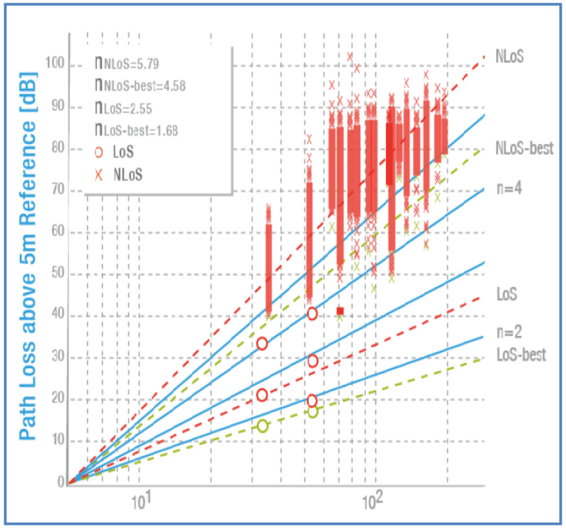
Supélec

MAGISTER SOLUTIONS



- *The mm-Wave bands provided up to 25 times more spectrum than available for 4G*
- *Very large blocks of contiguous spectrum to support future applications*
- *Small wave-length makes possible use of large antenna arrays for adaptive beam forming*
- *Propagation exponent is very similar to spectrum below 7 GHz, as long as beam forming is maintained between BS and terminal*





Source: Maziar Nekovee, Samsung Electronic R&D, ISWCS 2013

Test Results Range

- **Outdoor Line-of-Sight (LoS) Range Test**
  - Error free communications possible at 1.7 km LoS with > 10dB Tx power headroom
  - Pencil BF both at transmitter and receiver supporting long range communications

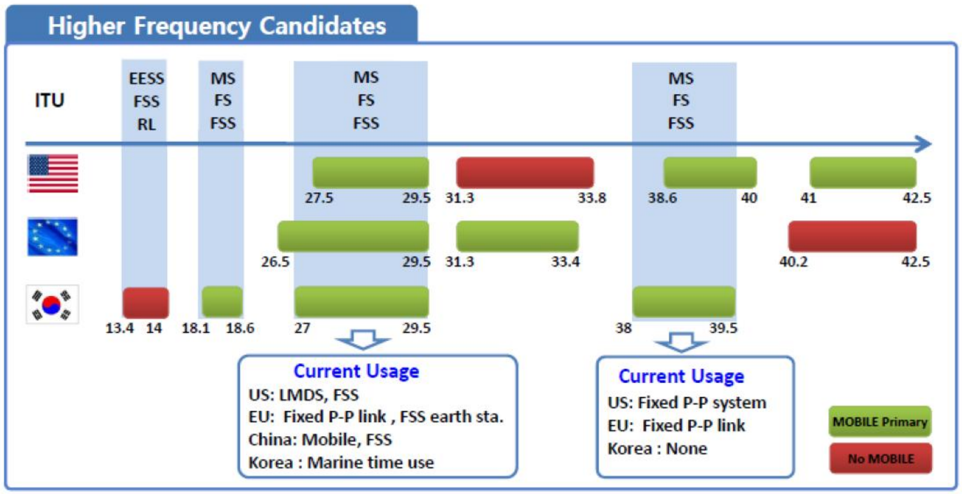
Source: Maziar Nekovee, Samsung Electronic R&D, ISWCS 2013

LoS Range

☐ **Support wide-range LoS coverage**

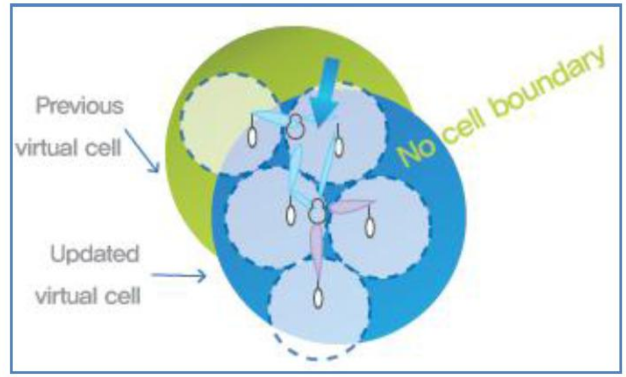
- ✓ 16-QAM (528Mbps) : BLER 10^{-6}
- ✓ QPSK (264Mbps) : Error Free

mm-wave 5G Research challenges



EESS (Earth Exploration-Satellite Serivce) FSS (Fixed Satellite Service) RL (RadioLocation service),
MS (Mobile Service) FS (Fixed Servce) P-P (Point to Point) LMDS (Local Multipoint Distribution Services)

- ▷ *The lower mm-Wave bands are already allocated to other services (mobile backhaul, Satellite)*
- ▷ *Feasibility of sharing need to be researched*
- ▷ *Sharing mechanism will be required, e.g. cognitive radio techniques, databases , interference cancellation*
- ▷ *Opportunity to develop shared use of mm-Waves for both backhaul and access, hence enabling fast spectrum release*

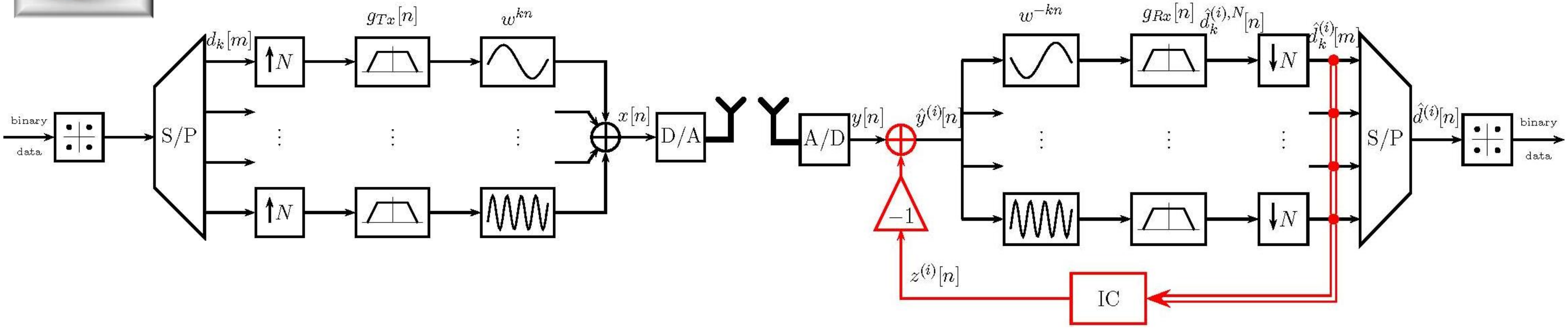


Advanced cooperation between base stations to realize virtual cell concept ("edge –less" user experience)

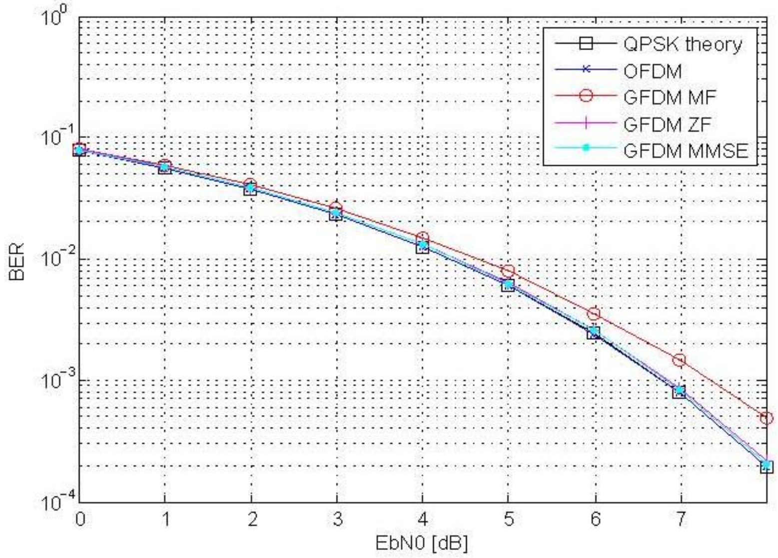
Multi-tier and multi-frequency network architectures including mm-wave overlay

Source: Maziar Nekovee, Samsung Electronic R&D, ISWCS 2013

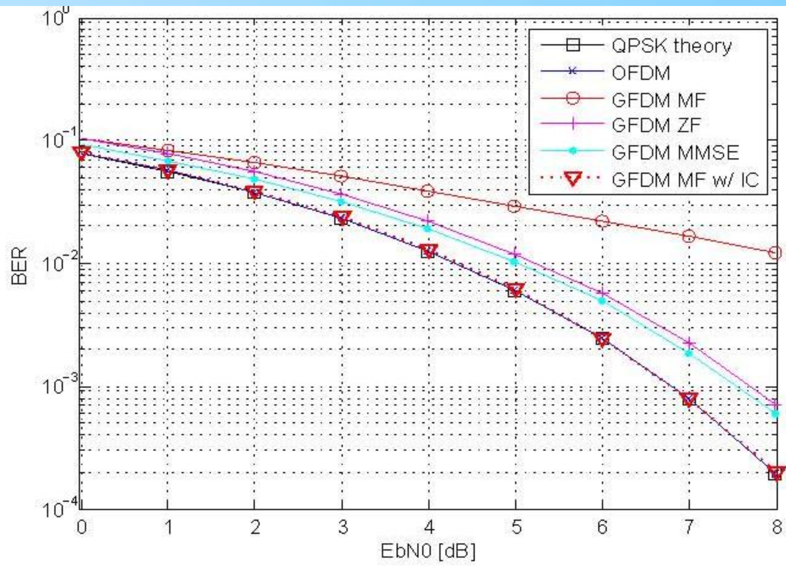
Generalized Frequency Division Multiplexing (GFDM)



Source: 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



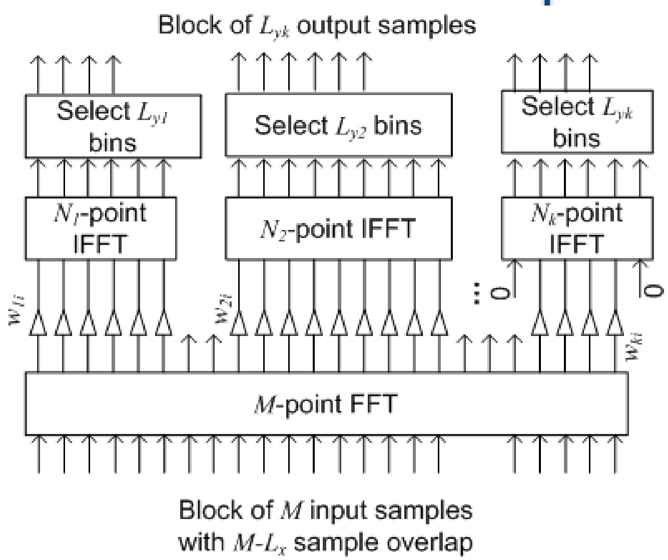
(a) $K = 128,\ M = 5,\ \alpha = 0.1$

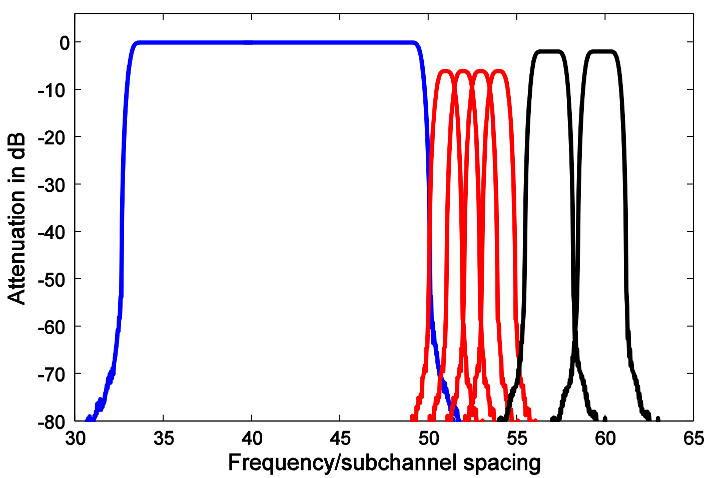


(b) $K = 128,\ M = 5,\ \alpha = 0.5$

Fast convolution based filter bank structure

- Subchannel bandwidth and center defined by the choice of used FFT bins.
- Subchannels may be overlapping
- Decimation factor: $L_x/L_{yk} = M/N_k$
  - Output sampling rate adjustment through additional 0-bins.
- Typically 2x-oversampling in subchannels
  - Consistent with OQAM model and fractionally-spaced equalization model.

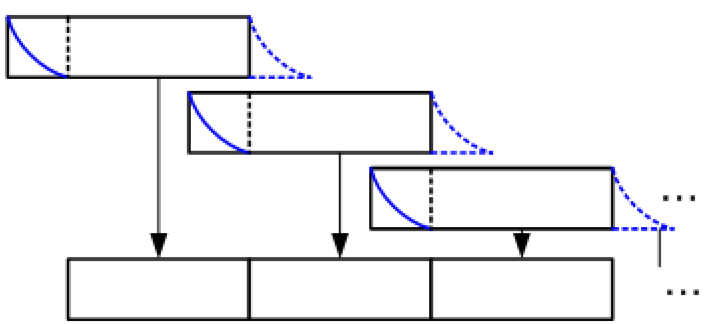


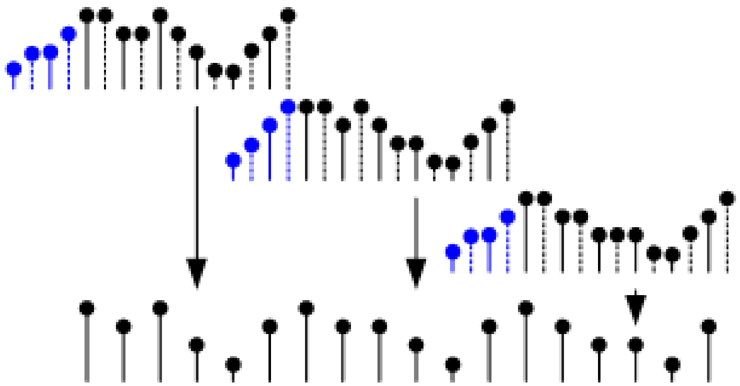


Markku Renfors, Faouzi Bader, Leonardo Baltar, Didier Le Ruyet, Daniel Roviras, Philippe Mege, Martin Haardt, "**On the Use of Filter Bank Based Multicarrier Modulation for Professional Mobile Radio,** " IEEE VTC-Spring 2013, Dresden, Germany.

Solution based on fast convolution

- Fast convolution:
- $$y[n]=c[n] * x[n] = \mathrm{IFFT}(\mathrm{FFT}(c([n]) \cdot \mathrm{FFT}(x([n]))$$
  – Finite block length: $L_y=L_c+L_x-1$
  – Block-wise processing for continuous input sequence
    • Overlap-save (i.e., overlap-dump) preferred over overlap-add





- Multirate fast convolution:
  – Decimation case:

    decimation factor = input block-length/output block-length

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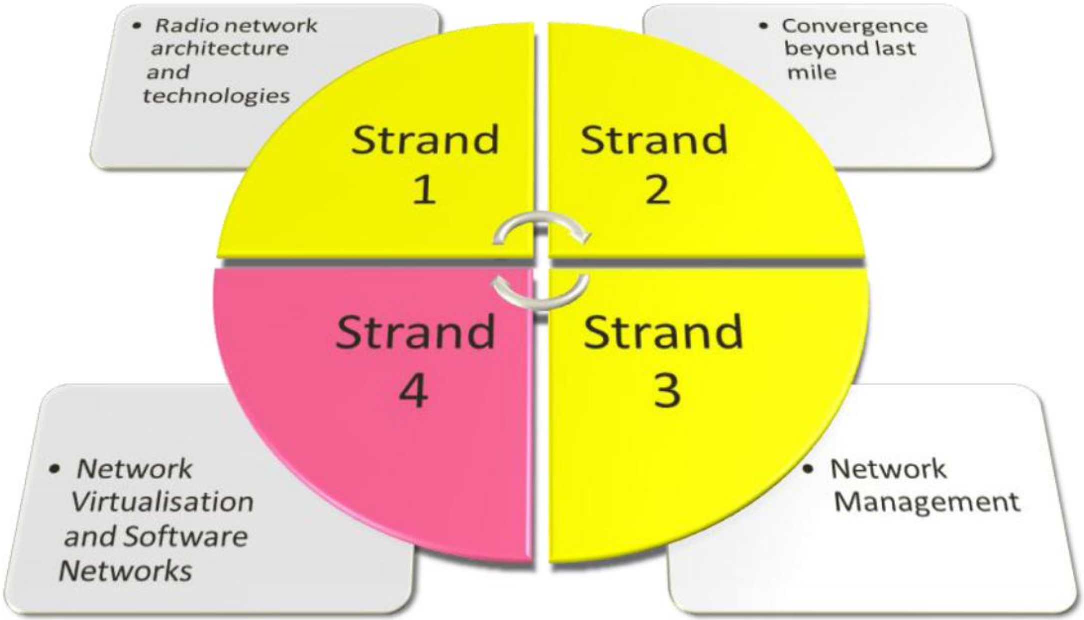
Part IV: 5G Wireless Communication Concept Eco-System

B- EC H2020 5G Infrastructure PPP..

H2020 5G Infrastructure PPP
PPP Pre-structuring Model Approach (4/5)

5G PPP

Pulling Strands Together



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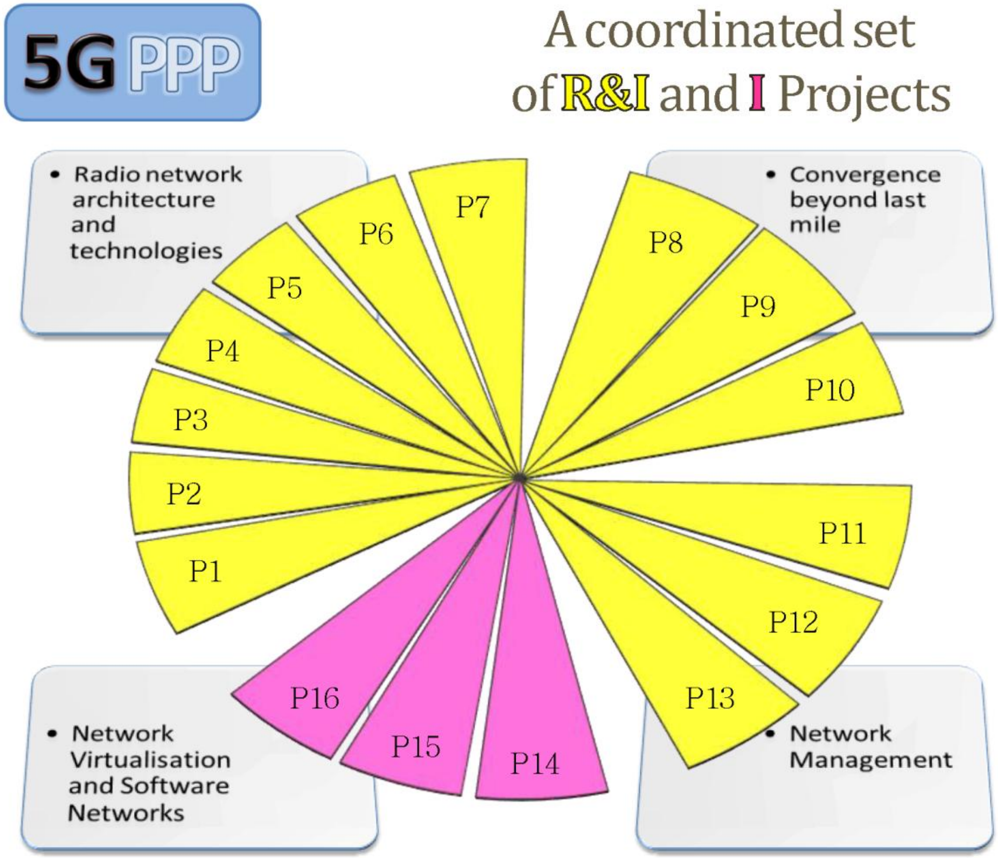
H2020 5G Infrastructure PPP
PPP Pre-structuring Model Approach (5/5)



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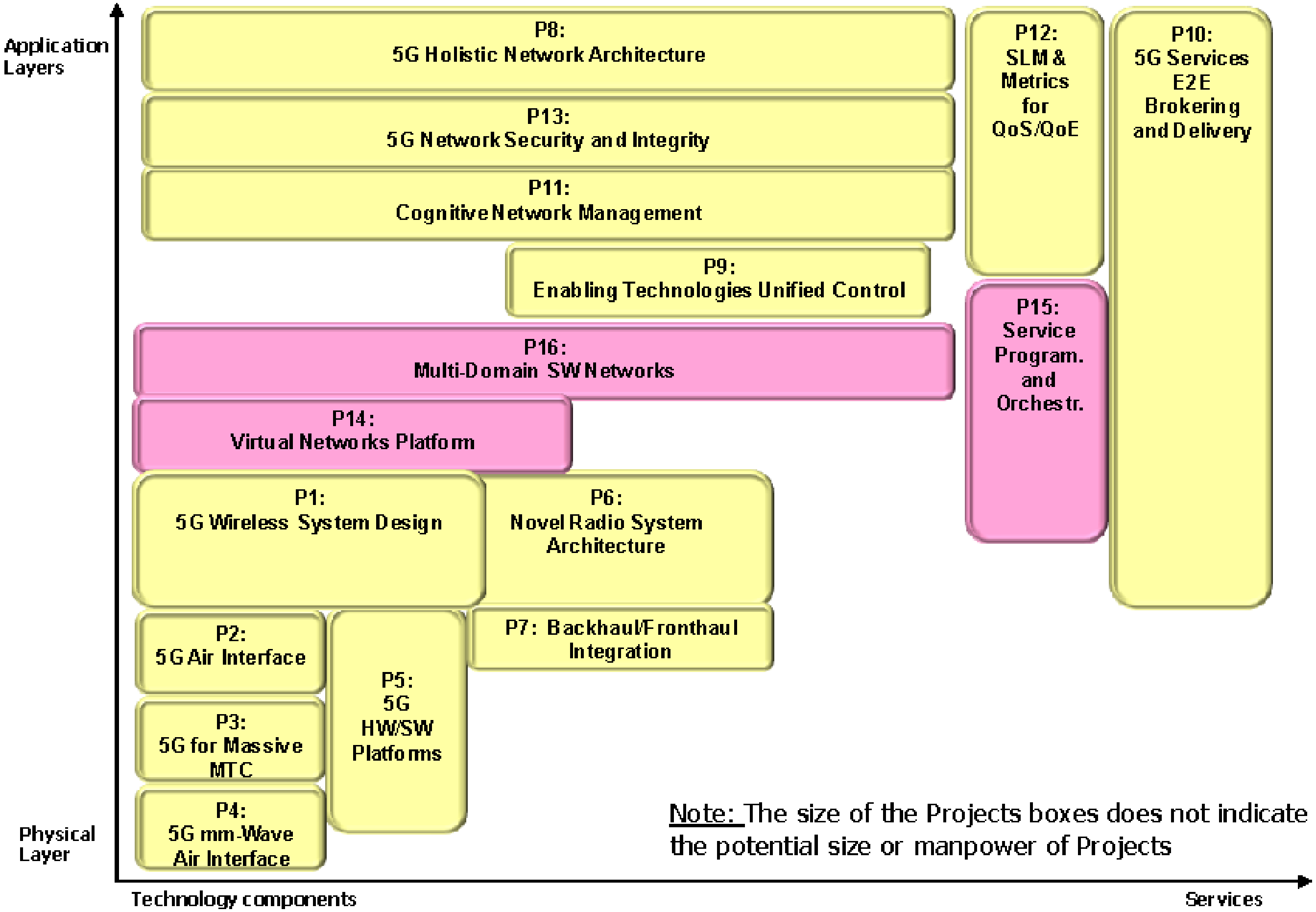
H2020 5G Infrastructure PPP
PPP Pre-structuring Model – System Perspective (2/2)



Note: The size of the Projects boxes does not indicate the potential size or manpower of Projects

8

P1: 5G Wireless System Design

Objective

- Design the 5G wireless system that
  - efficiently meets the large variety of use cases and application requirements beyond 2020
  - builds upon a smooth migration from current technology
  - also considers satellite and broadcast potential

Scope

- Identify and evolve key 5G scenarios and consolidate the requirements for 5G within the 5G-PPP and with external stakeholders
- Design a Multi-RAT system that efficiently integrates legacy and 5G air interfaces
  - Integration of new radio access concepts especially from other 5G PPP project, and exploiting radio access capabilities to address the service requirements
  - Interference, mobility and spectrum management
  - Control- and user-plane design for novel 5G components
  - Moderation of service requirements versus radio access capabilities
  - Integration of innovative spectrum usage concepts (e.g. sharing, pooling…)
- Define an architecture that supports the 5G system concept whilst also making it as RAT agnostic as possible to anticipate future RATs integration
- Ensure overall KPI evaluation by providing an evaluation framework and performing an overall assessment in close collaboration with other 5G-PPP projects
- Tight cooperation with most related/relevant 5G-PPP projects

Expected Impact

- A 5G wireless system that meets the requirements for integrated wireless communications well beyond 2020
- Industrial and global alignments: Preparation of WRC 18 and contribution to the ITU-R 5D evaluation work, preparation of a European headstart in standardization of 5G in e.g. 3GPP
- Demonstrate the key 5G system components

P2: Air Interface and Multi-Antenna, Multi-Service Air Interface below xx GHz

Objective

- To design a highly flexible and adaptable air interface being able to support efficiently
  - the multitude of service classes (from continuous high rate to sporadic low rate and with an option for very low latency) and service types (bi-directional unicast, uni-directional broadcast / multicast)
  - and device types (from high-end tablet to low-end device, incl. Body Area Devices)
  - and MIMO capabilities (in both UE and eNB)
  - in various areal settings (from heterogeneous ultra dense urban setting with cooperation to macro cell dominated rural/remote –land, sea and air areas)
  - with flexible spectrum usage

Scope

- **Scalability, adaptability, flexibility** - to meet temporal and areal fluctuations of active service and device class mixes and to support massive simultaneous network access
- **Energy efficiency** - both for the radio access network and devices
- **Uniform coverage, high capacity** – interference-robustness, adaptability to a wide range of spectrum allocations, high spectral efficiency at minimal control overhead
- **Unified multi-antenna support** - support localized, distributed and co-ordinated multi-antenna systems as an embedded feature in a natural way, and channel models
- **Robustness** – to support very high velocity (high-speed trains and other environments, access and backhaul) and relaxed synchronisation (low-end devices)

Expected Impact

- Enable 5G to support both broadband and machine type transmissions within the same band with high efficiency and at similar costs (devices and energy) compared to dedicated solutions
- Expand the business model and broaden the market of providing wireless services
- Easy implementation under various settings (deployment, carrier frequency …)
- Increased and uniform quality of experience
- Contribution to standardisation bodies

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Conclusions

Main Conclusions

- FBMC, is actually attracting more and more interest from the EC through several research proposals in actual ICT calls
- Clearly, OFDM is not the most efficient physical layer and it is not the best choice for systems that must support sharing/dynamic spectrum access and also for CR.
- Flexible waveforms will play a key role in future systems more and more frequently considered as the natural scheme for HetNet based communication scenarios
- A framework for multi-service communicatio eco-system

Main Conclusions

- Filter based scheme (PHYDYAS) very suitable for narrowband band system coexistence
- Actually pushed/analysed by world wide manufactures (Samsung, Alcatel-Lucent, Orange-Labs, etc.)
- Still open technical challenges are remaining open (PAPR, uniform framework, real time trials, etc)

THANK YOU

FOR YOUR ATTENTION

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Acknowledgements to:

Dr. Michael Fitsh (BT, UK), Dr. Musbah Shaat (CTTC, Spain), Dr. Yahia Medjahdi et al. (UCL, Belgium), Dr. Dominique Noguet (CEA-LETI, France), and Dr. Erdem Bala (InterDigital, USA), and Adrian Kliks (PUT, Poland).

Courses of the 24th Jyväskylä Summer School , August 2014. Finland

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Course on: Beyond OFDM Radio Interfaces Facilitating Spectrum Coexistence and Secondary Access

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Associate Professor
SUPELEC, Rennes-France

Dr. Dmitry Petrov,
MAGISTER Solutions Ltd.

Part 5-1

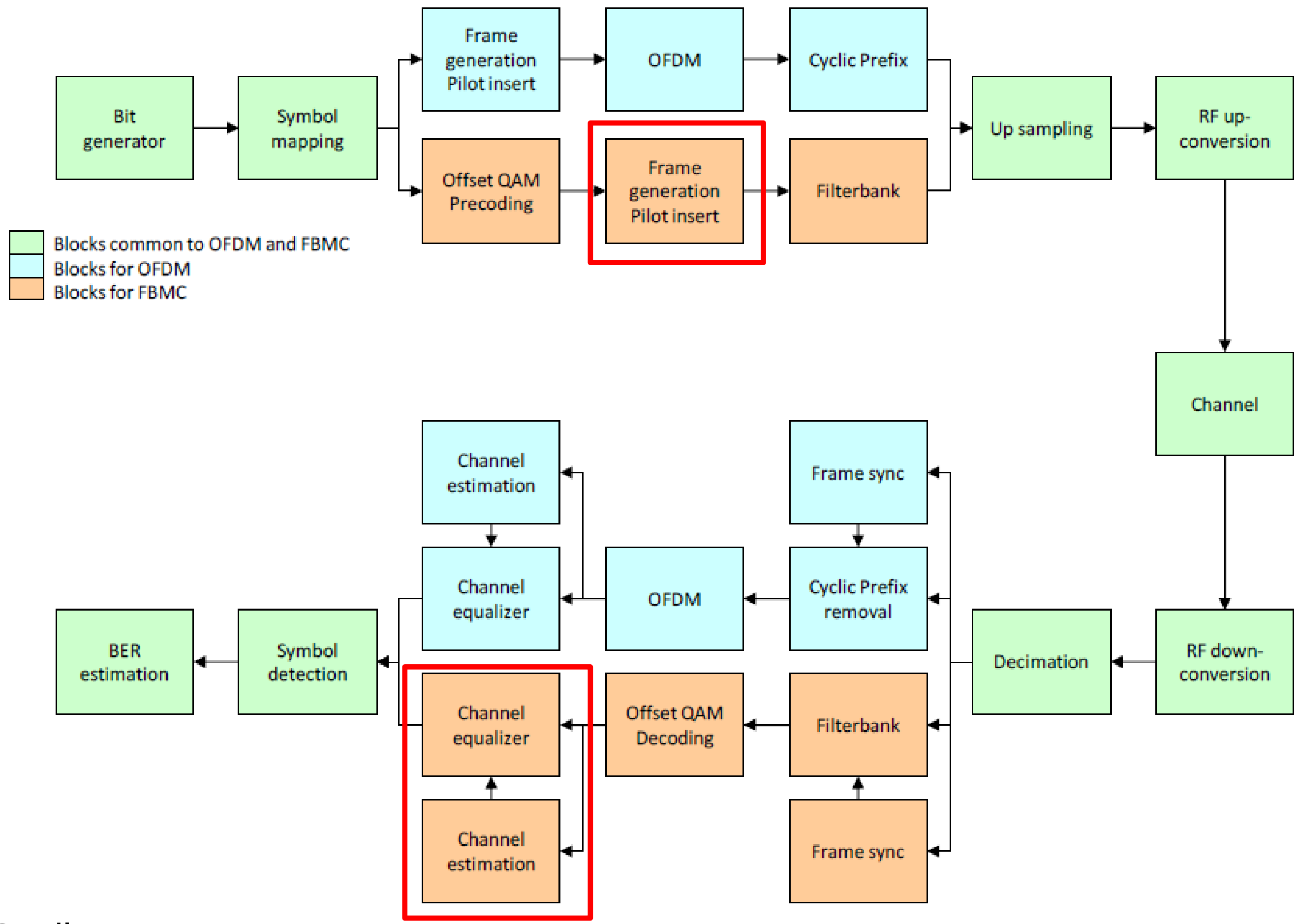
FBMC APPLICATION CHALLENGES

Contents

Introduction

- OFDM dominating technique
- Filter bank multicarrier (FBMC) is a serious competitor:
  - No need for guard intervals
  - Spectral shaping of sub-channels
  - High flexibility
  - At the cost of higher implementation complexity

Block diagram of OFDM/FBMC, SISO case



* ICT-EMPhAtiC Milestone 4

Equalization issues in FBMC

- Channel estimation and pilot structures:
  - equalizer designs are based on the assumption that some channel estimate is available
- Sufficient number of sub-carriers:
  - narrowband, easy equalization <-> complexity
- OQAM demodulation:
  - Avoid interference between real and imaginary parts due to channel selectivity
  - Working at fractional sampling T/2

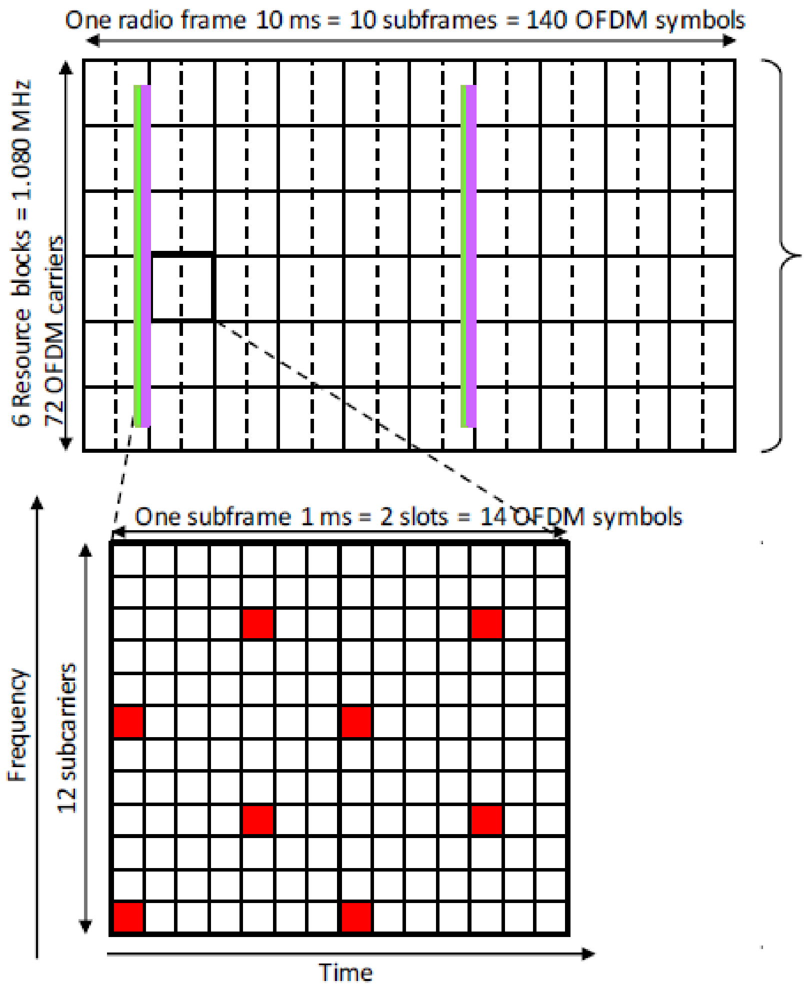
Equalization issues in FBMC (cont.)

- Synchronization:
  - tracking of Channel Frequency Offset (CFO) and symbol timing during transmission

- Multi-user schemes:
  - FBMC allows an easy multi-access schemes by allocation different sets of sub-carriers to different users.

- It is more efficient for all operations to be performed in the **frequency domain** on a per-subcarrier basis in order to take advantage of the selectivity of the filter bank.

Pilot structure in LTE OFDM

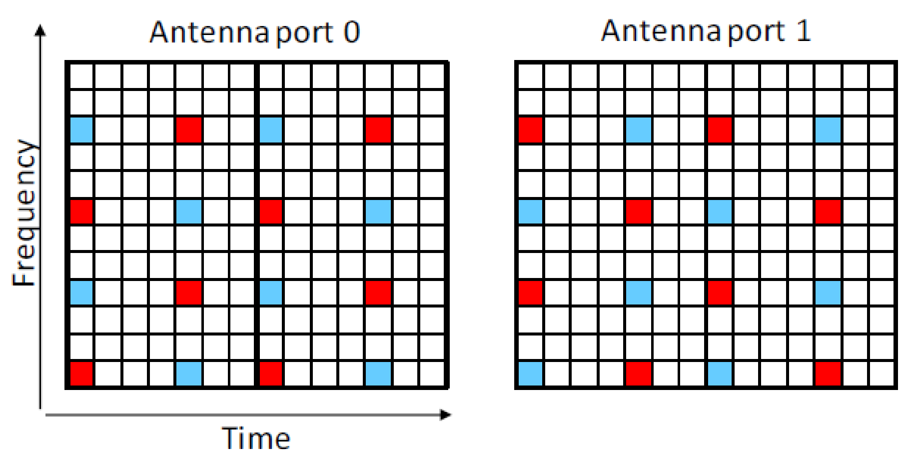


Channel BW is 1.4 MHz

One frame
SSS
PSS

Pilot carrier
Empty carrier

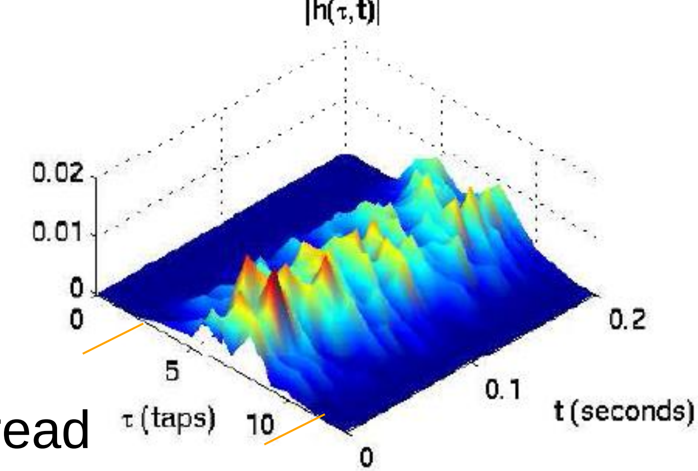
Scattered pilots



One Resource Block (RB) = 1slot x 12sc

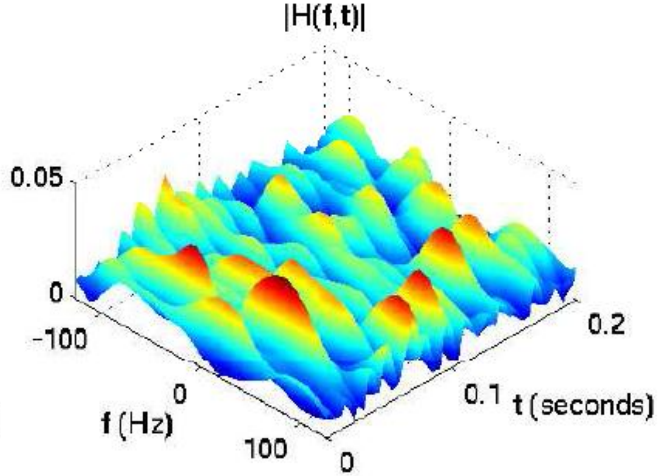
Fading channels

Channel Impulse Response (CIR)



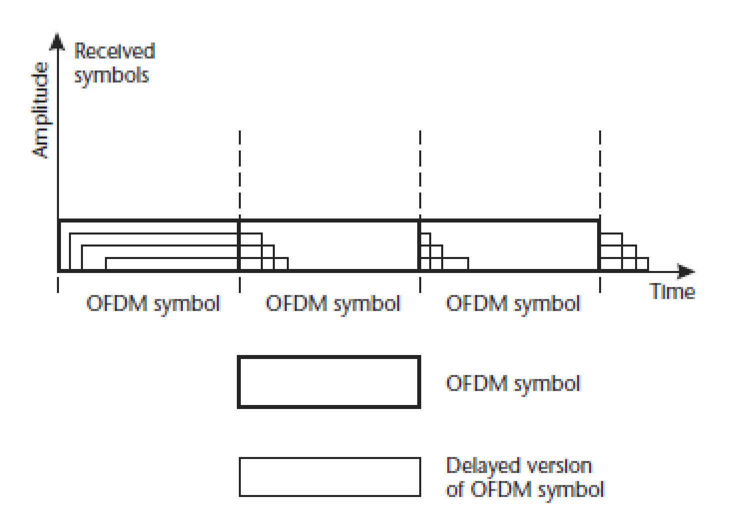
Delay spread

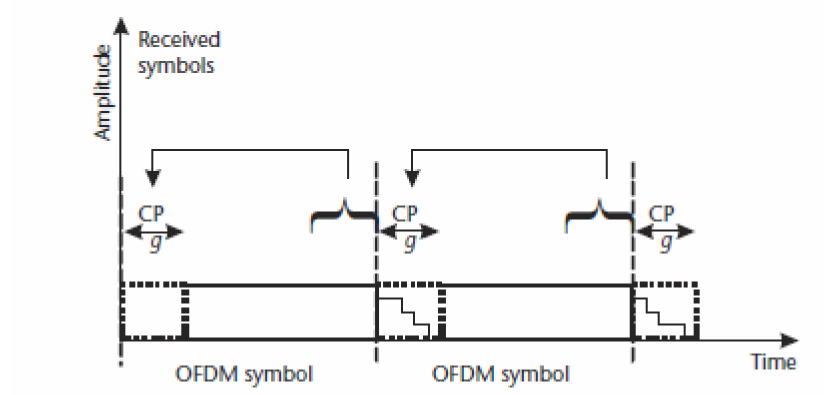
Channel Frequency Response (CFR)



- Quasy-static channel $\mathrm{H}[l, m] = H[m]$;
- Finite dealy spread $\boldsymbol{h} = [h(0)\ h(1) \ldots h\ (I-1)]$
- Approximately flat channel, if sub-carrier bandwidth is much less than the coherence bandwidth.

Channel estimation in OFDM





- Received signal: $y[n] = h[l,i] * s[n] + \eta[n]$,
- Slow fading channel: $y_{wn}[n] = h[i] * s[n]$,

$$Y_{wn}[m] = S[m]H[m] \rightarrow \widehat{H}[m] = H[m] + N[m]/S[m].$$

FBMC signal

- Rx signal: $y[n] = \sum_{i=0}^{I-1} s[i-n]h[i] + \eta[n]$

- Tx signal: $s[n] = \sum_{m=0}^{M-1} \sum_{l} d_{m,l} g_{m,l}[n]$,

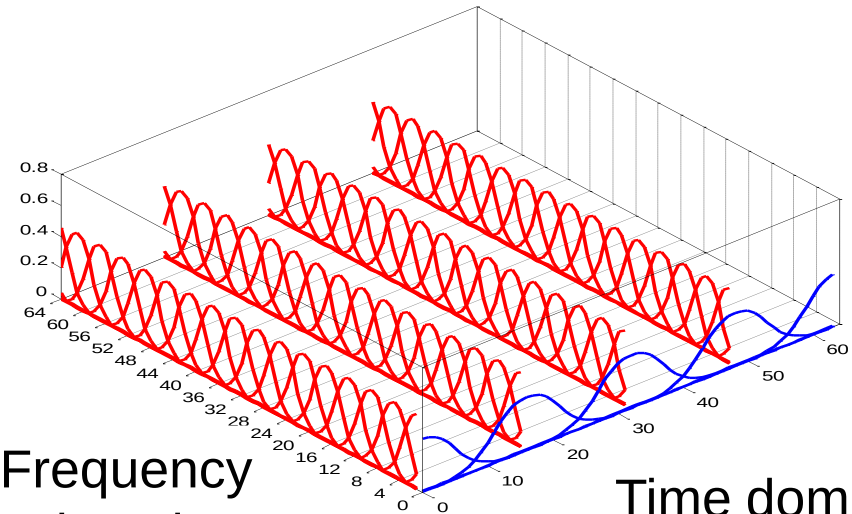
$$g_{m,l}[n] = g\left[n - l\frac{M}{2}\right] e^{j\frac{2\pi}{M}m\left(n-\frac{N-1}{2}\right)} e^{j\varphi_{m,l}},$$

$$N = \mathrm{M} \cdot L, \varphi_{m,l} = \tfrac{\pi}{2}(m+l) - ml\pi$$

- Real orthogonality of sub-carrier functions:

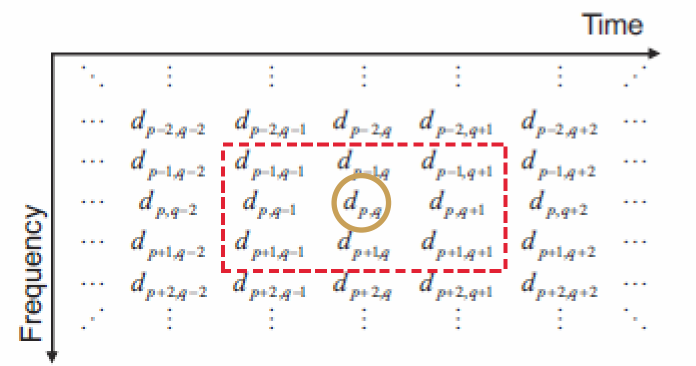
$$Re\underbrace{\left\{\sum_{n} g_{m,l}[n] g_{p,q}^{*}[n]\right\}}_{= j\langle g\rangle_{m,n}^{p,q}} = \delta_{m,p}\delta_{l,q}$$

FBMC signal structure



Frequency domain

Time domain



Neighborhood $\Omega_{p,q}$

- Overlapping in Time Domain, no CP
- Real orthogonality
- Nearly Perfect Reconstruction (NPR) FBs

- **Result:** there is always **intristic interference** (complex ICI and ISI even in the absence of channel distirotion and noise)

FBMC interference

- Analysis Filter Bank (AFB) output at the p-th subcarrier and q-th FBMC symbol:

CFR

$$y_{p,q} = H_{p,q} d_{p,q} + \underbrace{\sum_{m=0,(m,l)\neq(p,q)}^{M-1} \sum_{l} H_{m,l}\, d_{m,l} \langle g \rangle_{m,l}^{p,q}}_{= I_{p,q}} + \eta_{p,q}$$

Interference

Gaussian, noise

0	0.0006	-0.0001	0	0	0	-0.0001	0.0006	0
0.0054	- 0.0429i	-0.1250	0.2058i	0.2393	- 0.2058i	-0.1250	- 0.0429i	0.0054
0	-0.0668	0.0002	0.5644	1.0000	0.5644	0.0002	-0.0668	0
0.0054	0.0429i	-0.1250	- 0.2058i	0.2393	0.2058i	-0.1250	0.0429i	0.0054
0	0.0006	-0.0001	0	0	0	-0.0001	0.0006	0

OFDM-like channel estimation

- Constant CFR and negligible interference outside $\Omega_{p,q}$:

$$y_{p,q} \approx H_{p,q} c_{p,q} + \eta_{p,q},$$

Interference

$$c_{p,q} = d_{p,q} + \sum_{(m,l)\in\Omega_{p,q}} d_{m,l} \langle g \rangle_{m,l}^{p,q} = d_{p,q} + j u_{p,q}$$

Pilot

Virtually transmitter symbol

Unknown data

- If $c_{p,q}$ **can be approximated -> pseudo pilot:**

$$\hat{H}_{p,q} = \frac{y_{p,q}}{c_{p,q}} \approx H_{p,q} + \frac{\eta_{p,q}}{c_{p,q}}$$

IAM

MIMO case

- For j-th of N_r receive antenna:

$$y_{p,q}^{j} \approx \sum_{i=1}^{N_t} H_{p,q}^{j,i} c_{p,q}^{i} + \eta_{p,q}^{j},$$

M-point CFR from i-th TX to j-th RX antenna:

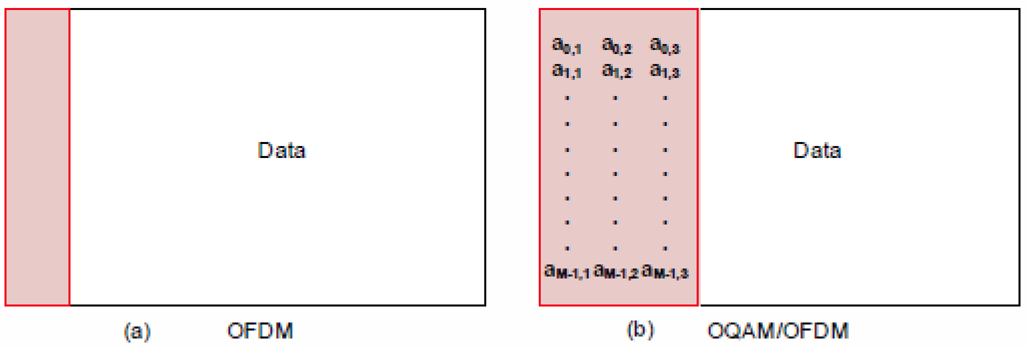
$$\boldsymbol{H}_{p,q} = \begin{bmatrix} H_{p,q}^{1,1} & H_{p,q}^{1,2} & \cdots & H_{p,q}^{1,N_r} \\ H_{p,q}^{2,1} & H_{p,q}^{2,2} & \cdots & H_{p,q}^{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ H_{p,q}^{N_r,1} & H_{p,q}^{N_r,2} & \cdots & H_{p,q}^{N_r,N_t} \end{bmatrix}$$

- In each FT point for MIMO-FBMC we get:

$$\boldsymbol{y}_{p,q} \approx \boldsymbol{H}_{p,q}\boldsymbol{c}_{p,q} + \boldsymbol{\eta}_{p,q}, \qquad \boldsymbol{c}_{p,q} = \boldsymbol{d}_{p,q} + \jmath \boldsymbol{u}_{p,q}, \quad \boldsymbol{d}_{p,q} = \begin{bmatrix} d_{p,q}^{1} & d_{p,q}^{2} & \cdots & d_{p,q}^{N_t} \end{bmatrix}^T$$

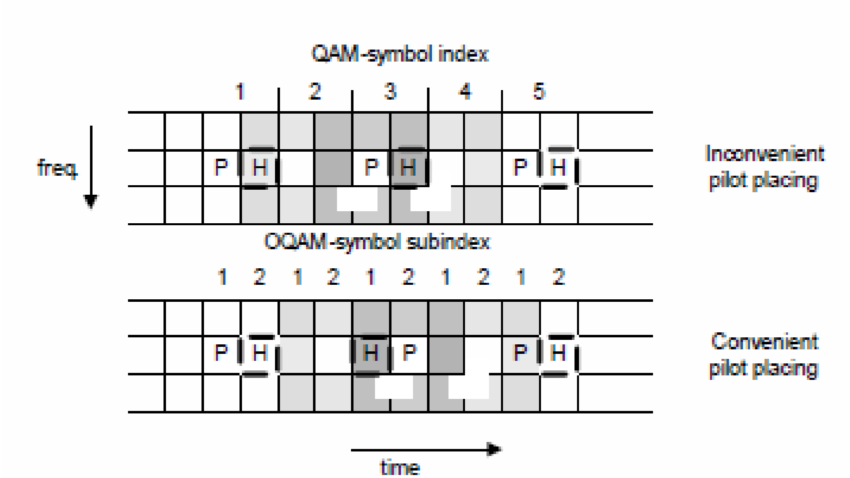
Channel estimation in FBMC

- Data-aided methods, based on on known transmitted symbols (pilots or preamble)
- Due to OQAM use of pilots is not that straightforward as in OFDM.
- Methods:
  - Auxiliary pilot scheme (scattered pilots)
  - Preamble-based schemes



*Katselis, D., Kofidis, E., Rontogiannis, A., & Theodoridis, S. (2010). Preamble-based channel estimation for CP-OFDM and OFDM/OQAM systems: a comparative study. *Signal Processing, IEEE Transactions on*, *58*(5), 2911-2916.

Auxiliary pilot scheme



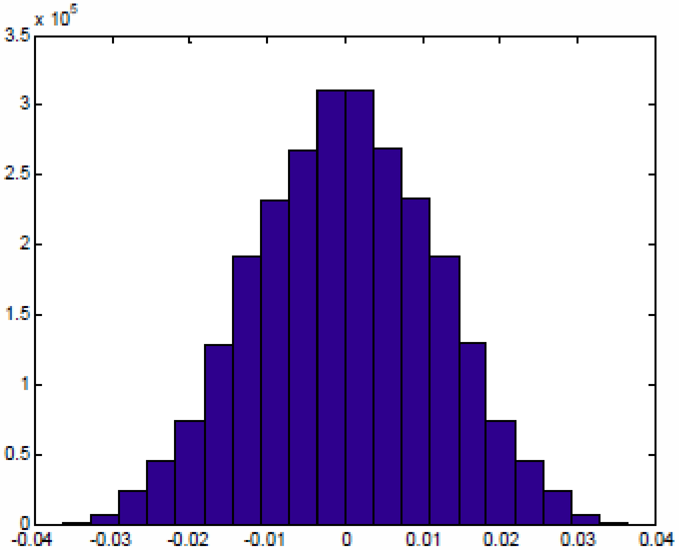
0	0.0006	-0.0001	0	0	0	-0.0001	0.0006	0
0.0054	- 0.0429i	-0.1250	0.2058i	0.2393	- 0.2058i	-0.1250	- 0.0429i	0.0054
0	-0.0668	0.0002	0.5644	1.0000	0.5644	0.0002	-0.0668	0
0.0054	0.0429i	-0.1250	- 0.2058i	0.2393	0.2058i	-0.1250	0.0429i	0.0054
0	0.0006	-0.0001	0	0	0	-0.0001	0.0006	0

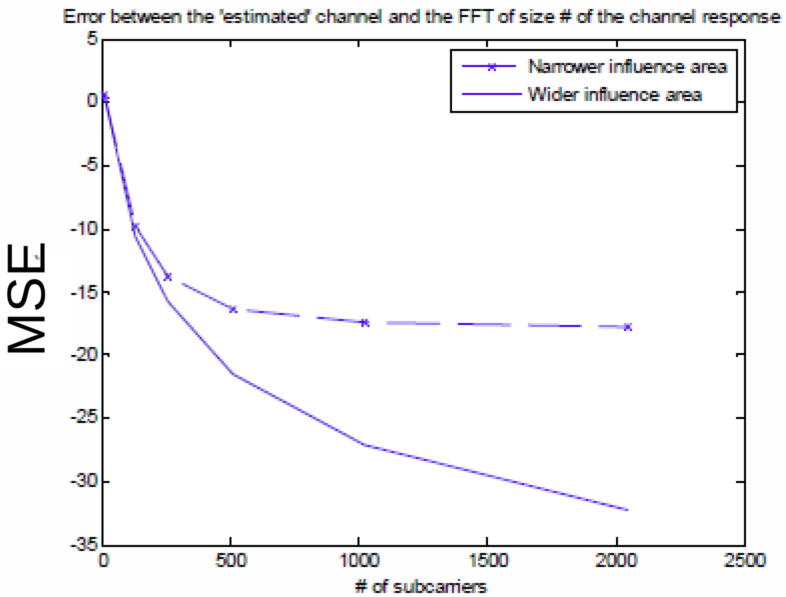
- Auxiliary pilot at position (p_a, q_a) is selected to zero-out interference in pilot (p_p, q_p) :

$$d_{p_a,q_a} = -\frac{\sum_{(m,l)\in\Omega_{p_p,q_p};(m,l)\neq p_a,q_a} d_{m,l}\langle g\rangle_{m,l}^{p_p,q_p}}{\langle g\rangle_{p_a,q_a}^{p_p,q_p}}$$

Maximize

Effect of wider window



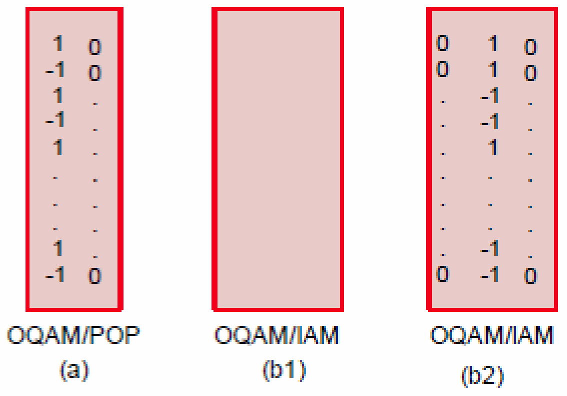


Residual pilot interference

* PHYDYAS Deliverable D.3.1

Preamble-based channel estimation methods

- Pair of Pilots (POP)
  simple algebraic relations for the input/output samples in a consecutive time instants.
- Interference Approximation Method (IAM)
  approximating the intrinsic imaginary interference from neighboring pilots
- Cancelling or avoiding interference



Pair of Pilots (POP) method

- Consecutive time intervals $l_1 = 0, l_2 = 1$:

$$\frac{y_{m,0}}{H_{m,0}} = d_{m,0} + ju_{m,0},$$
$$\frac{y_{m,1}}{H_{m,1}} = d_{m,1} + ju_{m,1}.$$

- Assume that $H_{m,0} \approx H_{m,1}$:

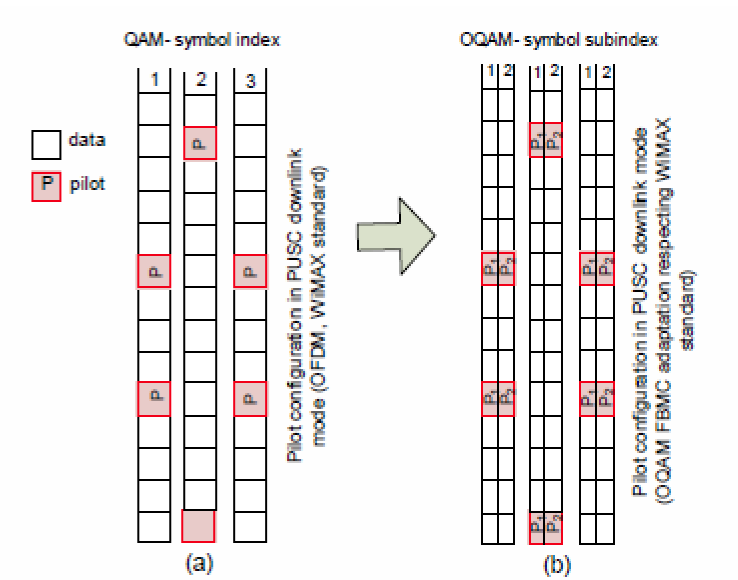
$$\begin{bmatrix} \Re y_{m,0} & -\Im y_{m,0} \\ \Im y_{m,1} & \Re y_{m,1} \end{bmatrix} \begin{bmatrix} \Re \frac{1}{H_{m,0}} \\ \Im \frac{1}{H_{m,0}} \end{bmatrix} = \begin{bmatrix} d_{m,0} \\ d_{m,1} \end{bmatrix}$$

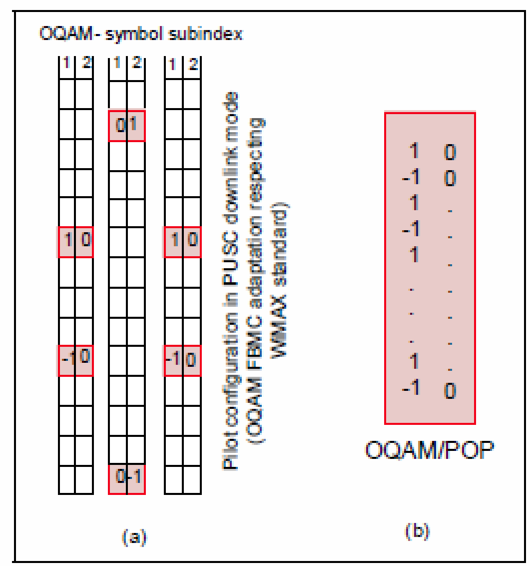
- Let $d_{m,1} = 0$ and for even k, $d_{m,0} = 1$:

$$H_{m,0} = \frac{\Re(y_{m,0} y_{k,1}^*)}{y_{k,1}^*}$$

POP method (cont.)

- Simplicity
- Overhead is similar to that used in CP-OFDM
- No dependence on the prototype filter
- Only holds, when noise is neglected





Interference Approximation (IAM)

- All symbols in the neighborhood should be known
- Interfering weights from neighboring TF can be pre-calulated
- 1.5 complex symbols are required for training
- Channel estimation:

$$\widehat{H}_{k,l} = H_{k,l} + \frac{\eta_{k,l}}{d_{k,l} + ju_{k,l}} \longrightarrow \text{max}$$

- Pseudo-pilots should minimize the effect if the noise term

$$\begin{array}{ccc}
(-1)^p\epsilon & 0 & -(-1)^p\epsilon \\
(-1)^p\delta & -\beta & (-1)^p\delta \\
-(-1)^p\gamma & d_{p,q} & (-1)^p\gamma \\
(-1)^p\delta & \beta & (-1)^p\delta \\
(-1)^p\epsilon & 0 & -(-1)^p\epsilon
\end{array}$$

IAM schemes

- Selection of pseudo-pilots with guard symbols:
  - **IAM-R**: nulls at the 1st and 3rd symbols of the preamble
  - **IAM-I**: imaginary pseudo-pilots will give bigger magnitude in the delimiter: $\left|d_{p,1} + u_{p,1}\right|$
  - **IAM-C**: combination of IAM-R and IAM-I.
- Optimal preambles:
  - Extended IAM-C (E-IAM-C): sparse and full.

$$
\begin{array}{ccc|ccc|ccc|ccc|ccc}
0 & 1 & 0 & 0 & d_0 & 0 & 0 & 1 & 0 & \jmath & 1 & -\jmath & -1 & 1 & 1 \\
0 & -1 & 0 & 0 & -\jmath d_0 & 0 & 0 & -\jmath & 0 & -1 & -\jmath & 1 & -\jmath & -\jmath & \jmath \\
0 & -1 & 0 & 0 & -d_0 & 0 & 0 & -1 & 0 & -\jmath & -1 & \jmath & -1 & -1 & 1 \\
0 & 1 & 0 & 0 & -d_1 & 0 & 0 & \jmath & 0 & 1 & \jmath & -1 & -\jmath & \jmath & \jmath \\
0 & 1 & 0 & 0 & \jmath d_1 & 0 & 0 & 1 & 0 & \jmath & 1 & -\jmath & -1 & 1 & 1 \\
0 & -1 & 0 & 0 & d_1 & 0 & 0 & -\jmath & 0 & -1 & -\jmath & 1 & -\jmath & -\jmath & \jmath \\
0 & -1 & 0 & 0 & -d_0 & 0 & 0 & -1 & 0 & -\jmath & -1 & \jmath & -1 & -1 & 1 \\
0 & 1 & 0 & 0 & \jmath d_0 & 0 & 0 & \jmath & 0 & 1 & \jmath & -1 & -\jmath & \jmath & \jmath
\end{array}
$$

Interference cancellation/avoidance methods

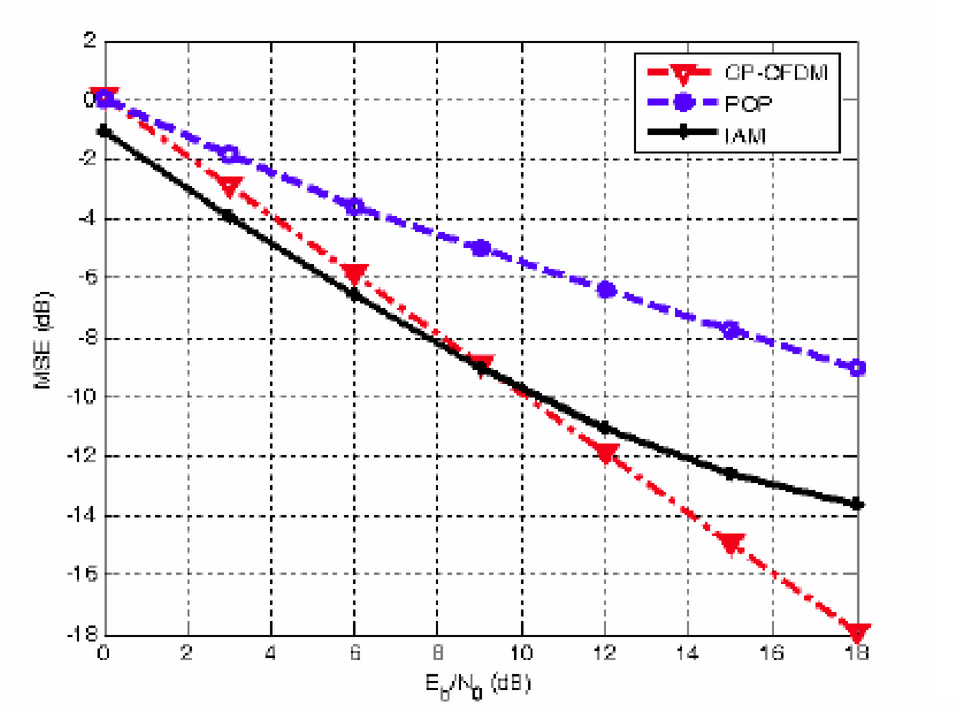
- Direct: null the data surrounding the pilots
- Use symmetries in interference of the area
- Consider firs-order neighbors and cancel interference from them in pairs (more spectral efficiency)

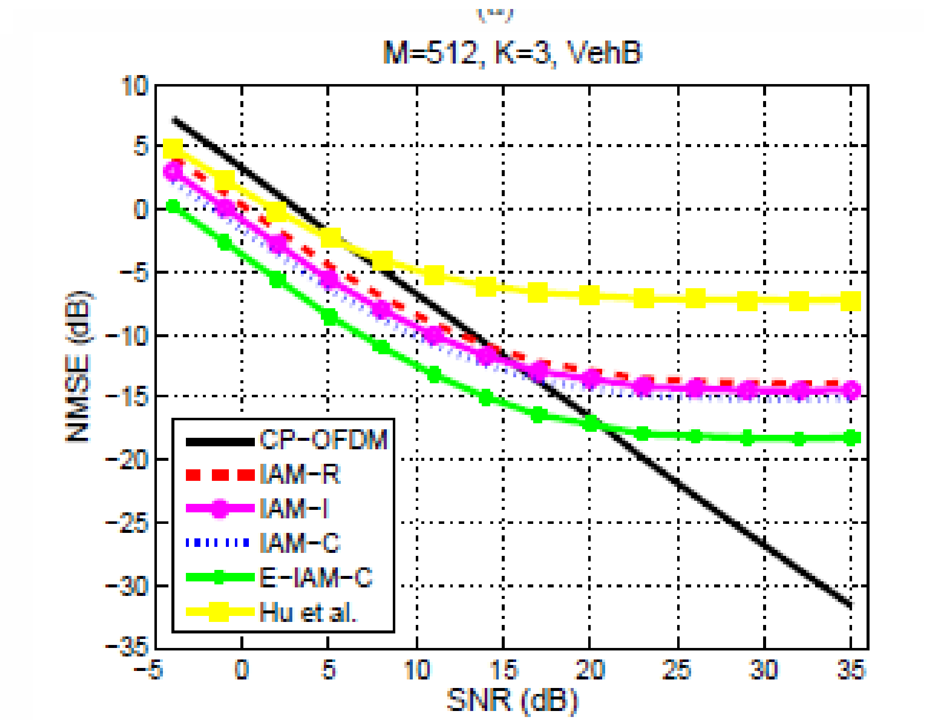
$$\begin{array}{ccc} a & b & c \\ d & \times & d \\ -a & b & -c \end{array}$$

- Iterative methods:
  - in each iteration the available channel estimate is used to approximate the surrounding data and vice versa

$$\begin{array}{ccc|ccc|ccc|c}
0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & -1 & 0 & -1 & -1 & -1 & -1 \\
0 & -1 & 0 & 0 & 1 & 0 & -1 & 1 & -1 & 1 \\
0 & 0 & 0 & 0 & -1 & 0 & 1 & -1 & 1 & -1 \\
0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & -1 & 0 & -1 & -1 & -1 & -1 \\
0 & -1 & 0 & 0 & 1 & 0 & -1 & 1 & -1 & 1 \\
0 & 0 & 0 & 0 & -1 & 0 & 1 & -1 & 1 & -1
\end{array}$$

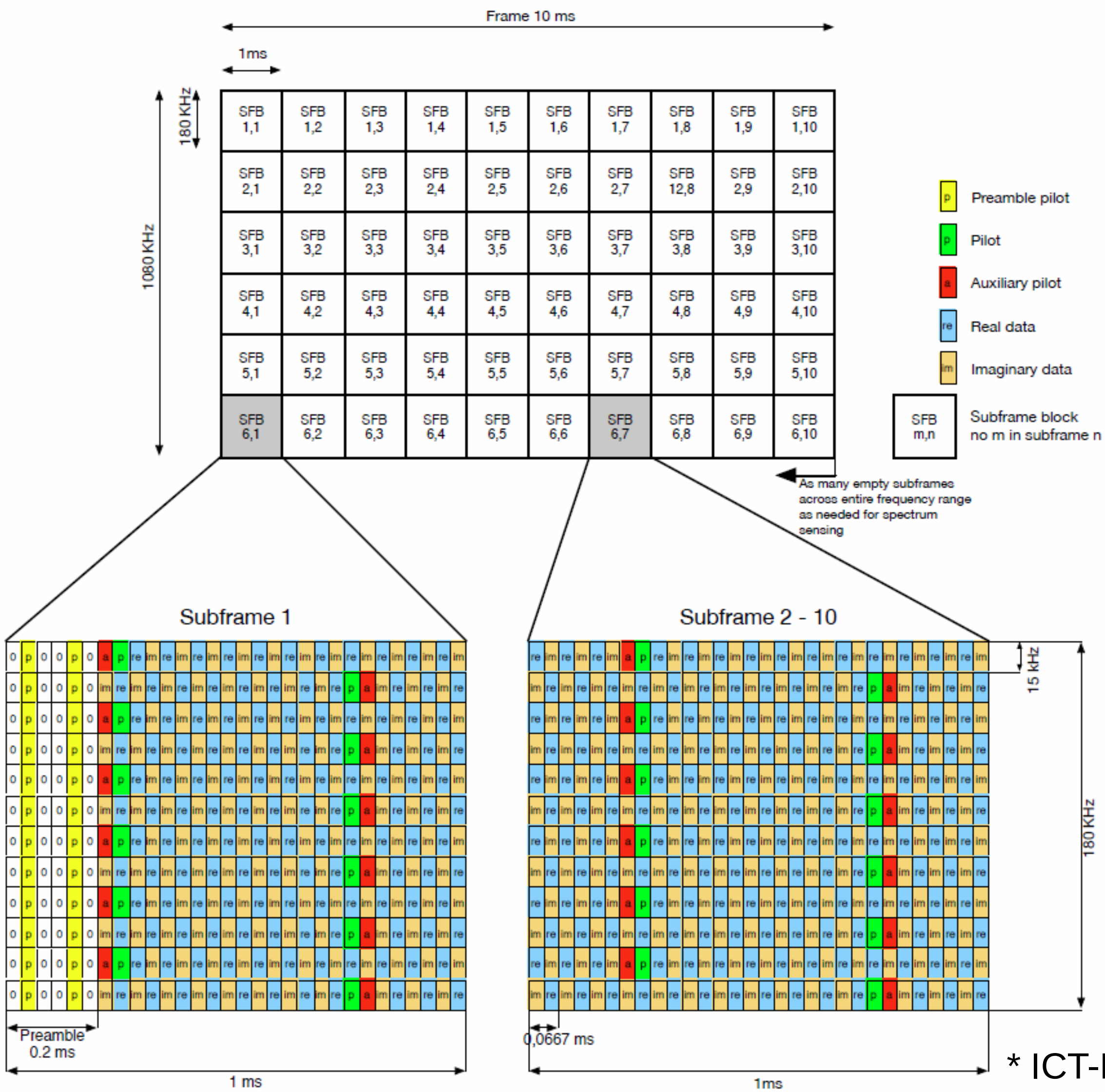
Simulation results





* PHYDYAS Deliverable D.3.1

FBMC frame structure



* ICT-EMPhAtiC Milestone 10

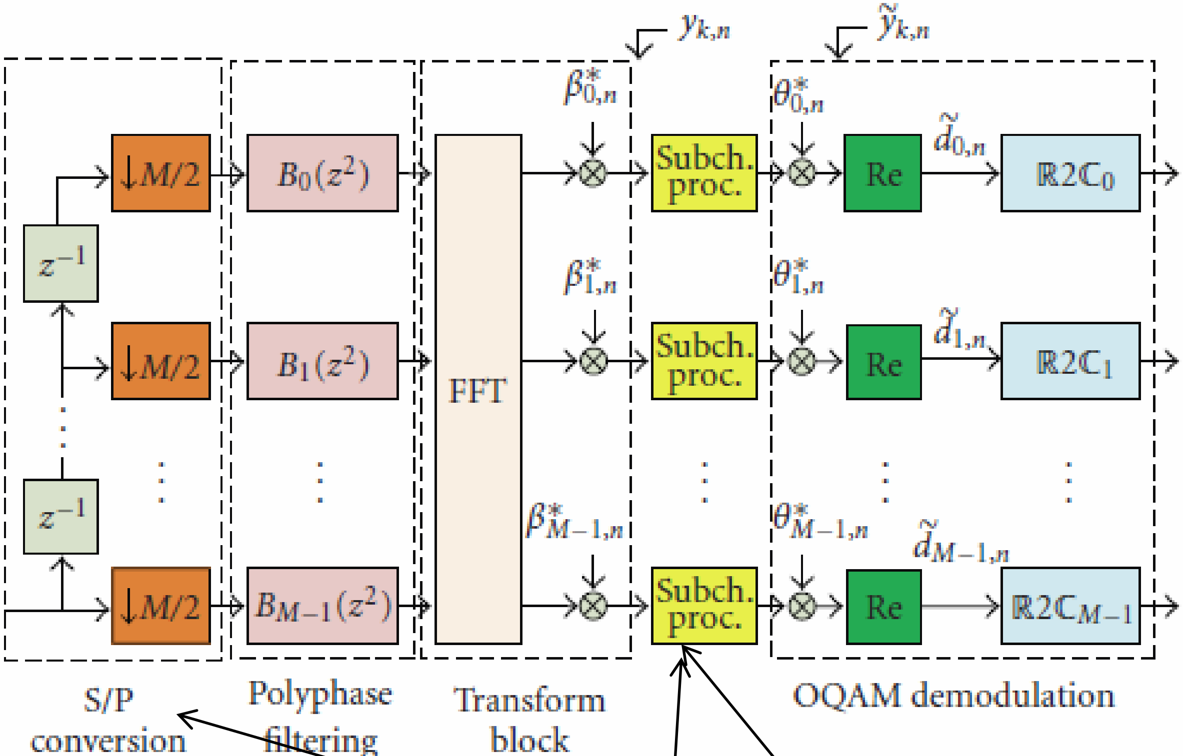
Interpolation

- Most of the methods used for the classical OFDM system are also valid for OQAM-FBMC systems
- Optimum interpolation is determined by the channel statistics (delay profile and Doppler frequency, but difficult to obtain)
- 2D Wiener filter is optimal 2D linear channel estimator (in terms of MSE)
  - Based on statistics properties of the channel
  - Large computational complexity
- Separable filters (use of two 1D filters)

Equalization

- In OFDM channel delay spread and sync errors are behind CP. -> Equalization is just complex coefficients multiplication at sub-carrier level.
- In FBMC this can be used only in flat channel.
- More effective channel equalization methods has to be developed for FBMC.

FBMC transmultiplexer (TMUX)



Sub-channel processing

Received signal for <u>“flat” </u>channel at rate 2/T: Transmultiplexer response

$$y_{k,n} = H_k \sum_{n'=-\infty}^{\infty} \sum_{k'=k-1}^{k+1} d_{k',n'} \theta_{k',n'} t_{k-k',n-n'} + \eta_k[n] = H_k \theta_{k,n}(d_{k,n} + j u_{k,n}) + \eta_k[n]$$

OQAM interference, ISI+ICI

Per-subcarrier equalization

- Channel knowledge (perfect) at the receiver is assumed
- Particularities:
  - Acts independently on each sub-carrier and may take into account the effect of adjacent sub-carriers
  - Less complex to compute
- Alternatives:
  - Multi-band: very small gain
  - Pre-equalizer before analysis bank: very small gain and less versatile

- References:

  - ICT-EMPhAtiC Milestone 7 “Available algorithms for synchronization and channel estimation”
  - Jerome Louveaux, “Equalization in FBMC/OQAM” on Newcom Summer School. May 2014.
  - Stitz, Tobias Hidalgo, et al. "Pilot-based synchronization and equalization in filter bank multicarrier communications." EURASIP Journal on Advances in Signal Processing 2010 (2010): 9.

Virtual complex model

- Assume that $z_{k,n} = d_{k,n} + ju_{k,n}$ was sent
- Compute equalizer as if to recover full complex $z_{k,n}$
- Then take real part (perfect case)

- Usual equalization methods based on complex symbols can be applied
- Efficient for mildly selective channels
- Rejects interference on imaginary part (only)

Example: one-tap equalizer

- Flat fading assumption:

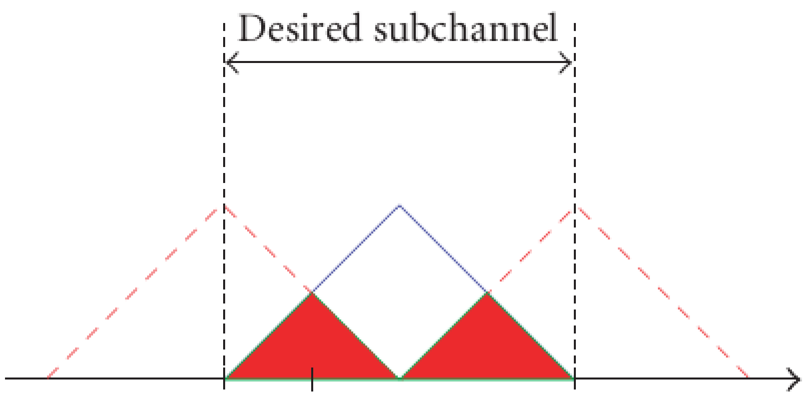
$$y_{k,n} = H_k \theta_{k,n} \left(d_{k,n} + j u_{k,n} \right) + \eta_k[n]$$

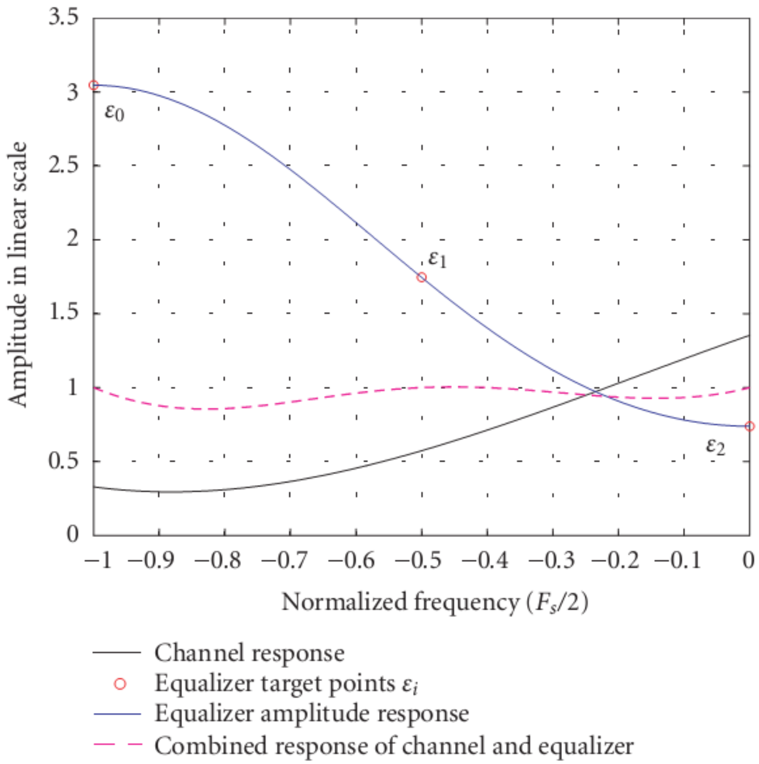
- Usually Zero-forcing:

$$w_k = \frac{1}{H_k} \longleftarrow \text{Equalization coefficient}$$

$$\tilde{d}_{k,n} = \mathrm{Re}\{\theta^*{}_{k,n} w_k y_{k,n}\} = d_{k,n} + \text{noise}$$

Frequency sampling (interpolation)





1. Estimate channel at L points in sub-carrier band-width (**L – number of taps**)
2. Compute equalizer values at these points

- T. Ihalainen, T. Hidalgo Stitz, M. Rinne, and M. Renfors, "Channel equalization in filter bank basedmulticarrier modulation for wireless communications," EURASIP Journal on Advances in Signal Processing, vol. 2007, pp. Article ID 49 389, 2007.

3-tap equalizer example

- Channel is measured on the frequency grid of 2M points
- For sub-carrier k: 3 channel measurements

$$\widehat{H}_k^{(-1)}, \widehat{H}_k^{(0)}, \widehat{H}_k^{(1)} \text{ at } f_k - \frac{1}{2T}, f_k, f_k + \frac{1}{2T}$$

- Desired equalizer values (Zero-forcing):

$$\chi_{k,i} = \frac{1}{\widehat{H}_k^{(i)}} = \frac{\widehat{H}_k^{(i)*}}{\left|\widehat{H}_k^{(i)}\right|^2}$$

- 3 equalizer coefficients $\omega_k(-1)$, $\omega_k(0)$, $\omega_k(1)$
- The transfer function of 3-tap FIR:

$$W_k(z) = \omega_k(-1)z + \omega_k(0) + \omega_k(1)z^{-1}$$

3-tap example (cont.)

- Force equalizer frequency response at normalized frequencies $-\frac{\pi}{2}, 0, \frac{\pi}{2}$

$$
\begin{aligned}
W_k(e^{-j\frac{\pi}{2}}) &= -jw_k(-1) + w_k(0) + jw_k(1) = \chi_{k,-1} \\
W_k(e^{-j0}) &= w_k(-1) + w_k(0) + w_k(1) = \chi_{k,0} \\
W_k(e^{j\frac{\pi}{2}}) &= jw_k(-1) + w_k(0) - jw_k(1) = \chi_{k,1}
\end{aligned}
$$

- Solve the linear system of equations
- Solution:

$$
\begin{aligned}
w_k(-1) &= \frac{-\chi_{k,-1}(1-j) + 2\chi_{k,0} - \chi_{k,1}(1+j)}{4} \\
w_k(0) &= \frac{\chi_{k,-1} + \chi_{k,1}}{2} \\
w_k(1) &= \frac{-\chi_{k,-1}(1+j) + 2\chi_{k,0} - \chi_{k,1}(1-j)}{4}
\end{aligned}
$$

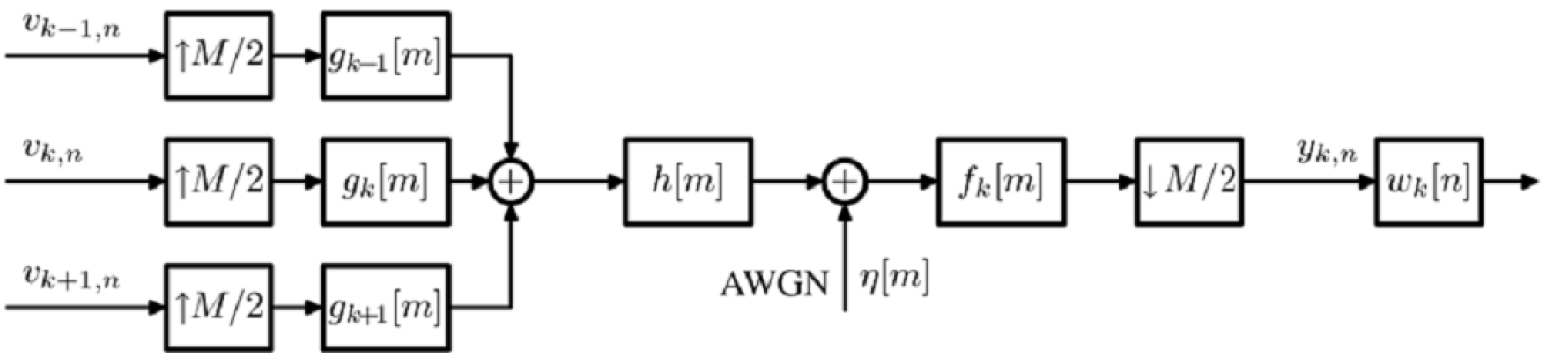
3-tap example (conclusions)

- Very low complexity of 1, 2, 3 taps
- Approximate -> not efficient for highly selective channels
- MSE can be used instead of Zero forcing:

$$\chi_{k,i} = \frac{\widehat{H}_k^{(i)*}}{\left|\widehat{H}_k^{(i)}\right|^2 + \eta}$$

Factor, depending on SNR

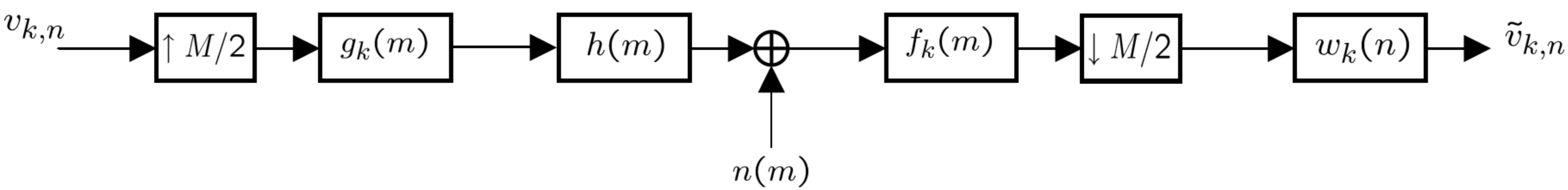
MMSE equalizer



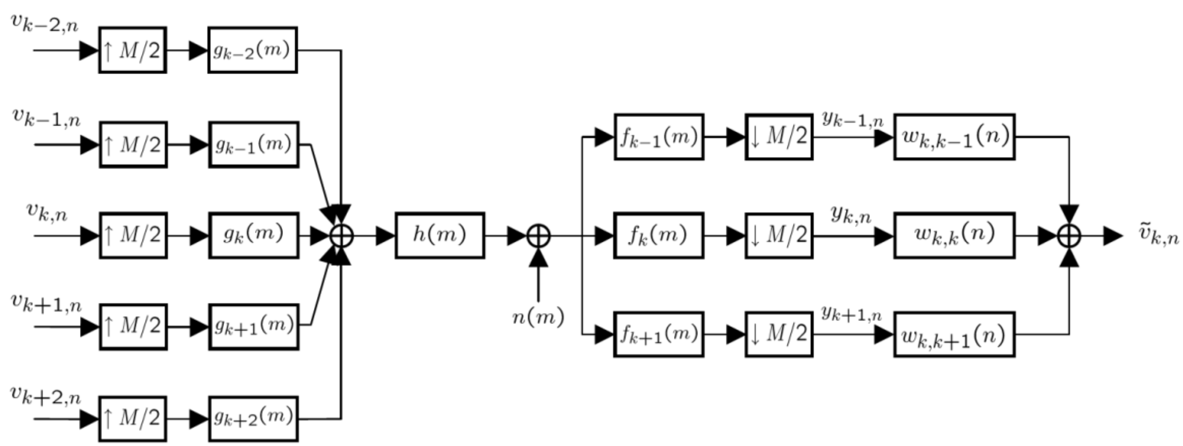
- Not based on virtual complex model
- Takes into account OQAM structure
- Tries to recover real symbols $d_{k,n}$
- Fractional sampling rate
- Considers all possible interferers: current + 2 adjacent sub-carriers

D. Waldhauser, L. Baltar, and J. Nossek, "MMSE subcarrier equalization for lter bank based multicarrier systems," IEEE 9th Workshop on Signal Processing Advances in Wireless Communications, SPAWC 2008, pp. 525-529, 6-9 July 2008.

- Simplified version (interference coming from current sub-carrier):

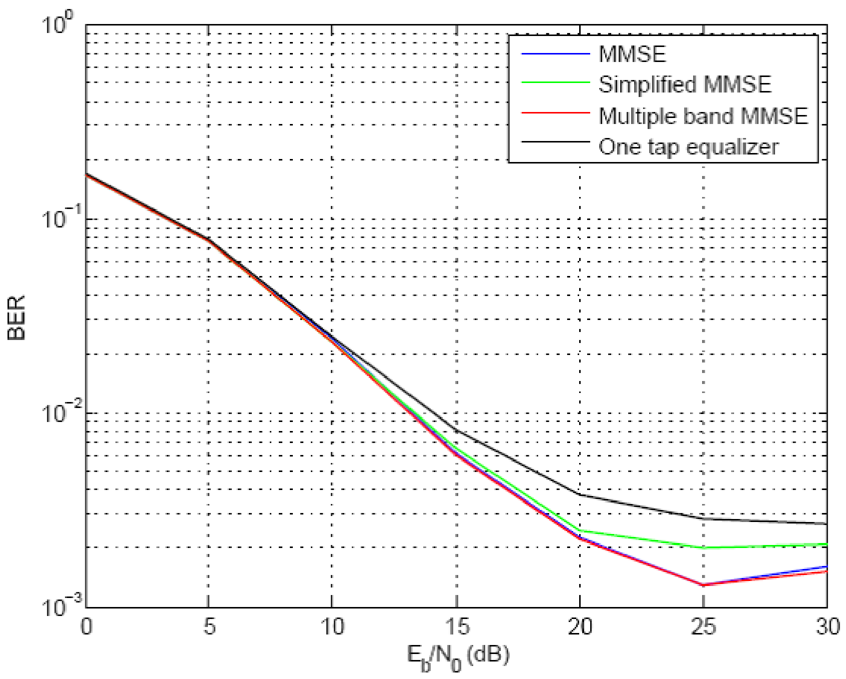


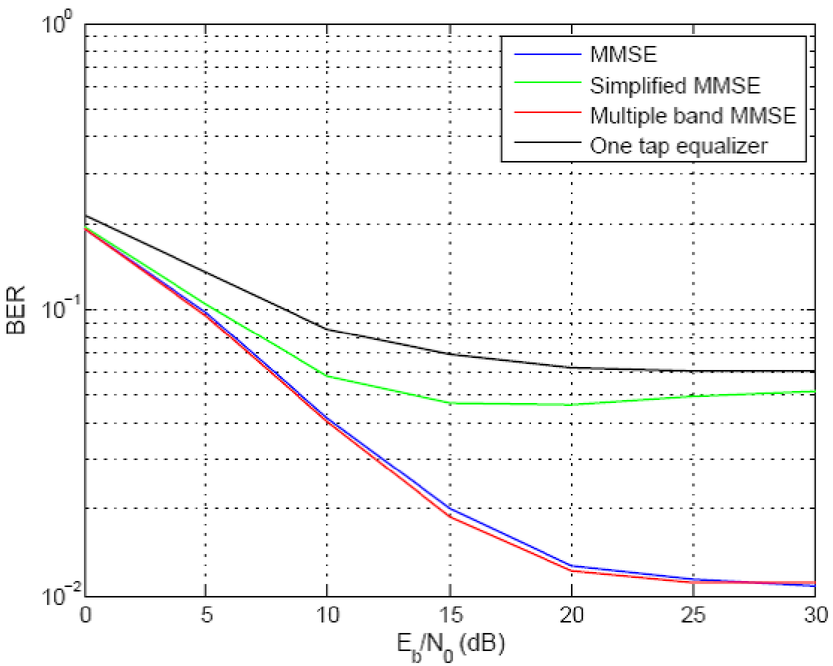
- Multi-band instead of per-subcarrier:



J. Louveaux et al., "Deliverable 3.1 - Equalization and demondulation in the receiver (single antenna)," Tech. Rep., FP7-ICT PHYDYAS - PHYsical layer for DYnamic AccesS and cognitive radio, 2010.

Performance comparison





- Veh-A channel (M = 256), 3-tap equalizers
- One-tap already effcient in mildly selective channels

- Veh-B channel
- Good results in highly selective channels
- Multiband has very low additional value
- Simplified MMSE inefficient

Equalization (further studies)

- **Least mean squares (LMS) implementation**
  D. S. Waldhauser, L.G. Baltar, and J. A. Nossek, "Adaptive equalization for Filter bank based multicarrier," in Proc. IEEE Int. Symp Circuits Syst. (ISCAS'08), May 18-21, 2008.
- **Decision-feedback equalizer**
  L.G. Baltar, D. Waldhauser, and J. Nossek, "MMSE subchannel decision feedback equalization for FBMC systems," in IEEE ISCAS'09, Taipei, Taiwan, 24-27 May 2009.
- **Non-linear equalization with interference cancelation**
  A. Ikhlef and J. Louveaux, "An enhanced MMSE per subchannel equalizer for highly frequency selective channels in FBMC/OQAM systems," in IEEE SPAWC09, Perugia, Italy, June 2009.
- **Asymptotic approach for parallel multi-stage equalization**
  X. Mestre, M. Majoral,S. Petschinger, "An Asymptotic Approach to Parallel Equalizationof Filter Bank Based Multicarrier Signals," IEEE Transactions on Signal Processing, vol.61,no.14, pp.3592-3606, July 2013.
- **Equalization in MIMO**
  T. Ihalainen, A. Ikhlef, J. Louveaux, M. Renfors, "Channel Equalization for Multi-Antenna FBMC/OQAM Receivers," IEEE Transactions on Vehicular Technology, vol.60, no.5, pp.2070-2085, Jun 2011.
  E. Kodis, A.A. Rontogiannis, "Adaptive BLAST decision-feedback equalizer for MIMOFBMC/OQAM systems," IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), pp.841-846, 26-30 Sept. 2010.

Syncronization

- Closely related to channel estimation, because propagation parameters should be estimated
- Synchronization includes:
  - Timing
    - Locating the start of a transmission burst (Frame sync)
    - Estimation of Fractional Time Delay (FTD)
  - Carrier Frequency Offset (CFO) estimation

$$r(t) = (s(t) \star h(t,\tau) \star \delta(t - \tau_{FTD}T))e^{j2\pi\frac{\varepsilon}{T}t} + \eta(t),$$

Part 5-2

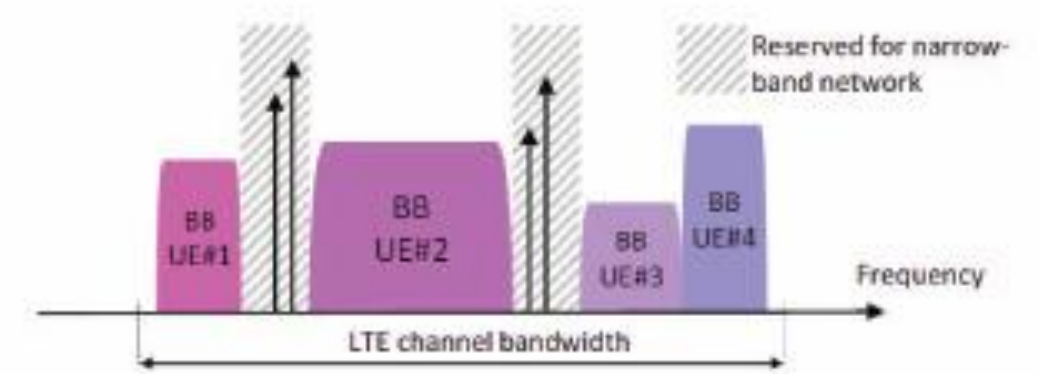
FBMC EXTENSIONS

Contents

- Fast Convolution Filter Banks (FC-FB)
- Non-uniform FBs
- Generalized Frequency Division Multiplexing (GFMD)

Flexibility in FBs

- OFDM or FBMC are usually used in continious spectrum and with uniform FBs
- Felexible multichannel channelization filters are needed:
  - Software defined radios
  - Wideband Professional Mobile Radios (PMR)
  - Other dynamic spectum use scanrios without cross-interference
- Computational complexity issues



The idea of Fast Convolution (FC)

Finite-length linear filter
impulse reponse

- Linear convolution:

$$y[n] = c[n] * x[n] = \sum_{m=-\infty}^{\infty} c[m]x[n-m] = \sum_{m=0}^{N_c-1} c[m]x[n-m]$$

- Circular convolution:

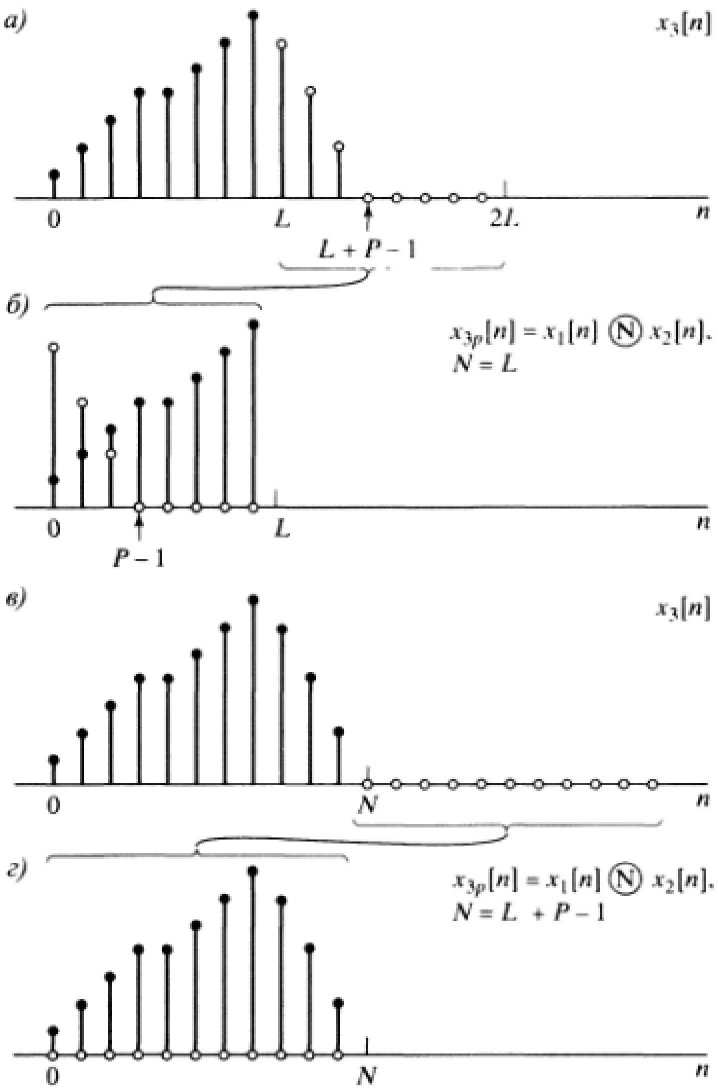
$$x_1[n] \circledast_N x_1[n] = \sum_{m=0}^{N-1} x_1[m]x_2[(n-m)_N],\, 0 \le n \le N-1$$

- **Fast convolution:**

$$x_1[n] \circledast_N x_1[n] = \mathrm{IFFT}\big(\mathrm{FFT}(x_1[n]) \cdot \mathrm{FFT}(x_2[n])\big)$$

- Linear convolution can be calculated though circular convolution (with overlapping)
  - FFT and IFFT length is at least of size $N \ge N_c + N_x - 1 > N_c$ (block length, legth of convolution)
  - $c[n] \circledast_N x[n] = c[n] * x[n], 0 \le n \le N-1$

Overlapping in circular convolution



*Oppenheim, Alan V., Ronald W. Schafer, and John R. Buck. *Discrete-time signal processing*. Englewood Cliffs: Prentice-hall, 1989.

Overlap-save method

- If one sequence is much longer than the other, **blockwise FC** can be used in conjunction **with overlap-save processing**
  - Very long signal $x[n]$ and FIR filter c$[n]$

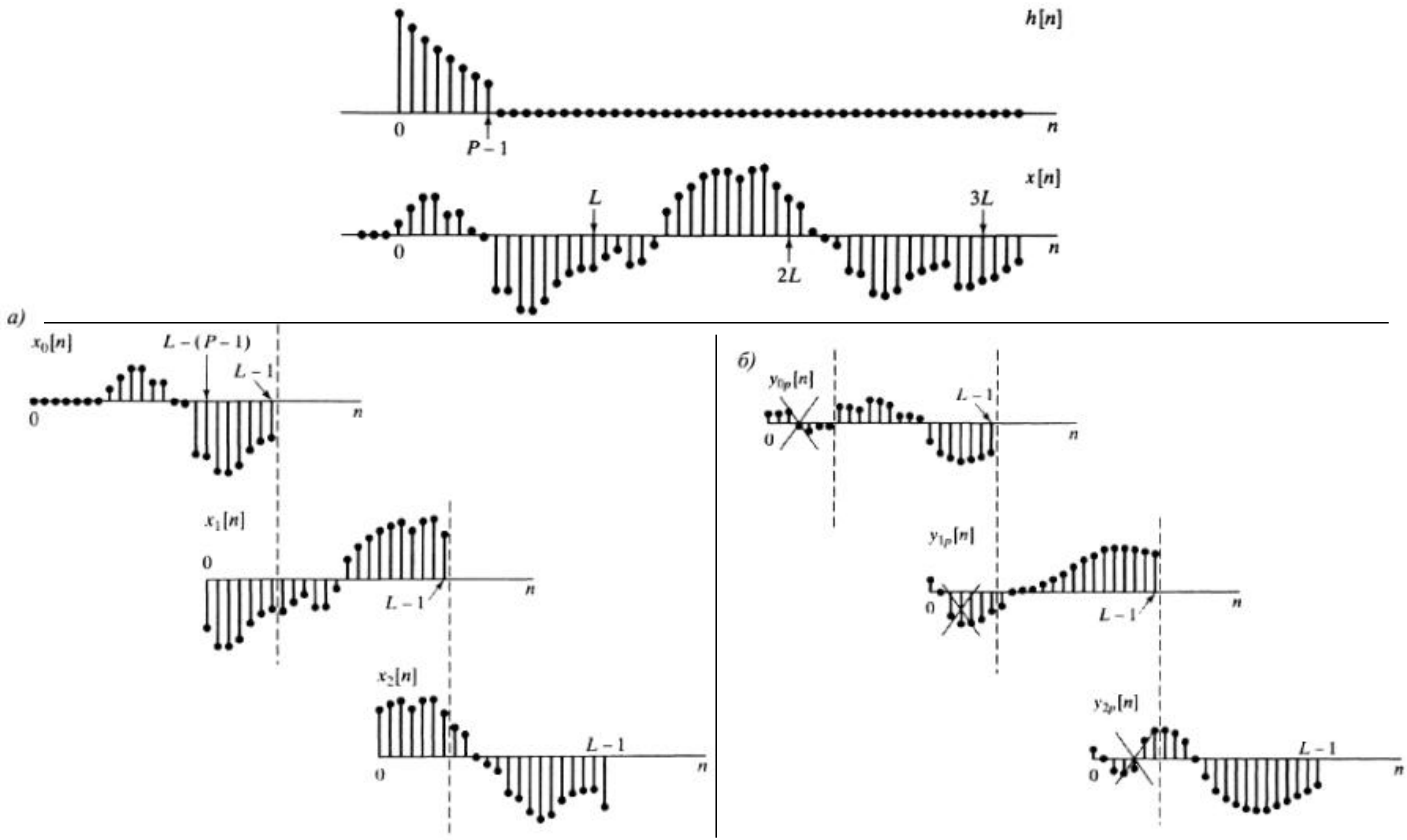
- The concept is to compute short segments of $y[n]$ of an arbitrary length L and concatenate them:

$$x_k[n] = x[n + k(L - N_c + 1) - N_c + 1], 0 \leq n \leq L - 1,$$

$$y_{kp}[n] = x_k[n] \circledast_N c[n] \text{ of length } N, 0 \leq n \leq N - 1$$

$$y_k[n] = y_{kp}[n], N_c - 1 \leq n \leq L - 1$$

Overlap-save processing



Overlap–save algorithm for linear convolution

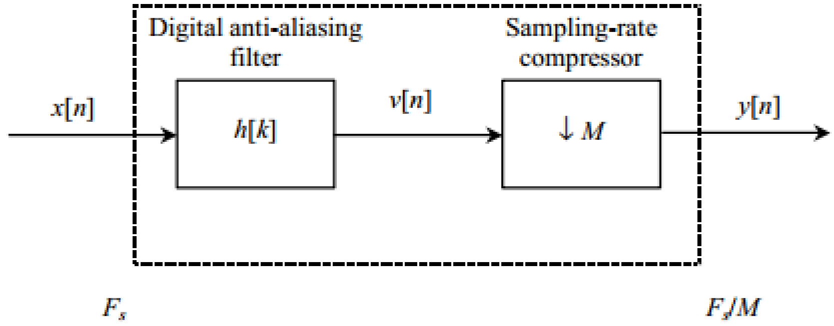
```
1.  Nc = length (c)
2.  overlap = Nc-1
3.  N = 2*overlap #(power of two)
4.  L = N – overlap
5.  C = FFT(c, N)
6.  position = 0
7.  while (position+N) <= length(x)
    1.  yt = IFFT( FFT( x(1+position : N+position),N ) .* C, N )
    2.  y(1+position : L+position) = yt(Nc : N)
        #discard Nc-1 y-values
    3.  position = position + L
8.  end
```

M-fold decimation

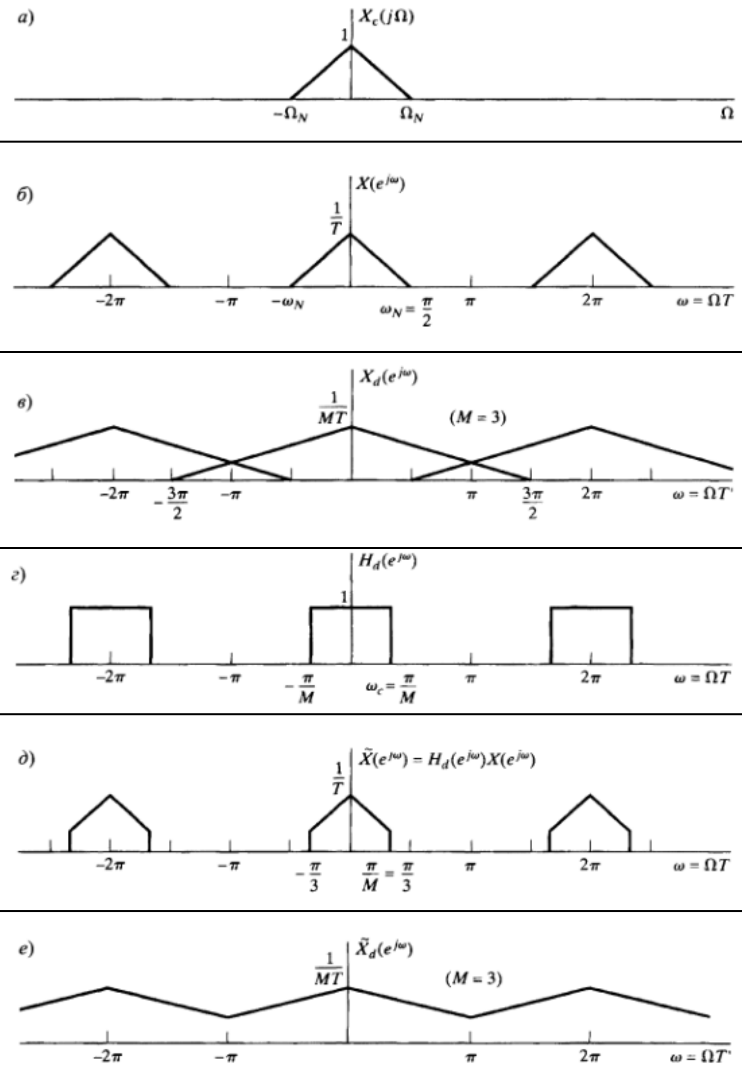
- Down-sampling or Compressing

$$x_d[n] = x[nM] = x_c(nMT)$$

- Decimation can include low-path filtering to avoid aliasing:



Example of decimation



FT (continuous) of $x_c($

DFT of sequence $x[n] = x_c(nT)$

$$\frac{2\pi}{T} = 4\Omega_N$$

Down-sampling at rate M =

DFT of $x_d[n] = x[3n]$;

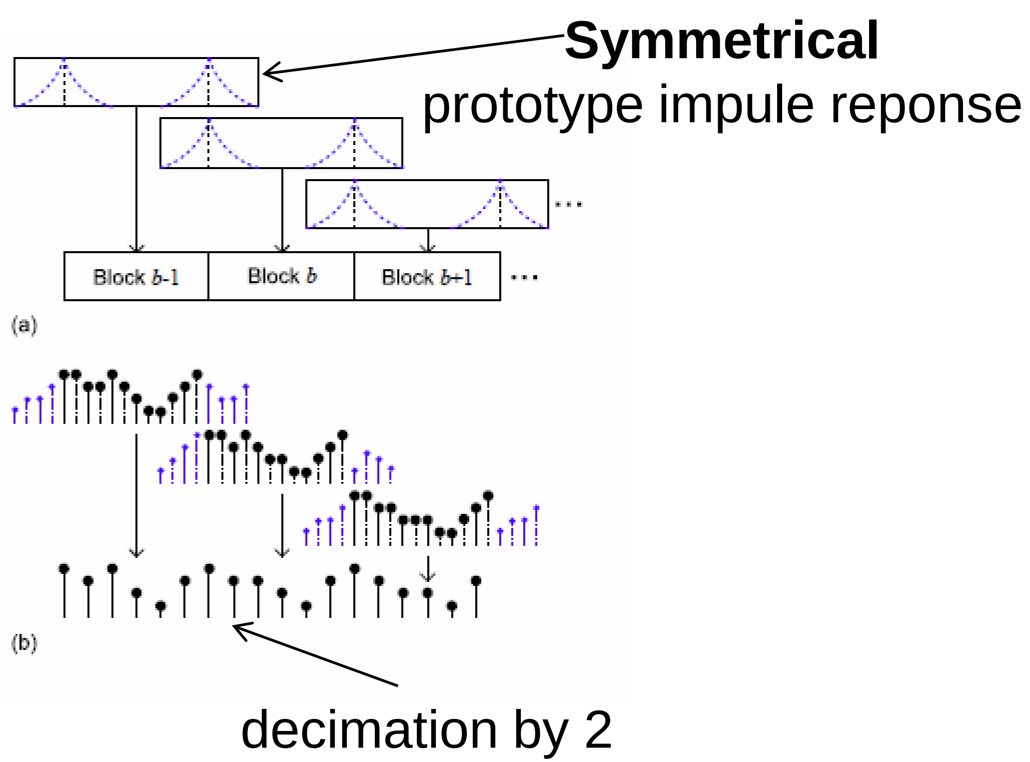
alaising, because $\omega_N N > \pi$

Low path filter with cut-off $\pi/$

Filtered spectrum

No aliasing

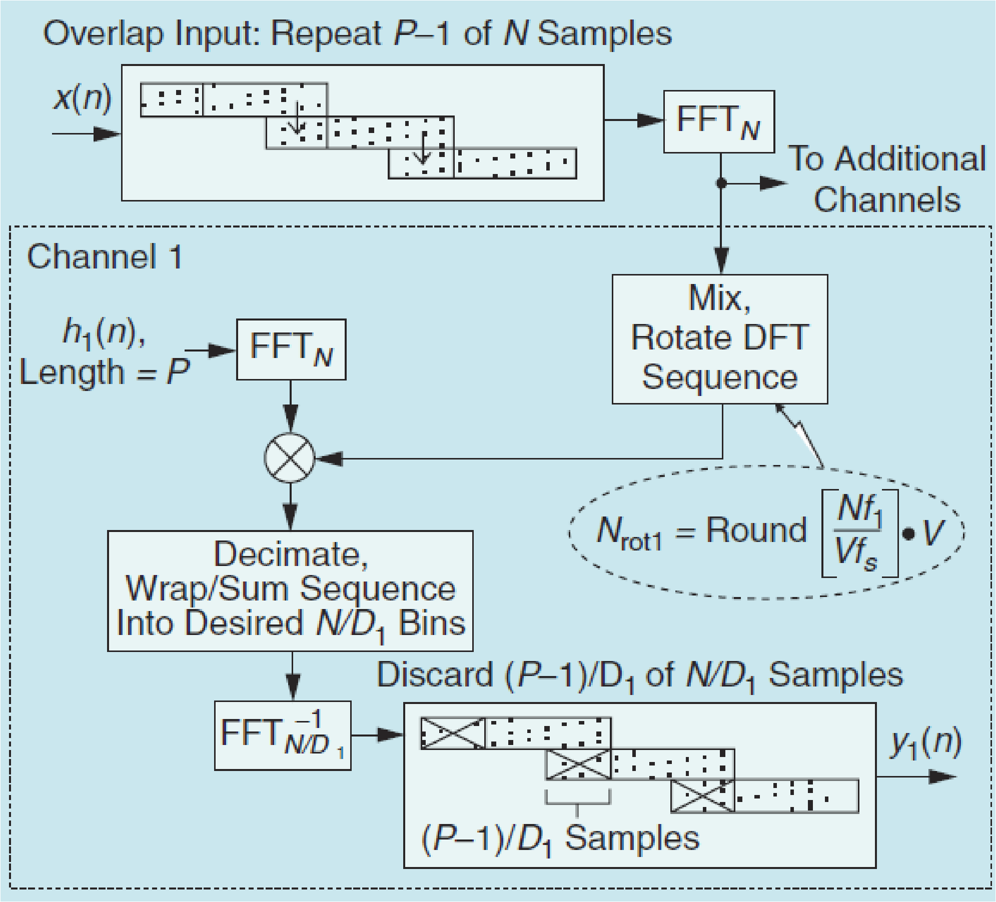
Symmetric overlap-save FC processing



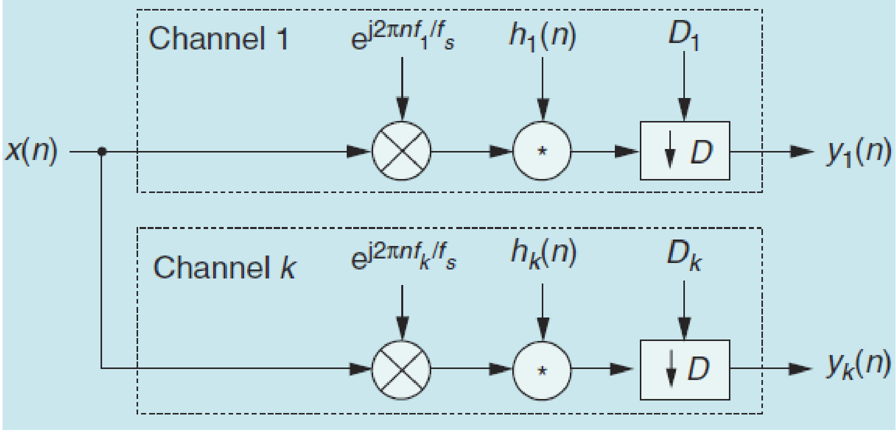
*Renfors, Markku, and Fred Harris. "Highly adjustable multirate digital filters based on fast convolution." *Circuit Theory and Design (ECCTD), 2011 20th European Conference on*. IEEE, 2011.
* Yli-Kaakinen, Juha, and Markku Renfors. "Fast-convolution filter bank approach for non-contiguous spectrum use." *Future Network and Mobile Summit (FutureNetworkSummit), 2013*. IEEE, 2013.

Overlap-save filter bank

OS-FB

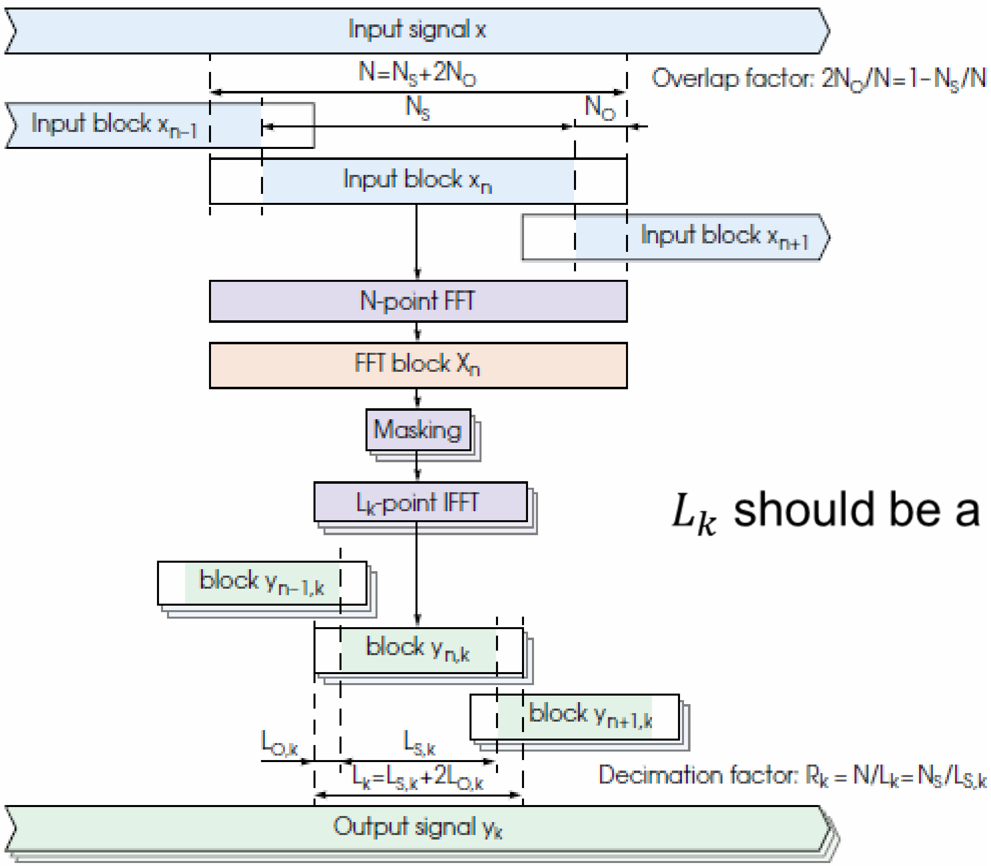


Conceptual model of a filter bank



* Borgerding, Mark. "Downsampling Filter Bank." *Streamlining Digital Signal Processing: A Tricks of the Trade Guidebook* (2007): 135.

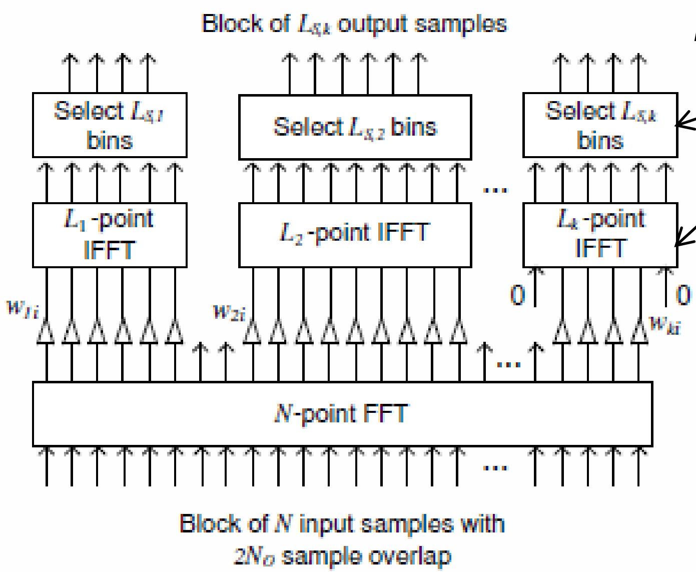
Overlap-save processing for FC



L_k should be a multiple of $N/\text{gcf}(N, N_s)$

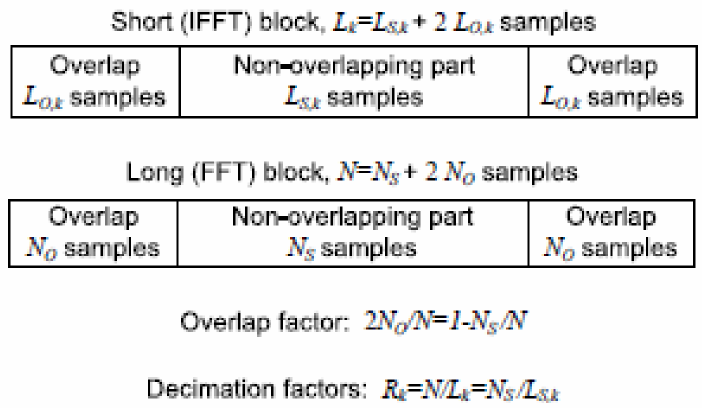
- Example: $N_s = 3N/4$ -> L_k is multiple of 4.
- f_s - input sampling rate -> possible output sampling rate is multiple of $4f_s/N$

Multirate FC base analysis FB



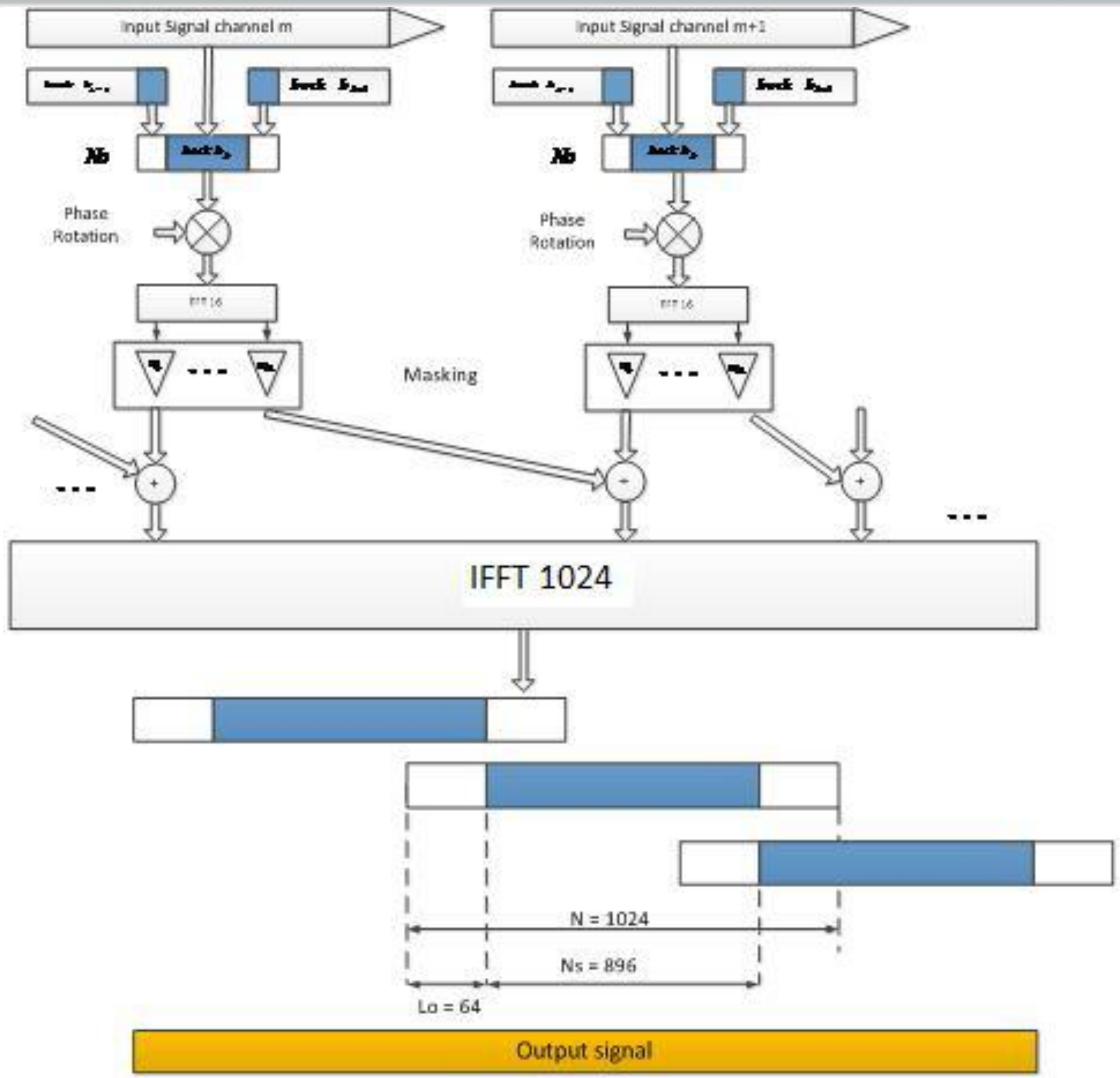
k is sub-band index

FFT bins

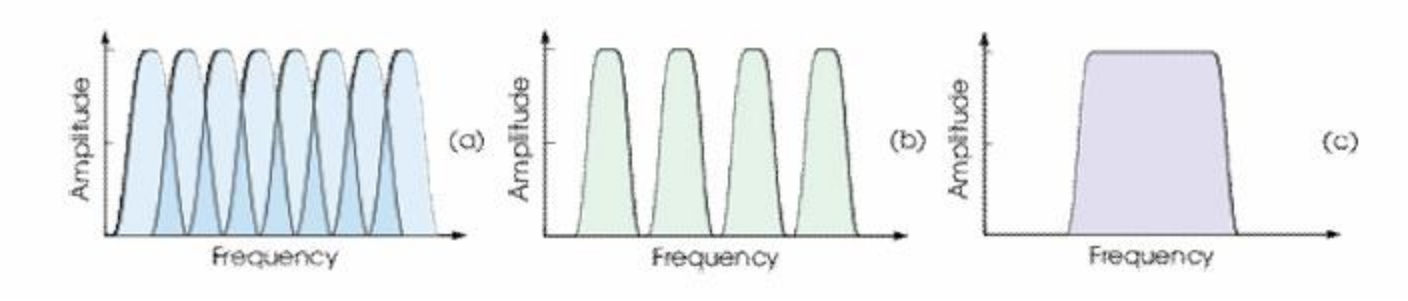


- Multi-rate version of FC
- Wideband signal is to be split into several narrowband signals with adjustable frequency regions and smapling rates
- The strurcture is dual: can be used to combine several low-rate, narrowband signals into as single wideband signal.

Synthesis FC-FB



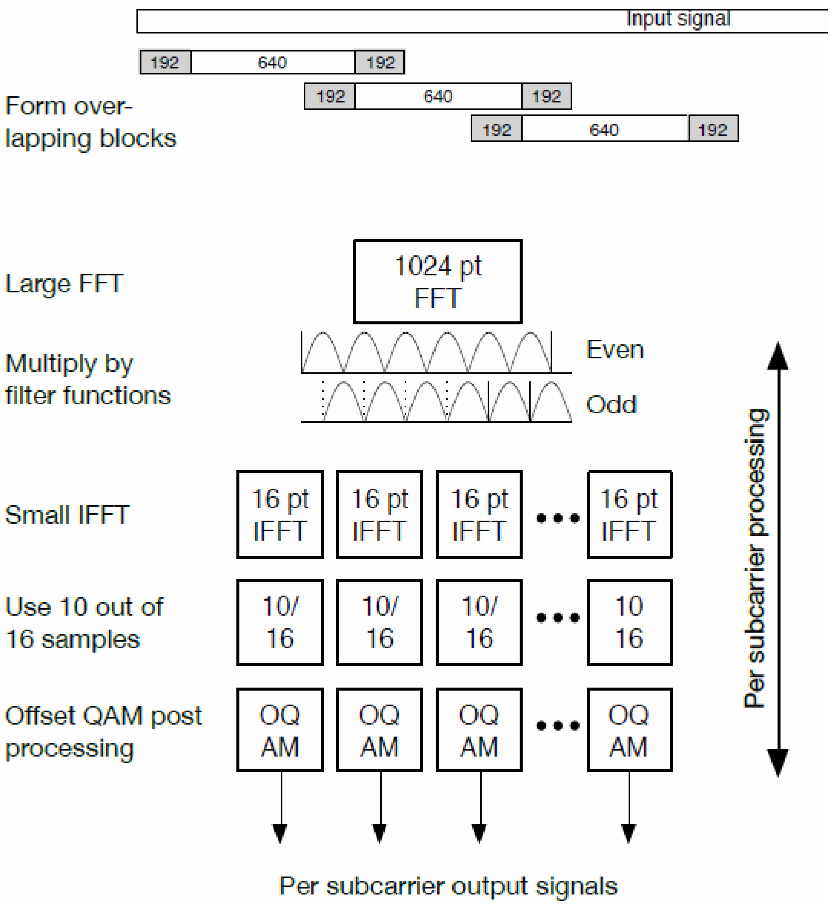
Different waveforms for FC-FBs



- Simultaneously processing of multiple communication signals of different waveform types, bandwidths, and other characteristics is possible:
  - OFDM, FBMC/OQAM;
  - Filtered MultiTone (FMT) , no-overlapping sub-channels.
  - Single carrier transmission

Configuration example

- 1.4 MHz bandwidth (1.92 MHz sampling frequency)
  - 128 sub-carriers (72 active)
  - FC-FB parameters:
    - Samples per short transform block (Ns = 640)
    - Long (I)FFT is N =1024 points
    - Short (I)FFT is L=16 points
    - Used samples per short transform block Ls = 10 (5 QAM symbols)
    - Overlap factor = ?
    - Decimation factor = ?



Spectral characteristics of FC-FB scheme

- Short IFFT size L defines how well the filter frequency response can be optimized.
    - Increasing the value of L helps to improve the stopband attenuation.

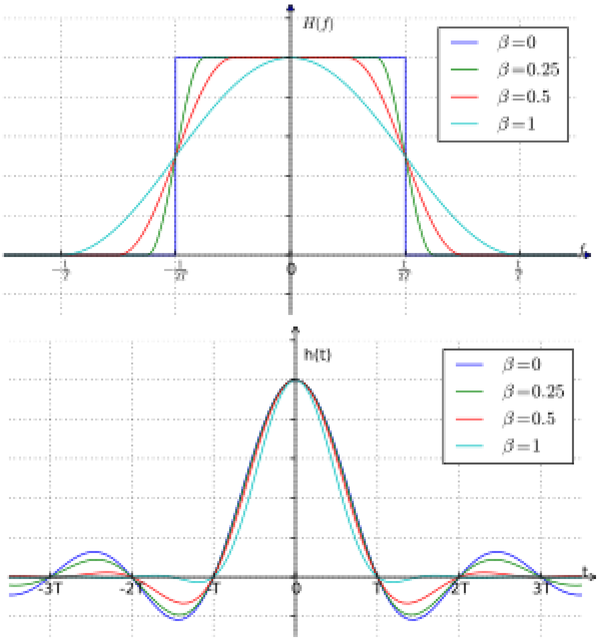
- The overlap factor $1 - L_s/L$ define **cyclic distortion** effect because the overlapping part of the of the processing block cannot be made big enough to absorb the tails of the filter impulse response.
    - This effect can be reduced by increasing the overlap factor.

(Root) Raised Cosine (RRC) filter

Frequency response of RC filter:

Roll-off factor

$$H(f) = \begin{cases} T, & |f| \leq \frac{1-\beta}{2T} \\ \frac{T}{2}\left[1 + \cos\left(\frac{\pi T}{\beta}\left[|f| - \frac{1-\beta}{2T}\right]\right)\right], & \frac{1-\beta}{2T} < |f| \leq \frac{1+\beta}{2T} \\ 0, & \text{otherwise} \end{cases}$$



Nyquist ISI criterion:

$$h(nT_s) = \begin{cases} 1; & n = 0 \\ 0; & n \neq 0 \end{cases}$$

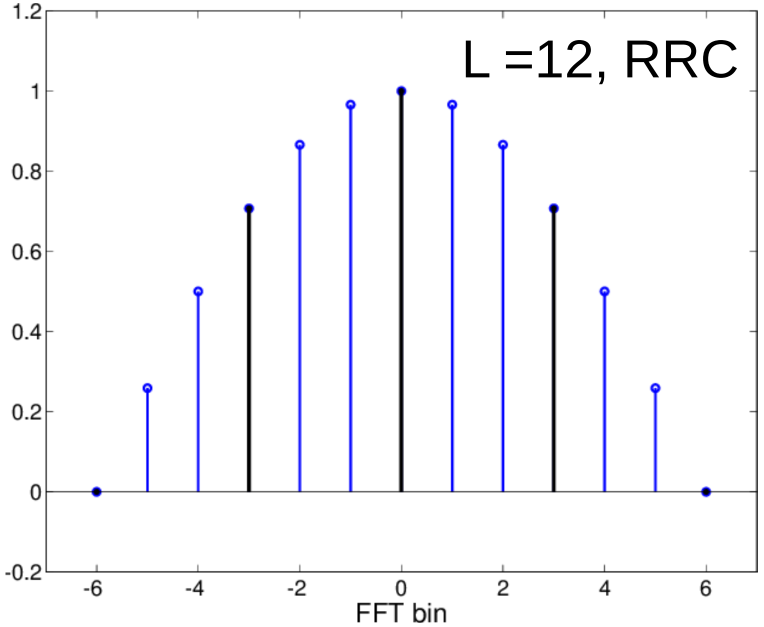
$$\frac{1}{T_s} \sum_{k=-\infty}^{+\infty} H\left(f - \frac{k}{T_s}\right) = 1 \quad \forall f$$

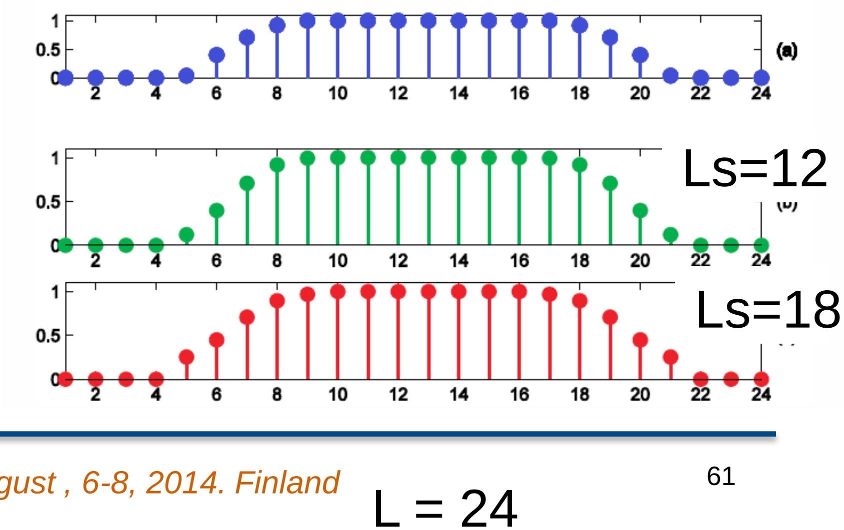
Frequency response of RRC filter:

$$|H_{rrc}(f)| = \sqrt{|H_{rc}(f)|}$$

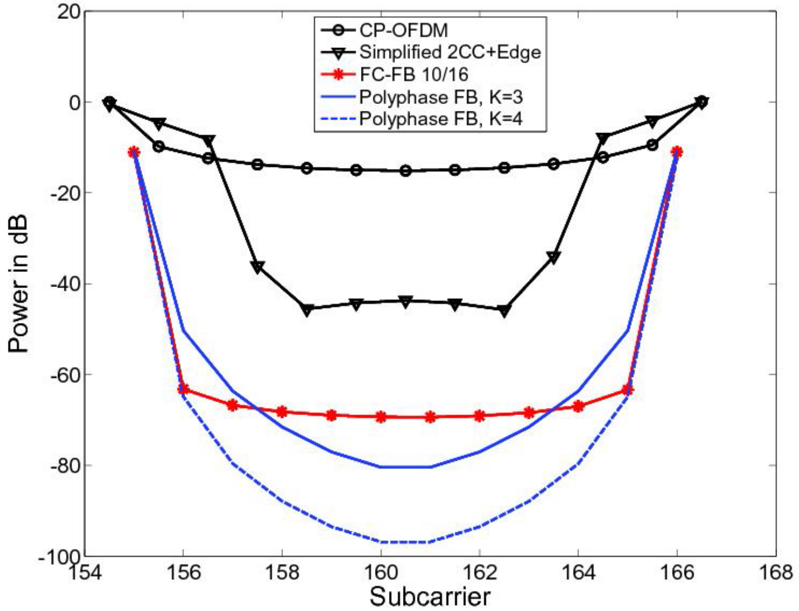
FC Filter Bank Design

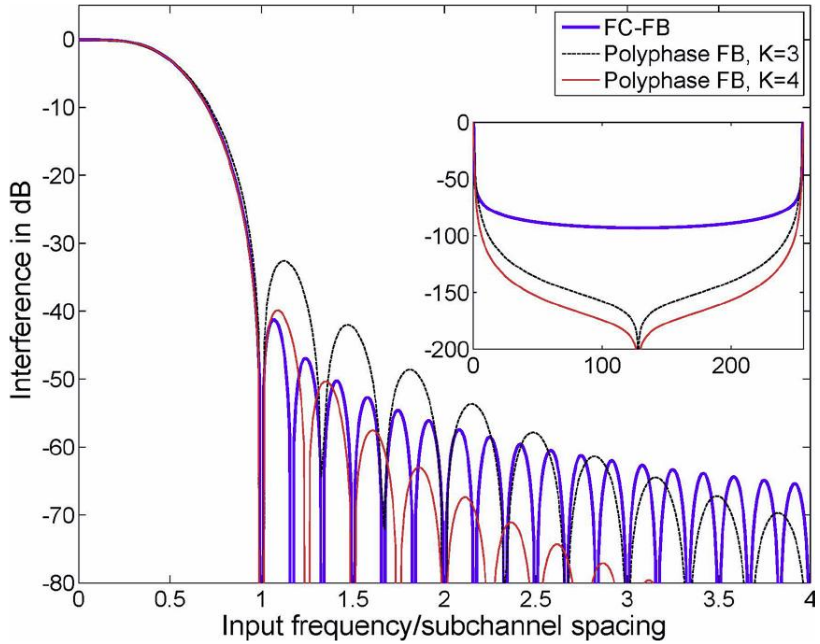
- RRC or RC filter with roll-off = 1
- NPR filter banks
- Usage of FFT weights to optimize performance
- Optimization criteria:
  - Stop-band attenuation
    - 2^{nd} adjacent sub-channel
    - Most distant sub-channel
  - $\lceil L/4 \rceil - 1$ optimization parameters





Spectral containment comparison

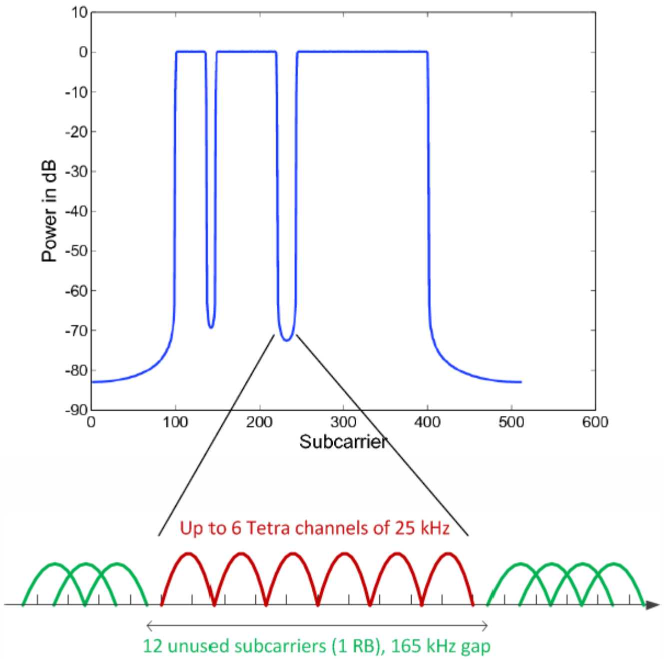




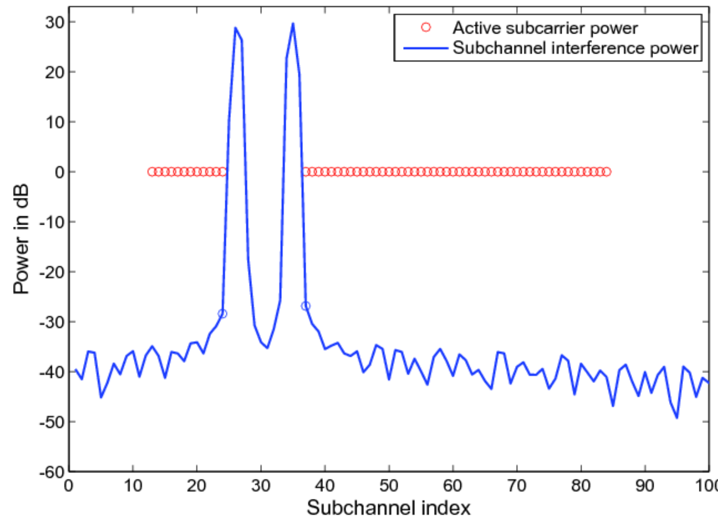
- Average spectrum leakage level in different multicarrier systems
- 5MHz LTE parameterization
- Spectrum leakage in a one resource block (12 subcarriers) wide gap

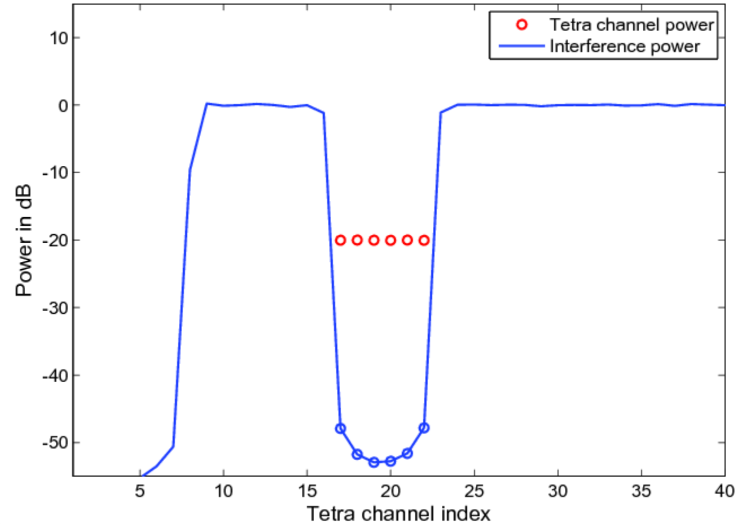
PMR scenario example

Heterogeneous spectrum

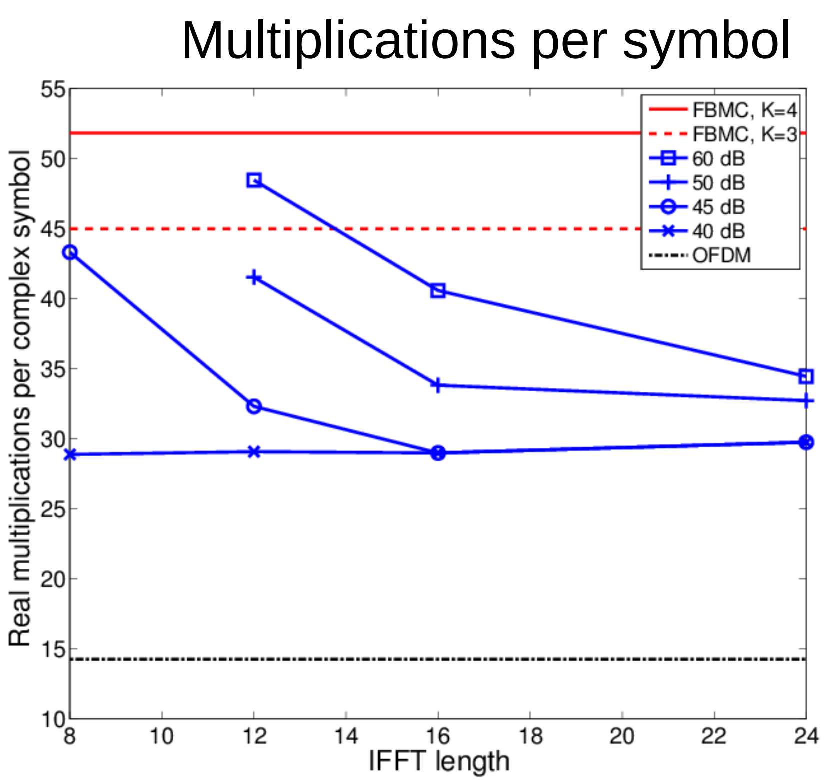


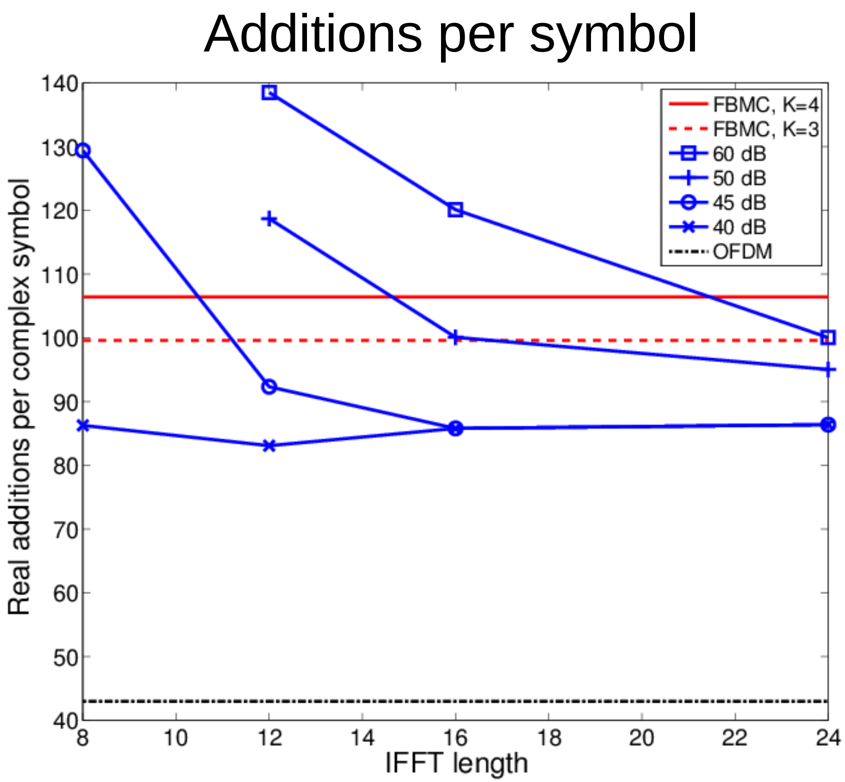
Interference leakage





Implementation complexity





Equalisation with FBMC

- 2 possible configurations:
  - Per-subcarrier processing after IFFTs in the receiver
  - Embedding the channel equalization and synchronization offset compensation with the FFT-domain weights
    - Variable FFT-domain weights
    - Improved performance and reduced complexity.
- Integrated time- and frequency synchronization:
  - Time delays of different sub-channels: tuning weights
  - Frequency offsets: choice of FFT bins connected to each SC

FC-FB conclusions

- Very flexible scheme for waveform processing.
- Simultaneous processing of different waveforms
- Tunability of bandwidths, center frequencies and spectral characteristics
- Potential for supporting fully asynchronous FDMA operation with minimal guardbands
- High spectral containment, i.e., good control of spectral leakage effects

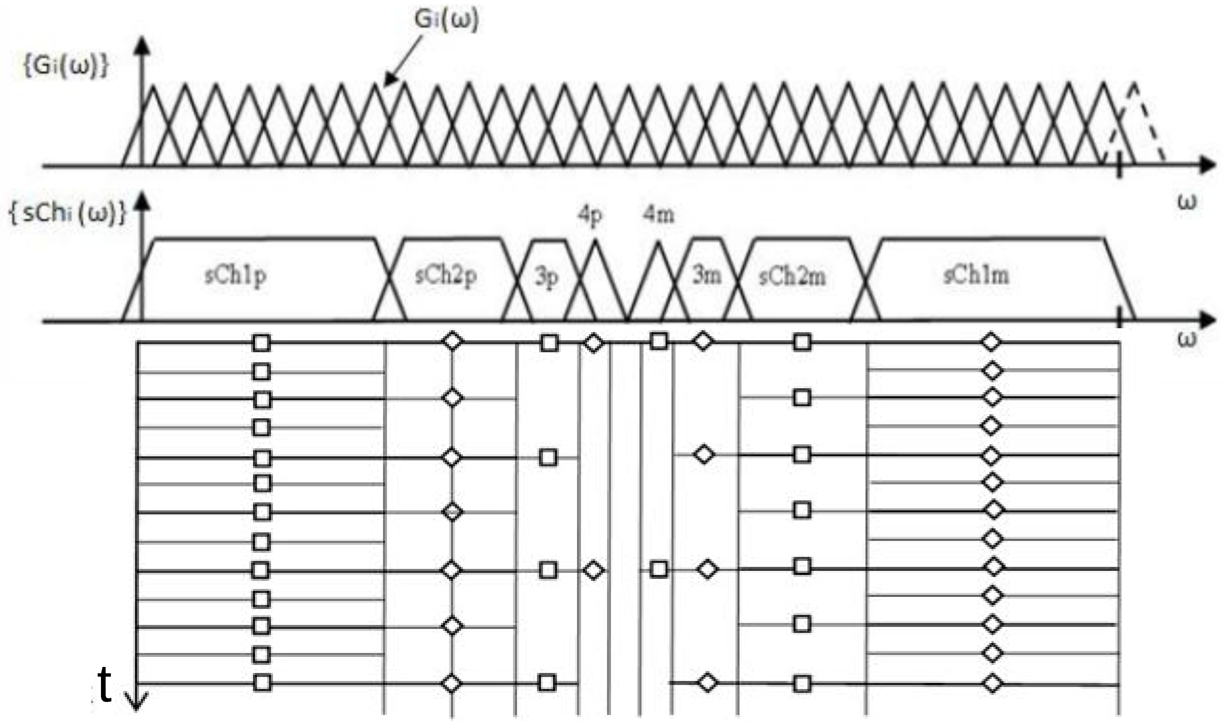
Non-uniform FBs (NU-FBMC)

- Utilization of sub-channels with differing widths within scattered frequency bands
- Reduction of Peak to Average Power Ration (PARP)
- Individual and flexible user channelization

*Josilo, Sladana, Milos Pejovic, and Slobodan Nedic. "Non-uniform FBMC-A Pragmatic Approach." *Wireless Communication Systems (ISWCS 2013), Proceedings of the Tenth International Symposium on*. VDE, 2013.

Spectral aggregation for NU-FBMC

RRC filter,
Roll off = 1



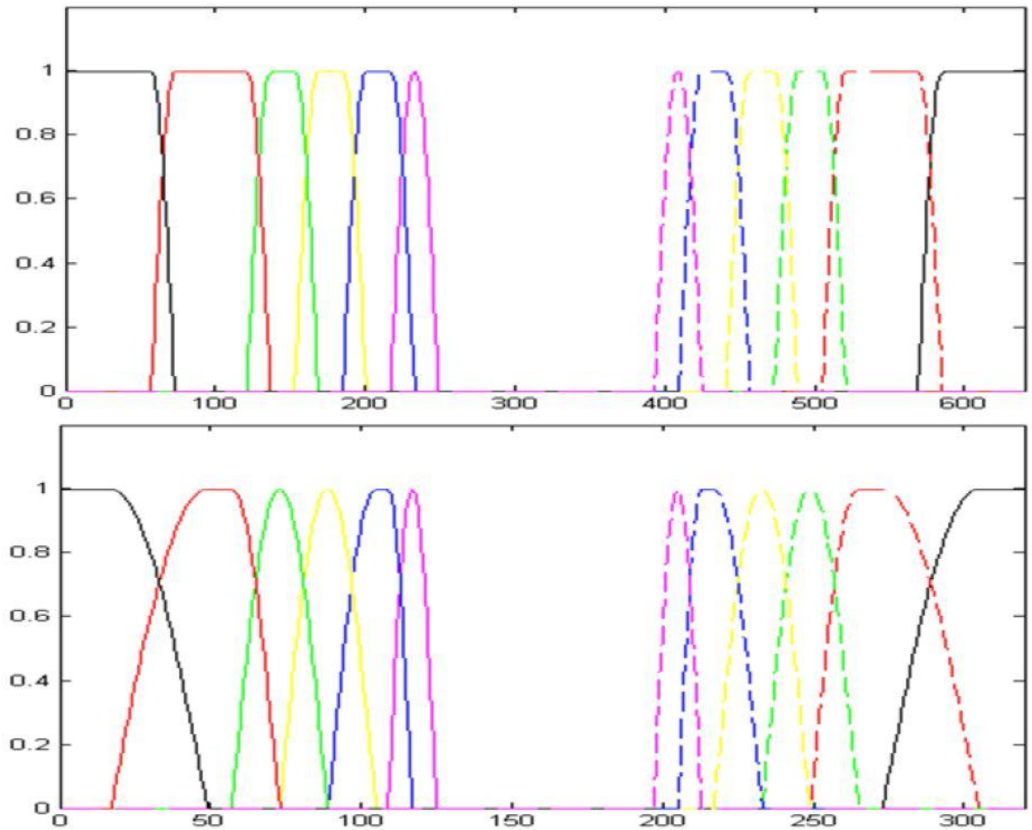
- Direct extension of uniform FBs:

$$sCh1p = \sqrt{\sum_{i=0}^{7} G_i^2}$$

- Orthogonality is kept

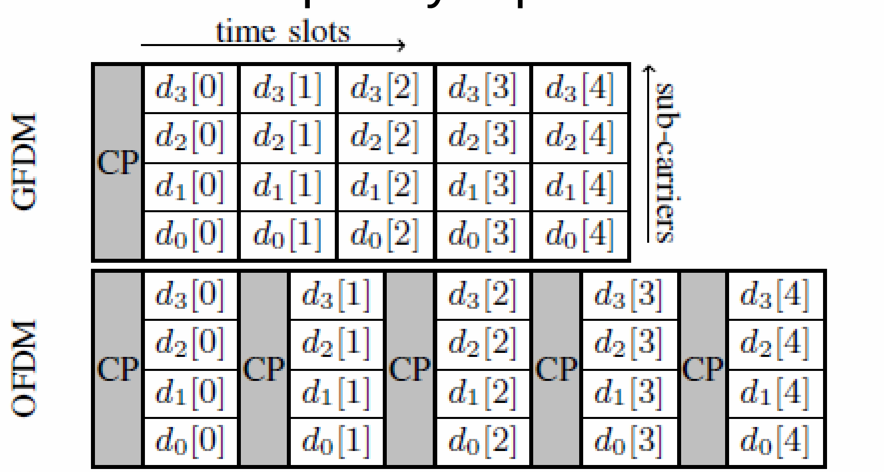
Use of asymmetrical sub-channel spectra

- Adjusting roll-off of aggregates
- No need to separate adjacent user channels



Generalized FDM (GFDM)

- Flexible MC transmission with additional degrees of freedom (in addition to OFDM)
- Adjustable pulse shaping filter is applied to the <u>individual subcarriers</u>
- Further processing of 2D data bloc of variable size
- CP can be used for low complexity equalization



* Fettweis, Gerhard, Marco Krondorf, and Steffen Bittner. "GFDM-generalized frequency division multiplexing." *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*. IEEE, 2009.
* Gaspar, Ivan, et al. "Low Complexity GFDM Receiver Based On Sparse Frequency Domain Processing." *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*. IEEE, 2013.

GFDM signal

- Transmit signal:

$$x[n] = \sum_{m=0}^{M-1} \sum_{k=0}^{K-1} d_k[m] \tilde{g}_{Tx}[n - mN] e^{j2\pi \frac{kn}{N}}$$

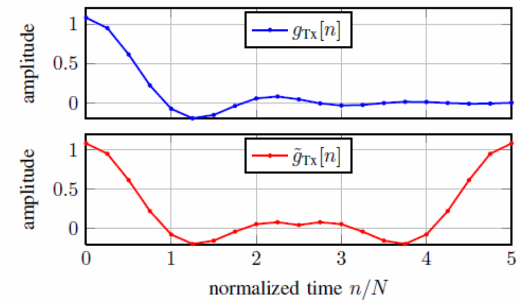
Data symbols KN

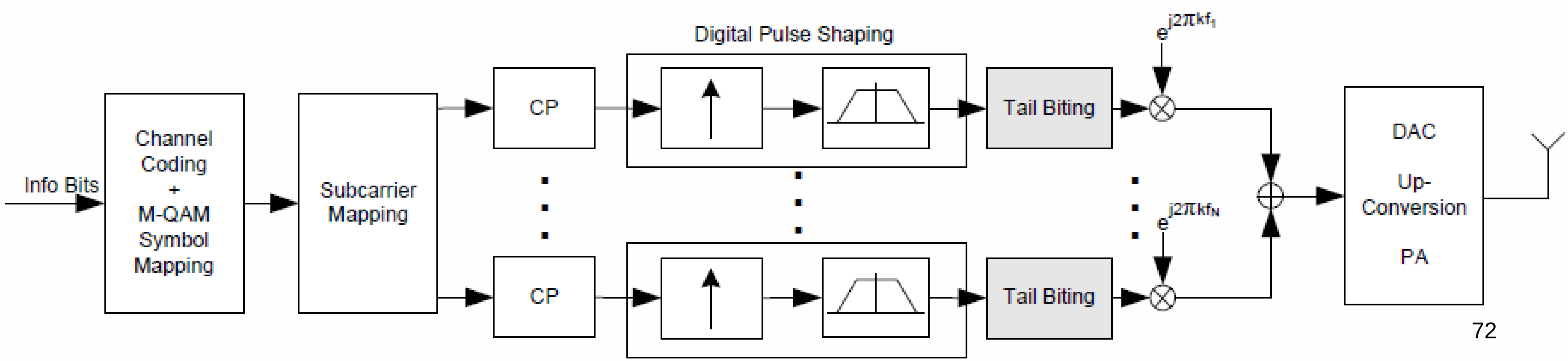
Active time slots subcarriers Transmit filter Center frequency

- Symbol is sampled $N \geq K$ times (MN samples per sub-carrier)
- $\tilde{g}_{Tx}[n]$ is circular with periodicity $n \bmod (NM)$
- Matrix presentation:

$$x = Ad$$

A of size $NM \times KM$





Efficient GFDM implementation

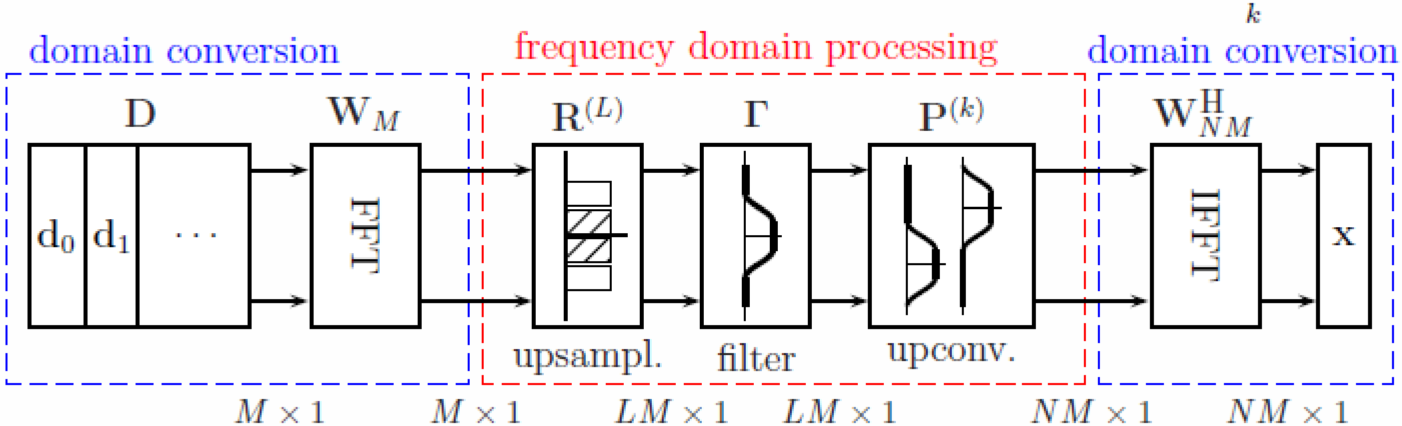
- Sub-channel processing: $x[n] = \sum_k x_k[n]$,

$$x_k[n] = [(d_k[m]\delta[n - mN]) \circledast_{MN} g_{Tx}[n]]e^{j2\pi\frac{k}{N}n}$$

- Equivalently:

$$x_k[n] = IDFT_{NM}(DFT_{NM}(d_k[m]\delta[n - mN]) \cdot$$
$$\cdot\, DFT_{NM}\,(g_{Tx}[n]) \circledast_{MN} DFT_{NM}(e^{j2\pi\frac{k}{N}n}))$$

$$\mathbf{x} = \mathbf{W}_{NM}^{\mathrm{H}} \sum_k \mathbf{P}^{(k)} \mathbf{\Gamma} \mathbf{R}^{(L)} \mathbf{W}_M \mathbf{d}_k.$$



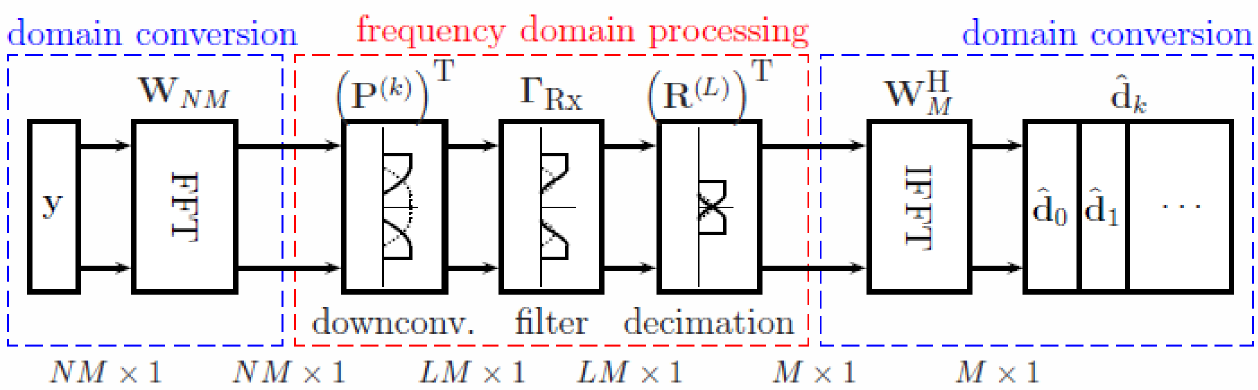
GFDM reception

- Match filter operation:

$$\hat{y}[n] = \left(y[n]e^{-j2\pi\frac{k}{N}n}\right) \circledast \tilde{g}_{Rx}[n],$$
$$\hat{d}_k[m] = \hat{y}[n = mN]$$

- Matrix representation: $\hat{d} = \boldsymbol{A}^H y$

$$\hat{\mathbf{d}}_k = \mathbf{W}_M^{\mathrm{H}} \boxed{\left(\mathbf{R}^{(L)}\right)^{\mathrm{T}} \Gamma_{\mathrm{Rx}}^{(L)} \left(\mathbf{P}^{(k)}\right)^{\mathrm{T}} \mathbf{W}_{NM}\, \mathbf{y}}$$



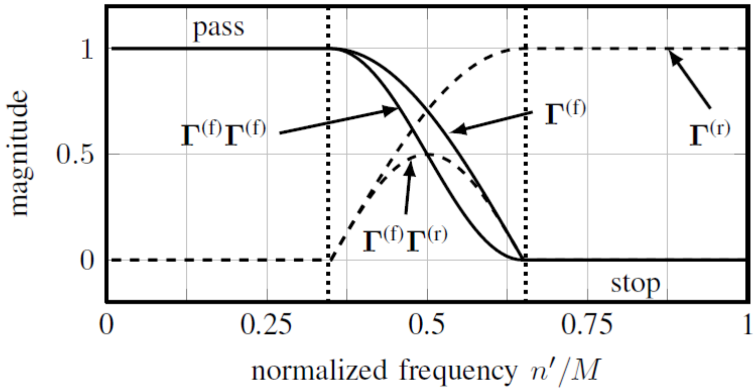
GFDM Equalization (Interference cancelation)

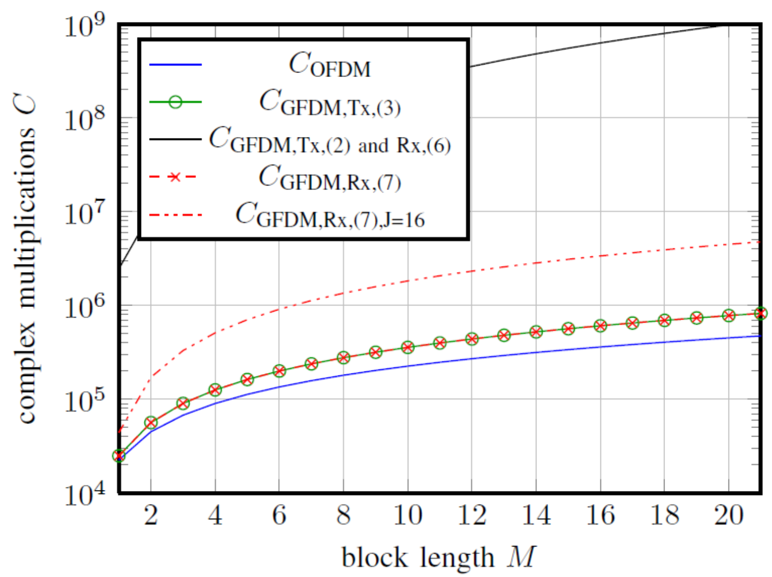
- Interference:

$$\begin{aligned}
\mathbf{y}_k &= \left(\mathbf{R}^{(L)}\right)^{\mathrm{T}} \mathbf{\Gamma}_{\mathrm{Rx}}^{(L)} \left(\mathbf{P}^{(k)}\right)^{\mathrm{T}} \mathbf{W}_{NM}\, \mathbf{y} \\
&= \underbrace{\mathbf{\Gamma}^{(\mathrm{r})}\mathbf{\Gamma}^{(\mathrm{r})}\mathbf{d}'_k + \mathbf{\Gamma}^{(\mathrm{f})}\mathbf{\Gamma}^{(\mathrm{f})}\mathbf{d}'_k}_{\text{signal}} + \dots \\
&\quad \underbrace{\mathbf{\Gamma}^{(\mathrm{f})}\mathbf{\Gamma}^{(\mathrm{r})}\mathbf{d}'_{k-1} + \mathbf{\Gamma}^{(\mathrm{f})}\mathbf{\Gamma}^{(\mathrm{r})}\mathbf{d}'_{k+1}}_{\text{interference}} \\
&= \mathbf{d}'_k + \mathbf{\Gamma}^{(\mathrm{f})}\mathbf{\Gamma}^{(\mathrm{r})}\left(\mathbf{d}'_{k-1} + \mathbf{d}'_{k+1}\right)
\end{aligned}$$

- Iterative IC:

receive all sub-carriers as $\mathbf{W}_M^{\mathrm{H}}\mathbf{y}_k^{(0)}$
map each symbol to closest QAM point to obtain $\hat{\mathbf{d}}_k^{(0)}$
for $j = 1$ to J **do**
  for $k = 0$ to $K-1$ **do**
    remove interference by computing
    $\mathbf{y}_k^{(j)} = \mathbf{y}_k^{(0)} - \mathbf{\Gamma}^{(\mathrm{r})}\mathbf{\Gamma}^{(\mathrm{f})}\mathbf{W}_M\left(\hat{\mathbf{d}}_{k-1 \bmod K}^{(j-1)} + \hat{\mathbf{d}}_{k+1 \bmod K}^{(j-1)}\right)$
    update the received symbols with $\mathbf{W}_M^{\mathrm{H}}\mathbf{y}_k^{(j)}$
    map each symbol to closest QAM point to obtain $\hat{\mathbf{d}}_k^{(j)}$
  end for
end for

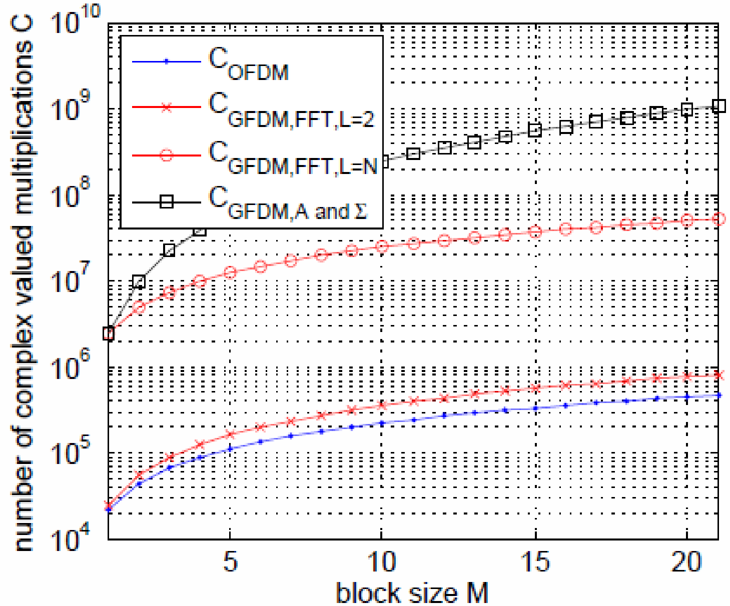


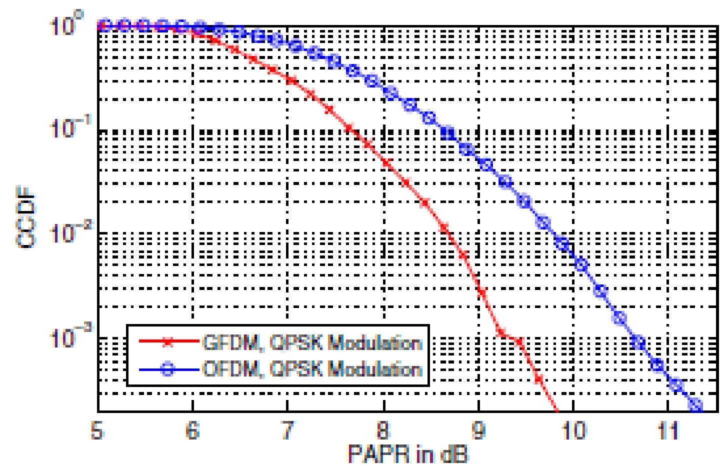


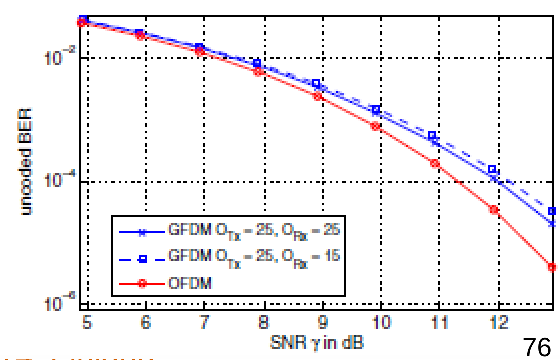
GFDM performance

Parameter	OFDM	GFDM
Signal Bandwidth	20 MHz	20 MHz
Number of Subcarriers	64	4
Subcarrier bandwidth	312.5 kHz	5 MHz
Symbol duration w/o CP	3.2 μs	0.2 μs
CP overhead	25%	25%
CP length	16 Samples	Variable
Pulse Shape	rectangular	FIR: Cos-roll r=0.1

Complex multiplications







Part 6

COMPUTER SIMULATIONS

How may networks be studied?

- Measurements from real deivces / networks
  - Protocol analysers and monitors
  - Drive test with specialized erquipment
  - Measurements from real devices
  - *$ and time consuming, new devices not always avaliable*
- Test networks / emulation
  - Access to all equipment / software
  - Open-sourse software
  - *Expencive and not large enough*
- Mathematical analysis
  - Matlab, pen’n’paper
  - *Too many simplifications in complex dynamc systems*

Why to simulate?

- Develop and test vast amount of potential solutions for current and future challenges without excessive costs

- Wireless
  - Reproducibility
  - Fidelity (especially, real-time constraints)
  - Radios may not exist or be available
  - Field tests in realistic conditions cost $$
  - Scenarios with desired parameters

- Scalability
  - 10,000+ nodes?
  - For smaller configurations, execution time

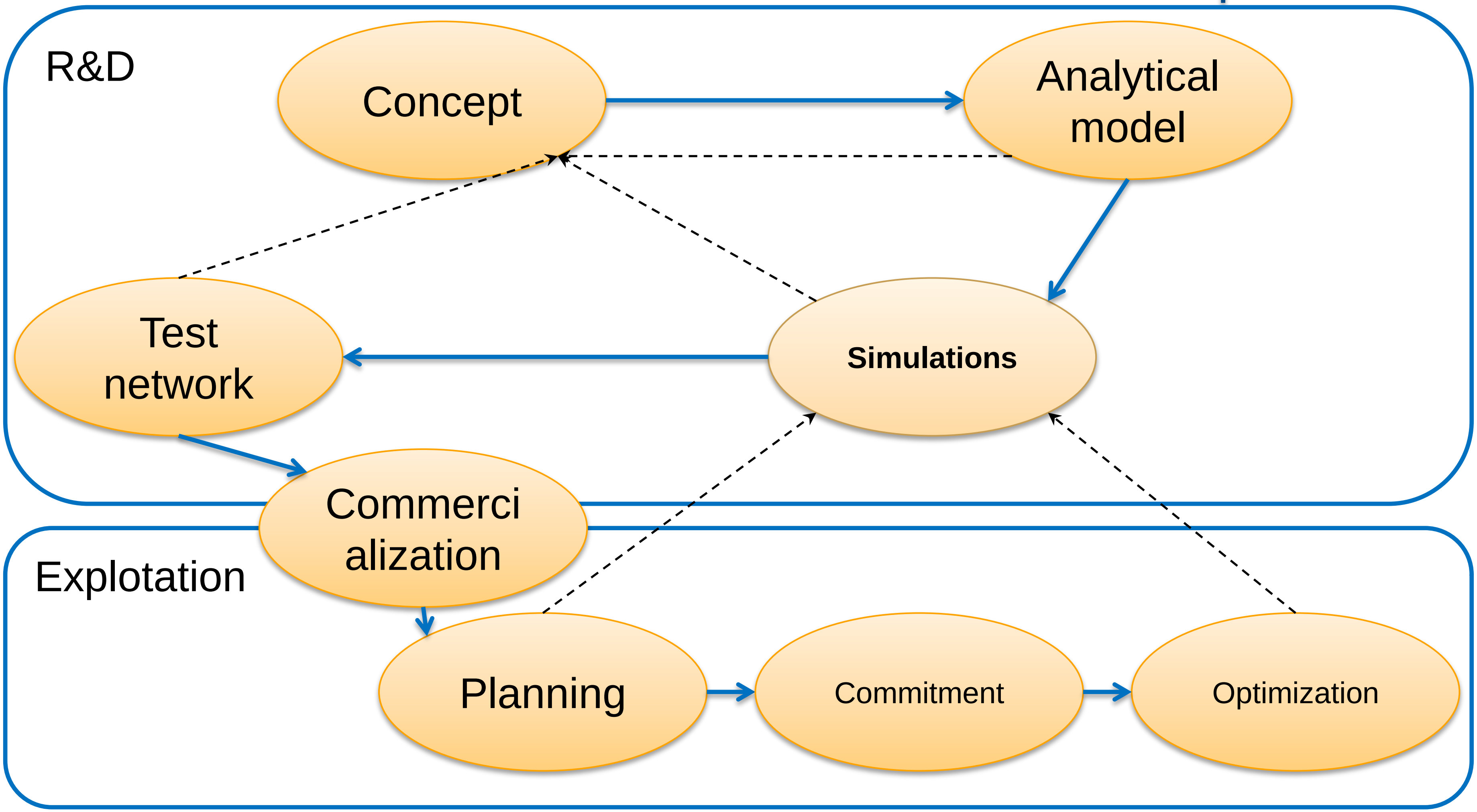
When to use simulations?

- When the **analytical model/solution is not possible or feasible.**
- Many times, simulation results are used to **verify analytical solutions** in order to make sure that the system is modeled correctly using analytical approaches.
- **Dynamic systems**, which involve randomness and change of state with time.
- **Complex dynamic systems**, which are so complex that when analyzed theoretically will require too many simplifications. In such cases, it is not possible to study the system and analyze it analytically.

Simulators and Network Planning Tools

- NPTs:
  - Focus on radio part:
    - propagation and interference models
    - Real maps
  - Radio planning and optimization
  - Some posses simulation possibilities:
    - Traffic modeling
- Simulators:
  - Representation of a real system
  - Both Radio and Core planes (end2end)
  - Detailed realization of protocols and features
  - Statistics for specific UE, eNB, link
  - RB or even symbol resolution on PHY
  - Packet tracing

New technology path



What can be achieved with simulations?

- Test new and advanced features and their gains
- Study wide range of scenarios
- Identify bottlenecks in processes
- Prevent under or over-utilisation of resources
- Safe and chaper way to evaluate the side effects
- Optimize the performance of the system
- Balance expences and improvements in user experience

“Essentially, all models are wrong, but some are useful”

[George E. P. Box and Norman R. Draper. *Empirical Model-Building and Response Surfaces*. Wiley, 1987]

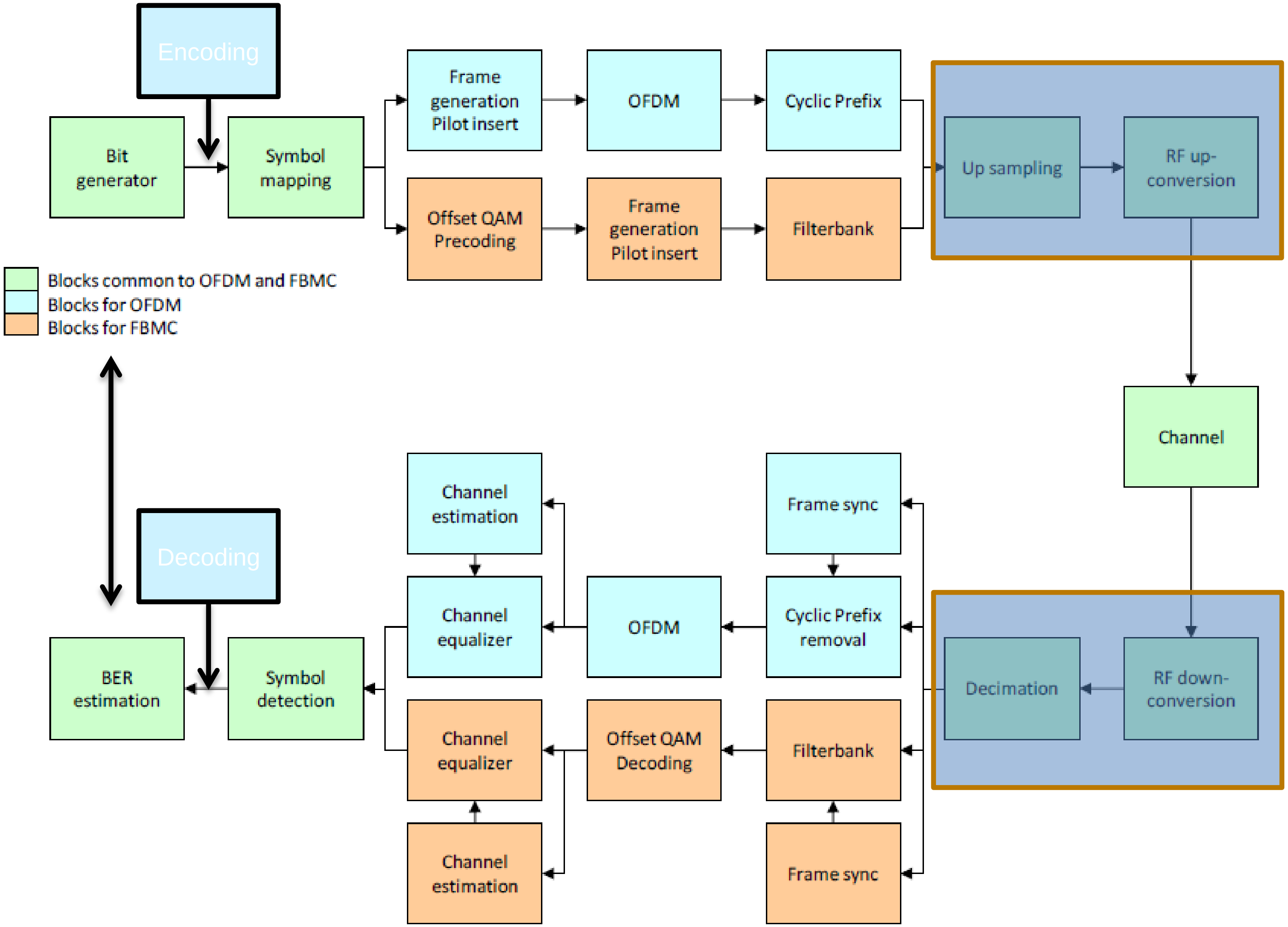
Simulator types

- Different ways of dividing simulators
  - Running principle: discrete event, continuous, …
  - Level of detail: static, quasi-static, dynamic, …
  - Modeling purpose: wireless radio access, wired, …
  - Confidentiality: proprietary, open

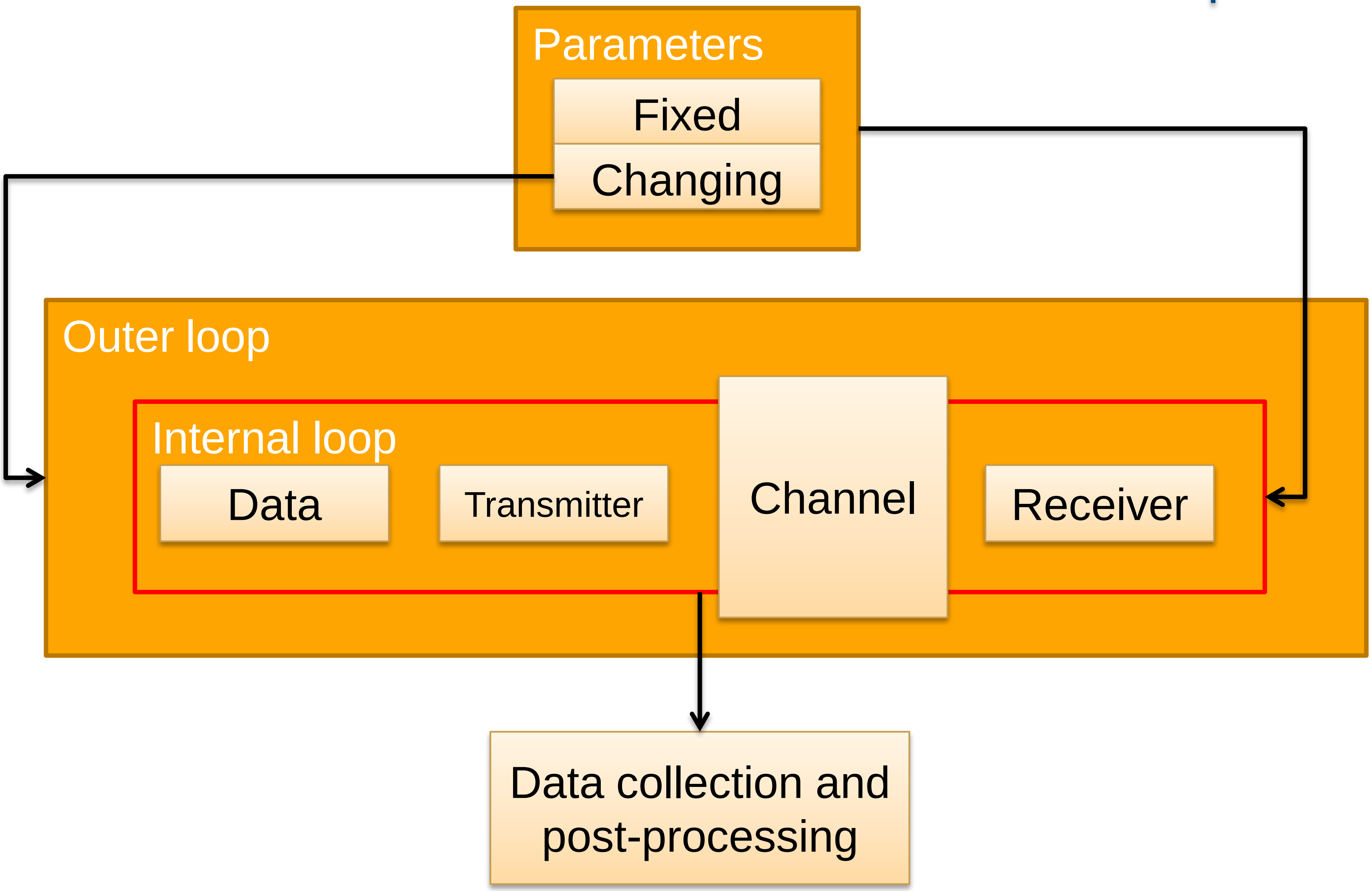
Link and System level simulations

- Link Level:
  - 1 UE – 1eNB connection is simulated
  - 1 subcarrier / 1 time slot resolution
  - Mainly physical layer procedures:
    coding, modulation, complicated channel models, channel estimation etc.
  - Provides input for system level simulations
  - Actual data transmission
- System Level:
  - Hundreds of UEs - tens of eNBs
  - Resource Block (RB) resolution and more simple channel models (pathloss + shadowing + fast fading)
  - Includes full protocol stack and many other procedures
  - TBER is defined by BLER-SINR curves form Link level
  - Simulation of received SINRs

Link level simulation of FBMC



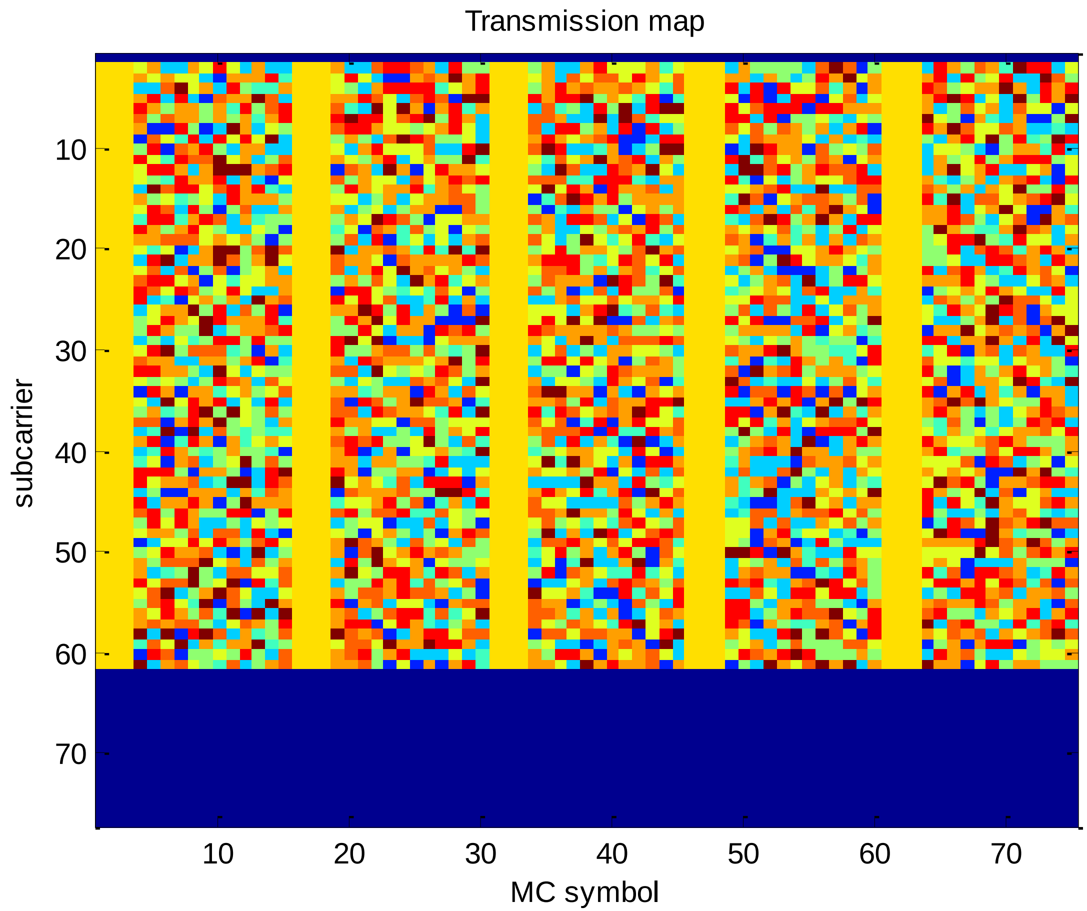
LL simulation architecture



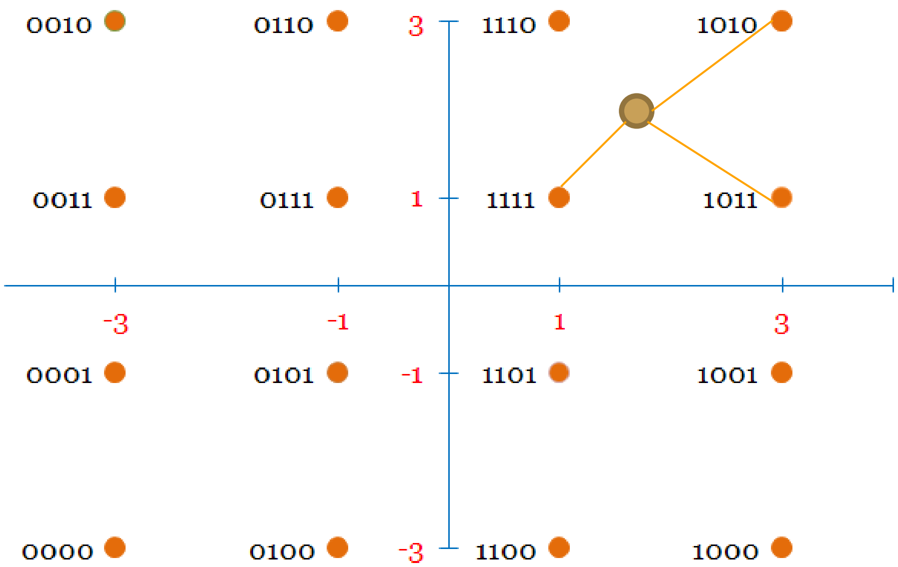
Main simulation parameters

- **Coding parameters:** coding rate, block size
- **Modulation:** 4QAM, 16 QAM, 64 QAM
- **Waveform:** CP-OFDM, PHYDIAS, FC-FB
- **Antenna configuration**: SISO, MIMO
- **Bandwidth**: 1.4MHz, 5 MHz, 20 MHz
- **Number of Sub-carriers (active)**: 128 (72), 512(300), …
- **Sub-frame length in MC symbols (1ms)**: 14 for OFDM, 15 for FBMC
- **Physical Resource Block size:** 12 subcarriers
- **Channel model:** AWGN, Ped, Vec, Hilly Terrain, etc.
- **Velocity**
- **Channel estimation type**
- **Equalization type**
- **Symbol damping:** soft or hard
- **Vector of EbNo values** (or other variating parameters, like CFO)
- **Number of independent loops**

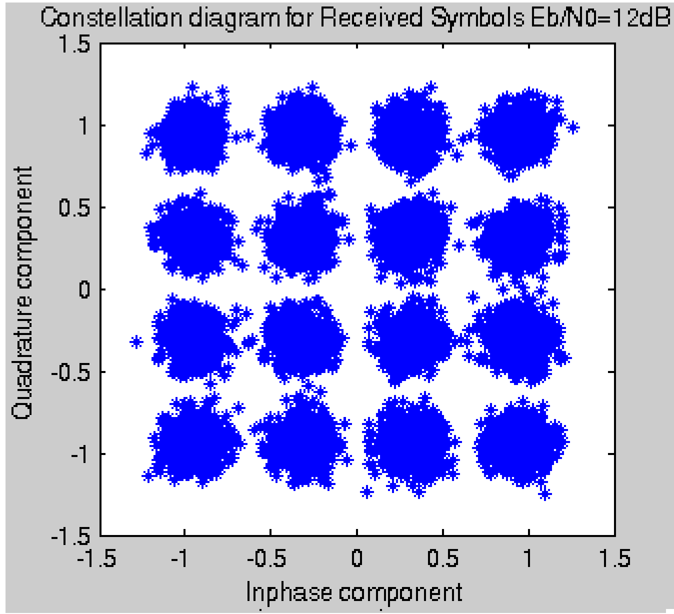
Transmission example



QAM modulation and demapping



16 QAM



Soft demapping:

Log Likelihood ratio (LLR)

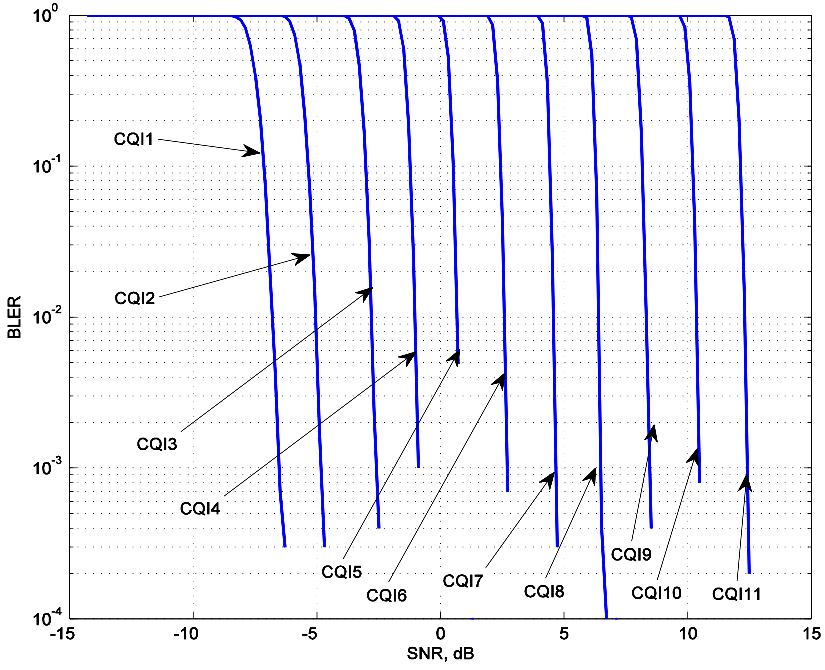
$$L(b) = \log\left(\frac{\Pr(b=0 \mid r=(x,y))}{\Pr(b=1 \mid r=(x,y))}\right)$$

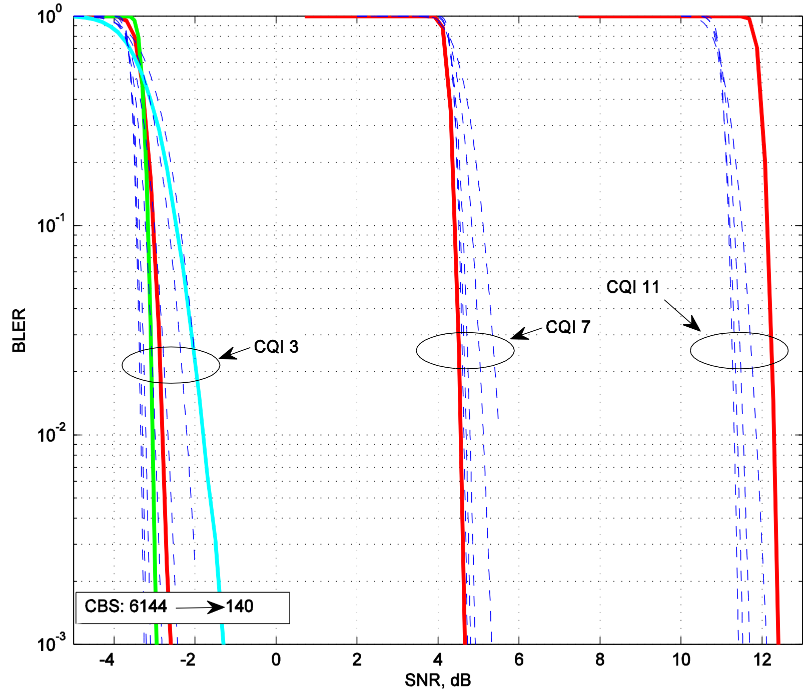
$$L(b) = \log\left(\frac{\sum_{s \in S_0} e^{-\frac{1}{\sigma^2}\left((x-s_x)^2+(y-s_y)^2\right)}}{\sum_{s \in S_1} e^{-\frac{1}{\sigma^2}\left((x-s_x)^2+(y-s_y)^2\right)}}\right)$$

All symbols with bit 0 at certain position

All symbols with bit 1 at certain position

BER/BLER curves



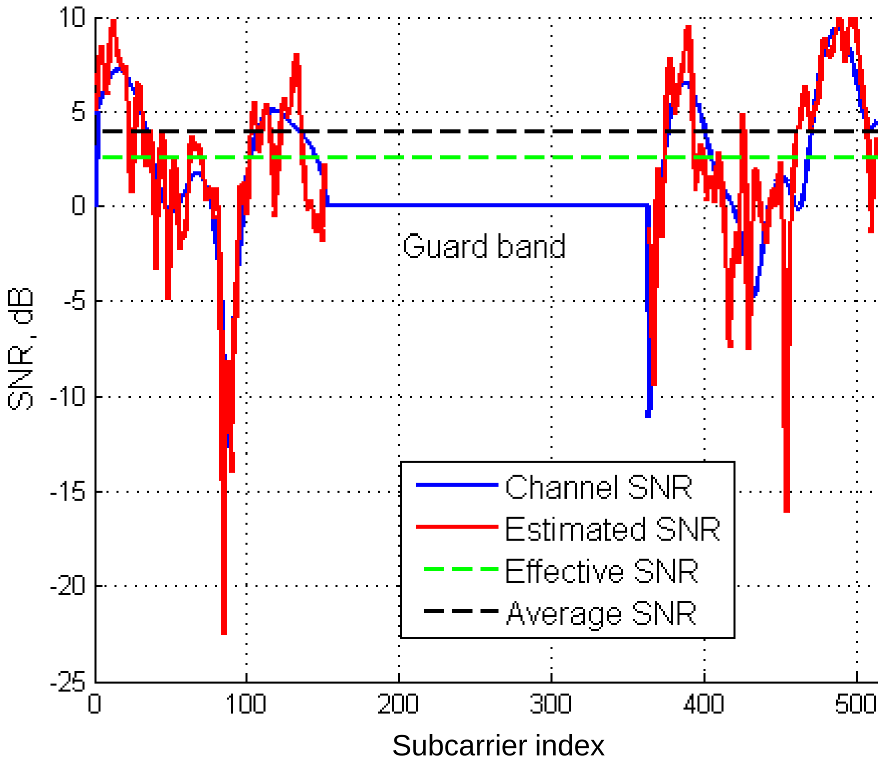


Part 6-2

LINK2SYSTEM INTERFACE FOR MC AND FBMC SYSTEMS

MC systems

- Dynamic channel behavior
- Multi-state wireless channels with deep fades
- Simple SINR averaging cannot be used



* Petrov, Dmitry, Pavel Gonchukov, and Tobias Hidalgo Stitz. "Link to System Mapping for FBMC Based Systems in SISO case." *Wireless Communication Systems (ISWCS 2013), Proceedings of the Tenth International Symposium on*. VDE, 2013.

Principles of Effective SNR Mapping (ESM)

1. *Non-linear averaging of per-resource unit SNRs*:

$$\mathrm{SNR_{eff}} = I^{-1}\left(\frac{1}{N}\sum_{n=1}^{N} I(\mathrm{SNR}_n)\right).$$

2. *AWGN channel with* $\mathrm{SNR_{eff}}$ *should have the same error performance as caused by* $\{\mathrm{SNR_n}\}$:

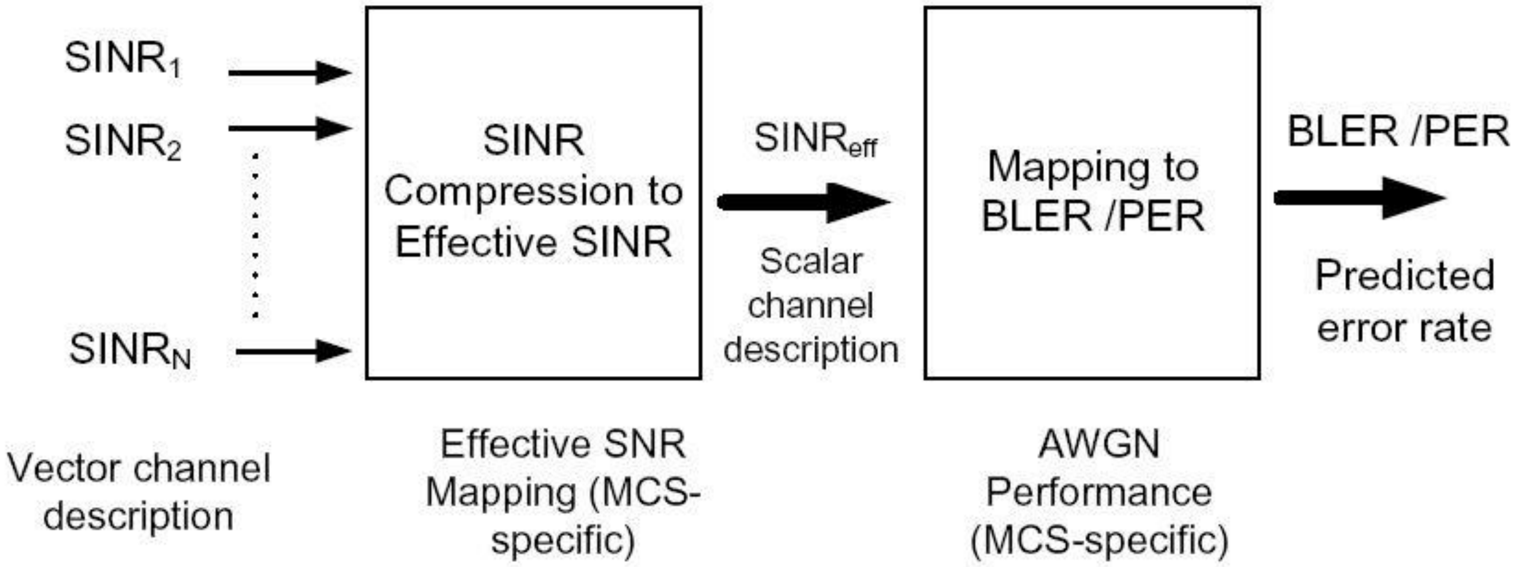
$$\mathrm{BLER}(\{\mathrm{SNR_n}\}) \approx \mathrm{BLER_{AWGN}}(\mathrm{SNR_{eff}}).$$

3. Fitting coefficients: $\mathrm{SNR_{eff}}(\alpha_1, \alpha_2) = \alpha_1 I^{-1}\left(\frac{1}{N}\sum_{n=1}^{N} I\left(\frac{\mathrm{SNR}_n}{\alpha_2}\right)\right)$:

$$\left[\sum_{d=1}^{D}\left(\mathrm{BLER}^d - \mathrm{BLER_{AWGN}}\left(\mathrm{SNR}^d_{\mathrm{eff}}(\alpha_1, \alpha_2)\right)\right)\right] \to \min.$$

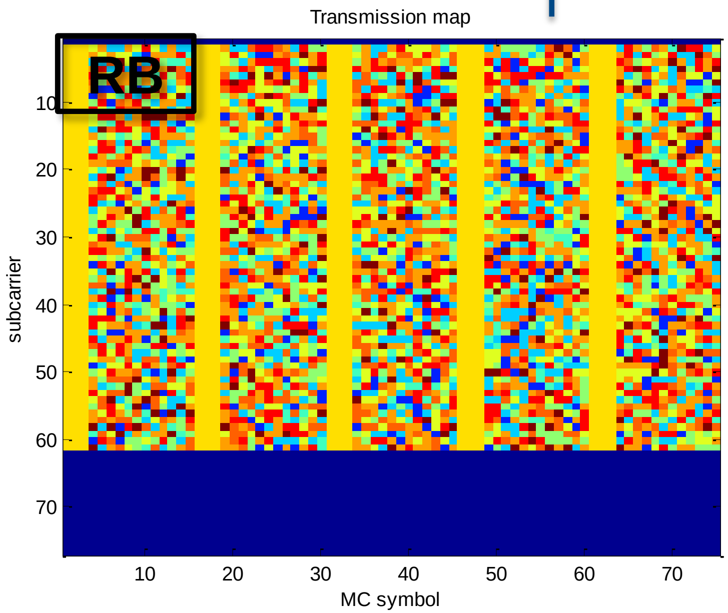
ESM scheme

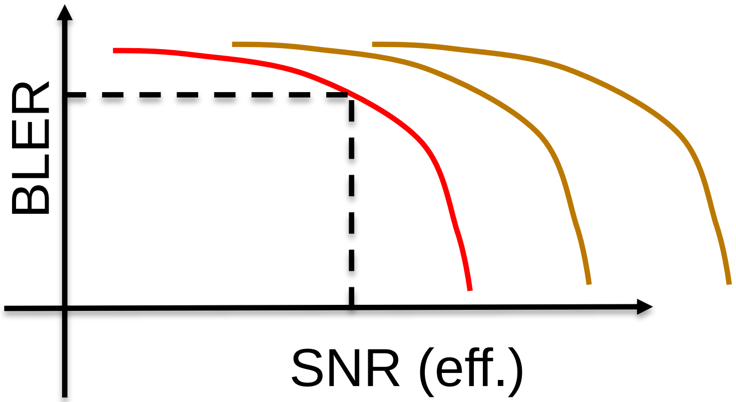
$$\mathrm{SINR}_{eff} = I^{-1}\left(\frac{1}{N} I\left(\mathrm{SINR}_n\right)\right)$$



ESM error modeling steps

1. Calculate $\mathrm{SNR}_{\mathrm{eff}}$ from $I(\mathrm{SNR}_n)$ mapping
2. Select appropriate AWGN SNR-BLER link performance curve
3. Calculate BLER corresponding to $\mathrm{SNR}_{\mathrm{eff}}$





Types of information measure functions

- Logarithmic ESM (**LESM**):

$$I(\gamma) = \log_{10}(\gamma).$$

- Capacity ESM (**CESM**):

$$I(\gamma) = \log_2(1+\gamma).$$

- Exponential ESM (**EESM**):

$$I(\gamma) = \exp(\gamma).$$

  – Can be derived theoretically based on Union-Chernoff bound of error probabilities for BPSK ($\beta = 1$) and QPSK ($\beta = 2$):

$$\mathrm{SNR_{eff}} = -\beta ln\left(\frac{1}{N}\sum_{n=1}^{N}\exp\left(-\frac{\mathrm{SNR_n}}{\beta}\right)\right)$$

  – β should be calculated for every modulation, CR, CB size

Mutual Information ESM

- MI measures the information that 2 random variables share

$$\mathrm{MI}(x,y) = \mathrm{E}_{x,y}\left[\log_2\left(\frac{p_{y|x}(y|x)}{p_y(y)}\right)\right]$$

- Log-Likelihood Ratio (LLR) shows how i-th realization of x is probable given y

$$\mathrm{LLR}_{x_i}(y) = \ln\left(\frac{P(x_i|y)}{\sum_{k=1,k\neq i}^{X} P(x_k|y)}\right)$$

- Using Bayes' theorem we can show

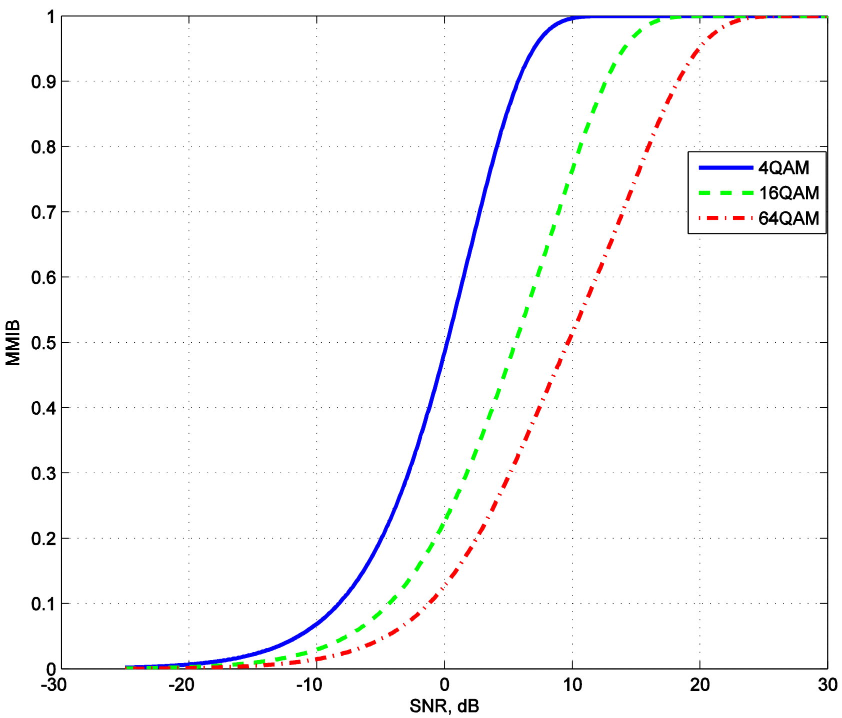
$$\mathrm{MI}(x,y) = \frac{1}{X}\sum_{i=1}^{X} \mathrm{E}_{y|x_i}\left[g\left(\mathrm{LLR}_{x_i}(y)\right)\right]$$

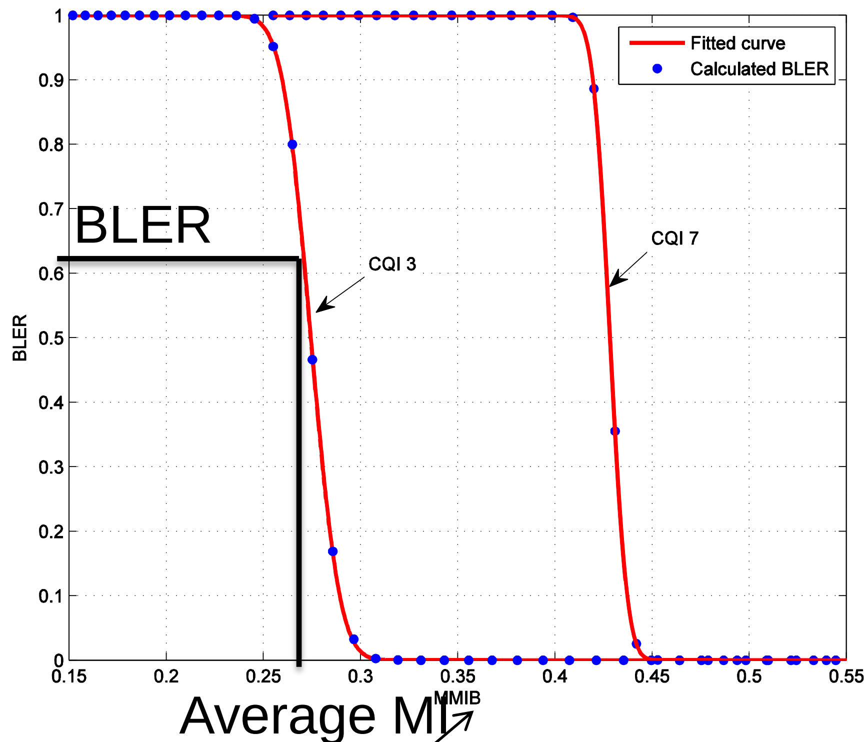
- MI can be calculated if PDF of $\mathrm{LLR}_{x_i}(y)$ is known

RBIR and MMIB

- **Received Bit Mutual Information Rate (RBIR) ESM**
  - y are channel disturbed symbols; x_i constellation symbols
  - $\mathrm{LLR}_{x_i}(y)$ are normally distributed (SINR, modulation)
  - MI per received bit $I_{RBIR}(SNR) = \frac{MI_{symbol}(SINR)}{M}$
  - $I_{RBIR}(SNR)$ approximation → mapping tables
- <u>**Mean Mutual Information per coded Bit (MMIB) ESM**</u>
  - y are channel disturbed symbols; x_i is bit at certain position
  - $\mathrm{LLR}_{x_i}(y)$ are mixtures of Gaussian distributions
  - Mean MI per bit $I_{MMIB}(SNR) = \sum_{j=1}^{M} MI_{bit_j}(SNR)/M \approx I_M(SNR)$
  - $I_M(SNR)$ has analytical expression for 4QAM, 16QAM and 64QAM

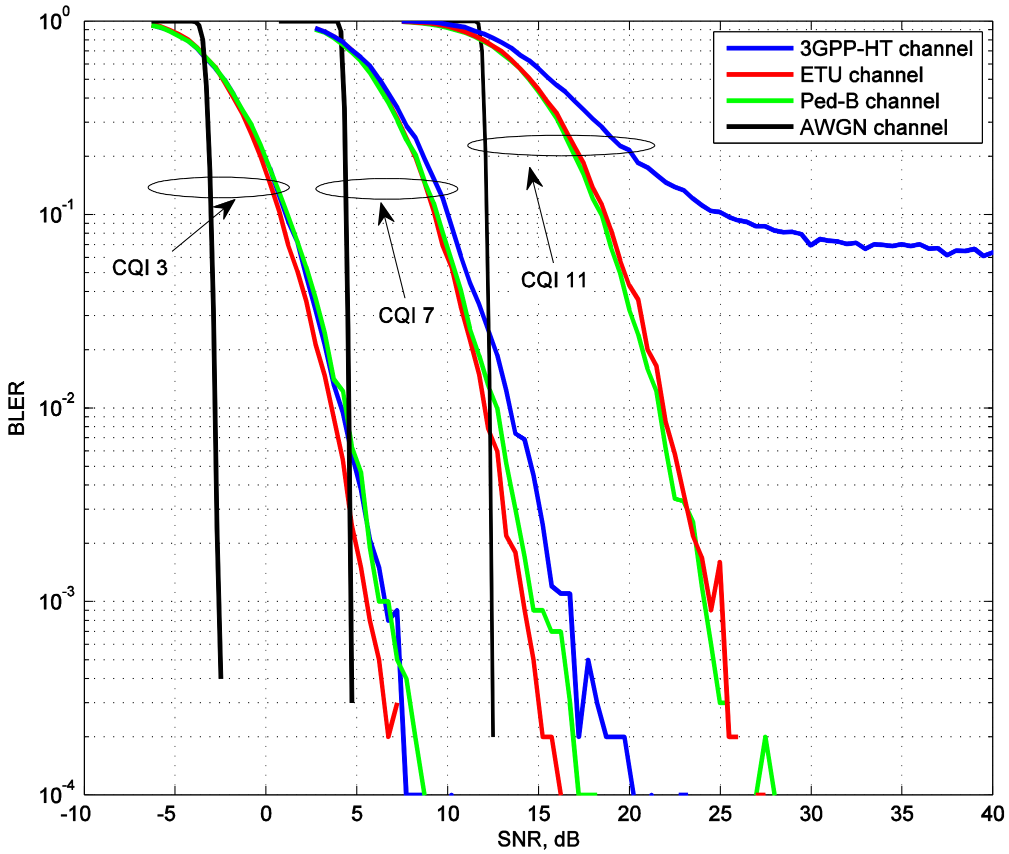
MMIB approach





Difficult to inverse MMIB measure function

FBMC performance in fading channels



FBMC/OQAM distortion

- Approximation of the received signal (R-order expansion)

$$r[n] \approx \sum_{l=-\infty}^{\infty} \sum_{m=0}^{M-1} d_{l,m} \sum_{r=0}^{R-1} (-j2\pi)^r \frac{1}{r!} g_{l,m}^{(r)}[n] H^{(r)}[l,m] + \eta[n]$$

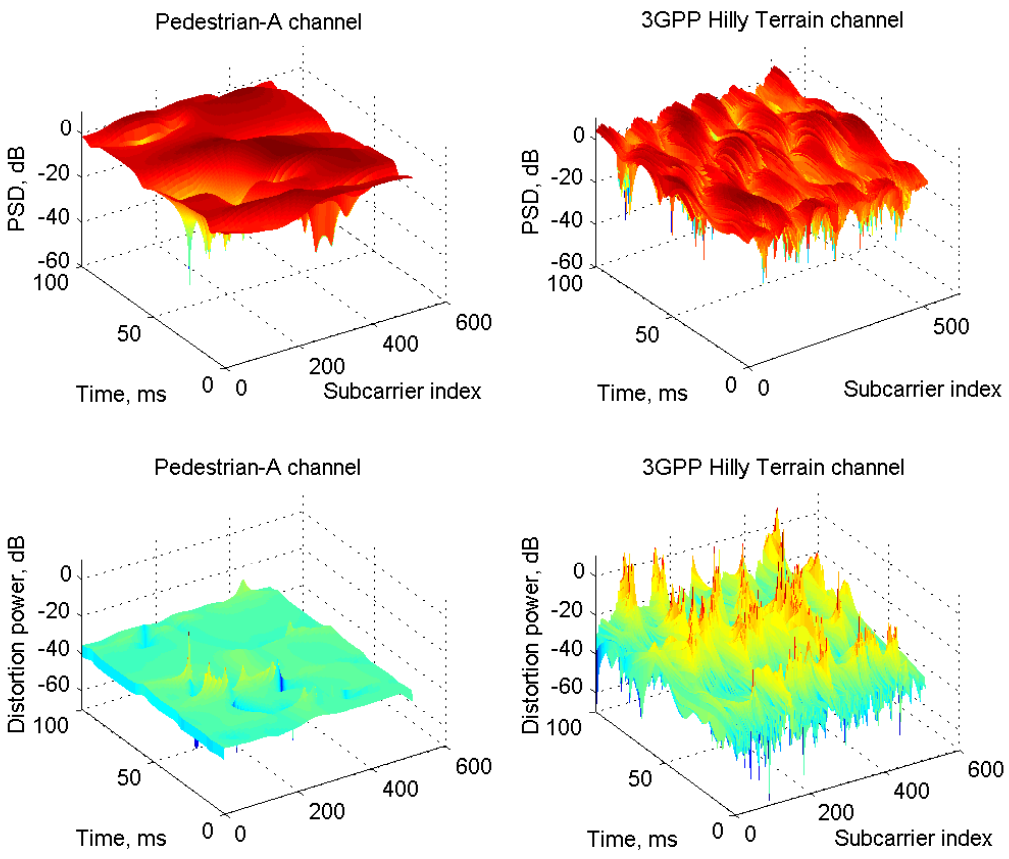
- Estimated real information symbols

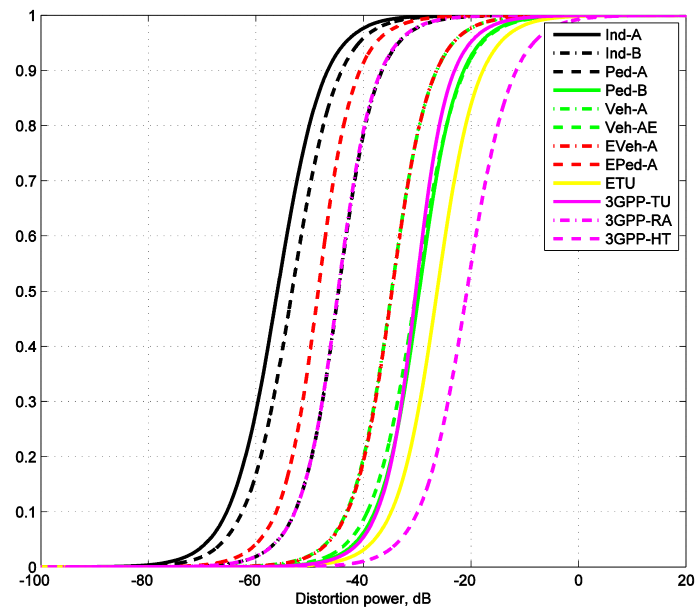
$$\widehat{d_{l,m}} \approx d_{l,m} + Re\{I_{l,m}^{R}\},$$

- First order approximation of Residual Error Power (REP)

$$P_e^{(1)}[m] = \frac{2P_s}{M^3} \left\| \frac{H'[m]}{2\pi H[m]} \right\|^2 G$$

FBMC distortion power





Link-level abstraction algorithm

1. MI-BLER AWGN curves (or approximations) are given

2. Calculate channel quality measures γ_k (SNDR):

$$\gamma_k = \frac{P_s}{N_0 + P_e^{(1)}}$$

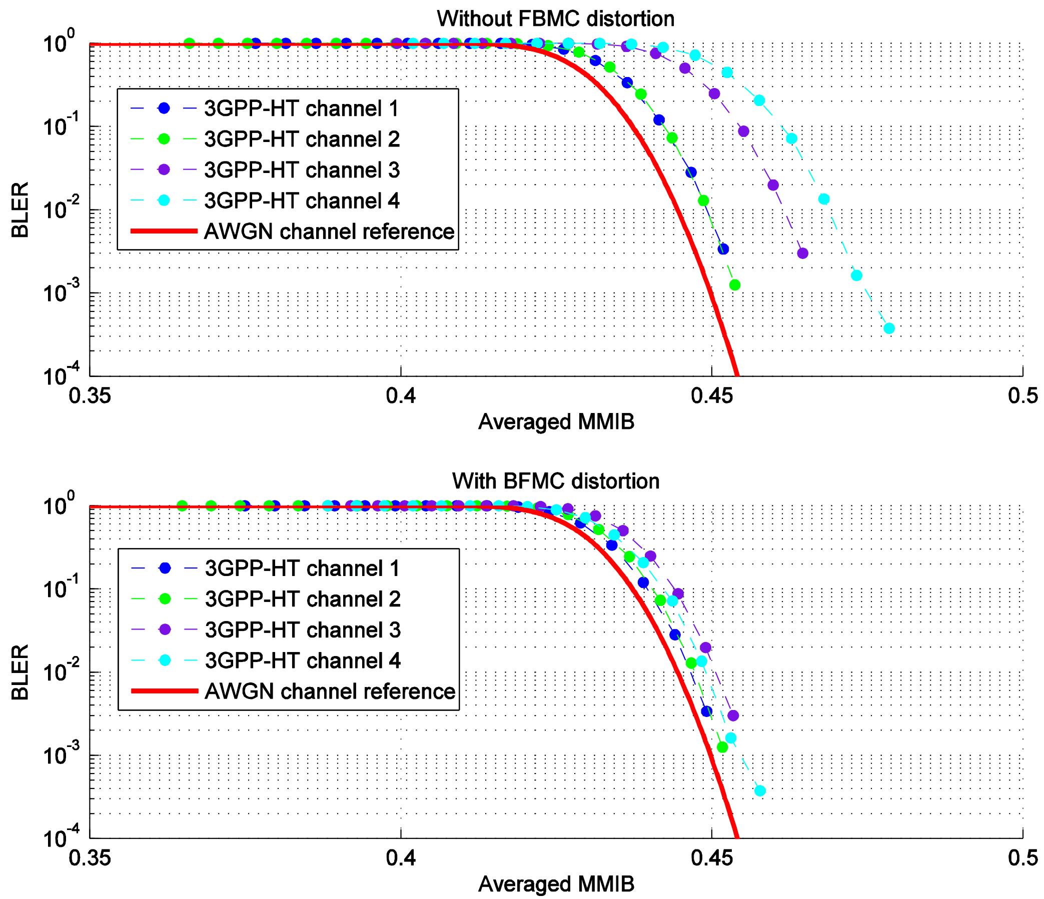
3. Calculate MMIB values for each SNDR γ_k

4. Averaging of MMIB values:

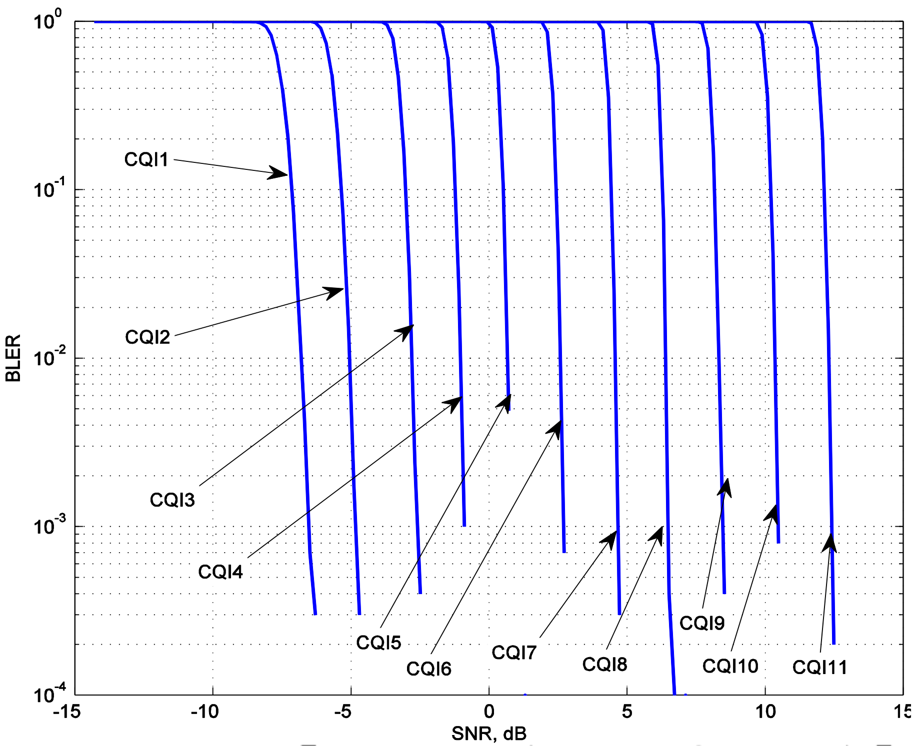
$$AMI = \frac{1}{K}\sum_{k=1}^{K} I_{xxQAM}(\gamma_k),$$

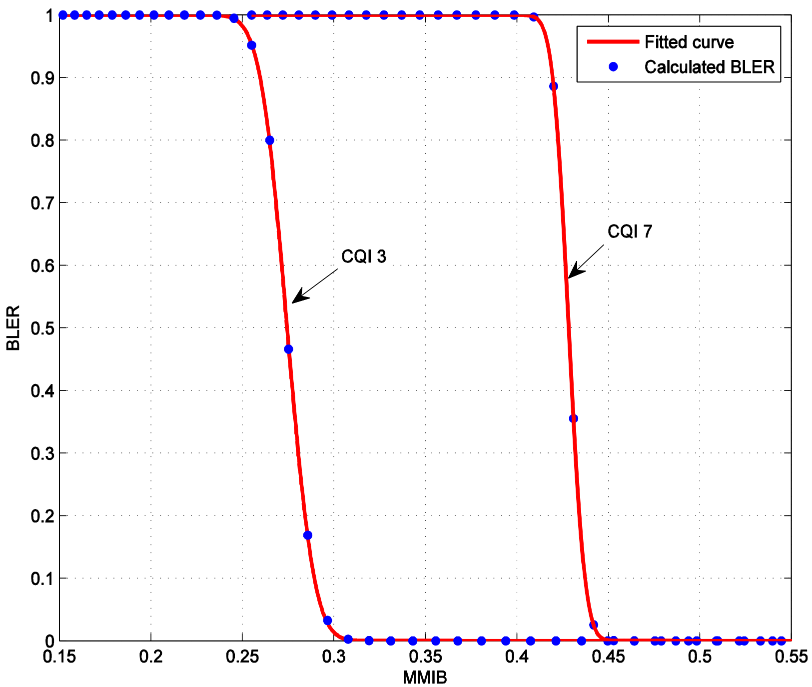
5. Define BLER from MI-BLER curve

SNDR instead of SNR, results



AWGN BLER curves for FBMC/OQAM





$$BLER_{CQI,CBS}(MMIB) = \frac{1}{2}\left[1 - erf\left(\frac{MI - b_{CQI,CBS}}{\sqrt{2}c_{CQI,CBS}}\right)\right]$$

CQI	CBS	$b_{CQI,CBS}$	$c_{CQI,CBS}$
3	1248	0.274	0.012
7	4864	0.428	0.07
11	6144	0.604	0.07

Applications of link-level abstraction in System-level simulations

- Defining reception for given channel realization (usually RB resolution)
- Prediction of BLER level (UE reported CQI) for channel adaptation

Part 6-3

SYSTEM-LEVEL SIMULATIONS AND NS-3

Static vs. dynamic simulators

System simulators			
	Static simulators "Snapshot"	**Quasi-Static simulators**	**Dynamic simulators**
Algorithms	Simplified and limited algorithms, e.g no outer power control	Extensively modelled RRM	Fully modelled RRM
Path Loss	Fixed	Fixed	Varied every timeslot (slot, TTI, etc.)
Time Domain	No	Yes	Yes
Mobility	Static	Static	Moving randomly
Computational Complexity	Fast	Middle	Slow
USE Cases	Interference study between systems, etc.	RRM study excluding mobility, etc.	Mobility Study, RRM Study, etc.

Simulator input, i.e. parameterization

- Basically everything within a simulation may/need to be parameterized
  - Number of terminals
  - Simulation length
  - Scenario and topology
  - Mobility
  - Traffic
  - RRM specifics
  - …

Fading types

- Radio propagation
  - Empirical mathematical formulation for the characterization of **radio wave propagation as a function of frequency, distance** and other conditions
  - In practice, most simulation studies use **empirical models** that have been developed based on measurements taken in various real environments
    - Hata model
    - COST 231 extension to Hata model
    - COST 231 Walfish-Ikegami model

Fading types (cont.)

- Slow fading
  - Shadow fading is caused by **obstacles in the propagation path** between the UE and the eNodeB and can be interpreted as the irregularities of the geographical characteristics of the terrain introduced with respect to the average pathloss obtained from the macroscopic pathloss model
  - Some part of the transmitted signal is lost through **absorption, reflection, scattering, and diffraction**
- Fast fading
  - Fast fading occurs if the channel impulse response changes rapidly within the symbol duration
  - Fast fading occurs when the coherence time of the channel is smaller than the symbol period of the transmitted signal
  - This causes frequency dispersion or time selective fading due to Doppler spreading
  - Fast Fading is due to reflections of local objects and the motion of the objects relative to those objects

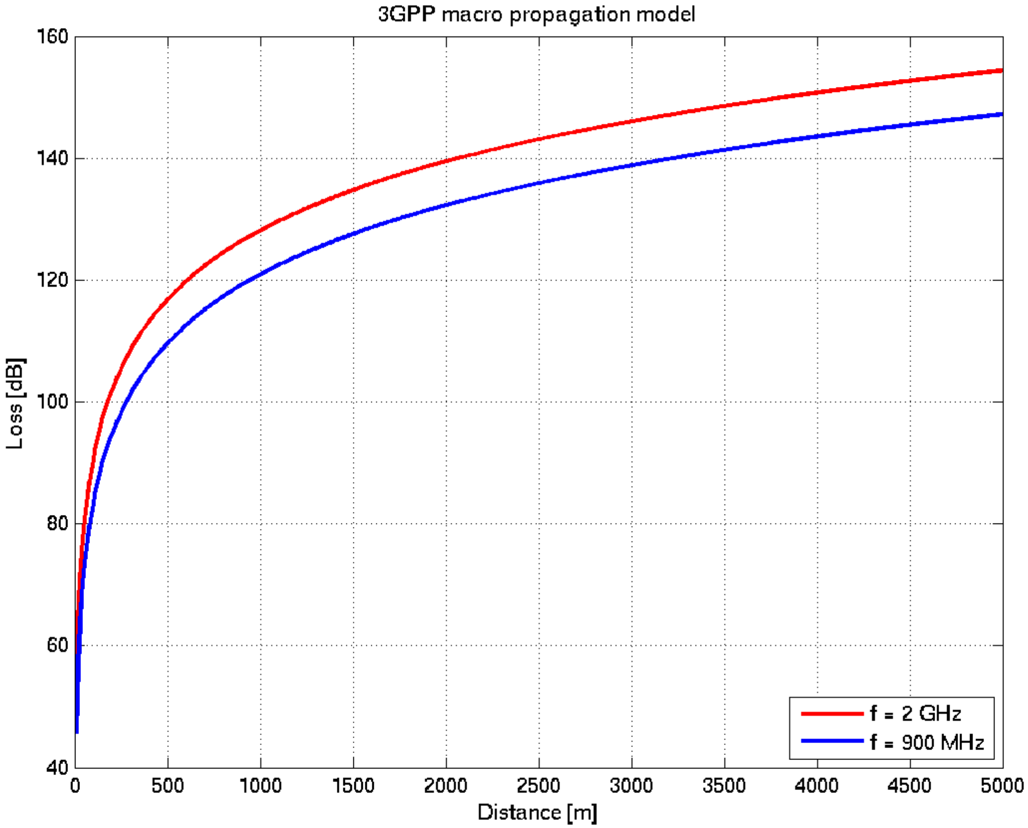
3GPP Macro Propagation

- 3GPP 25.942
  - Macro cell propagation model is applicable for the test scenarios in urban and suburban areas outside the high rise core where the buildings are of nearly uniform height
    - **L= 40(1-4x10-3Dhb) Log10(R) -18Log10(Dhb) + 21Log10(f) + 80 dB.**
  - Where:
    - R is the base station - UE separation in kilometers
    - f is the carrier frequency of 2 000 MHz
    - Dhb is the base station antenna height, in meters, measured from the average rooftop level
- The base station antenna height is fixed at 15 meters above the average rooftop (Dhb = 15 m). Considering a carrier frequency of 2000 MHz and a base station antenna height of 15 meters, the formula becomes:
  - **L = 128.1 + 37.6 Log10(R)**

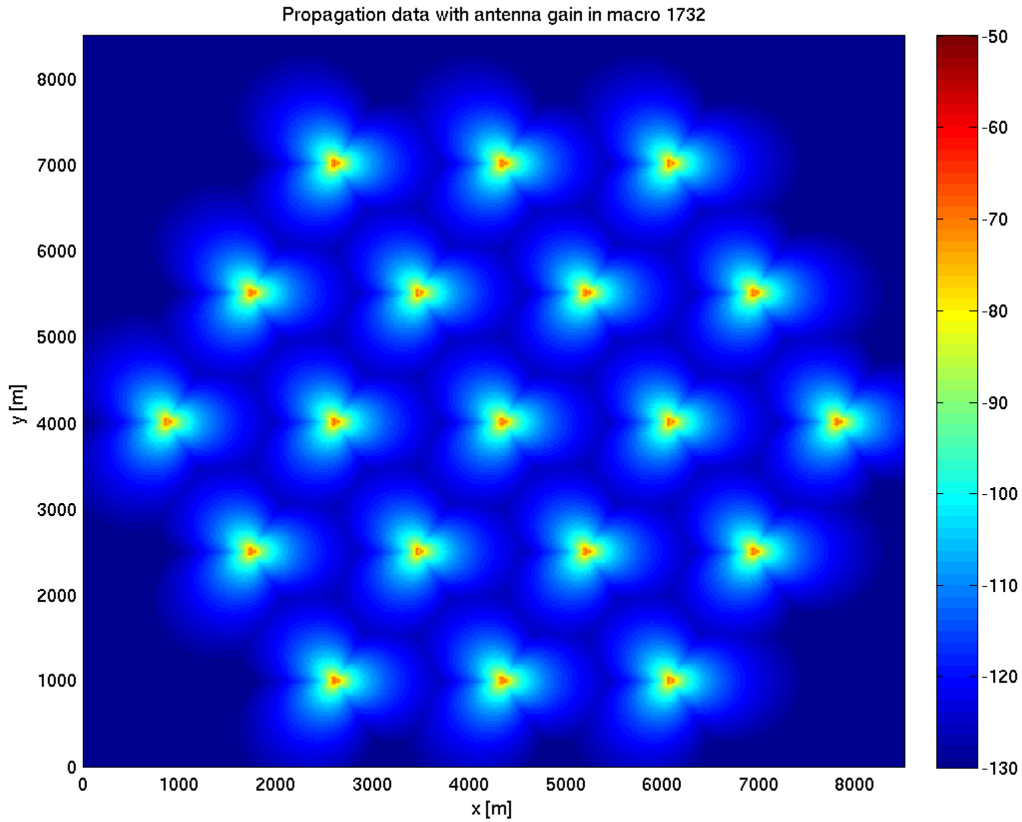
Parameters of propagation models (EMPHATIC)

Parameter description	Parameter value
Carrier frequency	- 422.5 MHz (Downlink), 412.5 MHz (Uplink), - 760.5 MHz (Downlink), 790.5 MHz (Uplink)
Pathloss model	- Communication with BS: ○ SISO case: Extended Hata (Seamcat) for communication ○ MIMO: Rural Macro-cell, COST2100 - DMO communication: ○ ITU-R P.1411-4 (LOLA) in the absence of Line of Site (LoS) ○ Extended HATA for LoS and distance less 100m
Shadowing (optional)	Lognormal, standard deviation: 9 dB Correlation distance: 50 m Shadowing correlation: between cells 0.5, between sectors 1.
Penetration loss	20 dB
Fast fading channel models	- SISO case: ITU PedA, ITU PedB, ITU VehA, ITU VehB, Extended TU (ETU), PedB, 3GPP-HT, 3GPP-TU ; - MIMO: Rural Macro-cell, COST2100
Channel estimation	Ideal, delay free

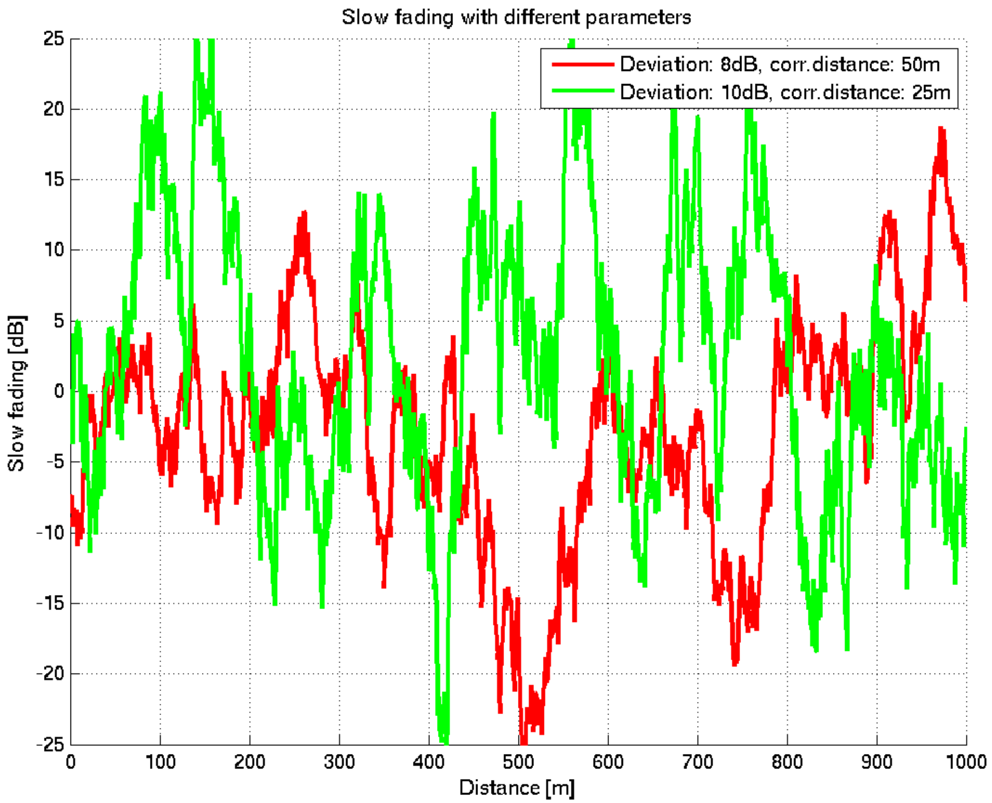
3GPP propagation data



3GPP propagation data

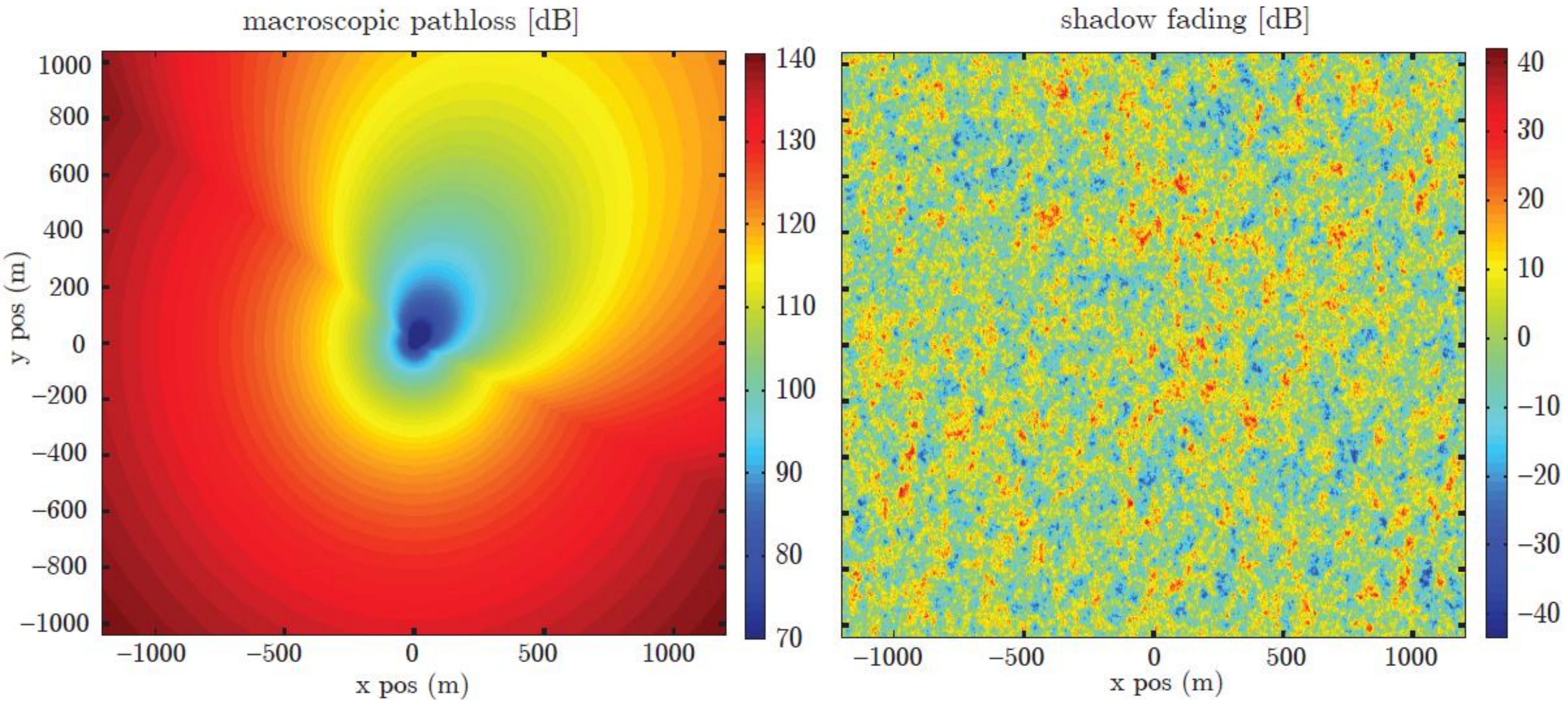


Slow fading



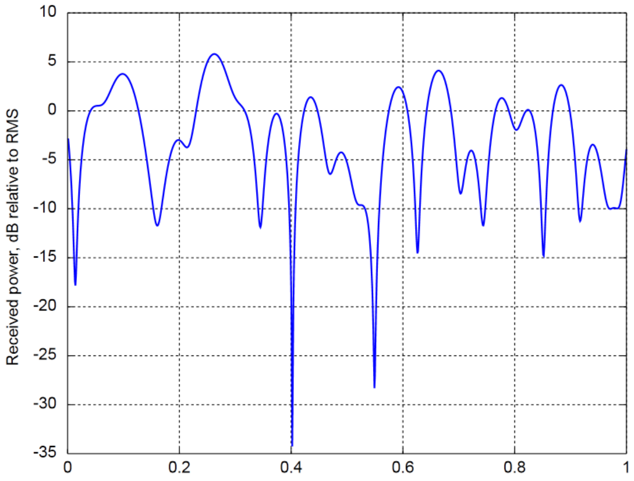
- Log-normal distribution
- Mean: 0dB
- Deviation: x dB
- Correlation distance: y m

Propagation + slow fading



Fast fading

- A stochastic model
  for radio propagation anomaly caused by partial cancellation of a radio signal by itself
  - the signal arrives at the receiver by several different paths (hence exhibiting multipath interference), and at least one of the paths is changing (lengthening or shortening)
  - Rayleigh fading
  - Rician fading



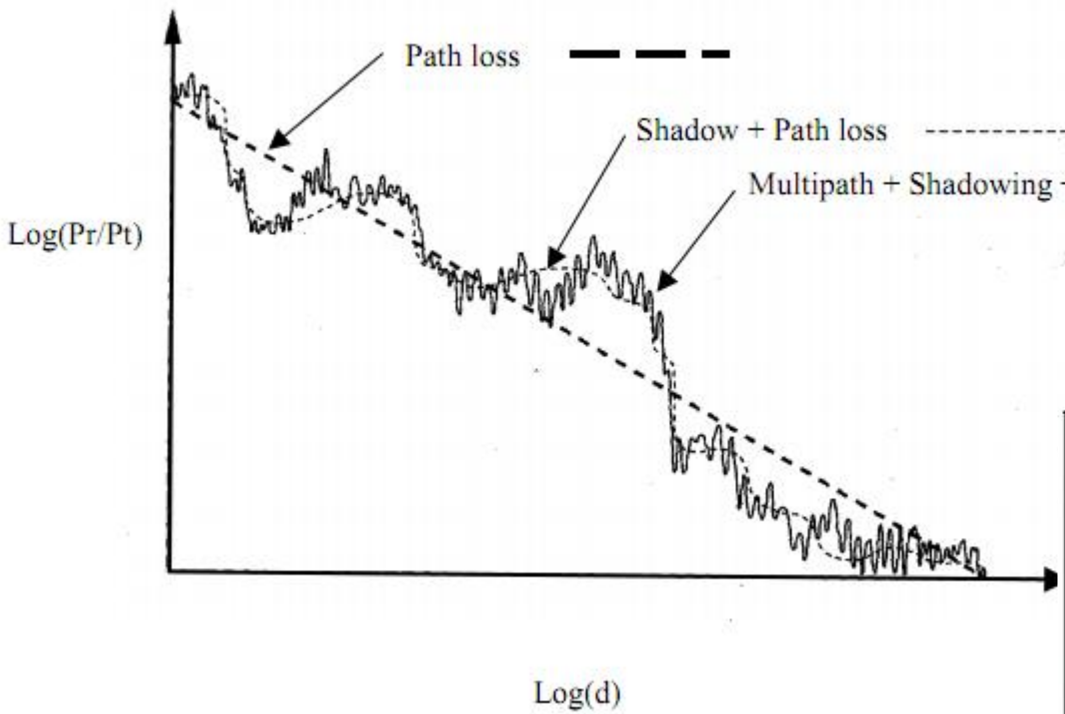
ITU vehicular channel models

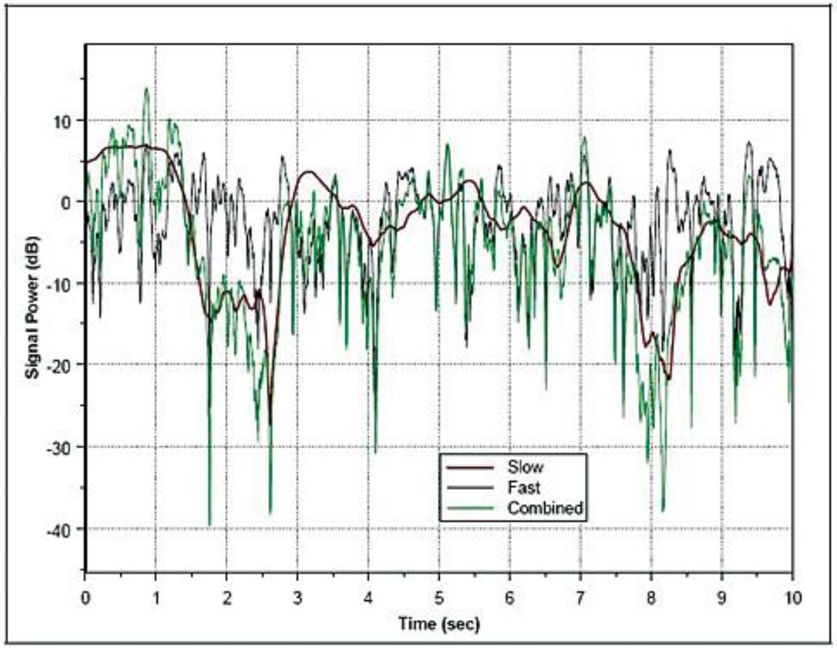
Tap	Channel A		Channel B		Doppler spectrum
	Relative delay (ns)	Average power (dB)	Relative delay (ns)	Average power (dB)	
1	0	0	0	0	Classic
2	110	–9.7	200	–0.9	Classic
3	190	–19.2	800	–4.9	Classic
4	410	–22.8	1 200	–8.0	Classic
5	–	–	2 300	–7.8	Classic
6	–	–	3 700	–23.9	Classic

Tap	Channel A		Channel B		Doppler spectrum
	Relative delay (ns)	Average power (dB)	Relative delay (ns)	Average power (dB)	
1	0	0.0	0	–2.5	Classic
2	310	–1.0	300	0	Classic
3	710	–9.0	8.900	–12.8	Classic
4	1 090	–10.0	12 900	–10.0	Classic
5	1 730	–15.0	17 100	–25.2	Classic
6	2 510	–20.0	20 000	–16.0	Classic

- ITU-R recommendation M.1225
- Outdoor-to-indoor pedestrian
- Vehicular
- Low delay spread (A),
- Medium delay spread (B)

Propagation, slow and fast fading



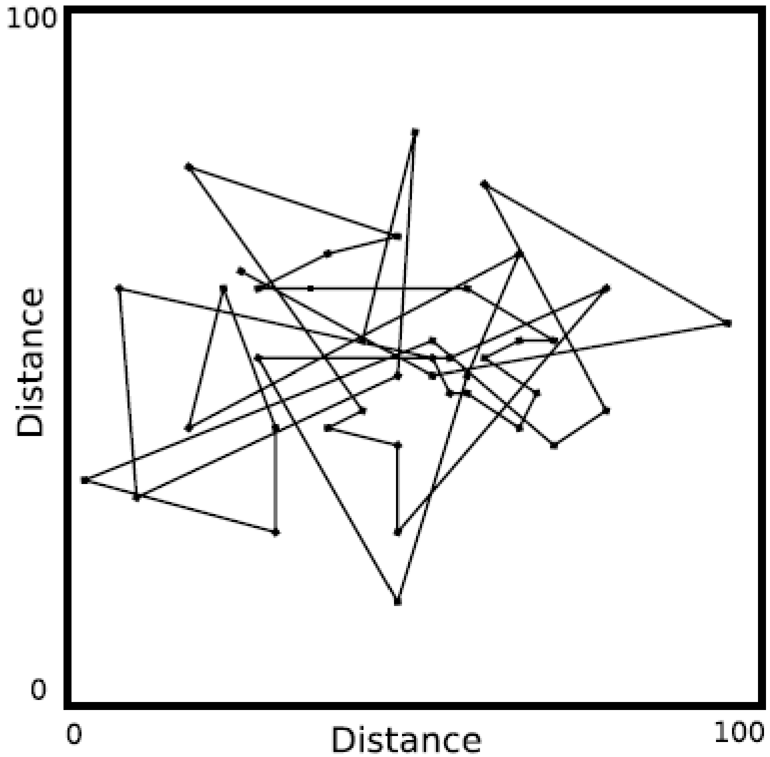


Mobility models

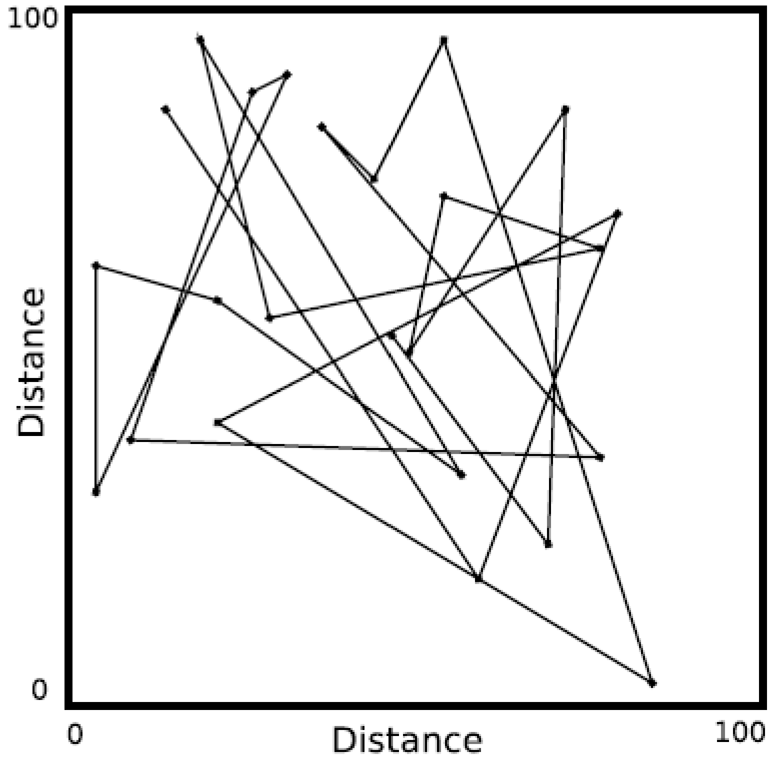
- Mobility models represent the movement of mobile users, and how their location, velocity and acceleration change over time
- In certain scenarios the mobility plays an important role, e.g. mobile ad hoc networks
- Several ways of categorizing mobility models
  - Traces and synthetic mobility models
  - Entity and group mobility models
  - Human, animal and vehicle mobility models
  - Normal situation and special situation mobility models
- Usual factors
  - Speed: [speedmin; speedmax]
  - Direction: [0, pi]
  - Time or distance before making the next turn

Mobility models

Random walk

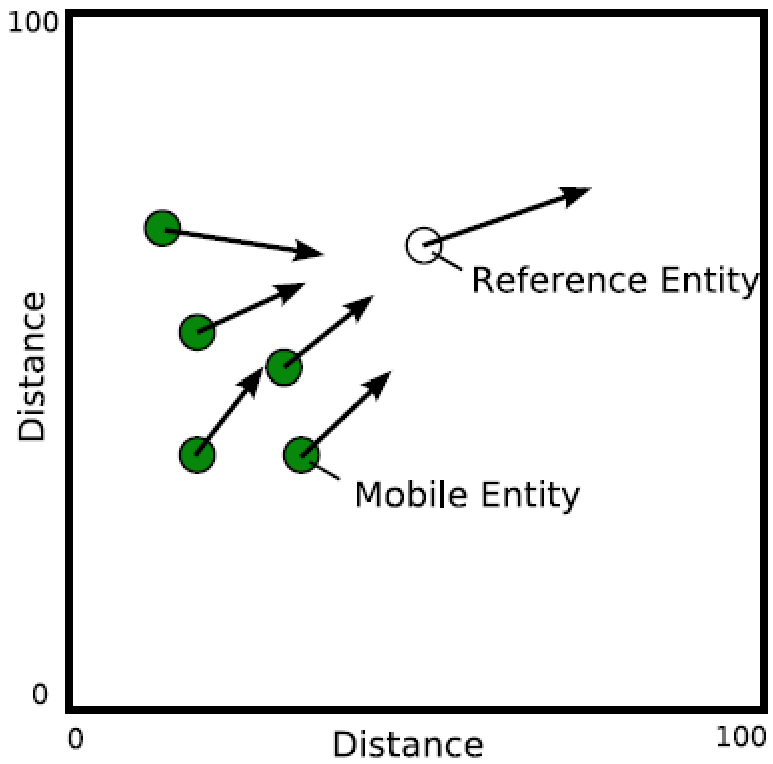


Random waypoint

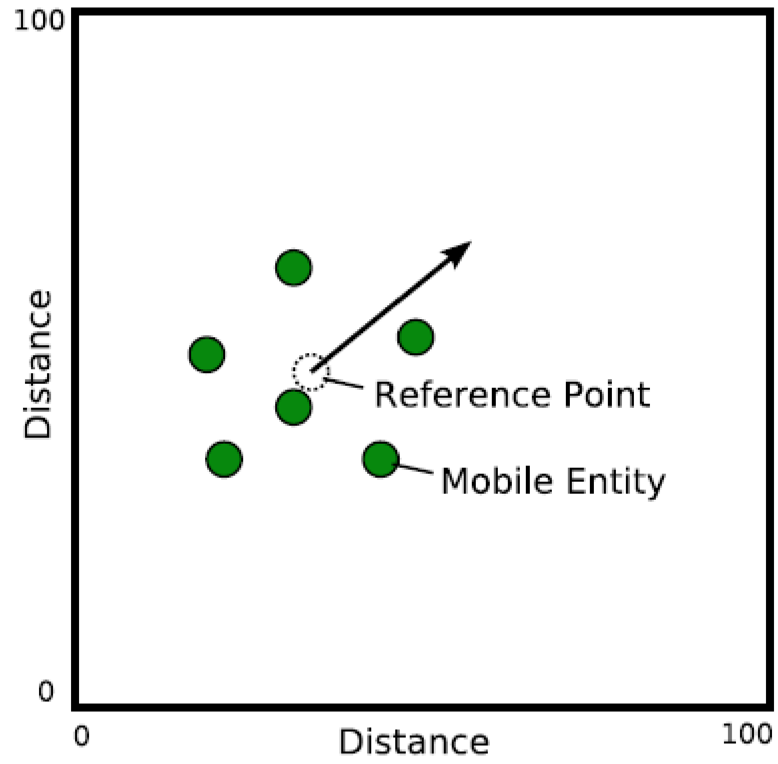


Mobility models

Pursue

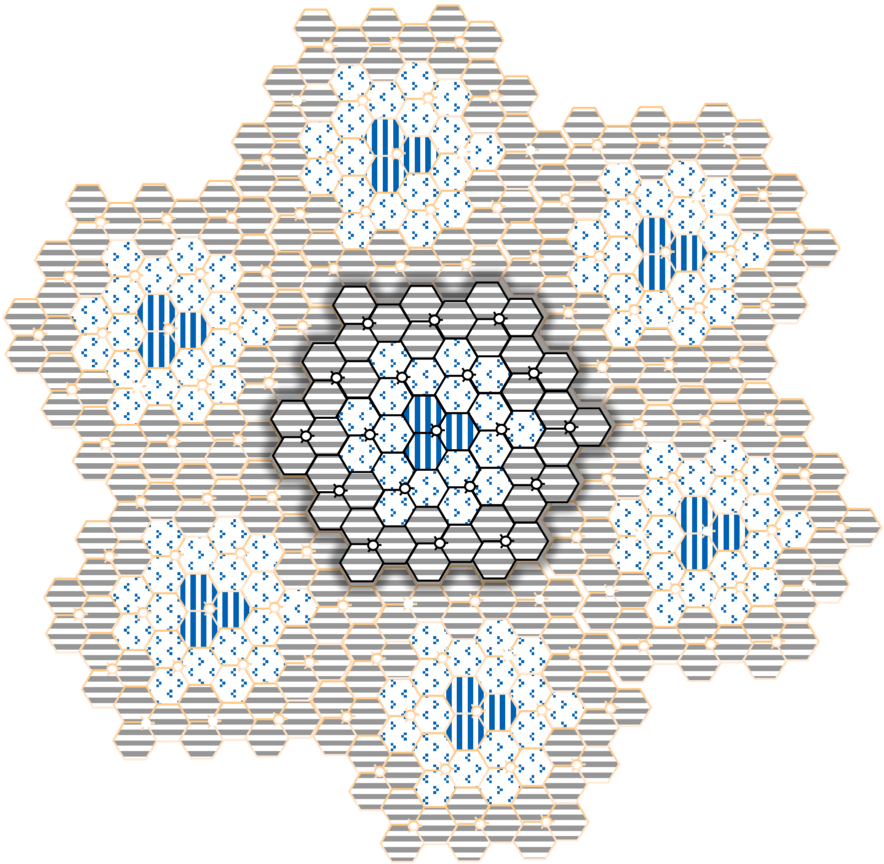


Nomadic Community



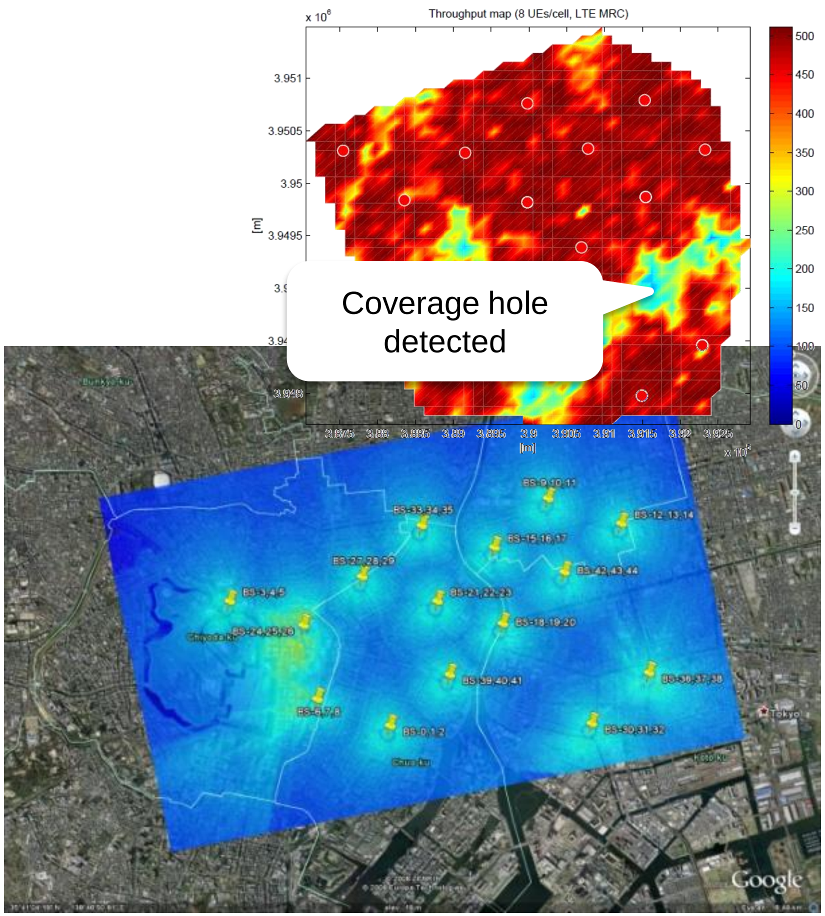
Simulation scenarios

- With wrap-around radio conditions of the actual simulation area are replicated around the actual simulation area where UEs are located



Simulation scenarios

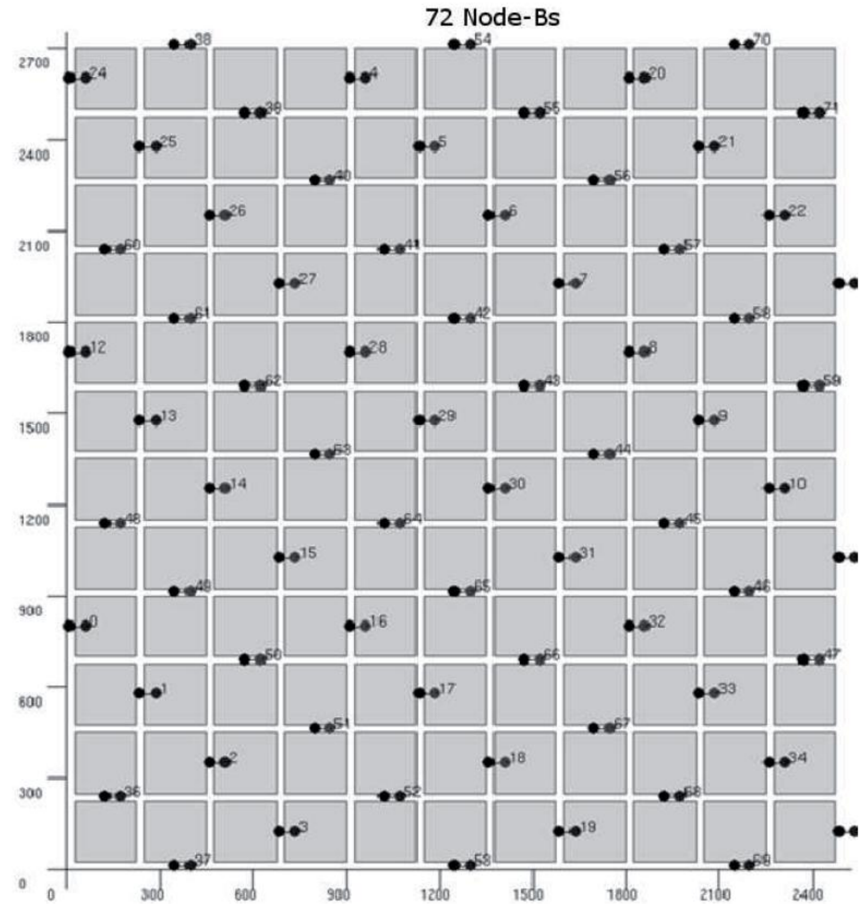
- Propagation data acquired for a certain real-world area from a network planning tool
- Defined site positions
- E.g. In the figure, Tokyo downtown



* J. Puttonen, I. Repo, K. Aho, T. Nihtilä, J. Kurjenniemi, T. Henttonen, M. Moisio, K Chang, “Non-regular network performance comparison between HSDPA and LTE”

Simulation scenarios

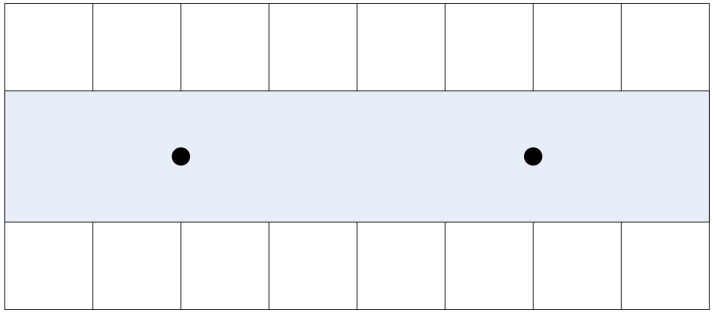
- UMTS 30.03
- Scenario
  - Block sizes
  - BS locations
- Mobility
  - Turn probabilities
- Propagation
  - LOS
  - NLOS



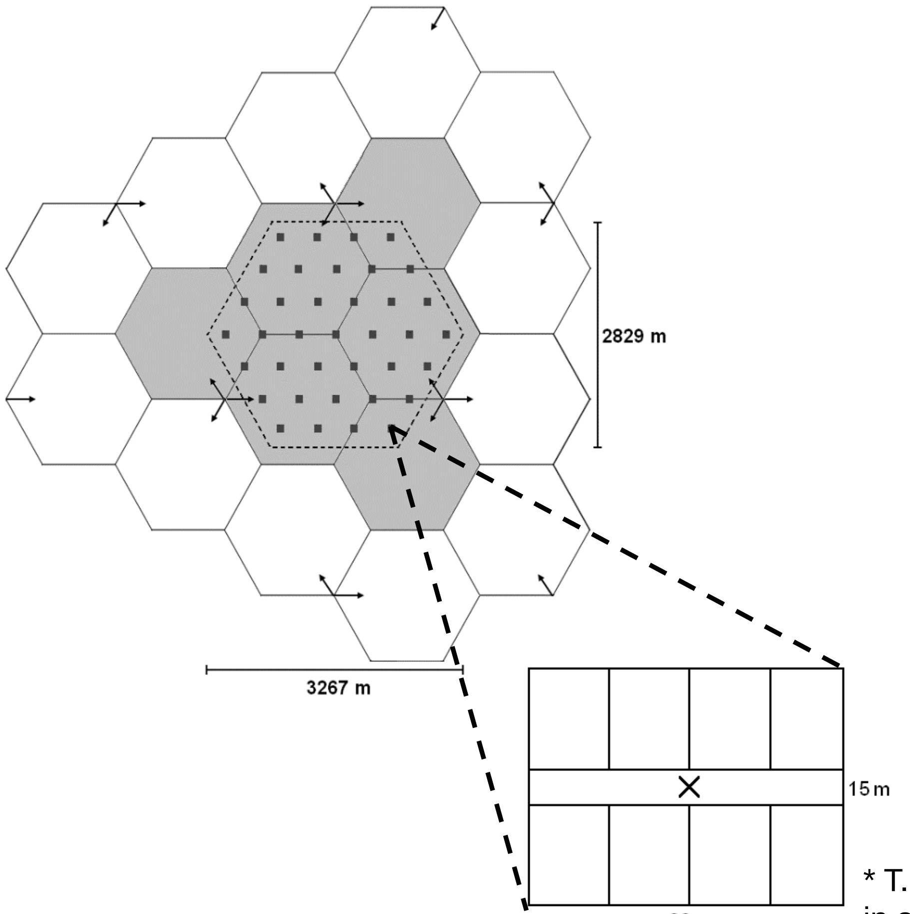
Simulation scenarios

- Indoor
  - COST 321 multi-wall model with wall dependent additional losses
  - 3GPP indoor propagation with LOS and NLOS components

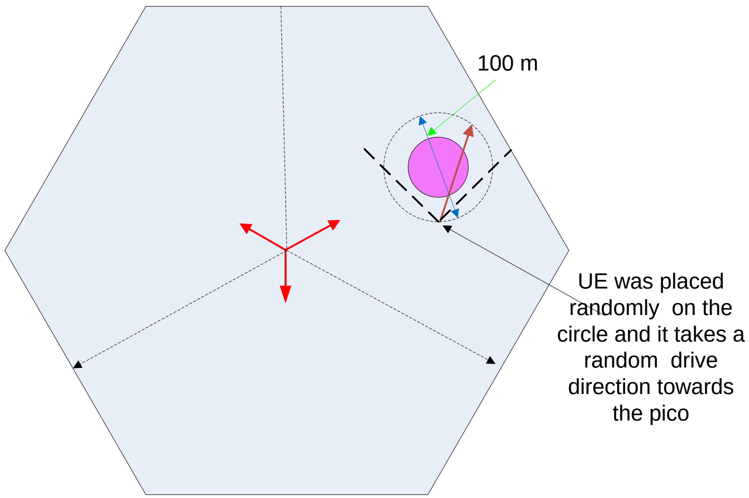
ITU-R evaluation scenario for LTE-A



Simulation scenarios



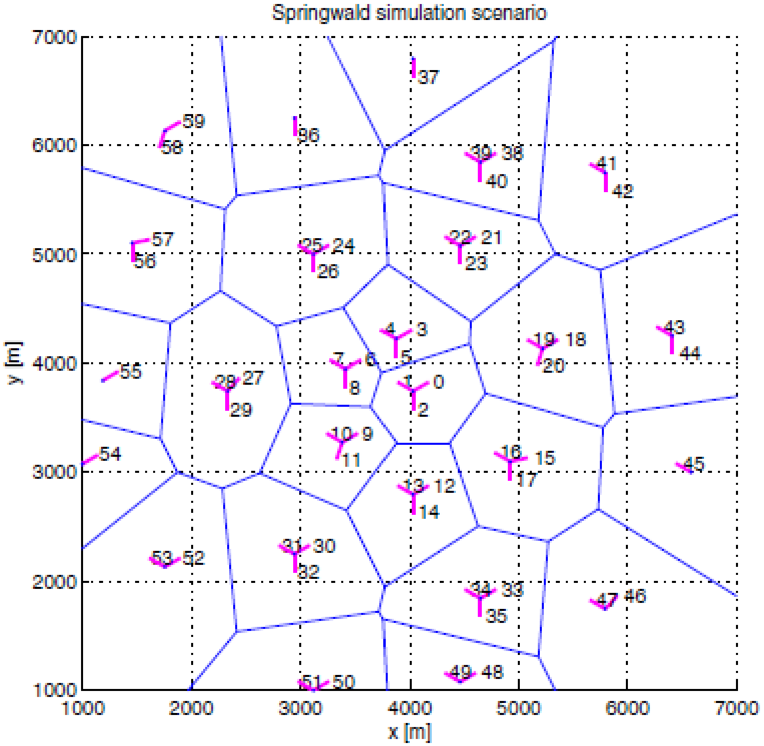
[3GPP TR 36.839]



* T. Nihtilä, "Capacity Improvement by Employing Femto Cells in a Macro Cell HSDPA Network", Proc. of the IEEE Symposium on Computers and Communications, Marrakech, Marocco, July 6-9, 2008

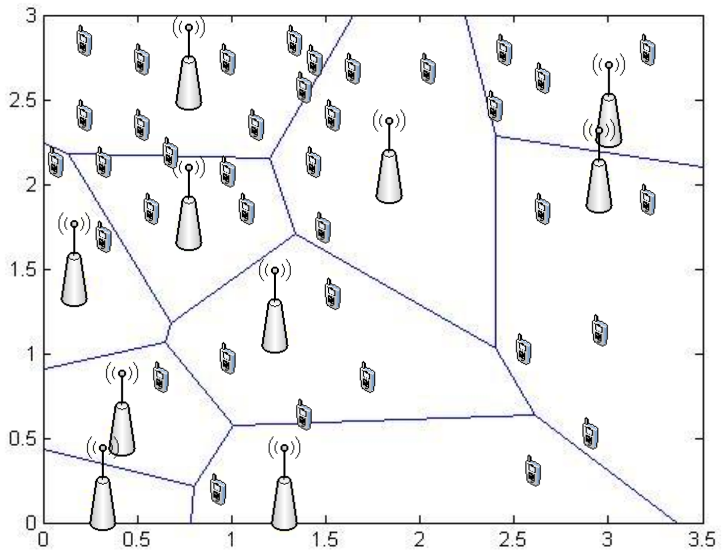
Simulation scenarios

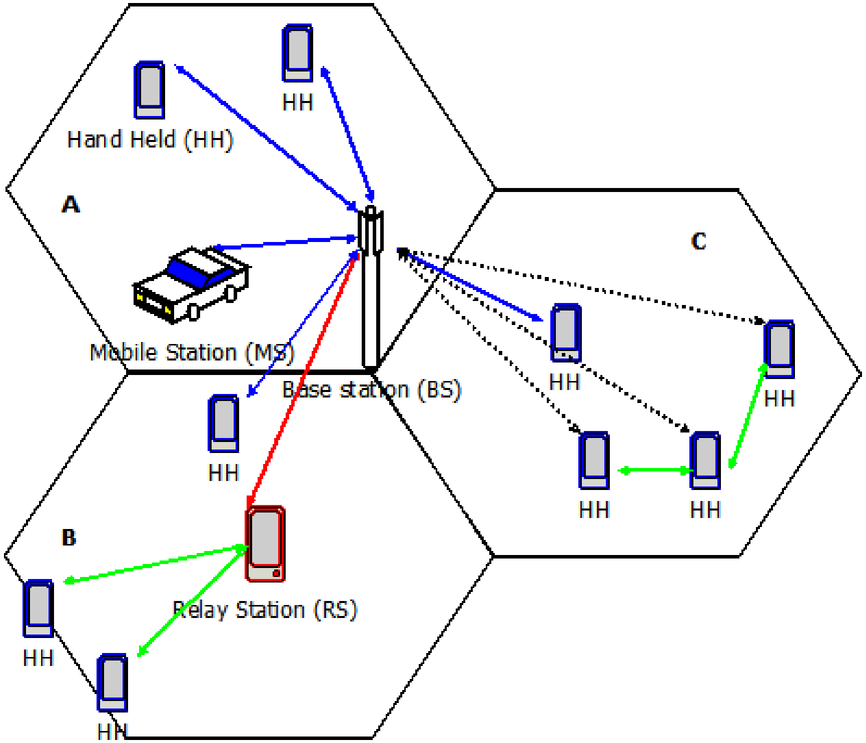
- Springwald
  - ISD varies being about 500m in minimum and about 1500m in maximum
- Realism
  - Varying load per BS
  - Mobility problems, coverage holes
  - UL / DL imbalance issues



* J. Turkka and A. Lobinger, “Non-regular Layout for Cellular Network System Simulations”, Proc. of the 21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Istanbul, Turkey, September 26-29, 2010

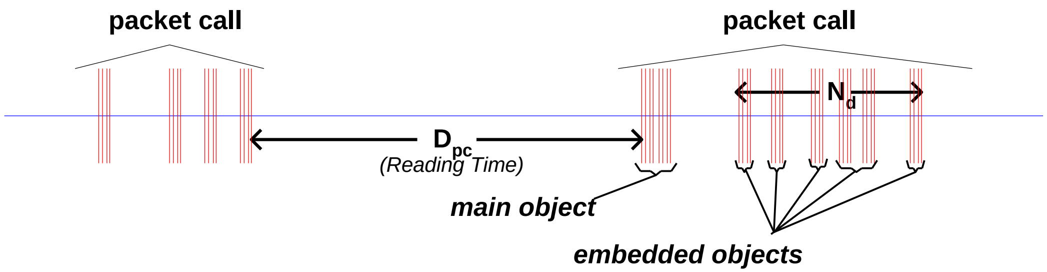
EmPhAtic simulation scenarios

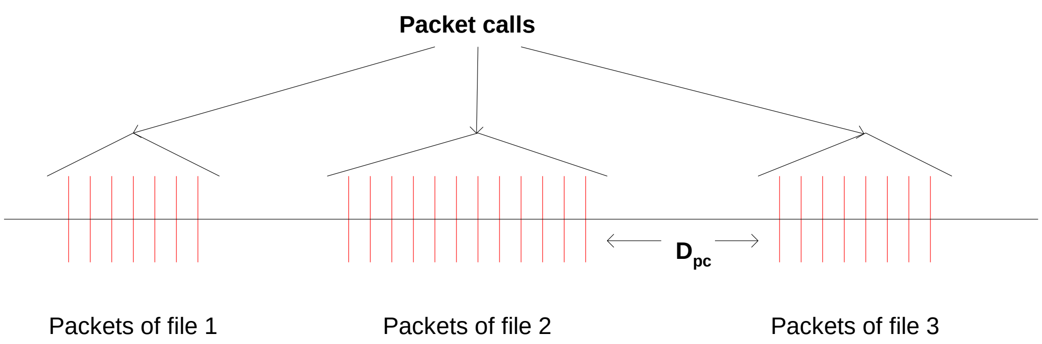




Traffic models

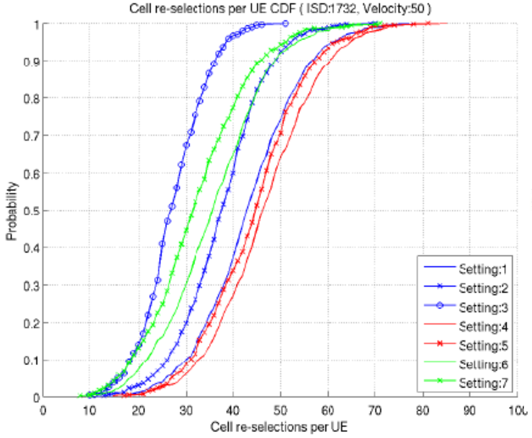
- Defined by standardization organizations
  - Infinite buffer
  - FTP
  - Constant Bit Rate (CBR)
  - HTTP models (bursty)
  - AMR codecs for VoIP
  - NRT traffic (video)

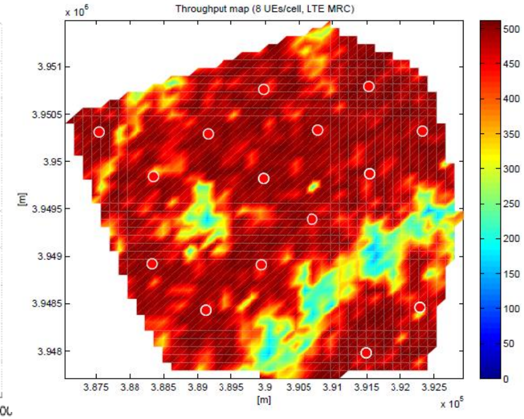


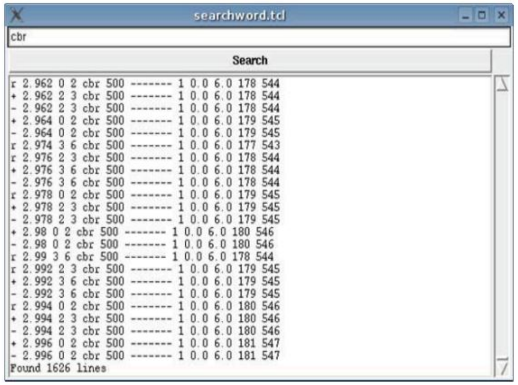


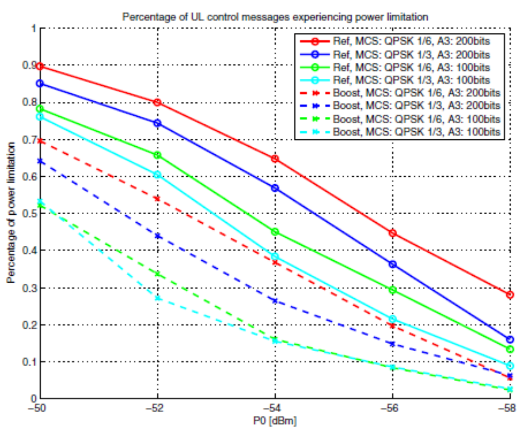
Metrics and performance indicators

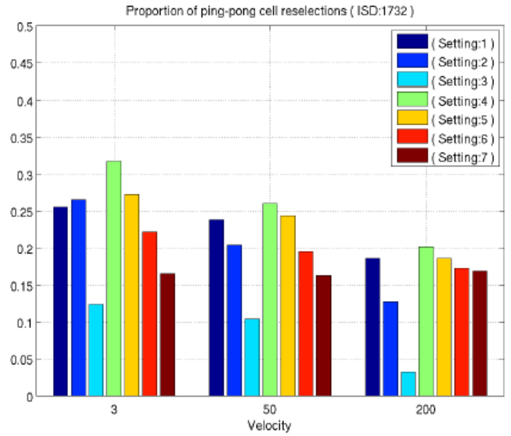
- Cumulative distribution function (CDF)
- Line plots
- Bar plots
- Map plots
- Traces











Available system-level simulators

- Most suitable:
  - **Network Simulator-2 (NS-2)** http://isi.edu/nsnam/ns/
  - **Network Simulator-3 (NS-3)** http://www.nsnam.org/
  - **OMNeT ++** http://www.omnetpp.org/
  - openWNS https://launchpad.net/openwns
  - LTE-Sim http://telematics.poliba.it/index.php/en/lte-sim
  - **The Vienna LTE simulators** http://www.nt.tuwien.ac.at/about-us/staff/josep-colom-ikuno/lte-simulators/
- Other open
  - JiST http://jist.ece.cornell.edu/
  - GoMoSim http://pcl.cs.ucla.edu/projects/glomosim/
- Proprietary
  - QualNet http://www.scalable-networks.com/products/qualnet/
  - NetSim http://tetcos.com/software.html

Simulators comparison

	ns-2	ns-3	OMNeT++	openWNS	Vienna LTE Simulator
License	GNU GPLv2	GNU GPLv2	Free for academy and education	LGPL	Academic usage only
Technologies	+	+	+	-	LTE link + system
Support/development	-	+	+	-	+
Real time integration	+-	+	+	-	-
Platform	C++ and OTcl	C++ and Python	C++ and NED	Python with C++ libraries	Matlab and C
Performance	-	+	+-	?	?

Advantages of Open Source tools

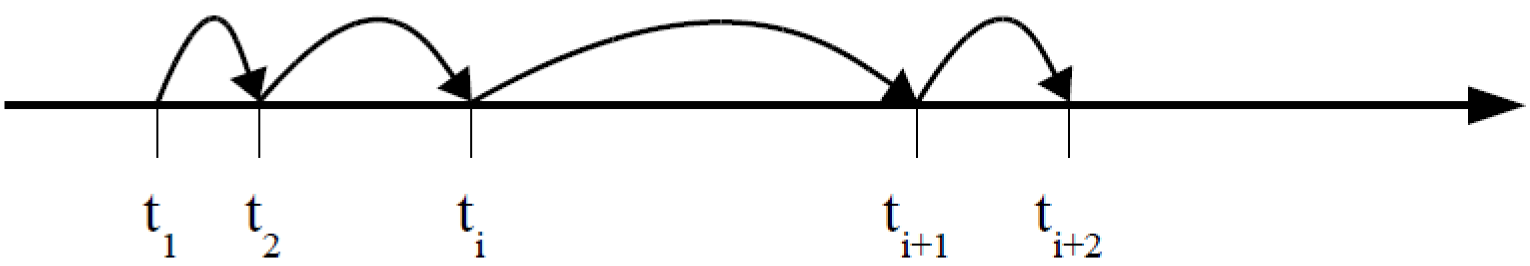
- All models are open, possible to check and validate
- Free of charge
- Big community for development, discussion, support
- Easy to develop/modify models on top of existing code

- Usual disadvantages:
  - Adjustments are needed to adopt to specific needs
  - No official support
  - How well code is managed and maintained (many separate repos)?

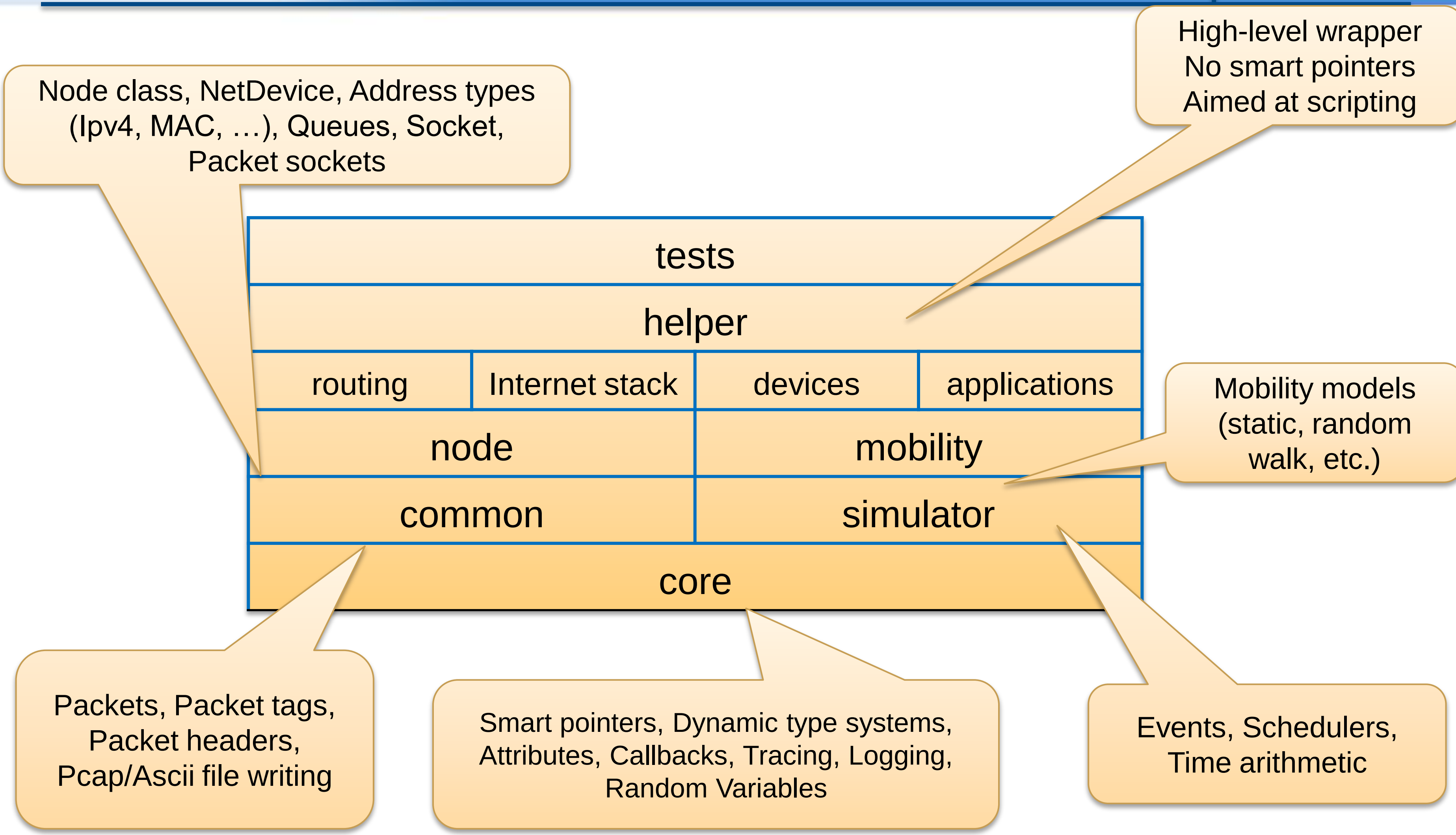
- Started in July 2006, the first release on June 30, 2008.
- Open-sours project (GPLv2)
- Simulation core and models are implemented in C++; Bindings in Python for python simulations
- NS-3 is a discrete-event network simulator
- Elaborated API, solid simulation core and module structure
- Logging and Tracing mechanisms
- Already big variety of existing models
- Targeted to be used as a realtime network emulator
- NS-2 experience was taken into account.
- Strict process of contribution, code review and maintenance

Discrete-event simulation

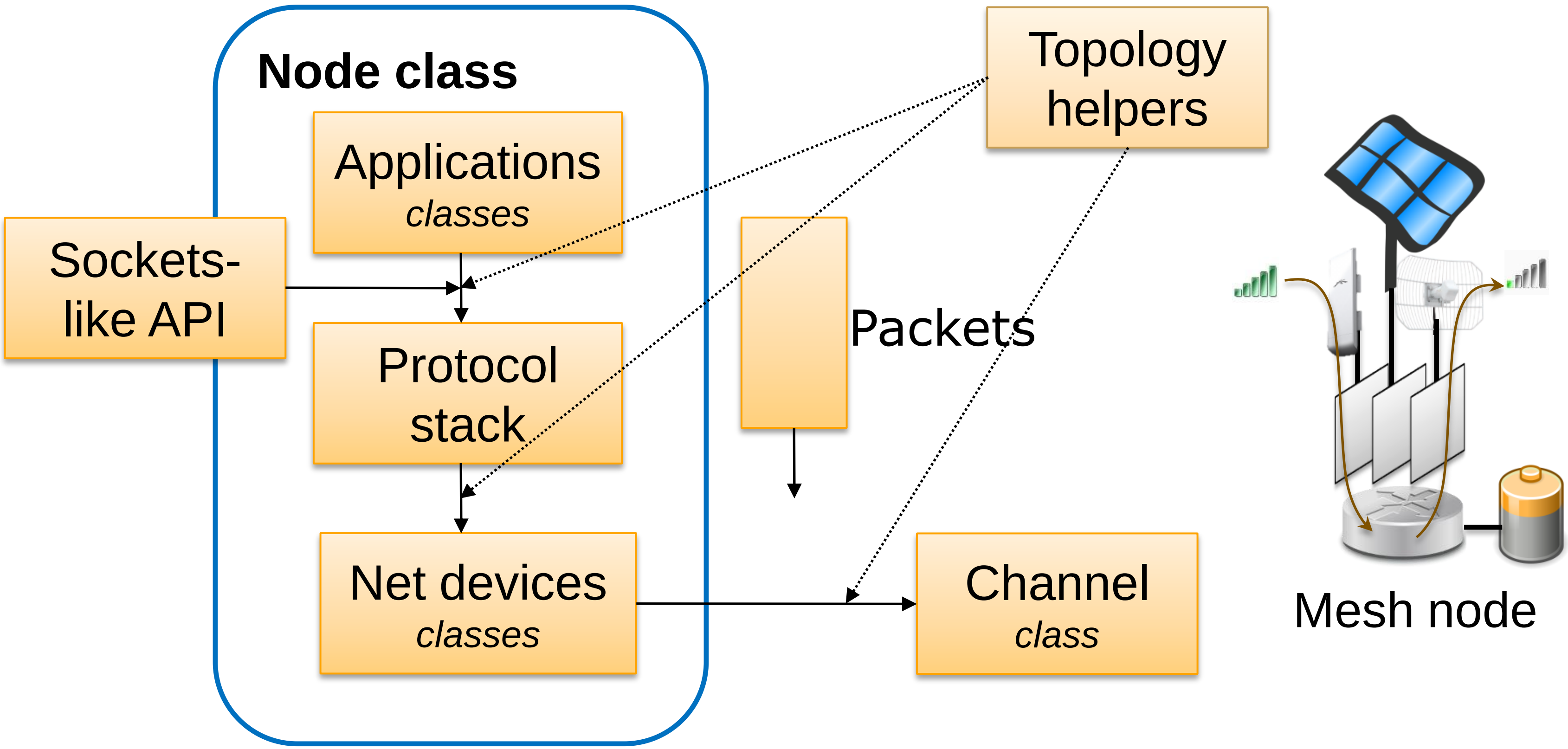
- The idea is to jump from one event to another
- Events are recoded in a future event list (FEL)
- Each event notice is composed at least to data: time, type
- Event routine or handler to process each event
- Each event may change the system state and generate new event notices



NS 3 structure



Main objects, attention to realism



- Model nodes like real computer
- Support key interfaces such as sockets API

ns-3 modules

Devices

- Spectrum
- Brige
- WiMAX
- CSMA
- Mesh
- FD
- Point2 Point
- LTE UE/eNB
- WiFi
- OpenFlow switch
- UAV

Protocols

- Routing:
  AODV, DSDV, DSR, IP, OLSR, HWMP
- Iternet:
  IPv4, IPv6, TCP, UDP, ARP

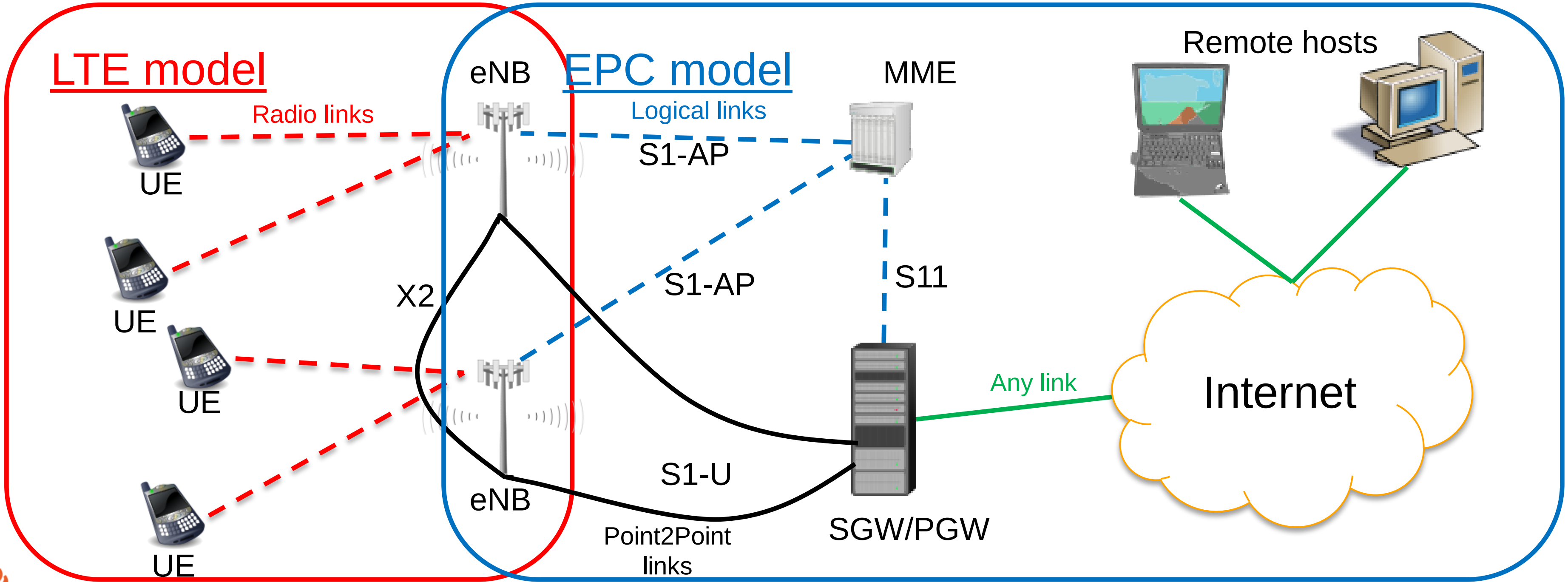
- Applications
- Mobility
- Propogation
- Energy
- Network
- Core

Utilities

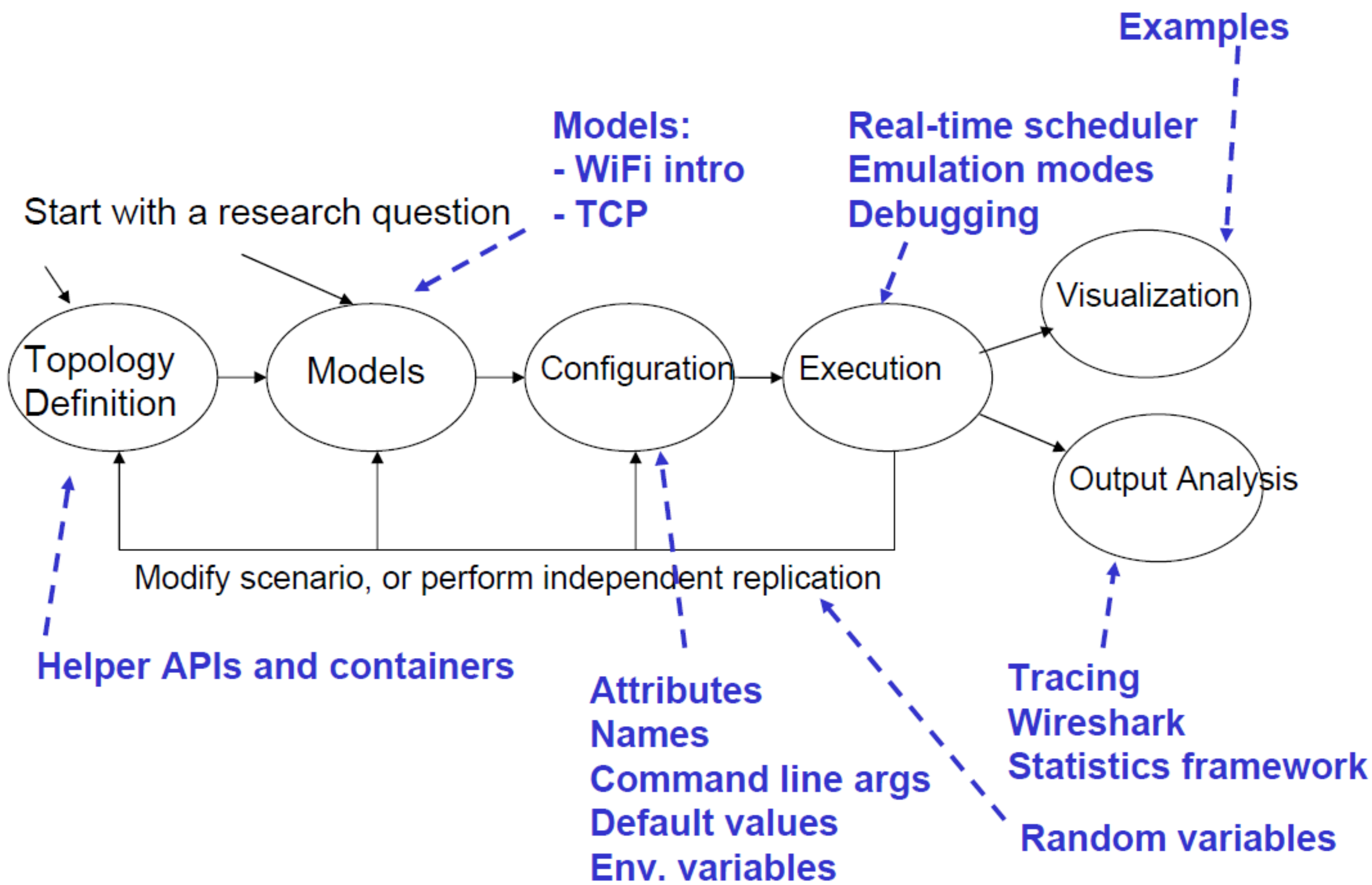
- Stats
- Topology-readers
- ConfigStore
- Flow Monitor
- GnuPlot
- NetAnim

Overview of LTE simulation model

- **The LTE model**: LTE radio part (UE – eNB)
- **The EPC model:** core network part (eNB, SGW, PGW and MME nodes)

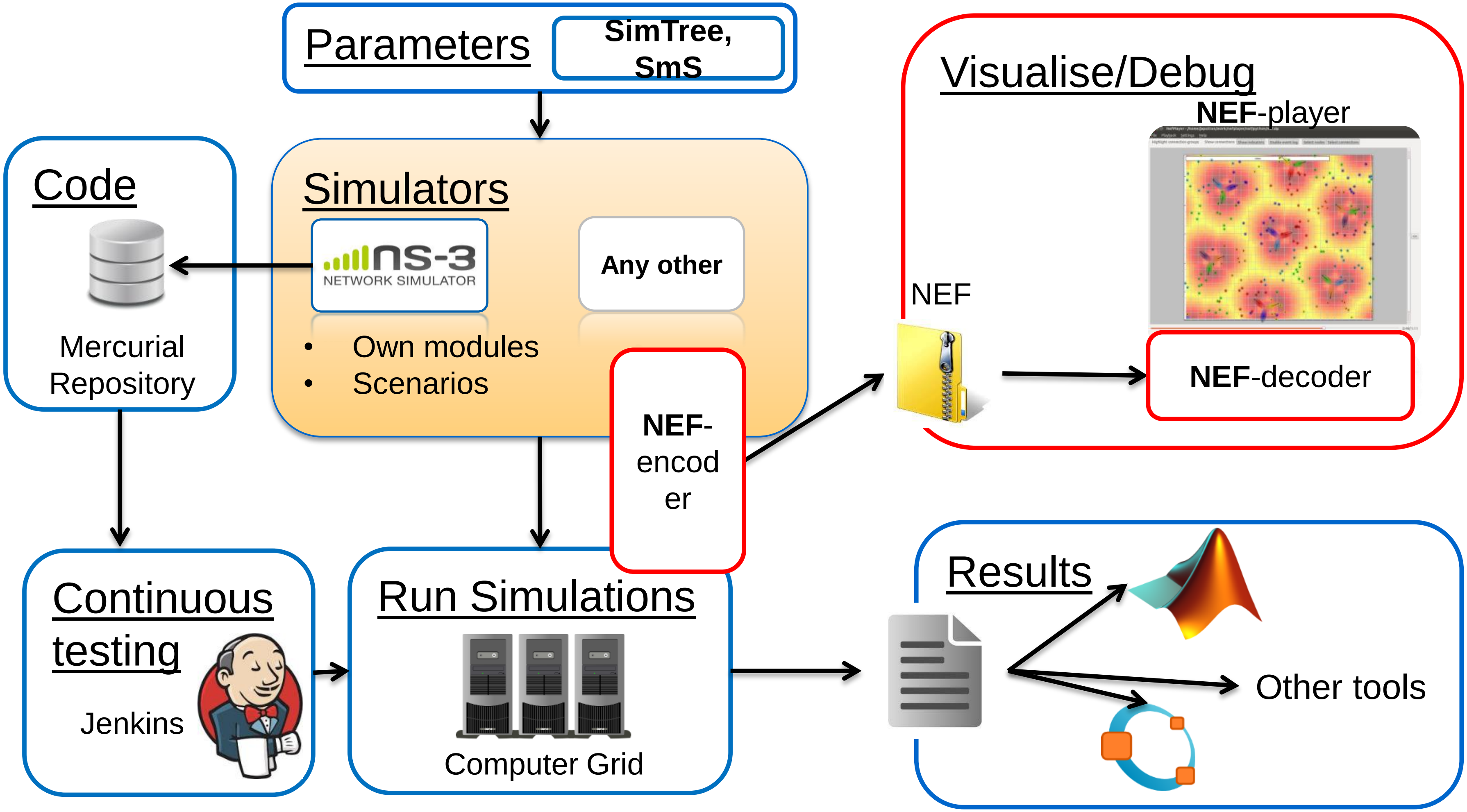


Workflow



* Tom Henderson and Mathieu Lacage, ns-3 tutorial, Workshop on ns-3, March 2009

Magister simulation environment



NEF player demo

THANK YOU

FOR YOUR ATTENTION

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- Acknowledgements:
  - Tapani Ristaniemi
  - Carlos Bader
  - Markku Renfors
  - Jerome Louveaux
  - Tobias Hidalgo Stitz
  - Colleagues from Magister Solutions