Radio Communications Tutorial:
From the Basics to Future Developments

SEVENTH FRAMEWORK PROGRAMME

Spectrally Efficient Multicarrier Architectures and Algorithms

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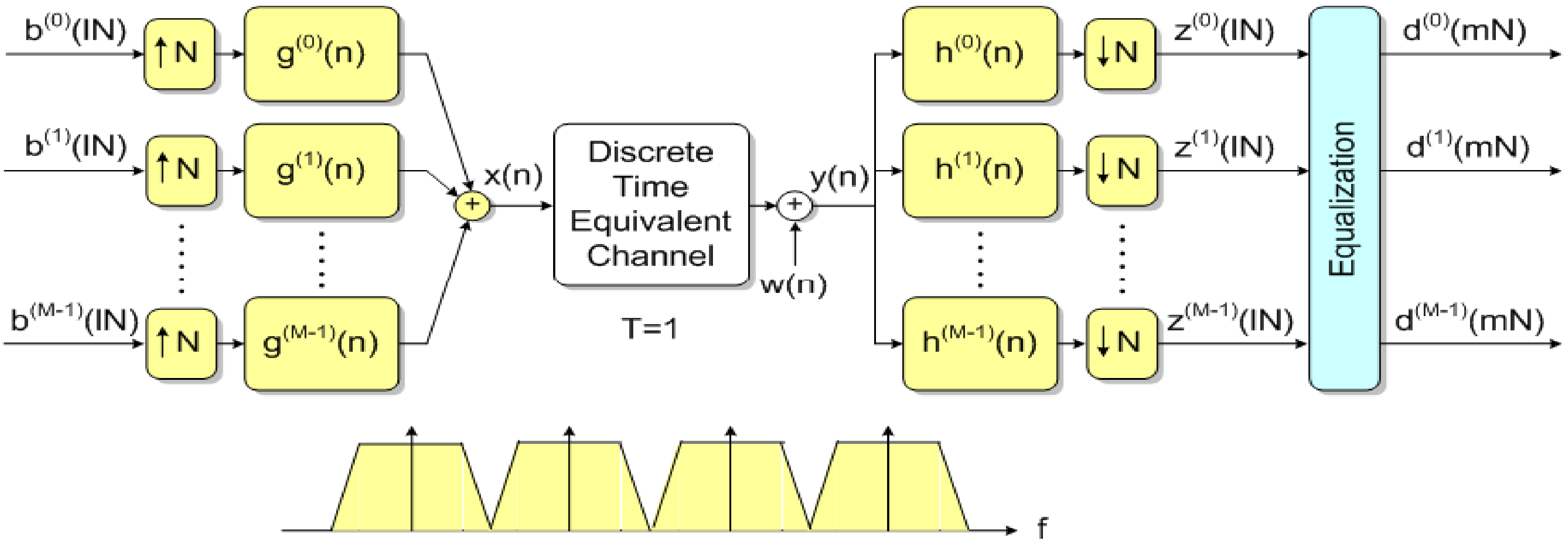
Contents

- ☐ Multicarrier modulation concept
- ☐ State-of-art radio systems based on MC modulation
- ☐ OFDM and improvements
- ☐ Filtered multitone modulation (FMT) and improvements

Unified View of MC Modulation



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

Considered MC Schemes

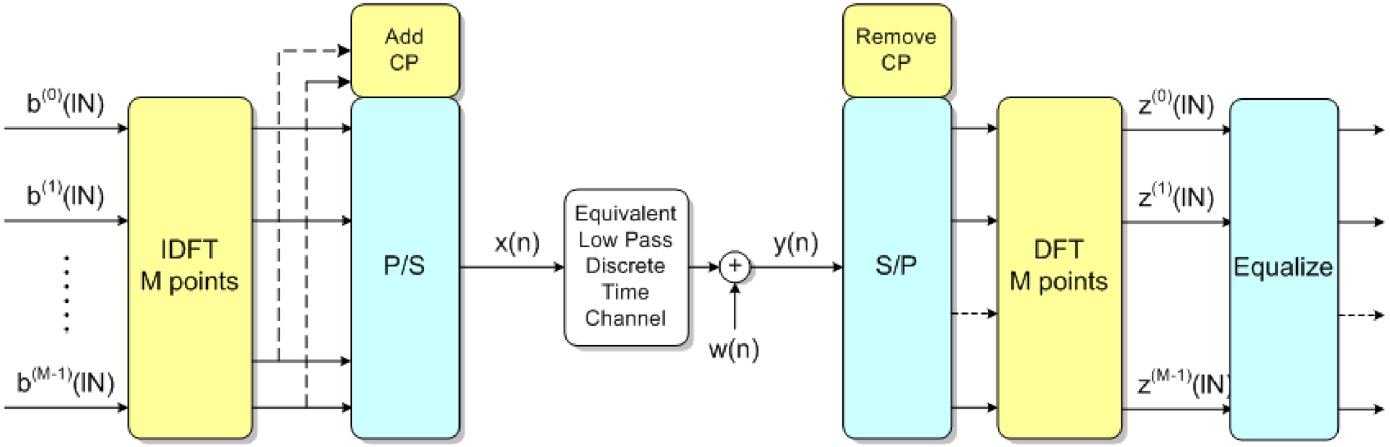
- **OFDM:** Orthogonal Frequency Division Multiplexing
- **FMT:** Filtered Multitone Modulation
- **Concatenated OFDM-FMT**

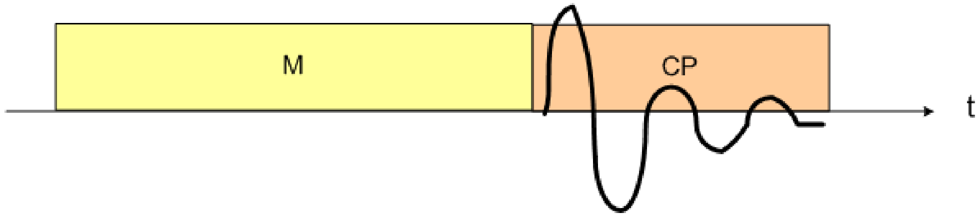
State-of-the-art Radio Systems

	WPAN WiMedia	IEEE 802.15.3c mmWave	IEEE 802.11 WLAN	IEEE 802.16 WMAN WiMax	DVB-T WMAN DTT	3GPP CELLULAR LTE (DownL)	IEEE 802.11p V2V
Modulation	Multiband OFDM: 14 sub-bands in 3.1-10.6 GHz M=128 per band	Multiband OFDM: 58.32, 60.48, 62.64, 64.8 GHz M=512 per band	OFDM M=64, 128	OFDM M=512, 1024	OFDM M=2048, 8192	OFDM M=128 to 2048	OFDM M=32,64
Mapping	QPSK	QPSK, 16-QAM, 64-QAM	2, 4, 16, 64-QAM	QPSK 16, 64-QAM	QPSK 16, 64-QAM	QPSK 16, 64-QAM	2, 4, 16, 64-QAM
Channel Coding	CC	LDPC, RS-LDPC	CC (mandatory) LDPC (optional)	CC	CC+RS	Turbo coding	-
RF (Approx)	Function of the used band	57-64 GHz	2.4, 5GHz	2.4 GHz	VHF-UHF	2.6 GHz	5.9 GHz
Bandwidth	528 MHz	2.592 GHz	20, 40 MHz	5, 10 MHz (Europe)	6, 7, 8 MHz	1.25 up to 20 MHz	10, 20 MHz
Rate	53 to 480 Mbit/s	59 Mbit/s to 6.3 Gbit/s	11 to 600 Mbit/s	<70 Mbit/s	4 to 32 Mbit/s	<100Mbit/s	3 to 54 Mbit/s
MAC	CSMA-CA, TDMA	Point to Point	CSMA-CA, TDMA	OFDMA, TDMA	-	OFDMA	CSMA/CA
CP	303 ns	24.69, 49.38 μs	0.8, 0.4 μs	1/4, 1/8, 1/16, 1/32	1/4, 1/8, 1/16, 1/32	4.69 to 16.67 μs	-
MIMO	NO	NO	Up to 4 spatial streams	up to 4 spatial streams	NO	4x2, 2x2, 1x2, 1x1	-
RANGE	<10 m	<10 m	<100 m	some Km		up to 30 Km	Up to 1Km

OFDM

Cyclically Prefixed OFDM





- *M* tones (sub-channels)
- Rectangular sub-channel pulse (window) of duration *N* > *M* samples
- Cyclic prefix (CP) of length $\mu=N-M$ samples (typically longer than the channel duration)

FFT Output

- A CP shorter than the channel duration introduces inter-symbol and inter-carrier interference:

$$z^{(k)}\left(\ell N\right)=\underset{\substack{\uparrow\\ \text{Sub-channel response}}}{H^{(k)}}\underset{\substack{\uparrow\\ \text{Data}}}{a^{(k)}}\left(\ell N\right)+\underset{\substack{\uparrow\\ \text{ISI+ICI}}}{I^{(k)}}(\ell N)+\underset{\substack{\uparrow\\ \text{Noise}}}{W^{(k)}}(\ell N)$$

- The signal-to-interference-plus-noise ratio (SINR) is

$$SINR^{(k)}(\mu)=\frac{P_U^{(k)}(\mu) \longleftarrow \text{Useful power}}{\underset{\substack{\uparrow\\ \text{Noise power}}}{P_W^{(k)}}+\underset{\substack{\uparrow\\ \text{Interference power}}}{P_I^{(k)}(\mu)}}$$

Optimal CP Design

- With Gaussian inputs, AWGN, and single tap equalization the achievable rate (capacity) for a given CP is

$$R(\mu) = \frac{1}{(M+\mu)T} \sum_{k=0}^{M-1} \log_2\left(1 + \frac{SINR^{(k)}(\mu)}{\Gamma}\right) \qquad [bit/s]$$

Sampling period ↑ **Gap factor** ↑

- The achievable rate is a function of the CP

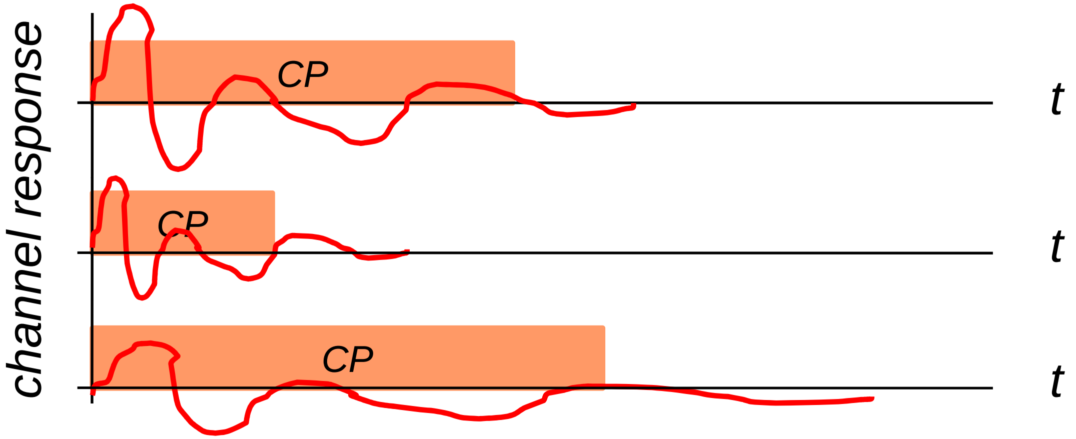
- The optimal CP is found maximizing the achievable rate

$$\mu_{OPT} = \underset{0 \le \mu < ch.length}{\operatorname{argmax}} \left\{ \frac{1}{(M+\mu)} \sum_{k \in K_{ON}} \log_2\left(1 + \frac{SINR^{(k)}(\mu)}{\Gamma}\right) \right\}$$

Adaptive CP-OFDM

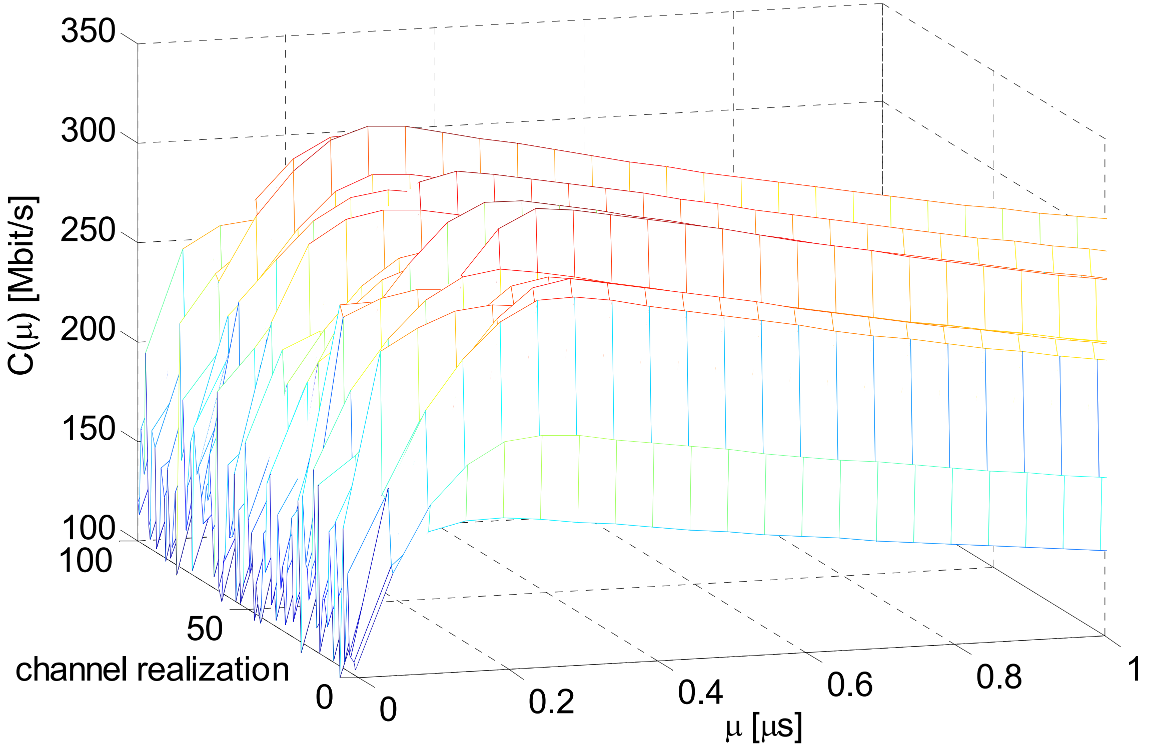
- ☐ We can adapt the CP to the specific channel response

- ☐ We can also choose a “globally optimal CP”



Ref: D’Alessandro,Tonello, IEEE WD2009, MOBILIGHT 2010

Application in WLAN Scenarios



System Parameters	
M	64
B = 1/T	20 MHz
PSD TX	-53 dBm/Hz
NOISE	-168 dBm/Hz
Baseline system	μ = 0.8 μs
Channel	Class B – 10 m

Capacity vs. CP length for 100 channel realizations

Bit-Loading and CP Adaptation

A. Estimate the sub-channel SINRs at the receiver

B. Compute energy distribution and optimal CP

C. Compute sustainable rate on a given sub-channel

D. Allocate bits (finite size constellation) and energy to sub-channels such that you do not exceed the sustainable rate, i.e.,

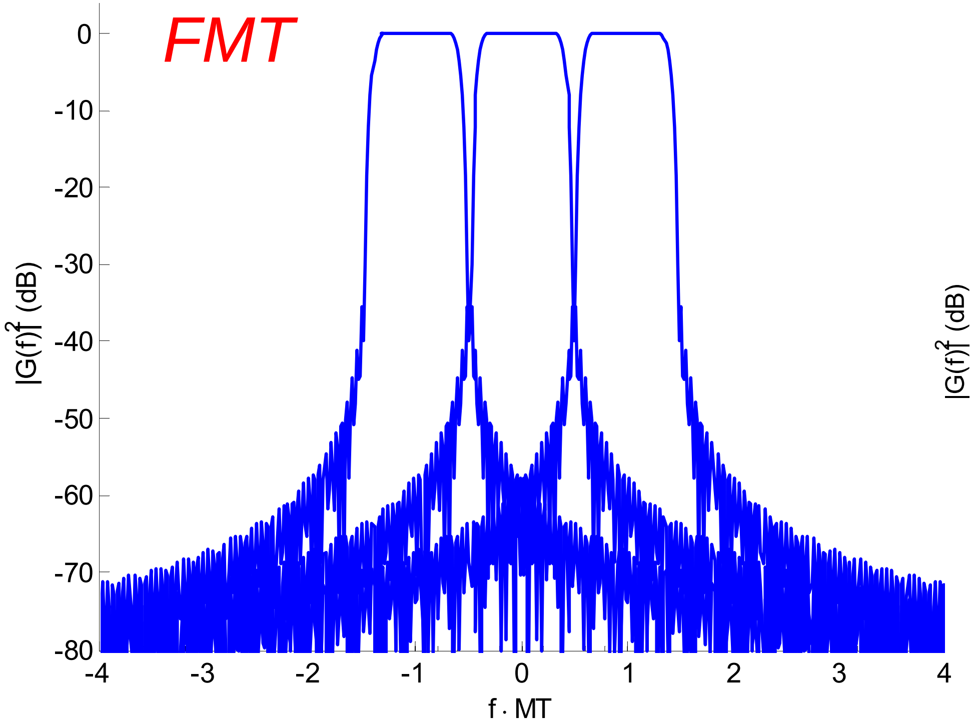
$$b^{(k)} = \left\lfloor \log_2\left(1+\frac{SINR^{(k)}(\mu_{OPT})}{\Gamma}\right)\right\rfloor$$

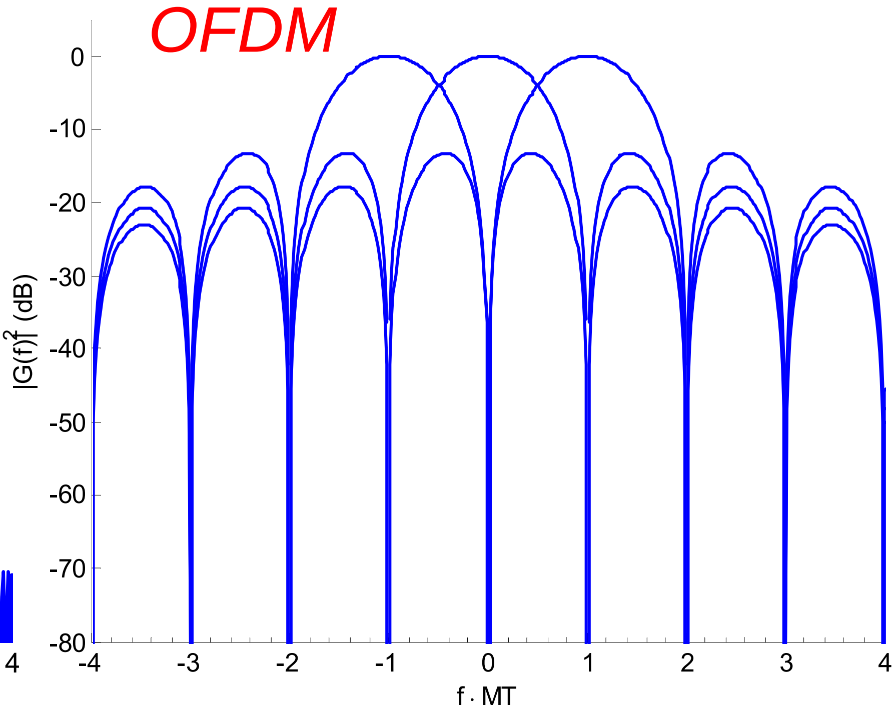
Number of bits allocated to sub-channel *k*

FMT

Ref: *Cherubini et al, IEEE JSAC 2000*

FMT Basics

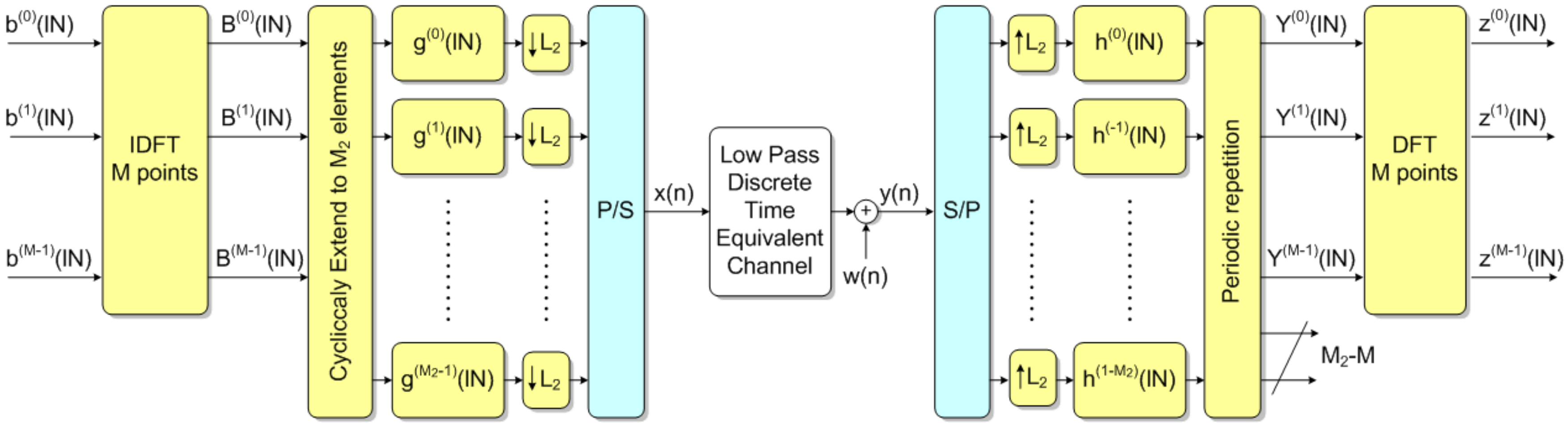




❑ Pulses obtained from modulation of a prototype pulse

- Root-raised-cosine
- Time/Frequency confined pulses
- Perfect reconctruction solutions provided that $N > M$

Efficient Realization



❑ *Synthesis*

- M point IDFT and Cyclic extension to $M_2 = l.c.m.(M,N) = L_1 M = L_2 N$
- **Pulses**: PP components of order *N,* i.e., $g^{(i)}(nN) = g(i+nN) \quad i = 0,...,N-1$
- Sample with period L_2

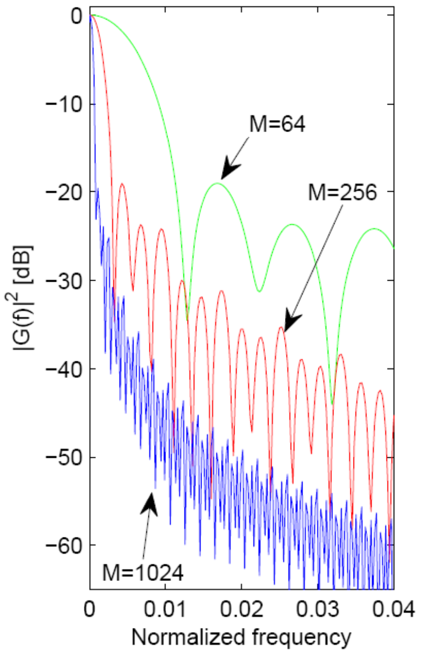
❑ *Analysis*

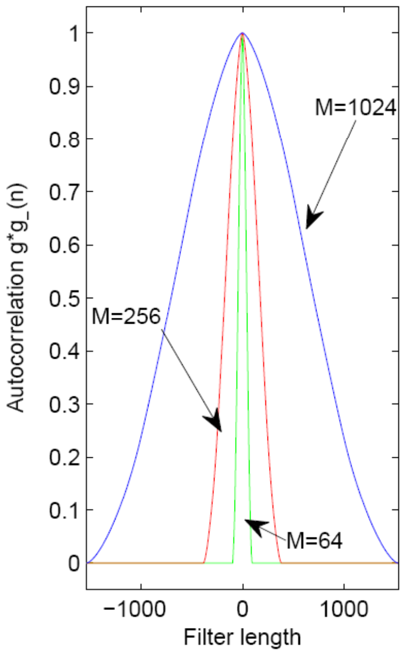
- Dual operations

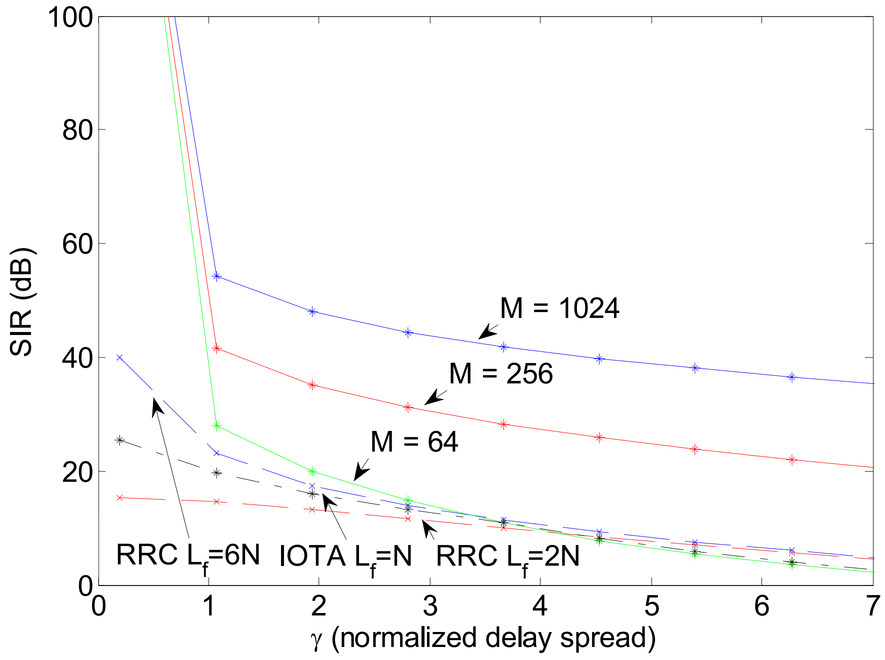
- *Complexity:* $M \log_2 M + L_{g,h}$ (pulse length) operations/sample

Orthogonal FMT

- ❑ The IDFT output coefficients at the TX and DFT input coefficients at the RX must be identical to have perfect reconstruction
- ❑ Parameterize the pulse coefficients via trigonometric functions of angles. Search for pulses that fulfill the orthogonal relations and maximize the in-band energy







Ref: Moret, Tonello, EURASIP Journal on Advances in Signal Processing, 2010.

Equalization

- ☐ In FMT, the intercarrier interference (ICI) is negligible

- ☐ We can handle the inter-symbol interference (ISI) with sub-channel equalization

  - Linear sub-channel equalization is the easiest solution
  - One tap equalization is possible if *M* is large
  - Fractionally spaced equalization easies synchronization
  - Multichannel equalization (MIMO MAP-ML) is also applicable

Ref: Tonello, Bell Labs Tech. Journal 2003

Matched Filter Bound of FMT in Fading Channels

- For uncoded transmission the best attainable performance corresponds to that obtained with *ideal maximum likelihood detection (MFB)*
- It allows to predict the effect of the prototype filter and number of sub-channels
- The exact matched filter bound BER can be computed in closed form:

$$P_{e,MFB}(k)=\frac{1}{2}\sum_{i=1}^{N'}\sum_{n=1}^{m_i}A_{i,n}\left[1-\sum_{l=0}^{n-1}\frac{2l}{2^{2l}l^2}\sqrt{\frac{\lambda_i/4N_0}{(1+\lambda_i/4N_0)^{2l+1}}}\right]$$

- $A_{i,n}$: coefficients of the partial fraction expansion of the characteristic function of

$$d^2_{MFB}(k)=D_e\sum_{i\in\mathbb{Z}}\sum_{p,p'\in\mathbf{P}}e^{j\frac{2\pi}{M}f_k(p-p')T}\alpha^*_p(iT)\alpha_{p'}(iT)g^*(iT-pT)g(iT-p'T)$$

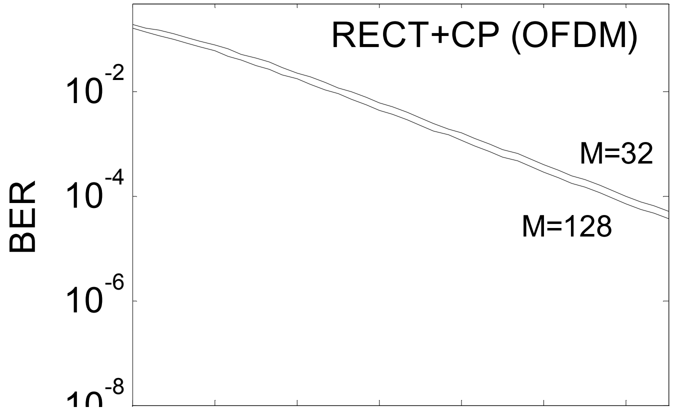
$$=D_e\boldsymbol{\alpha}^H\mathbf{W}_k^H\mathbf{G}\mathbf{W}_k\boldsymbol{\alpha}$$

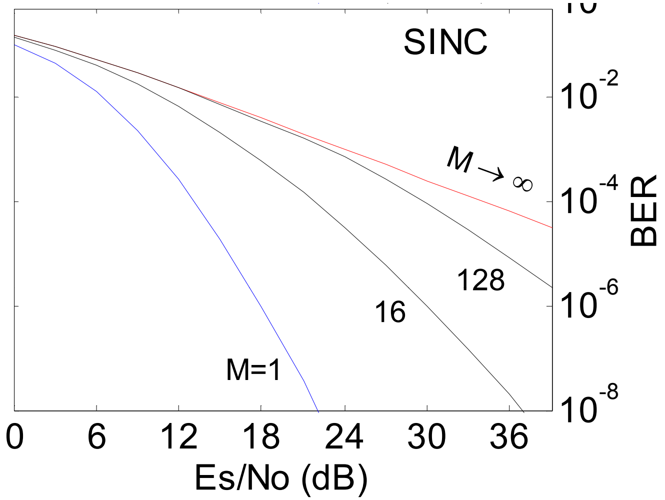
- λ_i: eigenvalues of $D_e E[\boldsymbol{\alpha}\boldsymbol{\alpha}^H]\mathbf{W}_k^H\mathbf{G}\mathbf{W}_k = D_e\mathbf{R}\mathbf{G}_k$

Vector channel taps *Prototype pulse correlation*

Ref: Tonello, IEEE TW 2005

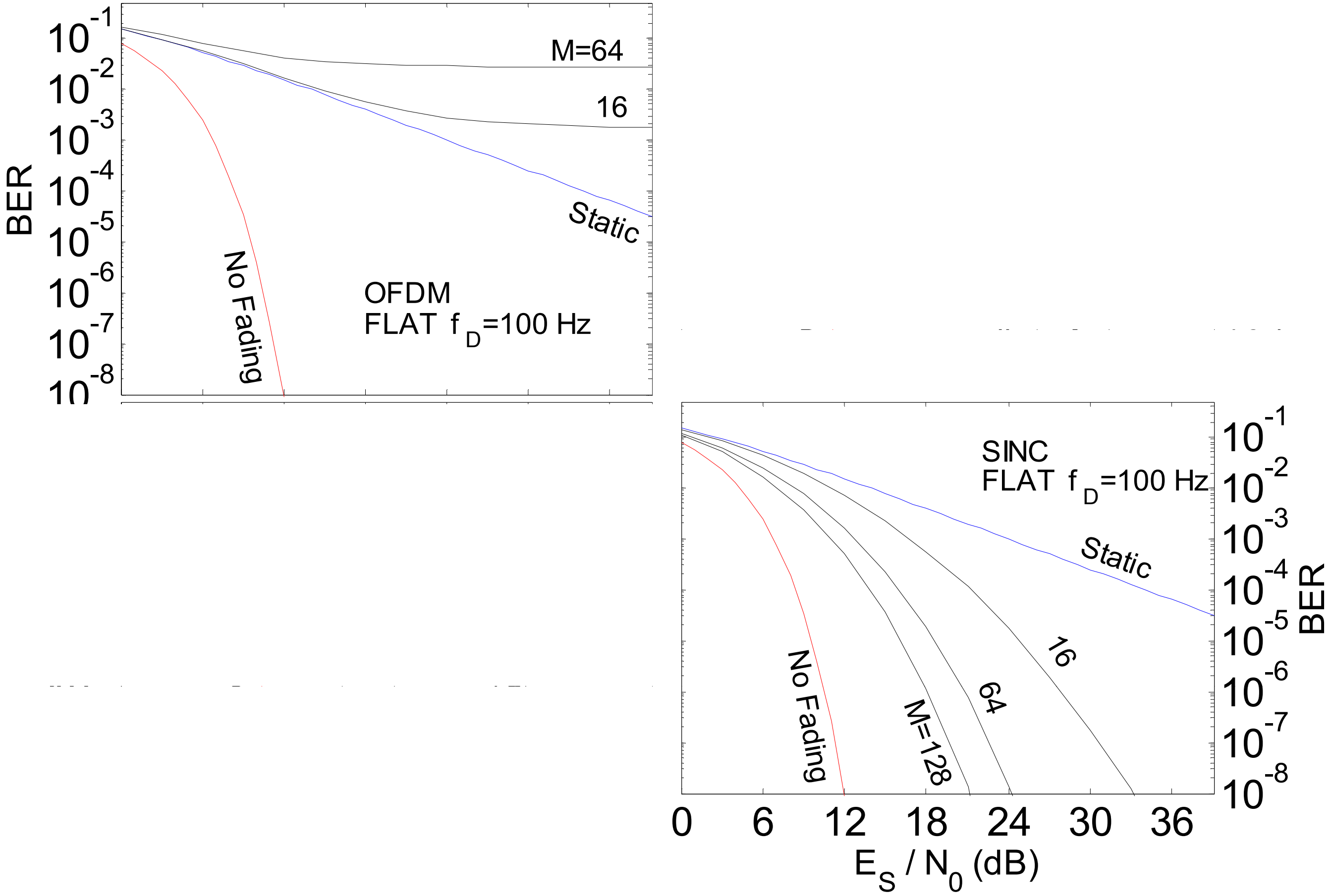
ITU PB channel with quasi static fading
Bandwidth W=3.84 MHz – ITU-3GPP PB Channel





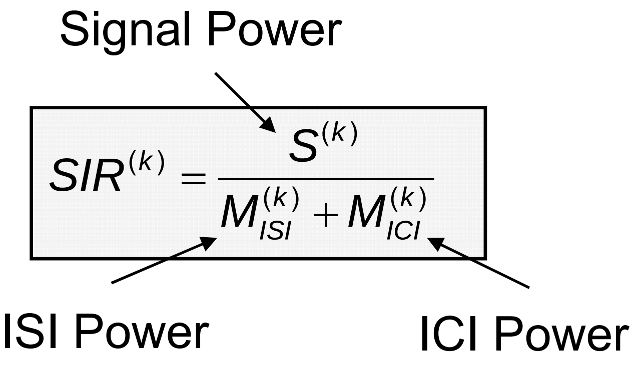
- ❑ **FMT is a diversity transform**. In Frequency Selective Fading
  - FMT is a good choice complexity wise
  - Single Carrier modulation is a good choice performance wise.

Flat Fading with Jakes' Doppler spectrum W=24.3 kHz



- ☐ **FMT is a diversity transform.** In Time Selective Fading
  - FMT is a good choice performance wise.
  - Single carrier modulation is a good choice complexity wise.

Performance with Linear Equalization



Signal Power

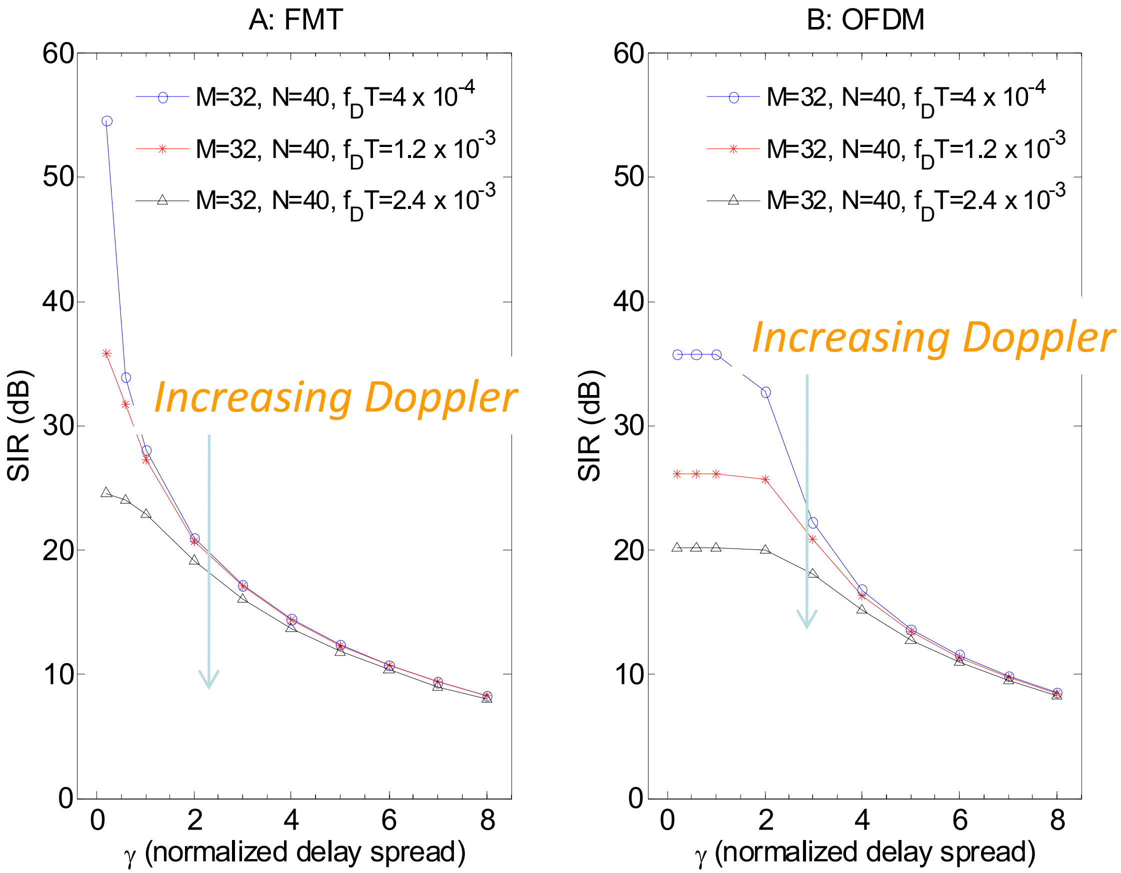
$$SIR^{(k)} = \frac{S^{(k)}}{M_{ISI}^{(k)} + M_{ICI}^{(k)}}$$

ISI Power

ICI Power

Hypothesis

- Exponential power delay profile and isotropic scattering
- Data symbols with equal power



☐ If **Doppler spread dominates** FMT has superior performance w.r.t. OFDM with single tap equalizer

☐ If **Delay spread dominates** similar performance with single tap equalizer

Ref: Tonello, Pecile, IEEE TW 2006

Adaptive FMT

Adaptive FMT

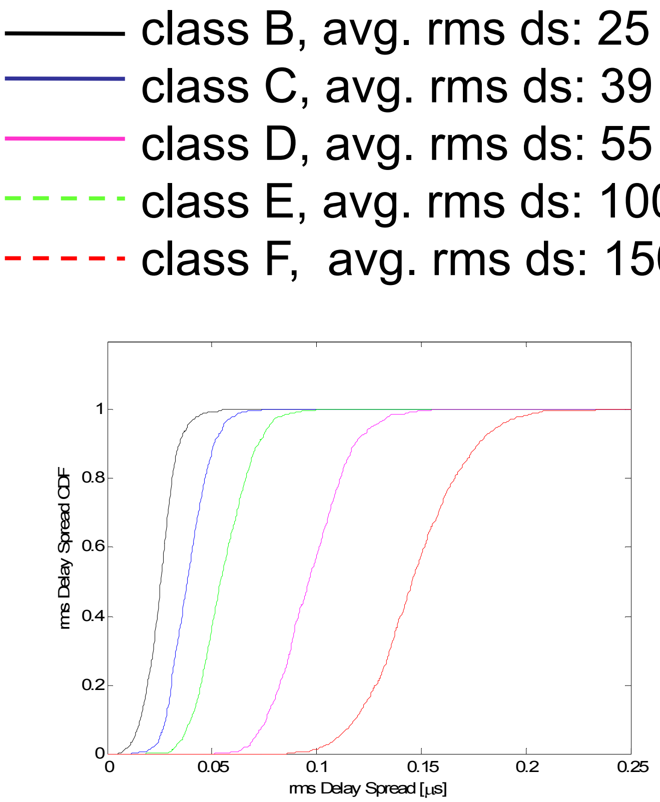
- ☐ We can generalize the idea of Adaptive OFDM to FMT
  - ✓ Optimize the **overhead β = *N-M*** such that capacity is maximized

$$R(\beta) = \frac{1}{(M+\beta)T} \sum_{k \in K_{ON}} \log_2\left(1 + \frac{SINR^{(k)}(\beta)}{\Gamma}\right) \quad [bit/s]$$

  - ✓ We can also adapt the pulse shape

Application to WLAN Scenario

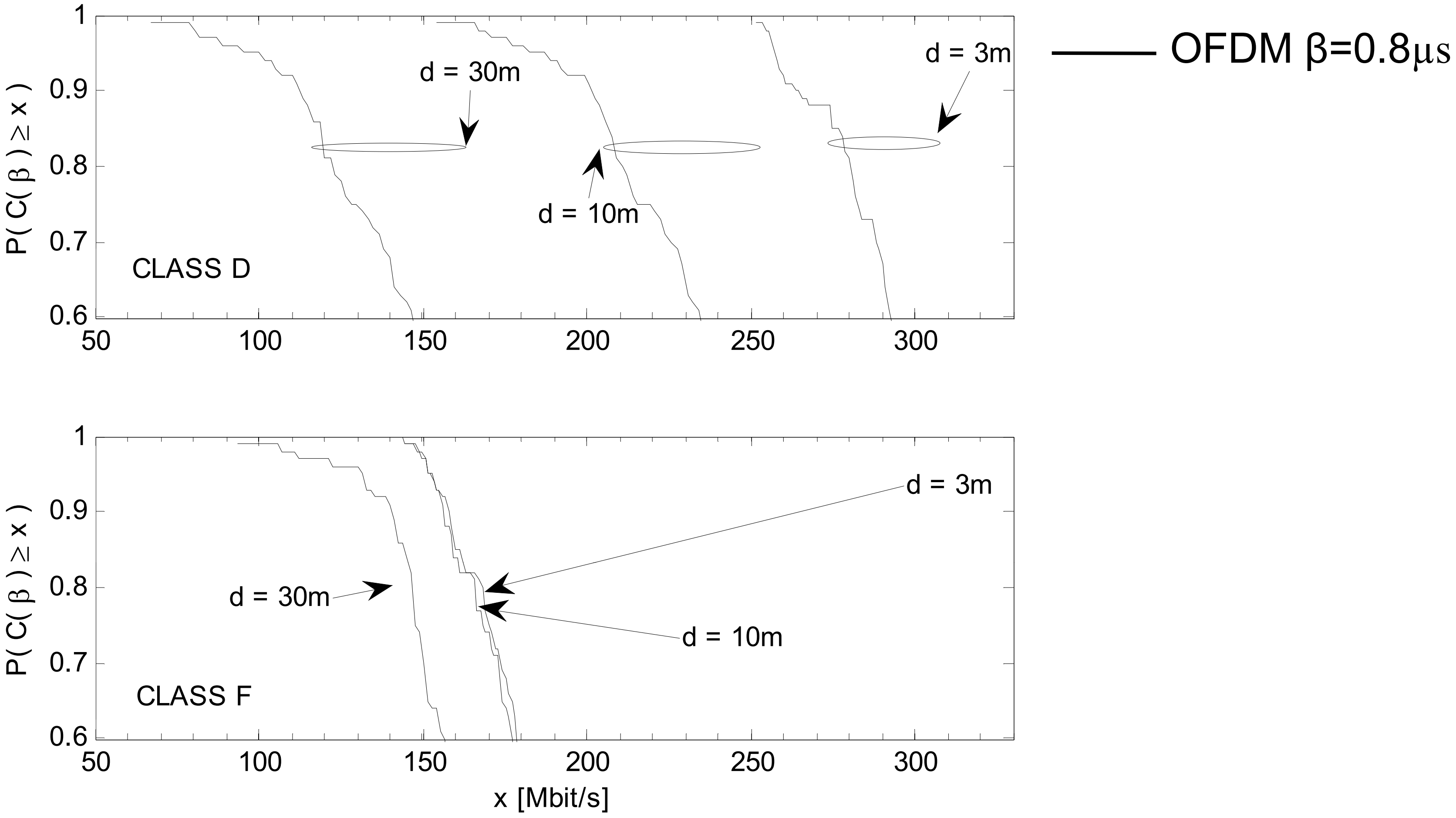
System Parameters	
M	64
B = 1/T	20 MHz
PSD TX	-53 dBm/Hz
NOISE	-168 dBm/Hz
Baseline system	β = 0.8 μs
Channel	Class B – 10 m



Ref: Ercegl, Shumacher et al. : IEEE P802.11Wireless LANs, TG.n ChannelModels

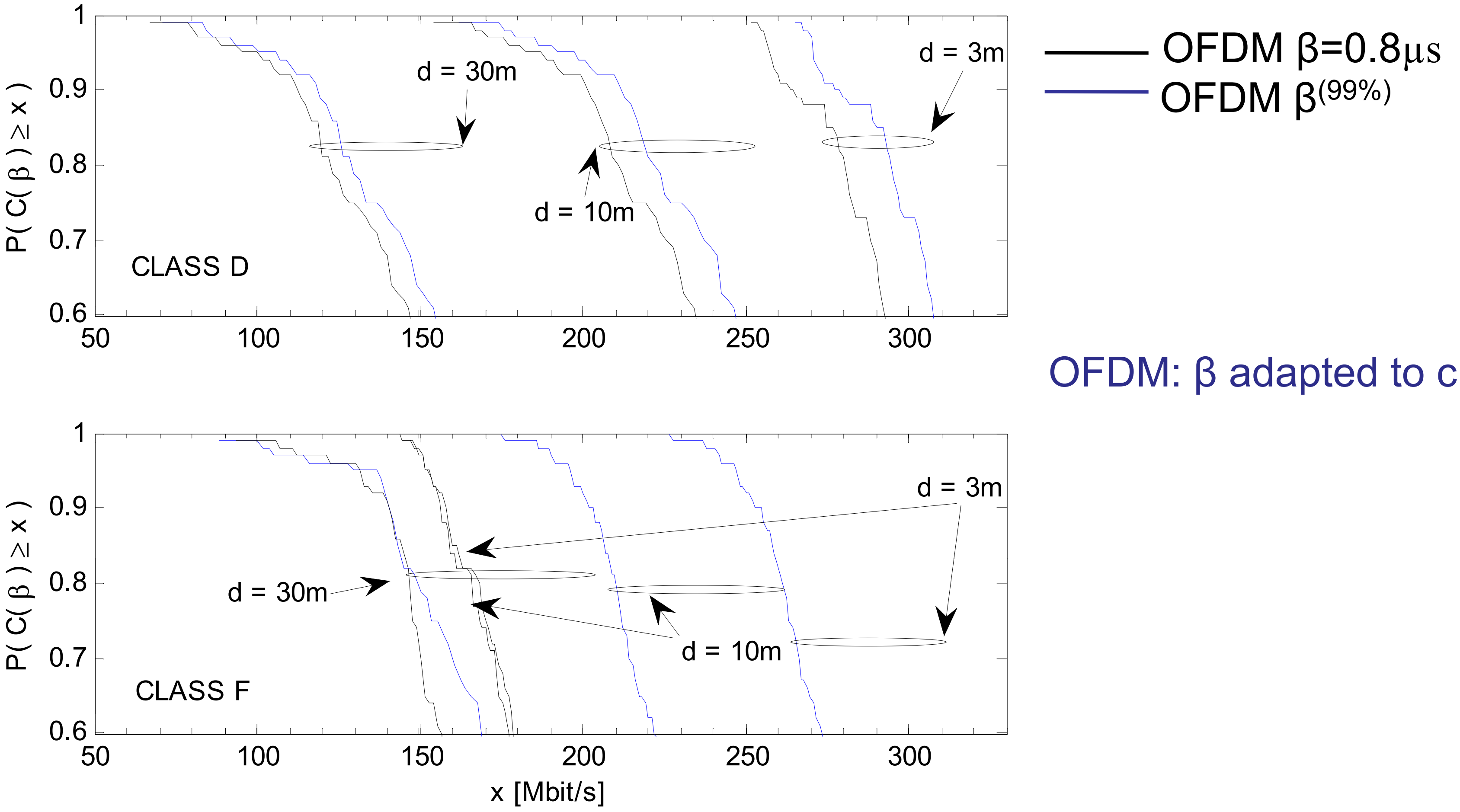
Application in WLAN Scenarios

FMT vs. OFDM



Application in WLAN Scenarios

FMT vs. OFDM

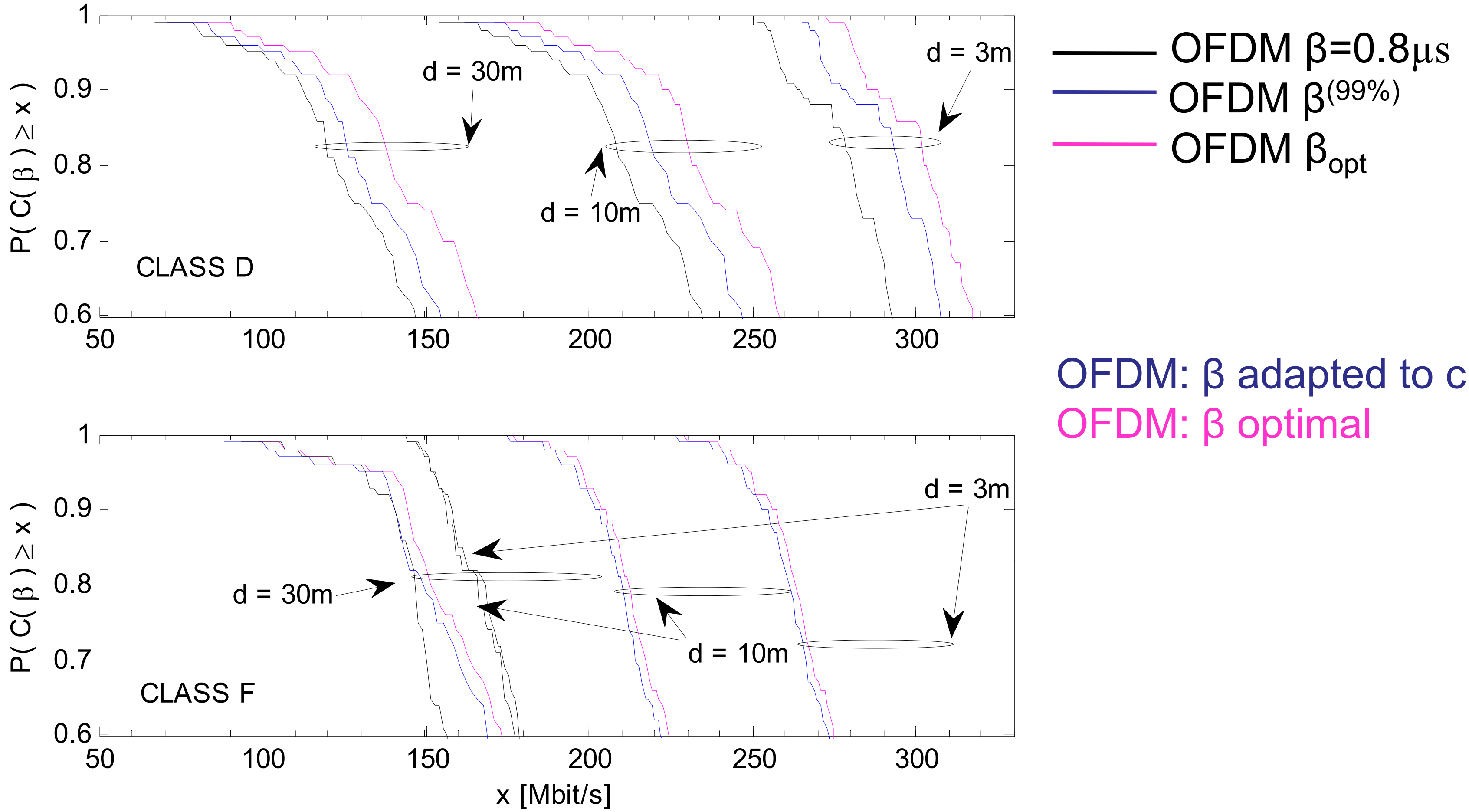


OFDM: β adapted to class

$$\beta_{OFDM}^{(99\%)}(B,C,D,E,F)=\left\{0.4,0.5,0.6,0.9,1.1\right\}\mu s$$

Application in WLAN Scenarios

FMT vs. OFDM



OFDM: β adapted to class

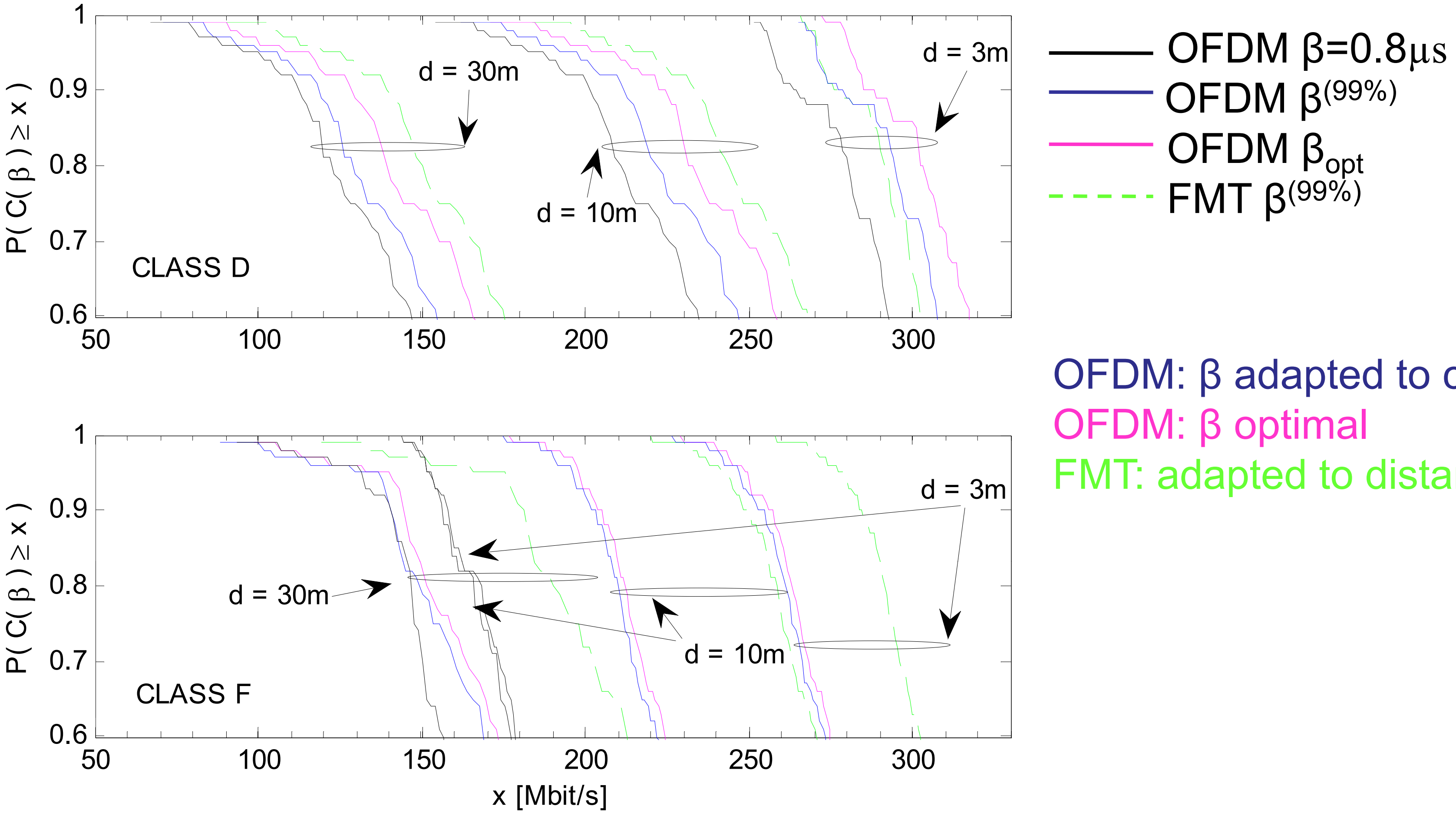
OFDM: β optimal

$$\beta^{(99\%)}_{OFDM}(B,C,D,E,F)=\{0.4,0.5,0.6,0.9,1.1\}\,\mu s$$

$$\beta^{(99\%)}_{FMT}(3,10,30,60)=\{0.8,0.5,0.2,0.2\}\,\mu s$$

Application in WLAN Scenarios

FMT vs. OFDM



OFDM: β adapted to class

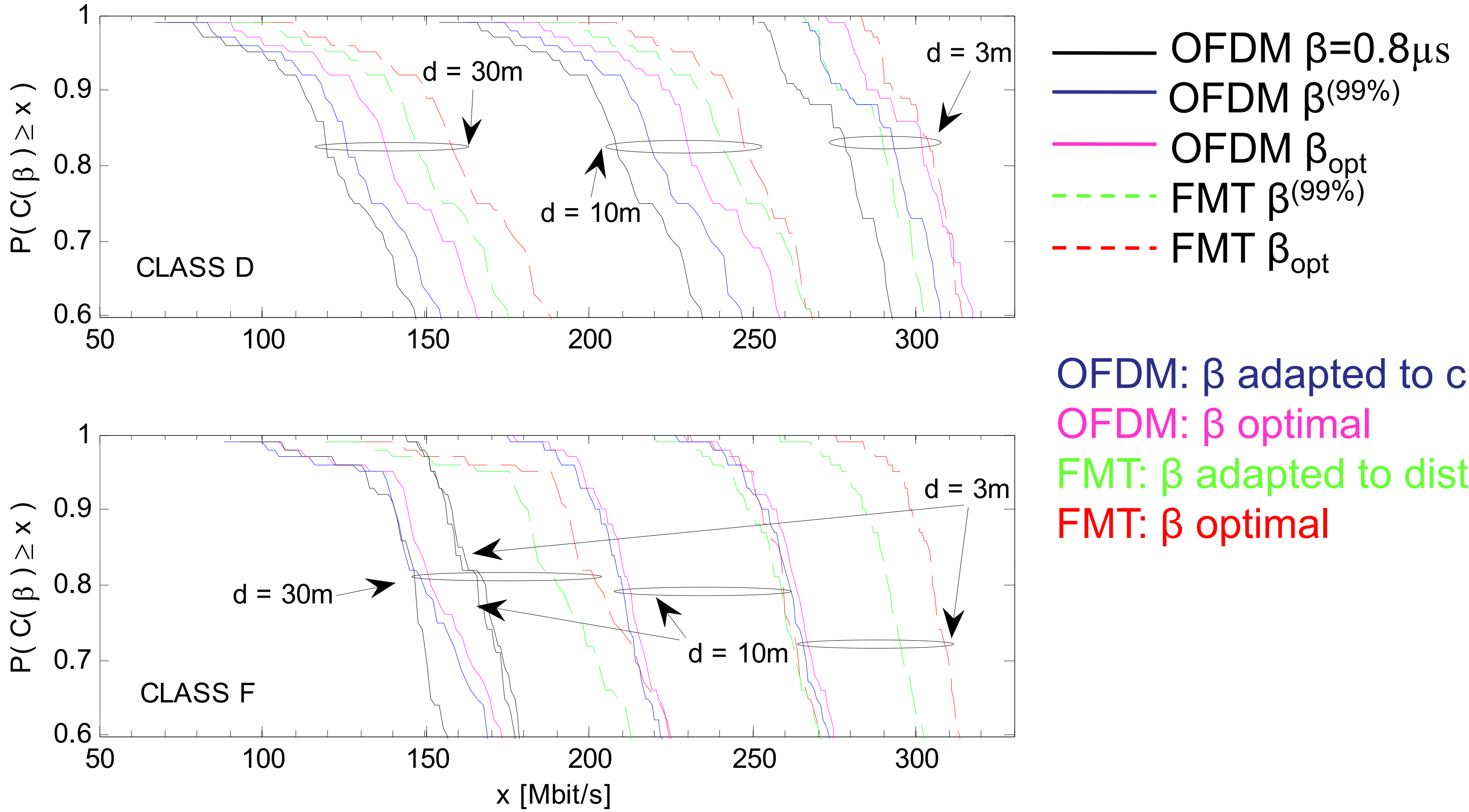
OFDM: β optimal

FMT: adapted to distance

$$\beta_{OFDM}^{(99\%)}(B,C,D,E,F)=\{0.4,0.5,0.6,0.9,1.1\}\,\mu s$$

Application in WLAN Scenarios

FMT vs. OFDM



OFDM: β adapted to class

OFDM: β optimal

FMT: β adapted to distance

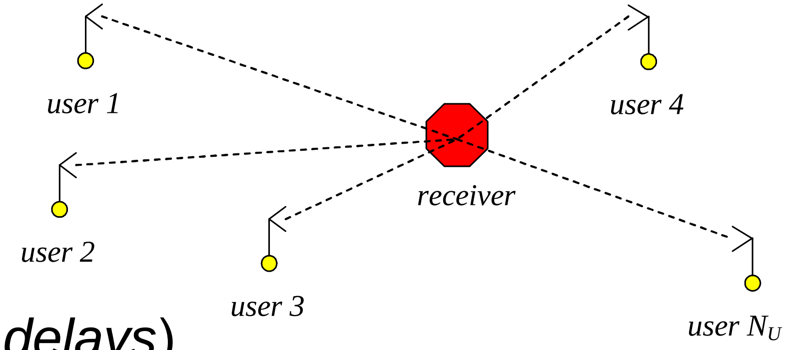
FMT: β optimal

$$\beta^{(99\%)}_{OFDM}(B,C,D,E,F)=\{0.4,0.5,0.6,0.9,1.1\}\,\mu s$$

$$\beta^{(99\%)}_{FMT}(3,10,30,60)=\{0.8,0.5,0.2,0.2\}\,\mu s$$

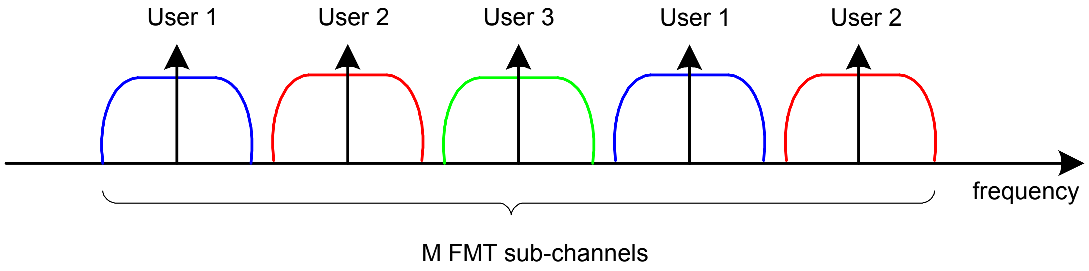
Multiuser OFDM and FMT

Multiuser Uplink



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

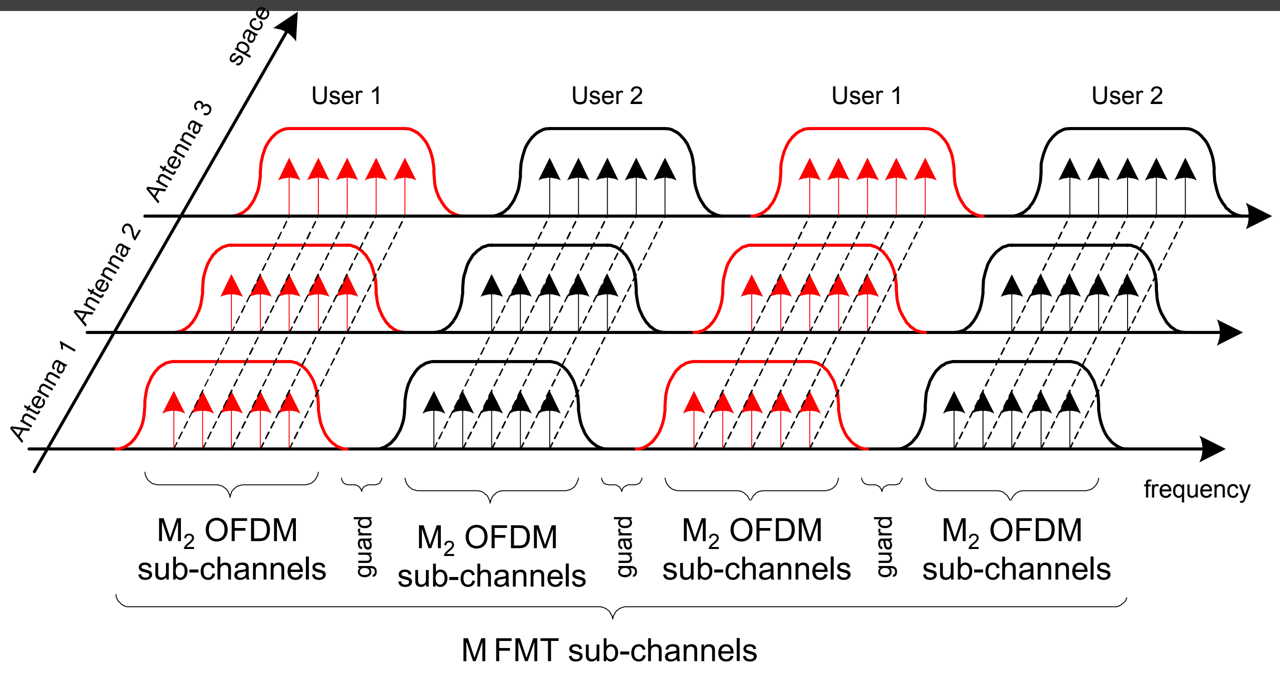
- ❑ MC modulation allows implementing a form of FDMA by partitioning the sub-channels among the users



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

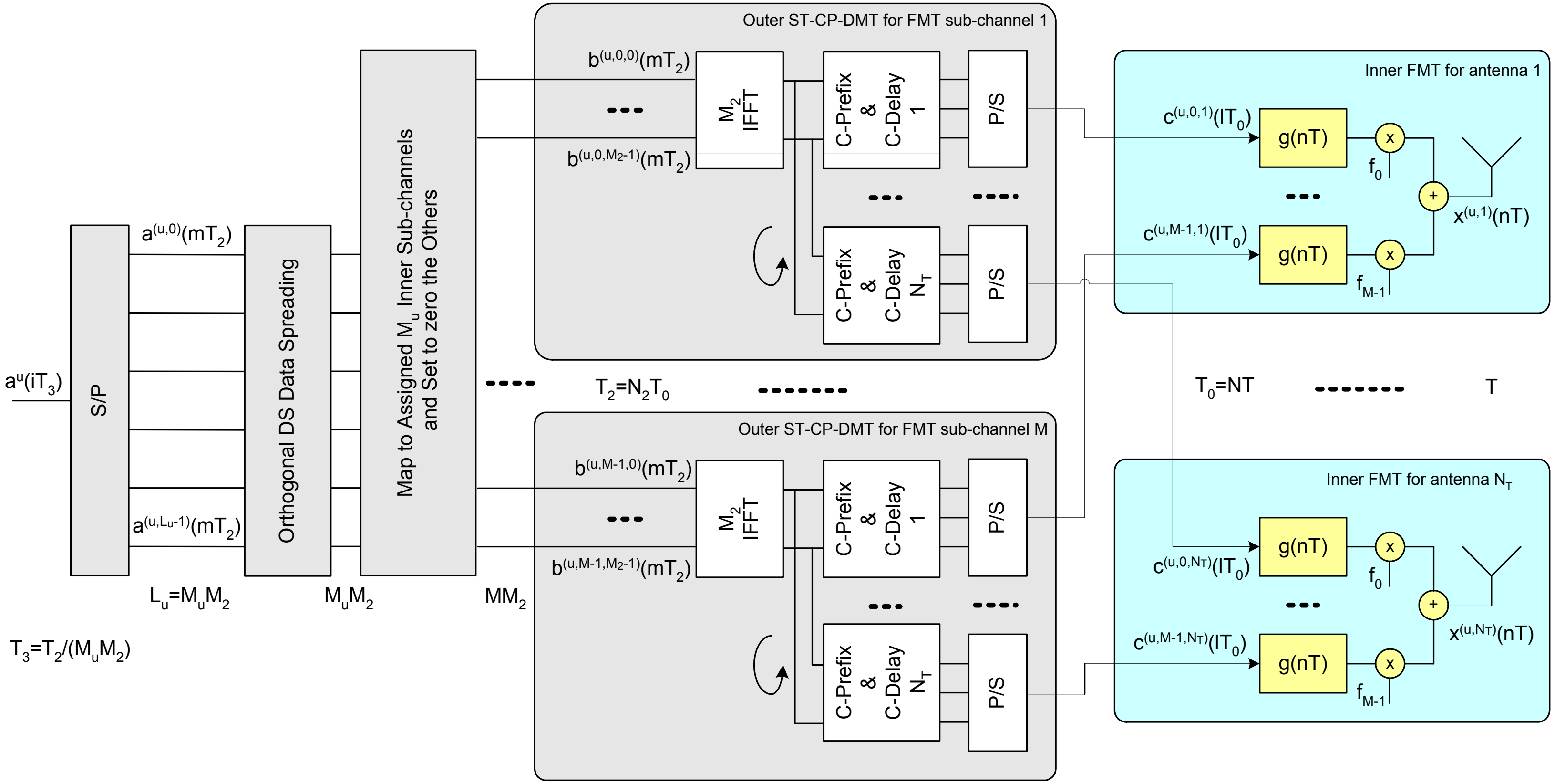
Concatenated OFDM with FMT

Basics of Concatenated OFDM-FMT



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

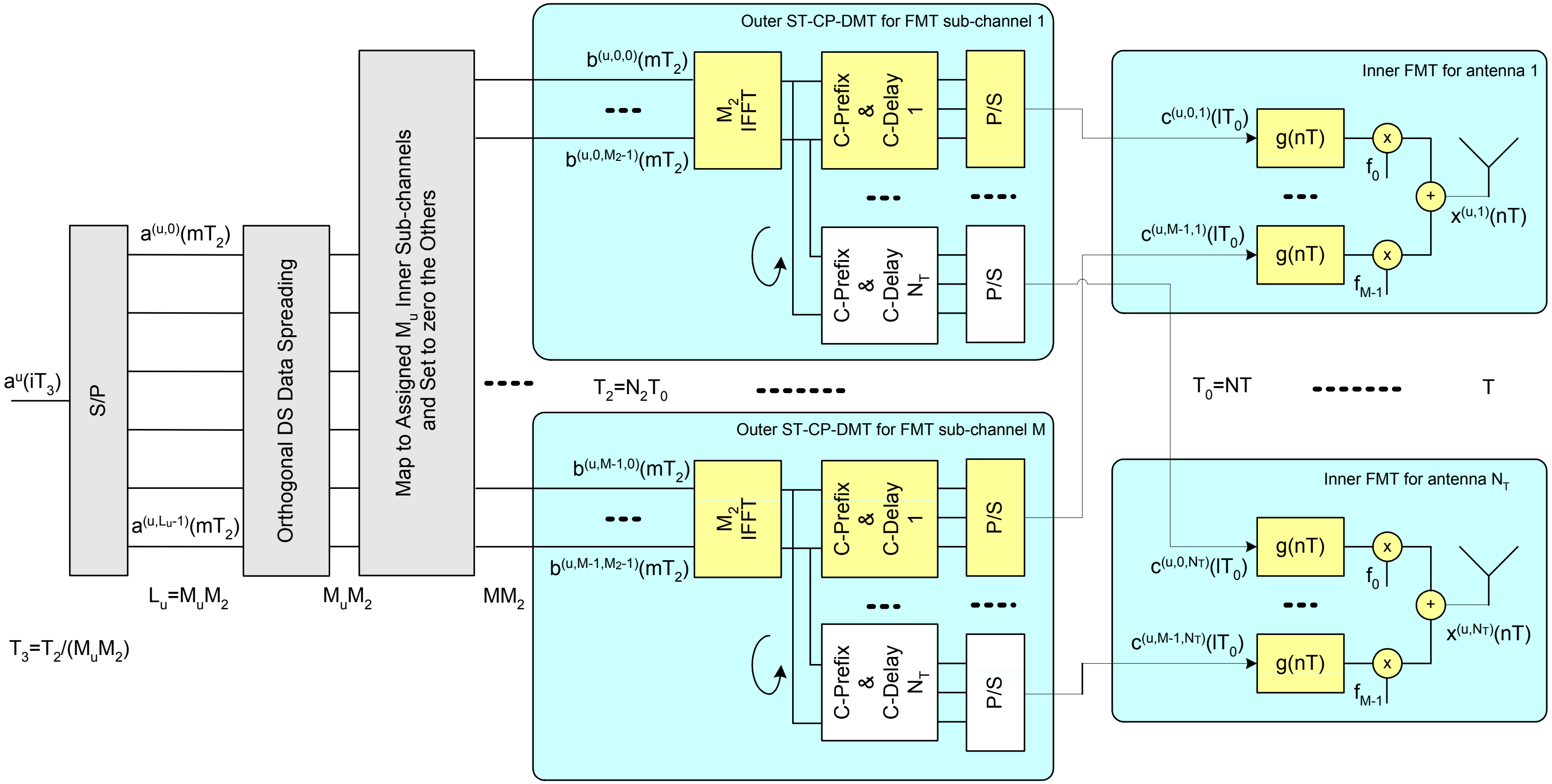
FMT Stage



Inner FMT to: orthogonalize the multiple access channel and multiplex the users.

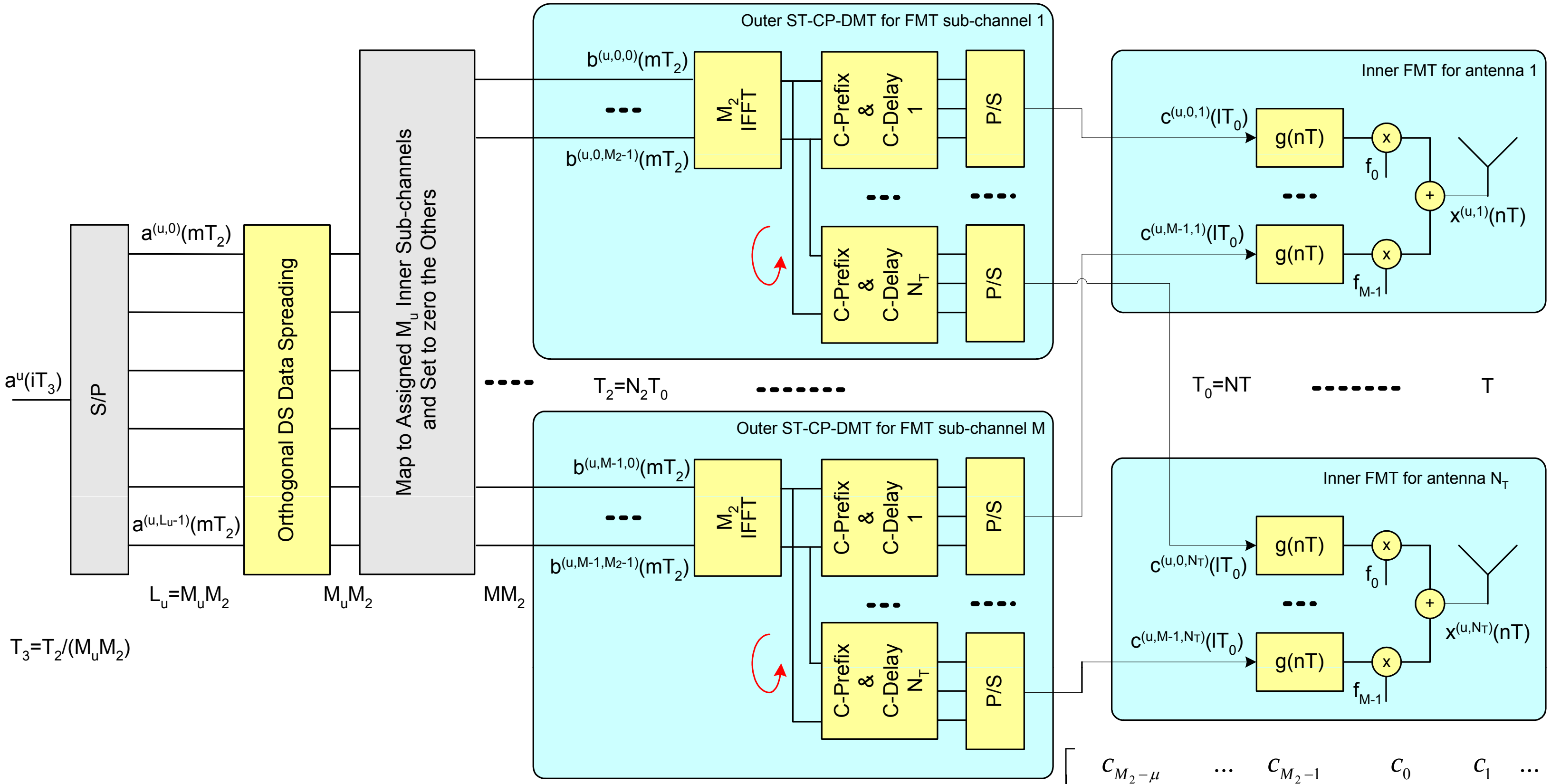
Ref: ***Tonello, IEEE JSAC 2006, Tonello, Bellin IEEE TVT 2009***

OFDM Stage



Outer CP-DMT to remove the sub-channel residual ISI

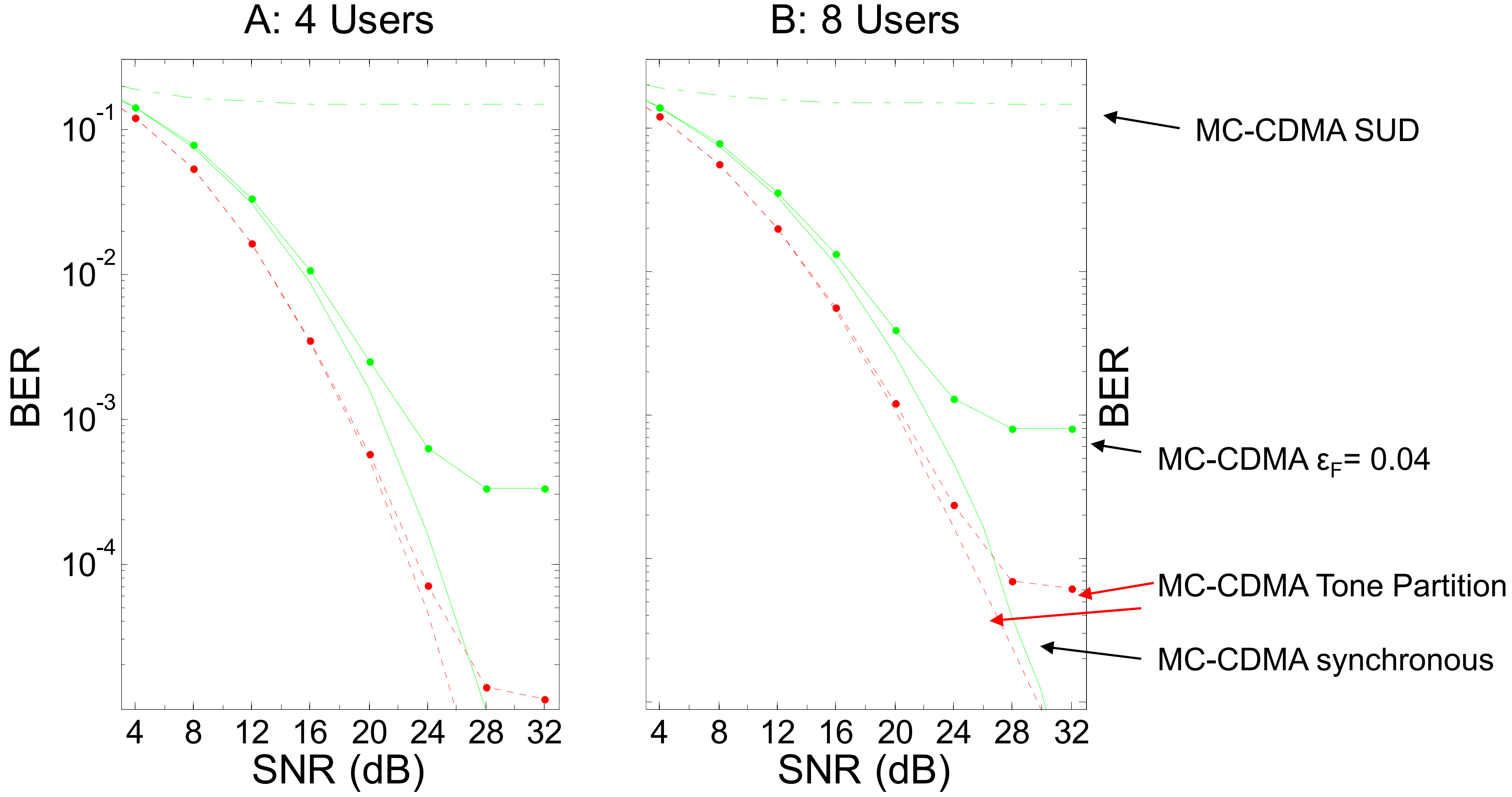
Cyclic Transmit Diversity + Linear Precoding



$$N_T \updownarrow \begin{bmatrix} c_{M_2-\mu} & \cdots & c_{M_2-1} & c_0 & c_1 & \cdots & c_{M_2-1} \\ c_{M_2-\mu-1} & \cdots & c_{M_2-2} & c_{M_2-1} & c_1 & \cdots & c_{M_2-2} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{M_2-\mu-N_T+1} & \cdots & c_{M_2-N_T} & c_{M_2-N_T+1} & \cdots & \cdots & c_{M_2-N_T} \end{bmatrix}$$

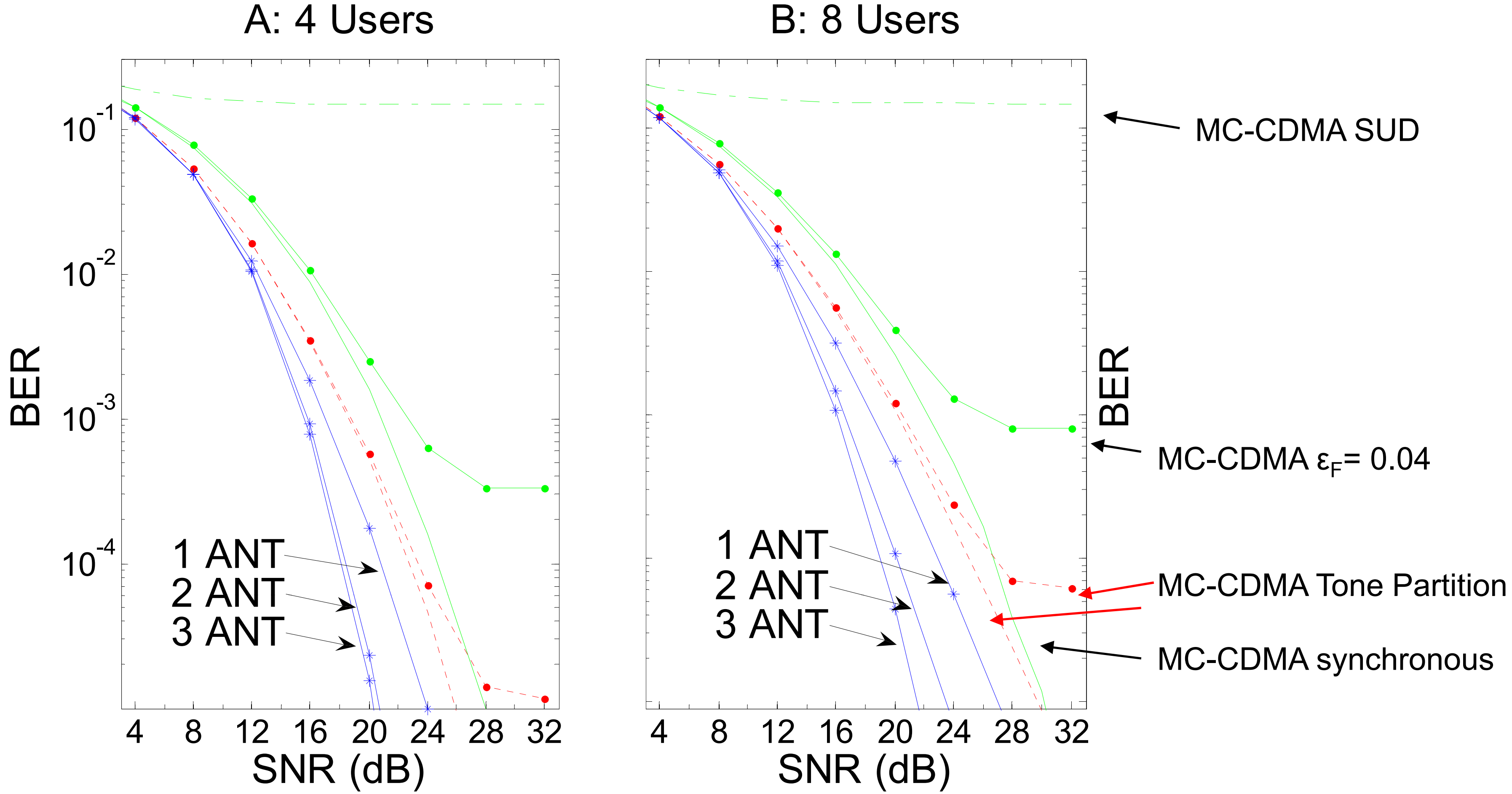
Orthogonal Data Spreading + Cyclic TX Diversity Based to increase spatial diversity.

Concatenated OFDM-FMT vs. MC-CDMA



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

Concatenated OFDM-FMT vs. MC-CDMA



MC-CDMA SUD

MC-CDMA $\varepsilon_F = 0.04$

MC-CDMA Tone Partition

MC-CDMA synchronous

- ☐ FMT with 32 Tones, OFDM with 32 Tones, and Walsh Codes Length 256 or 128.
- ☐ MC-CDMA with 128 Tones and with Walsh Codes Length 128.
- ☐ **Concatenated DMT-FMT performs better than MC-CDMA in the uplink !**

Final Remarks

- ☐ MC modulation is a spectral efficient and “low” complexity transmission technique in wide band frequency selective channels
- ☐ *CP-OFDM:*
  - The most simple and elegant solution
  - Coding is required to obtain diversity benefits
  - Sensitive to channel time selectivity, timing and carrier frequency errors
  - OFDMA is not robust in the uplink
  - Adaptive OFDM provides significant gains
- ☐ *FMT:*
  - More complex than OFDM with the same number of tones
  - Perfect reconstruction FMT can be designed with very short pulses
  - Some frequency and time diversity benefit is achievable with equalization
  - More robust than OFDM in doubly dispersive channels, in the multiuser uplink
  - Adaptive FMT provides higher throughput than adaptive OFDM
  - Concatenated OFDM-FMT with transmit diversity is able to orthogonalize the asynchronous multiple access channel and has better performance than MC-CDMA with simpler detection.

References

- FP7: Theme 3 ICT-213311 OMEGA, Deliv. D2.6,” Performance report of cross-layer mechanisms,” Dec. 2009.
- S. D'Alessandro, A. M. Tonello, "Adaptive Filter Bank Modulation for Next Generation Wireless In-Home Networks," Proc. of ICST MOBILIGHT 2010, Barcelona, May 9-12, 2010.
- S. D'Alessandro, N. Moret, A. M. Tonello, "A Hybrid Filtered Multitone System for WLAN Applications," to appear in IEEE PIMRC 2010, Instanbul, Turkey, September 2010.
- N. Moret, A. M. Tonello, "Design of Orthogonal Filtered Multitone Modulation Systems and Comparison among Efficient Realizations," EURASIP Journal on Advances in Signal Processing, 2010.
- A. Tonello, M. Bellin, "Low Complexity Realization of a Concatenated DMT-FMT Multiuser Uplink System with Transmit Diversity," IEEE Trans. on Vehicular Technology, vol. 58. no. 7, pp. 3844-3850, Sept. 2009.
- A. Tonello and F. Pecile, “Efficient Architectures for Multiuser FMT Systems and Application to Power Line Communications,” *IEEE Transactions on Communications*, vol. 57, no. 5, pp. 1275-1279, May 2009.
- A. Tonello, F. Pecile, “Synchronization Algorithms and Receiver Structures for Multiuser Filter Bank Uplink Systems,” *EURASIP Journal on Wireless Communications and Networking*, April 2009.
- A. Tonello, F. Pecile, “Analytical Results about the Robustness of FMT Modulation with Several Prototype Pulses in Time-Frequency Selective Fading Channels,” *Transactions on Wireless Comm*., vol.7, no. 4, April 2008.
- A. M. Tonello, "A Concatenated Multitone Multiple Antenna Air-interface for the Asynchronous Multiple Access Channel," IEEE Journal on Selected Areas of Communications (JSAC), special issue on 4G systems, vol. 24, no. 3, pp. 457-469, March 2006.
- A. M. Tonello, "Performance Limits for Filtered Multitone Modulation in Fading Channels," IEEE Trans. on Wireless Communications, vol. 4, no. 5, pp. 2121-2135, September 2005.
- A. Tonello, S. D’Alessandro, L. Lampe, “Bit, tone and Cyclic Prefix Allocation in OFDM with Application to In-Home PLC,” *Proc. of IFIP Wireless Days 2008*, Dubai, November 2008.
- F. Pecile, A. Tonello, “On the Design of Filter Bank Systems in Power Line Channels Based on Achievable Rate,” *Proc. of IEEE Inter. Symposium on Power Line Communications and Its Applications, ISPLC 2009*, Dresden, March 2009.
- A. Tonello, “Asynchronous multicarrier multiple access: optimal and sub-optimal detection and decoding,” *Bell Labs Technical Journal*, vol. 7, no. 3, pp. 191-217, 2003.

References

802.11p

- G. Abdalla, M. A. Abu-Rgheff, S.-M. Senouci, “Current Trends in Vehicular Ad Hoc Networks,” *Special Issue of Ubiquitous and Communications Journal*, 2007.

802.11n/WiMedia/802.15.3c

- Seventh Framework Programme: Theme 3 ICT-213311 OMEGA, Deliverable D2.1, “Technical Requirements,” June 2008.
- IEEE Std.802.11, “Wireless LAN Medium Access Control and Physical Layer Specification,” June 2007.

DVB-T

- http://it.wikipedia.org/wiki/DVB-T
- DVB Fact Sheet, “Digital Terrestrial Television,” July 2009.
- DVB Fact Sheet, “Second Generation Terrestrial,” March 2010.

3GPP-LTE

- J. Zyren, “Overview of the 3GPP Long Term Evolution Physical Layer,” *white paper of freescale semiconductor*, doc. 3GPPEVOLUTIONWP, July 2007.

WiMax

- IEEE 802.16e Standard, “Air Interface for Fixed and Mobile Broadband Wireless Access Systems,” Feb. 2006.
- WiMax Forum, “Mobile System Profile,” Release 1.0, Sep, 2008.