# *Introduction to*

# *FMT Modulation and Multiuser Multitone Wireless Uplink Systems*


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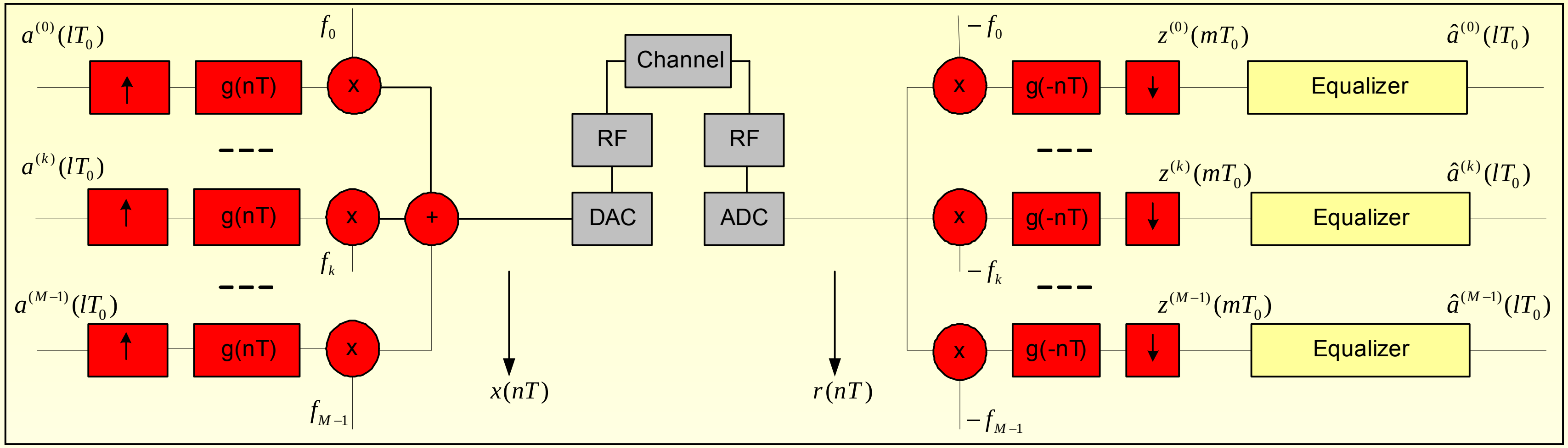
# Outline

- Filtered Multitone (FMT) Modulation
  - Principles
  - Detection and Performance Limits
  - Synchronization
- Asynchronous Multiuser Multitone Systems
  - Multiuser DMT/OFDM
  - Multiuser FMT
  - Synchronization in Multiuser FMT

# FMT Modulation

# Multicarrier Architecture



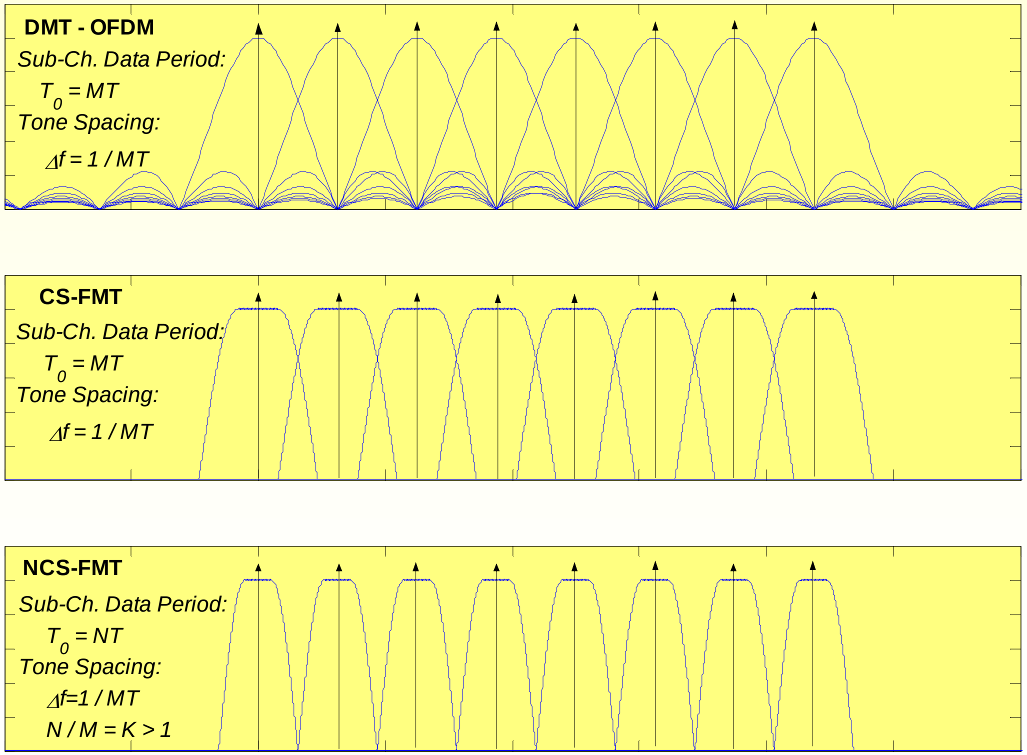

- Transmit a high data rate signal through a number of low rate sub-channels.

  - ✓ DMT (Discrete Multitone): well known OFDM scheme. It deploys a prototype filter with rectangular impulse response.

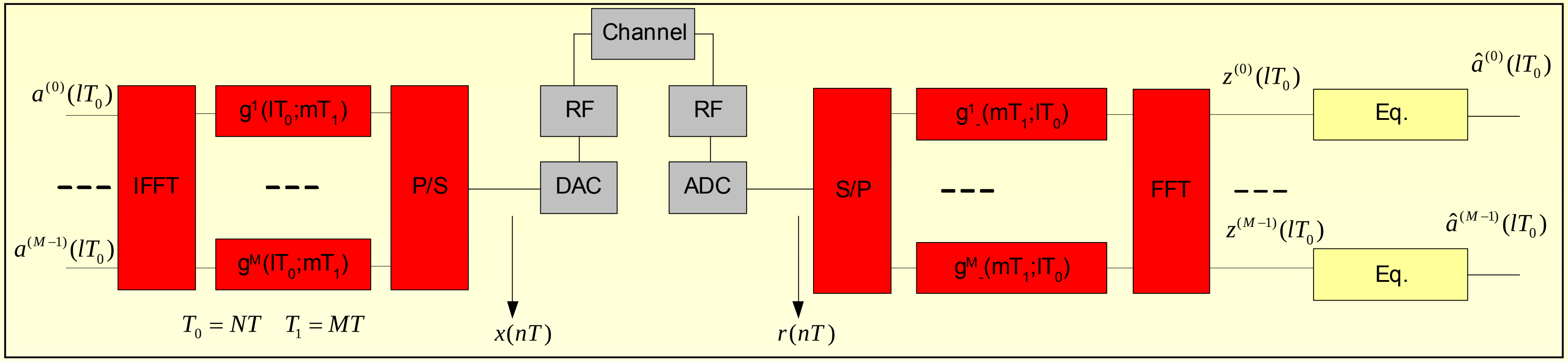
  - ✓ FMT (Filtered Multitone): deploys a sub–channel prototype pulse with time-frequency concentrated response.

# Filtered Multitone Architecture

- TX bandwidth: $W = 1 / T$.
- Sub-carriers: $f_k = k/(MT)$ , $k=0,\ldots,M-1$.
- Sub-channel period: $T_0=NT$
- *DMT – OFDM :* Rectangular impulse response prototype pulse $g(nT)$.
- *FMT :* Frequency concentrated prototype pulse, e.g., root-raised-cosine.



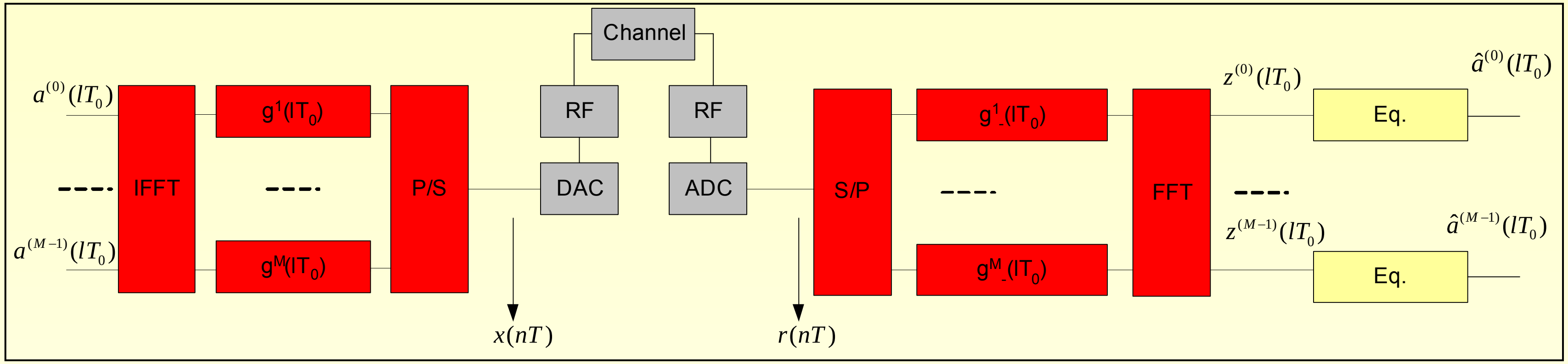
# Non-Critically Sampled FMT Efficient Implementation




- A possible efficient implementation is based on FFT and low-rate filtering as proposed by *Cherubini, Eleftheriou, Olcer, Cioffi*, *Comm. Mag. 2000.*

- In NCS-FMT the sub-channel pulse is cyclically time-variant.

# Critically Sampled FMT Efficient Implementation




**CS-FMT**

$$f_k = \frac{k-1}{T_0} \qquad T_0 = MT \qquad k = 1,\dots,M$$

$$g^k(mT_0) = g((k-1)T + mT_0) \qquad m \in \mathbb{Z}$$

↓ **Prototype pulse**

# Sub-channel Matched Filter Output

- RX front-end output sampled at symbol rate:

$$z^{(k)}(lT_0) = a^{(k)}(lT_0)g_{EQ}^{(k)}(0) + \sum_{m \neq 0} a^k(lT_0 - mT_0)g_{EQ}^{(k)}(mT_0) + ICI^{(k)} + \eta^{(k)}(lT_0)$$

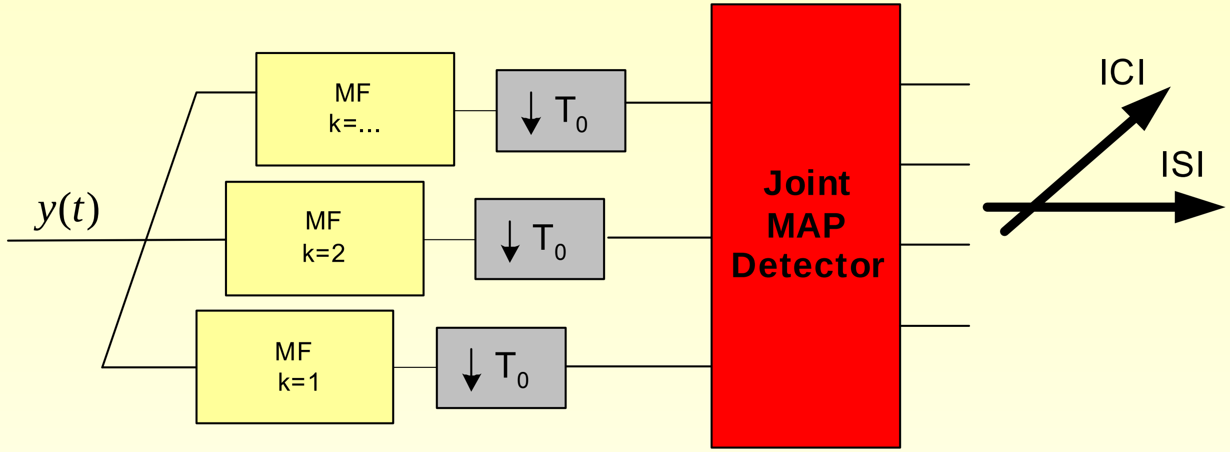
  - Δt=0, Δf=0: No ICI with band limited pulses but some ISI because of the channel frequency selectivity or non-ideal Nyquist pulses.
  - Δt≠0, Δf=0: Increased ISI because of wrong sampling phase.
  - Δt=0, Δf≠0: ISI and some ICI when Δf exceeds the frequency guards.

- When frequency concentrated pulses are deployed we get small ICI, however we need to run sub-channel equalization.
- We need time/frequency synchronization to minimize the amount of ISI and ICI.

# Detection in FMT

- FMT requires some form of equalization.
- The optimal detector is a multi-channel MLSE/MAP equalizer.
- Independent sub-channel equalization via linear or DFE equalization
  - ✓ As we increase the number of tones we obtain narrower sub-channels.
  - ✓ The sub-channel equalizer has low complexity since the sub-channel impulse response is short (sub-channel is narrow band).

# Optimal FMT Detector

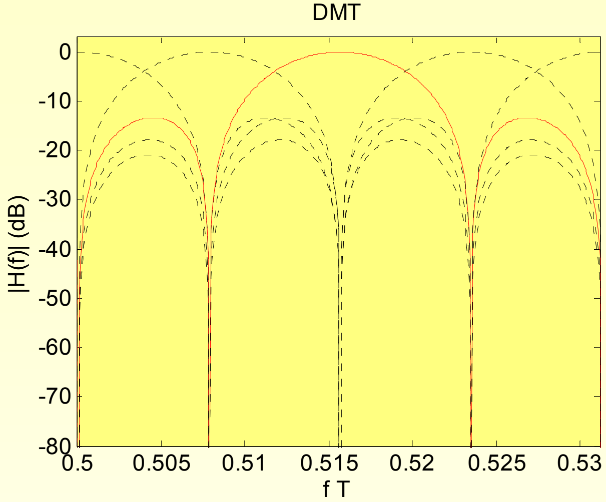


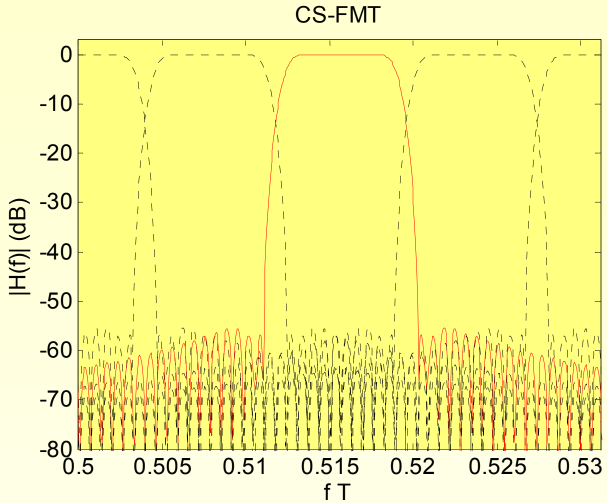

- The MAP detector computes the a posteriori probabilities of all data symbols by observing the input signal *y*( *t* ) over a time window.

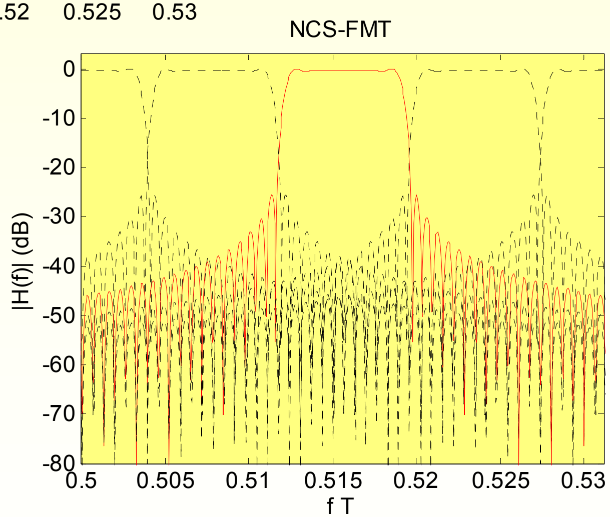
Ref: Tonello, *BLTJ 2003, Proc. VTC 2002 Fall.*

# Spectral Efficiency

# Example of Sub-Channel Frequency Response



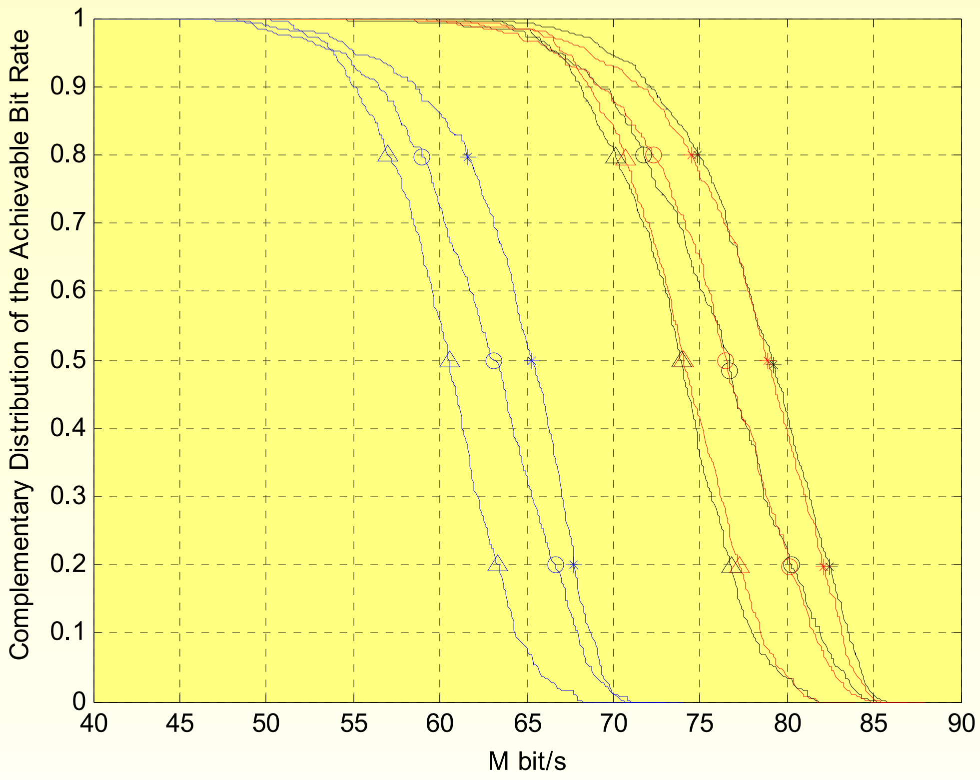

$M$ = 128  $B$ = 25 MHz

**CS-FMT:** rectangular windowed pulses + 4 virtual carriers

**NCS-FMT:** root raised cosine pulses  $N/M$ = 1.125 + 4 virtual carriers

**CP-DMT:** CP length = 30 chips + 16 virtual carriers

# *Probability* [ Achievable Bit Rate > K ]




------ **DMT**
------ **CS-FMT**
------ **NCS-FMT**

▲ **Rayleigh exponential with $\tau_{rms}$=100 ns**
● **Rayleigh exponential with $\tau_{rms}$=40 ns**
* **Ricean exponential with R=5 dB, $\tau_{rms}$=40ns**

- DFE sub-channel equalization in FMT.
- FMT has higher spectral efficiency than DMT/OFDM.

# Performance Limits for FMT Modulation

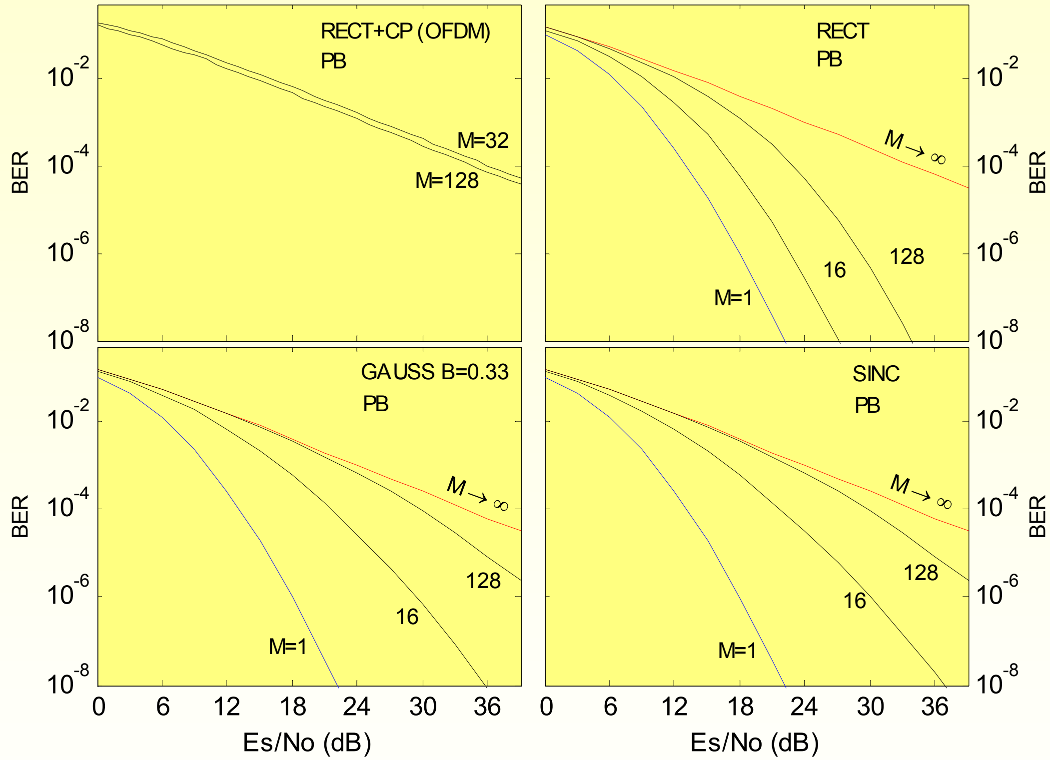
# Performance Limits

- Let us consider FMT modulation in time variant frequency selective fading.
- We can evaluate the matched filter bound performance in closed form:
  - BER performance with an ideal equalizer
- The analysis yields very interesting insights:
  - FMT modulation is a diversity transform and offers
    - time-frequency diversity gains and coding gains that are a function of the prototype pulse, and number of tones.

Ref: Tonello, *IEEE Trans. on Wireless Comm. in press ;* Tonello, *Proc. WPMC 2003.*

# Frequency Selective Time-Invariant Channel

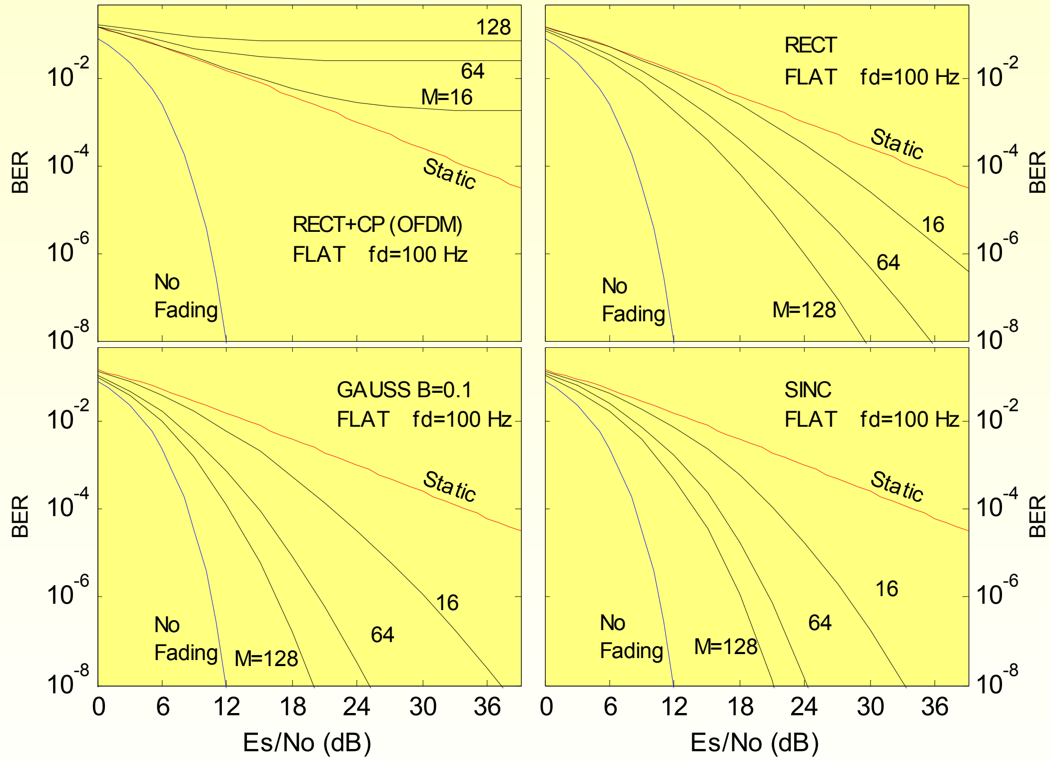
*ITU PB channel with quasi static fading*
*Bandwidth W=3.84 MHz. BPSK modulation.*




MF Bound performance for FMT with *rectangular*, *Gaussian*, and *sinc* prototype pulse

# Time-Variant Channel

*Flat fading with Jakes' Doppler spectrum*
*Bandwidth W=24.3 kHz. BPSK modulation.*



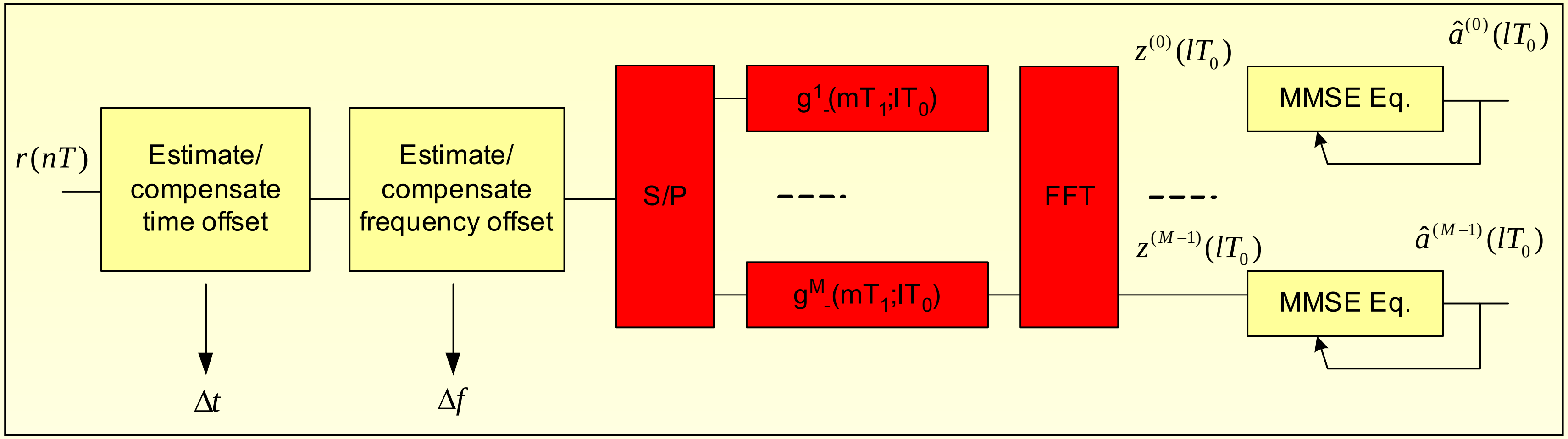

MF Bound performance for FMT with *rectangular*, *Gaussian*, and *sinc* prototype pulse

# Remarks

- In Frequency Selective Fading
  - ✓ FMT is a good choice complexity wise
  - ✓ Single Carrier modulation is a good choice performance wise.
- In Time Selective Fading
  - ✓ FMT is a good choice performance wise
  - ✓ Single carrier modulation is a good choice complexity wise.

# Synchronization

# Time-Domain Synchronization




❑ Estimation and compensation of time/frequency offsets can be done in the time domain.

- **Blind Synchronization**. The drawback is that channel estimation cannot rely on known training symbols.

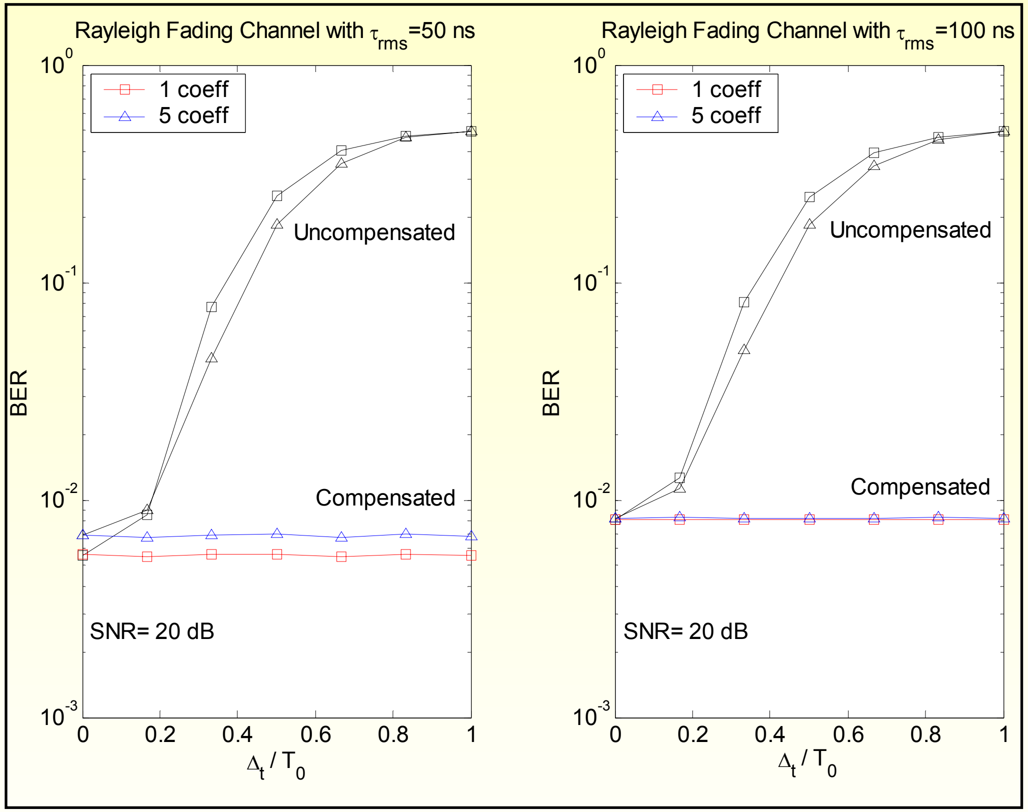
- **Cyclic Training Approach**. We generate training sequences that exhibit a periodic behavior at the tx-rx side, similarly in spirit to *Schmidl and Cox* method in OFDM.

- **PN Training Approach**. We generate PN training sequences.

Ref: Assalini, Tonello, Proc. *WPMC 2003* ; Tonello, Rossi, Proc. *WPMC 2004.*

# Bit-Error-Rate Performance with Time-Domain Sync.

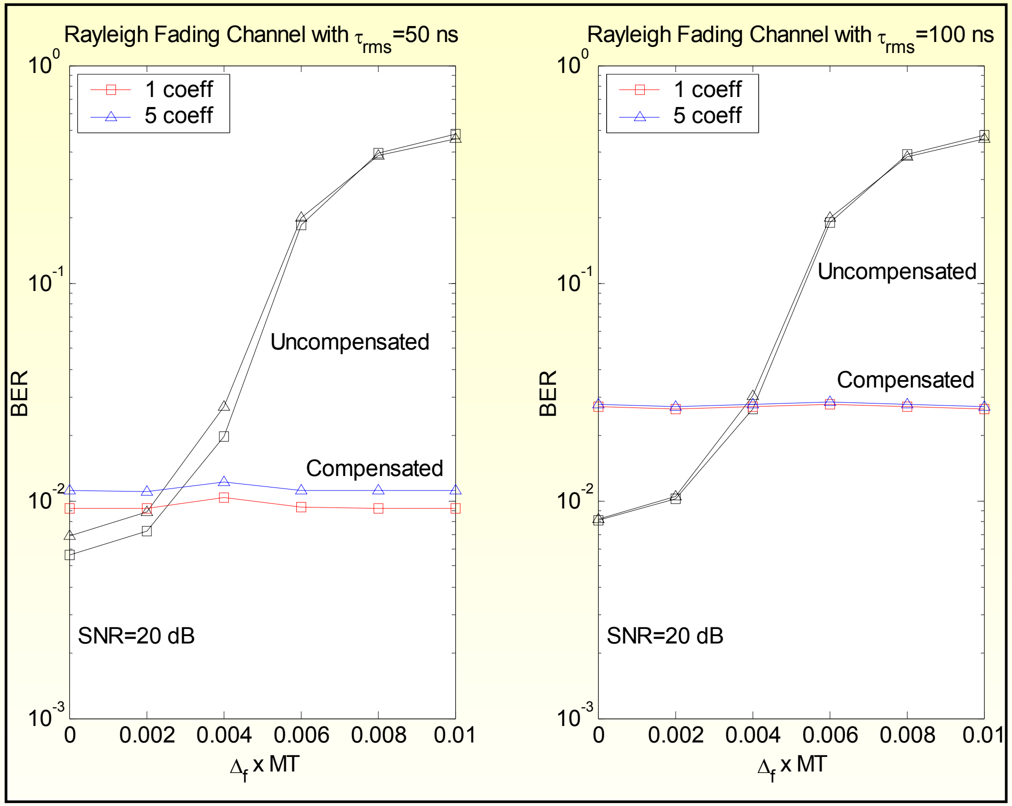
*Timing Error*




- 4-PSK modulation, M=32 Sub-channels,Root-Cosine Pulses, Bandwidth 20 MHz.
- Performance drastically decreases without time/frequency compensation.
- Synchronization with random sequences and 1-5 Tap RLS equalizer.

# Bit-Error-Rate Performance Time-Domain Sync.

*Frequency Error*




- The practical scheme with random training sequences performs well.
- A single tap equalizer is a good choice for delay spreads of ~100 ns.
- The performance of the synchronizer can be improved with a fine sync. method in the frequency domain.

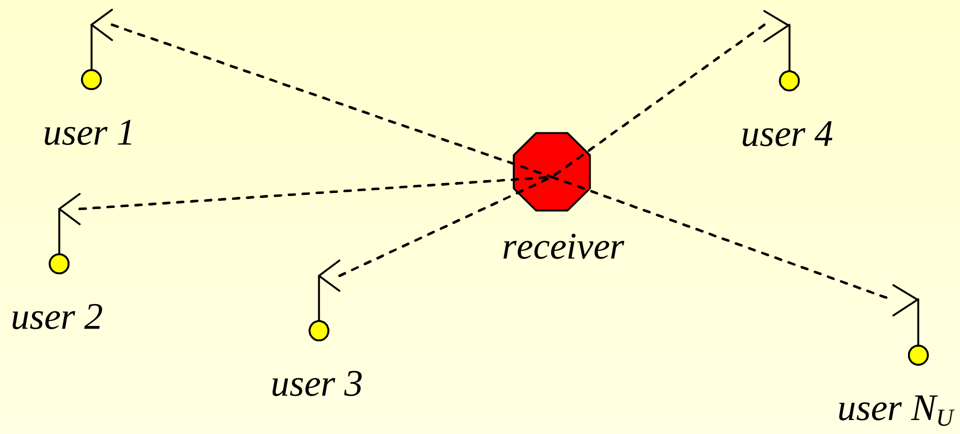
# Remarks

- OFDM is an elegant simple solution to cope with the channel frequency selectivity.
- FMT can yield higher spectral efficiency than DMT/OFDM.
- The sub-channel spectral containment of FMT makes it more robust to time and carrier frequency offsets than OFDM.
- Time-Frequency acquisition is still of great importance.
- FMT can be more complex than DMT since it requires filtering and equalization:

  - *we save complexity by using a smaller number of tones than in OFDM.*

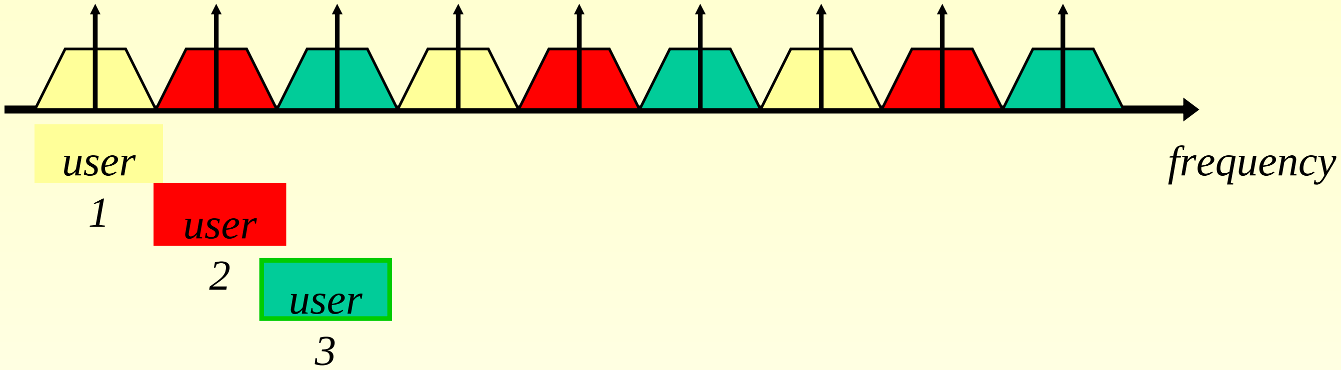
# Multiuser Multitone Architectures

# Asynchronous Multiple Access Channel




- Consider the Uplink
  - Users are asynchronous
  - Time offsets between users (*propagation delays*)
  - Carrier frequency offsets between users (*oscillators, Doppler*).
- Frequency Division Multiplexing is an Interesting Solution.

# Multitone Multiple Access




- *M* total tones
- Groups of tones are assigned to users
- Each user deploys multicarrier modulation over its set of tones
- Several tone allocation methods are possible:
  - ✓ *Orthogonal or non-orthogonal, Static or dynamic…*

# Solutions

❑ Two efficient implementation solutions

✓ Multiuser DMT : **MU-DMT** (OFDMA)

✓ Multiuser FMT : **MU-FMT**

Ref: Tonello, Pupolin, Proc. *WPMC 2001 ;* Tonello, *Bell Labs Tech. Journ. 2003.*

# Received Composite Signal

$$y(t)=\sum_{u=1}^{N_U}\sum_{k=0}^{M-1}\sum_{l=-\infty}^{\infty} a^{(u,k)}(lT_0)\,g_R^{(u,k)}(t-\Delta t_{u,k}-lT_0;t)\,e^{j(2\pi\Delta f_{u,k}t+\phi_{u,k})}+\eta(t)$$

Time-variant channel response for user *u* and sub-channel *k*

Time offset of user *u* and sub-channel *k* due to the propagation delay

Carrier Frequency offset due to Doppler and oscillators precision

| | |
|---|---|
| Propagation delay: | Δt=6.6 us/km = 6.6 chips/km [B=1 MHz] |
| Doppler: | Δ f=0.93 Hz [v=1 km/h -- fc=1 GHz] |
| Oscillator: | Δ f=1000 Hz [fc=1 GHz -- 1 p.p.m] |

*The values depend upon the hardware and the mobility/coverage requirements*

# MAI-ICI-ISI Components

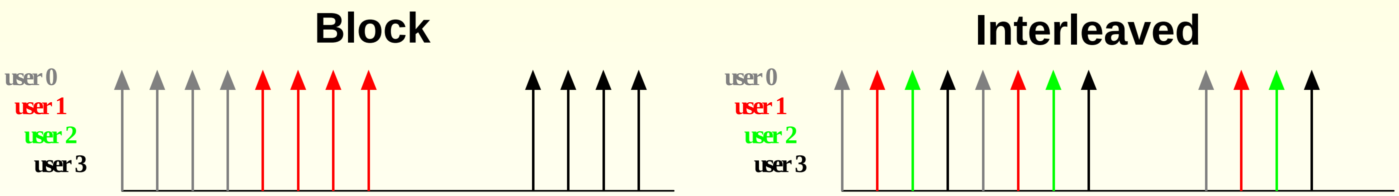
**The interference depends upon**

- sub-carrier spacing

- prototype filter

- tone allocation

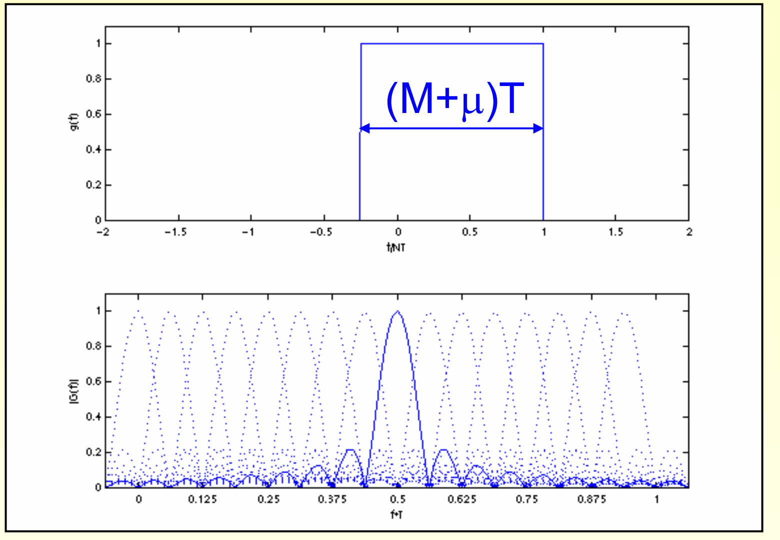
**Tone Allocation**




- **Block allocation** yields lower MAI than the interleaved.
- **Tone interleaving** is a better option to exploit the frequency diversity.
- **Frequency guards** can be inserted only with the block allocation in OFDM.
- The NCS-FMT architecture can comprise frequency guards.

# MU-OFDM Uplink Analysis

# Interference in MU-OFDM

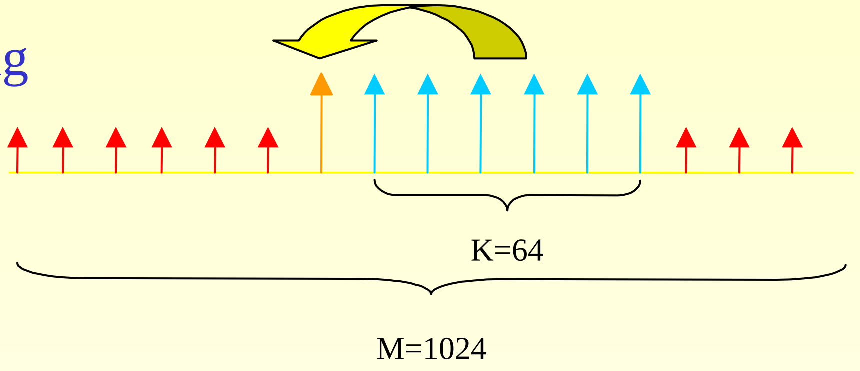



- ❑ The system is orthogonal in an ideal synchronous channel.
  - Users' time/frequency offsets generate MAI.
- ❑ A cyclic prefix can null the interference due to time misalignments.
- ❑ Interference from the carrier frequency offsets cannot be totally compensated.

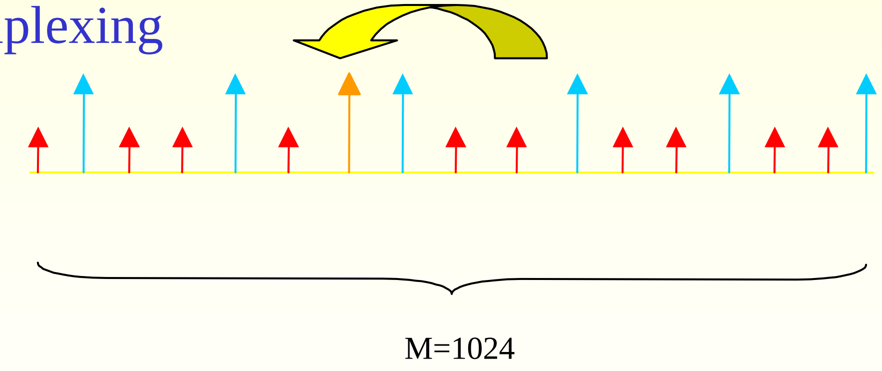
Ref: Tonello, Laurenti, Pupolin, Proc. *ICT 2000, Proc. VTC 2000 Fall.*

# MU-OFDM: *SIR on Adjacent Sub-Carrier*

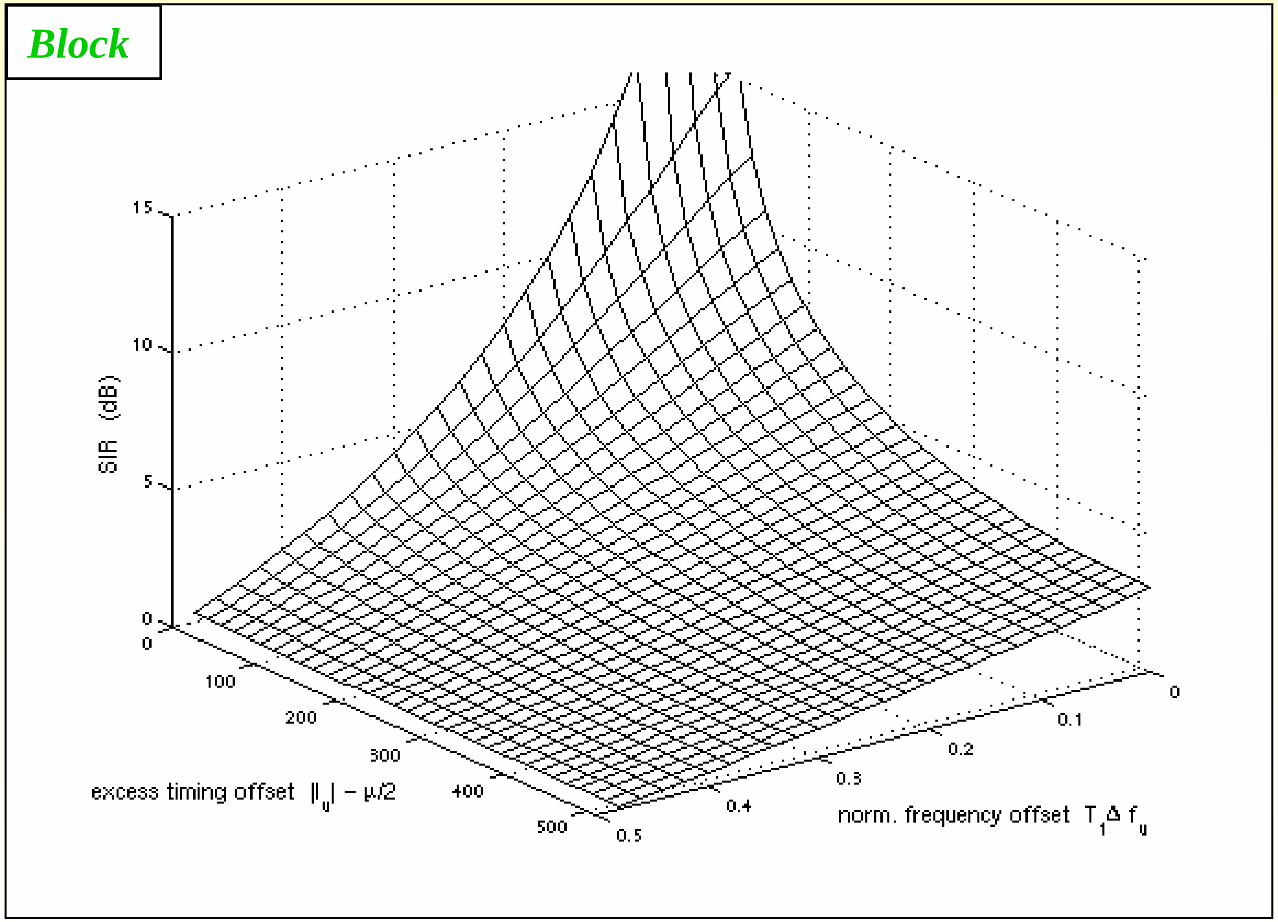
Block Multiplexing




Interleaved Multiplexing

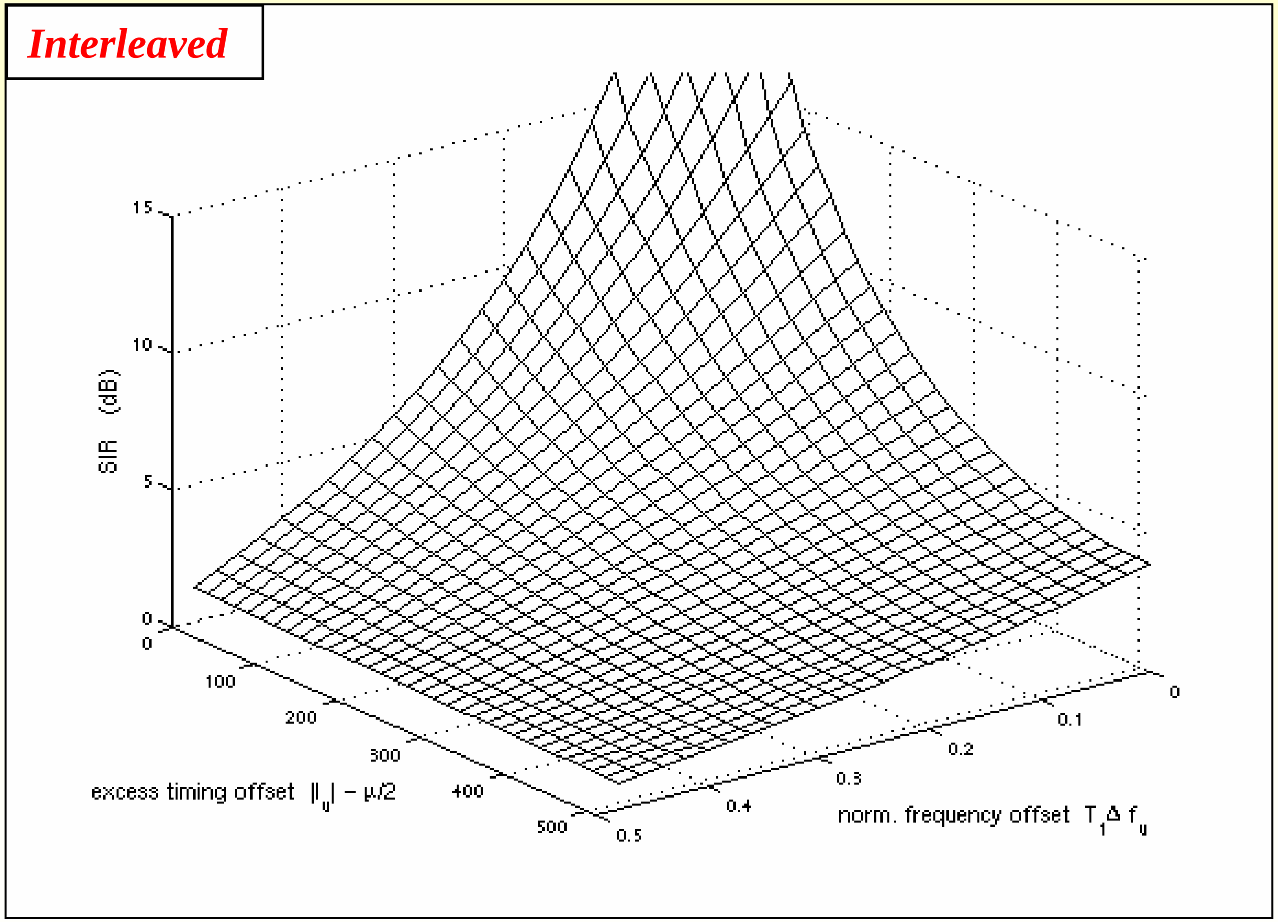


# SIR with Block Allocation in MU-OFDM



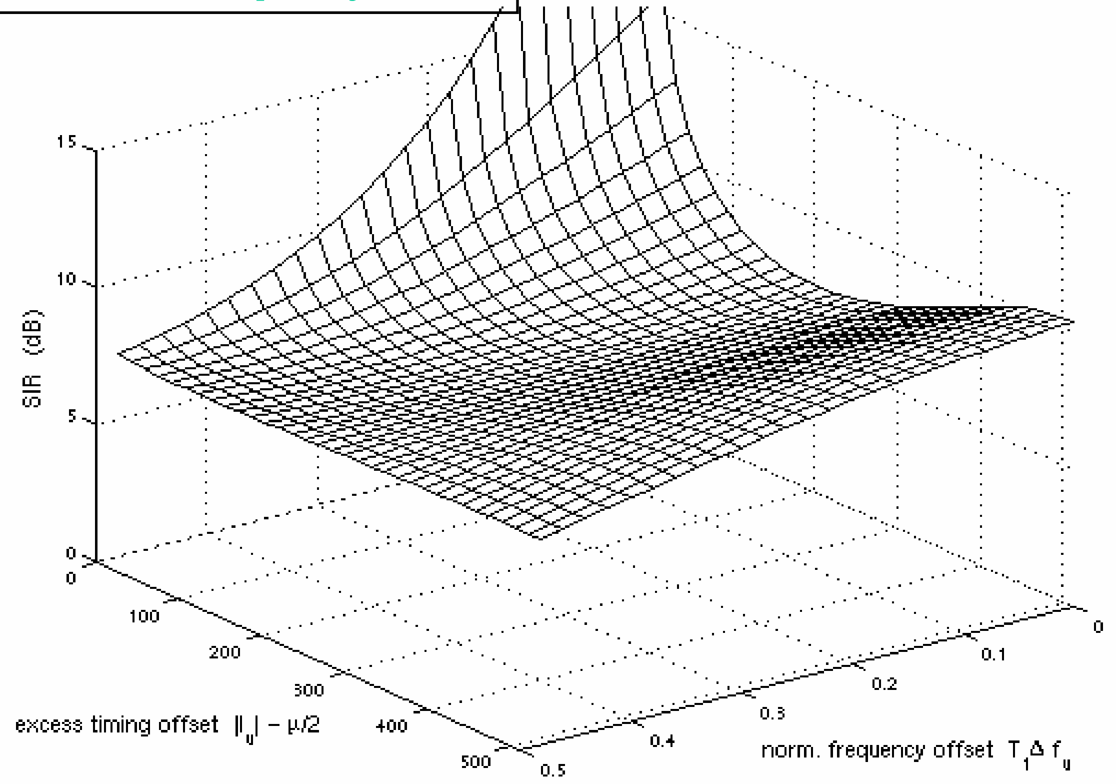

The SIR rapidly decreases as the frequency offset and the time offset increase.

# SIR with Interleaved Allocation in MU-OFDM



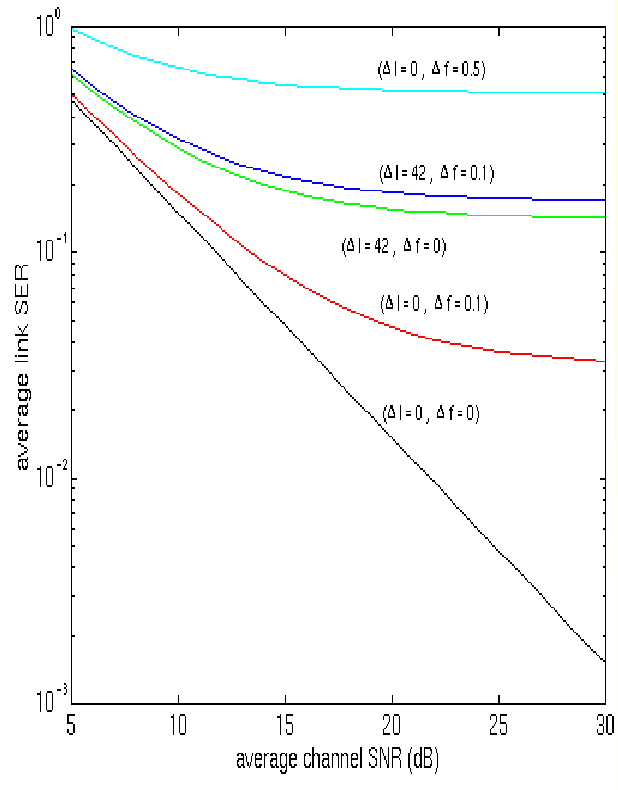
# SIR with Block Allocation and 1 Guard in MU-OFDM

*Block with 1 Frequency Guard*

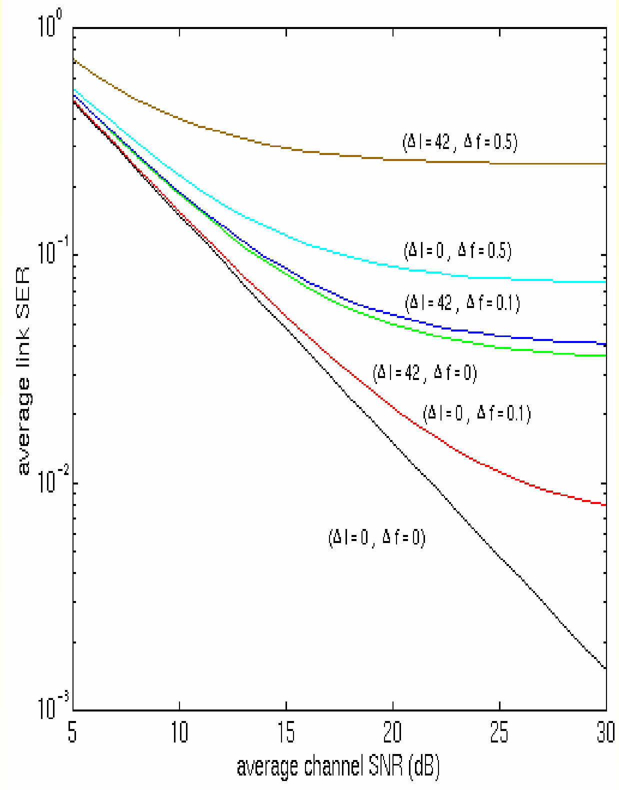


# MU-OFDM: *Average Symbol Error Rate*

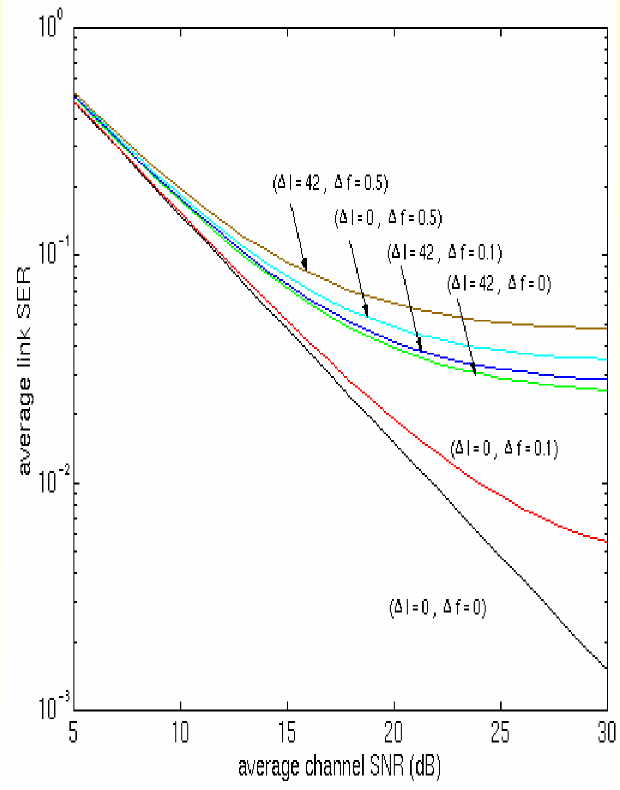
**Interleaved**




**Block**




**Block with One Frequency Guard**




4-PSK, 16 users, 12 tones/user, μ=64, W=4.096 MHz.

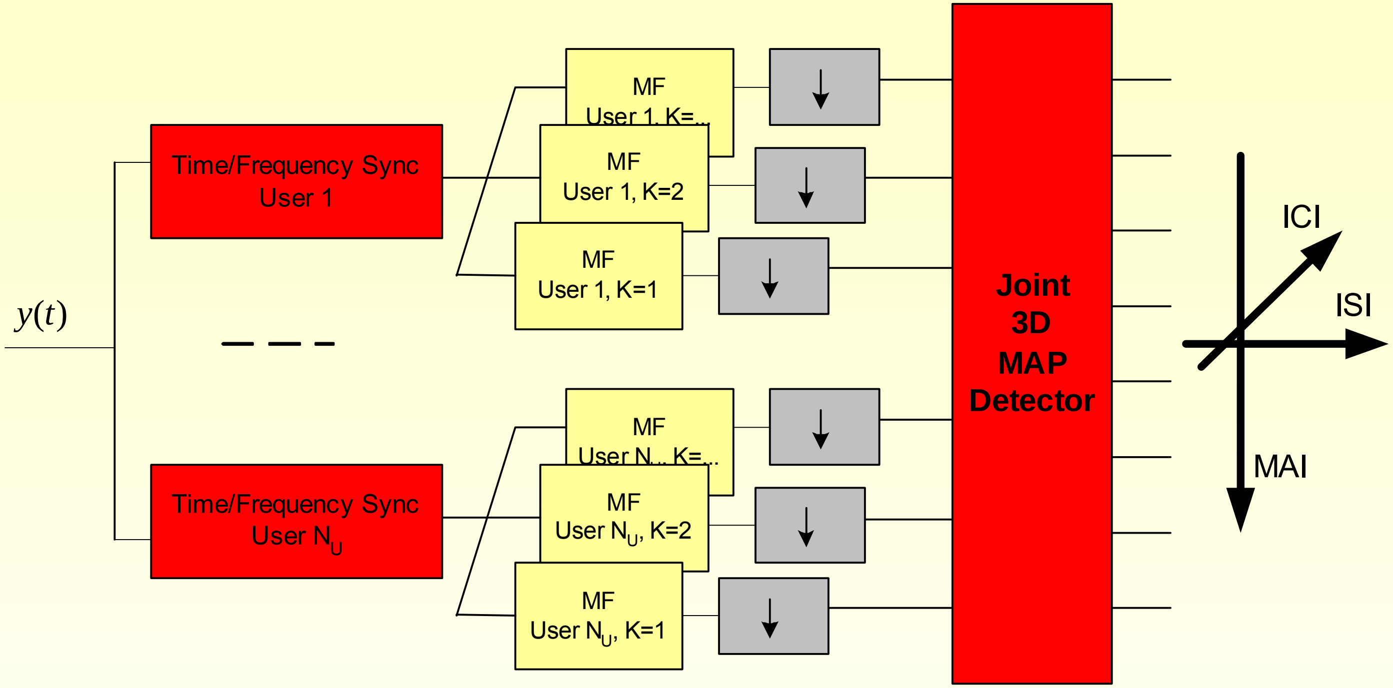
Excess time offsets and frequency offsets are independent and uniformly distributed between [-*Δ l* , + *Δ l* ] and [-*Δ f* , +*Δ f* ] respectively. The channel has an exponential power delay profile with d.s.=10 μs.

# Remarks

- MU-OFDMA is severely affected by users’ time/frequency offsets in the uplink.
- Time/Frequency guards reduce the spectral efficiency.
- Acquisition of timing and carrier frequency is difficult.
- Due to the spectral containment characteristics, FMT is a better option than OFDM for the uplink.

# Optimal Multiuser Multitone Detection

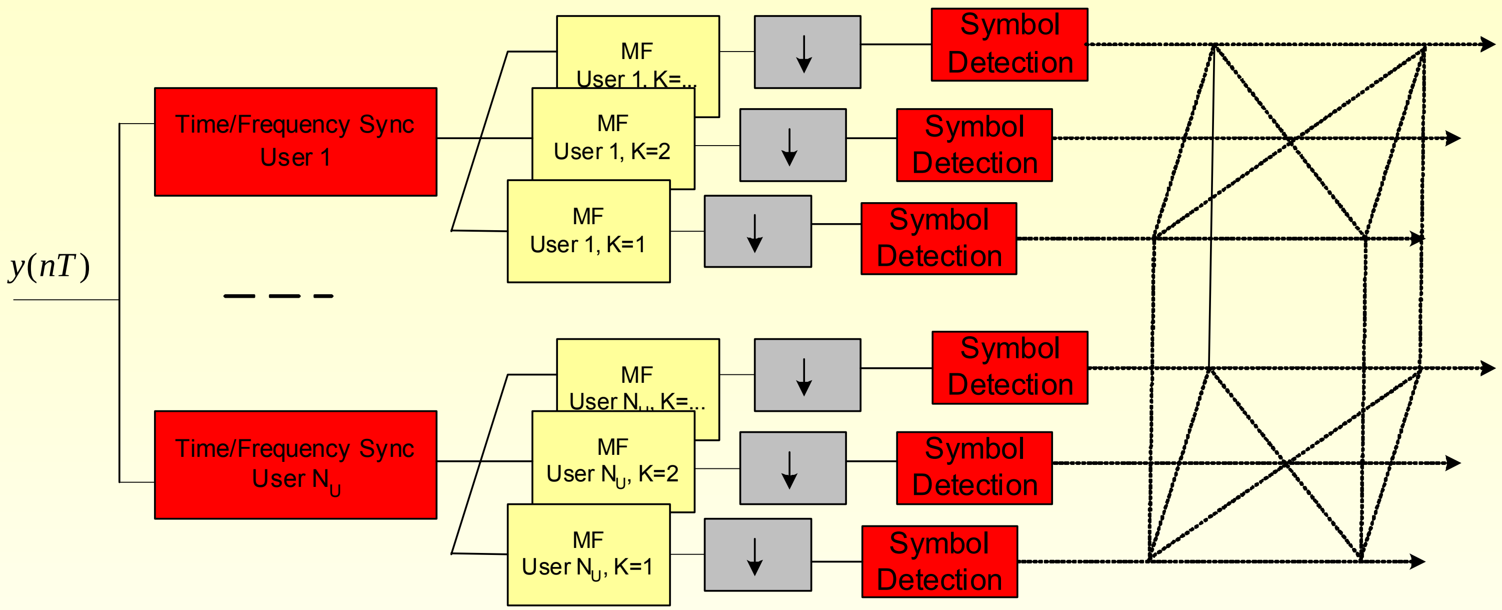
# Optimal MLSE/MAP Detection




- Optimal MAP Detection has a complexity that grows exponentially with the number of users, tones, and sub-channel memory.
- With frequency concentrated pulses and orthogonal tone assignment it simplifies to a bank of single channel MAP detectors.

Ref: Tonello, *VTC 2002 Fall*, *Bell Labs Tech. Jour. 2003*

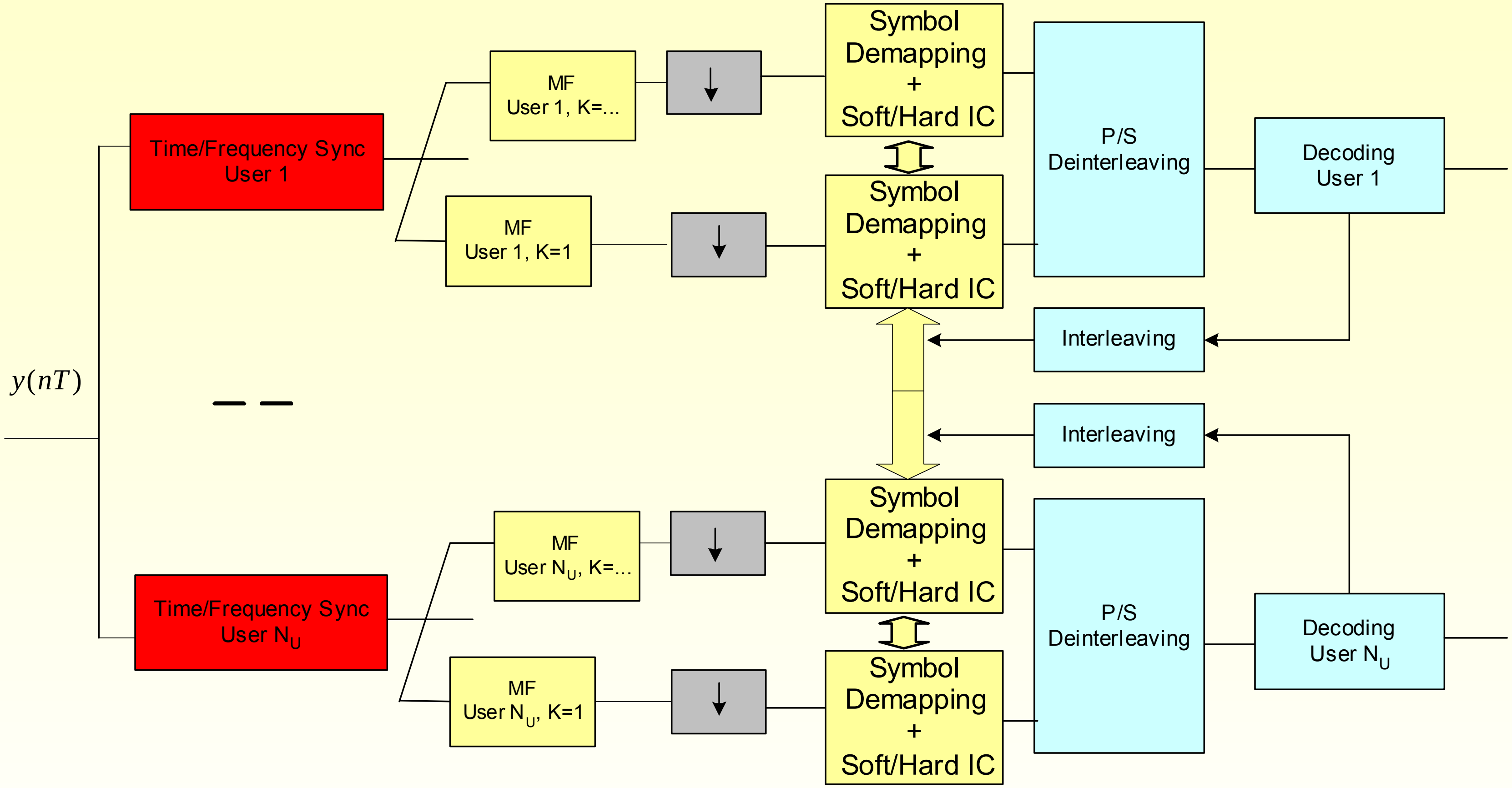
# Turbo Per-Symbol Detection




Simple approach

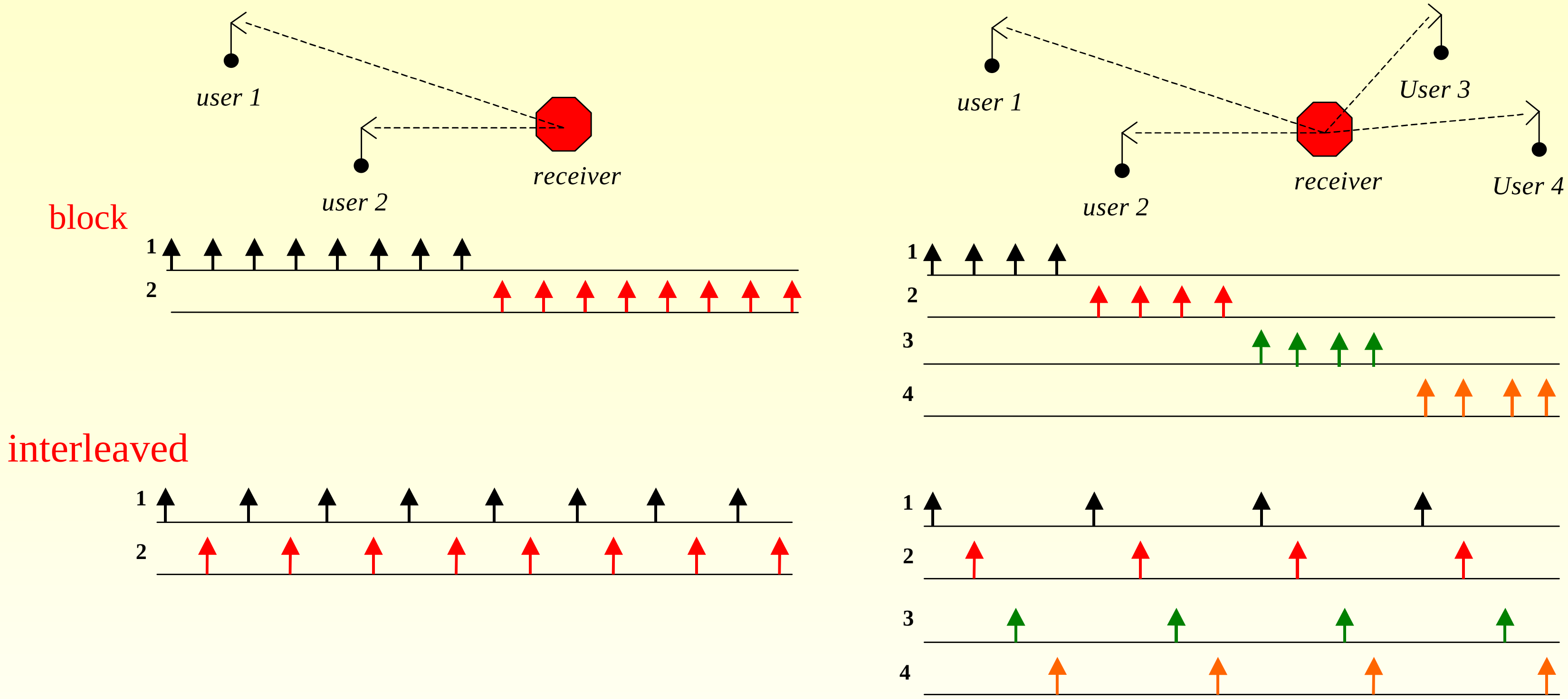
- Symbol-by-symbol detection with iterative interference cancellation

# Turbo Per-Symbol Decoding




- Feedback from the decoders if we assume to use bit-interleaved codes

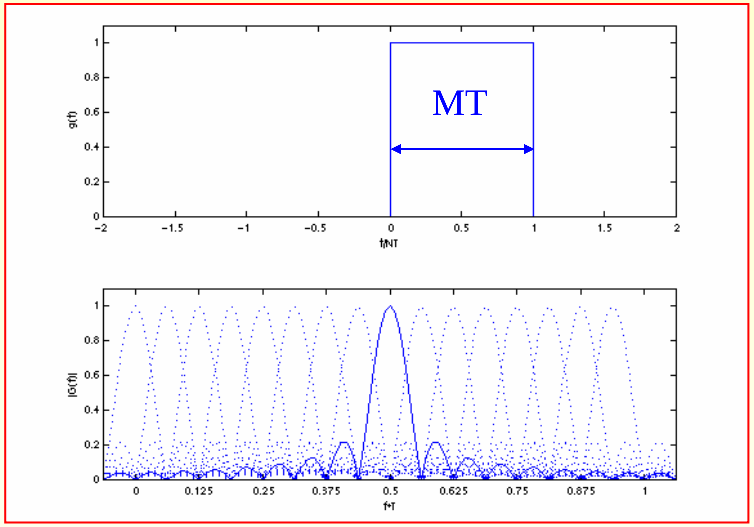
# Example of Multiuser Multitone System



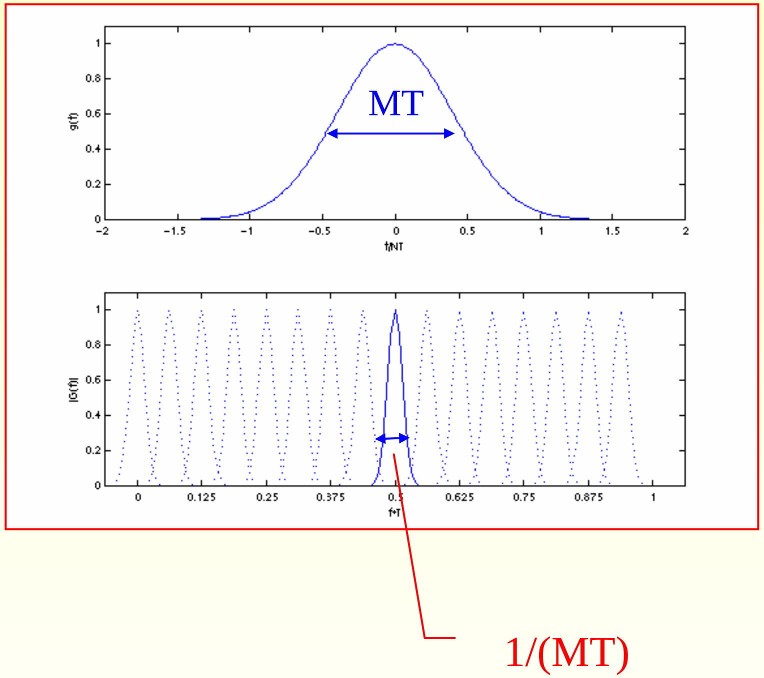

- **16 Total carriers**
- **QPSK – ½ Convolutional Code**
- **$\Delta t$ uniformly distributed in [- $\Delta t_m/2$, $\Delta t_m/2$]**
- **$\Delta f$ uniformly distributed in [- $\Delta f_m/2$, $\Delta f_m/2$]**

# Sub-Channel Pulses

**DMT: Rectangular Pulse**

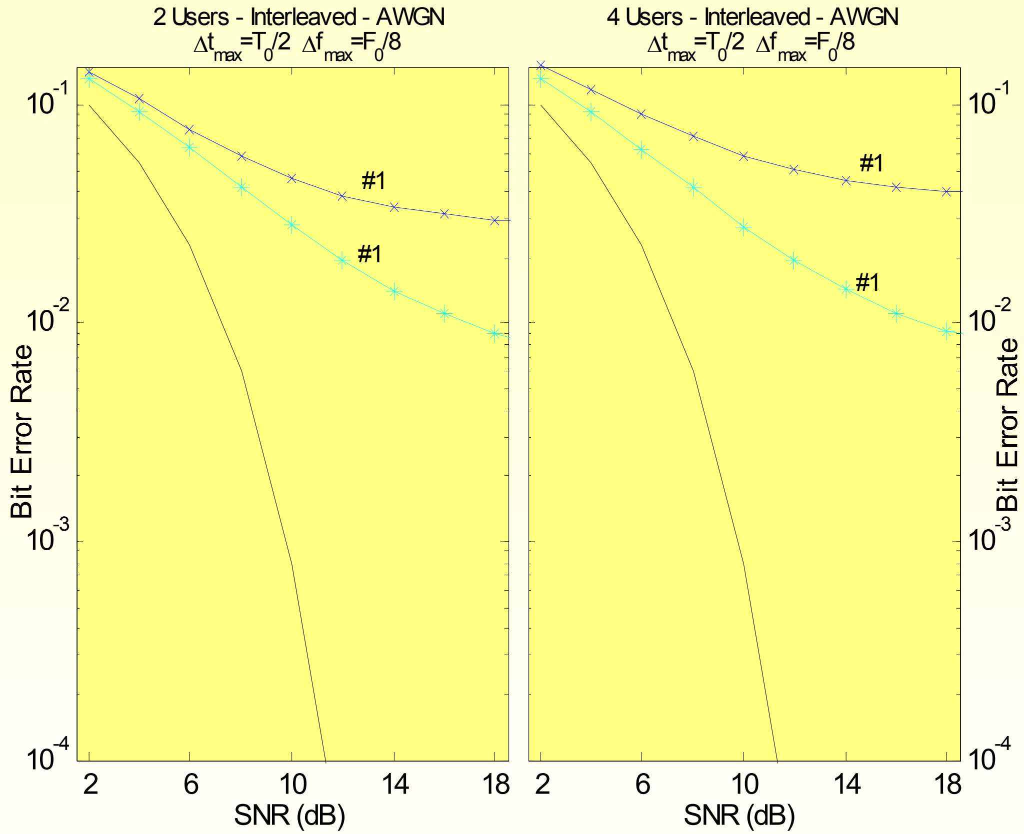



**FMT: Gaussian Pulse**




- Minimal sub-carrier spacing (no cyclic prefix)

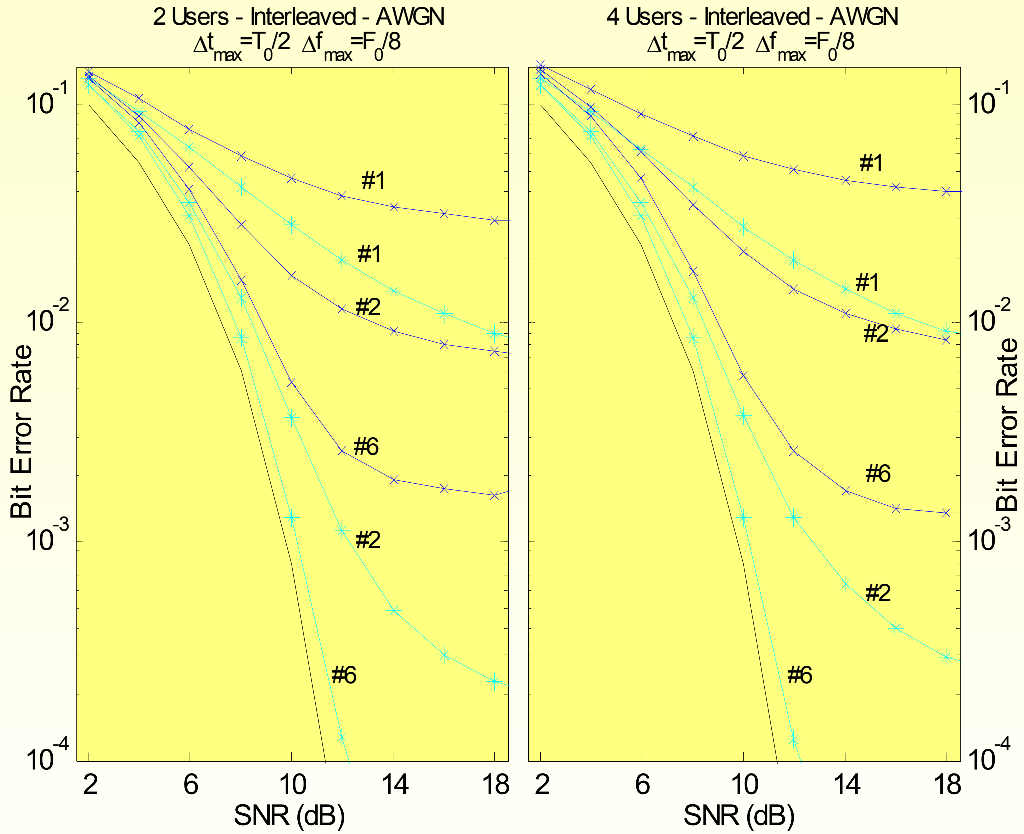
# BER Uncoded - Interleaved




**Uncoded**

------ **RECT pulses**
------ **GAUSS pulses**

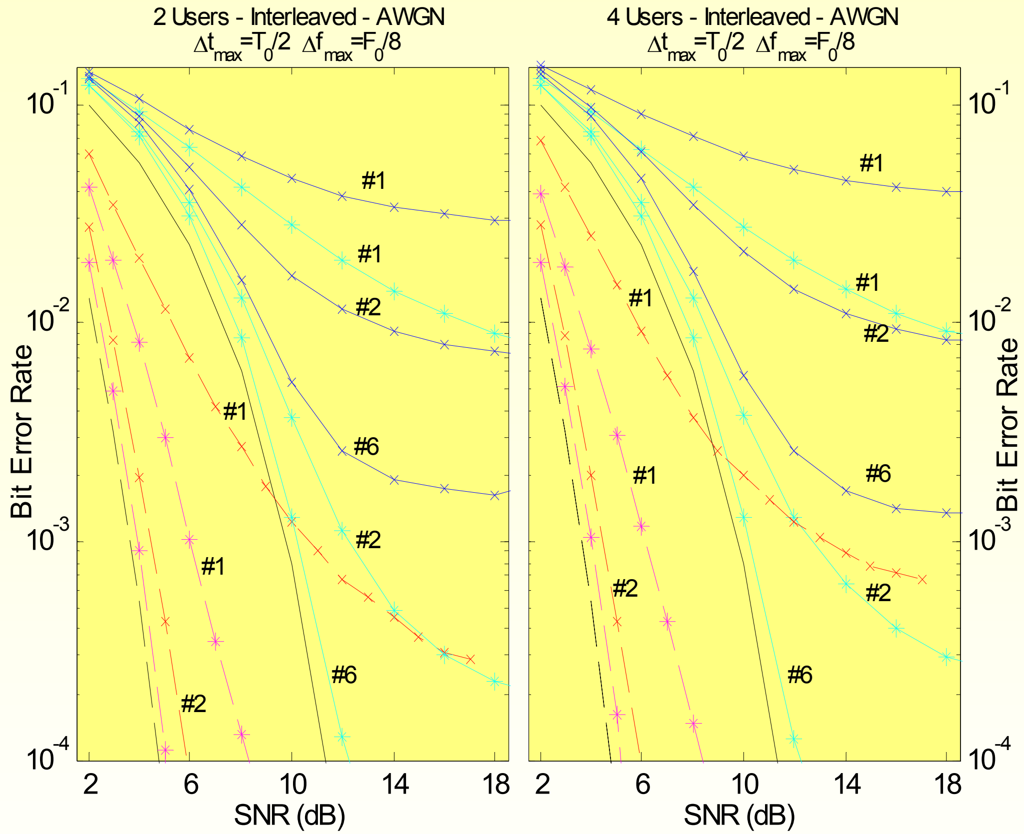
# BER Uncoded - Interleaved




**Uncoded**

------ **RECT pulses**
------ **GAUSS pulses**

# BER Coded - Interleaved




**Coded**

------ **RECT pulses**
------ **GAUSS pulses**

# Remarks

- FMT is a better solution than DMT for uplink asynchronous communications:
  - ✓ Single user detection with sub-channel equalization works fine if we use appropriate frequency confined sub-channel pulses!
- Optimal performance can be achieved with multitone multiuser detection.
- Simple iterative per-symbol detection/decoding shows fast convergence to the matched filter bound.

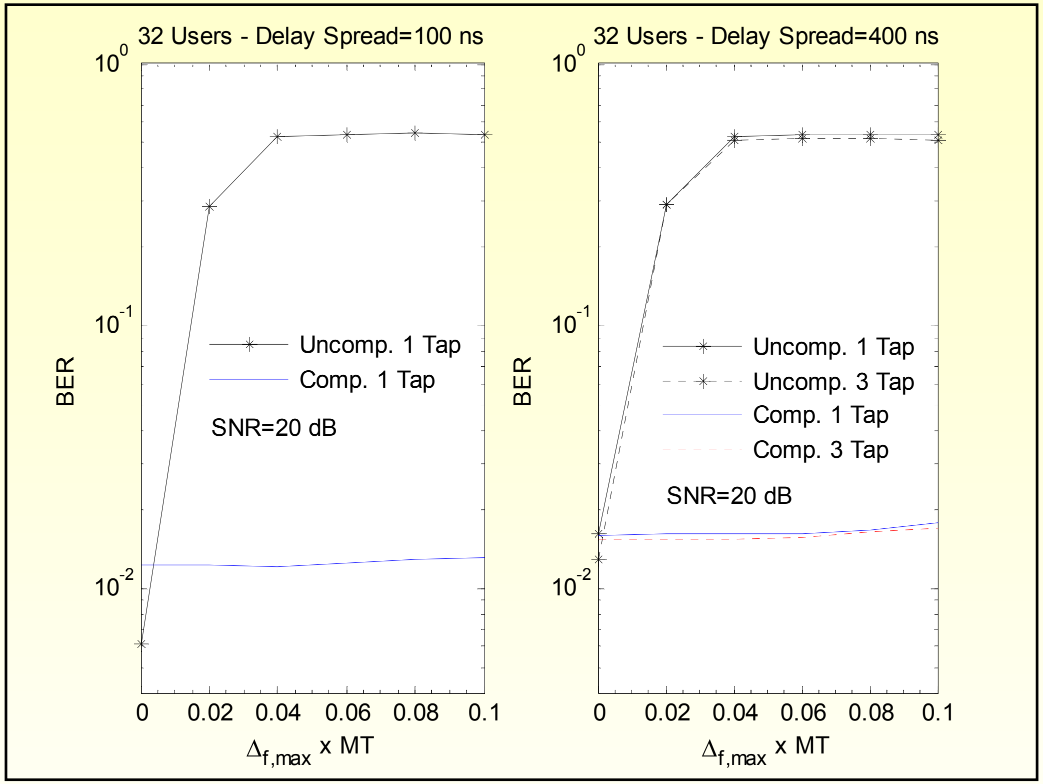
# Synchronization in MU-FMT

# MU-FMT Synchronization Algorithm

- We assume a single user receiver with training sequences and a 1-3 taps RLS equalizer per-sub-channel.

Ref: Tonello, Pecile, Proc. *VTC 2005 Spring.*

# Multiuser FMT - Synchronization Performance




- 4-PSK Modulation, M=32 Sub-channels, Root-Cosine Pulses, Bandwidth 10 MHz , Frequency guards of 12.5 kHz. Training of length 15 symbols.
- Delay spread 100 ns and 400 ns.
- Users are time-asynchronous with a random phase, the frequency offsets are uniformly distributed in [-Ε $f_{max}$, Ε $f_{max}$]. They have a single sub-channel each.

# Remarks

- The practical scheme with training sequences performs well.
- The MU-FMT architecture is very robust to the multiple access interference.
- Single user detection is simply required.

# Final Conclusion

**FMT is a promising technology that has great potentiality for the broadband uplink scenario !**

# Some References


***Multicarrier Systems Performance Analysis***

- A. Tonello, "**Performance limits for filtered multitone modulation in fading channels**", IEEE Trans. on Wireless Comm., in press, subm. April 2003.
- A. Assalini, S. Pupolin, A. Tonello, “**Analysis of the effects of phase noise in filtered multitone (FMT) modulated systems**”, Proc. of IEEE Globecom 2004, Dallas, November 2004.
- A. Tonello, "**Exact matched filter performance bound for filtered multitone modulation in fading channels**", Proceedings of Wireless Personal Multimedia Communications Symposium 2003, Yokosuka, October 2003.
- A. Tonello, R. Bernardini, "**On the exploitation of the time-frequency diversity in coded OFDM**", Proceedings of Wireless Personal Multimedia Communications Symposium 2003, Yokosuka, October 2003.
- A. Tonello, "**Performance limits of multicarrier based systems over fading channels with optimal detection**", Proceedings of IEEE WPMC 02, Honolulu, October 2002.

***Multicarrier Multiuser Systems***

- A. Tonello, "**Asynchronous multicarrier multiple access: optimal and sub-optimal detection and decoding**", Bell Labs Technical Journal Fall 2002, vol. 7 issue 3, February 2003.
- A. Tonello, A. Assalini, "**An asynchronous multitone multiuser air interface for high speed uplink communications**", Proceedings of IEEE Vehicular Technology Conference 2003 Fall, Orlando, October 2003.
- A. Tonello, "**Multiuser detection/decoding in asynchronous multitone multiple access systems**", Proceedings of IEEE WPMC 02, Honolulu, October 2002.
- A. Tonello, "**Multiuser detection and turbo multiuser decoding for asynchronous multitone multiple access systems**", Proceedings of IEEE VTC 02-Fall, Vancouver, September 2002.
- A. Tonello, S. Pupolin, "**Performance of single user detectors in multitone multiple access asynchronous communications**", Proceedings of IEEE VTC 2002 - Spring, Birmingham, Alabama, May 2002.
- A. Tonello, S. Pupolin, "**Discrete multi-tone and filtered multi-tone architectures for broadband asynchronous multi-user communications**", Proceedings of WPMC 2001,Aalborg, September 9-12, 2001.
- A. Tonello, N. Laurenti, S. Pupolin, "**Analysis of the uplink of an asynchronous multi-user DMT OFDMA system impaired by time offsets, frequency offsets, and multi-path fading**" , Proceedings of IEEE VTC 2000 - Fall, Boston, September 24-28, 2000.
- A. Tonello, N. Laurenti, S. Pupolin, "**Capacity considerations on the uplink of a DMT OFDMA system impaired by time misalignments, and frequency offsets**", in “Software Defined Radio”, Springer-Verlag, Del Re ed. 2000.
- A. Tonello, N. Laurenti, S. Pupolin, "**On the effect of time and frequency offsets in the uplink of an asynchronous multi-user DMT OFDMA system**", Proceedings of ICT 2000, Acapulco, May 22-25, 2000.

***Synchronization in Multicarrier Systems***

- A. Tonello, F. Pecile, “**Synchronization Algorithms for Multiuser Filtered Multitone (FMT) Systems**”, to appear in Proceedings of IEEE VTC 2005 Spring, Stockholm, Sweden.
- A. Tonello, F. Rossi, “**Synchronization and Channel Estimation for Filtered Multitone Modulation**”, Proceedings of Wireless Personal Multimedia Communications Symposium 2004, Abano Terme, September 2004.
- A. Assalini, A. Tonello, "**Time-Frequency synchronization in filtered multitone modulation based systems**", Proceedings of Wireless Personal Multimedia Communications Symposium 2003, Yokosuka, October 2003.

***Multicarrier Multiple Antenna Systems***

- A. Tonello, "**Orthogonal space-time discrete multitone and space-time filtered multitone coded architectures**", Proceedings of IEEE Vehicular Technology Conference 2004 Spring, Milano, May 2004.
- A. Tonello, “**A concatenated multitone multiple antenna scheme for multiuser uplink communications**”, Proceedings of IEEE ITG Workshop on Smart Antennas, Munich, March 2004.