Air Interfaces for Future-Generation Wireless Systems*

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* Influenced by participation in WINNER project and WWRF

What is Beyond 3G?

...faster bigger smarter handier closer cheaper friendlier smoother easier quicker better…

- Starting point is user needs.
- IP-based, designed for data.
- Ubiquitous seamless service – detects user requirements and service availabilities and adapts/ hands off accordingly.
- > 10 times maximum speed of 3G, with about the same allocated spectrum.
- More efficient spectrum use via spatial processing, spectrum sharing and multihop.
- Smarter systems, evolving capabilities, according to Moore's law.

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B3G Research Efforts Worldwide

- **Wireless World Research Forum (WWRF)**
- China: FuTURE
- Japan: mITF
- Korea: NGMC
- USA: DARPA neXt
- Europe:
  - 4MORE
  - DAIDALOS
  - MAGNET
  - PULSERS
  - **WWI:**
    - Ambient Networks
    - E2R
    - MobiLife
    - SPICE
    - **WINNER (Wireless Initiative New Radio)**

4G Requirements Impacting on Physical Layer*

- Efficient, economical accommodation of very low and very high bit rates (e.g. 1 Kb/s to 100 Mb/s, with high user densities. Ubiquitous coverage.
- Adaptive and self-configuring to user needs and transmission environment.
- Moderate cost. Terminal cost, power and battery requirements commensurate with required performance and data rate).
- Higher spectral efficiency than 3G - up to or greater than 10 B/s/Hz.
- Capability and intelligent design of adaptive array deployment depends on a good measurement-based understanding of MIMO channel characteristics

* From WWRF Vision document, 2005-2006

Air Interfaces

- Transmitted signal format:
  - Will be frequency domain-based - provide excellent performance/complexity tradeoff for expected large multipath spreads. In particular, Generalized Multicarrier (GMC), which includes:
    - OFDM(A), SC-FDE*, ... These can be considered as special cases of each other
    - MC-CDMA, DS-CDMA, …
    - Space-time coding, spatial multiplexing
  - Advanced detection and error control techniques: iterative (turbo) coding and processing, HARQ, space-time coding, MIMO,..

* Single carrier (serial modulation) with frequency domain equalization

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Air Interfaces (cont.)

- Air interface will be adaptive, depending on traffic and channel, in terms of:
  - code rate, modulation
  - spectrum occupancy, power
  - user terminal capability

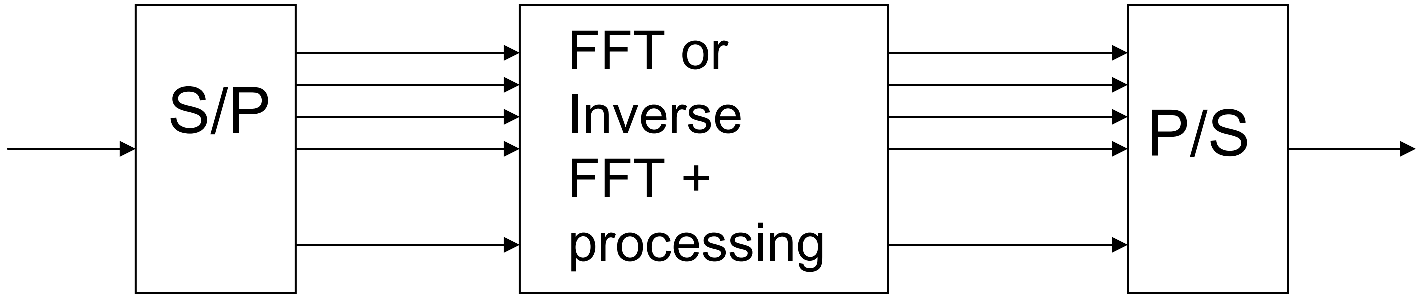
- Multiple access:
  - Packet based, with packets partitioned and assigned to time division/frequency division/space division “chunks”.
  - Multiple bandwidth frequency-domain-based transmission for opportunistic cognitive radio …

Other issues

- SPECTRUM – where and how much? Waiting for WRC 2007
- Spectrum sharing with satellite, fixed wireless, broadcast, etc. as well as other 4G service providers
- Cost commensurate with function:
  - Scalability - peak and average power, bandwidth, bit rate, hardware requirements
- Hardware impairments: power amplification, phase noise, power consumption, heat dissipation.

Frequency Domain – Based Air Interface

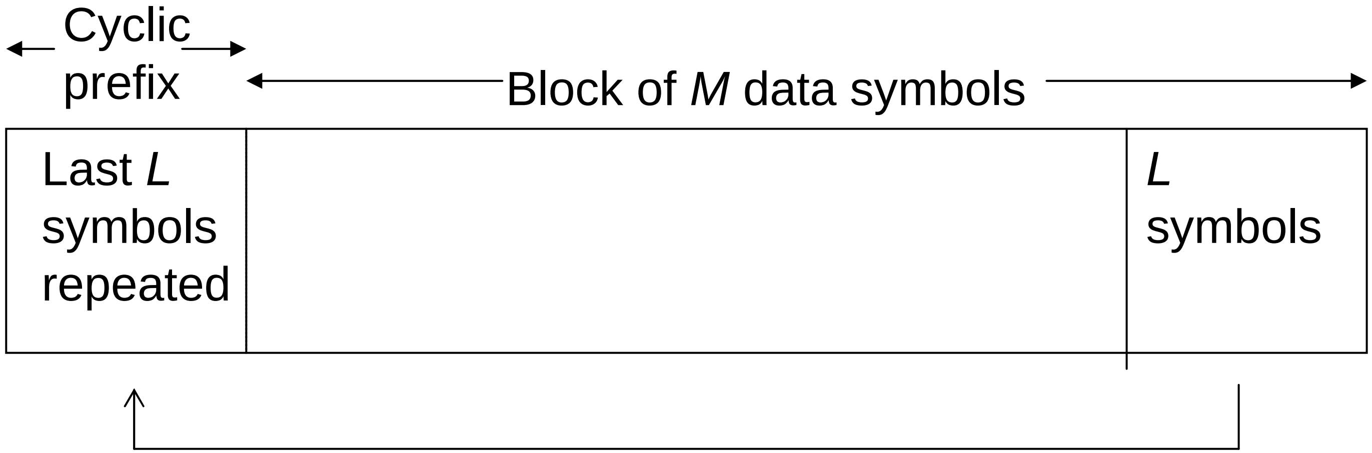
- Maximum aggregate bit rate up to 100 Mb/s, or even 1 Gb/s in non-line of sight frequency-selective radio propagation environments.
  - Calls for fast Fourier transform (FFT)-based block frequency domain transmission and reception.
  - Block length and cyclic prefix length determined by consideration of max. delay spread and frequency offset



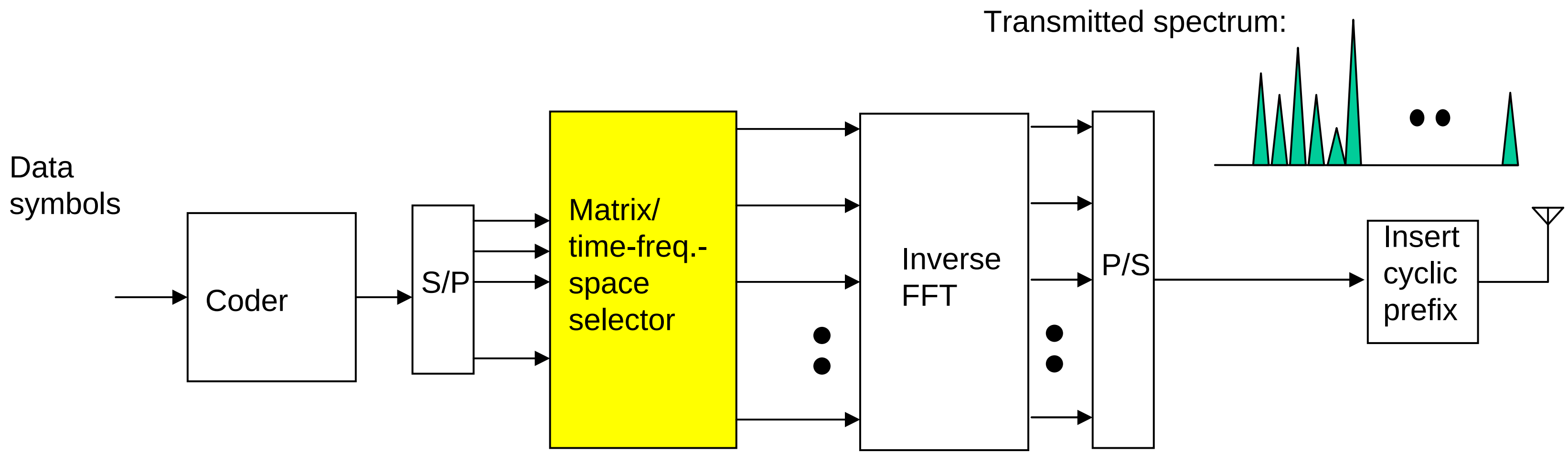
Complexity ~ log(delay spread)

Block Processing in Frequency Domain Equalization

- Data symbols $\{a_n\}$ are transmitted in blocks of $(M+L)$ symbols, with a cyclic prefix of length L> expected channel impulse response length.
- Receiver processes blocks of M symbol intervals in frequency domain by taking FFT (fast Fourier transform) of received block.
- Typically M is 5 to 10 times L.
- First and last L symbols may be training symbols.



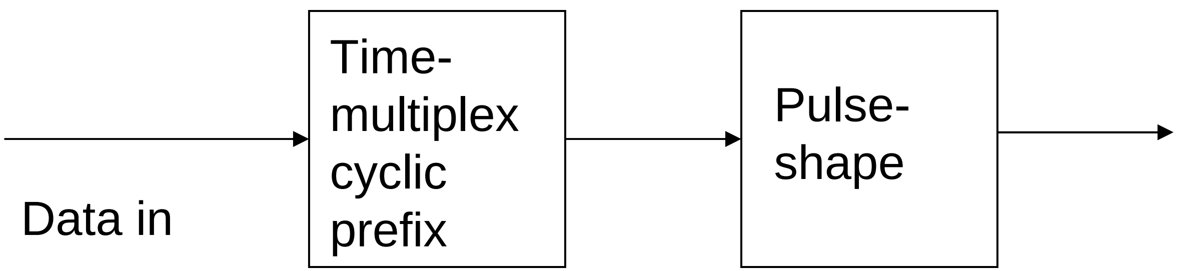
Generalized Frequency Domain Transmitter (Generalized Multicarrier)



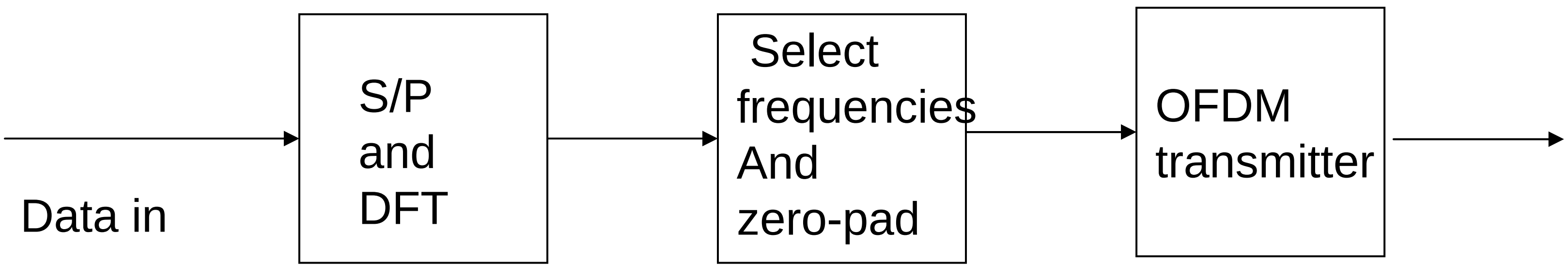
- OFDM, OFDMA, MC-CDMA, serial modulation, etc. can be generated by proper choice of matrix/selector.

Two Ways to Generate a Serial Modulation (Single Carrier) Signal Block

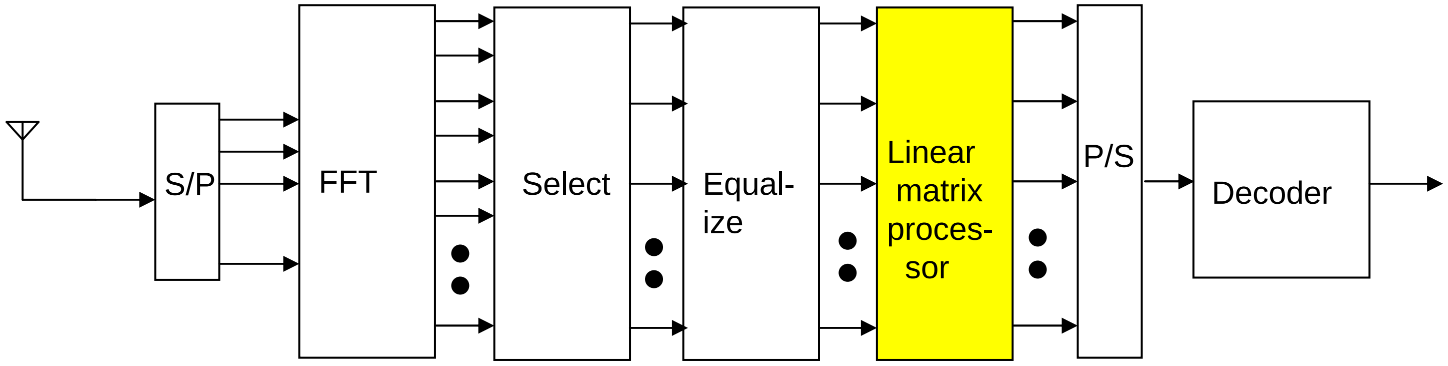
Conventional serial modulation:



Special case of generalized multicarrier:

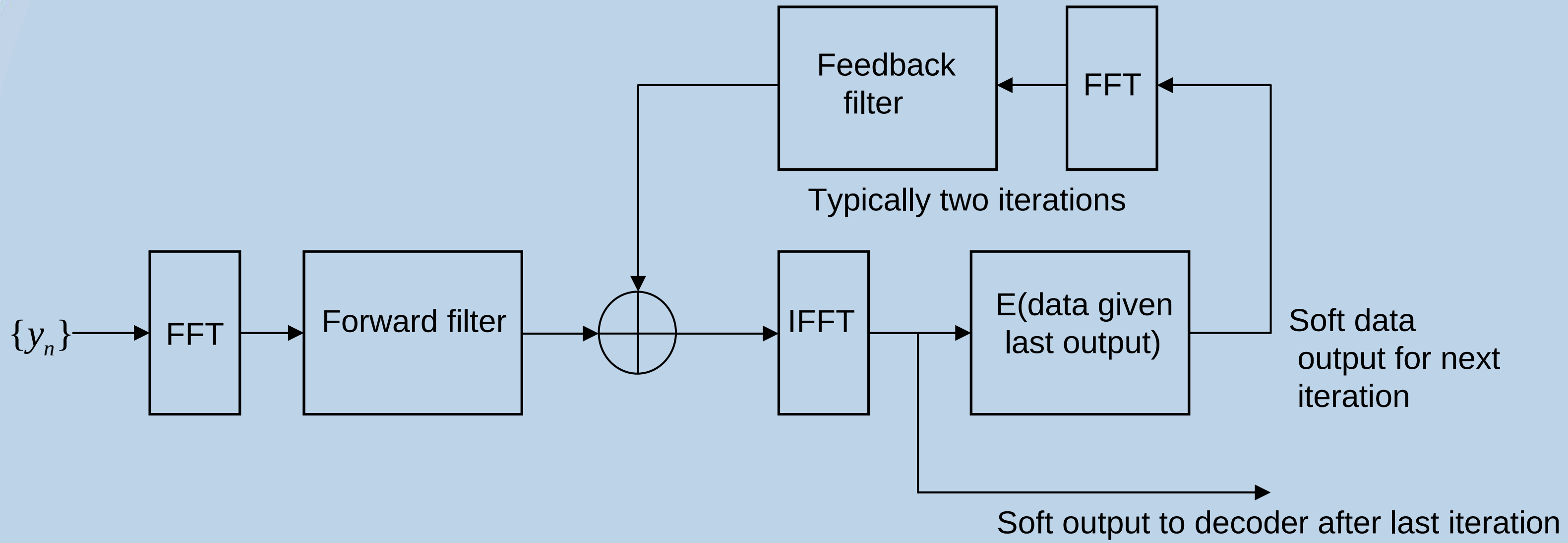


Generalized Frequency Domain Receiver



- For OFDM, OFDMA, MC-CDMA, etc. linear matrix processor at receiver is not necessary (replaced by IFFT at transmitter).
- For serial modulation, linear matrix processor at receiver is an IFFT.

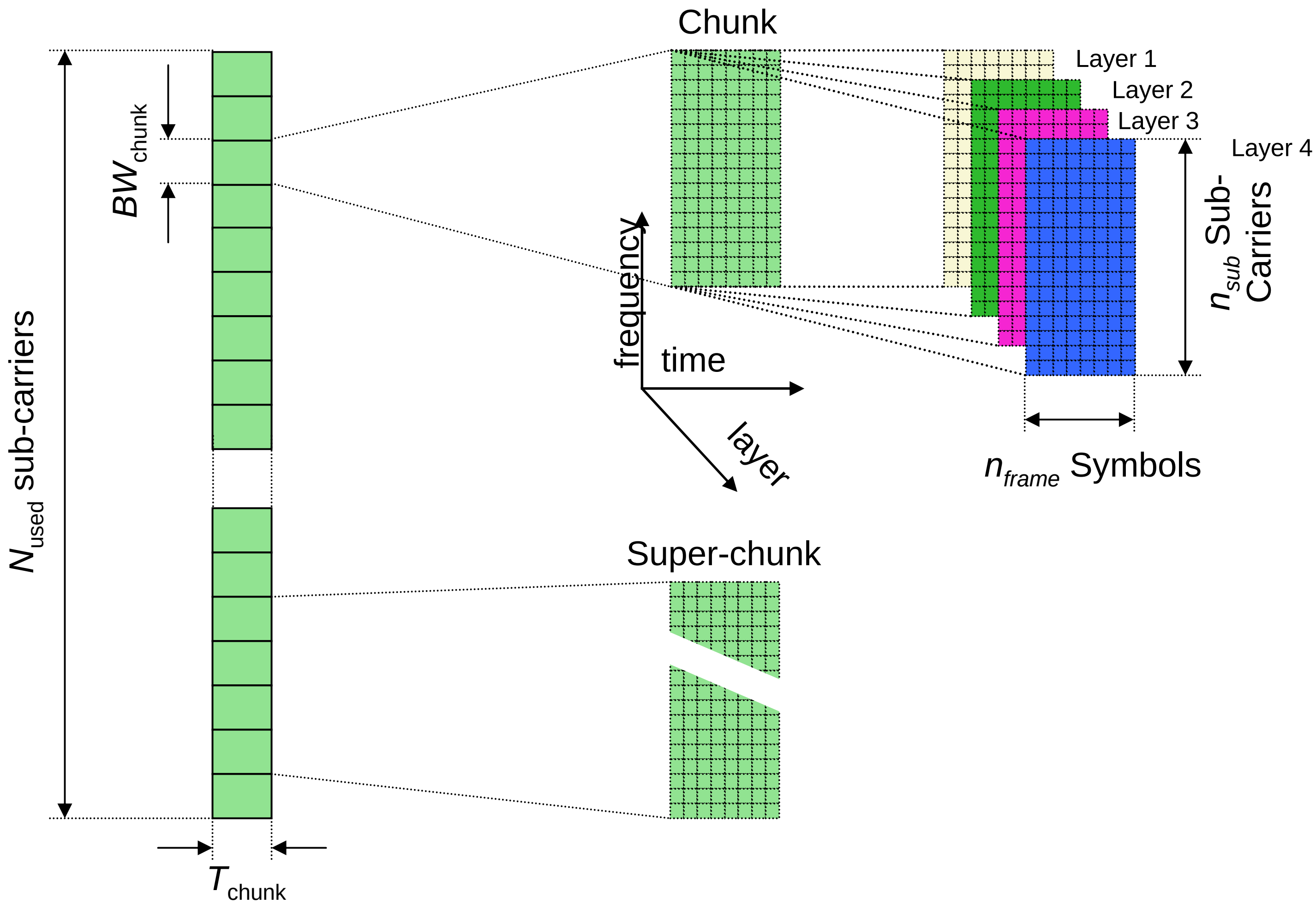
Soft Block Iterative Frequency Domain Equalizer (SDFE)



Initially forward filter=linear equalizer and feedback filter=0.

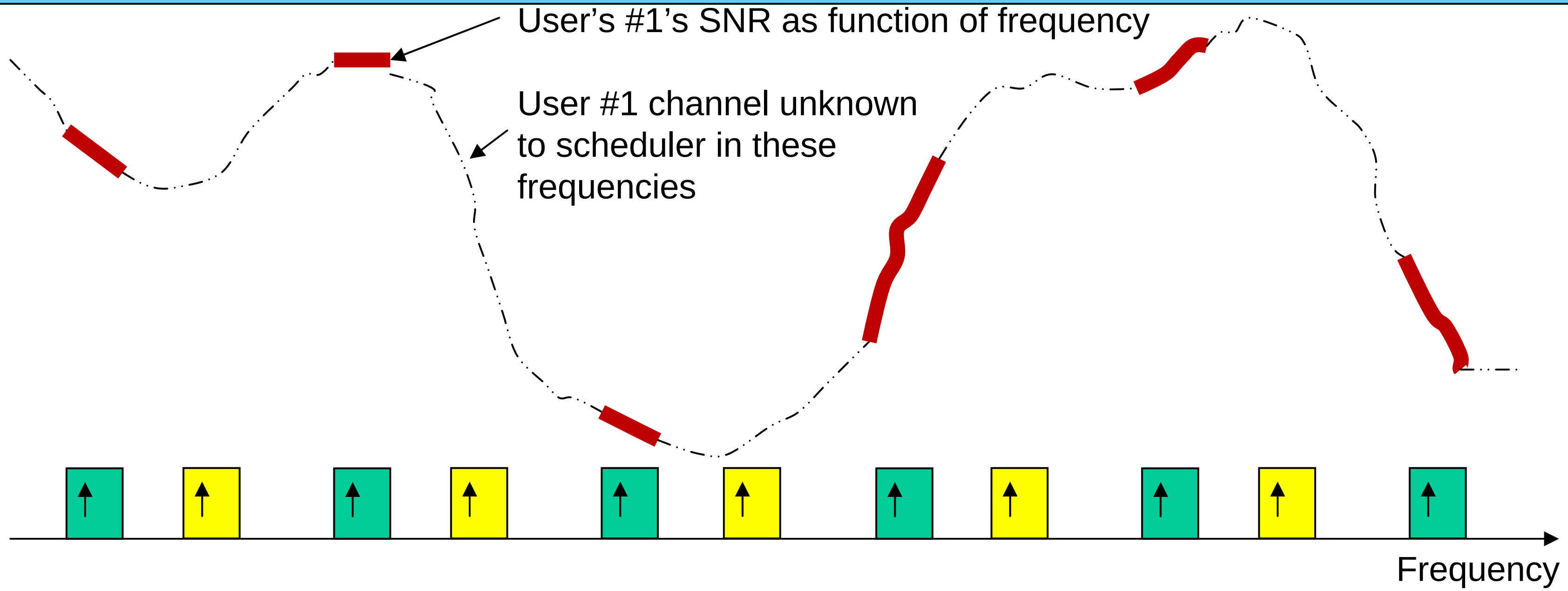
WINNER Medium Access Control

- **Chunk: The basic time-frequency unit for resource allocation**



[From "WINNER Air Interface Principles", G. Klang, WWW-MOCCA Workshop, Yokosuka, Mar. 30, 2006]

Uplink Frequency Non-Adaptive Case



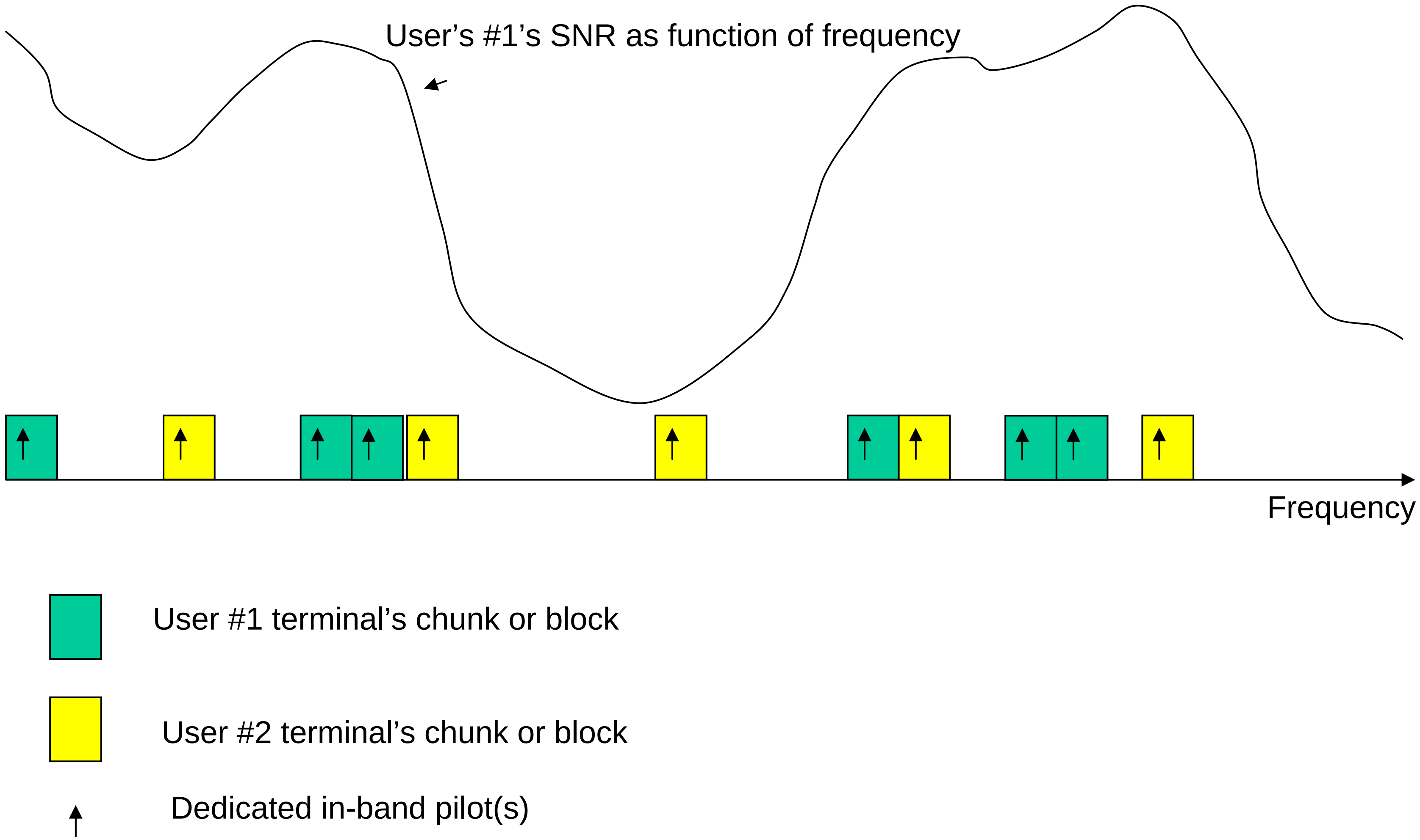
User #1 terminal's chunk or block

User #2 terminal's chunk or block

Dedicated in-band pilot(s)

Ideal Uplink Frequency Adaptive Case For User #1

Place each user's chunks at most favourable frequencies



Channel Estimation

- For both time and frequency-multiplexed pilots, interpolation in frequency and time is necessary, to keep pilot overhead low.
- Pilot overhead is generally less than cyclic prefix overhead. However it increases for spatial multiplexing/SDMA and adaptive transmission.
- Challenges: estimation of channels with rapid time variation and with large delay spread.

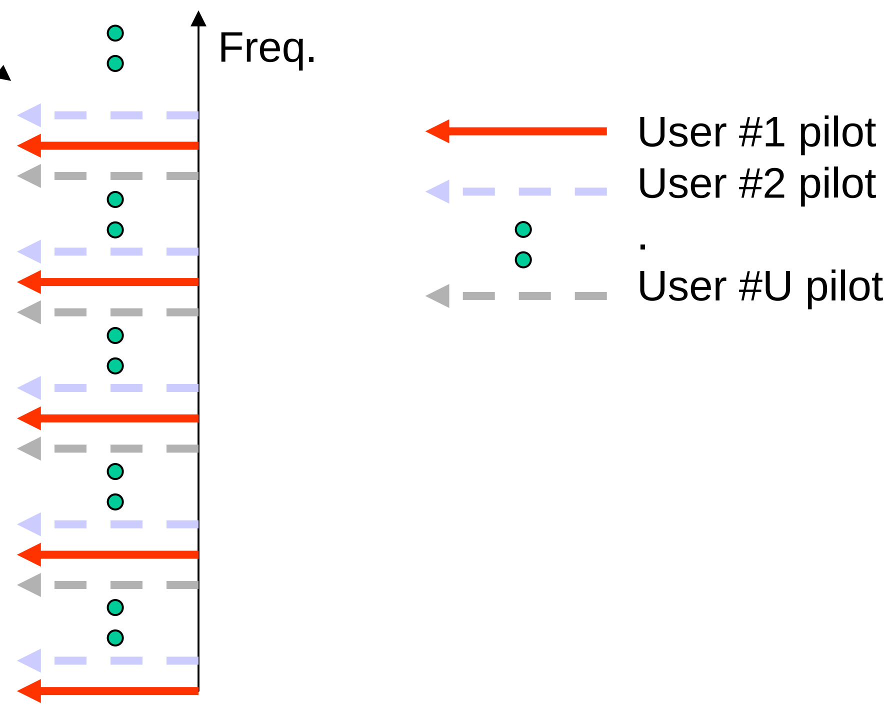
Time Division Multiplexed (TDM) Pilots

Block with pilots:

Time →

Data CP	Pilot CP	TDM pilots	Data

Extra overhead



Length of pilot block proportional to number of users

Each user's frequency domain pilot symbols are the DFT of a Chu sequence – to maintain constant amplitude property.

i.e. Each TDM pilot signal is an IFDMA signal.

Block without pilots:

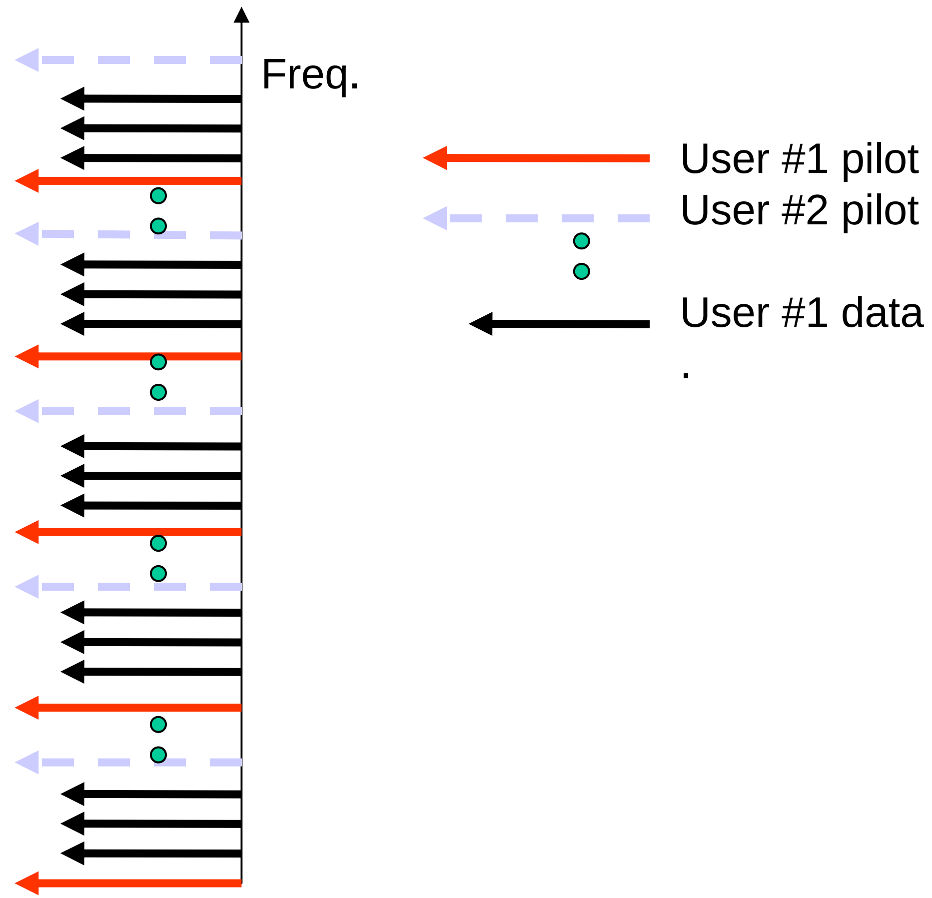
CP	Data

Frequency Division Multiplexed (FDM) Pilots

Time →

CP	Data and frequency-multiplexed pilots

Each user's frequency domain pilot symbols are the DFT of a Chu sequence (pilots are shown with a power boost)



Multiplexing of Frequency Domain Pilots: Two Variants

<u>FET</u> (frequency expanding technique):
(Data subcarriers shown in red, pilots in blue)

<u>FDSPT</u> (frequency domain superimposed pilot technique):

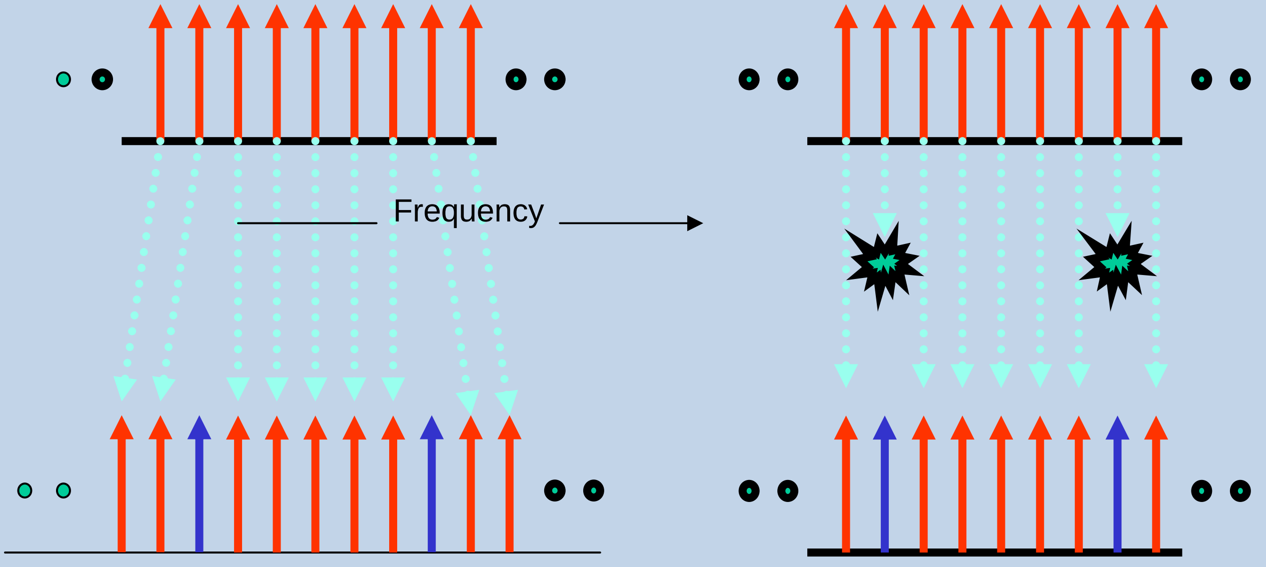
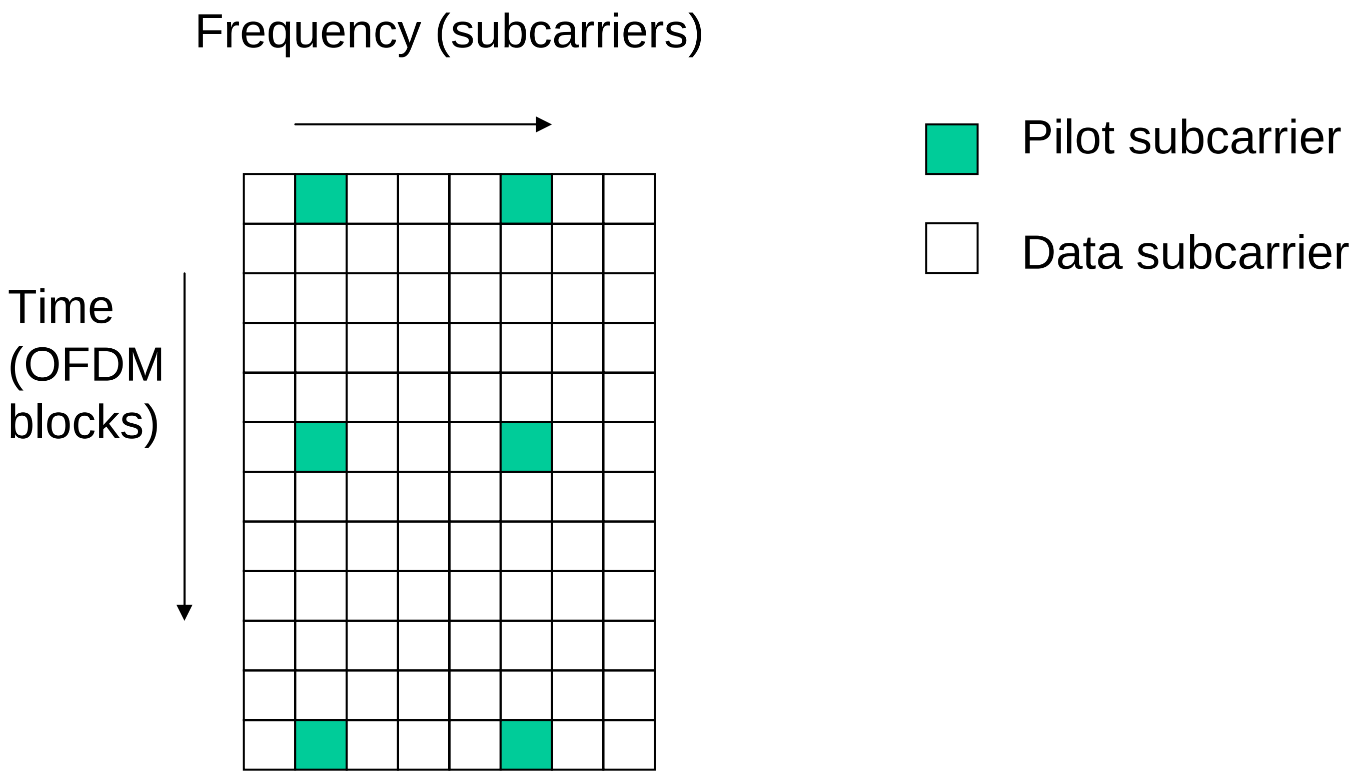
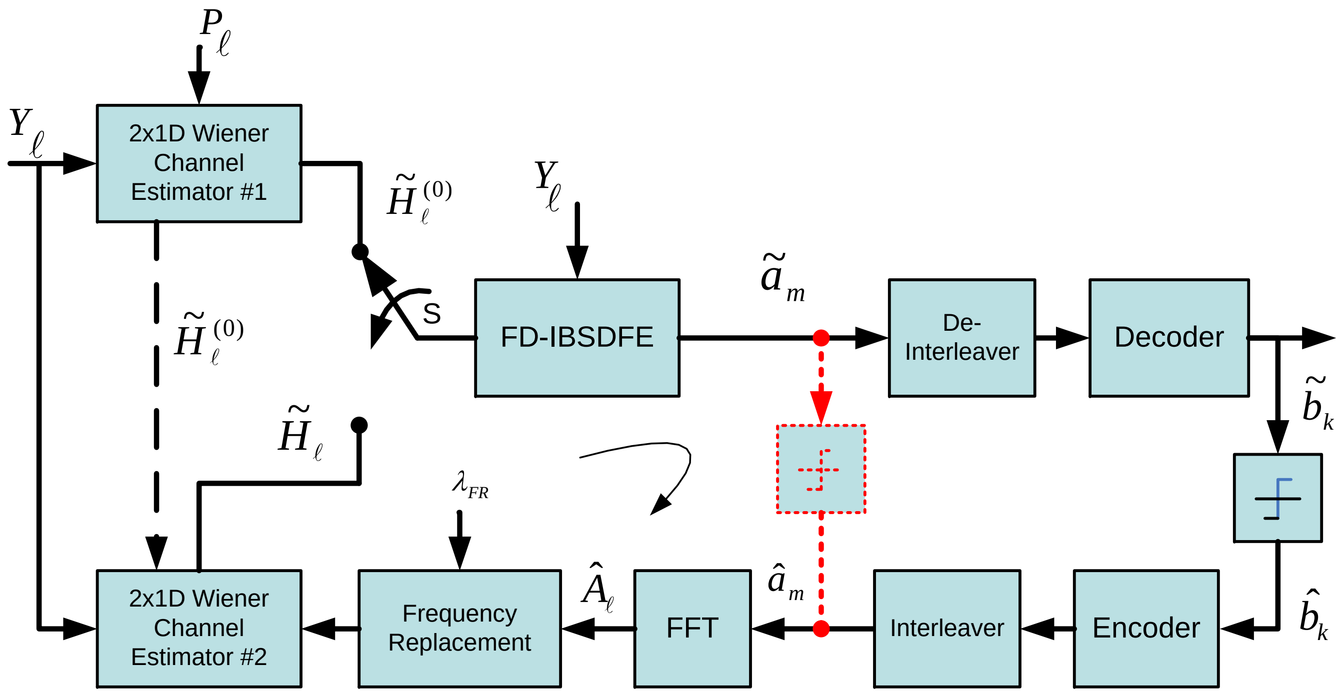


Illustration of a Chunk with Frequency Multiplexed Pilots



Full channel estimate requires interpolation in time and frequency

Iterative Channel Estimator for SC Systems*



- Issue of noise enhancement due to Gaussian like frequency response of data decisions:

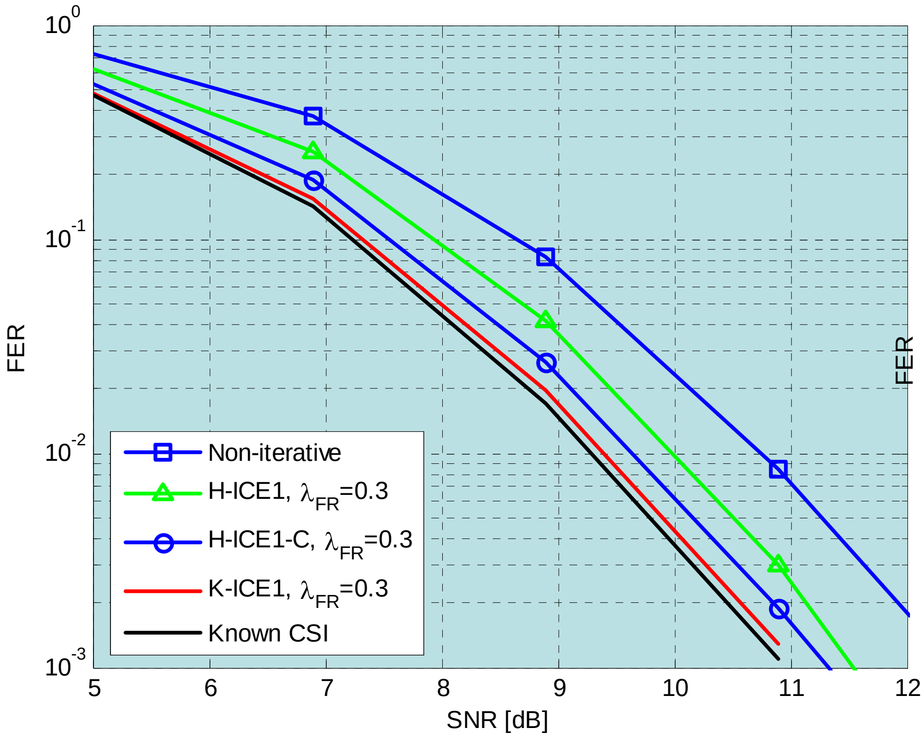
$$\hat{H}_\ell = H_\ell + V_\ell / \hat{A}_\ell$$

- Frequency replacement algorithm: replace the noise enhanced raw estimates with previouse estimates, using threshold λ_{FR}

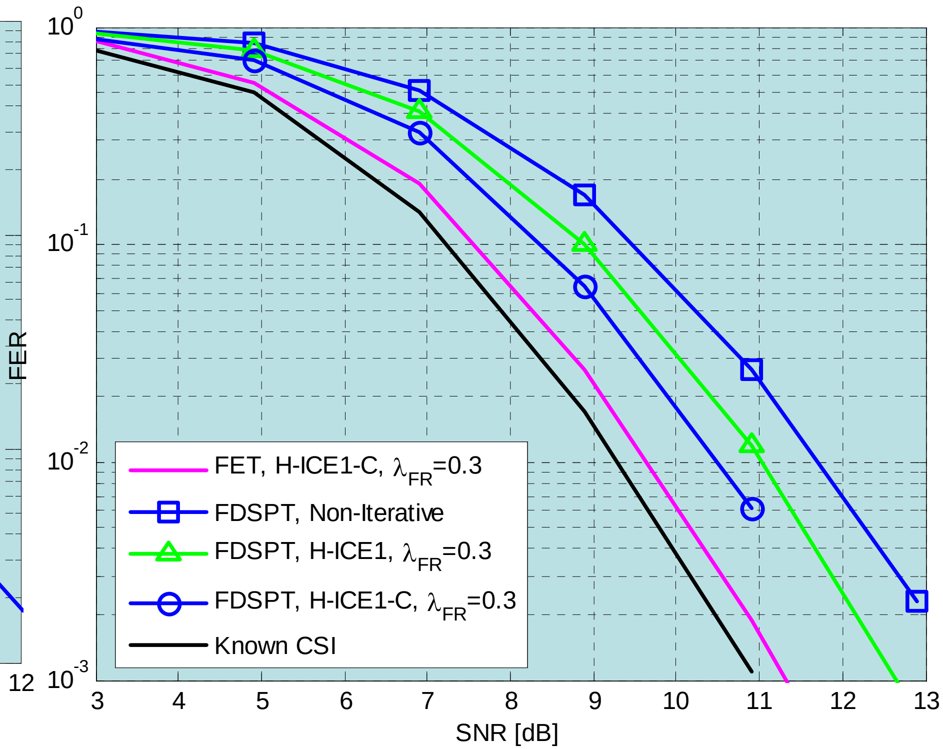
** C-T Lam, D. Falconer, and F. Danilo-Lemoine, "A Low Complexity Frequency Domain Iterative Decision-Directed Channel Estimation Technique for Single Carrier Systems", presented at VTC 2007, Spring, Dublin, April, 2007.*

Iterative Decision Directed Channel Estimation for DFT-precoded OFDM (C-T Lam)

a) Iterative CE (FET)



b) Iterative CE (FDSPT)



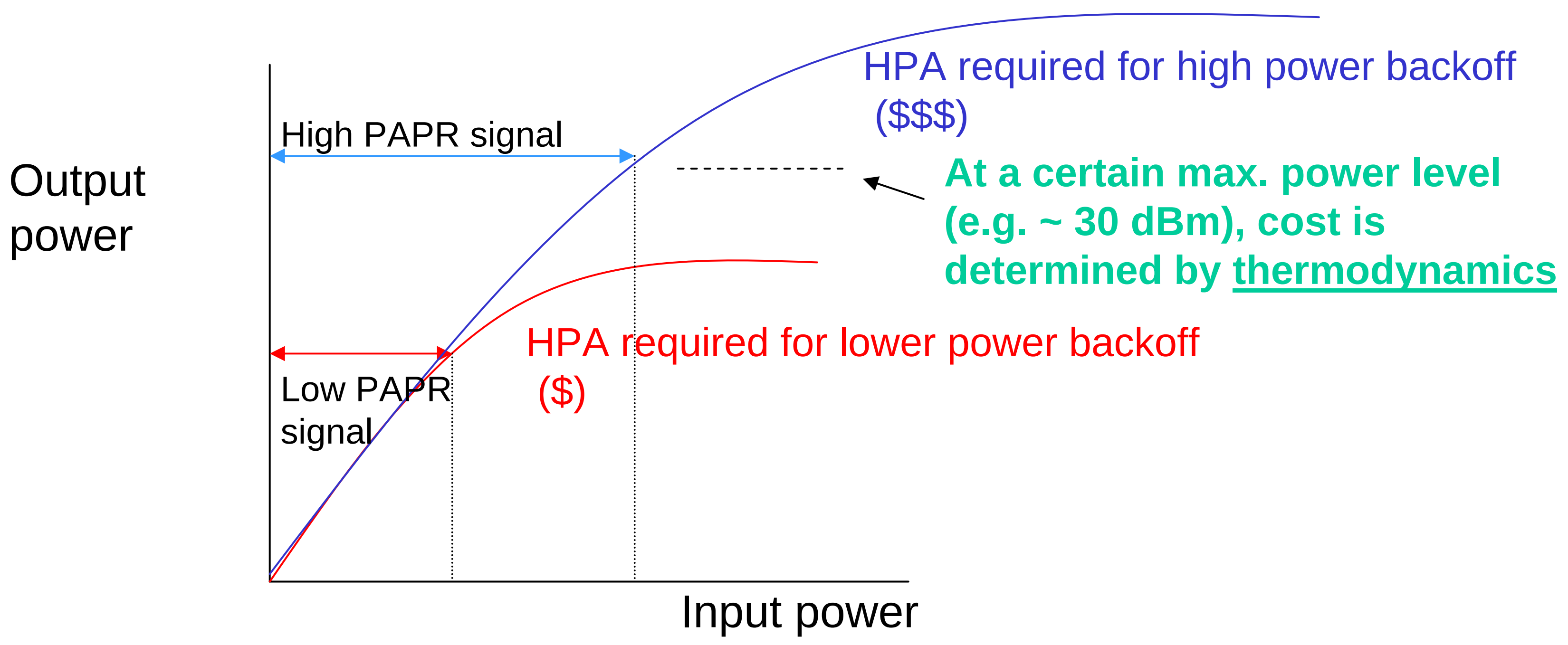
OFDM in the Downlink, Serial Modulation in the Uplink

- OFDM in the downlink can exploit adaptive loading of subchannels for high efficiency and performance, and can multiplex users in both time and frequency.
- The subscriber transmitter is single carrier (SC), and thus is inherently more efficient in terms of power consumption, due to the reduced power back-off requirements of the single carrier mode. This will reduce the cost of a subscriber’s power amplifier.
- SC is also less sensitive to user terminal frequency offset or phase noise.
- This concept is adopted for the WINNER wide area cellular scenario, and is also being proposed in 3GPP-LTE.

Power Amplifier Linearity Requirements and Cost

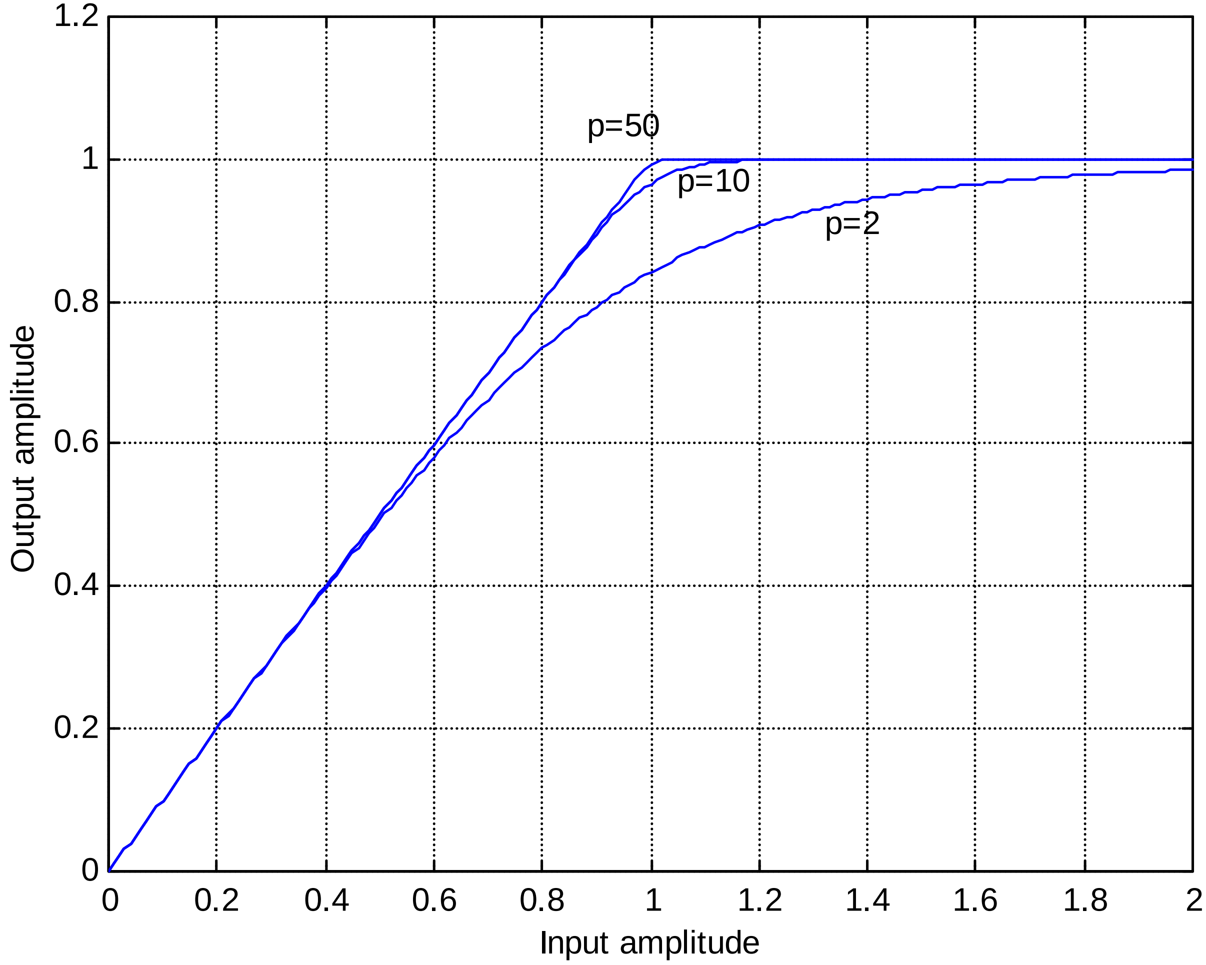
- The greater the modulation scheme’s peak to average ratio PAPR), the greater the required backoff, and the greater the required maximum rated power to achieve the link budget.

- <u>HPA cost rises sharply with maximum power rating.</u>

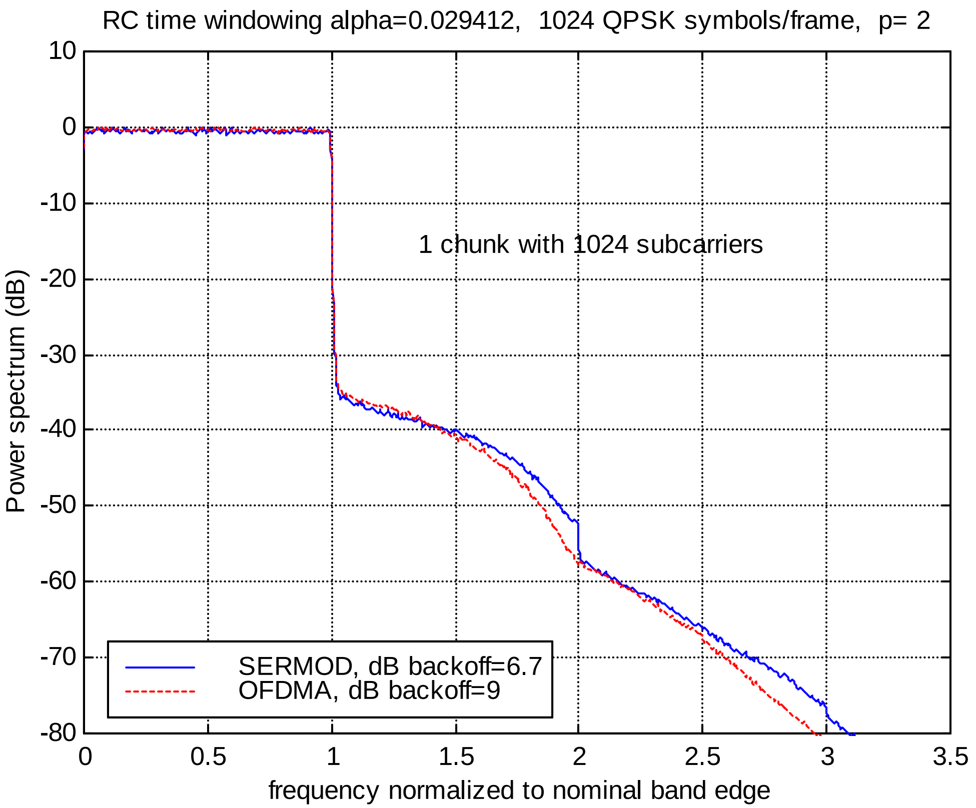


Nonlinear PA Characteristics

Rapp model AM/AM nonlinearity



One Chunk per User, *p*=2: Comparison of Backoff Required for OFDM and Serial Modulation

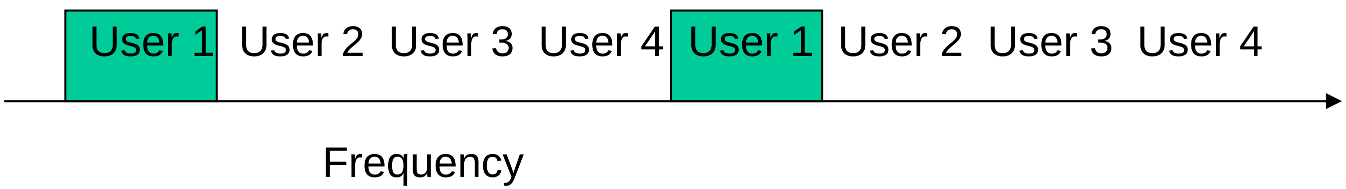


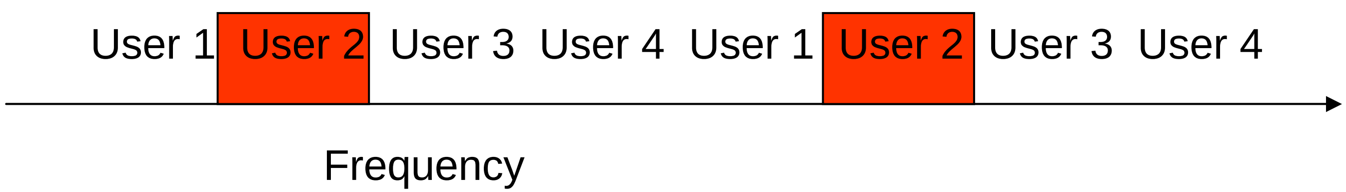
Backoff difference between OFDM and serial mod.=2.3 dB
Adjacent channel SNR~ 39 dB

Spread Serial Modulation with Chunks: HPA Backoff Considerations

- Multiple equally-spaced, equal-size chunks transmitted, round-robin interleaved in frequency among multiple users.

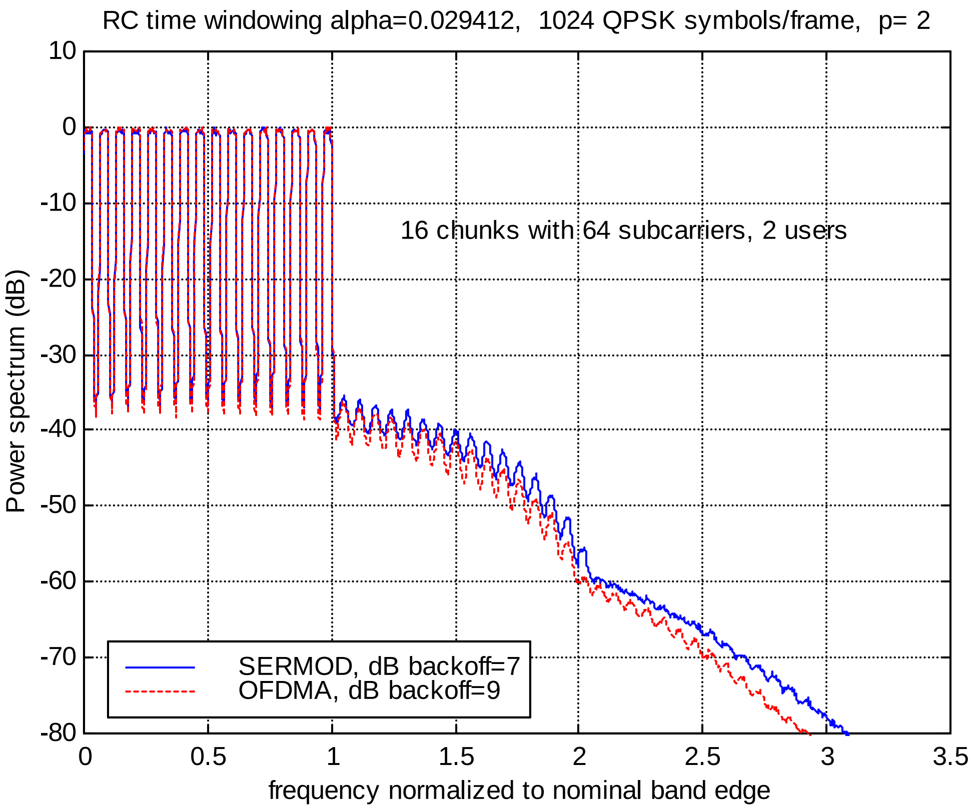
- Number of users determines spacing of chunks – makes little difference to transmitted power spectrum





Etc.

16 Chunks per User, *p*=2



Backoff difference between OFDM and serial mod.=2 dB
Adjacent channel SNR~37 to 38 dB

So effect of chunk transmission on backoff is minor.

Other Features of Frequency Domain-Based Radio Interface

- Adaptive modulation and coding
- Choice of LDPC, turbo codes or convolutional codes
- Self-organized inter-cell synchronization.
- Iterative or turbo equalization
- Combination with spectrally-efficient MIMO and SDMA modes.
- Spectrum-sharing and interference avoidance with other WINNER and non-WINNER systems.

Some Open Physical Layer Questions

- Role, efficiency and cost of adaptive transmission.
- Efficient pilot design and channel estimation for MIMO/SDMA and for frequency-adaptive transmission.
- Impacts of hardware constraints on cost and design of beyond 3G systems.
- Relays: power constraints and deployment. Just to optimize coverage, or capacity enhancement too? At what cost?
- Evolution and future-proofing air interfaces

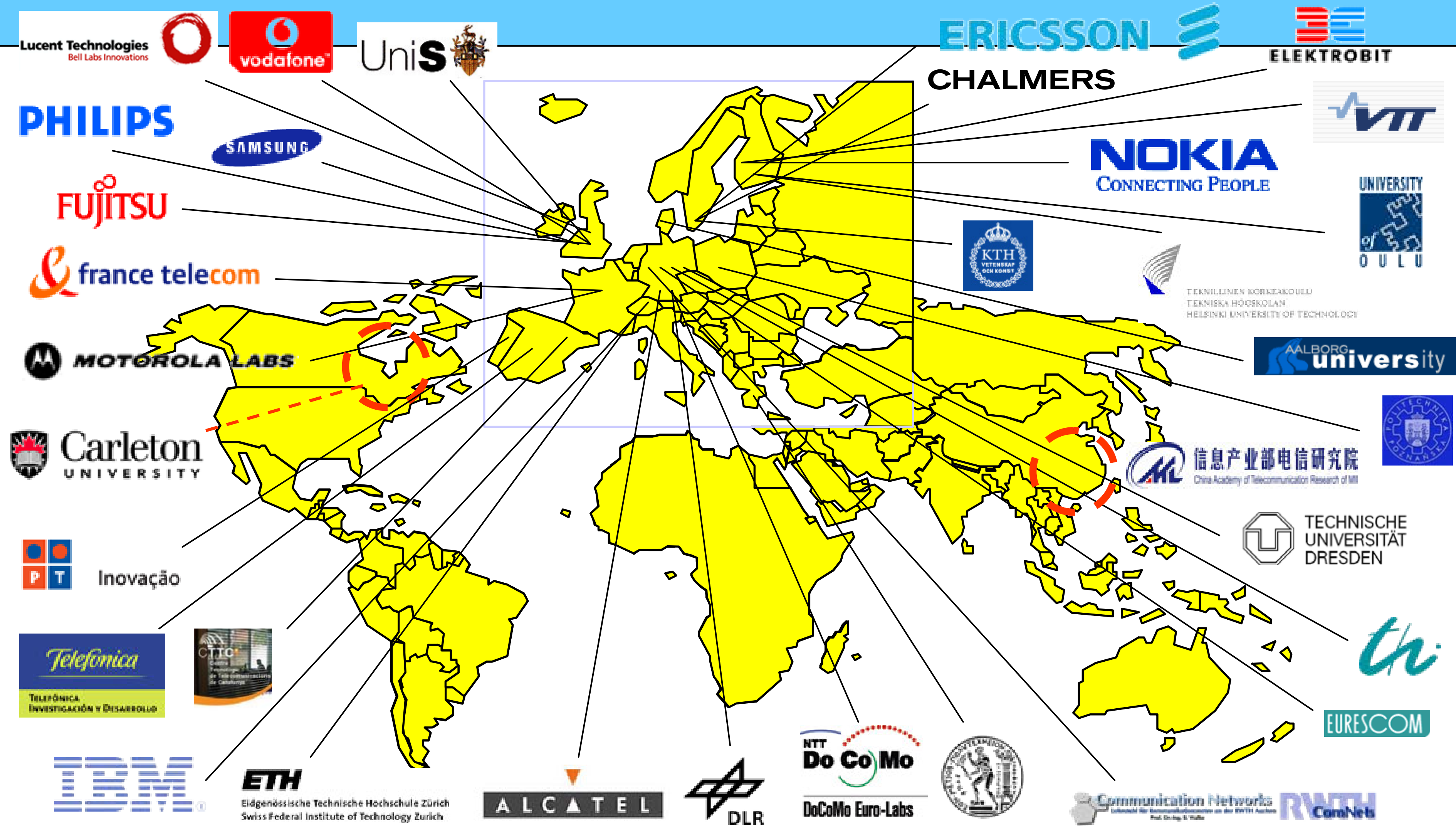
Summary

- Generalized multicarrier for spectrum and signal processing flexibility and scalability
- Adaptive and non-adaptive transmission: diversity advantage versus overhead cost
- Channel estimation: TDM and FDM pilots
- OFDM in downlink, serial modulation in uplink
- User terminal power amplifier is a cost- and power-sensitive element which affects the air interface design.

Books/ Web Sites

- WWRF Wireless World Research Forum):
  - www.wireless-world-research.org **(see WWRF's "Book of Visions")**
  - *Technologies for the Wireless Future,* WWRF, R. Tafazolli, ed., Wiley and IEEE Press, First edition, 2005, second edition 2006
- WINNER (Wireless Initiative New Radio):
  - https://www.ist-winner.org **(see public deliverable documents which can be downloaded)**

The WINNER Consortium



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EU WINNER (Wireless Initiative New Radio) Project

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THE WINNER PROJECT

Is based on a
common radio interface

that will
adapt to user needs and scenarios

by utilising
different modes of a common technology

covers the full range of scenarios

- Provides a significant improvement compared to current systems in terms of performance, efficiency, coverage and flexibility
- Makes efficient use of the radio spectrum to minimise the cost-per-bit by combining the technologies researched in an efficient way