# Cellular Electronics - Baseband Processing


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# Outline

- The team

- Multi-standard/Multi-mode
- Wrap-up: Multibase project and DFE Rx
- Sign-bit processing: an OK alternative?
- Knowing the channel: channel estimation for LTE.
- Multi-mode MIMO detection
- Life after OFDM: Going Faster than Nyqvist?

- Conclusion

# The Team

# Multi-standard/Multi-mode

Multi-standard: Do we need a motivation today?

Multi-mode:

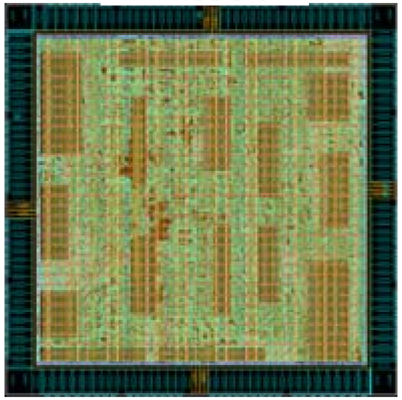
- experience fluctuating channel conditions
- satisfy dynamic system specifications
- static implementation for the worst case is highly inefficient
- Multi-mode implementation chooses the best mode dynamically

**Different Environments**

**Different Applications**

Main Focus: Investigate/develop algoritm with a hardware perspective!

# Lund focus in circuits: DFE Rx



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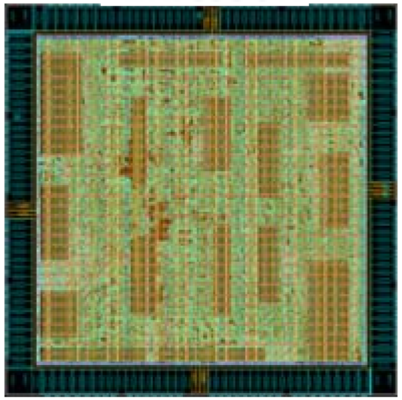
# Status of Multibase

Passed with flying colors at the final review.



Status:

- Complete DFE Rx taped out in June.
- Working Silicon.
- Infineon 65nm CMOS
- Chip area 5mm$^2$
- Core area 3.5mm$^2$

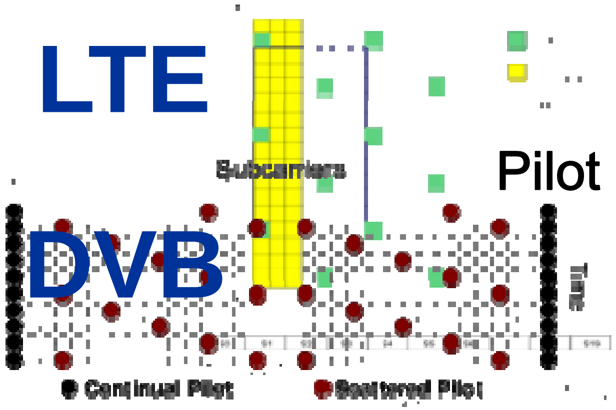
# Multi-standard concurrency…

- All three standards are OFDM based, however with different FFT-size:
  - LTE: 128-2048
  - DVB-H: 2048, 4092 (and 8192)
  - IEEE 802.11n: 64-128

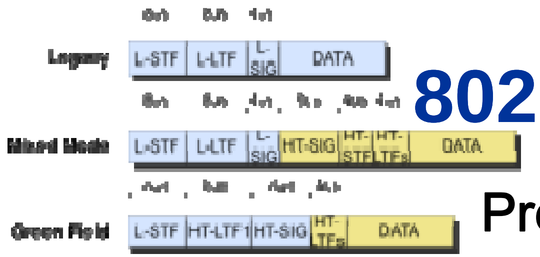
- …and different sample rates:
  - LTE: 30.72 Msps
  - DVB-H: 9.143 Msps
  - IEEE 802.11n: 20 or 40 Msps

LTE

DVB



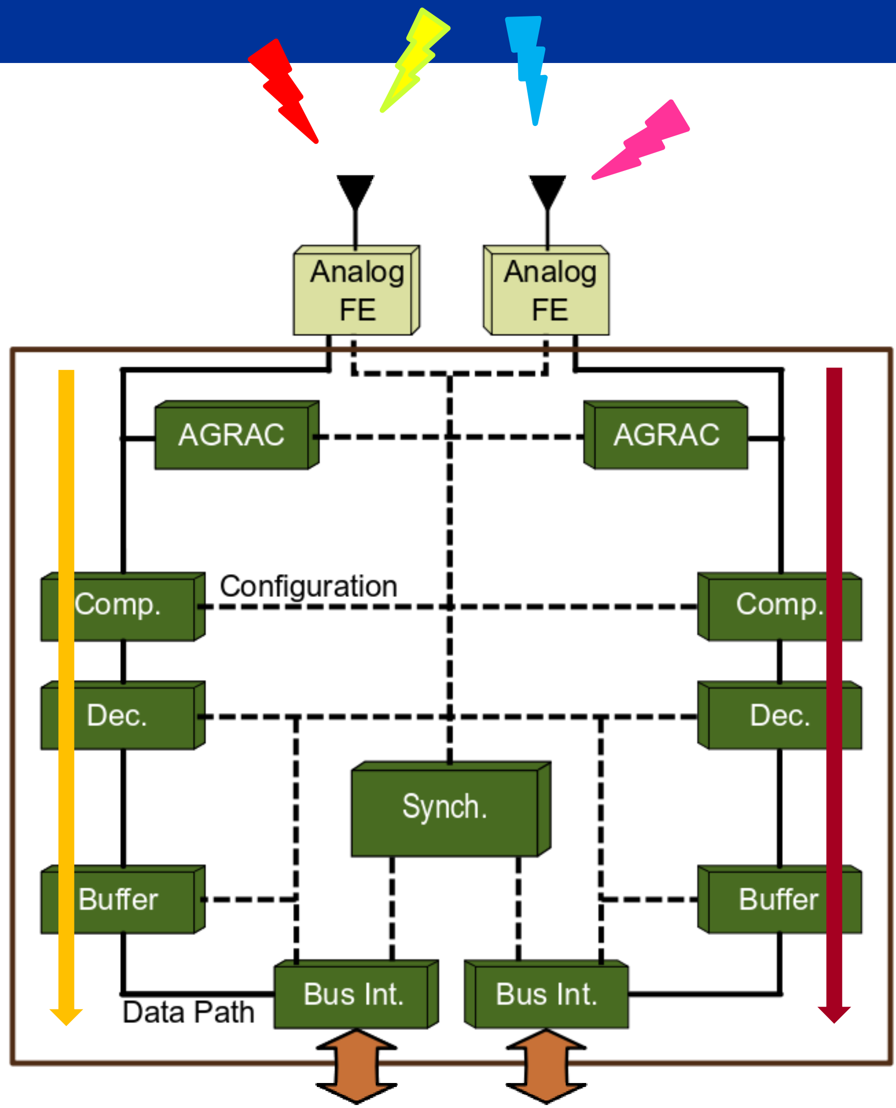
Pilot based



802.11n

Preamble based

# The Motivation: multi stream DFE-Rx

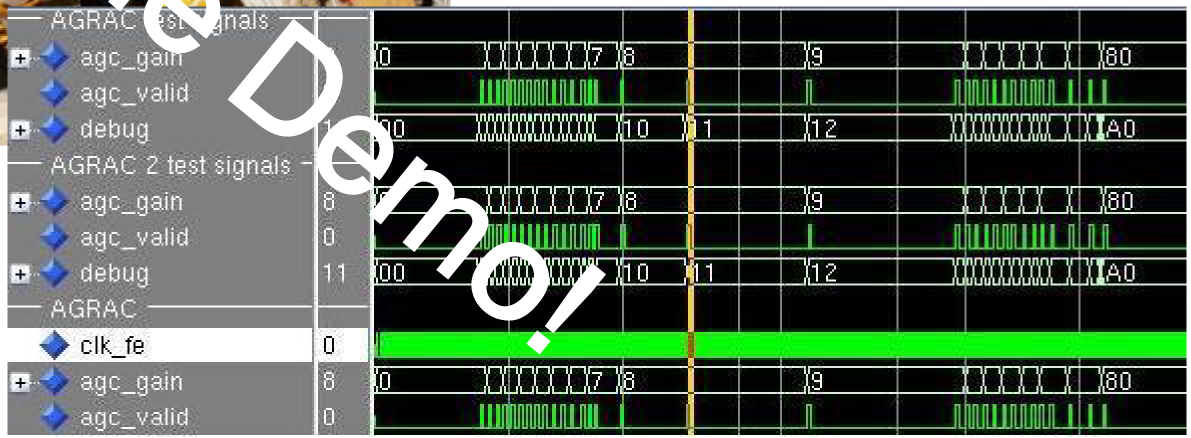



Two concurrent data streams in hardware.

More data streams possible since they do not transmit all the time.

# Verification and Test

Considerable testing is ongoing.



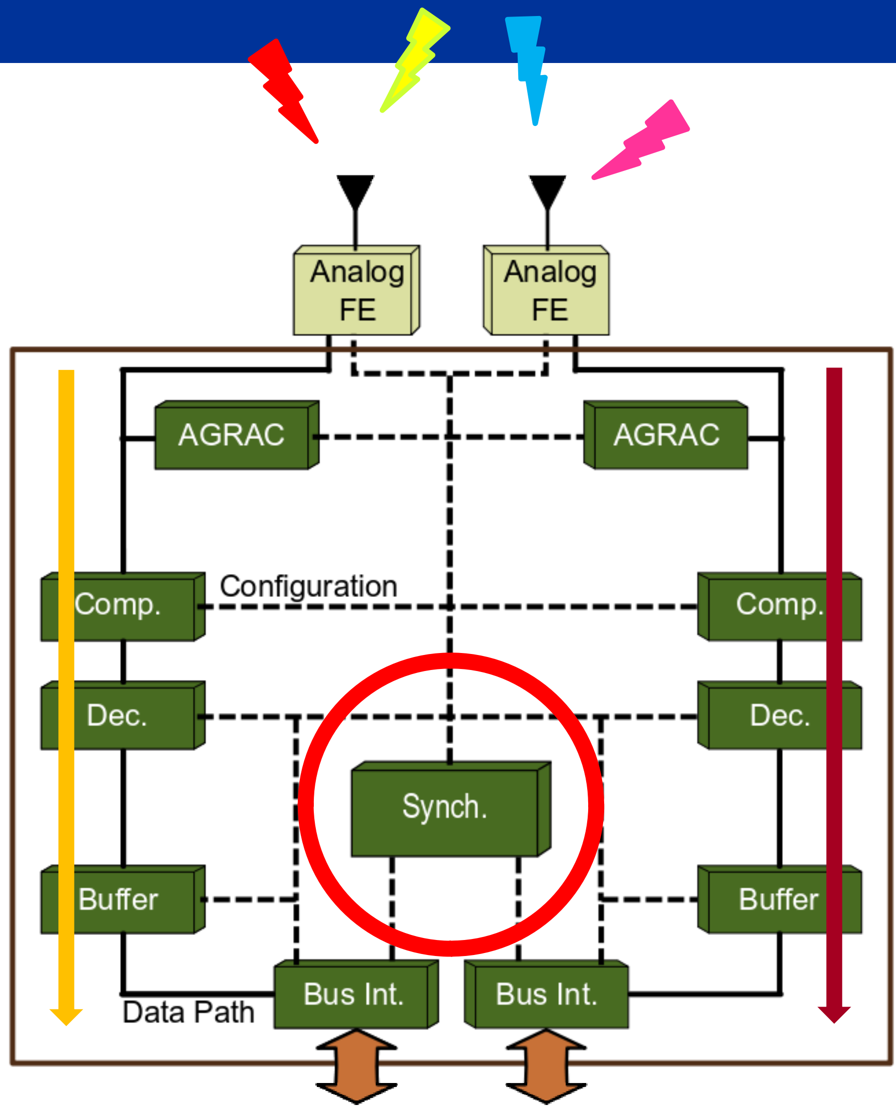

See the Demo!

# The Motivation: multi stream DFE-Rx

Two concurrent data streams in hardware.

More data streams possible since they do not transmit all the time.

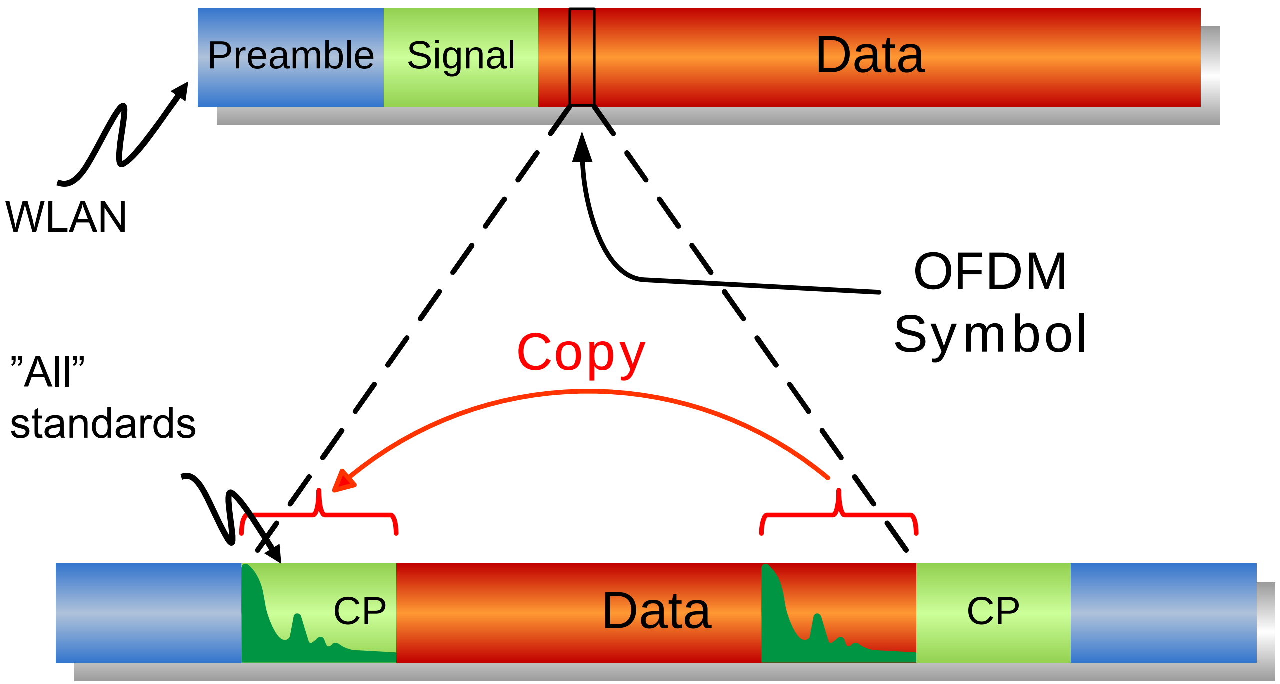
= Lund University



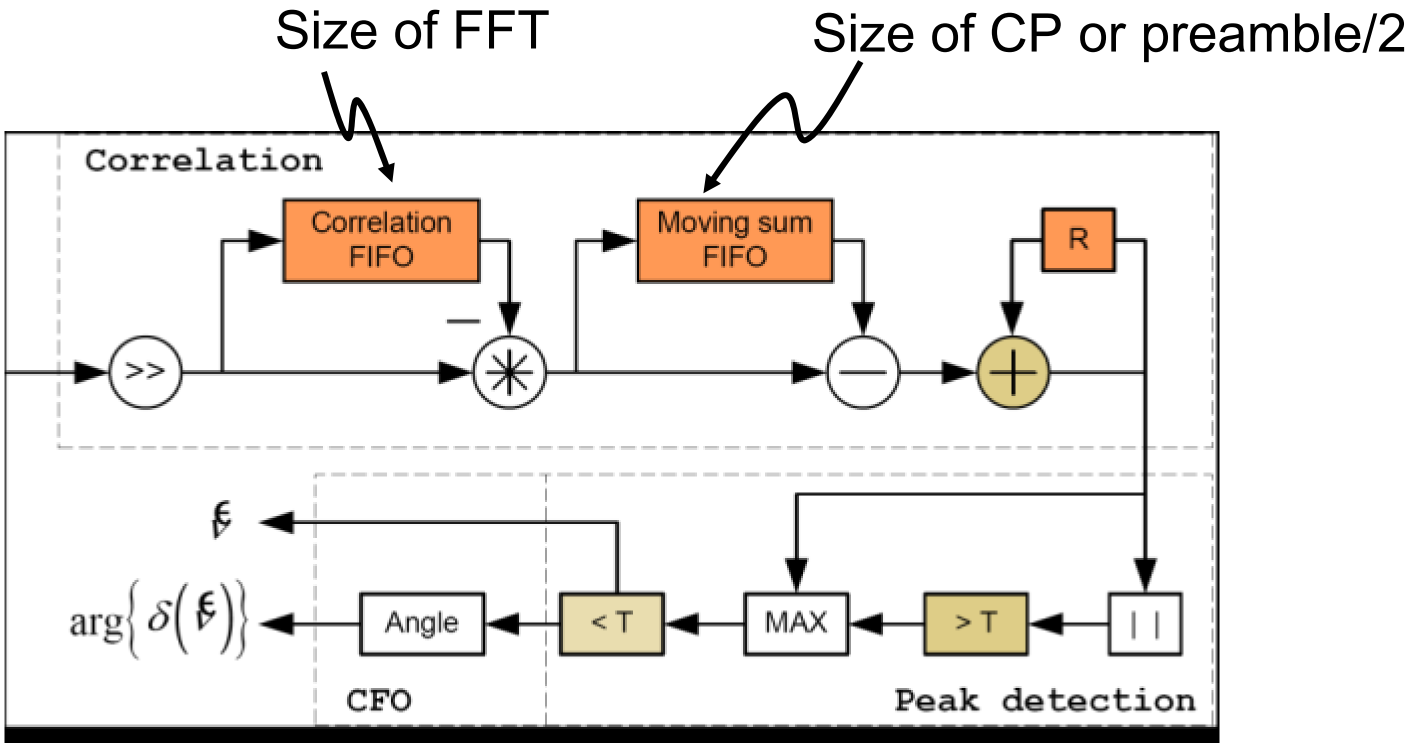
# OFDM Synchronization

Synchrhonization

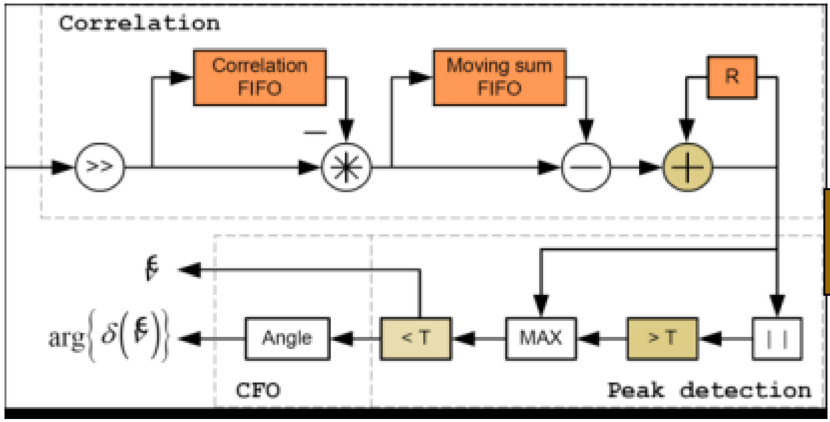
- either using the Preamble for WLAN
- or cyclic prefix for LTE and DVB-H (also WLAN but…)

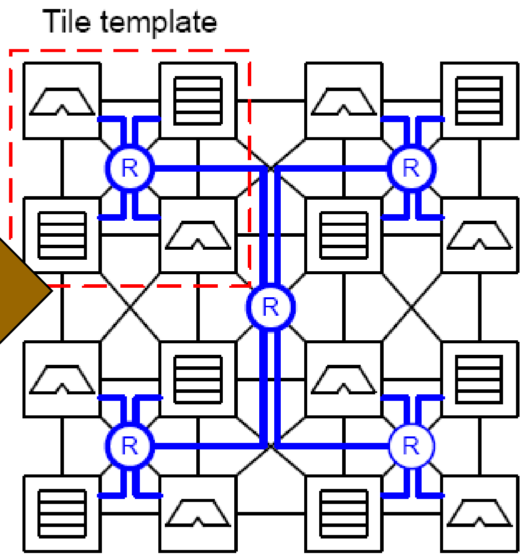


# Synchronization Architecture



# Multibase Synchronization Hardware



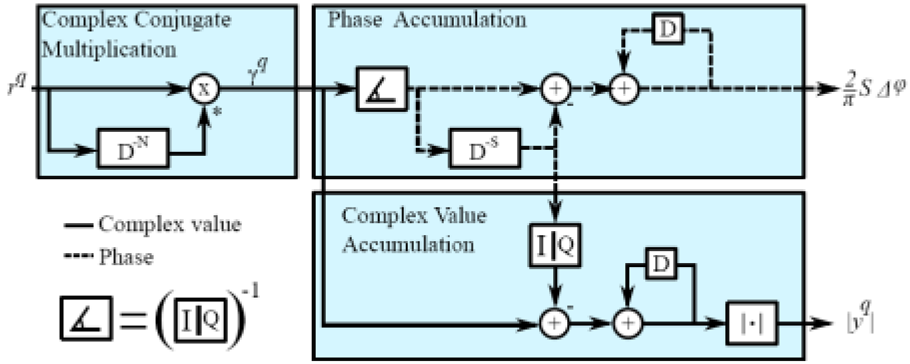

Mapped onto a reconfiguarble processing array:

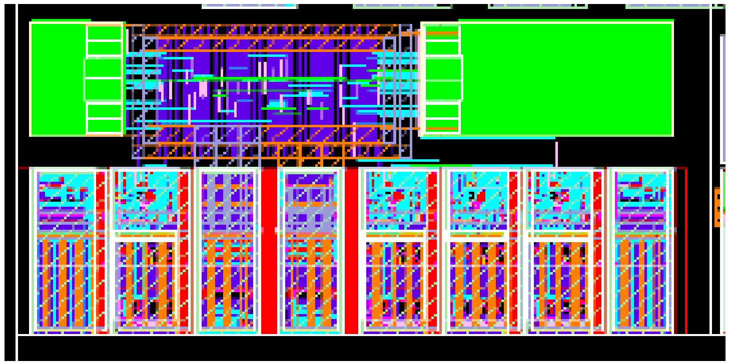
- flexibility since multi-standard
- hardware reuse since sync only part of the time

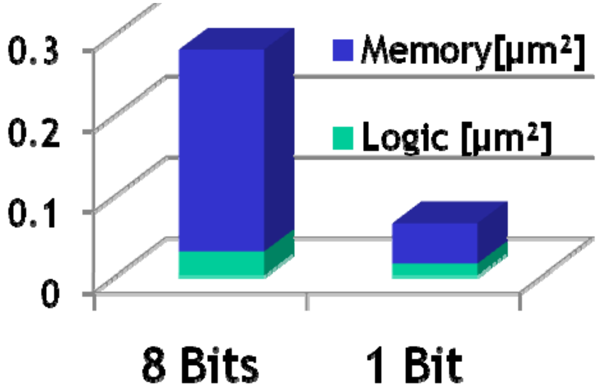
## Next presentation!

# Alternative: Sign-Bit Synchronization
## together with Leif Wilhelmsson @Ericsson

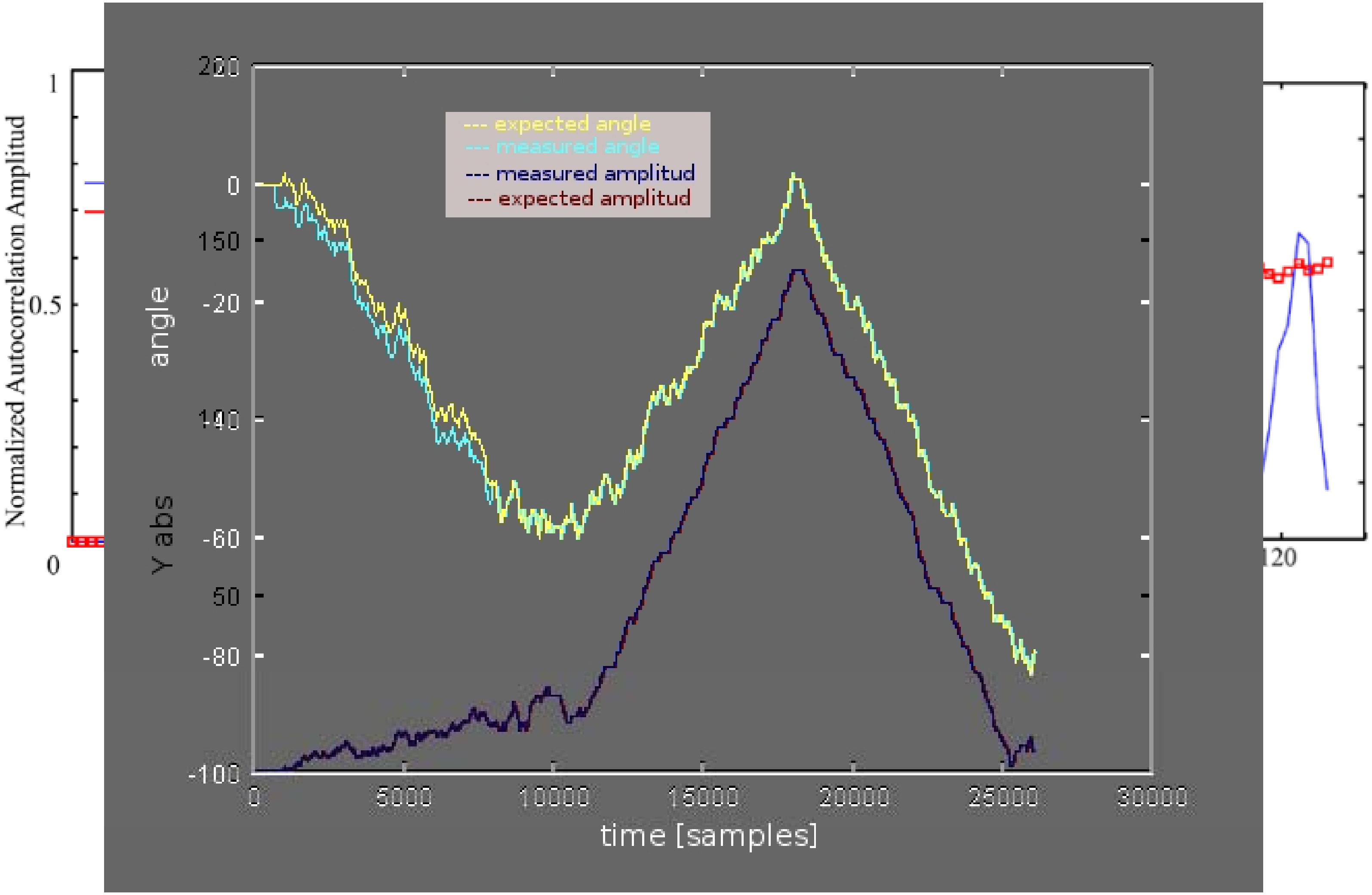
- Huge complexity reduction at a cost of performance degradation
- Area improvement for memories 97% when compared to 8-bits
- Area improvement for logic 70% when compared to 8-bits
- Total Area improvement 93% when compared to 8-bits



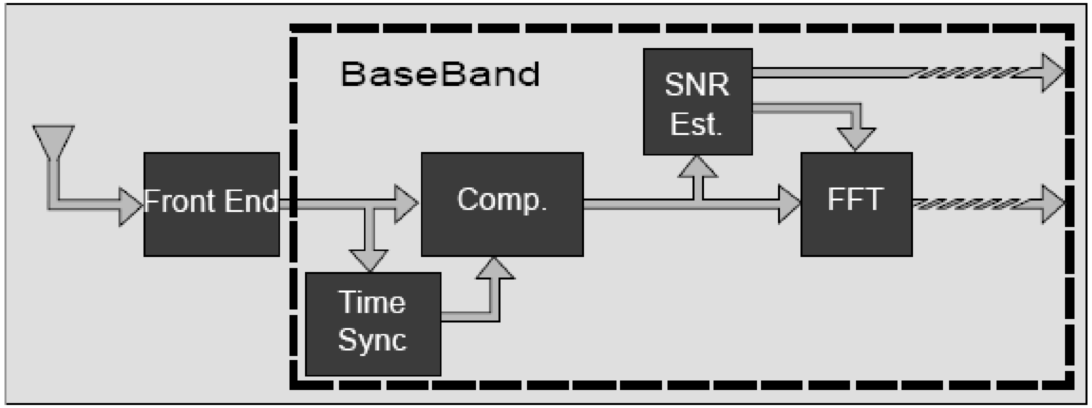





# Sign-Bit Synchronization: Performance

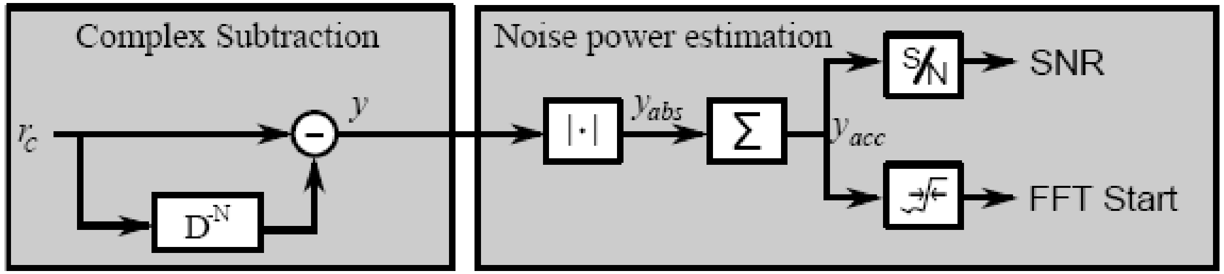


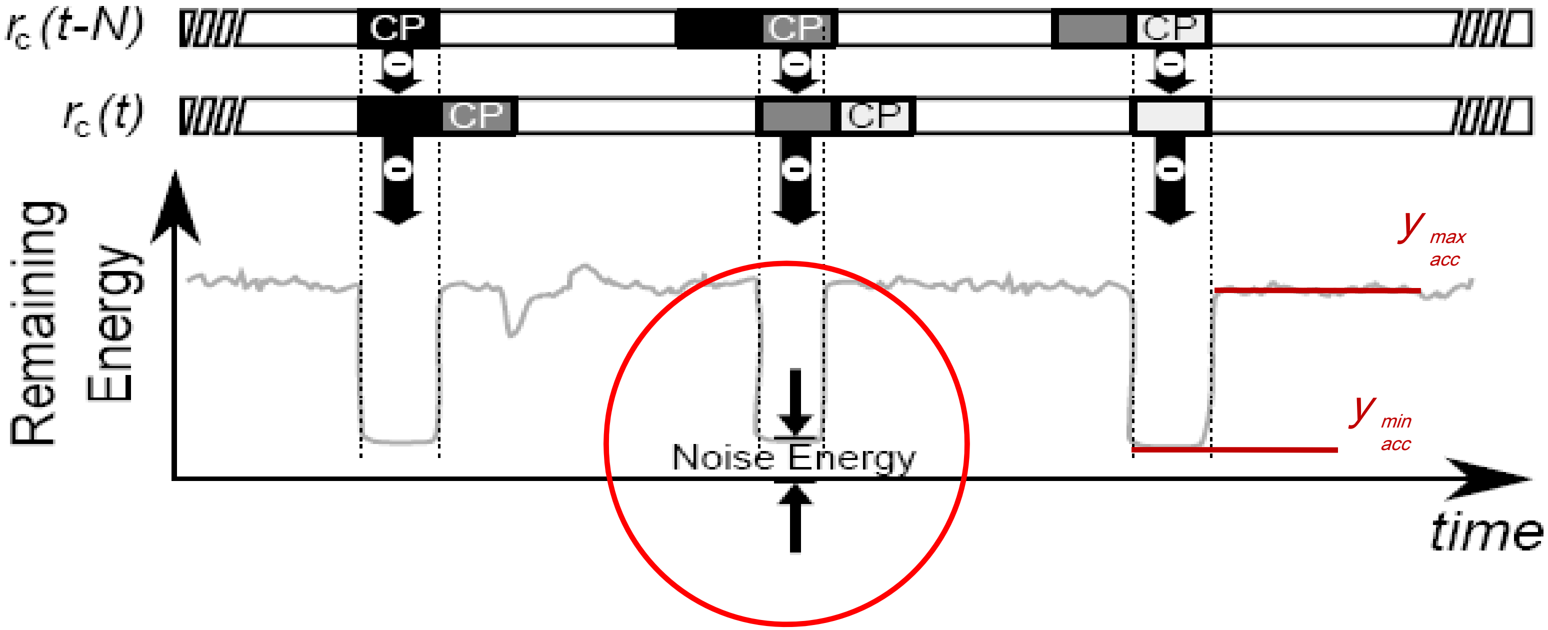
# Early SNR estimation: useful for many functions



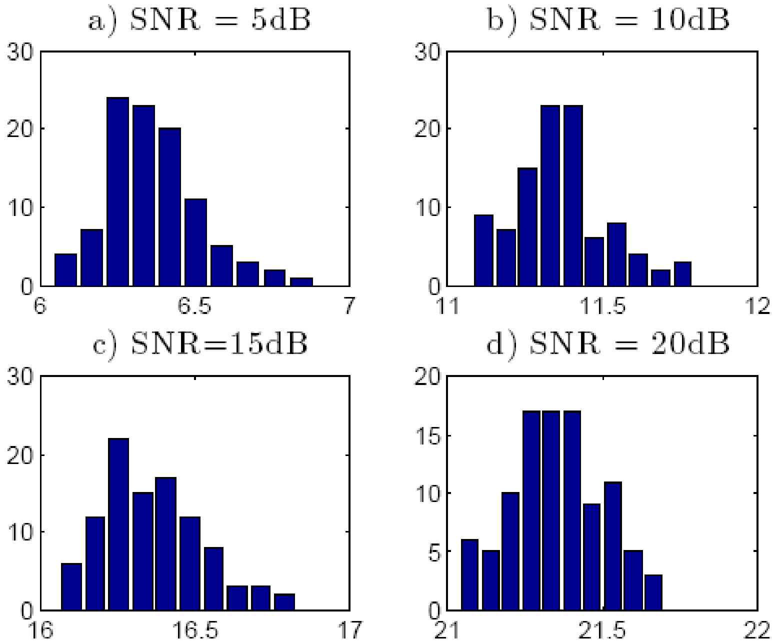

- Adapting Coding
- Channel Estimation
- Time Synchronization
- Base Station handover

# The SNR Estimator

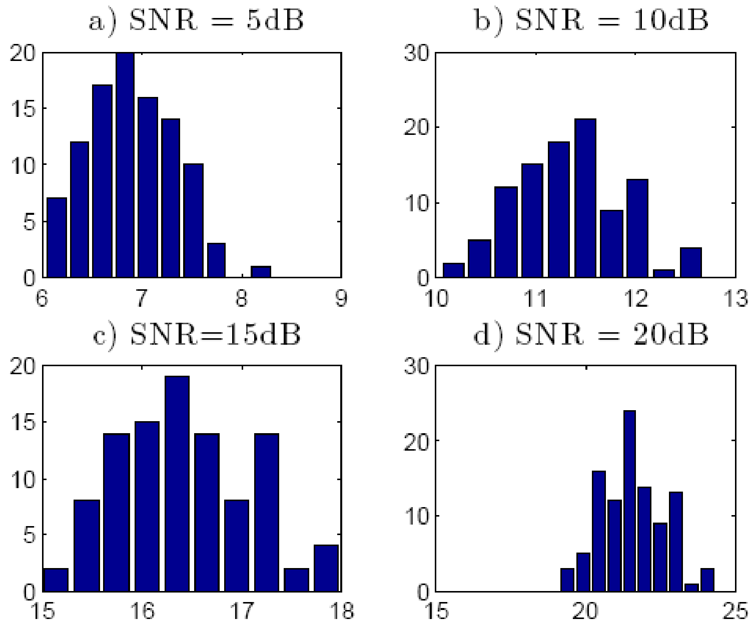


# Performance Analysis: clearly distinguishes low-medium-high SNR classes

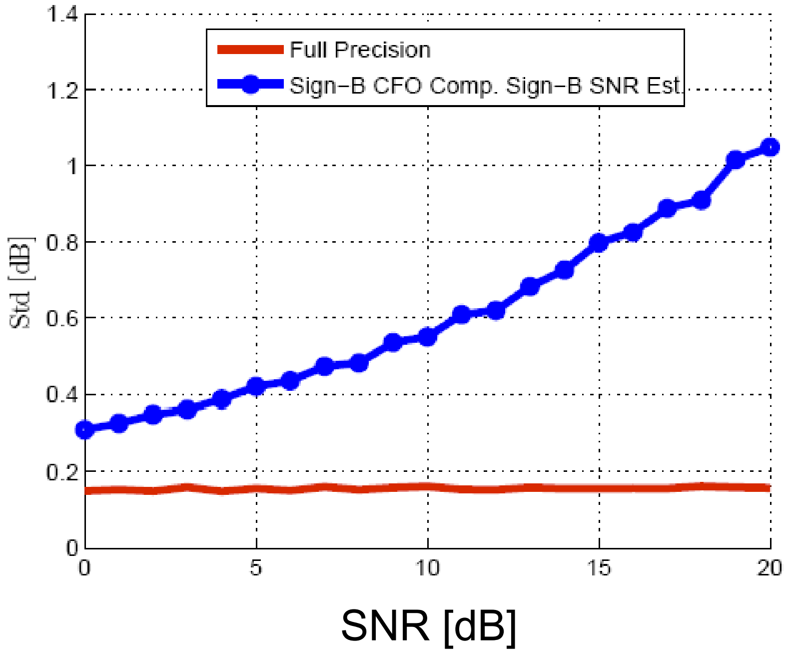



Full Precision under various SNR and CFO=50Hz

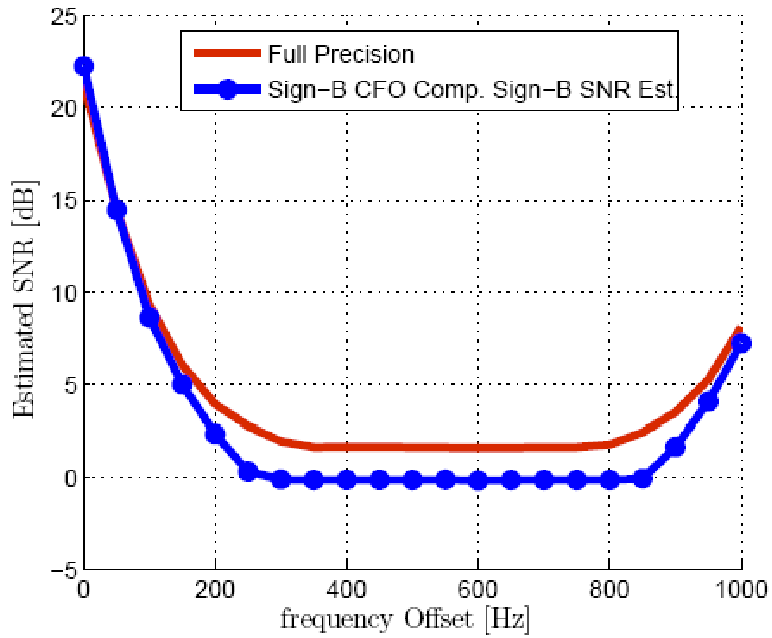



Sign Bit under various SNR and CFO=50Hz

# Performance Analysis: Good results, mind CFO

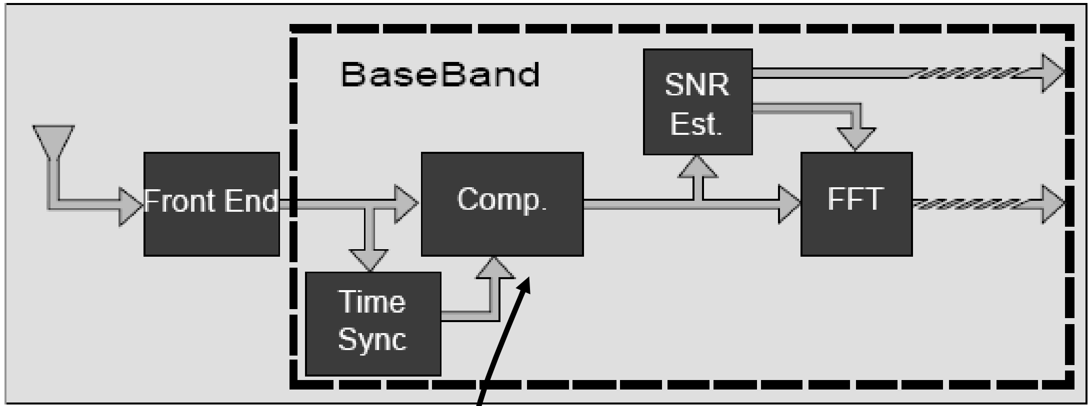


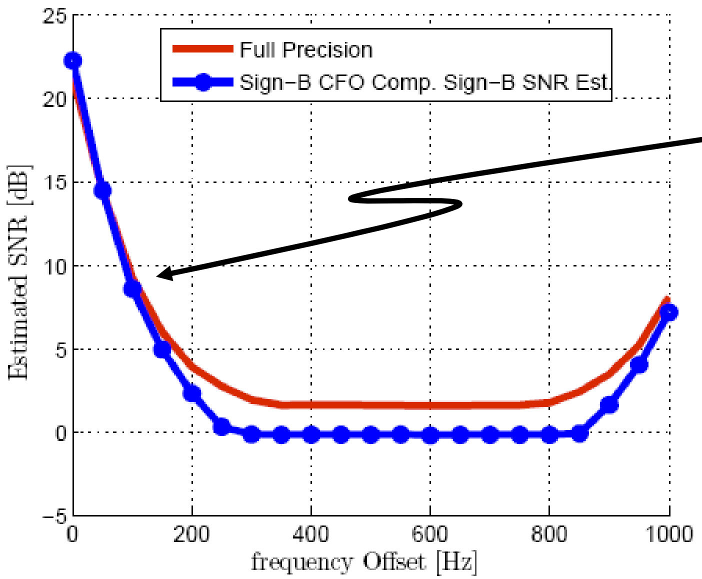

Standard deviation vs SNR




Estimated SNR vs CFO
(real SNR = 22dB)

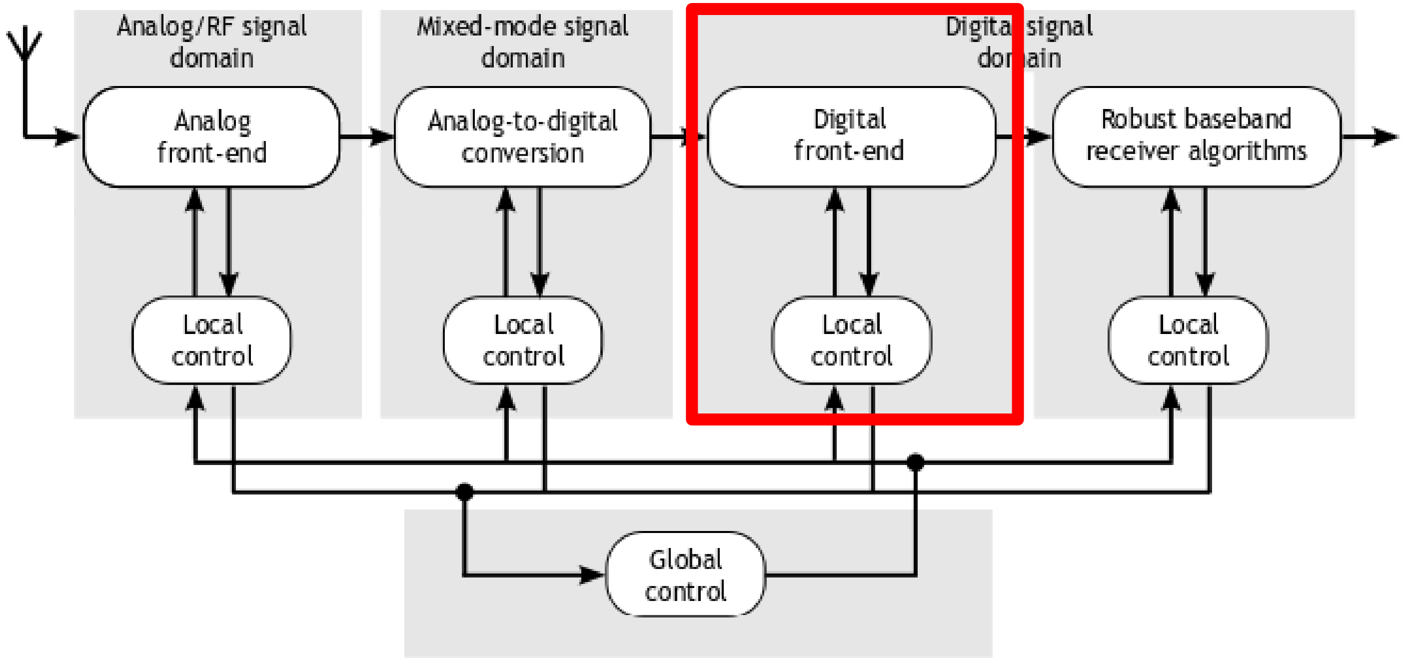
# SNR estimation in the baseband



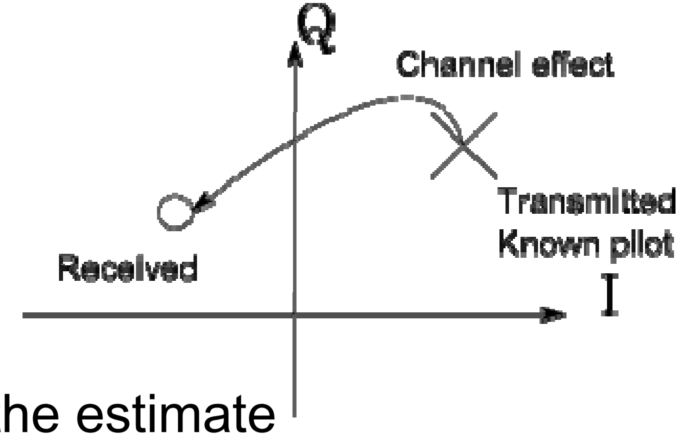

- It is crucial to fix the CFO before the SNR estimation

# We will continue the DFE within DARE!




- *Target: LTE – rel. 10 , a.k.a. LTE-advanced*
- Compensation in the digital domain, e.g. IQ-imbalance, CFO, mismatch, etc.
- Adapt analog and AD blocks
- Exchange info with following baseband processing

# Channel Estimation




## Matching Pursuit Algorithm:

- The channel is estimated in the time domain
- A  Successive Cancelation approach
  - The strongest tap is found and added to the estimate
  - At the same time its effects are removed from the input

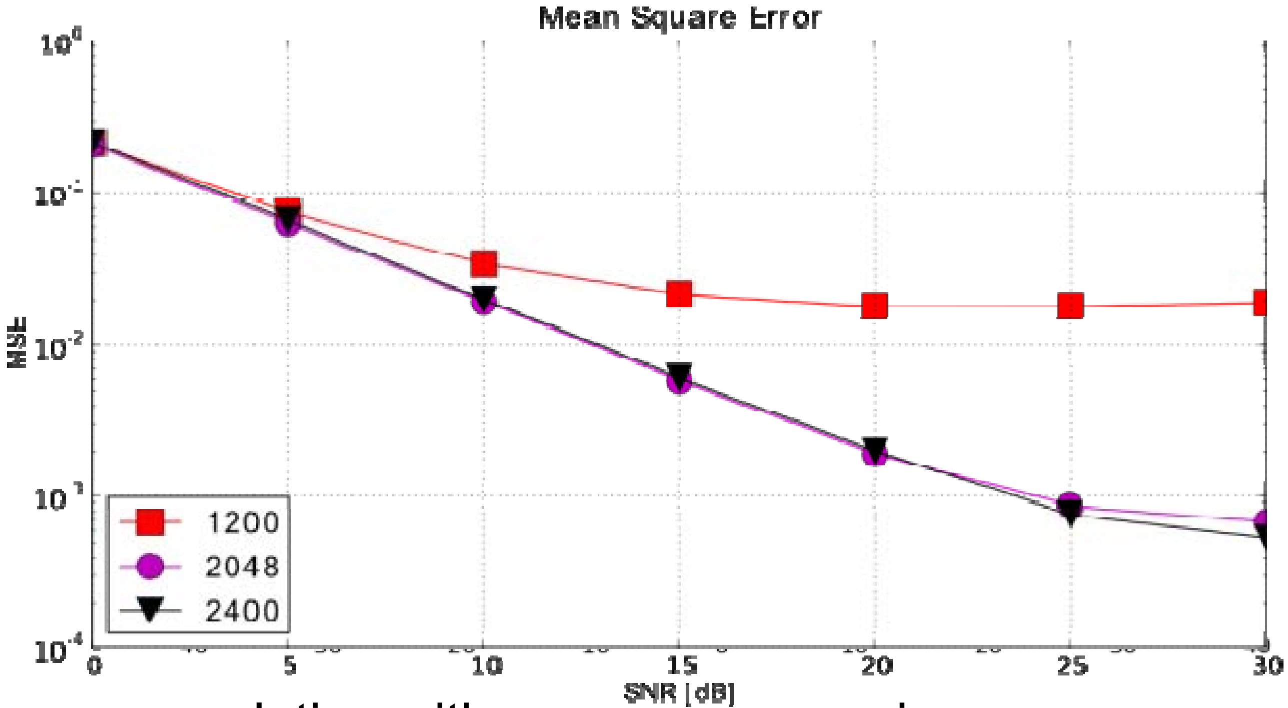
## What resolution should we use in the time domain?

- Higher resolution tends to improve the estimate
  ⇨ higher complexity.
- Certain resolutions with nice properties can be found
  ⇨ large number of zero coefficients
  ⇨ reduced complexity

# LTE parameters

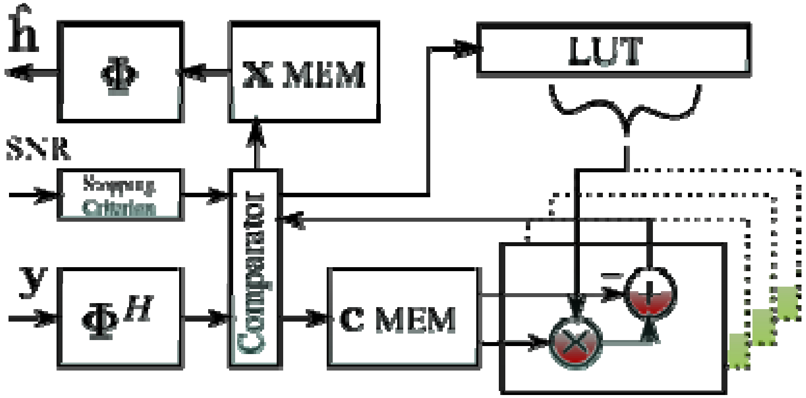
- Long Term Evolution
  - LTE Advanced has been accepted as the 4G standard
- Up to 20 MHz bandwidth
  - FFT Size (i.e. samples/symbol): 2048
  - Used Sub-Channels: 1200
- Two different cyclic prefix modes:
  - Short Cyclic Prefix: 144 samples
  - Long Cyclic Prefix: 512 samples
- Pilots or Reference Signals continuously transmitted

# The coefficients




- Chose a resolution with many zero crossings
  - 1200 samples gives only one non-zero coefficients
    - Unfortunately low performance
  - 2400 samples means that every second coefficient is zero
    - Leads to lower complexity than for 2048 samples!

# Hardware Architecture



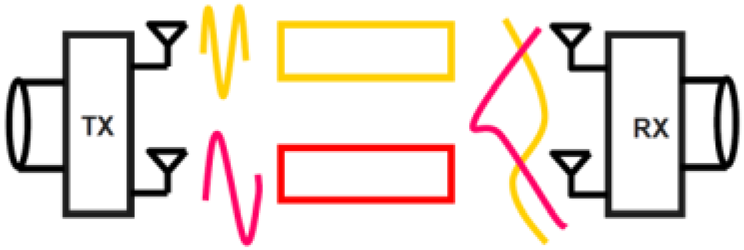

The FFT of 2400 points Decomposes as $N = 2^5 3^1 5^2$

⇨ requires Radix 3 and Radix 5 units

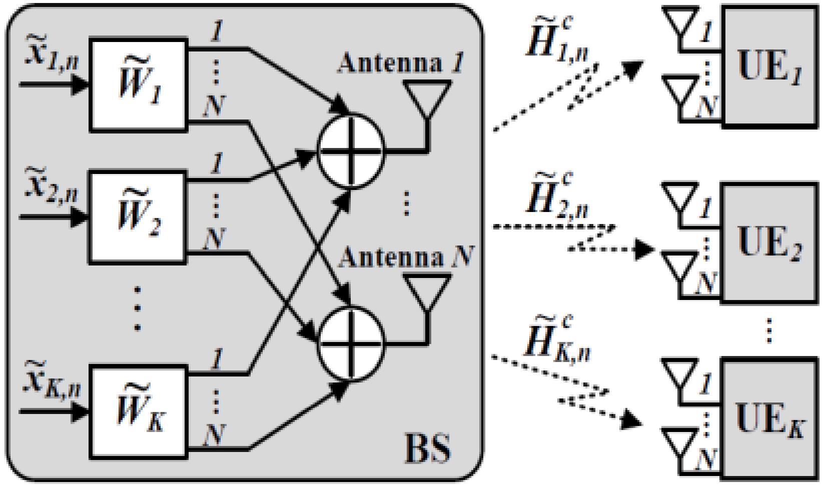
TABLE I
MULTIPLICATIONS IN DIFFERENT STAGES

| Design | One Iteration | IDFT/DFT | IFFT/FFT | Full Estimate |
|---|---|---|---|---|
| Original | 512 | ∼614K | ∼22.5K | ∼96K |
| Proposed | 300 | 720K | ∼27K | ∼84K |

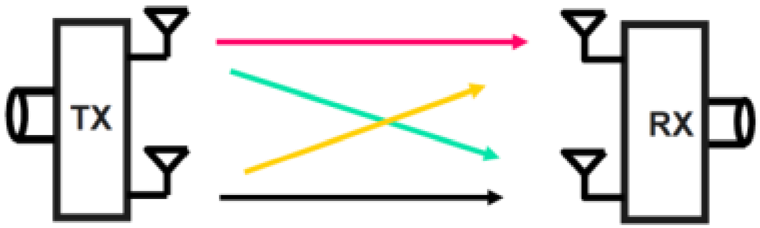
# Multi-mode MIMO in LTE-A




Spatial Multiplexing: Increased rate

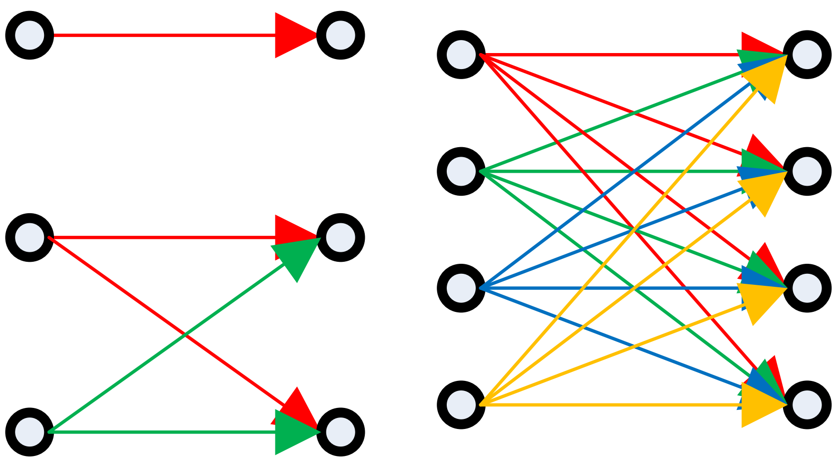


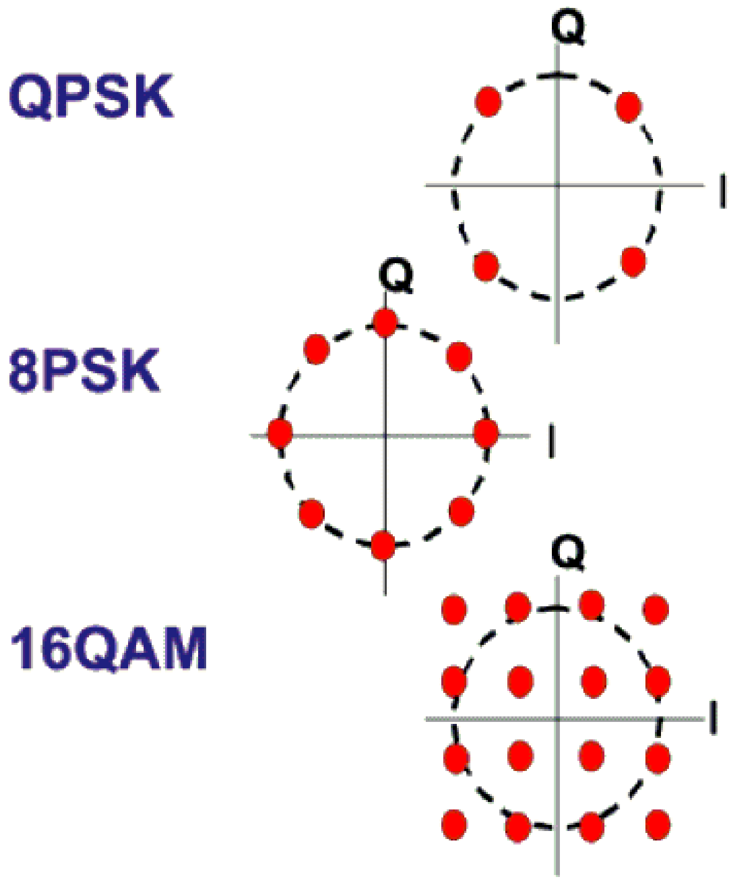

Space Division Multiple Access: Increase cell spectrum efficiency



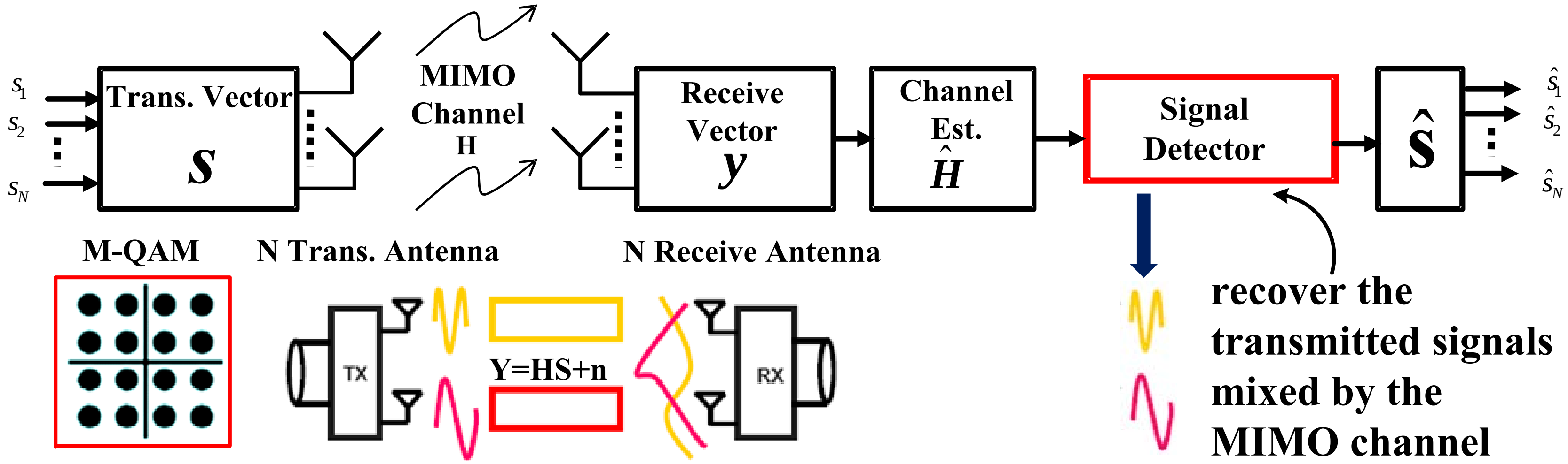

Spatial Diversity: Increased SNR

# Different antenna configurations and modulation schemes

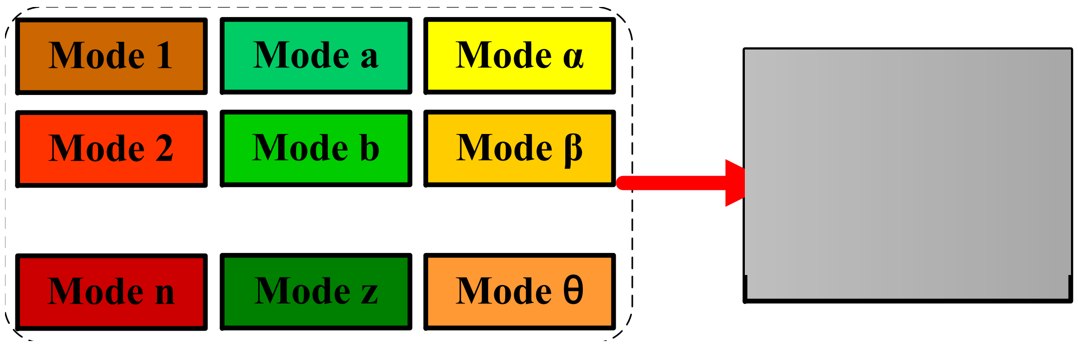




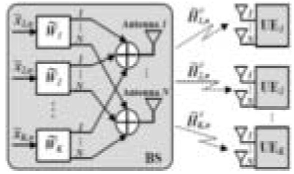
# Objective: unified multi-mode signal detector

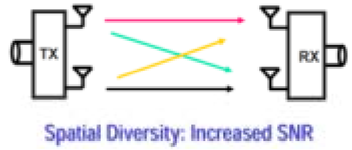



- Unified MIMO detector supporting multiple modes
  - Integrate multiple detectors into a single module → area efficiency



# Needed Resources

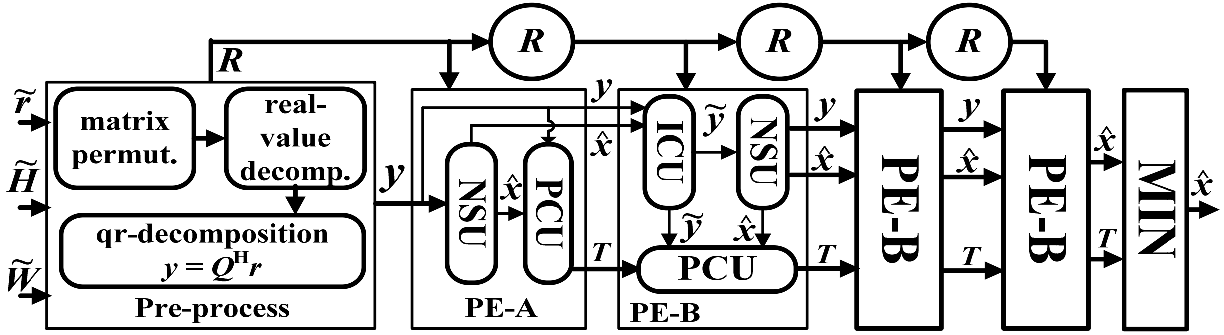



| Operations | MIMO Technologies | | |
|---|---|---|---|
| | SM | SDMA | SD |
| Matrix decomposition | ☑ | ☑ | ☑ |
| Matrix-permutation | ☒ | ☑ | ☒ |
| Node Selection | ☑ | ☑ | ☑ |
| Interference Cancellation | ☑ | ☑ | ☒ |
| Euclidean Distance | ☑ | ☑ | ☑ |
| Sorter | ☑ | ☑ | ☒ |

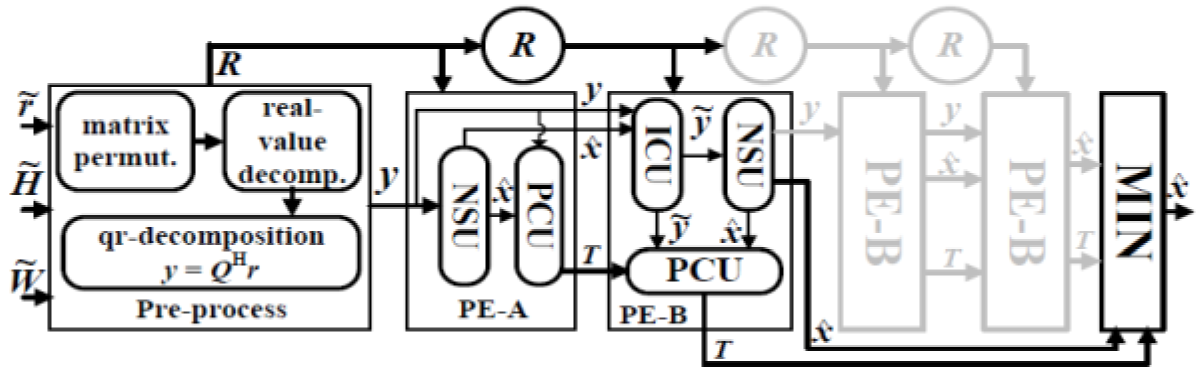
- SM – using Imbalaced fixed-complexity sphere decoder
- SDMA – using Matrix permutated fixed-complexity sphere decoder
- SD – using Real-valued succesive interference calculation

# Example: SDMA

- Unified at the architecture design level
  - Multi-stage architecture corresponding to antennas
  - Activate different stages according to antenna configuration

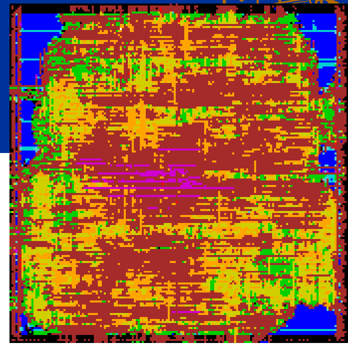



4×4 Mode




2×2 Mode

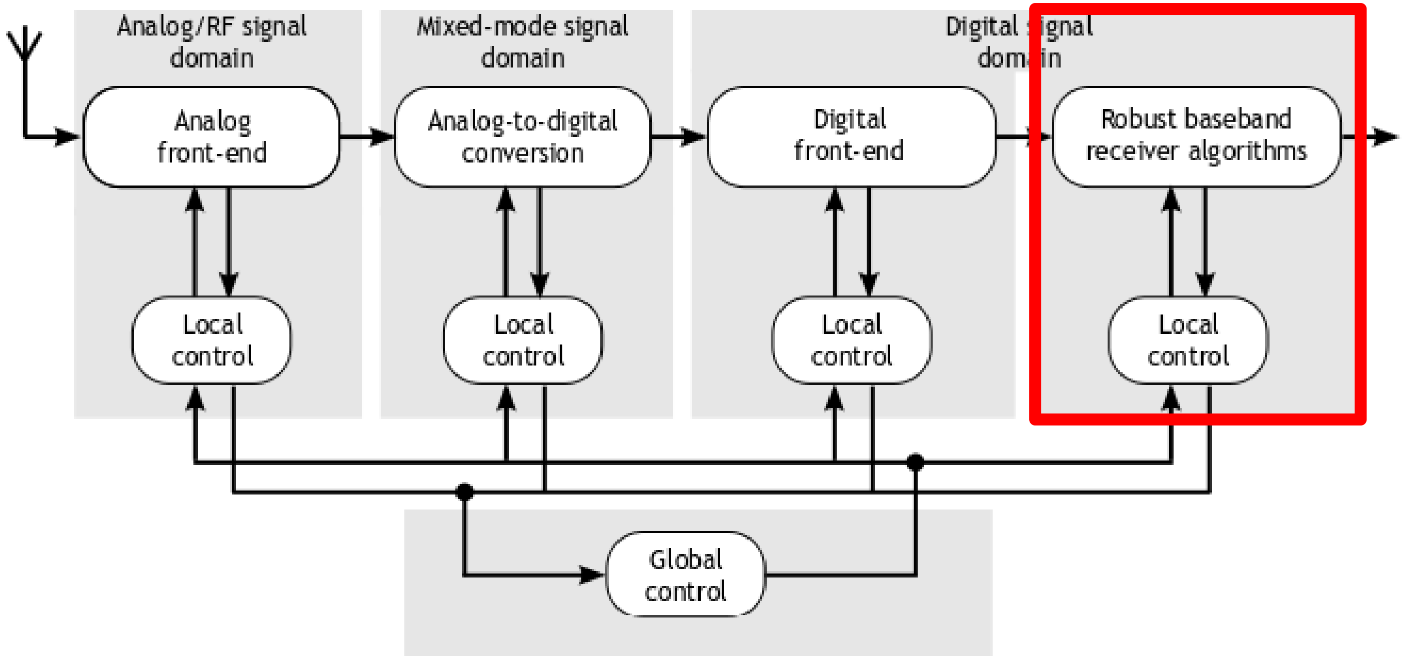
# Results



- Proposed work 65nm CMOS, other 0.13μm CMOS technology
- Supports the largest number ofMIMO modes
- Consumes the least hardware and energy

| | TCAS-I'09 | ISSCC'09 | TCAS-II' 10 | This Work |
|---|---|---|---|---|
| MIMO Tec. | SM | SM | SM | SM/SD/SDMA |
| Antenna Size | up to 6×4 | 4×4 | up to 4×4 | up to 4×4 |
| Modulation | up to 64-QAM | 64-QAM | up to 64-QAM | up to 64-QAM |
| Core Area | 1.46 $mm^2$ | 0.9 $mm^2$ | 3.9 $mm^2$ | 0.25 $mm^2$ |
| Gate Count | 205 KG | 114 KG | 491 KG | 88.2 KG |
| Clock Rate | 71 MHz | 282 MHz | 137.5 MHz | 165 MHz |
| Throughput | 114 Mb/s | 675 Mb/s | 1.1 Gb/s | 1.98 Gb/s |
| Power Consumption | 30 mW @ 1.1 V | 135 mW @ 1.3 V | 127.2 mW @ 1.2 V | 102.7 mW @ 1.2 V |
| Normalized Power | 17.9 mW | 57.5 mW | 63.6 mW | 102.7 mW |
| Normalized Energy | 156.6 pJ/b | 85.2 pJ/b | 57.8 pJ/b | 51.8 pJ/b |

# We will continue MIMO within DARE!




- *Target: LTE – rel. 10 , a.k.a. LTE-advanced*
  - Robust baseband receiver algorithms
  - Including carrier aggregation, e.g. Isael Diaz is currently visiting IMEC and is working on a project looking at hardware architectures within this area.

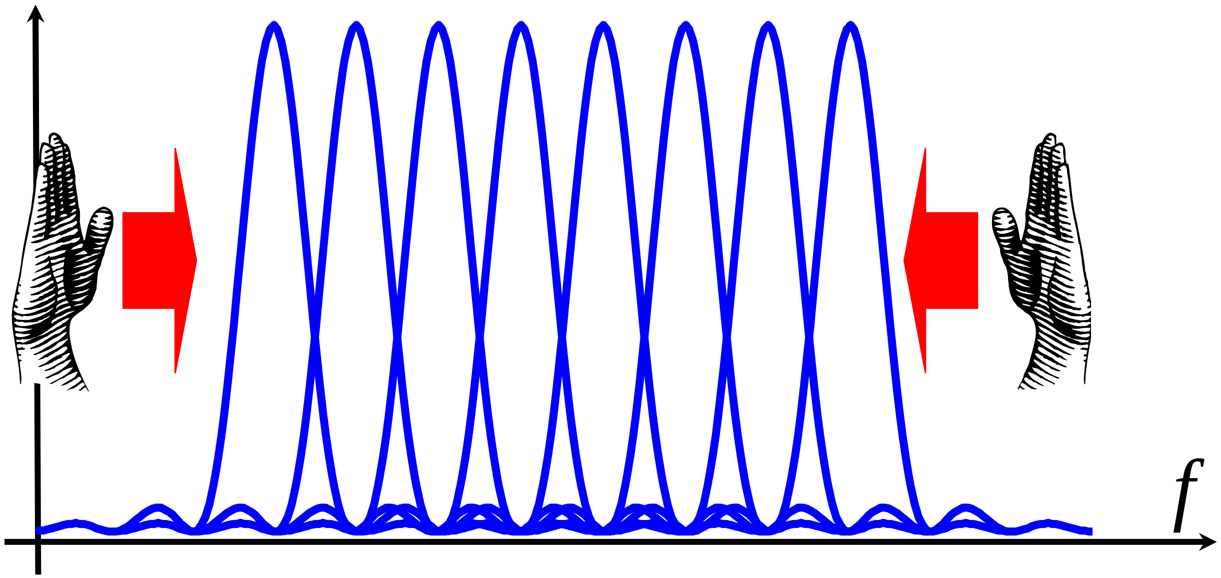
# Life after OFDM:

# Going Faster than Nyqvist?

# FTN Signaling

- Original concept by J.E. Mazo in 1975 (Bell Syst. Tech. J).

- Main idea
  - transmit  info beyond Nyquist's criterion for ISI free transmission.
  - Stack closer in time and/or freq – induce intentional interference.



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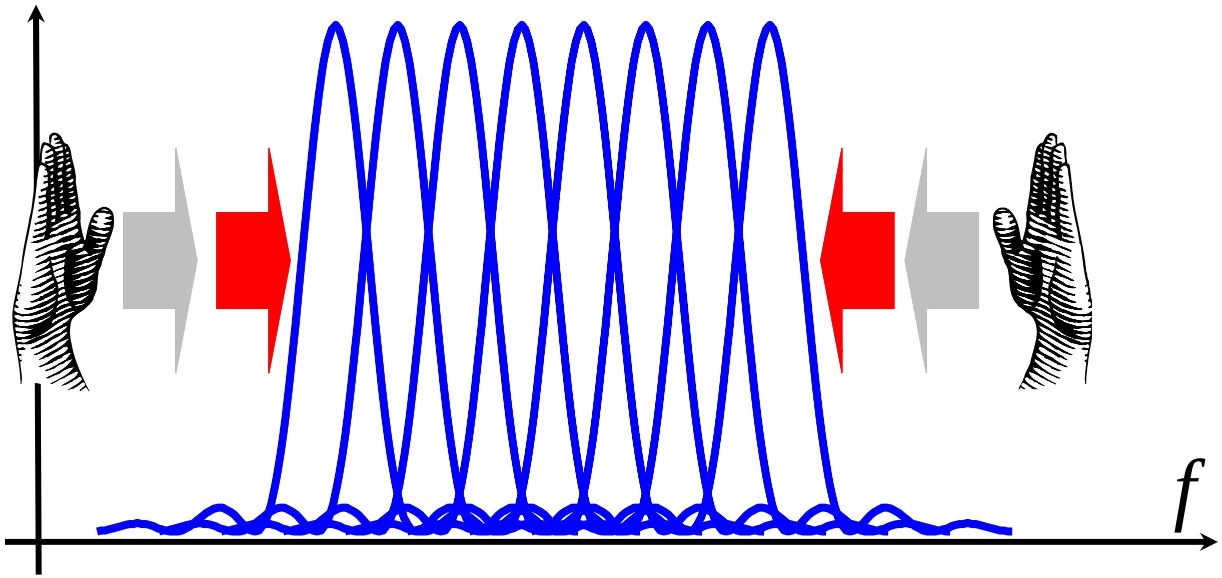


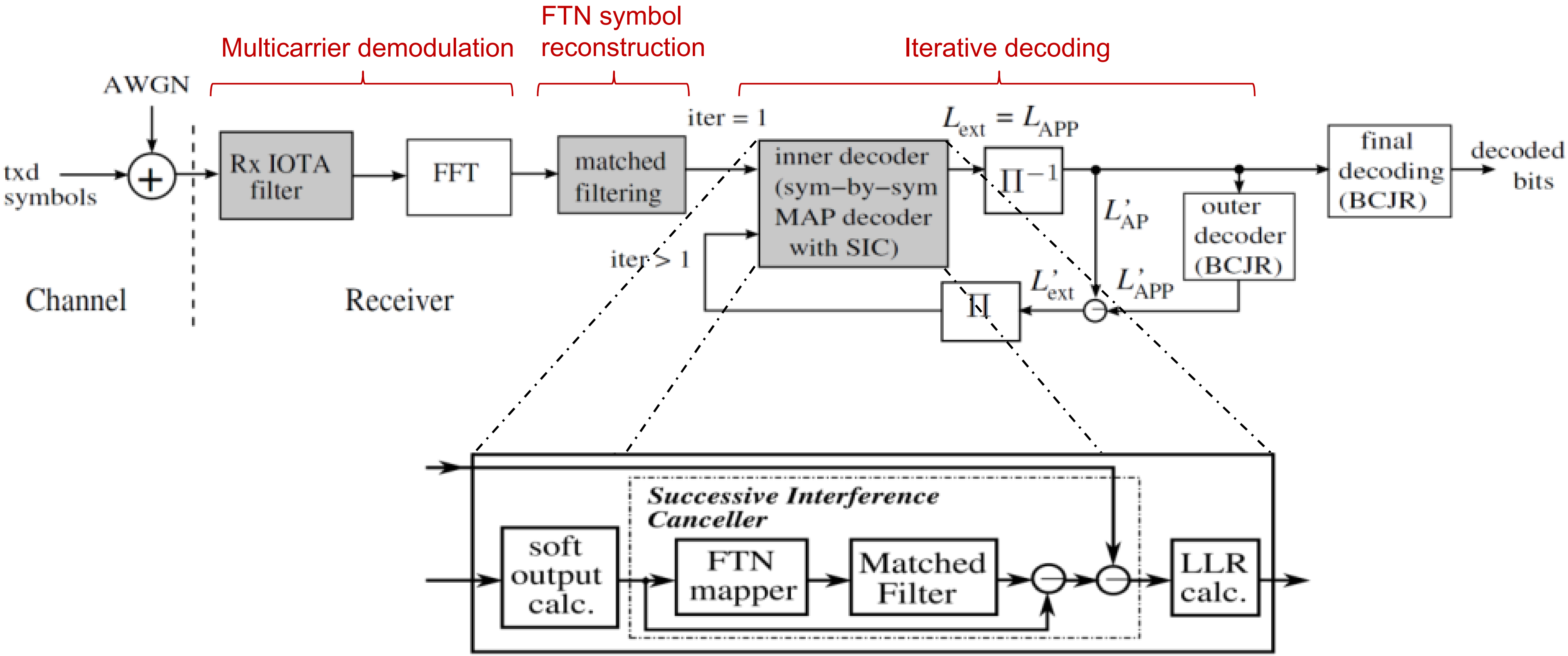
# FTN Signaling

- Original concept by J.E. Mazo in 1975 (Bell Syst. Tech. J).

- Main idea
  - transmit  info beyond Nyquist's criterion for ISI free transmission.
  - Stack closer in time and/or freq – induce intentional interference.
  - Investigate OFDM-systems due to their popularity
  - Reuse as much as possible from a ”standard” system

- Motivation: Bandwidth efficient systems
  - Alternative to higher order modulation
  - Study hardware feasability

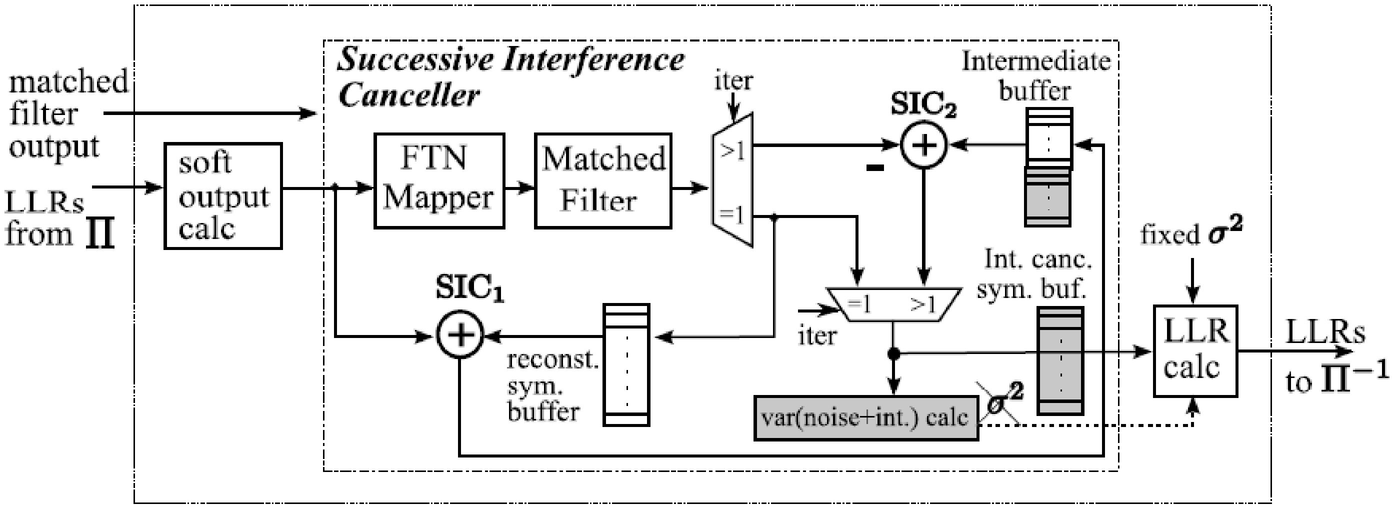
# FTN Architecture




- Trade-off bandwidth for hardware complexity!
- Keep as much as possible from a ”traditional” system.

# Optimizing the architecture

- Initial design: 0.5 $mm^2$ in ST65 nm standard cell CMOS
- Power: 44mW (80% in the memories)!

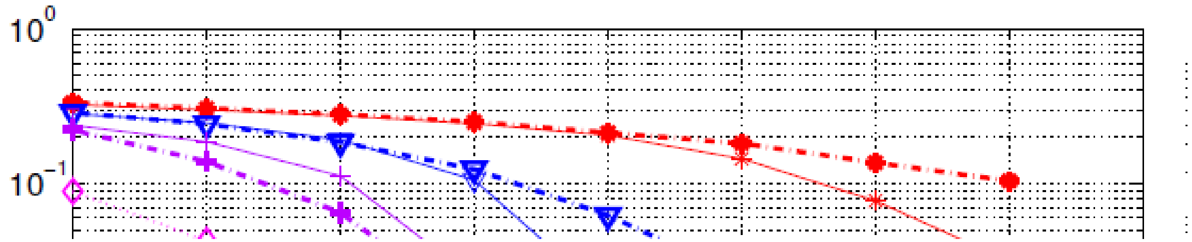



Main target for optimization: the memories!

For example by using a fixed variance:

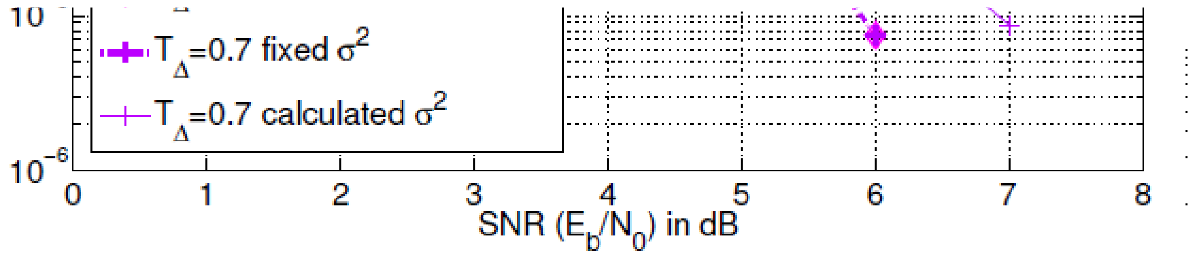
- Reduce algorithmic complexity (minor)
- Saves buffer (major)!

# Performance with fixed variance



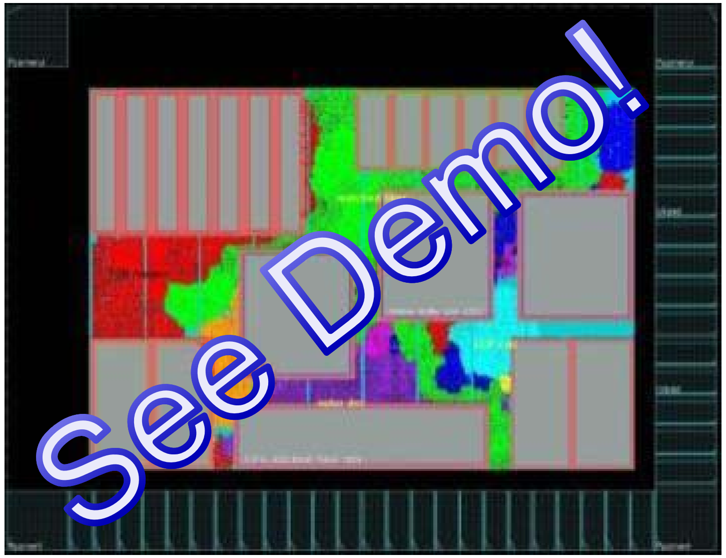

COMPARISON OF TOTAL AREA AND POWER BETWEEN BASELINE AND MEMORY OPTIMIZED IMPLEMETATIONS.

| | Baseline [7] | Memory optimized | Savings |
|---|---|---|---|
| Chip area | 0.519 $mm^2$ | 0.370 $mm^2$ | 28.7% |
| Total Power | 44.7 mW | 25.1 mW | 43.8% |
| - Logic | 8.0 mW | 6.5 mW | 18.7% |
| - Memory | 36.7 mW | 18.6 mW | 49.3% |



# Fabricated Silicon

- Chip area: 0.5 $mm^2$ in ST65 nm standard cell CMOS
- Power: 44mW (80% in the memories)
- Throughput: 3.2Mbps at 300MHz.
- Tape-out: November 2010
- Measured and working.




- FTN-signaling is deemed feasable from a hardware perspective.
- Complexity overhead.
  - Memory : same order as a max-log-MAP implementation, (7,5) conv code.
  - Logic: ~5 times

Published in IEEE Transactions of Circuits and System – I (TCAS-I)

# Conclusion

- Results and future plans for Digital Front End architectures
- Sign-bit processing for low complexity
- Reduced complexity channel estimation in LTE
- Multi-mode MIMO detection architectures
- Architecture and implementation of an FTN-signaling receiver.

# Thank You!