Flexible-Radio: A General Framework with PHY-layer algorithm-design insights

by

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Qualifiers/Disclaimers

- Qualifiers needed to protect my reputation (if any…)
- Much of the talk is tutorial/overview in nature
- No equations (good for a relaxing workshop)
- Many viewpoints are mine, and can be controversial, hence good for a debate
- Scientific view of the topic is fairly new, and new blood is welcome

Outline

- **Background**
- **FR Goals and Definitions**
- **Metrics and Costs**
- **Optimization Tools**
- **Examples of FR optimizing-algorithm designs**
- **Summary**

Background

- **Flexible Radios (FR) is a fairly recent field of scientific inquiry for commercial and non-military governmental**
- **Topic has existed in the military sector for some time under related names (Software Defined Radio—SDR)**
- **Theme affords quite general interpretations, if we include flexible network topologies (e.g., *ad hoc* or infrastructure-less mesh networks)**

The Players ("Who")

- **Industry involvement: no current commercial product, although some cellular BS's already exhibit some flexibility, modulation/coding adaptivity in UMTS, etc.**
- **Military products exist**
- **Research community involved in various forms:**
  - **SDR Forum (http://www.sdrforum.org)**
  - **DYSPAN (http://www.ieee-dyspan.com/about.htm)**
  - **Multiple EC projects:**
    FIRST, SUNBEAM, ADRIATIC, CAST, MUMOR, TRUST, SCOUT, ANWIRE, MOBIVAS, PASTORAL, WINDFLEX, E^2R, Project D of NEWCOM, URANUS

Goals of FR (“Why”)

Two main motivators can be discerned for radio flexibility:

1. **Multi-standard/Upgrade Enabler at design time**

- **multi-standard, multi-modal operation**
- **legacy-proofness (“backward compatibility”) and future-proofness (“easy upgrades”)**

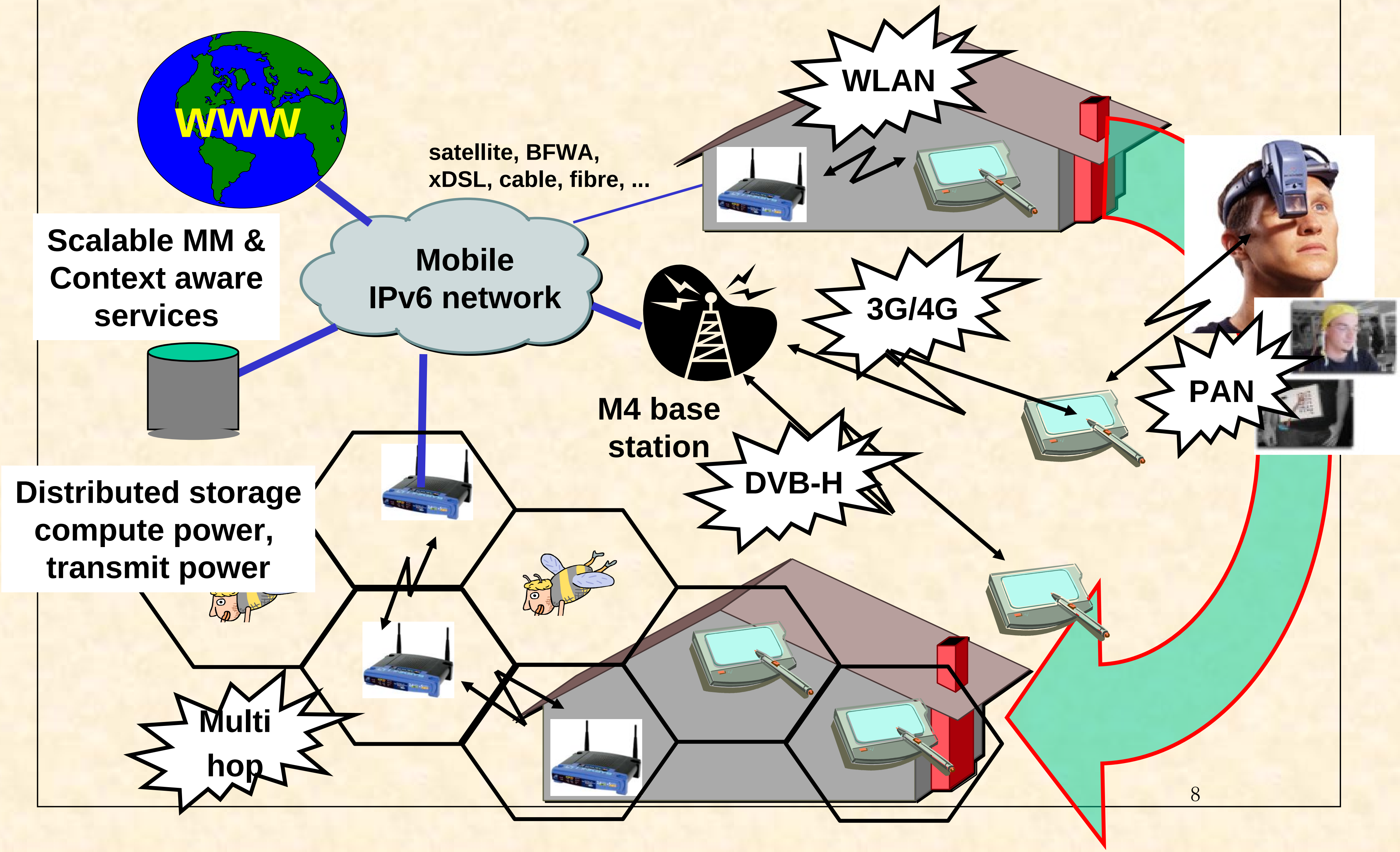
2. Optimization Enabler at run time

- **optimized performance as a function of the “scenario” =conditions/environment (user demands, application/service, networks, channels, …)**
- **QoS & user satisfaction of various metrics**
- **robustness to HW malfunctions during operation**

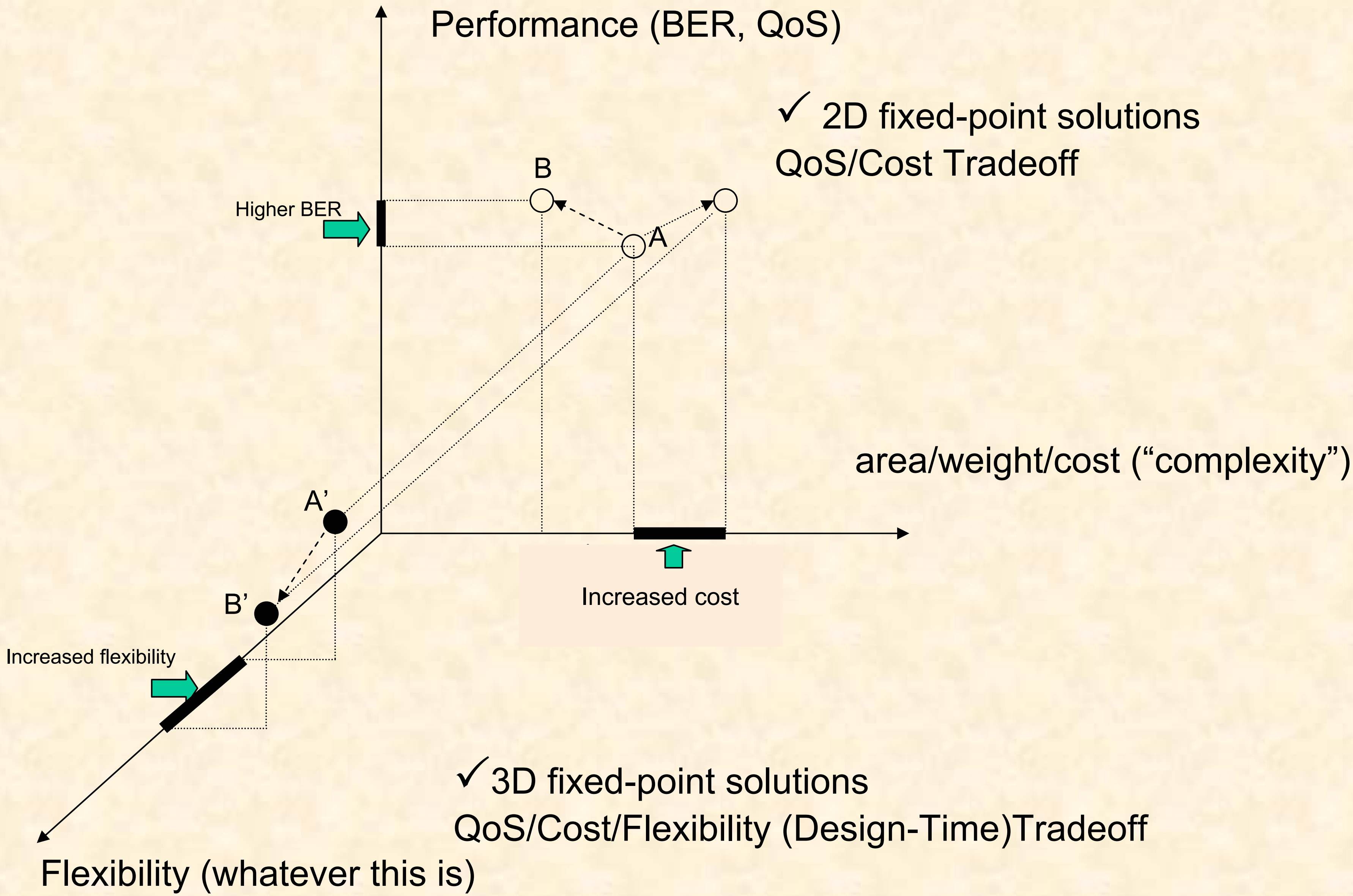
Newcom's Project D Goals

- **To fill up gaps in European knowledge on Flexible Radio**
  - To identify the knowledge gaps
  - To prepare an action plan to fill these knowledge gaps
- **3- pronged approach to novel solutions**
  - develop novel flexible ***baseband DSP algorithms***
  - study and evaluate novel flexible ***digital platforms***
  - devise novel ***QoS*** radio resource ***management concepts***
- **To identify common frameworks, platforms and performance metrics for comparison purposes**
- **To define and implement common SW/HW platforms to realize some key baseband modules**

Why multimode/multistandard?



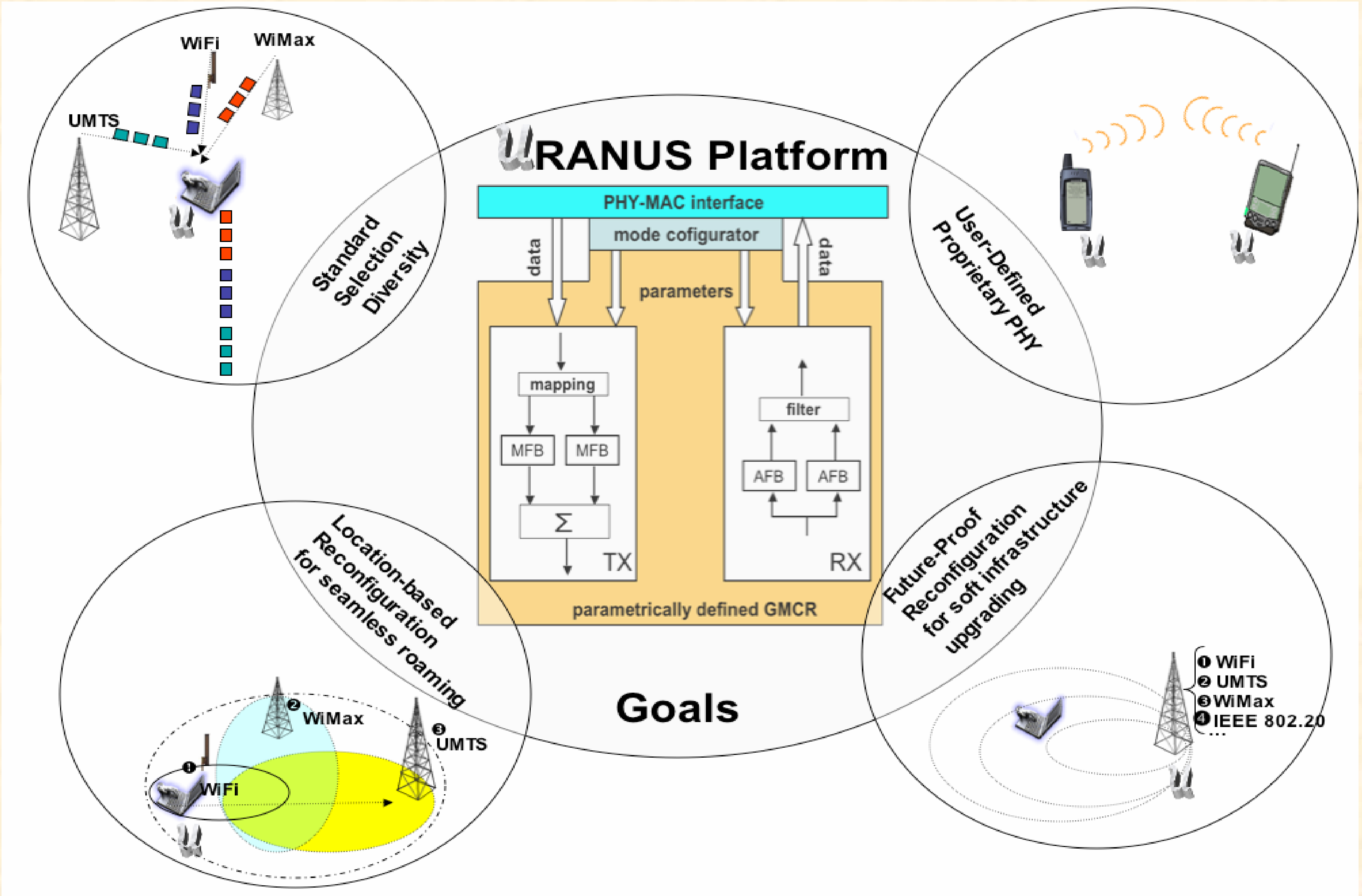
The 3 axes and the cost of flexible optimization



✓ 2D fixed-point solutions
QoS/Cost Tradeoff

✓ 3D fixed-point solutions
QoS/Cost/Flexibility (Design-Time)Tradeoff

"Celestial" Wish-list of Scenarios



The URANUS “representation” hypothesis

- Goal is to provide a platform for flexibly adjusting to the multitude of present (and future?) air interface waveforms
- Key ideas: **parameterization** and **canonical description** of all TRx functionalities art the PHY layer (leads to Canonical Parametric Description -- CPD); see later figure for such a functional description
- For set of “basis” functions of waveform representation, use Generalized Multi-Carrier Representation – GMCR)

Definitions & Terminology (“What’)

• A system is ***adaptive*** if it can respond to environment changes by properly altering the numerical value of a set of parameters.

• It is ***reconfigurable*** if it can be rearranged, at a structural or architectural level, by a non-quantifiable change in its configuration.

•It is ***dynamic*** if it is *adaptive* or *reconfigurable* in a real-time sense, based on run-time measurements and resulting actions

Flexibility may be defined as an “umbrella” concept, encompassing a set of features or attributes, such as ***adaptivity, reconfigurability, modularity, scalability***, ***seamlessness, ease of use, ease of design,*** etc., such that the presence of any subset of those would suffice to attribute the qualifying term flexible to any particular system under consideration.

Conceptual-Semantic Links

- **Flexible radio**: defined broadly before
- **Reconfigurable radio**: a similar notion, perhaps slightly narrower
- **cognitive (smart) radio**:
  - divided into *user-centric* (or "service"-centric) versus *technology-centric concepts*, the latter related to this discussion
  - deals a lot with wideband spectrum sensing, real-time spectrum allocation and acquisition (real-time leasing from primary users)
- **SR, SDR**: see next page

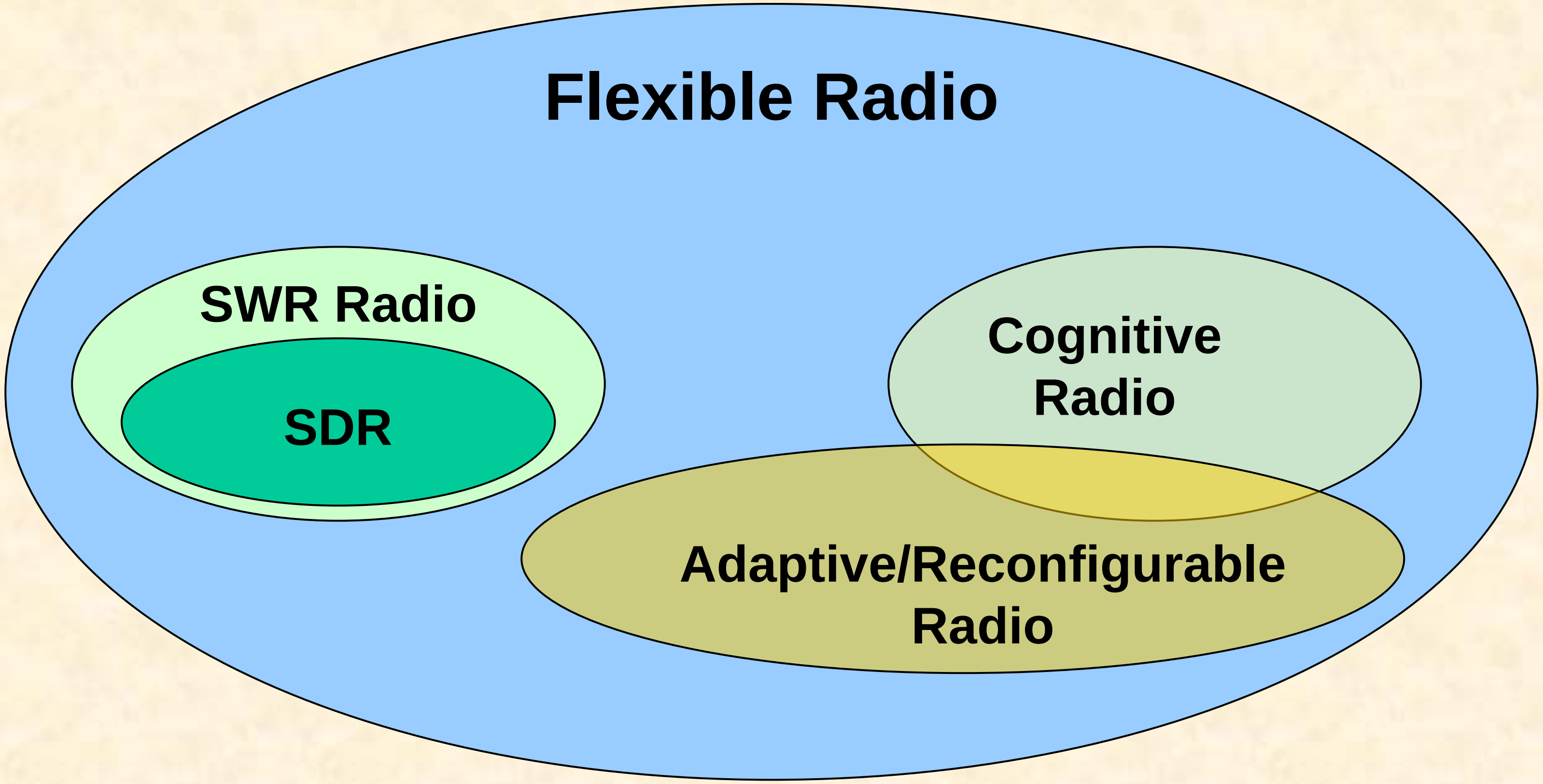
Note: emphasis on lower layer (PHY) in this presentation

SDR Forum Definitions

- **Tier 0: Hardware Radio**
- **Tier 1: Software-Controlled Radio**
- **Tier 2: Reconfigurable Radio**
- **Tier 3: Ideal Software Radio**
- **Tier 4: Ultimate Software Radio**

Defined for reference purposes only, could switch all functions in ms

A pictorial arrangement



Flexibility Metrics and Cost

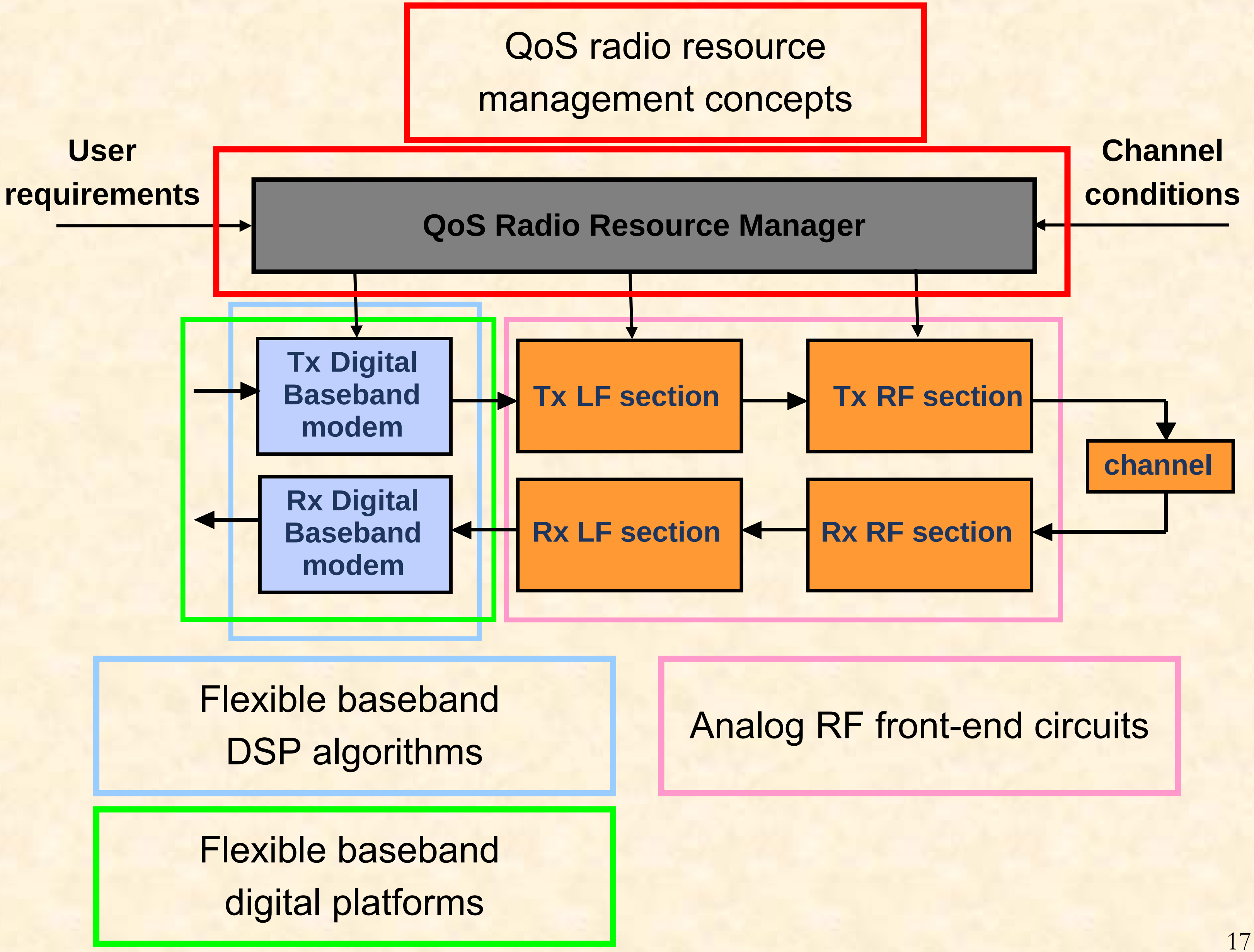
Metrics

- QoS (bit rate, bit-error rate, latency), link to applications plane
- transmission power (interference, health)
- energy efficiency via environment-aware processing
- time-to-market (not for the first round of design!)
- upgradeability
- number of accommodated standards/modes
- breadth of supported scenarios ("wide applicability"), either for the same system (e.g., channel conditions) or different systems

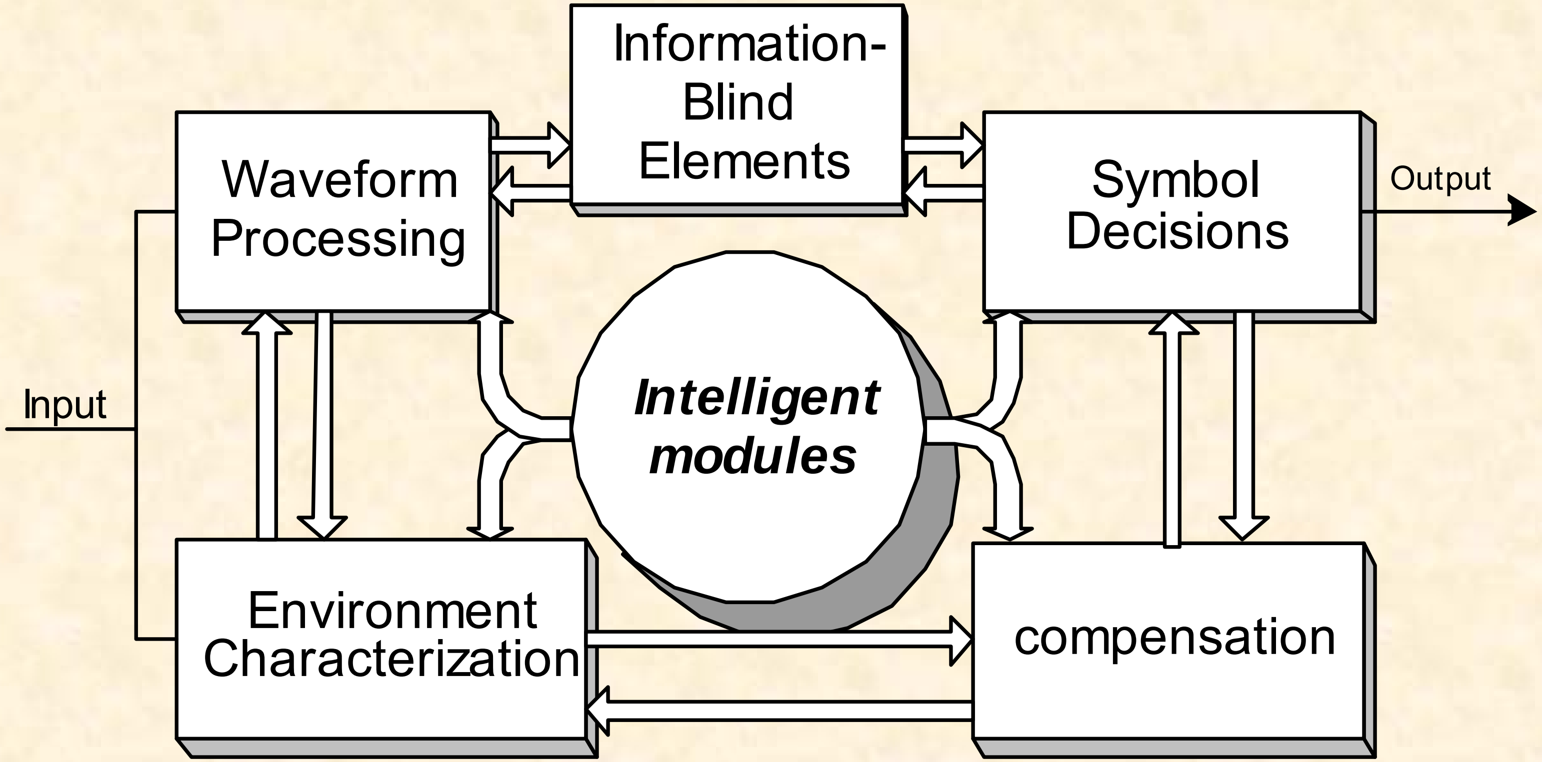
Cost of flexibility

- energy efficiency due to more power-hungry processors
- price, size, silicon area used
- reduced performance versus point-optimized solutions

FR Entities Under Change ("How")



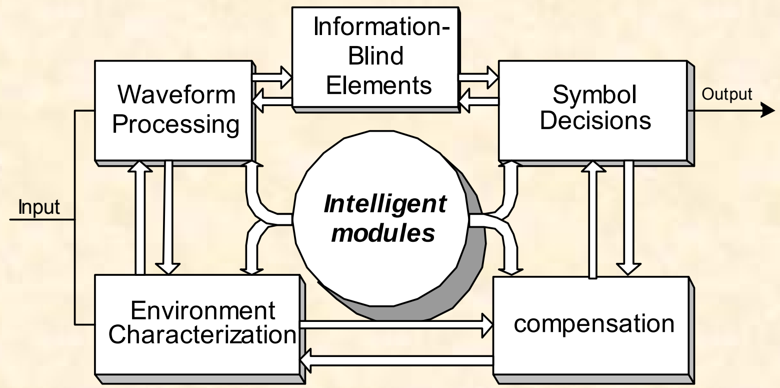
Generic FR algorithmic framework: exhaustive menu of transceiver functionalities



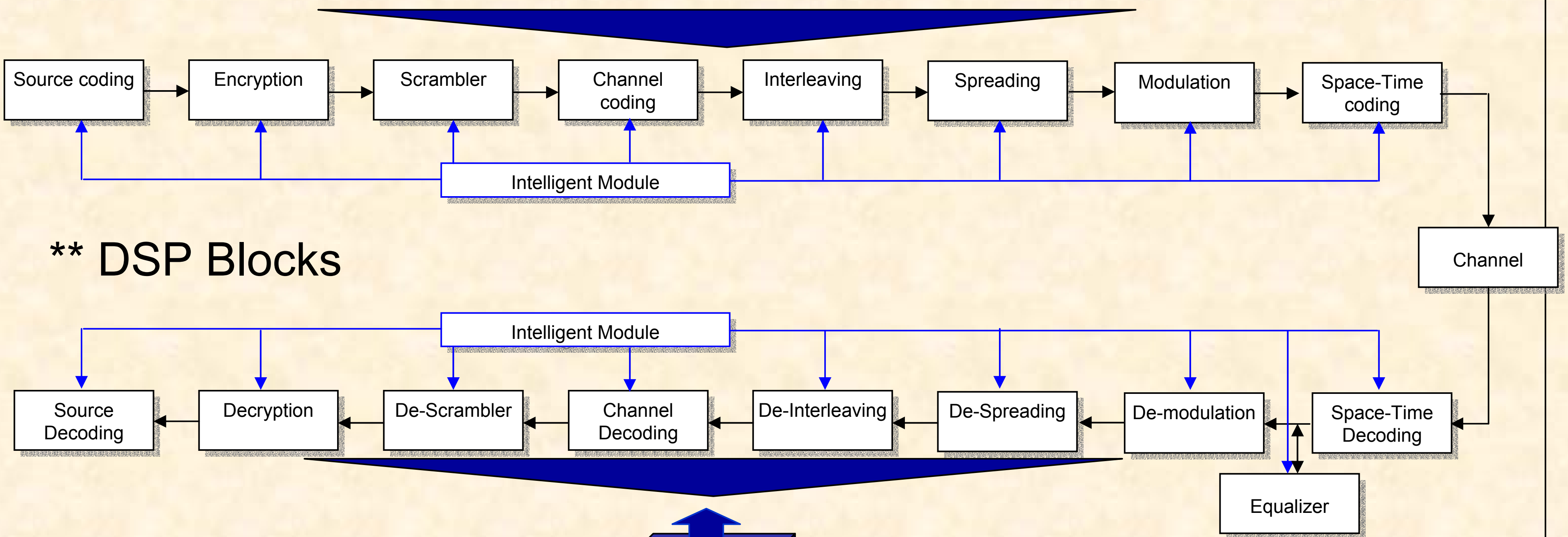
Note: instead of “symbol decisions”, the block should read “finite-field data encoding and related DLP”

Nesting: Functionalities/SP blocks/Algorithms

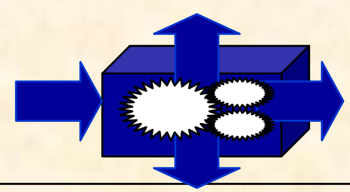
* Functionalities



** DSP Blocks

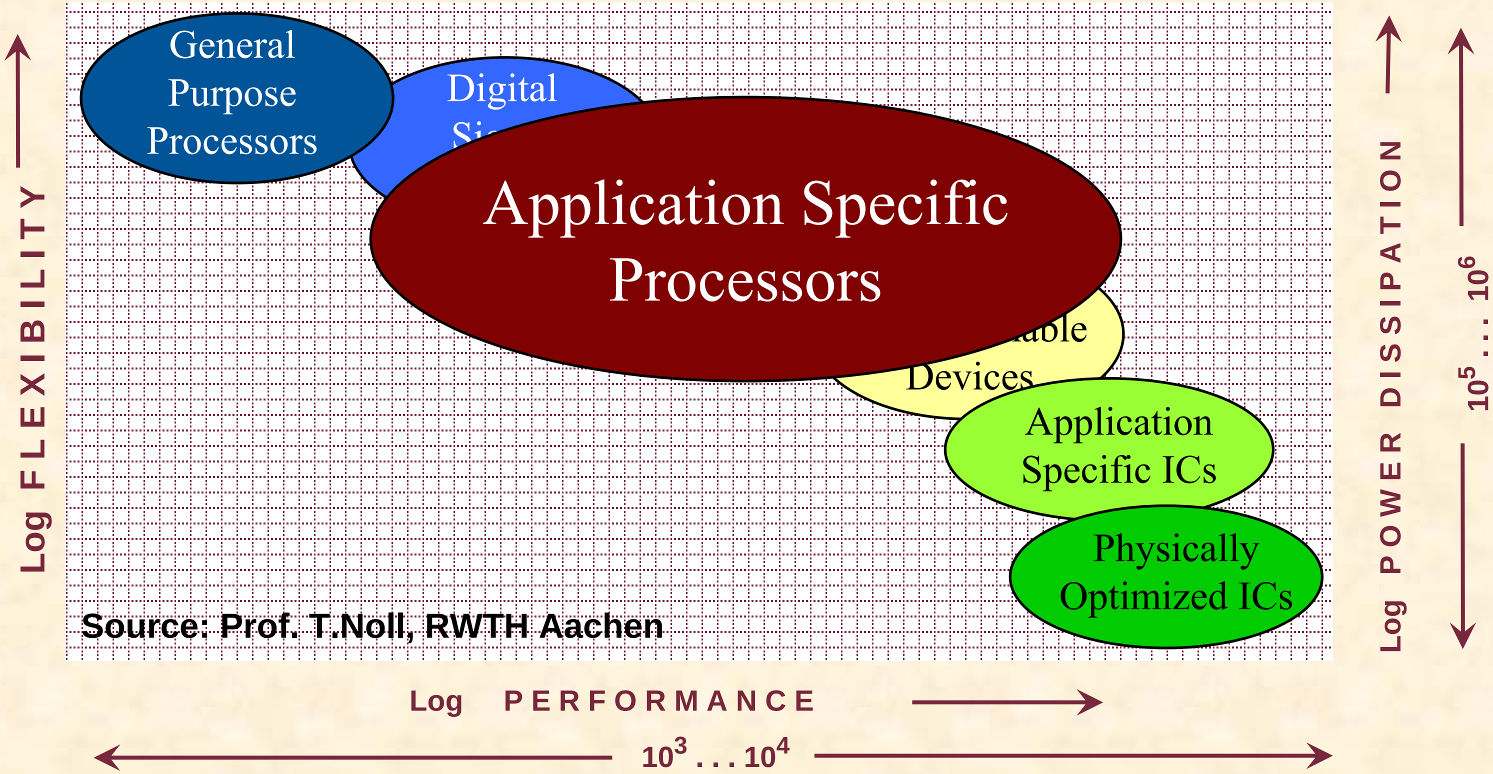


*** Algorithms

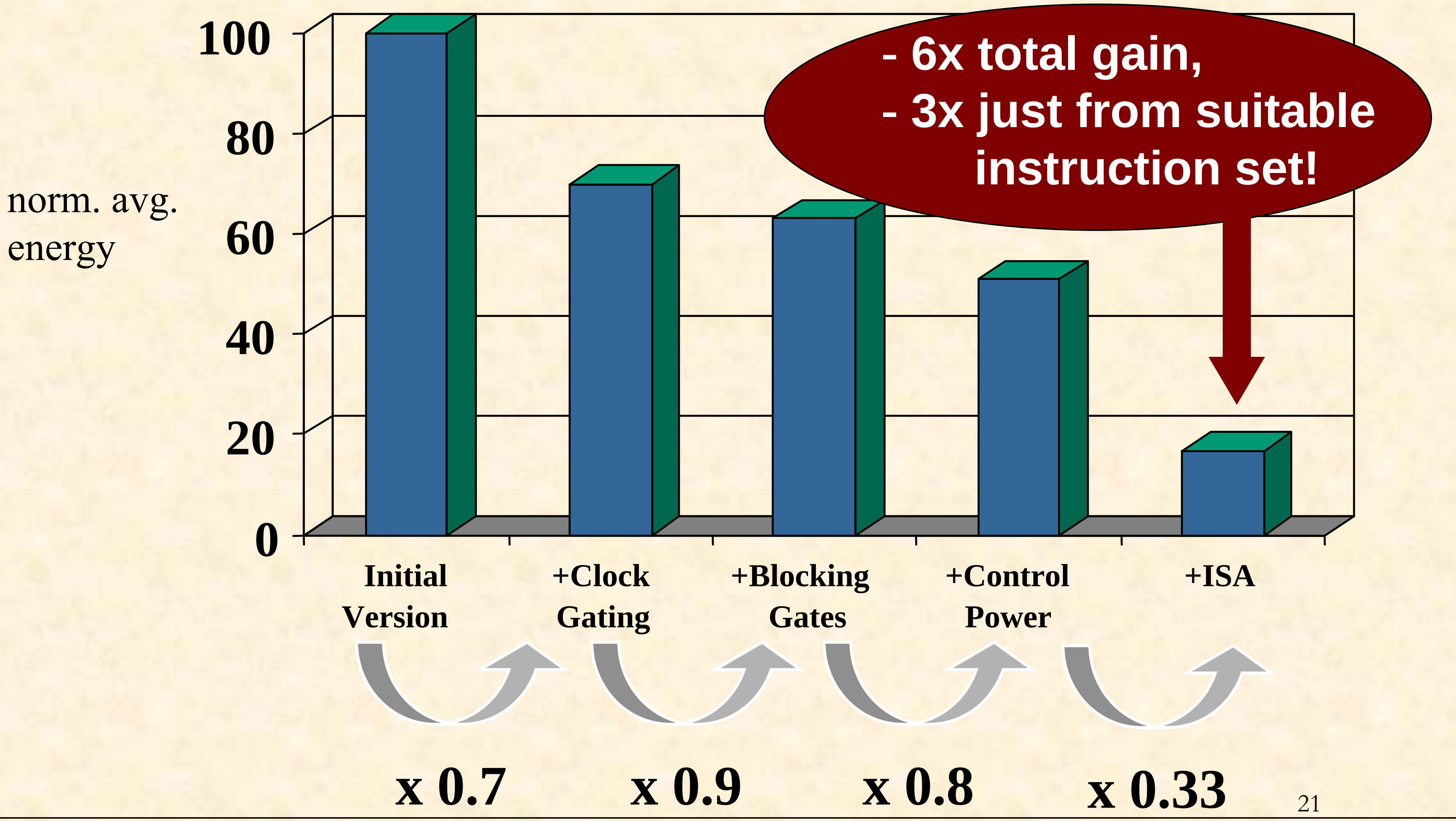


Flexible Platform Example: Application Specific Processors (ASIP)

- **Compromise between**
  - ↓ **Flexibility**
  - ↑ **Energy-efficiency and throughput**



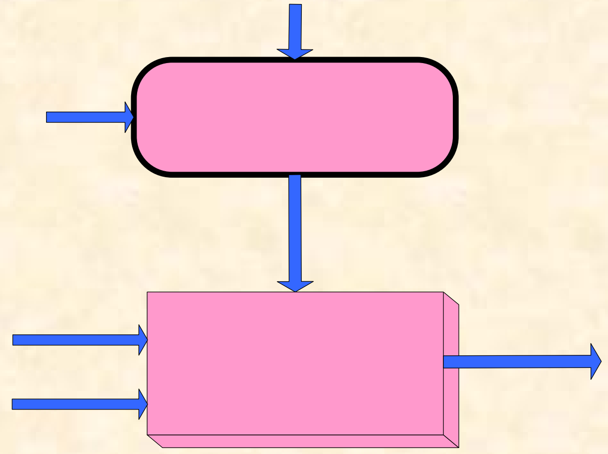
Ex: Energy Optimization (DVB-T Equalizer)



Flexible Algorithm Ex #1:AMC in SISO/OFDM

- SNR variation across OFDM sub-carriers degrades performance even with a strong outer code; static, measurable channel (feedback or reciprocity assumed)

<u>1st algorithm</u>: Rx evaluates and notifies the Tx about the *minimum* required *Tx* power for a specific {code rate, constellation size}, corresponding to a **<u>given bit rate</u>**, for an <u>arbitrary</u> channel-realization ("sample-path") shape to achieve a **<u>given coded BER</u>** (under an optimizable Equal-Power-Allocation constraint -- EPA).
If the required power is greater than the maximum available/allowable *Tx* power
→ re-negotiate the QoS level.



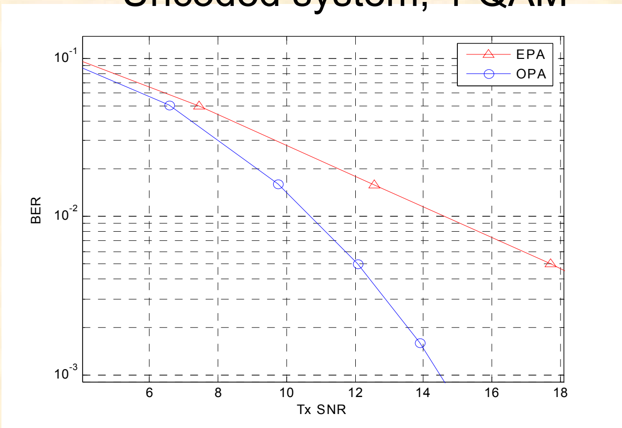
✓ low complexity and limited feedback information requirements

Performance of Algorithm#1

Simulation Parameters (WF)

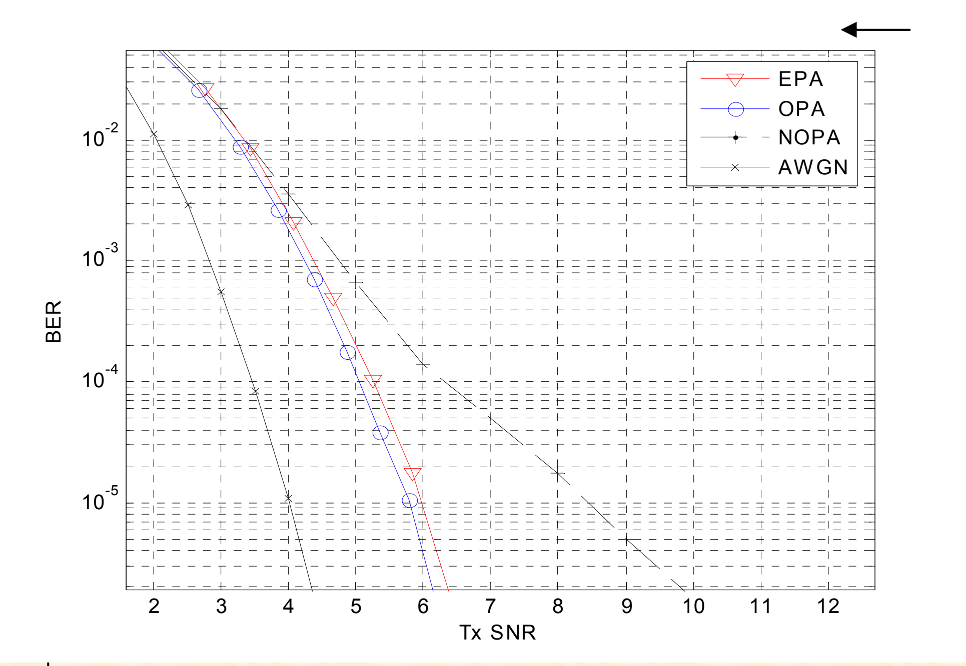
- 128 sub-carriers (100 active)
- No Line Of Sight channel scenario
- parallel- concatenated turbo coding scheme with variable rate via three puncture patterns (1/2,2/3,3/4)
- RSC polynomial used is (13,15)oct

Uncoded system, 4-QAM

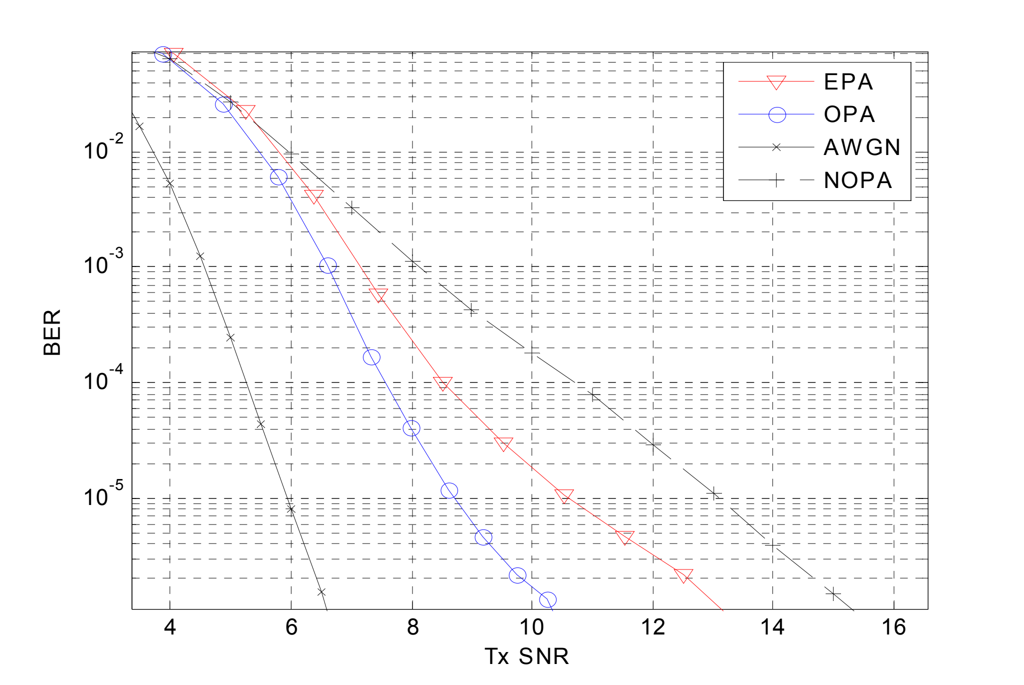


OPA: A system with Optimal Power Allocation.
It is plotted to show the performance limits of Alg#1 based on the power loading scheme.
NOPA: System without any power allocation.
AWGN: The performance under AWGN channel.

Rate 1 (4-QAM , ½)



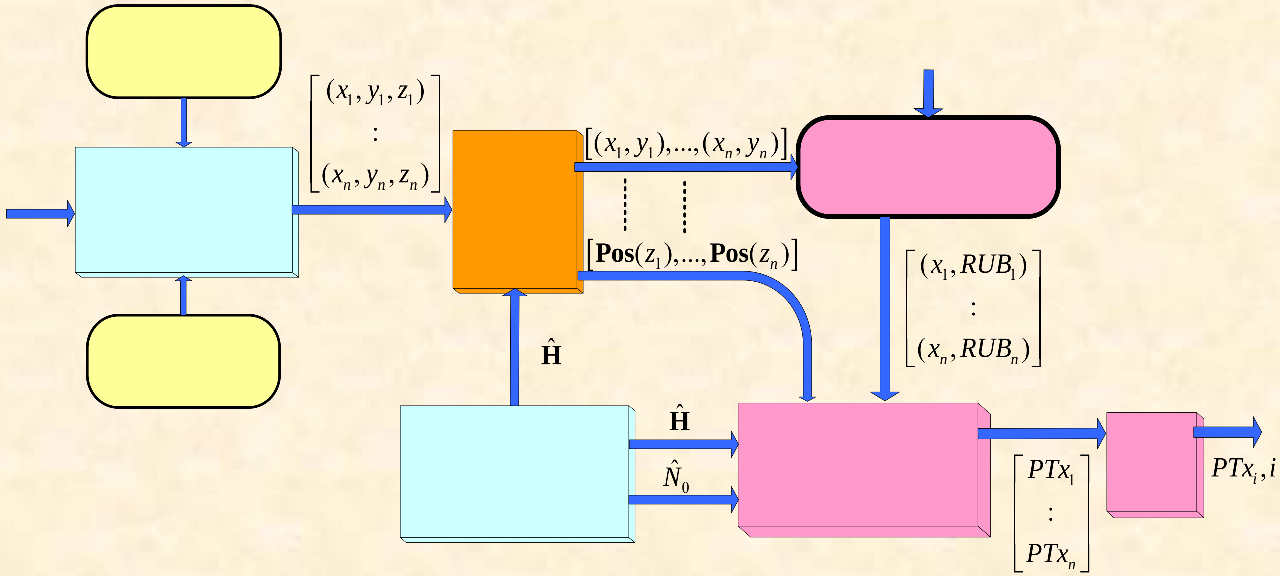
Rate 2 (4-QAM , ⅔)



FlexAlg Ex. #2: AMC with WSCE

2nd algorithm: Coded Weak Sub-Carrier Excision (CWSCE) method

- Weak Sub-Carrier Excision (WSCE) is the ability of the system to exclude a number of sub-carriers from transmission.
- Diagram below represents a proposed "canonical optimizing-module" structure (supervisor).



$x_i, i = 1 \ldots l$ → *i*th supported constellation.

$y_i, i = 1 \ldots M$ → *i*th supported outer channel codes.

$z_i, i = 1, \ldots, n$ → WSCE percentage for the *n* competitive triplets.

$\mathbf{Pos}(z_i)$ → Positions of the % of weakest gains.

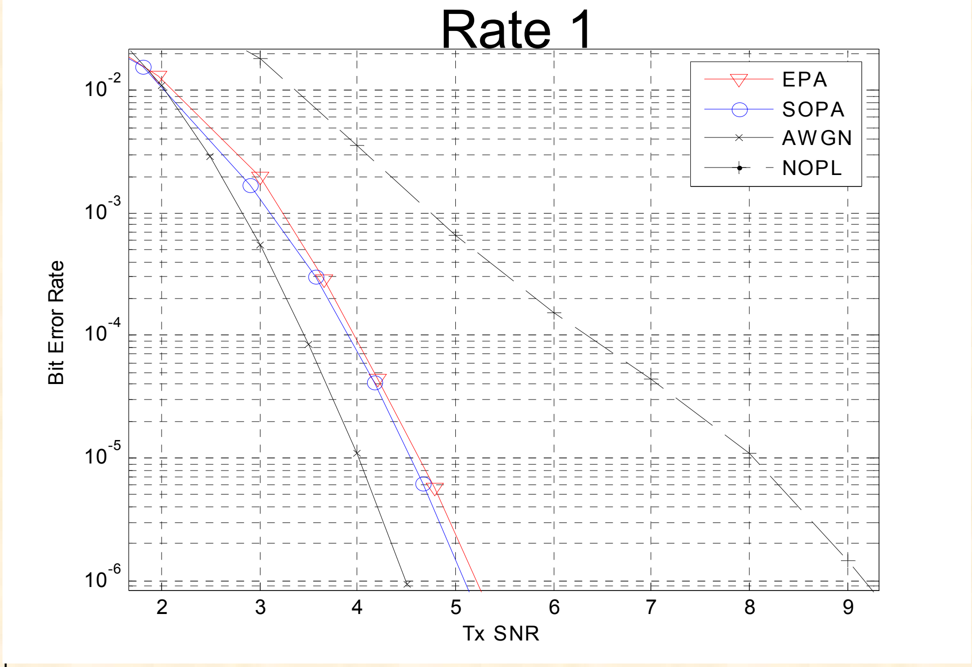
$\hat{\mathbf{H}}$ → Estimated channel gains at the frequency domain.

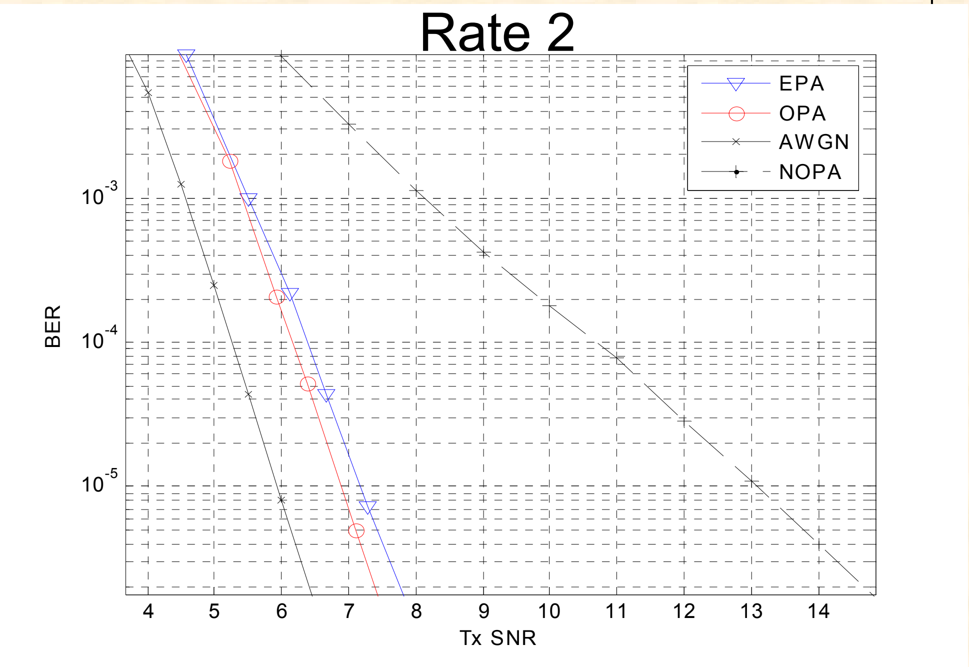
$\hat{N}_0$ → Estimated power spectral density of the noise.

$RUB_i, i = 1 \ldots n$ → Required uncoded BER for each mode/triplet.

$PTx_i, i = 1 \ldots n$ → is the required *Tx* power for the ith mode/triplet.

Performance of Algorithm #2





Transmission Modes

Modes	Rate 1	Rate 2
1	(4-QAM, ½, 0%)	(4-QAM, ⅔, 0%)
2	(4-QAM, ⅔, 25%)	(4-QAM, ¾, 12%)
3	(4-QAM, ¾, 34%)	(16-QAM, ½, 33%)
4	(16-QAM, ½, 50%)	(16-QAM, ⅔, 50%)

Mode Utilization

Modes	EPA (R1 / R2)%	OPA (R1 / R2)%
1	8.7 / 0.1	8 / 0.6
2	55.8 / 55	43 / 74
3	19 / 23.8	44 / 13.3
4	16.3 / 21	3.7 / 11.8

FlexAlg Ex #3: Adaptive STC in OFDM

Stingray is a Hiperman-compatible 2x2 MIMO-OFDM adaptive system.

The set of adjustable *Tx* parameters are:

1) The selected *Tx* antenna per sub-carrier, called: **Transmission Selection Diversity (TSD)**
2) The {outer code rate, QAM size} set

Selection Rules:

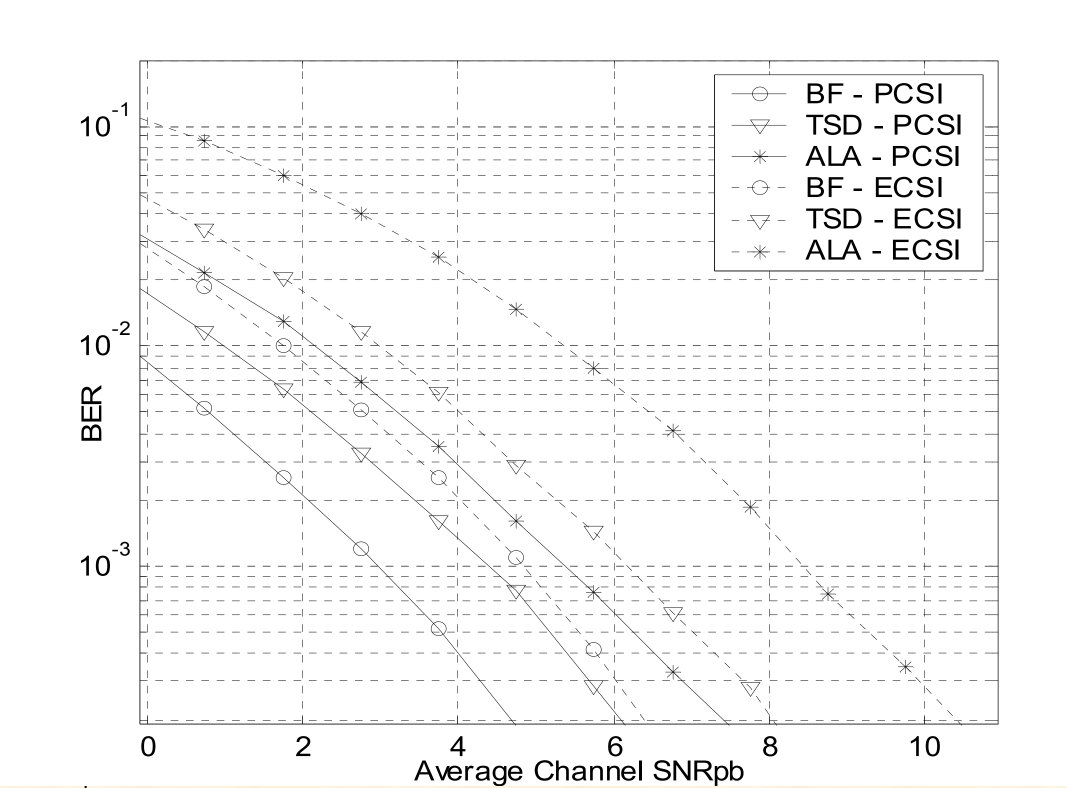
For TSD (1): For every carrier *k*, choose to transmit using the *Tx* antenna that gives the best performance when using Maximum Ratio Combining (MRC) at the Rx.

For the second set of parameters (2): Choose the set which maximizes the system throughput (bit rate), given a coded BER target.

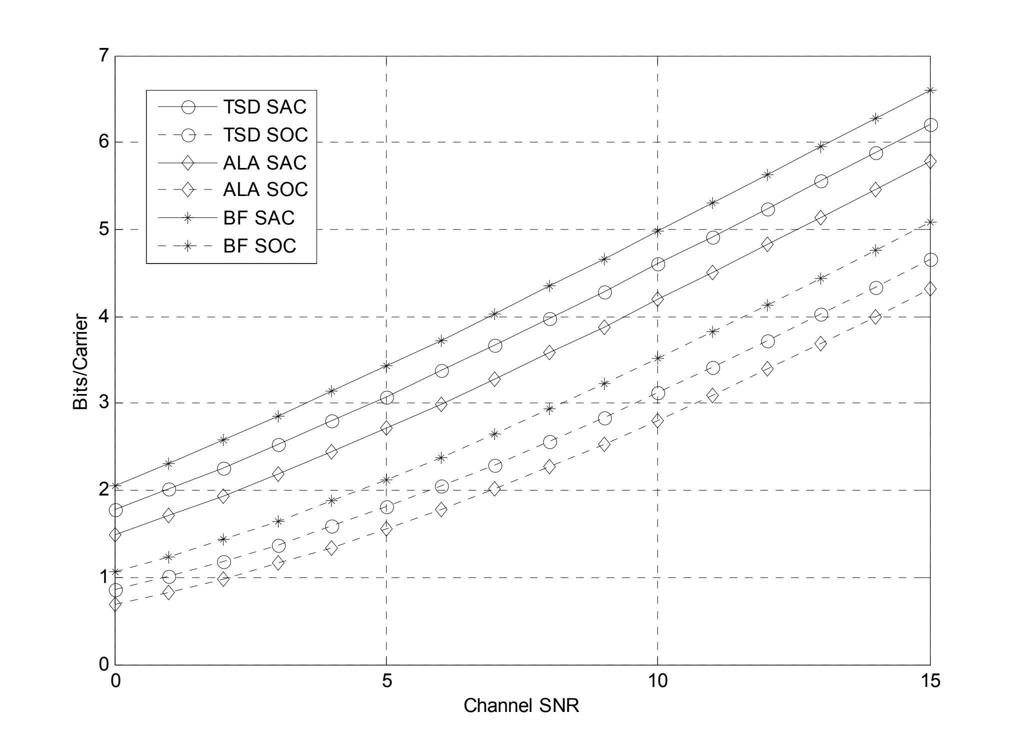
Adaptive-STC comparative performance

Performance Bounds of TSD:

Comparison with ***Beam-forming*** (optimal) and ***Alamouti*** (blind) STC techniques



STC's BER performance for perfect/estimated CSI (PCSI/ECSI) and 4QAM



System Average Capacity and System 1% Outage Capacity of different STC options

Algorithms for Phase Noise and Residual Frequency Offset Estimation

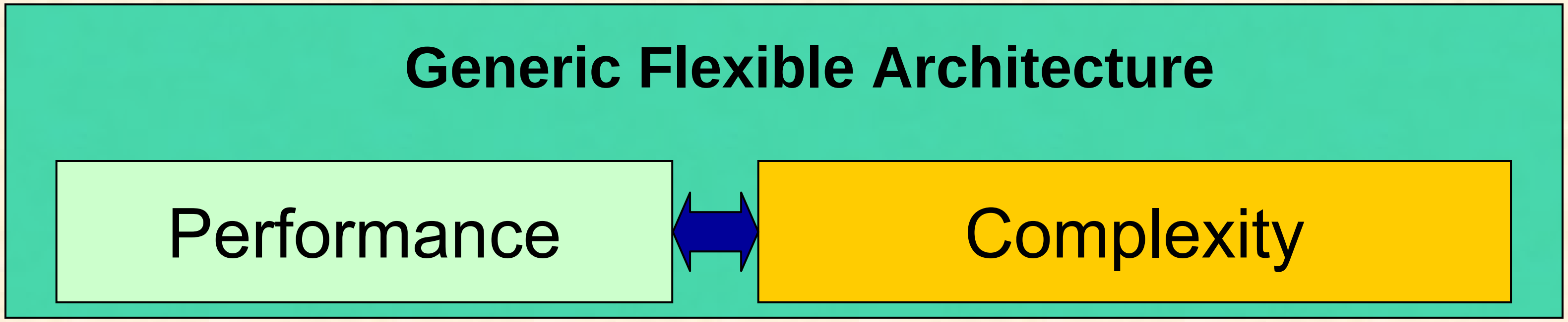
Flexible properties of the proposed schemes developed within Stingray and WF:

- ✓ Can be implemented either by the use of pilot symbols or by decision-directed methods.
- ✓ They are transparent to the selection of the Space-Time coding scheme
- ✓ They are easily adaptable to any number of *Tx*/ *Rx* antennas, down to the 1x1 (SISO) case
- ✓ Computation of the Variance of the Estimation Error (VEE)

  VEE affects drastically the performance of ST-OFDM schemes and is shown to be a function of:

  1. the number and the position of the sub-carriers used for estimation purposes
  2. the corresponding channel taps
  3. the pilot modulation method (when pilot assisted modulation methods are adopted).

Towards a flexible supervisor architecture



CWSCE and **TSD** methods are simple tools which provide acceptable performance under various system/channel environments.

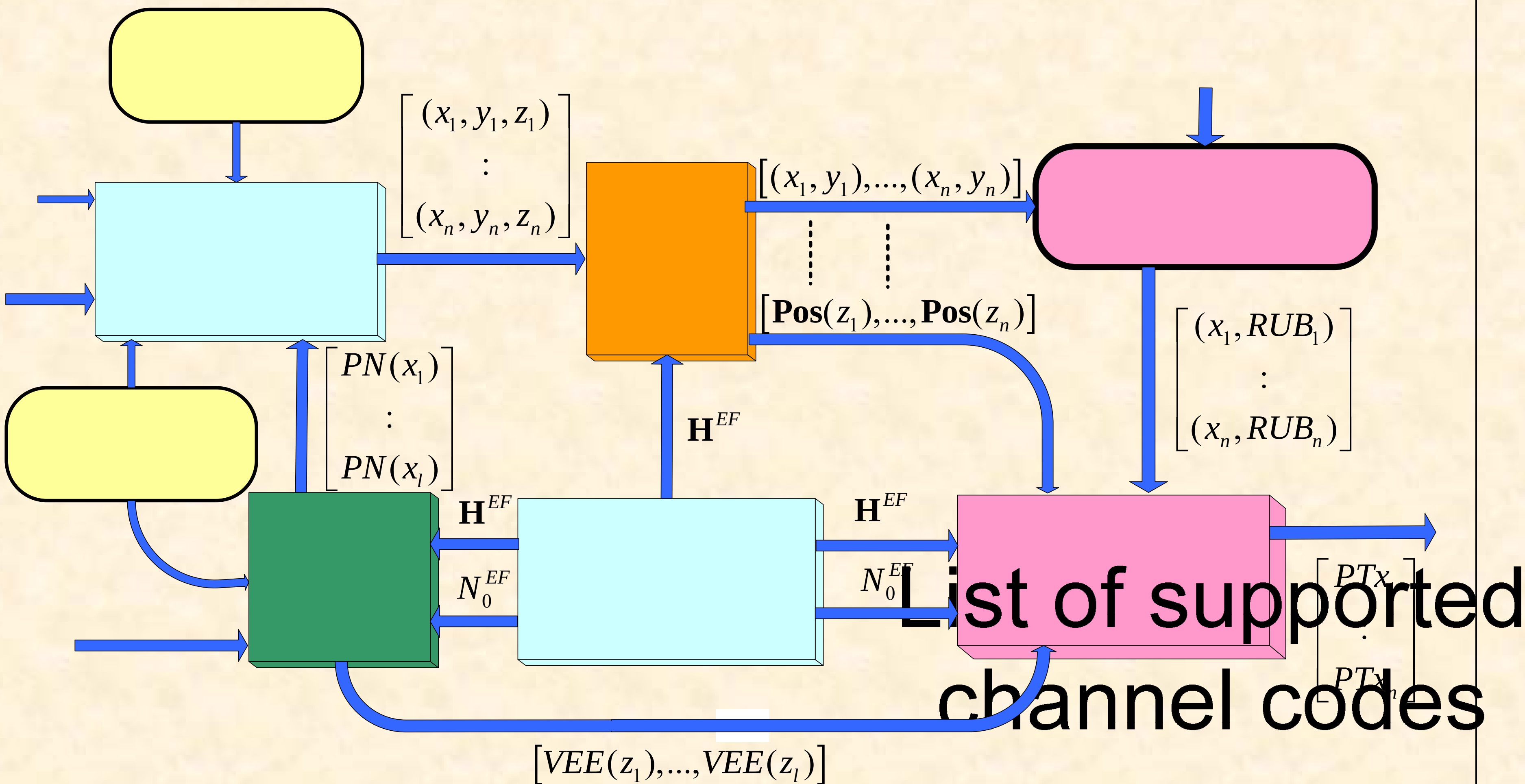
✓ The capacity penalty compared to the optimal solutions is shown to be small.

✓ Both require common feedback information (1 bit/carrier).

✓ Both can be incorporated appropriately in a system able to work under a variety of antenna configurations when feedback information is available.

✓ When SC feedback information is not available, CWSCE has the appropriate modules for mode selection (algorithm #1) for the SISO case, while Alamouti can be the choice for the MIMO case (still with alg. #1).

Sample of a flexible SPV architecture



$PN(x_i), i = 1, \ldots, l \rightarrow$ is the number of needed pilots in order to get a specific PHN/RFO performance, when the operation mode enables variable number of pilots.

$\hat{\mathbf{H}}^{EF} \rightarrow$ is the vector of the estimated effective channel gains at the frequency domain (STC related).

WSCE

Conclusions

- **Science of FR architecture and design evolving, art of FR already advanced in some topics; a very inter-disciplinary field in need of "intellectual" discipline.**
- **Limited perspective presented here (PHY/device); extensions to other layers important ("reconfigurable" networks).**
- **Subject harmonizes well with the R&D trends suggested by the EC: multi-modality, reconfigurability to enable service creation and interoperability.**