System Aspects of Smart Antennas Technology

Helsinki University of Technology

Communications Laboratory

Content

1. **Introduction**
2. **Main components of wireless network influenced by SA tech.**
3. **Radio Interface**

   Receiver Structure and Algorithms
   Air interface compatibility with SA
   Integration SA receiver into cell environments

4. **Network Planning**

   HSR, SFIR, SDMA , SFIR-SDMA concepts
   CDMA network planning with SA, 3-G /UTRA with SA
   Network upgrade with SA
   Network simulation with SA

5. **Network Control with SA**

   Layer 1, 2 ,3
   Handover, Initial access, Resource management with SA, packet transmission with SA

6. **Conclusion: research problems**
7. **Existing SA commercial and test systems their performance**

"Spatial Processing remains as the most promising, if not the last frontier, in the evolution of multiple access systems"

Andrew Viterbi

Existing SA commercial products and experimental systems

- MetaWave (Switched-Beam SA)

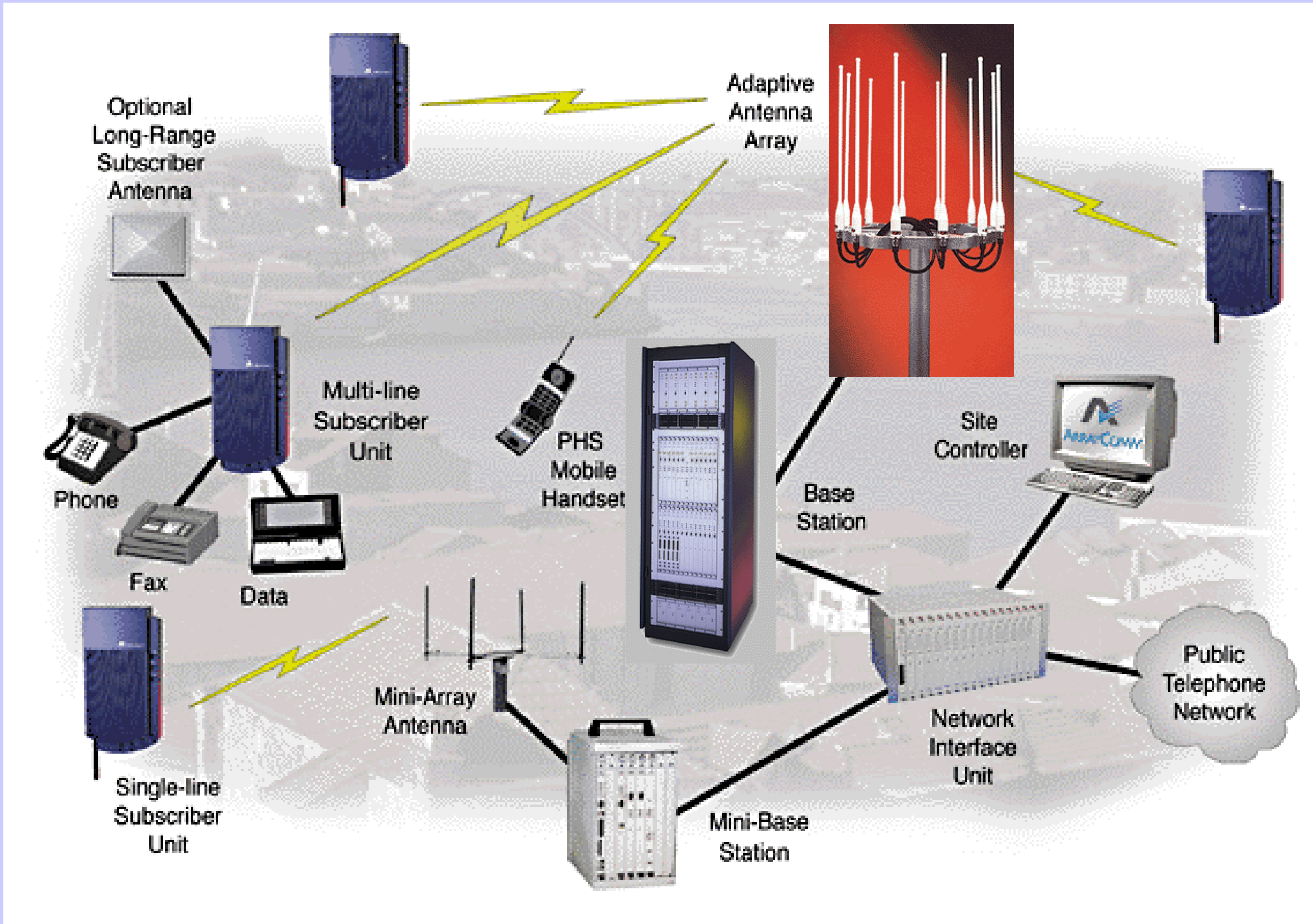
- ArrayComm (PHS,WLL,)
- Raytheon (SW based)

- Ericsson (System Level Testbed- GSM/DCS)
- DoCoMo (Testbed with 3 BS - W-CDMA)

- TSUNAMI - SUNBEAM

- Lucent ...

1. IntelliWave Wireless Local Loop System



1. Main Advantages of Smart Antennas Technology

- CCI cancellation at the up and down links -> capacity

- SNR improvement due to antenna gain -> coverage

- Effects of multi-path mitigation -> high QoS, bit rate

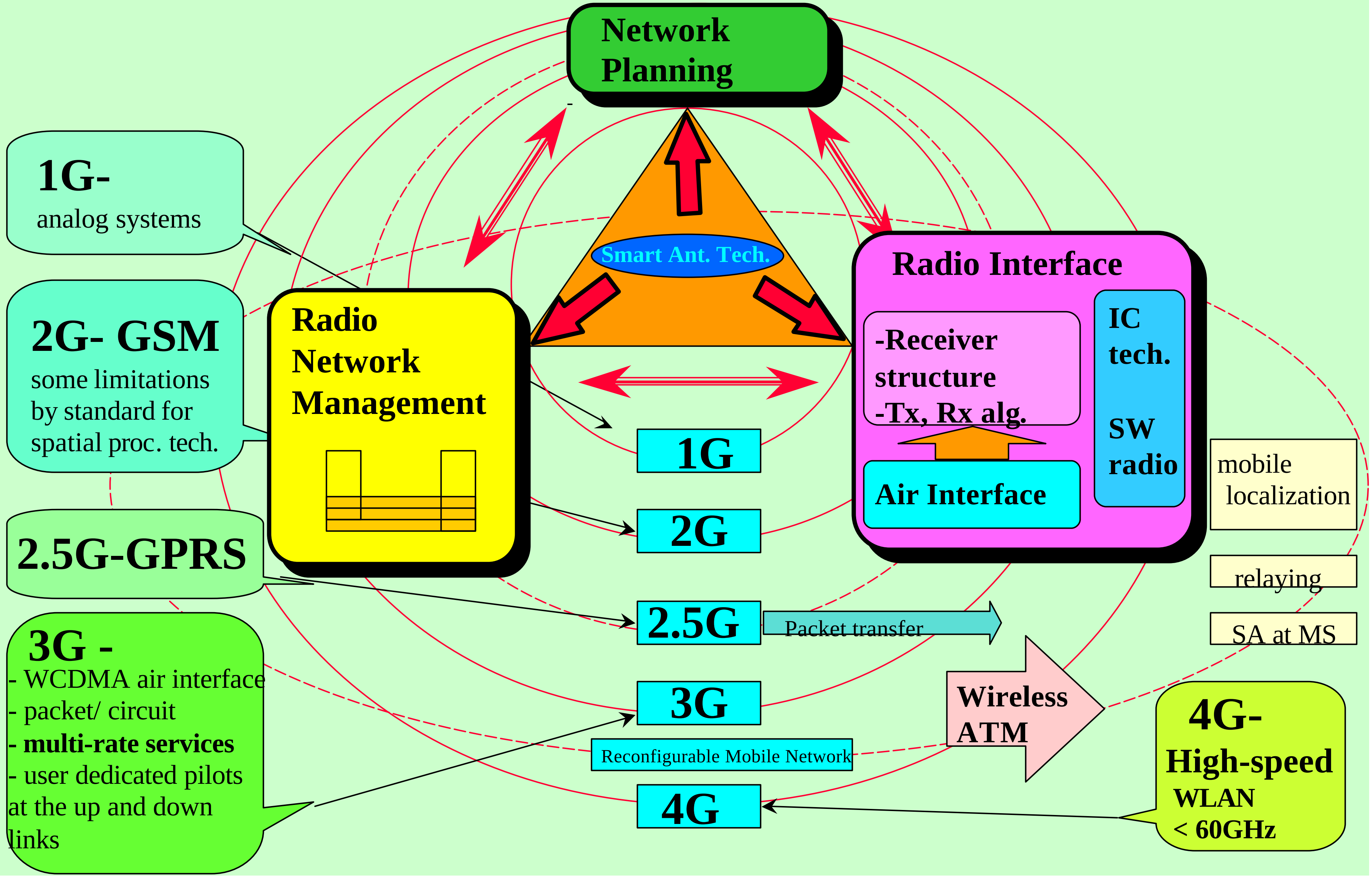
1. Main Advantages of Smart Antennas Technology for:

Operator -> Network capacity, coverage, filling "dead spots", less amount of BS, QoS, new services..

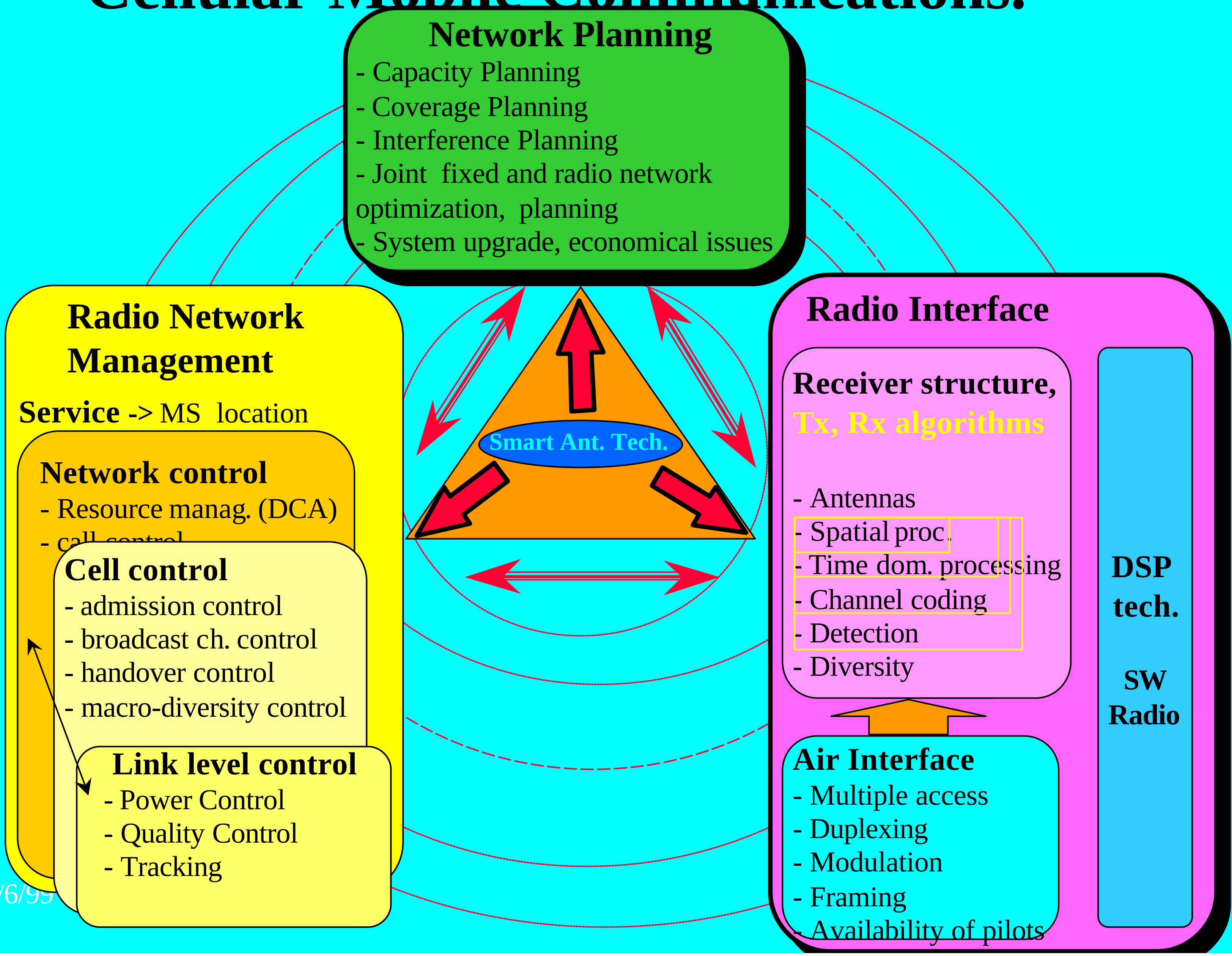
OEM -> New more advanced BSS equipment, more flexible radio network control...

User -> Higher QoS, more reliable, secure communication, longer battery life...

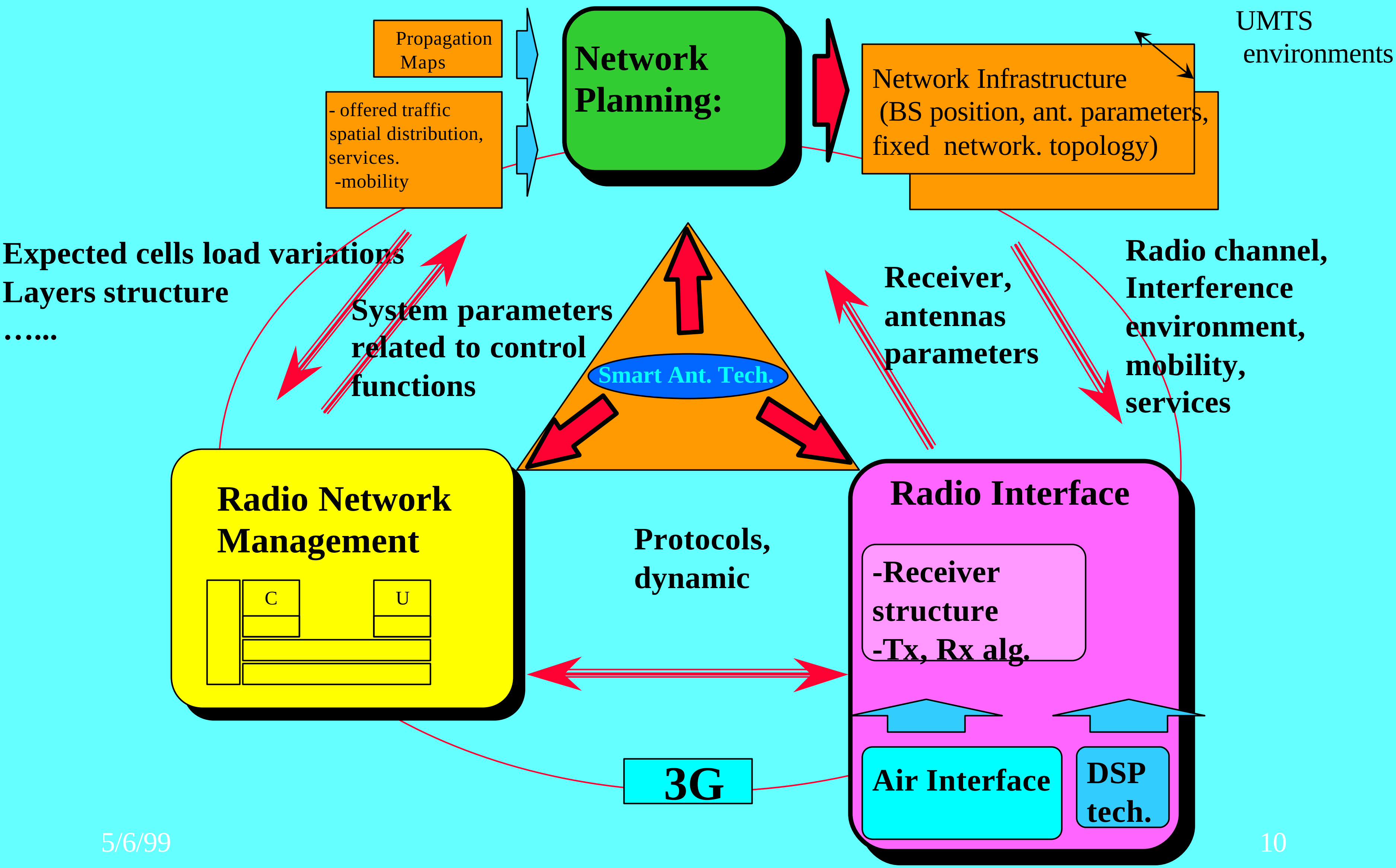
2. Impact of Spatial Processing Technology on Cellular Mobile Communications.



2. Impact of Spatial Processing Technology on Cellular Mobile Communications.

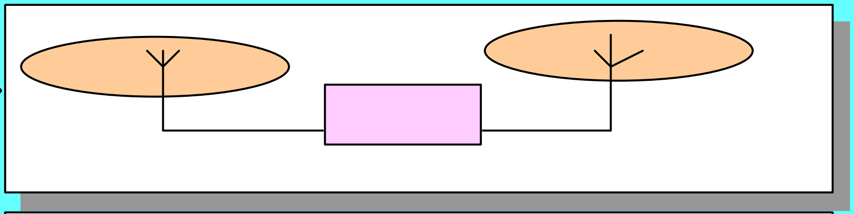


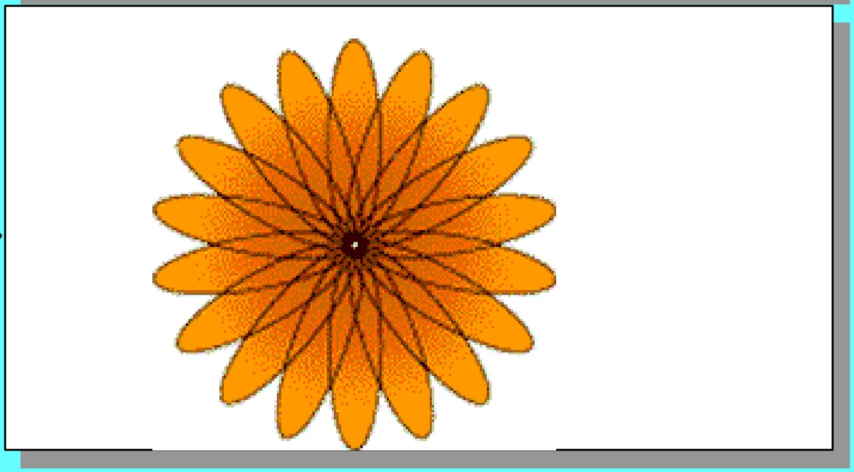
2. System Aspects of Spatial Processing Technology Mobile Communications. Main Interactions.

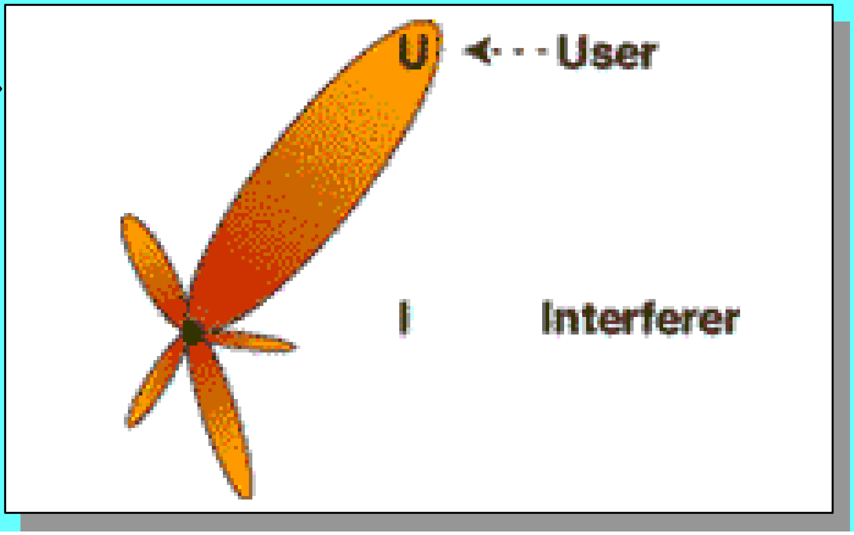


3. Spatial processing techniques

- Macro-diversity
(omni and directional ant.)
- Sectorisation
- Switched-beam system
- Phased arrays,
Adaptive Antennas
- Joint Space - Time,
MU ST processing,
Rec.- Trx .
- **Spatial-temp coding**
- **Multiple antennas at MS and BS**







3.Types of Smart Antenna Receivers

- Switched beam, adaptive algorithms..

- Side reference information available (Spat Ref. , Ref. Signal, signal structure and their combinations) for spatial processing

- Narrowband , broaband (CDMA)

- Optimization method (if any) (max ML, min MSE, MV, MAP)

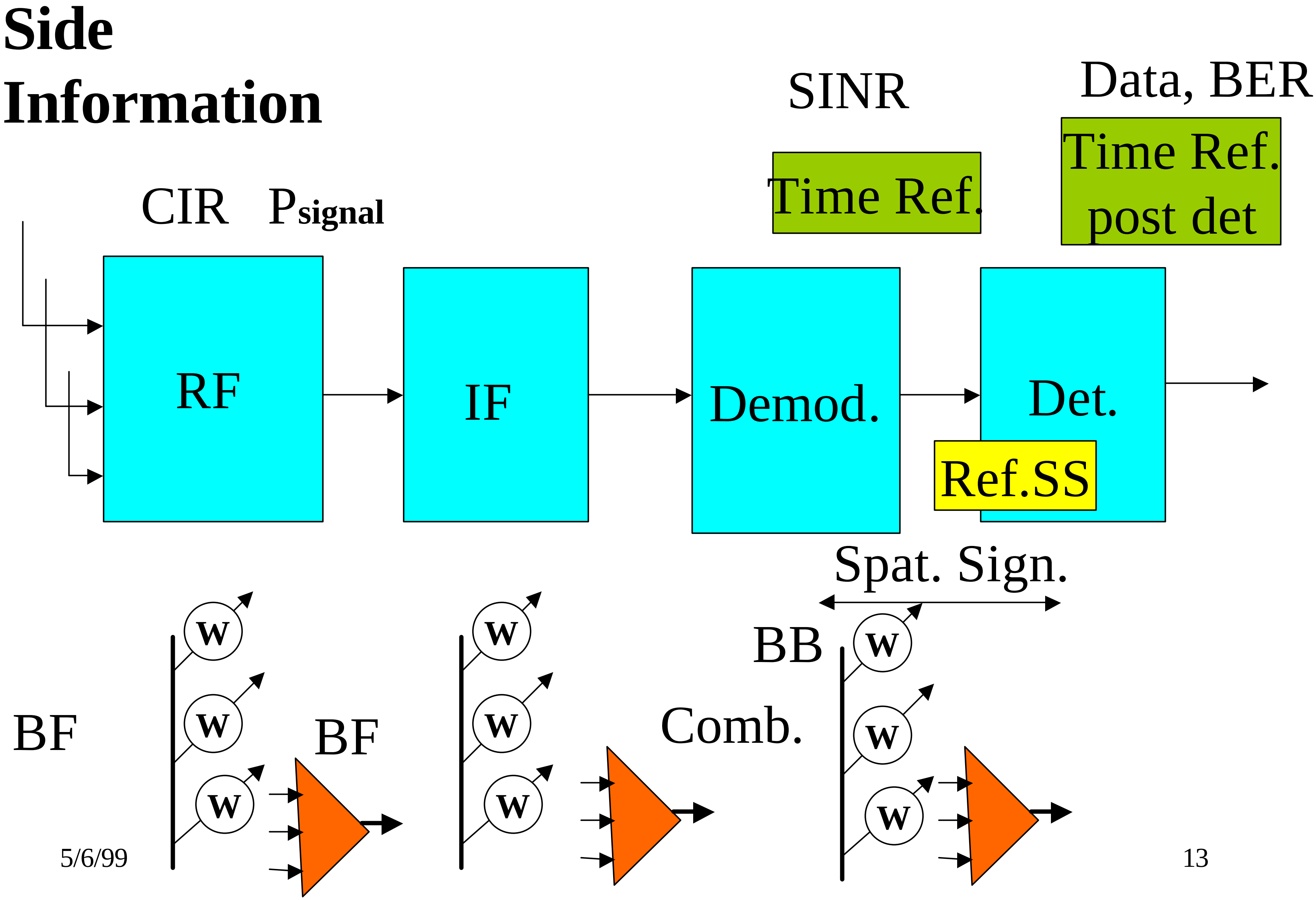
- Processing domain -> Space, Space-Time, …

- Amount and type of channel knowledge available

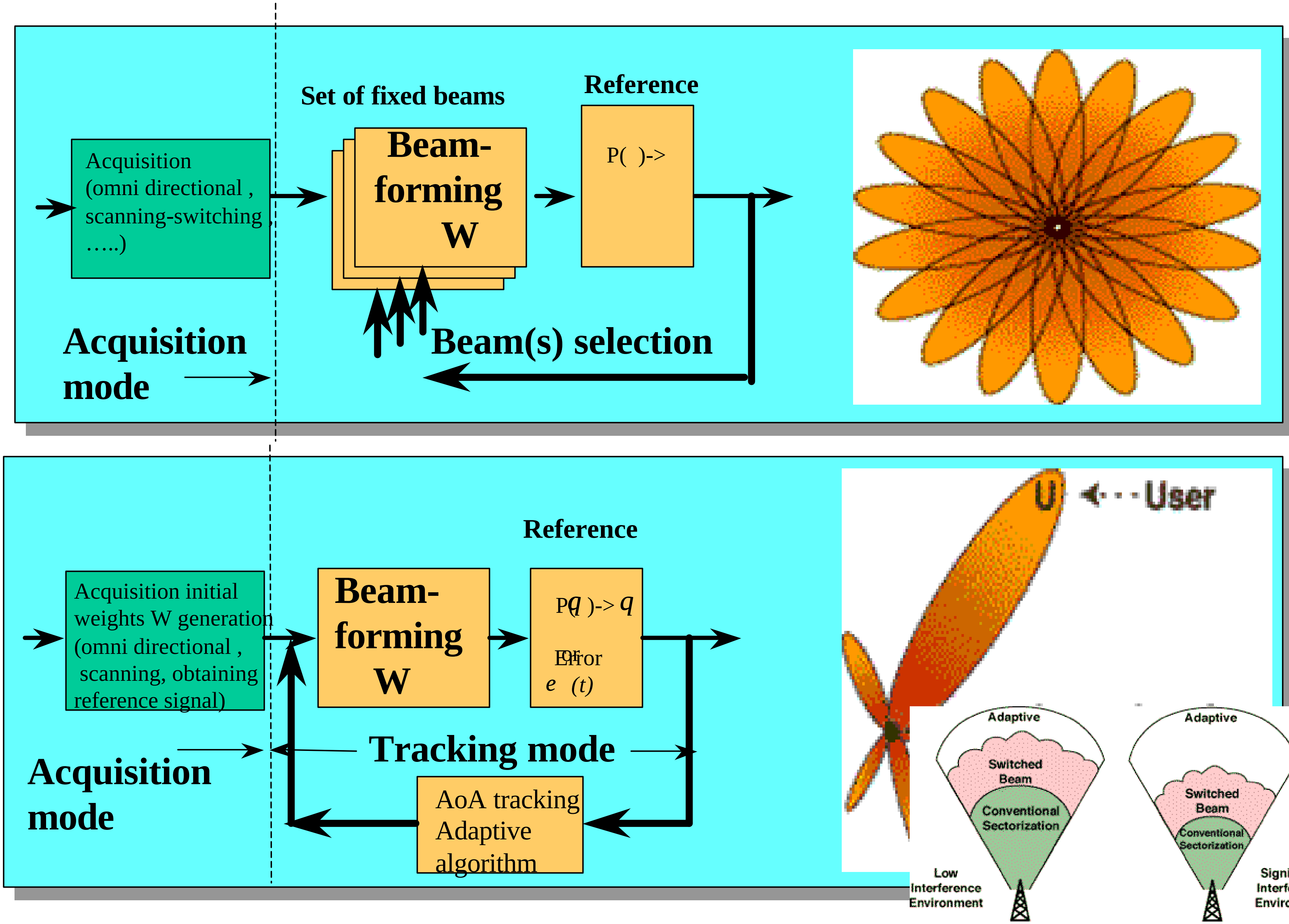
- Combination of space/space-time processing with other technologies (diversity, interference cancellation, channel coding, space-time coding …)

- SA at the MS

SA receivers structures



Switched-beam and adaptive antenna



3. References for beamforming or/and optimum combining

- Spatial Reference based BF,
Direction of arrival BF

- Reference signal based/
time reference BF and/or optimum combining

- Signal Structure (temporal /spectral)
based BF/ property restored BF

Optimal

3. Direction of Arrival Based Beamformers

- require angle of arrival (AOA) estimation

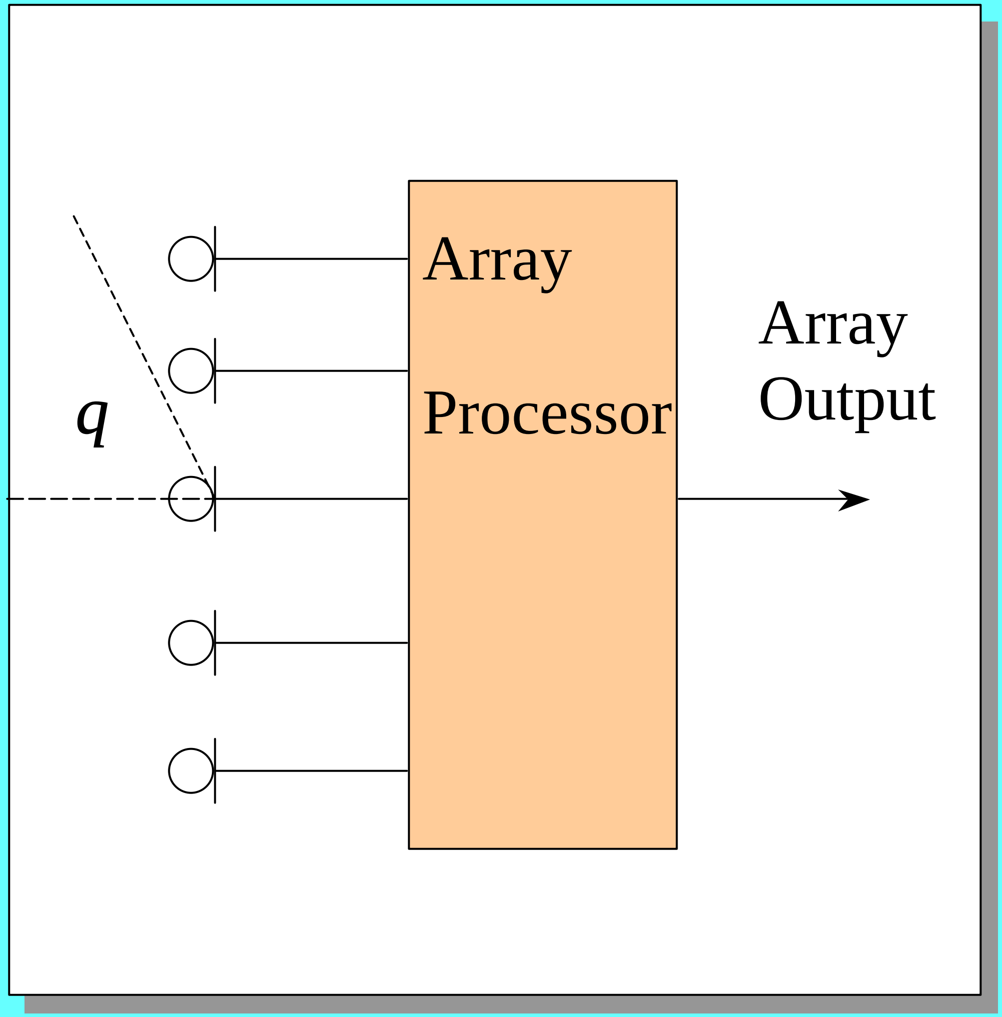
- estimates output power at the output
or eigen-decomposition of correlation matrix

- sensitive to AoA estimation errors,
calibration problem

- problem with coherent multipath

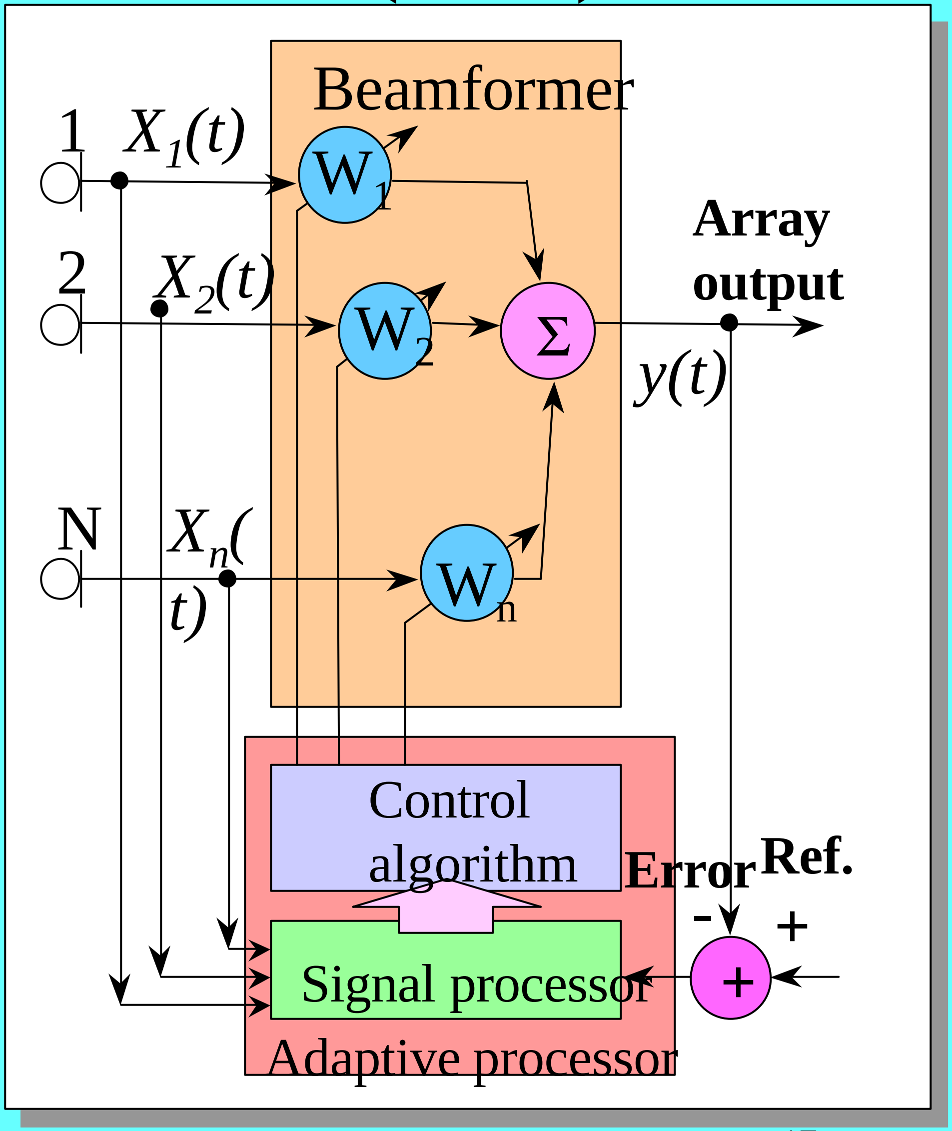
- As/A should be low

- FDD applications



3. Reference Signal (Time) Based Beamformers or/and optimal combiner (TRB)

- requires reference signal or the replica correlated with desired signal
- based on Wiener solution (MSE)
- reference signal multiplexed with des. signal or reconstructed signal obtained from detected symbols (det. and BF dep. attractive for tracking)
- better for varying radio channel
- diversity
- more processing extensive methods
- receiver is simpler at expense of spectral efficiency
- synchronization problem
- Ds/T should be low
- TDD applications



3. Signal Structure Based Beamforming

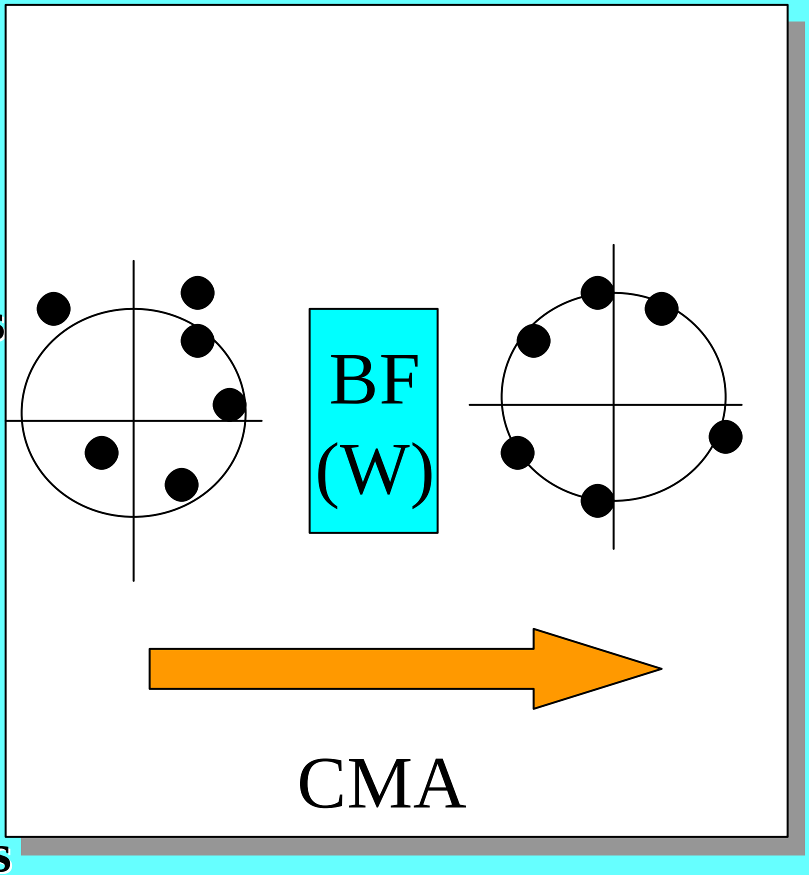
- Do not require reference signal - more spectral efficient

- useful method tracking between references

- convergence properties ?

- methods based on partial information are usually non-linear

- performance from robustness point of vie are similar to reference signal based methods



Beamforming Methods

Data independent beamforming (CBF,..)

↓ (GSLC,…)

Optimum BF

- Based on cost function maximization/minimization (max SINR,…)

- Based on Statistical Estimation
ML (Likelihood function)
MSE (Reference)

- Adaptive algorithms (LS…., MAP,…)

3. Achievable Improvements with SA

- Improvement in signal to noise ratio due to beamforming array gain. Improve coverage.

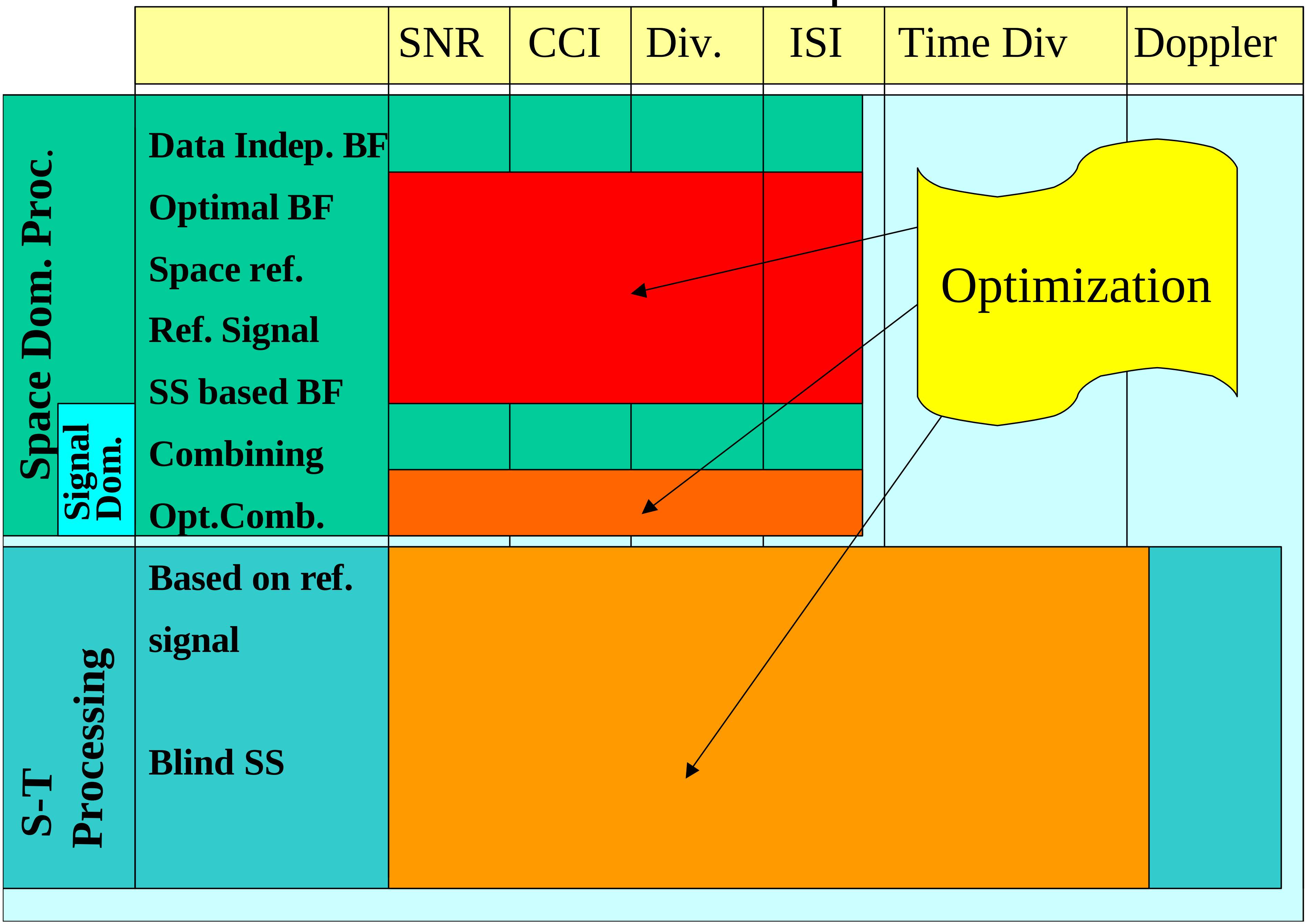
- Mitigation of multipath effects. Reduce ISI.

- Enhance spatial diversity.

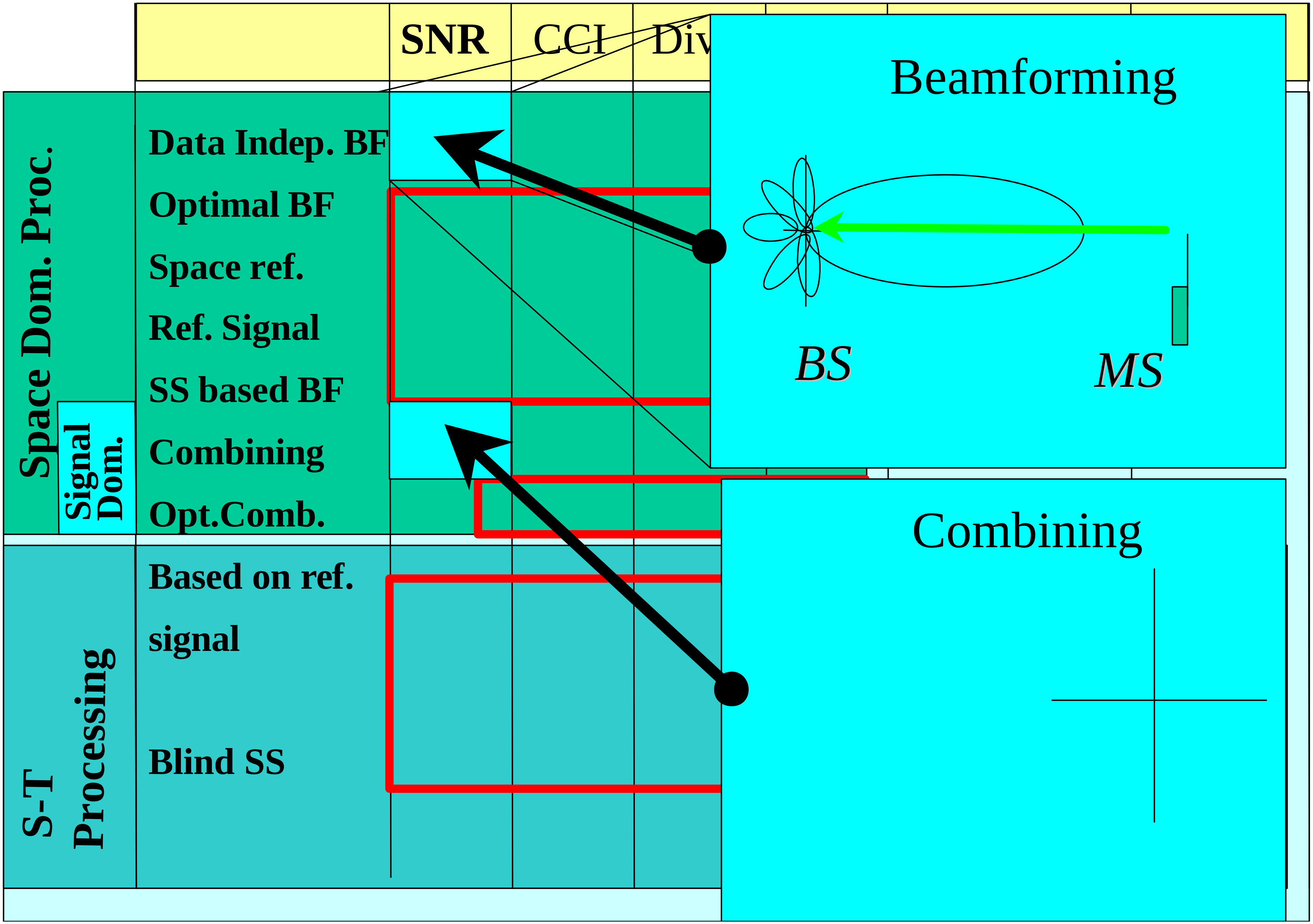
- Interference Cancellation. In Tx and Rx. Capacity.

These goals may be conflicting. Need blancing to achieve synergy with propagation enviroment, offered traffic, infrastructure.

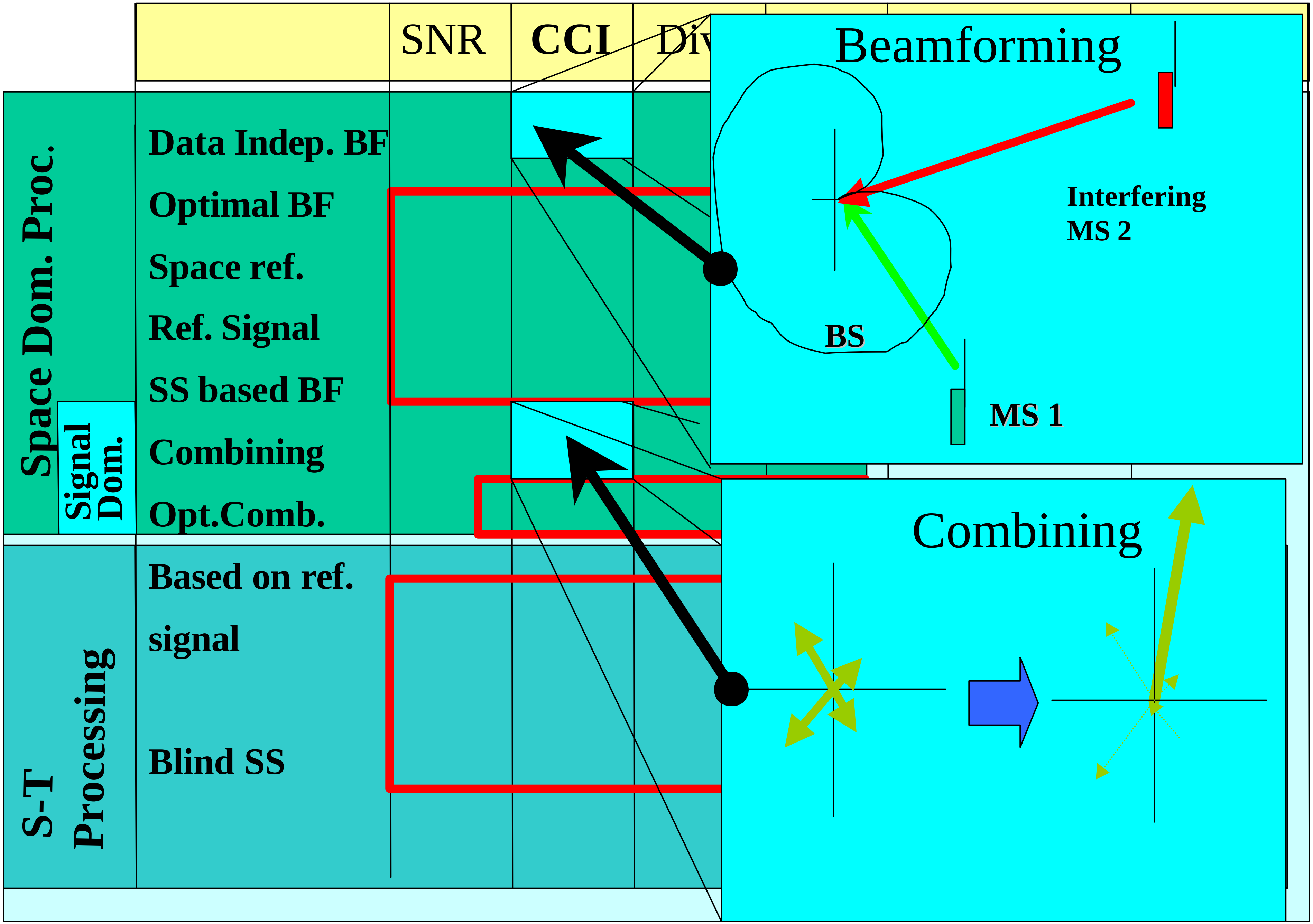
Trade-offs between achievable improvements with SA



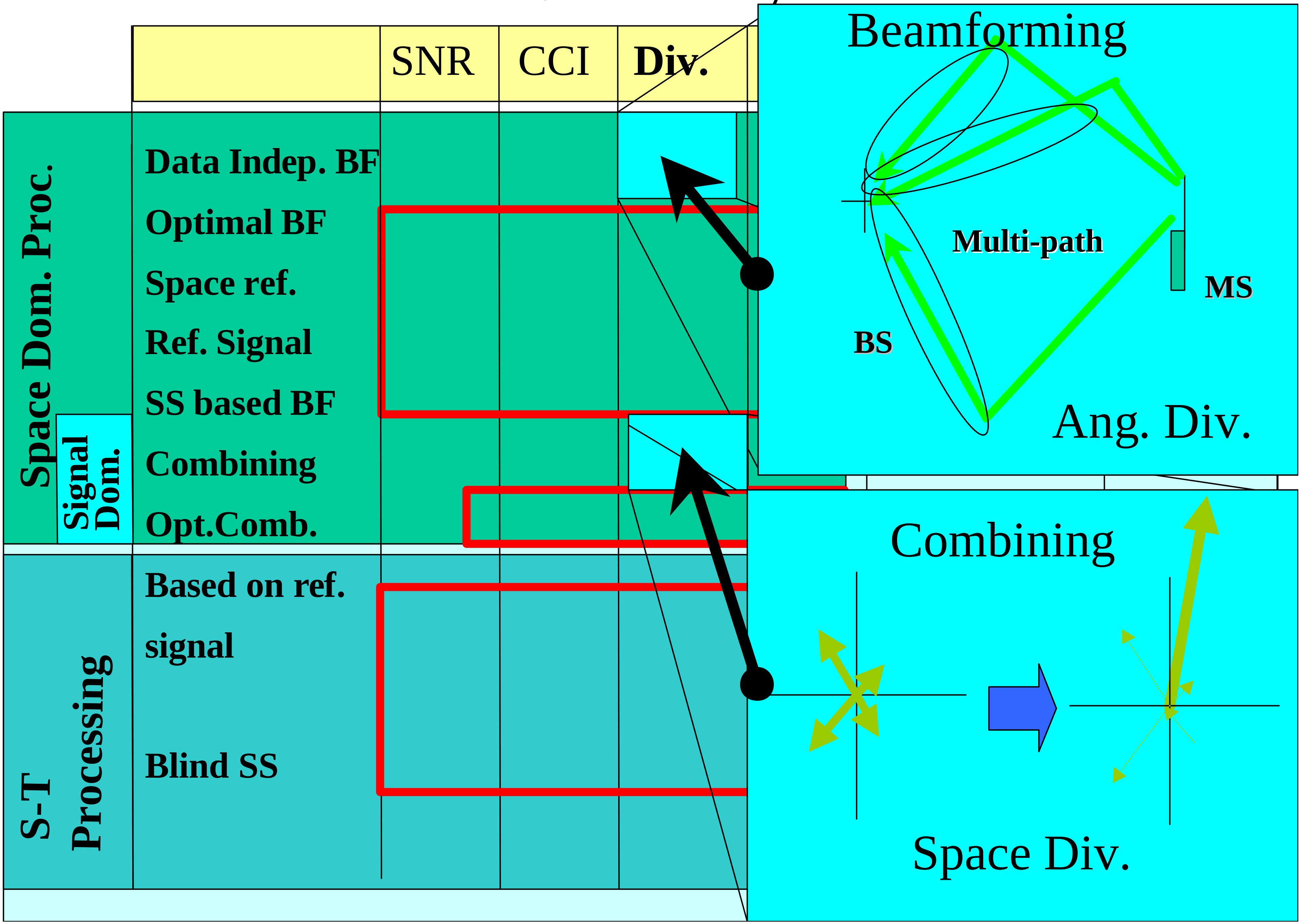
Max. SNR


SNR
CCI
Div
Space Dom. Proc.
Signal Dom.
S-T Processing
Data Indep. BF
Optimal BF
Space ref.
Ref. Signal
SS based BF
Combining
Opt.Comb.
Based on ref.
signal
Blind SS
Beamforming
BS
MS
Combining

3. CCI cancellation

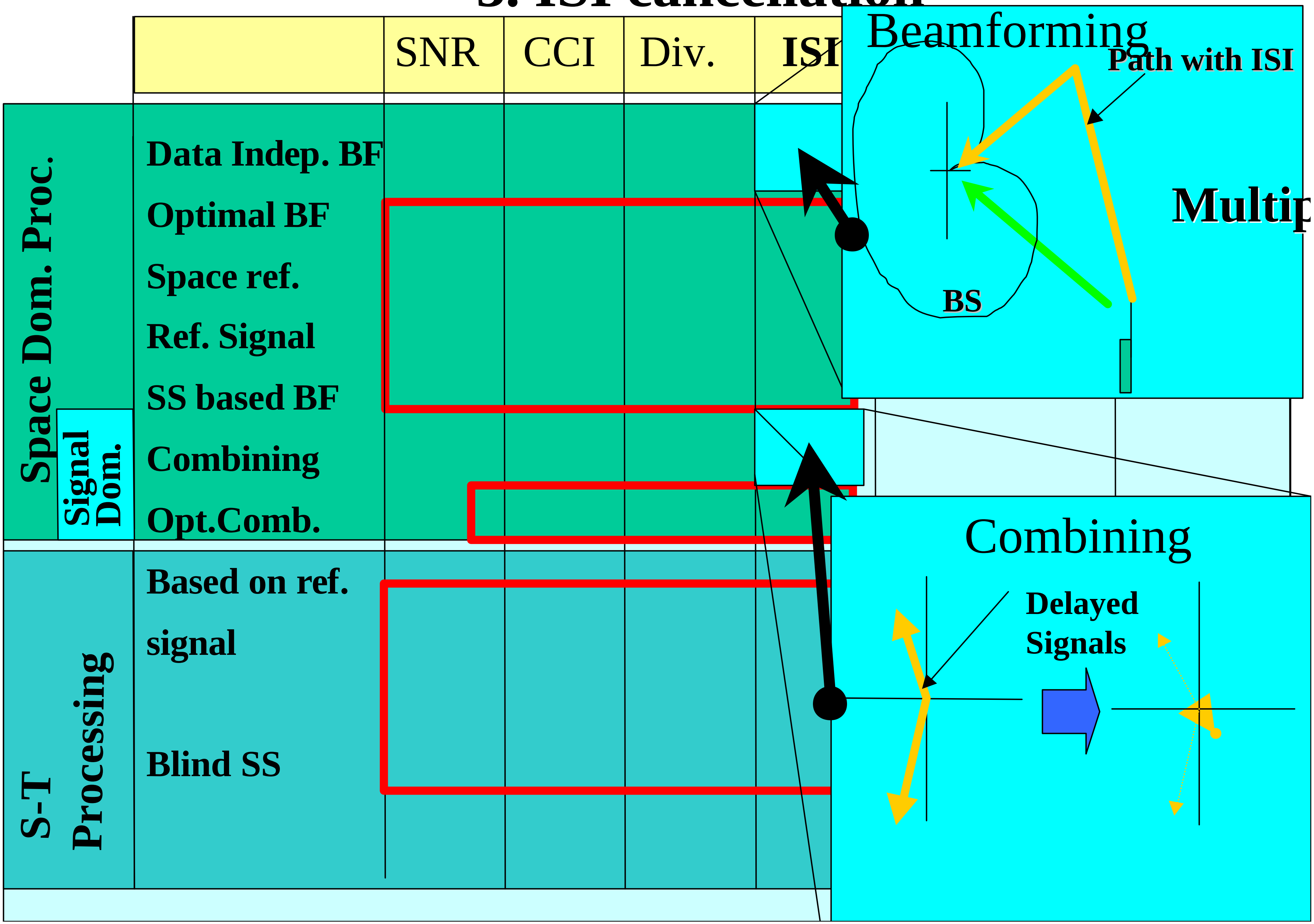


3. Diversity



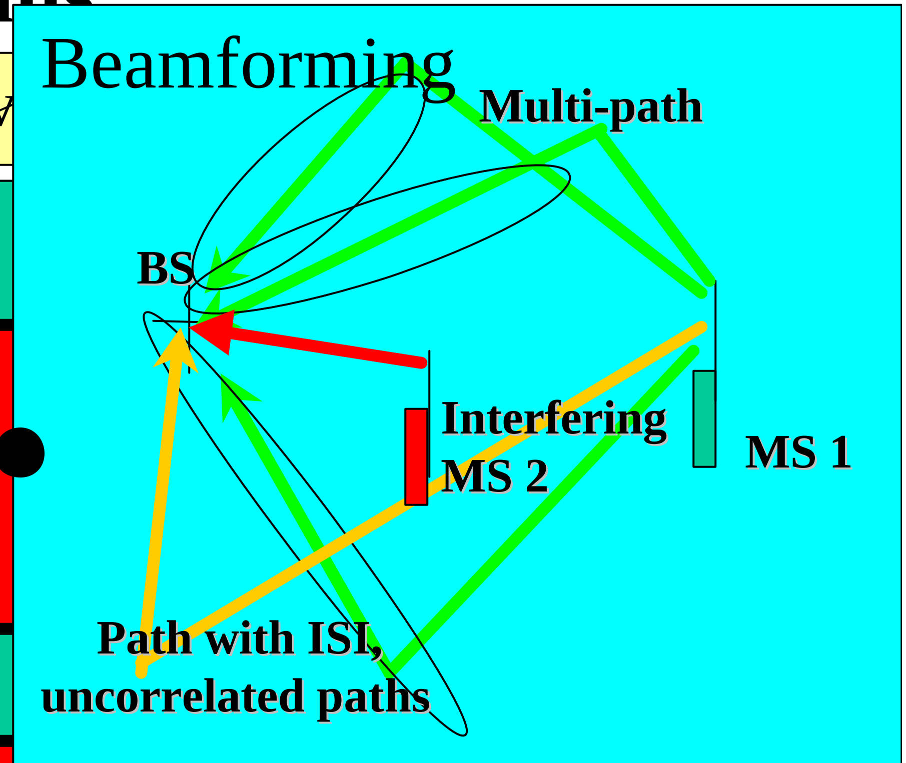
SNR
CCI
Div.
Space Dom. Proc.
Signal Dom.
Data Indep. BF
Optimal BF
Space ref.
Ref. Signal
SS based BF
Combining
Opt.Comb.
S-T Processing
Based on ref.
signal
Blind SS
Beamforming
Multi-path
BS
MS
Ang. Div.
Combining
Space Div.

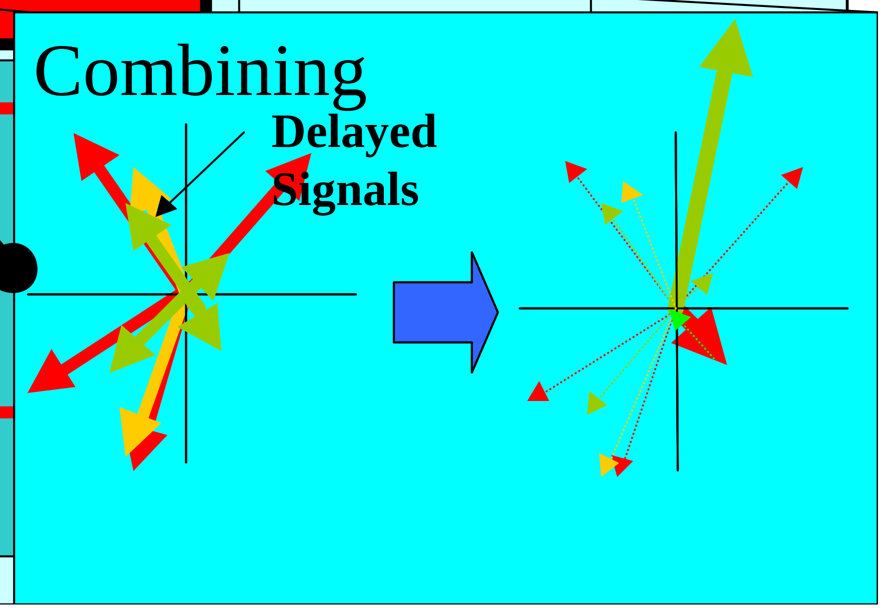
3. ISI cancellation

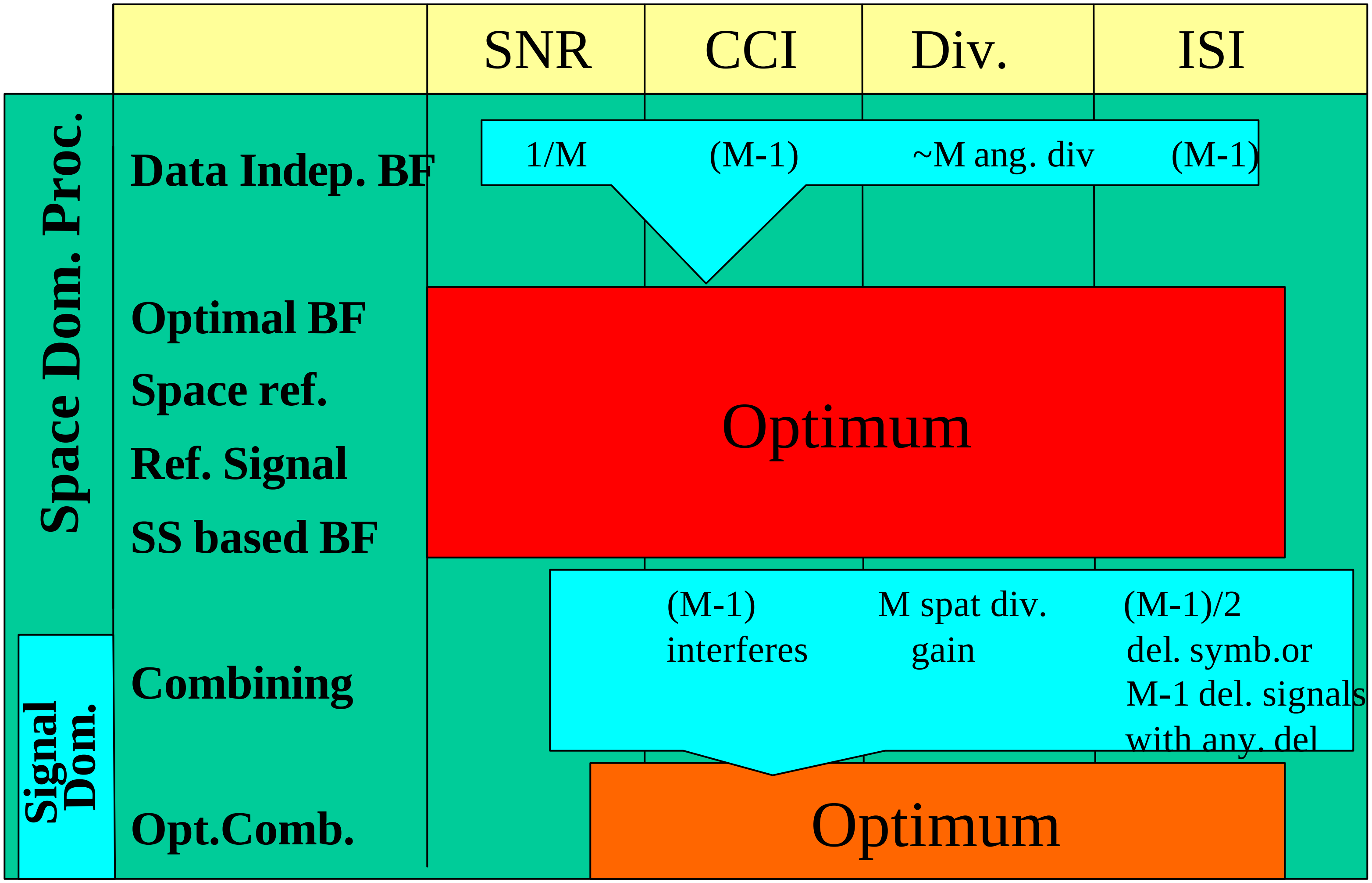


3. Optimal Algorithms

		SNR	CCI	Div
Space Dom. Proc.	Data Indep. BF			
	Optimal BF			
	Space ref.			
	Ref. Signal			
	SS based BF			
Signal Dom.	Combining			
	Opt.Comb.			
S-T Processing	Based on ref. signal			
	Blind SS			





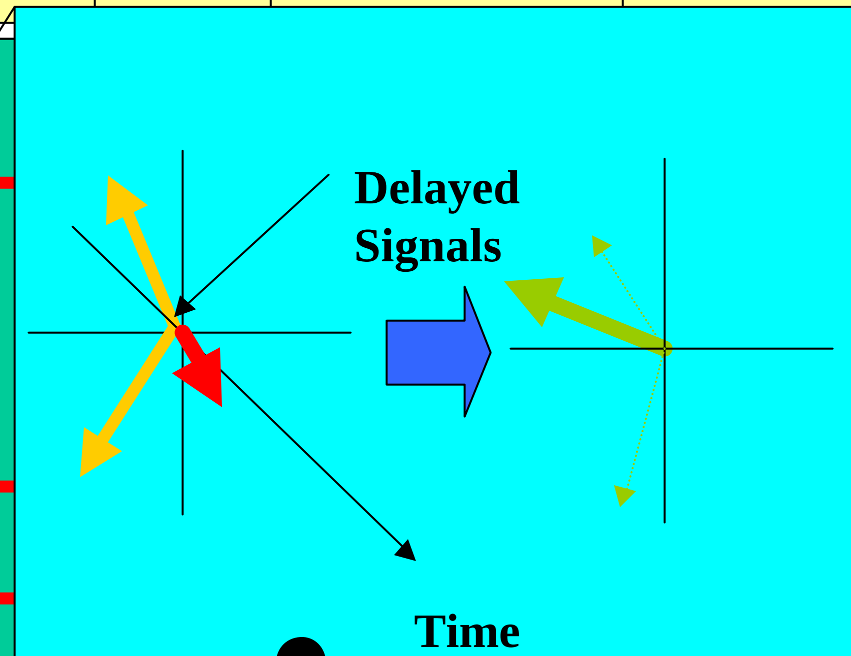


- amount of SA elements (M) can be considered as resource

- M define also "spatial selectivity" of SA

3. Optimal S-T Algorithms

		SNR	CCI	Div.	ISI	Time Div	Doppler
Space Dom. Proc.	Data Indep. BF						
	Optimal BF						
	Space ref.						
	Ref. Signal						
	SS based BF						
Signal Dom.	Combining						
	Opt.Comb.						
S-T Processing	Based on ref. signal						
	Blind SS						



3. S-T Processing

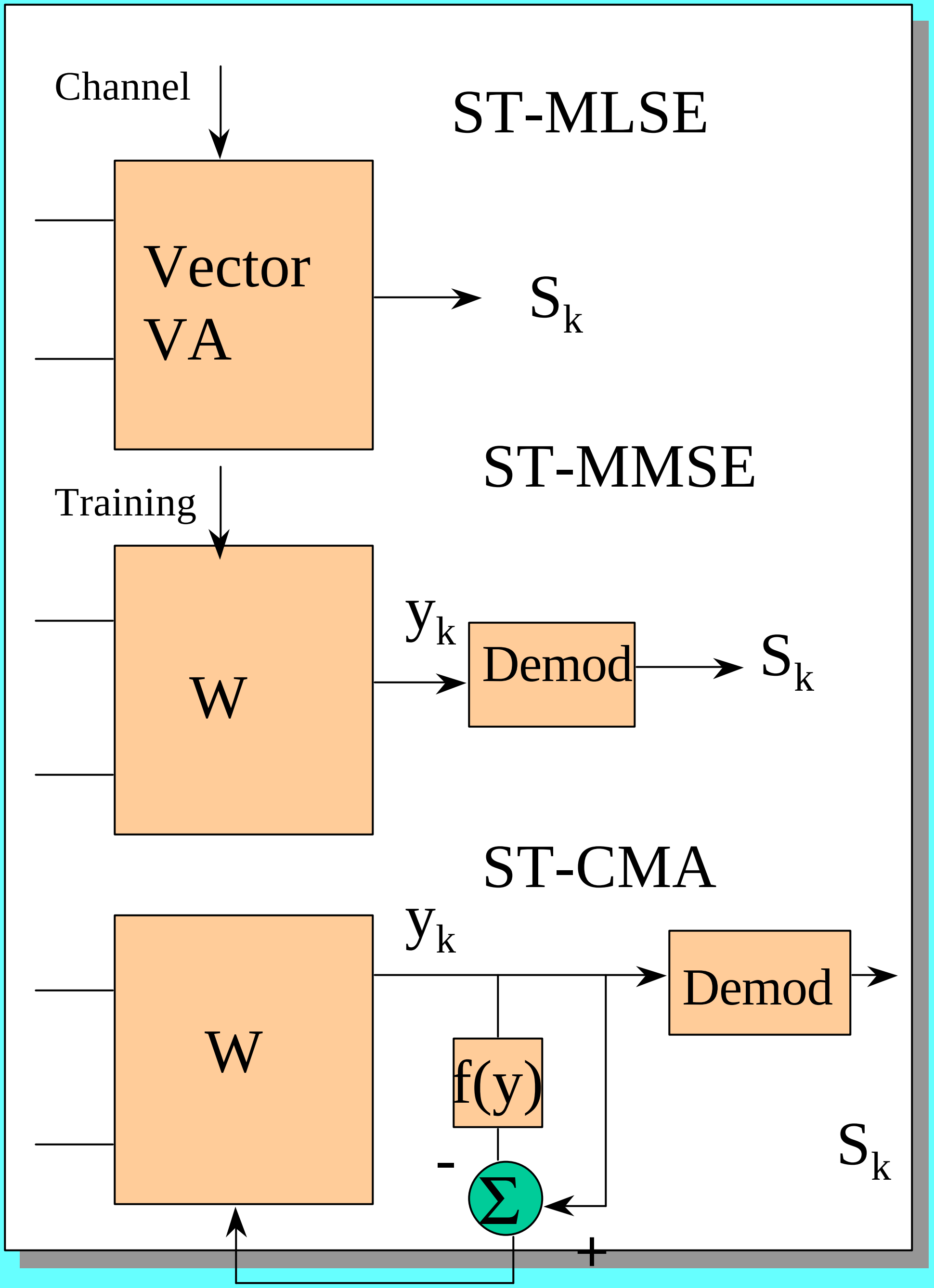
- Space Processing:
- Efficient CCI mitigation
- Space Diversity
- ISI mitigation depends on As of multipath and amount of SA elements and cannot be very efficient

- Time Only Processing
Very limited against CCI
Time diversity, ISI mitigation

- ST Processing
- Simultaneous operations in Time and Space
- ST-ML and ST-MMSE
Joint ST- Channel and Data Estimation (ST- JCDE)
- SS blind methods..

- MU-ST Processing

- Joint Rec. Tr. ST-Processing



Optimization Criteria

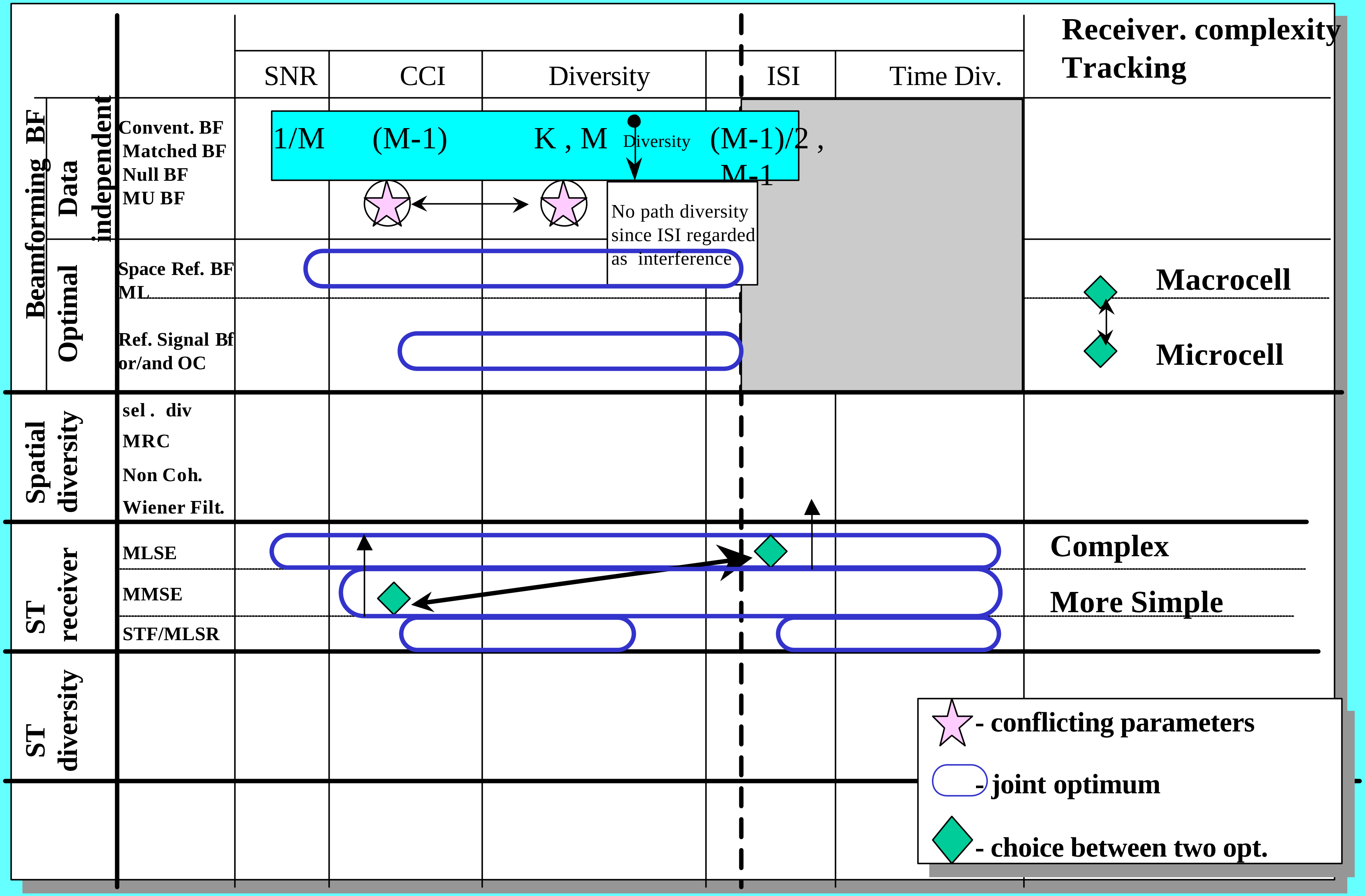
- Based on cost function maximization/minimization (max SINR,…)-> difficult to obtain

- Based on Statistical Estimation

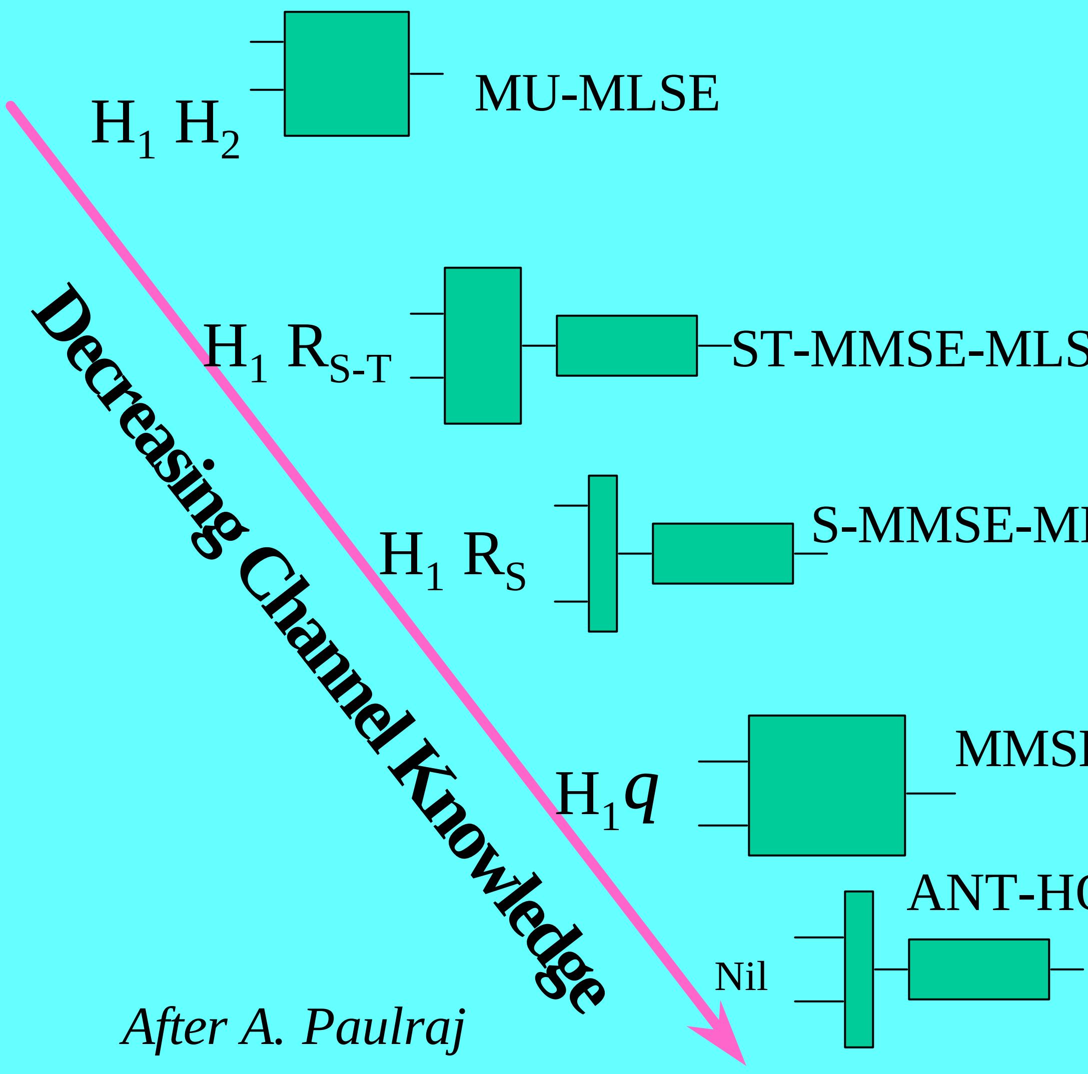
ML (Likelihood function)-> treats interference as temporally and spatially white. Balanced effect of noise

MSE (Reference)-> more attractive in presence correlated CCI.
-> More efficient in interference dominant environment. Do not balance effect of noise

3. SA Receiver integration into cell environment



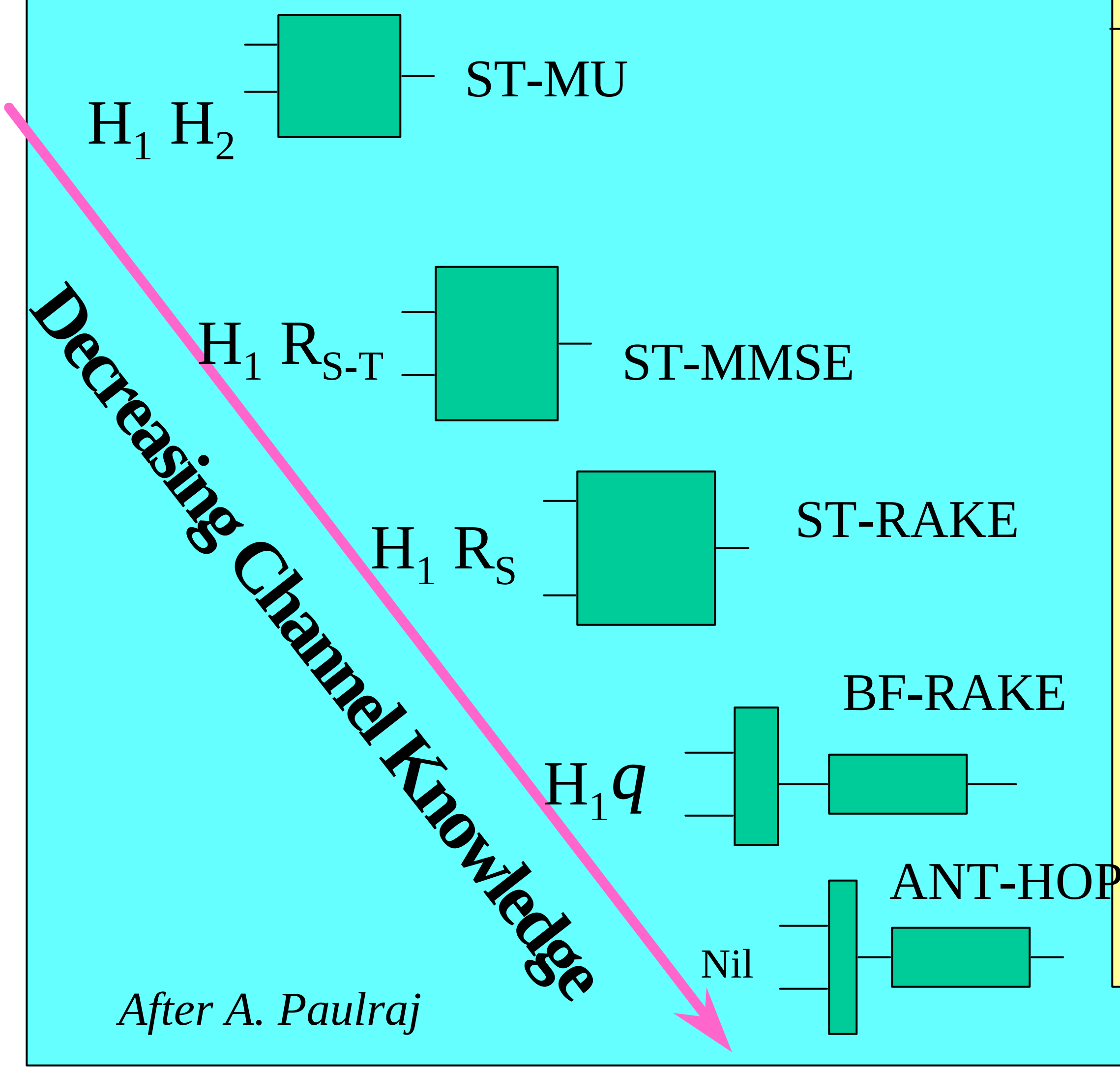
3.TDMA Rx Structures (Ch. Knowledge <-> Optimality)



	S-DIV	CCI	ISI	T-DIV
MU-MLSE	X	X	X	X
ST-MMSE-MLSE	X	X	X	X
S-MMSE-MLSE	X	X	X	X
MMSE	X	X	X	X
ANT-HOP	X			

After A. Paulraj

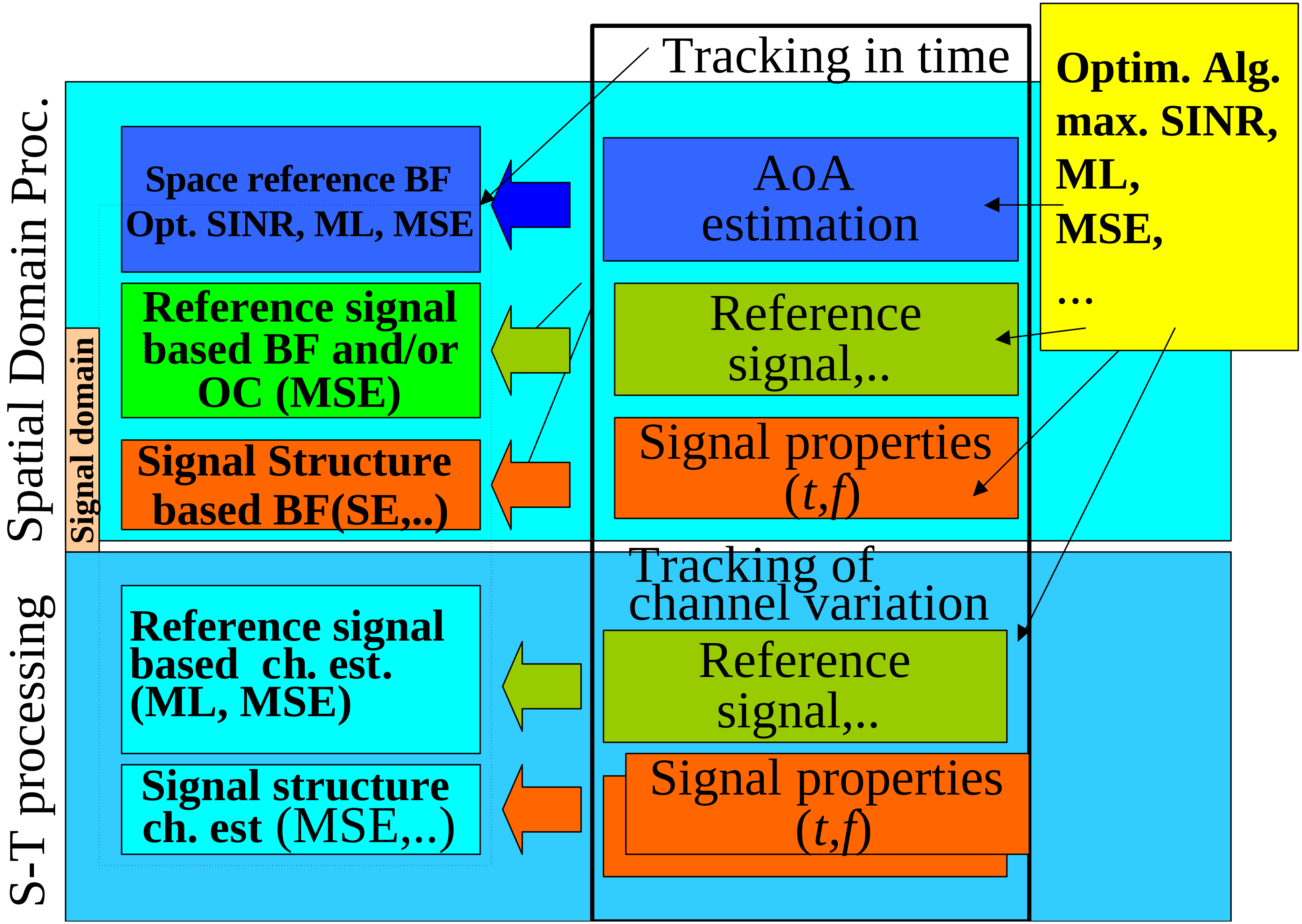
3. CDMA Rx Structures (Ch. Knowledge <-> Optimality)



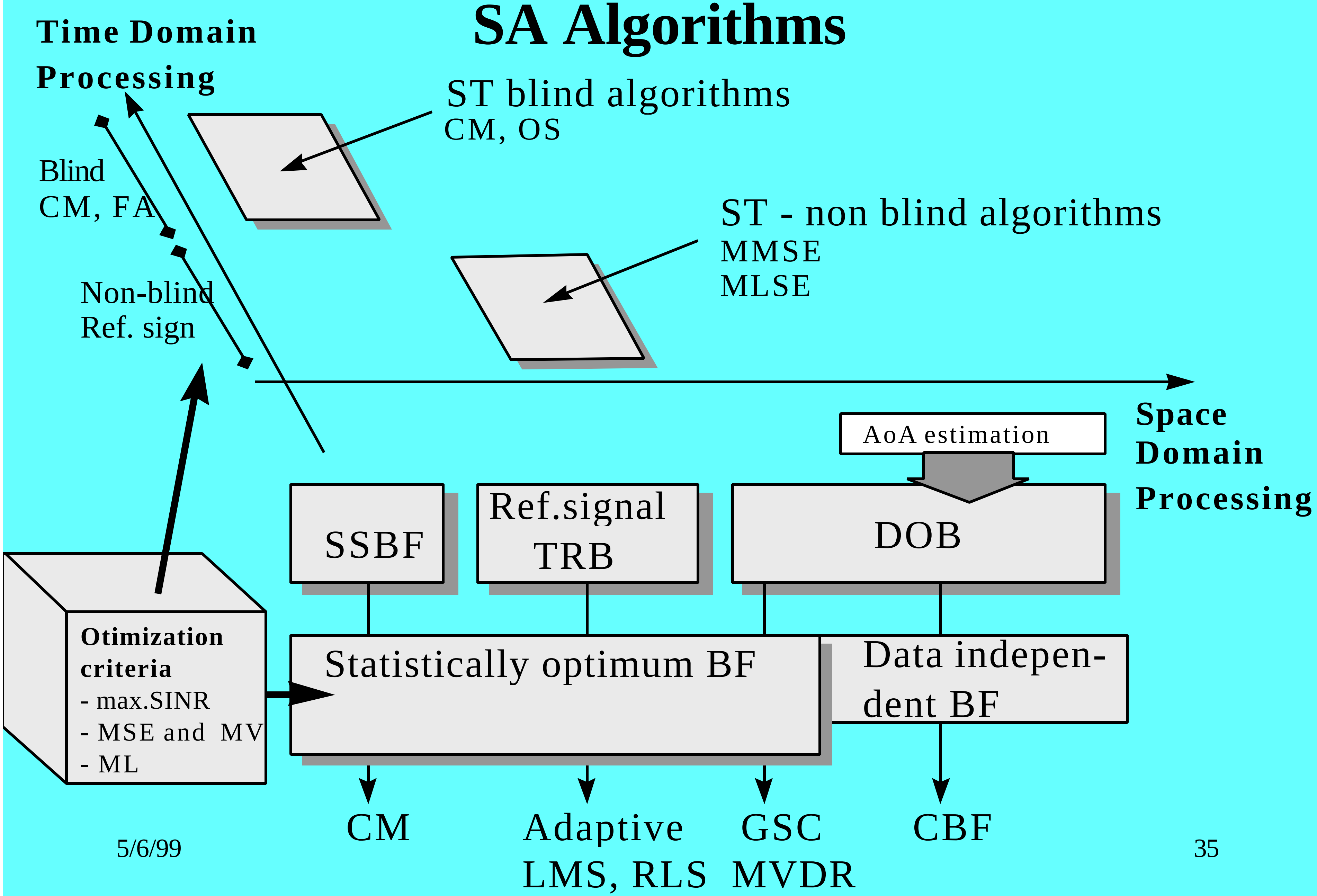
S-DIV	T-DIV	MUI
X	X	X
X	X	X
X	X	X
	X	X
X		

After A. Paulraj

3. SA receivers types and algorithms

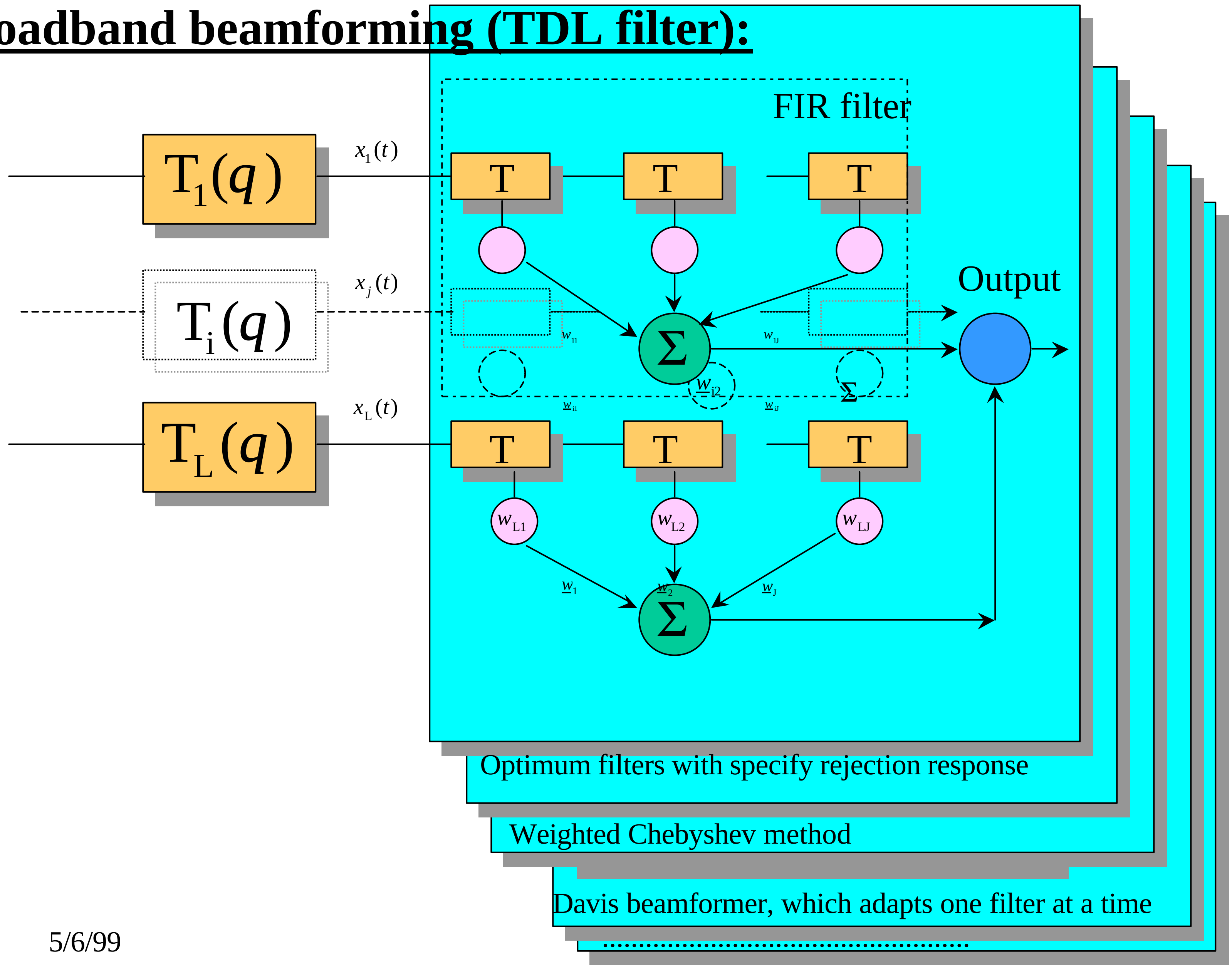


3. Space Domain Only and Space-Time SA Algorithms



3. Wideband Beamforming

Broadband beamforming (TDL filter):



3. Wideband SA receivers.
BF + Space-Time RAKE (single user approach)

Wideband
Beamformer (BF):

1 or 2D RAKE
receiver

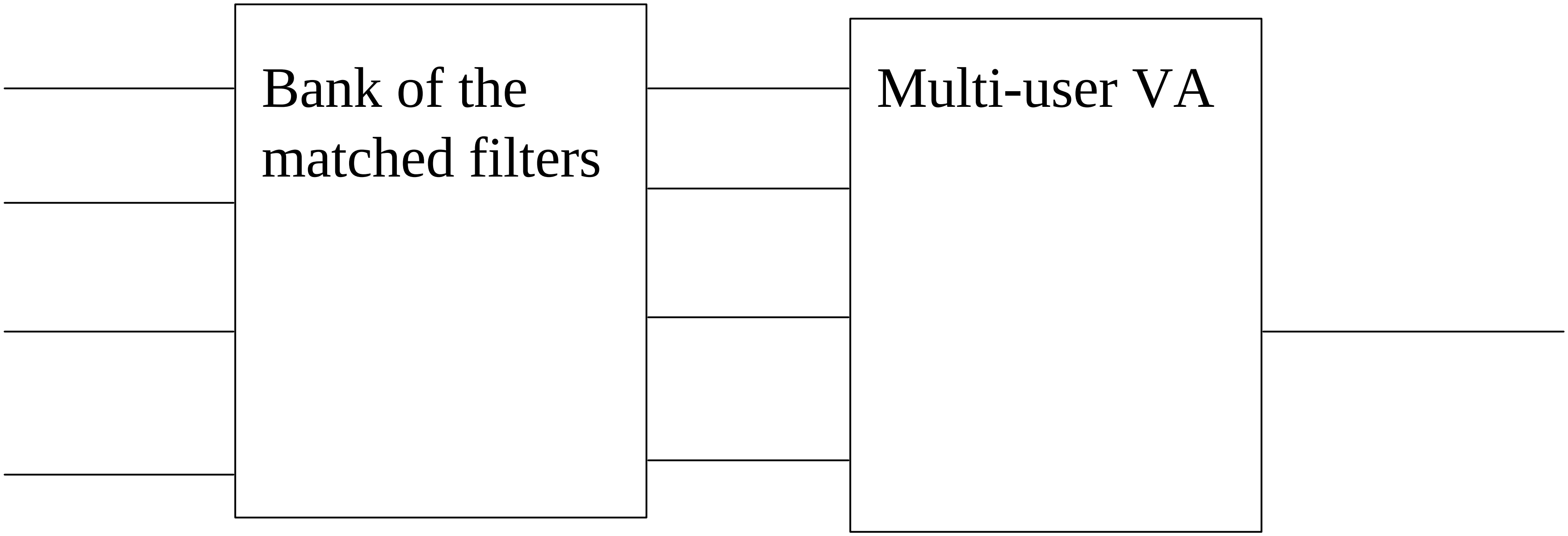
switched-beam

* AOA (Eigen, multi-targ. BF)
* Eigenfilter approach

- Ref. signal-.> MSE
- CMA ?
- code-filtering

exploit spatial and temporal siganal structure + Eigen F.

3. Wideband SA receivers . Multi-user MLSE.



- computational complexity linear to the number of users
- same degree of the near-far resistance and error rate performance as optimum MU receiver
- require knowledge of the all users channels
- optmal in Gaussian noise only

3. Wideband SA receivers

- In non-multiuser case users are seen as interference to each other and there are many weaker CCI in the uplink.

- Multipath gives rise to the MAI due to the losses of codes orthogonality.

- code can seen as “free” reference signal

- ISI compensation has less importance in CDMA than interchip interference (ICI). But for very high bit rate ISI cancellation may be required.

- Channel estimations can be based on spreading codes and it presumes introduction of novel techniques

- Wideband beamforming realization and methods of AOA estimation are different from narrowband

3. Wideband SA receivers

- For low SNR sophisticated spatial-based blind methods are not efficient and it was the reason of more extensive research in the area of switched-beam solutions for system with IS-95 air interface.

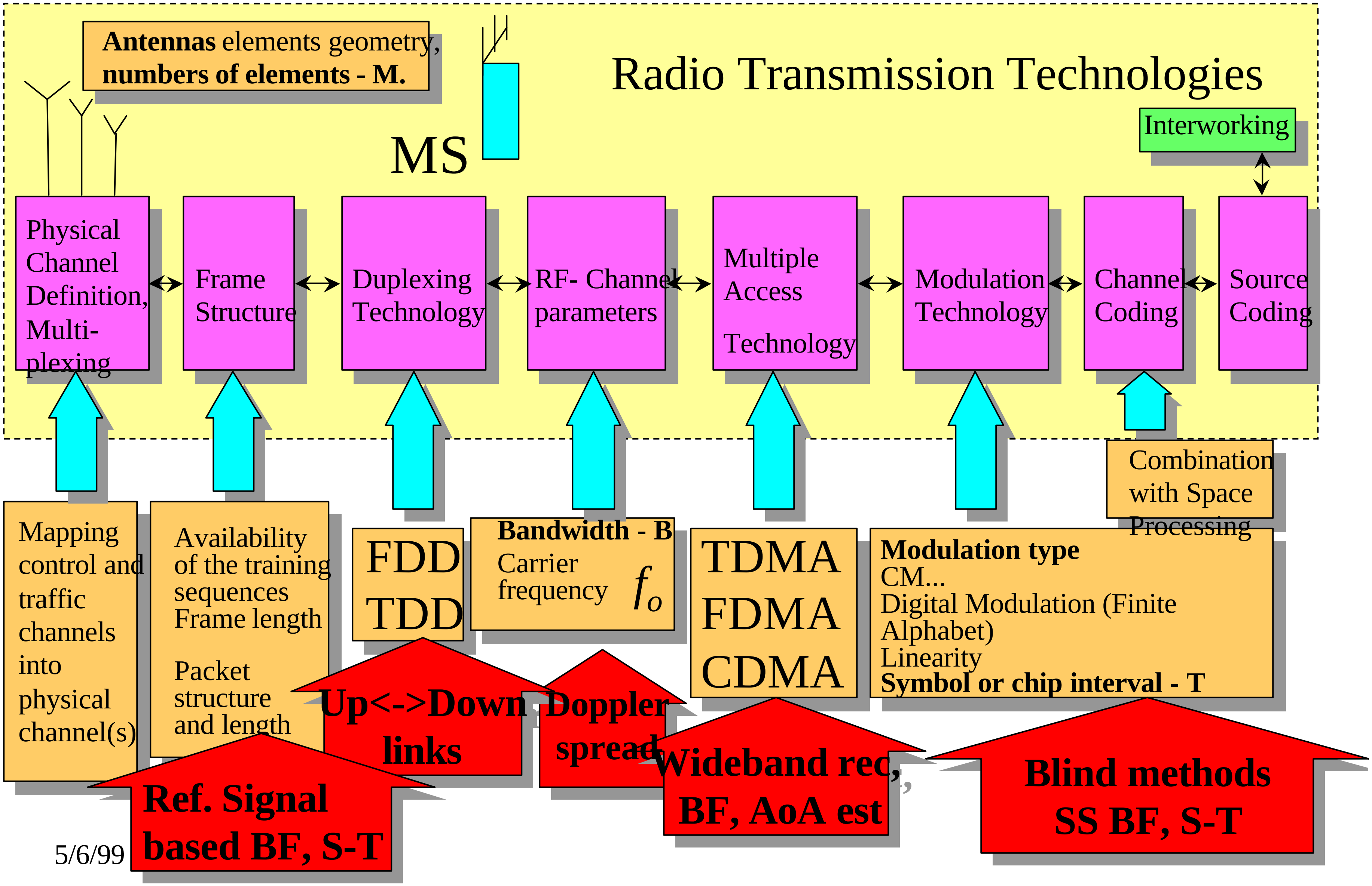
- User dedicated pilots at the up- and down-links of the UMTS air interface give additional advantage for SA technology especially in highly loaded cells (MMSE).

- In CDMA the forward link channel estimation problem is simpler than in TDMA because it is possible to decouple the channel mapping for each path and deal with lower angle spread.

- In CDMA SA receiver is less sensitive to channel estimation errors but beam pattern optimization can be is more complex.

- In multi-bit rate CDMA SA receiver can successfully cancel interference coming from the limited number of high bit rate users thus considerably increasing system capacity .

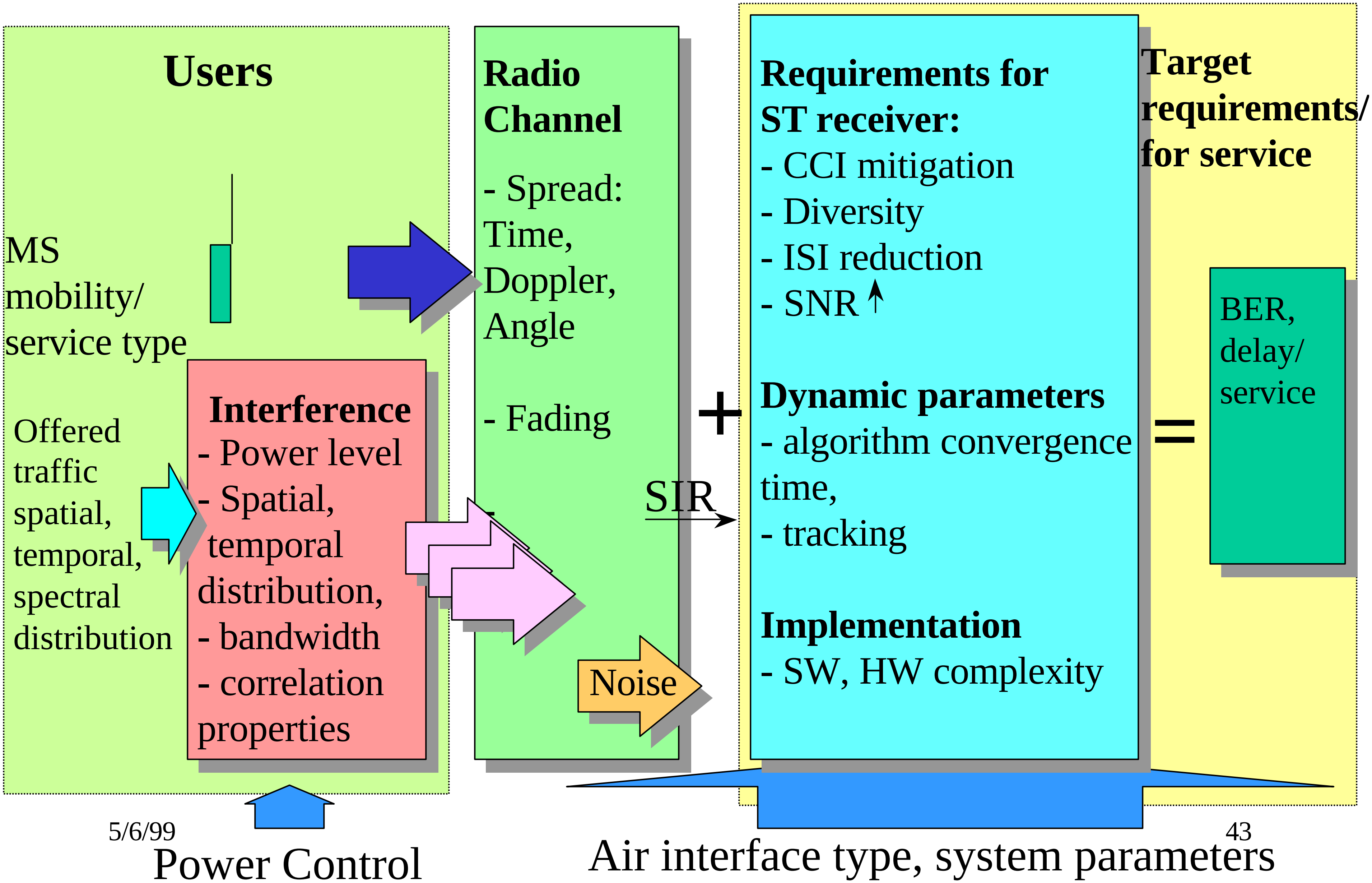
3. Impact of an air interface parameters on ST receiver structure and algorithms



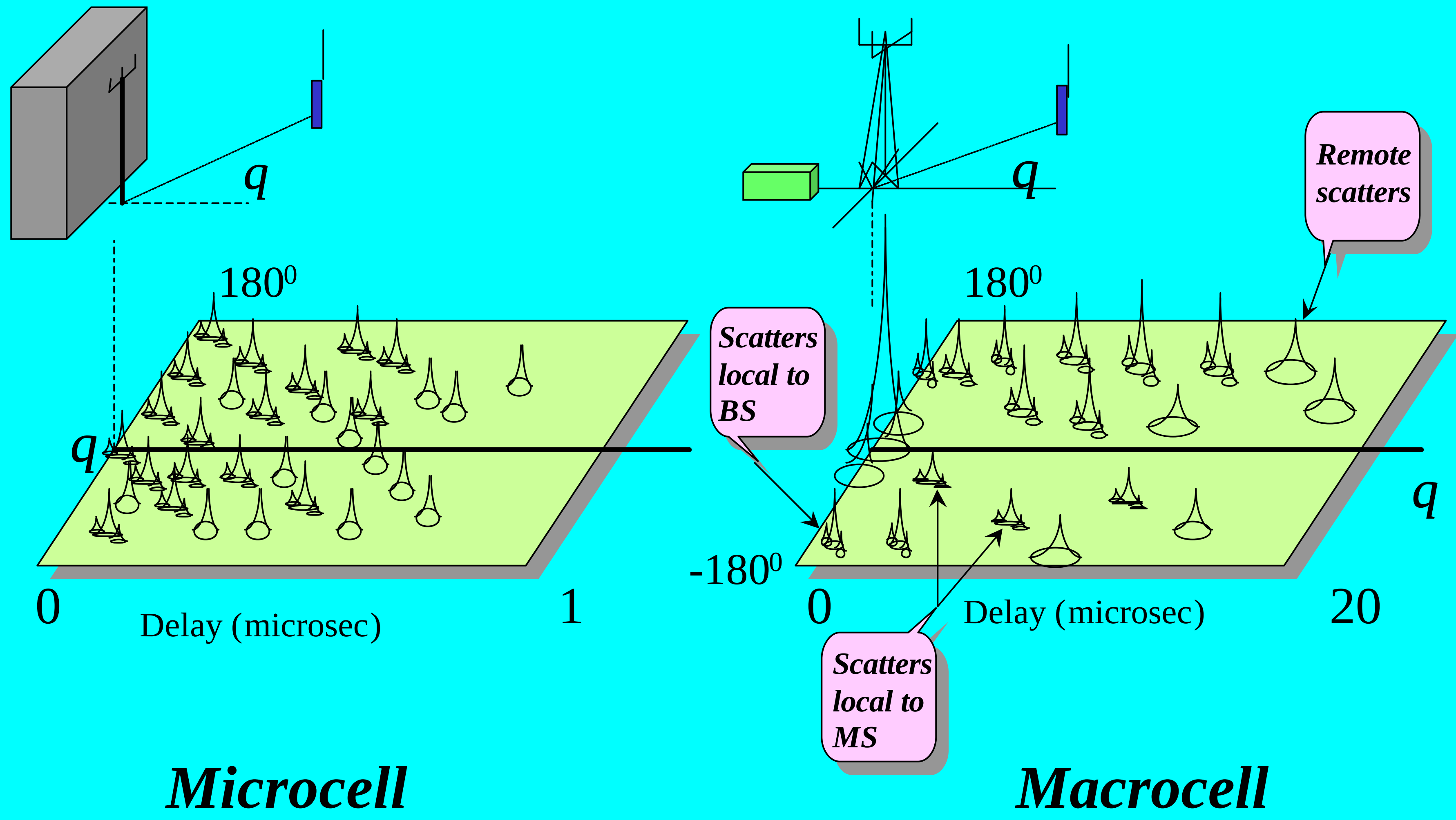
Combination SA receiver with other signal processing tech.

- Diversity (polarization, space)
- ST coding
- RAKE receiver
- MU detection
- Decoupled time domain processing

3. SA Receiver integration Algorithm (Up-Link)

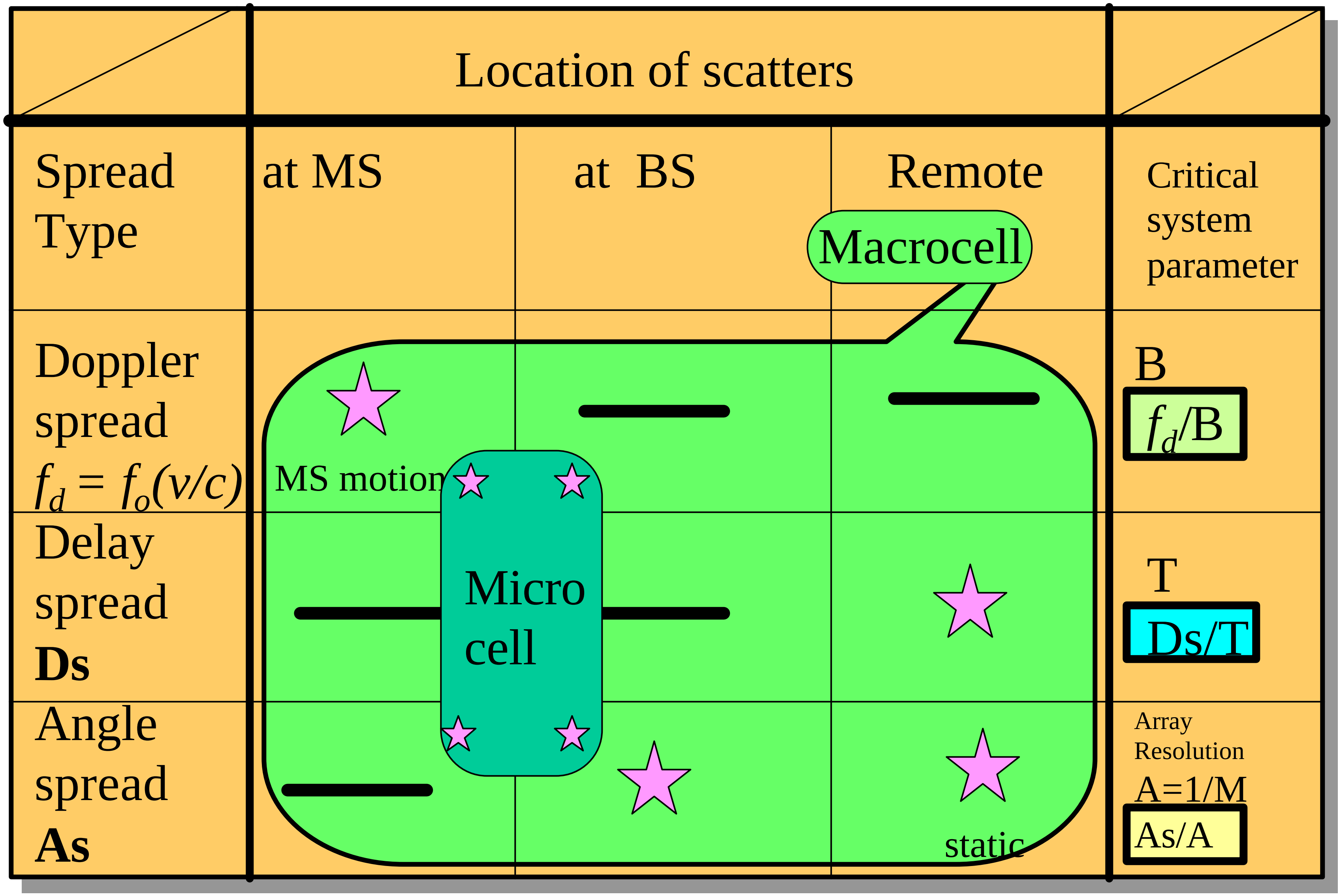


3. Macrocell and Microcell Channel Response



After A.Paulraj

3. Relations between spreads and relative quantities of interests for different types of cells.



3.Compatibility of SA receivers structures and algorithms

TDMA		
Cell type	**Spatial domain-only processing**	**Space - Time Processing**
Microcell High angular spread (As), High traffic - CCI dominant, low user mobility low delay spread	TRB (Reference signal based) Downlink spatial selective transmission to improve capacity. Downlink BF in TDD can be based on up-link BF.	ST-MMSE ST-MLSE - if ISI more important j than CCI
Macrocell low angular spread, low traffic, high user mobility	DOB. Performance depends on the ratio *As/M*. For ISI limited transmission some degree of freedom can be spent for ISI cancellation at expense of time diversity or CCI cancellation.	ST-MLSE ST-MMSE for users with high mol Mixed solution STF/MLSE
CDMA		
Microcell	Eigenfilter approach SSBF code-filtering TRB based on training signal	2D RAKE based on MMSE and R.
Macrocell	Some superresolution algorithms can be used for AoA estimation TRB based on training signal Switched beam SA	2D RAKE based on MMSE and R.

Table 1. Compatibility of SA receivers structures and algorithms.

4. Network Planning with SA

1. Concepts of HSR, SFIR, SDMA.. in TDMA networks

2. CDMA network planning with SA (near-far problem mitigation).

3. Feasibility of sectorization and SA (3-4 sectors with SA based on ULA)

4. Networks upgrade with SA (different areas, strategies)

5. Simulation tools

4. Three Stages of Introduction Adaptive Antenna Technology in Cell Planning Process

1. High Sensitivity Reception (HSR)

2. Spatial Filtering for Interference Reduction (SFIR)

3. Space Division Multiple Access (SDMA)

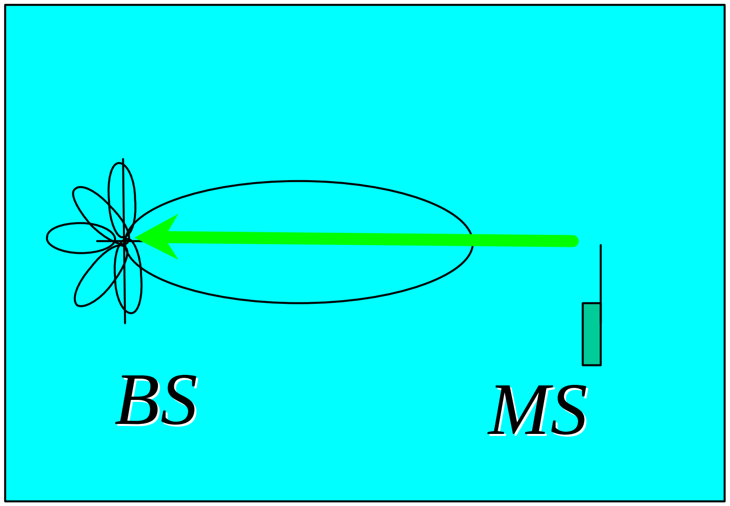
4. SFIR+SDMA ?

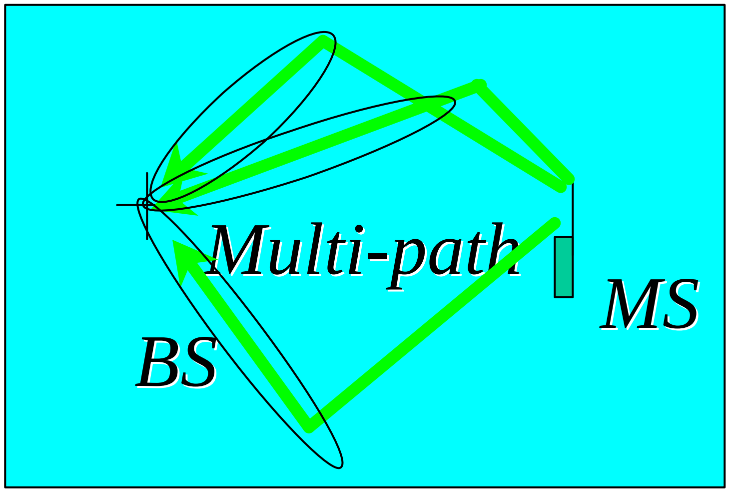
4. HSR concept

- SA at the up-link only

- Gain approx. *10logM*

- with 8 elements reduction of BS by factor of 0.3 by factor of 0.5 with diversity -



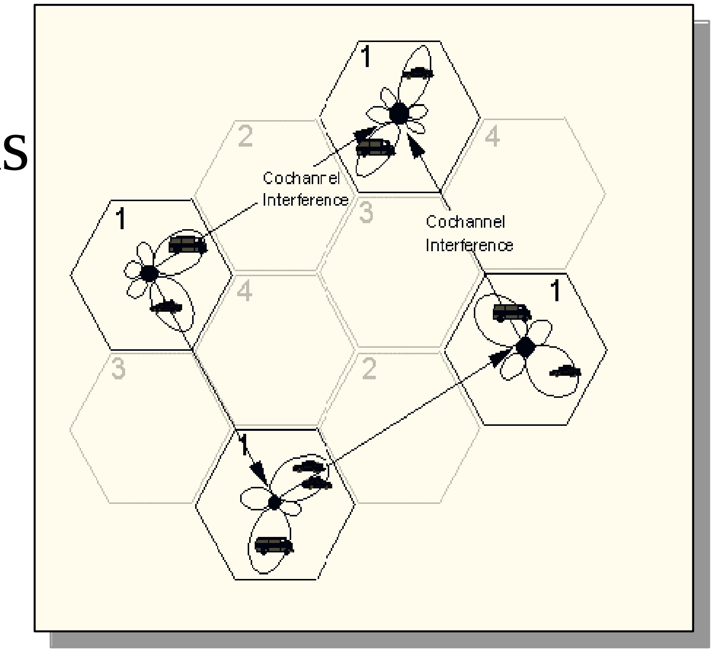


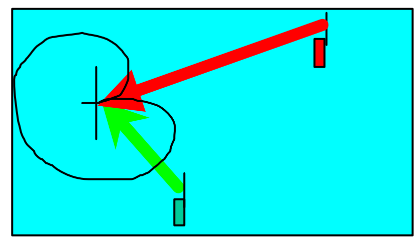
4. SFIR concept

- CCI cancel.+ SA at the downlinks

- Capacity improvements 2.5 require 6 dB CIR improvement (already achieved by Ericsson with simple SA algorithms)

- the same range exst. as HSR

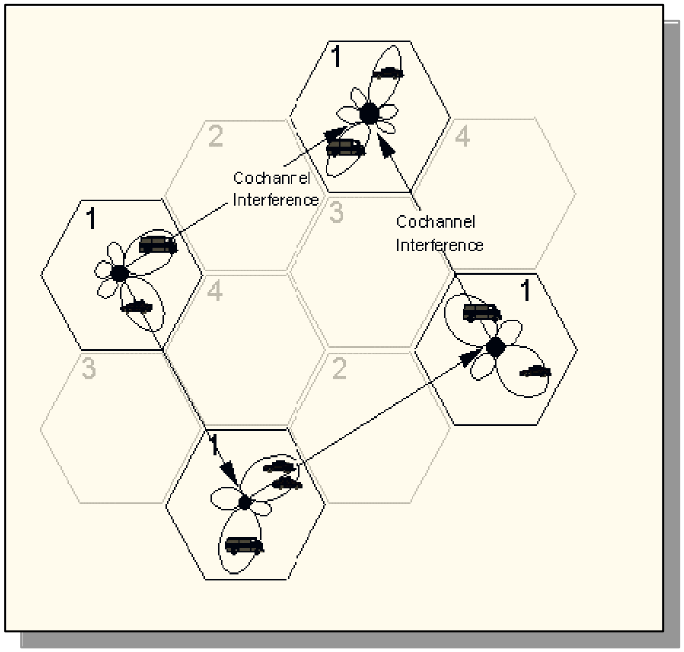


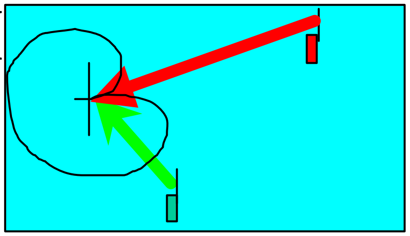


4. SFIR concept

- it was found reasonable to combine in GSM SFIR with random slow FH to benefit from interference and frequency div.

-reuse factor 1/3 seems resonable 1/1 possible but to complex since dynamic RR manag. based on CCI measurements is required





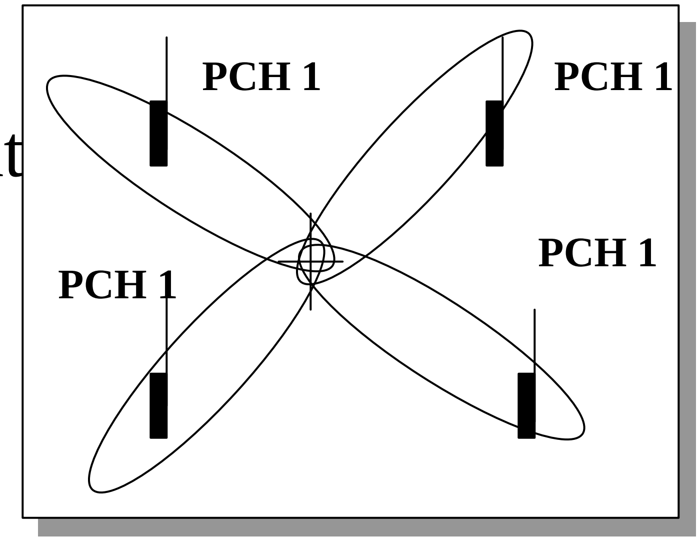
- frequency re-planning , but network control (RR) less affected

4. SDMA concept

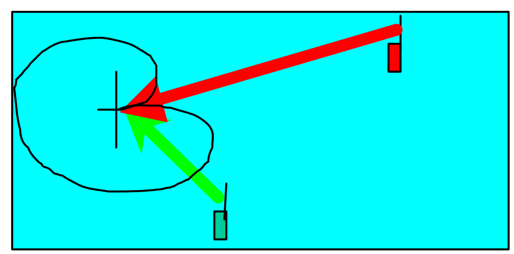
- Expected up to 8 times capacity improvements-

- power classes concept (dyn./ stat

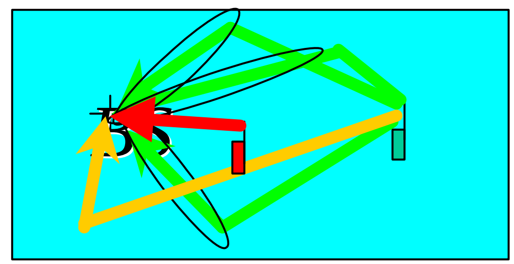
- with ref. signal BF MS can be separated even when they have the same angular position to BS!



- network planning (frequency) is simpler, but larger cell size can require new planning, smooth migration into existing network



- more network management upgrade required



4. SFIR+SDMA concept

- In theory it is possible to combine SFIR and SDMA concepts

- Intercell reuse distance (1/n) and intracell reuse distance of co-channels will increase

- Complexity is very high to be implemented in the near future

4. CDMA network planning with SA

- Reuse factor 1, only “SFIR” concept is applicable

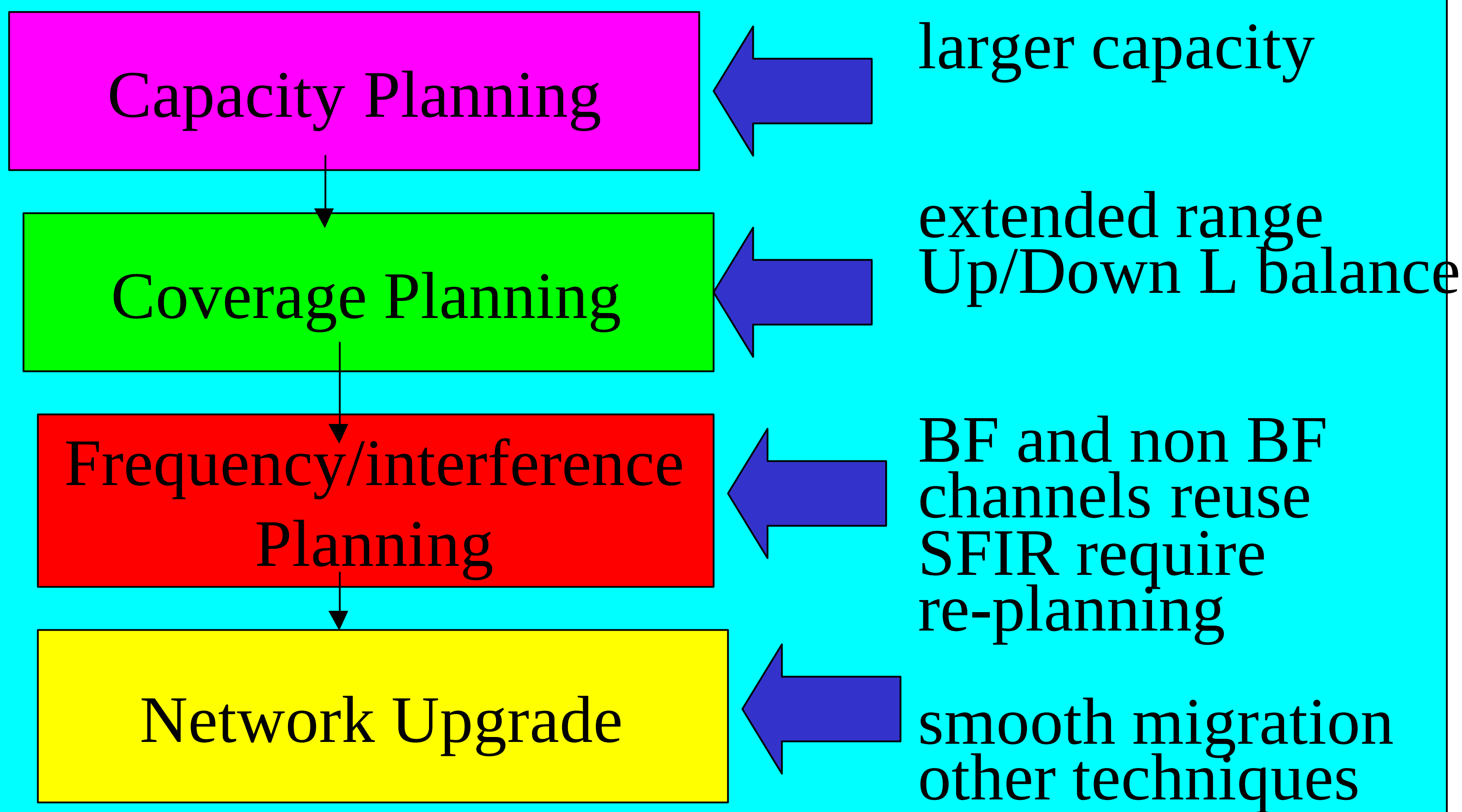
- In multi- layer (single carrier) CDMA network may (?)exist since SA can reduce near-far effect

- Range will increase

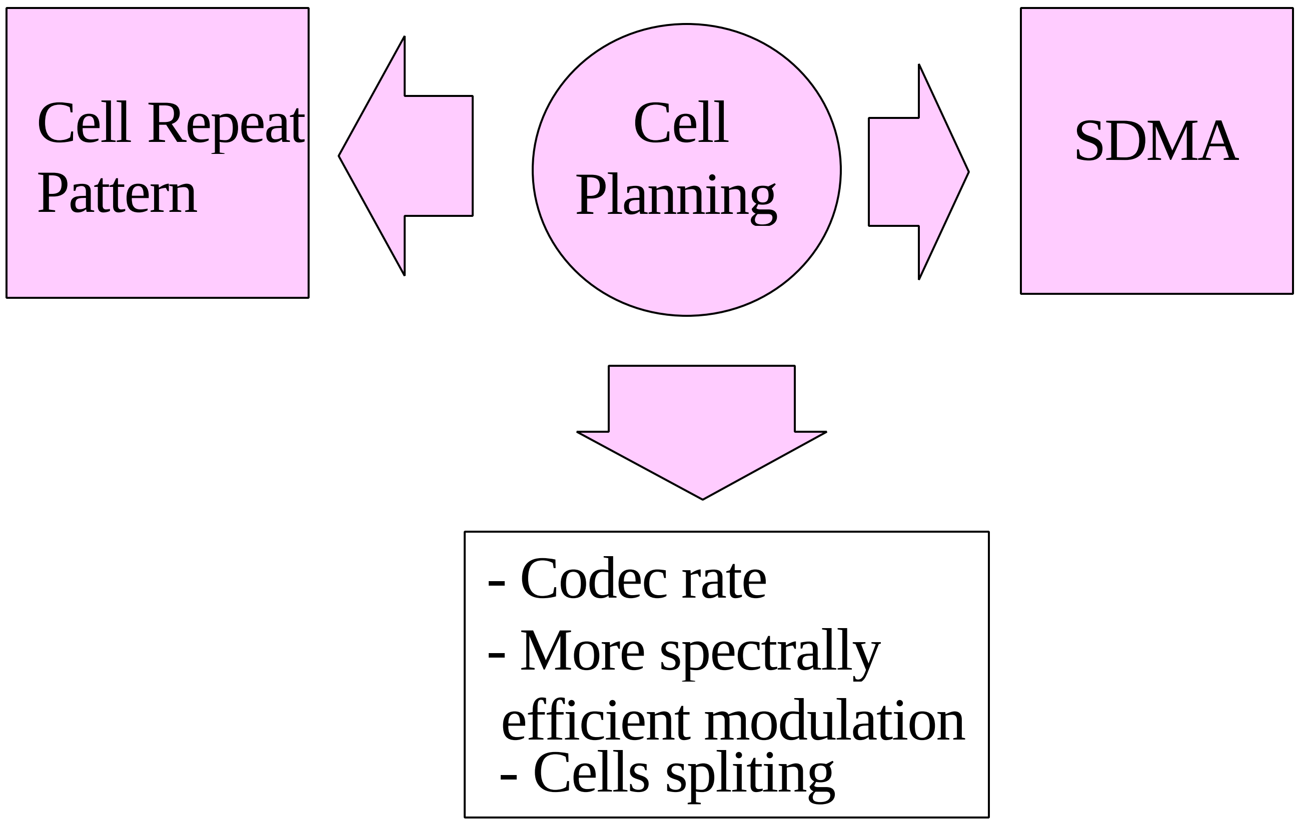
- Capacity will increase since less interference at the receiver

- SA can be very effective in interference suppression which is coming from high bit rate users (UTRA)

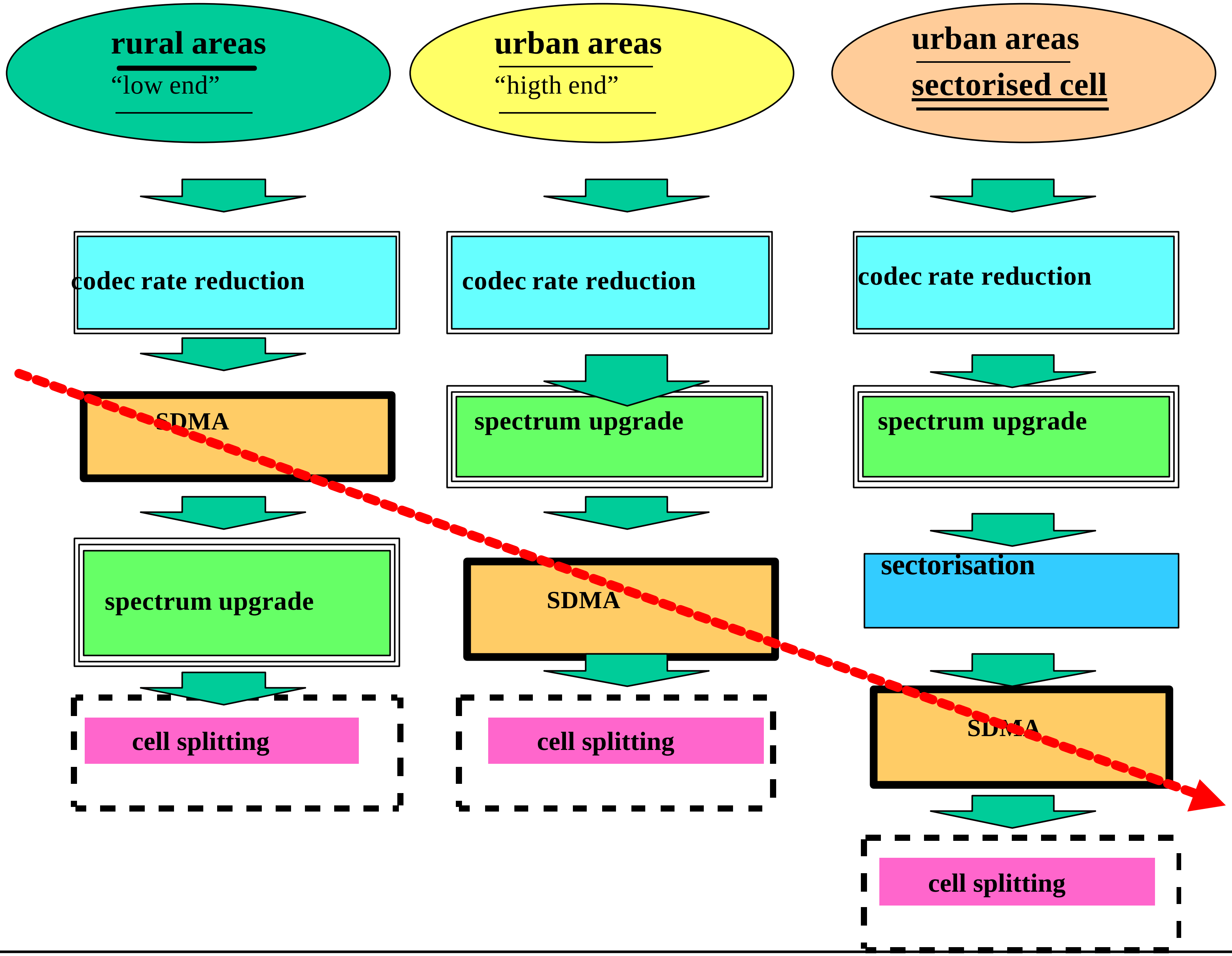
4. Impact of SA on Network Planning



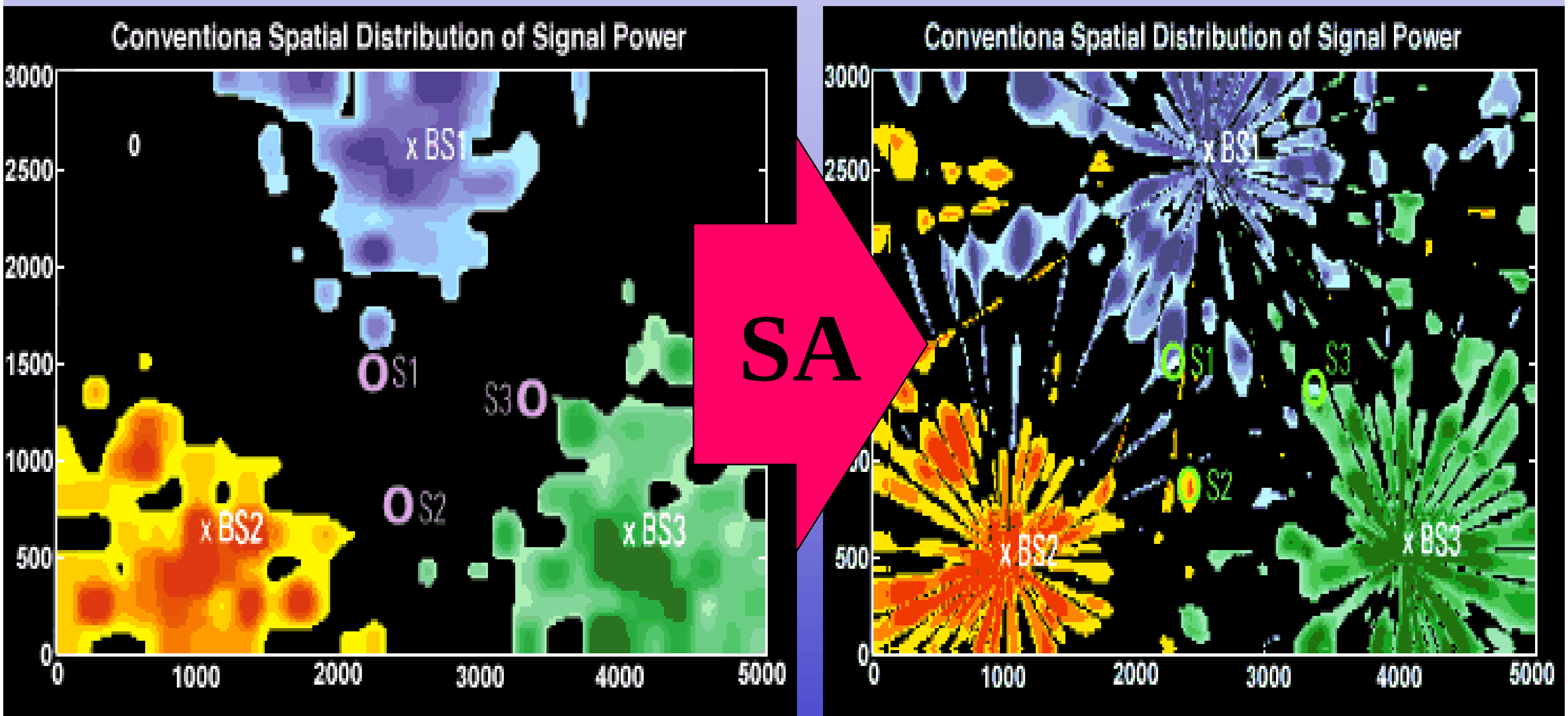
4. The Main Direction in Increasing Capacity of future Cellular Systems



4. Evolutional Path for System Upgrades of a Mobile Communication Systems



4. Spatial Distribution of Signal Power with SA



4. Radio Network Simulator “NetSim”

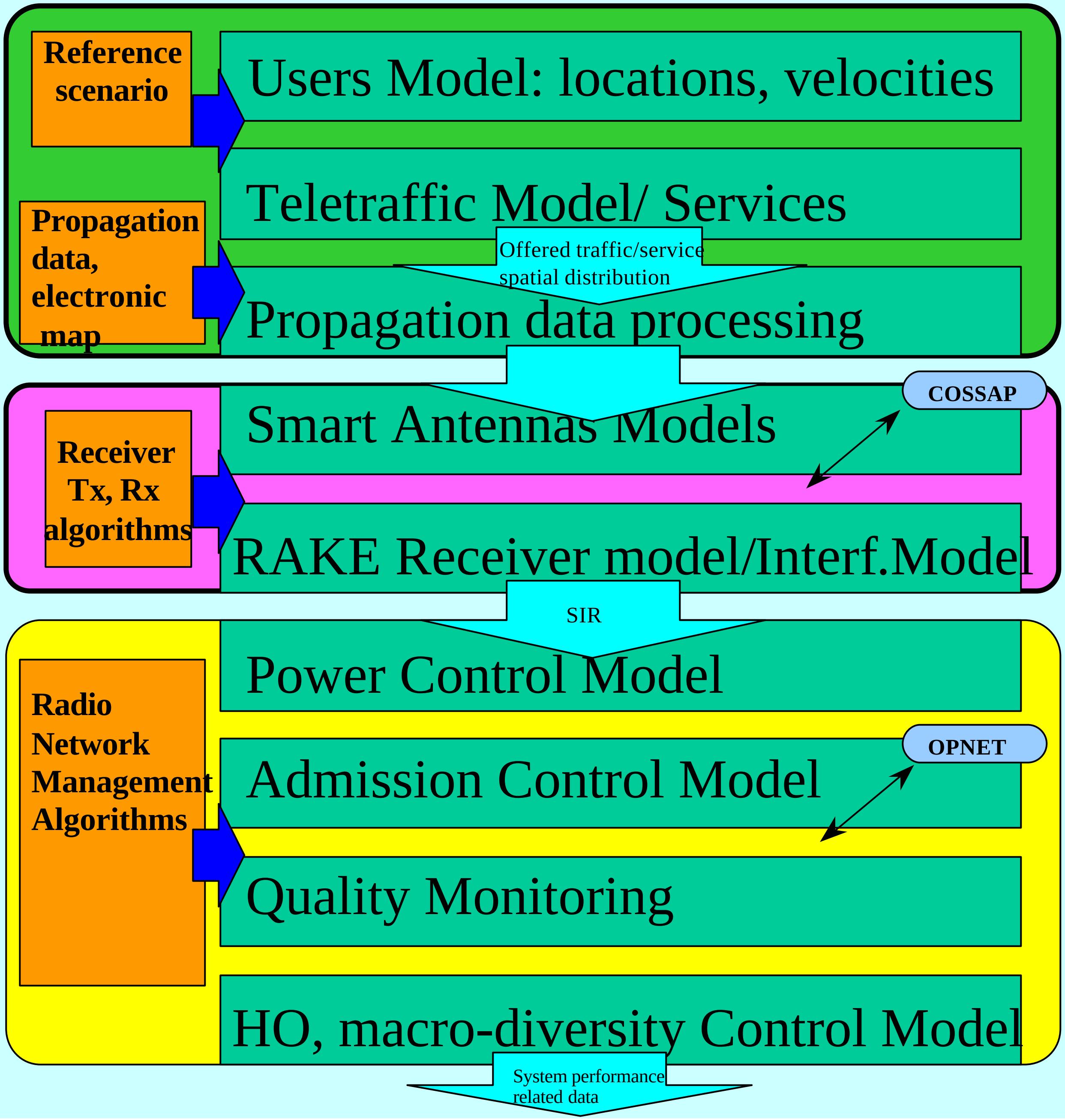
* NetSim - simulation tool for study Planning Methods and Control Algorithms (power , admission control, handover) for Cellular Radio Networks with Adaptive Antennas .

* NetSim provides detail information about capacity, coverage and control algorithms performance of cellular system.

* NetSim well fit to the existing gap between signal level simulators (COSSAP) and higher level network simulators (OPNET) and can used in combination with them.

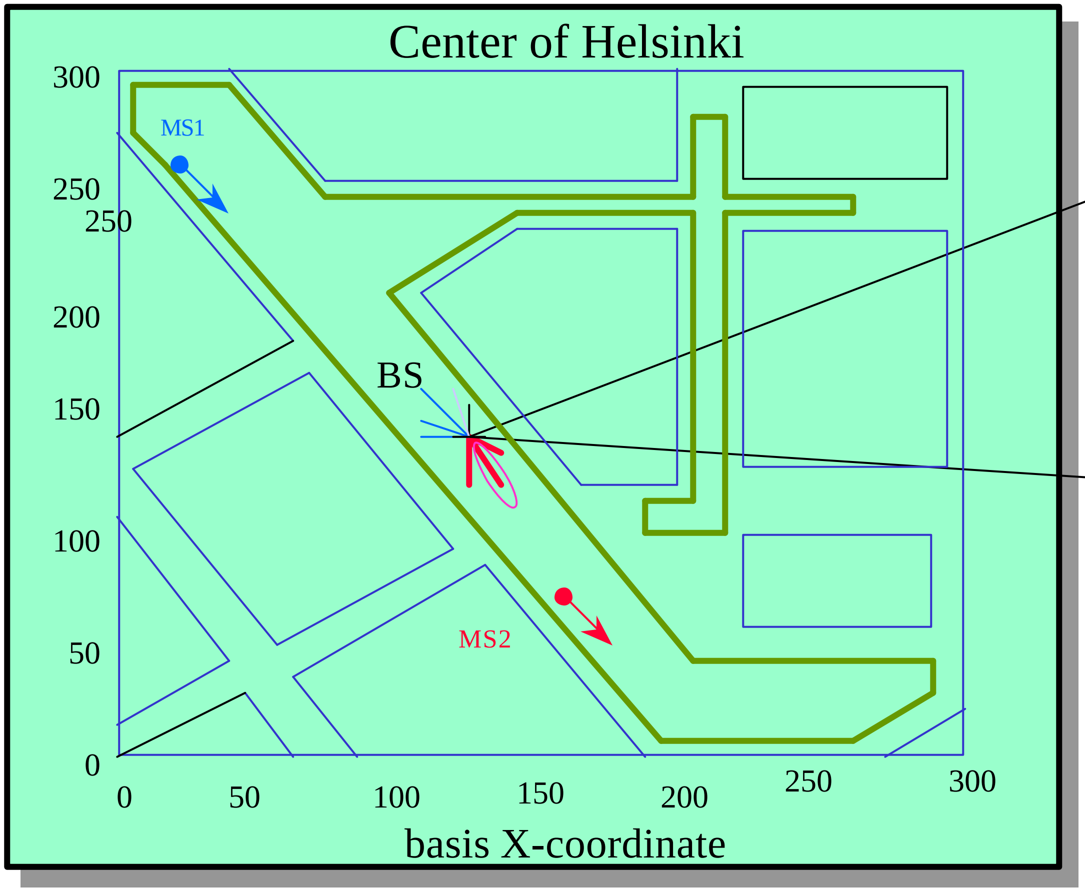
* NetSim can be easily updated for different air interface standards and propagation models.

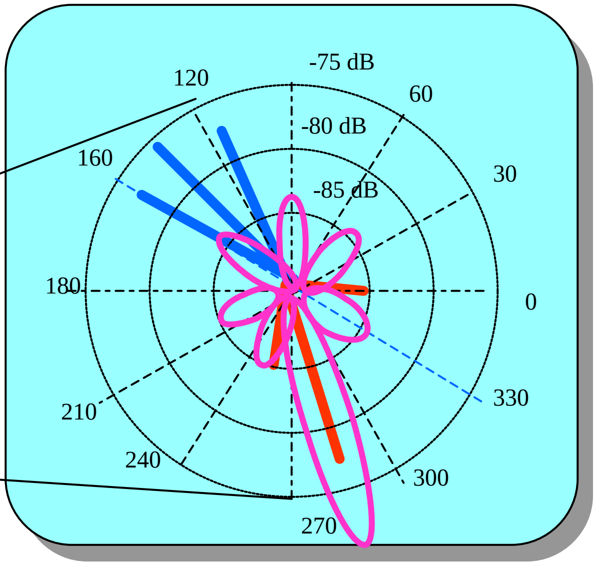
4. “NetSim” structure



Current version	Version under development
Pedestrians on predefined route	Models domestic users and car passengers
Control and traffic channels model Voice service with VAD	Multi-services model packet and circuit switched
Deterministic raytracing model	-Deterministic 3D raytracing models - Model based on measurements - Statistical model
Conventional, optimal beamformers	2D-RAKE, more complex SA models.. downlink model
SIR base distributed power control	Joint BS assignment, power control and beamforming
Soft/hard HO, optimum combining at the uplink	Multi-carrier network simulation
	Visualization tools

Two Users LOS propagation scenario





- incoming impulses from the MS1 - amplitude and AOA

- incoming impulses from the MS2 - amplitude and AOA, considered as "interference" for MS1 (and vs)

- Smart Antenna's radiation pattern antenna main lobe locked on the signals coming from MS1

4. NetSim specification

Platform:	UNIX, Windows under development
Language:	C
NetSim can simulate:	Voice and Data services, Smart Antennas, Packet Switched , Circuit switched Different users behavior and their spatial distribution Radio Network Control Functions (HO, admission, power control)
Simulation results:	Capacity function of traffic, propagation, BS parameters and location. Network Control algorithms performance Location of problem areas Coverage prediction
Output information:	ASCII format files can be easily read by MATLAB for statistical processing and visualization

5. Network Control with SA.

- Network control (initial access, HO, initial access, resource management)

- Packet transmission with SA

- FH with SA, fractional loading reuse ???

- DCA (AoA, link quality measurements, averaging)

5. Layer 1.Power control. Quality monitoring. Tracking.

- dynamic behavior of tracking , power control

- physical ch. structure, down-link problem FDD/TDD

- user identification problem to support SDMA individual color codes needed to support each SDMA traffic channel channel

- for “rescue” omni directional channel for call recovery is proposed

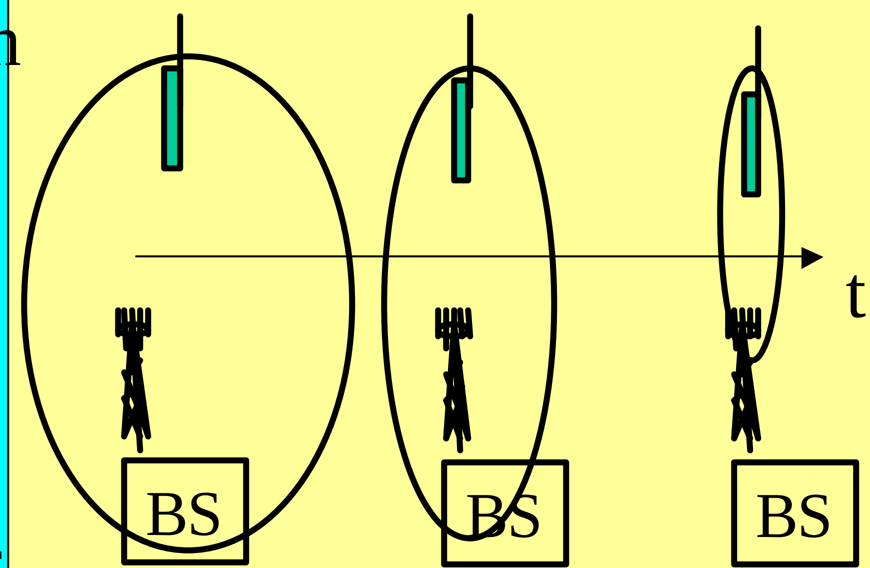
5. Layer 2. Initial access. Handover.

-location aware HO or through
omni-directional channel ?

- initial access with omni
dir. ch. further narrow beam

- to setup beamformer just before
user dedicated channel is allocated (access procedure
modification or increasing access are proposed)

- how to make down-link BF when ch. info at up-link
is not available yet (tempor. omni DL or longer acces)



Initial access

5. Layer 3. Resource management.

- new functions: physical ch. allocation based on angular information and or link quality monitoring

- DCA (Localization with different precision... ?? needed)
Precise localization - centralized DCA or
NO DCA with SFIR and interference averaging approach or
AoA -> subdivision on sectors and create list of forbidden sectors

- joint power control , beamforming and BS assignment problem

- centralized or distributed control ?

- spatial traffic distribution (smoothing)

-more benefit we expect to get the more RR should be aware of spat. characteristics

5. Network Control with SA. Higher layers. Geolocation.

New service (991, transport control…)

Combined DOA measurements and time delay based approach

Raytheon proposed commercial available geolocation system (SA option is included)

3-G network control with SA

- some loose form of synchronization between cells may required for ref. signal based BF

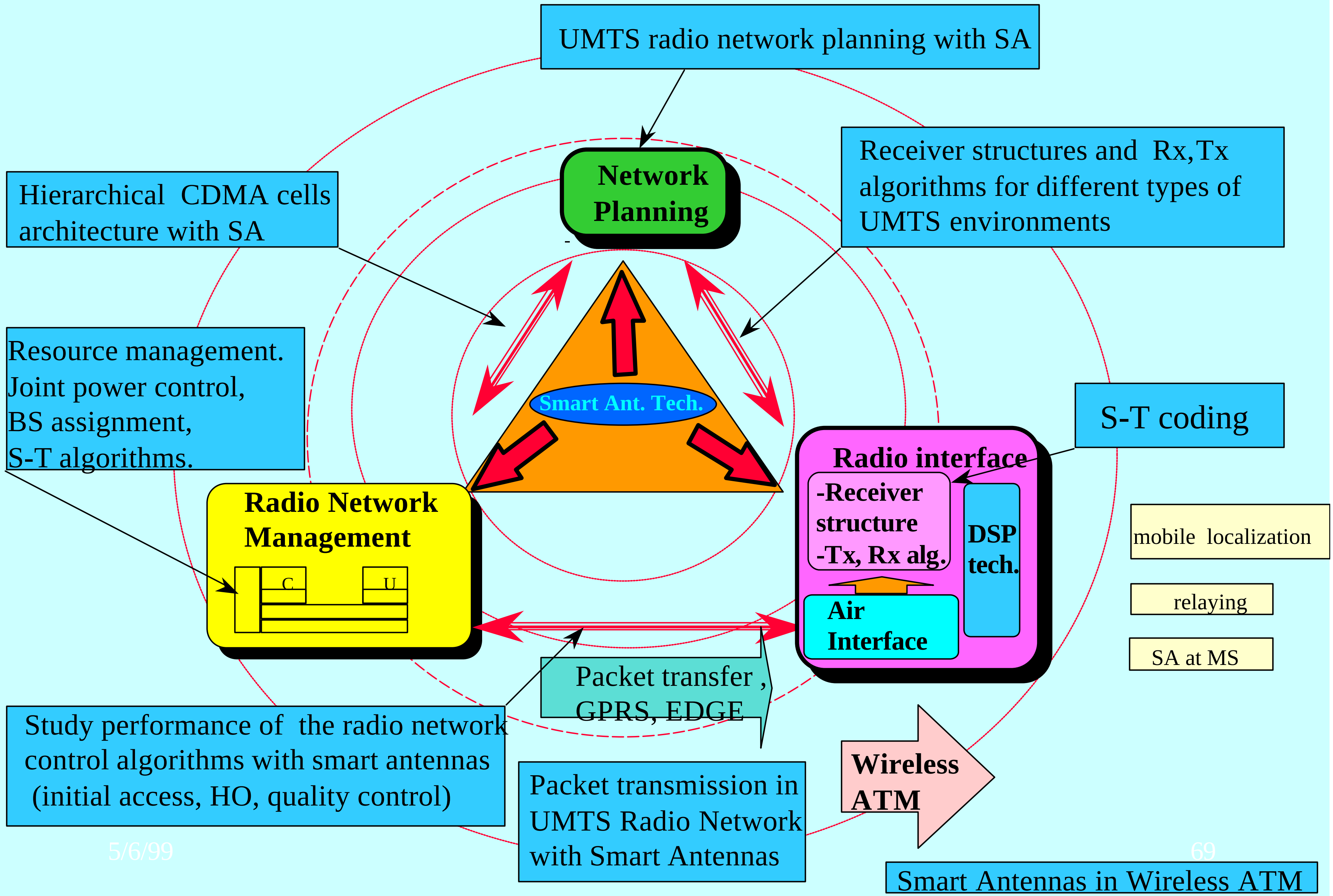
- user dedicated pilot channel or reference bits (implemented)
- combination with link adaptation (since at the beginning "channel history" is not available. This combination will increase "soft capacity limit"

- Packet mode and DTX can create difficulties for BF due to the "silence periods"

- With DTX downlink channel required during silence per.

-

6. Topics for Further Research



6. Research topics

<u>System integration of Smart Antennas technology in to UMTS environments</u>

- Resource management. Joint power control , BS assignment, S-T algorithms.

- Hierarchical CDMA cells architecture with SA.

- UMTS radio network planning with SA. GSM network planning (SFIR)

- Packet transmission in UMTS Radio Network with Smart Antennas at BS.

- GPRS and EDGE with SA

- Study optimal receiver structures and Rx,Tx algorithms for different types of UMTS environments.

- Study performance of the radio network control algorithms with SA (initial access, HO, quality control).

- S-T coding.

7.

Designer	**Air interface**	**Antenna** *(M)*	**SA Receiver algorithm**	**Remarks**	**Ref.**
			SA experimental systems		
Ericsson & Mannesmann Mobilfunk)	GSM/DCS 1800	8	**Up-link:** DOB **Down-link:** DOA switched-beam and adaptive	Several BS equipped with SA integrated into network	[41]
Ericsson Research (SW/US)	IS - 136 (D-AMPS)	spacing up-link 15λ & pol. div.	**Up-link:** MRC and IRC, **Down-link:** fixed beam approach		[43]
AT&T Labs-Research (US)	IS-136	4	**Up-link:** 4 branch adaptive TRB, DMI algorithm **Down-link:** switched beam with or without PC (up to 3 beams)	Up and down links are independent	[45]
NTT DoCoMo (Japan)	UMTS	6	**Up-link:** Decision directed MMSE (tentative data and pilot) 4 finger 2D-RAKE **Down-link:** calibration of weights generated for reverse link	-include 3 cell sites -data transmission up to 2 Mbps	[47]
TSUNAMI (SUNBEAM) Consortium (EU)	DECT -> SDMA ->DCS1800		ULA_MUSIC for DOA estimation Kalman Filtering for tracking	SDMA was Studied based on DECT	[48]
CNET & CSF-THOMPSON (F)	GSM/DCS1 80SDMA	10 circular	**Up-link:** DOA based BF Capon , MUSIC for DOA estim. **Down-link:** DOA based BF		[49]
Uppsala University (SW)	DCS 1800 SDMA	10 circular	**Up-link only:** TRB with SMI	Data traffic from DCS-1800 was used	[50]
			Commercially available products		
Metawave (US) Spotlight™2000	AMPS, CDMA	12	**Up- and down links :** 12 switched beam		[51]
Raytheon (US)	Flexible upgraded by SW	8	**Up-link:** DOB based algorithm (?)	SA can be connected to RF input at the BS	[52]
ArrayComm "IntelliCell"(US)	WLL, PHS, GSM	4	**Up-link:** ESPRIT Adaptive interference cancellation	First mass market commercial product	[53]