SPE-T 2009

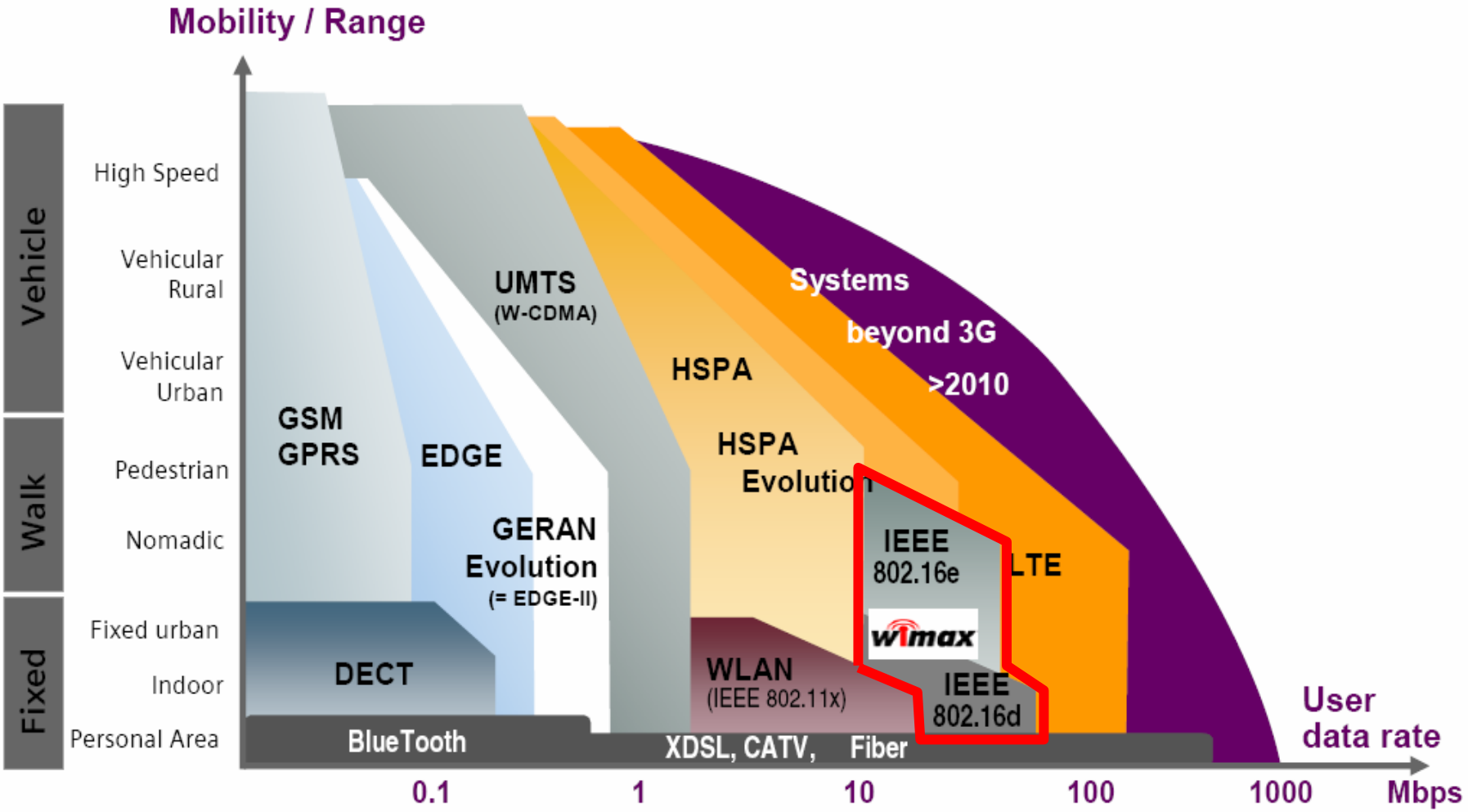
Advanced Radio Communications

Wireless Broadband Access

WiMAX and Mobile WiMAX

G. Villemaud - M. Gautier

WiMAX, why ?

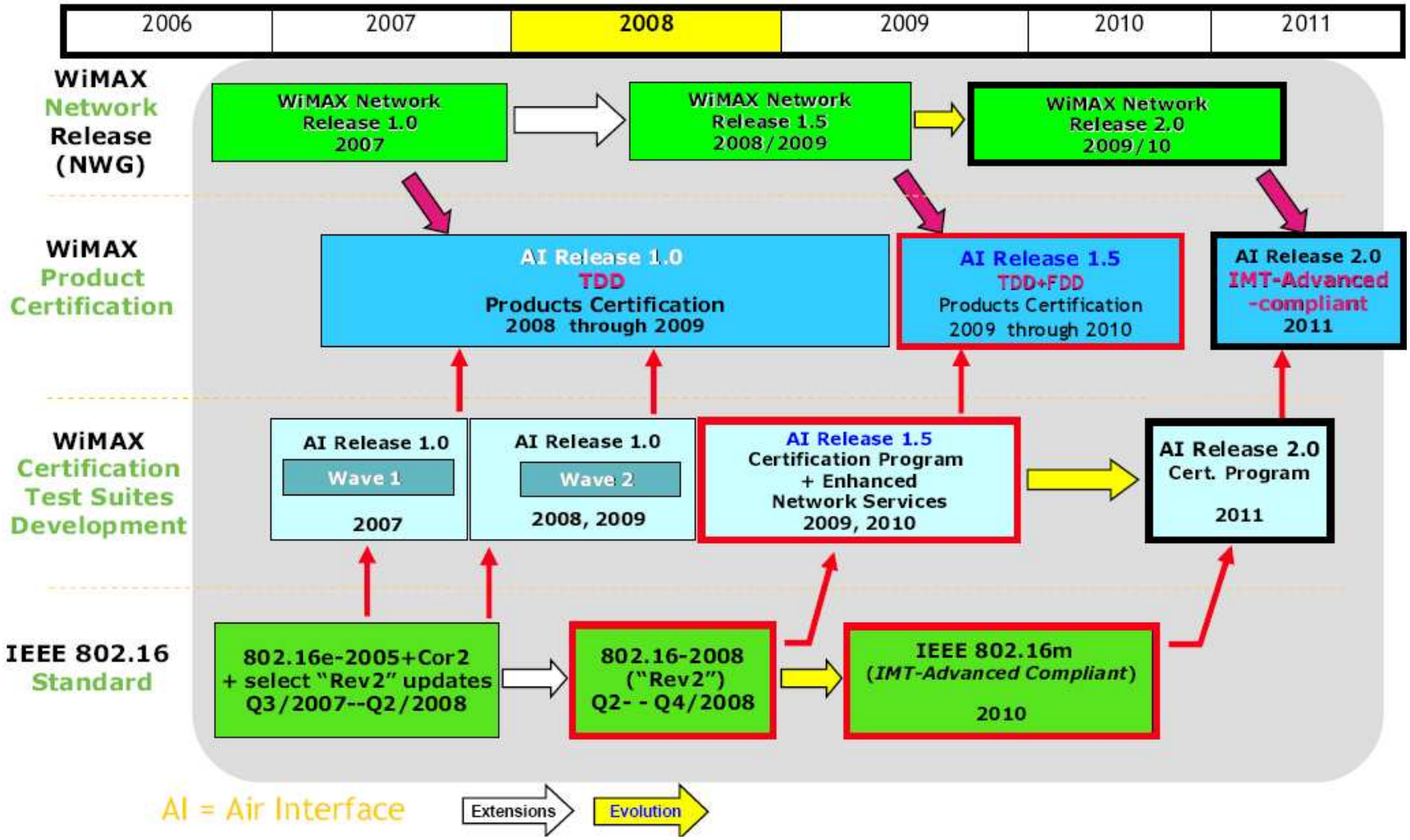

Mobility / Range
Vehicle
Walk
Fixed
High Speed
Vehicular Rural
Vehicular Urban
Pedestrian
Nomadic
Fixed urban
Indoor
Personal Area
GSM GPRS
EDGE
GERAN Evolution (= EDGE-II)
UMTS (W-CDMA)
HSPA
HSPA Evolution
Systems beyond 3G >2010
IEEE 802.16e
LTE
wimax
IEEE 802.16d
WLAN (IEEE 802.11x)
DECT
BlueTooth
XDSL, CATV, Fiber
User data rate
0.1
1
10
100
1000
Mbps

WiMAX, what ?

Worldwide Interoperability for Microwave Access

- WiMax is the IEEE: 802.16-2004/2005 standard of radio interface defining MAC and PHY layers for a Base Station to terminal link.
- PHY is based on OFDM/OFDMA
- WiMAX Forum (WMF) define an end-to-end (e2e) architecture.
- A WiMAX labeled product is certified to be compliant to the standard and interoperable with other certified products
- WMF takes in charge the definition and realization of certification tests

Timeline



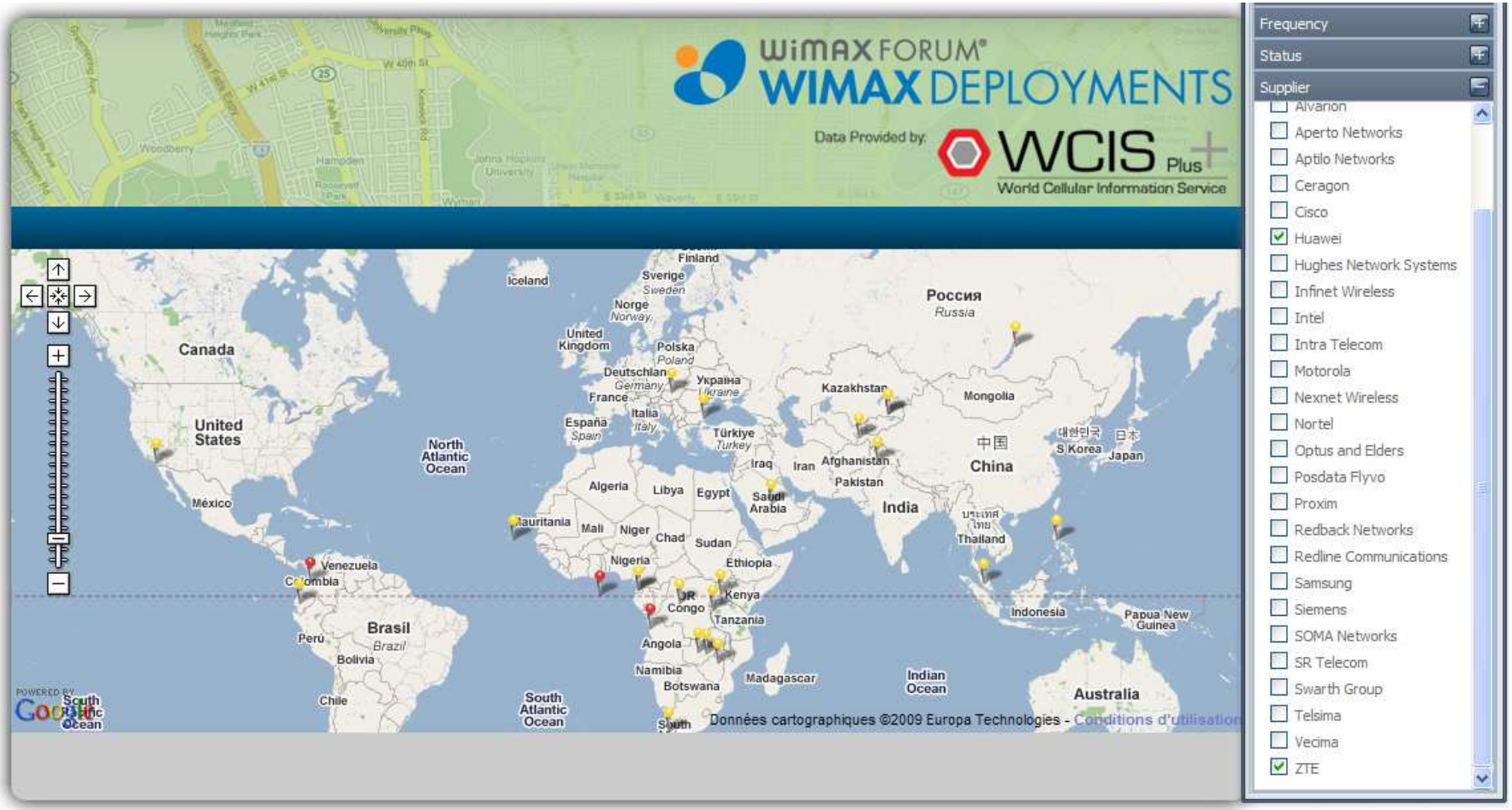
source Alcatel-Lucent

Everywhere ?

WiMAX FORUM®

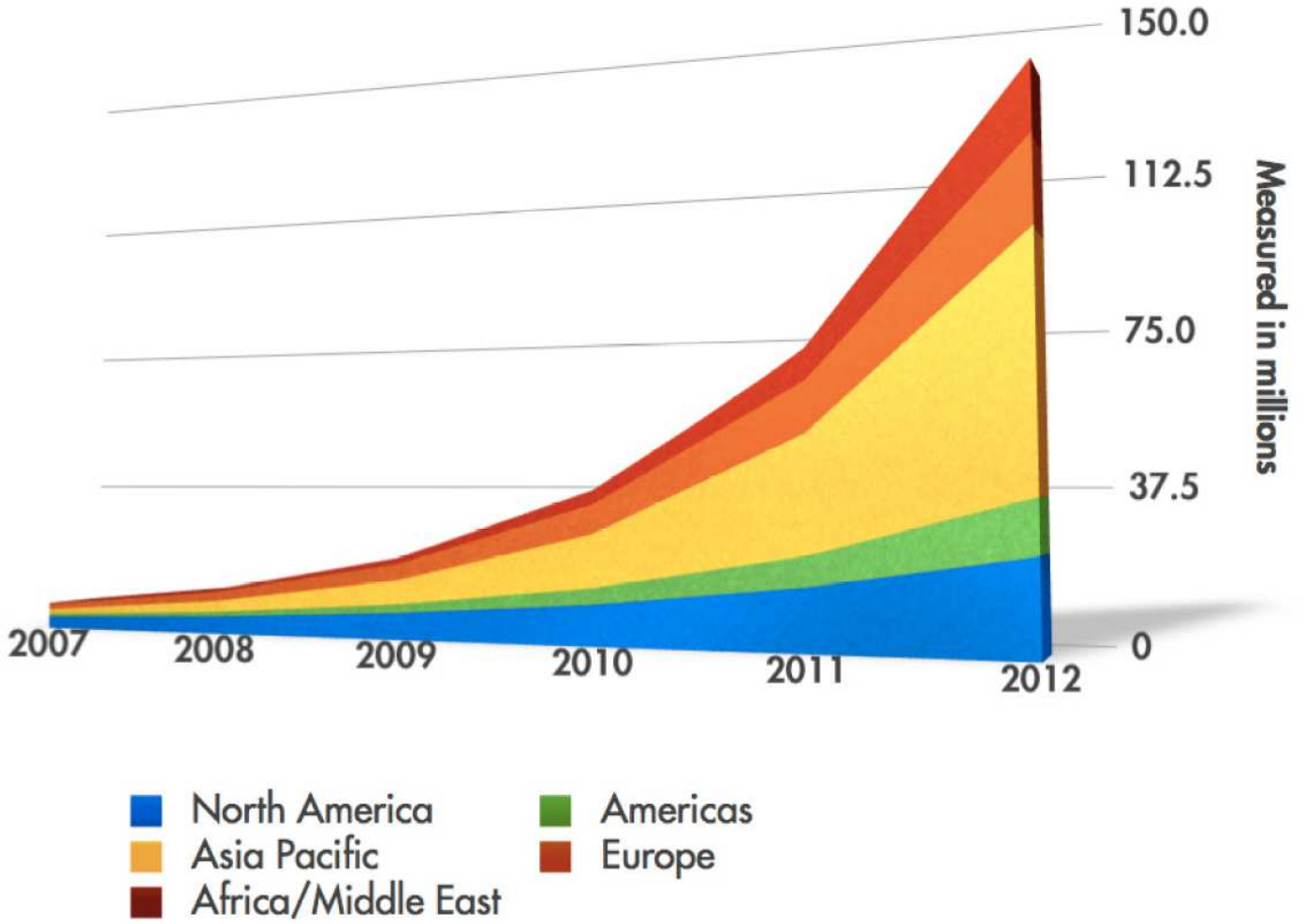
http://www.wimaxmaps.org/

Everywhere ?



http://www.wimaxmaps.org/

User Growth Forecasts



WiMAx Evolution

- *Fixed wireless broadband air interface 10-66 GHz*
- *Line-of-sight only*
- *Point-to-Multipoint applications*

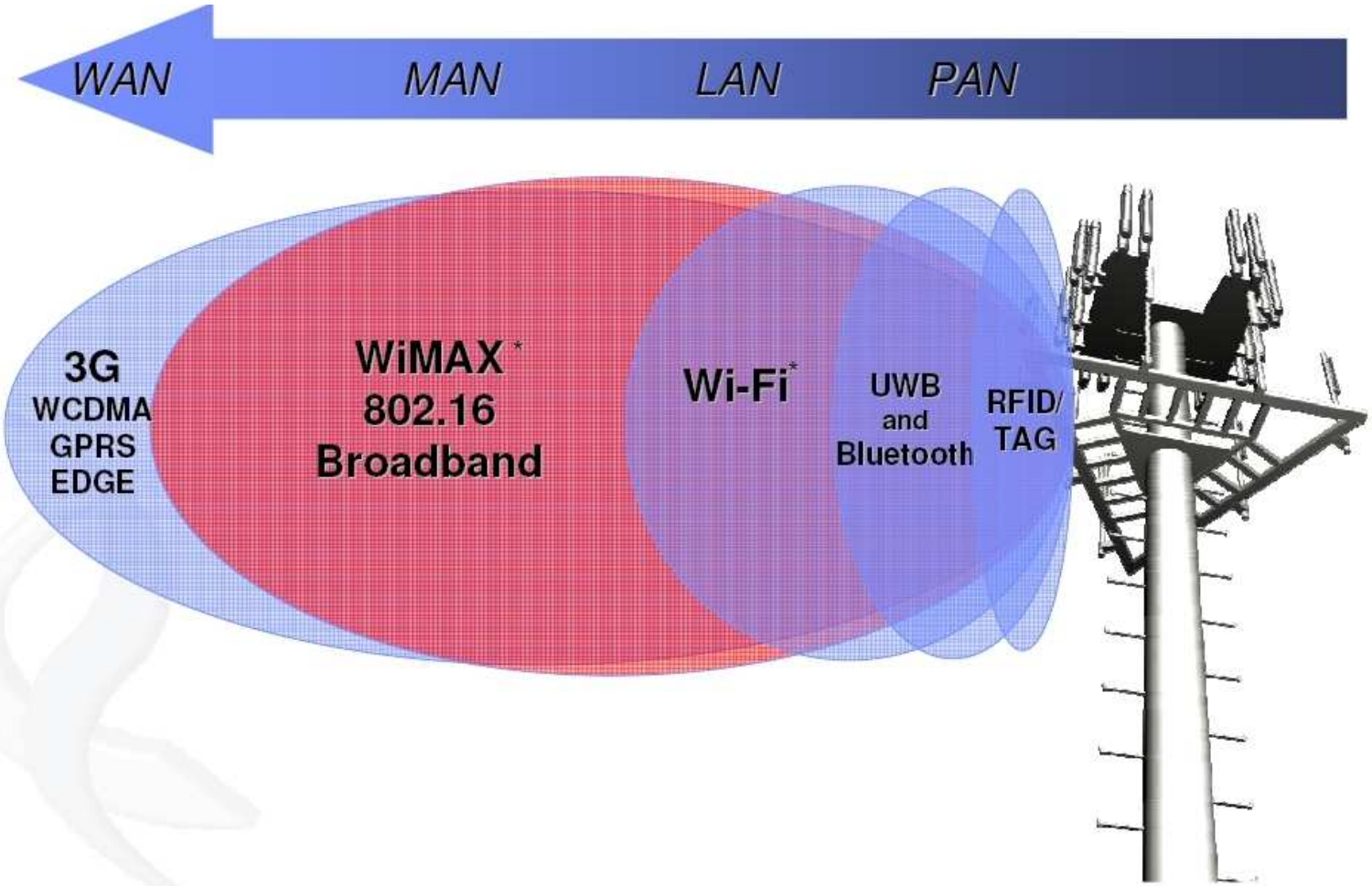
- *Extension for 2-11 GHz*
- *Non line-of-sight*
- *Point-to-Multipoint applications*

- *Revised version*
- *WiMAX system profiles*
- *Up to 75 Mb/s 6-15 km (20 MHz channel)*

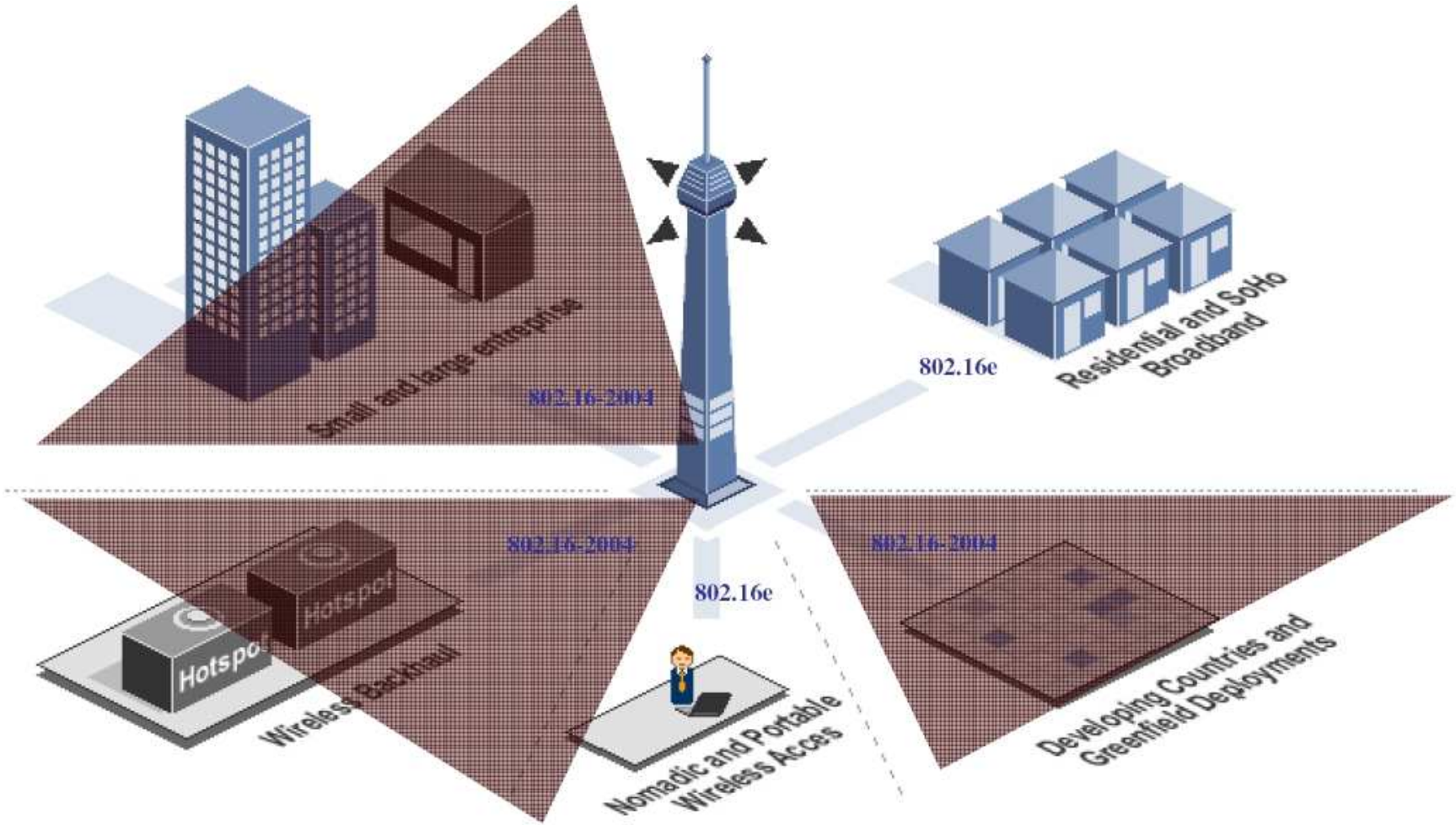
- *MAC/PHY enhancements to support mobility up to 120 km/h*
- *Up to 30 Mb/s 1-5 km (10 MHz channel)*

- *Up to 1 Gb/s (fixed) and 100 Mb/s (high speed)*
- *4G convergence*

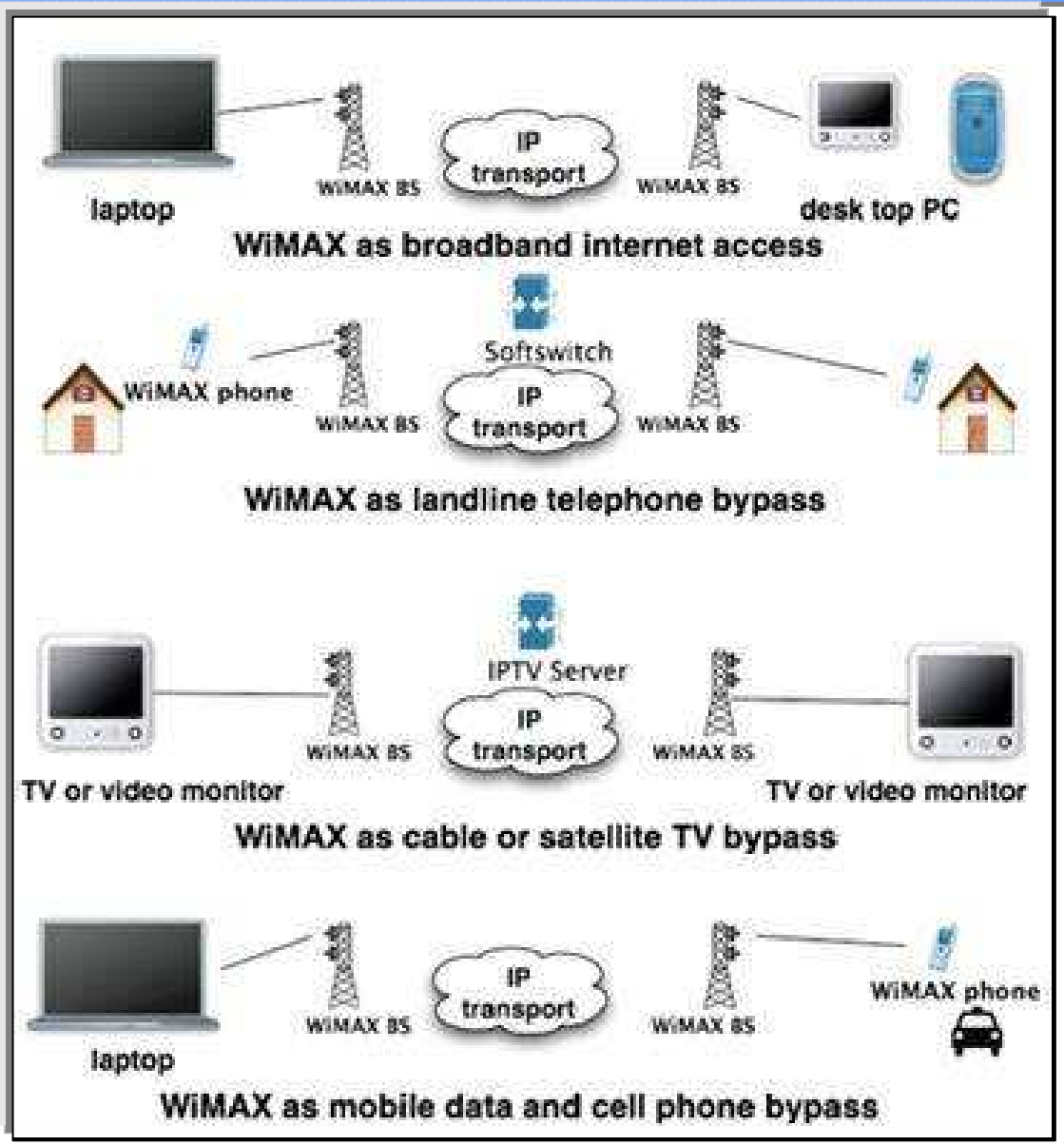
WiMAX purpose



Different structures



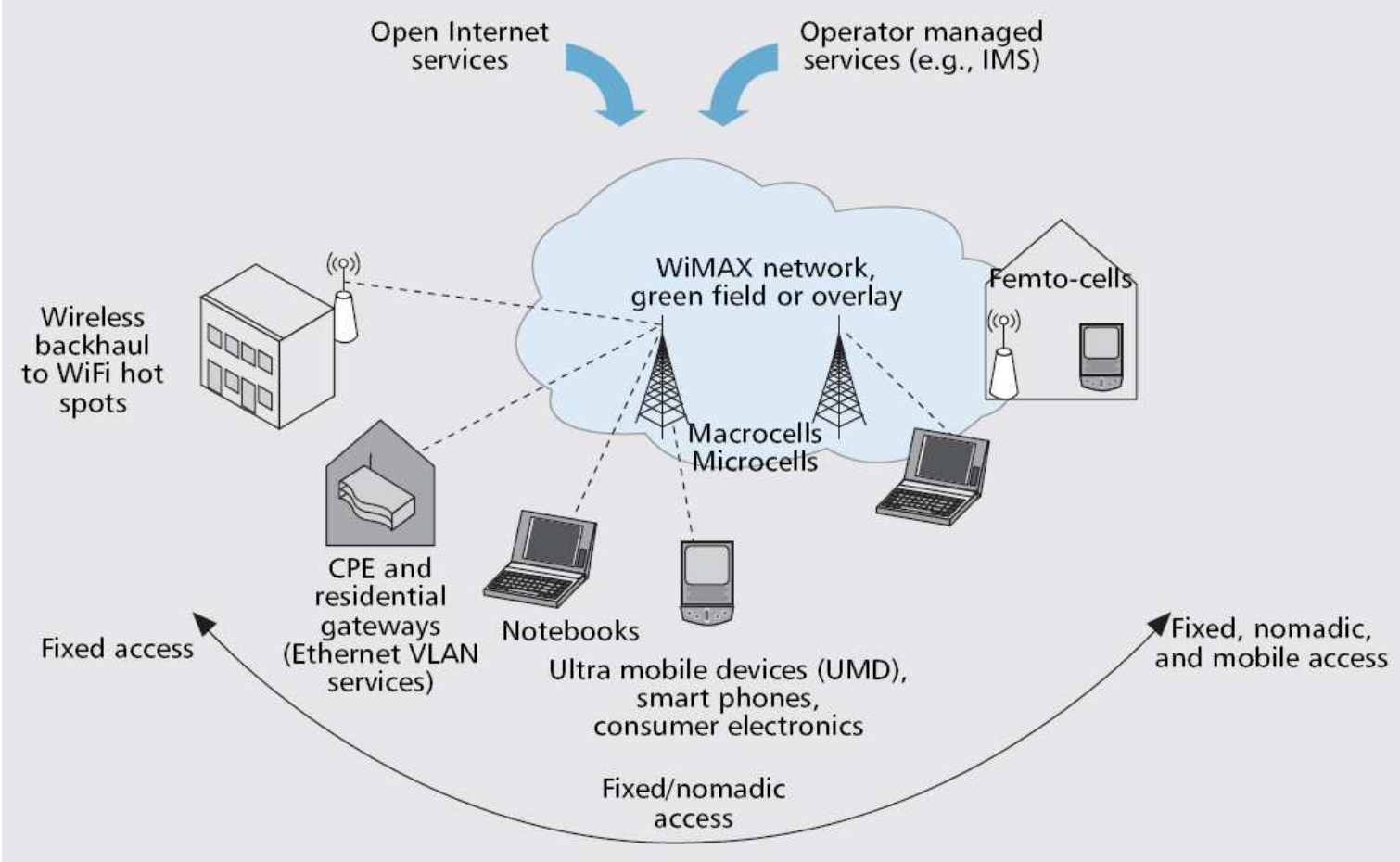
Different links



source C. Townsend

Complementarity

WiMAX and Mobile WiMAX enable a variety of usage models in the same network.



source IEEE Communications Magazine

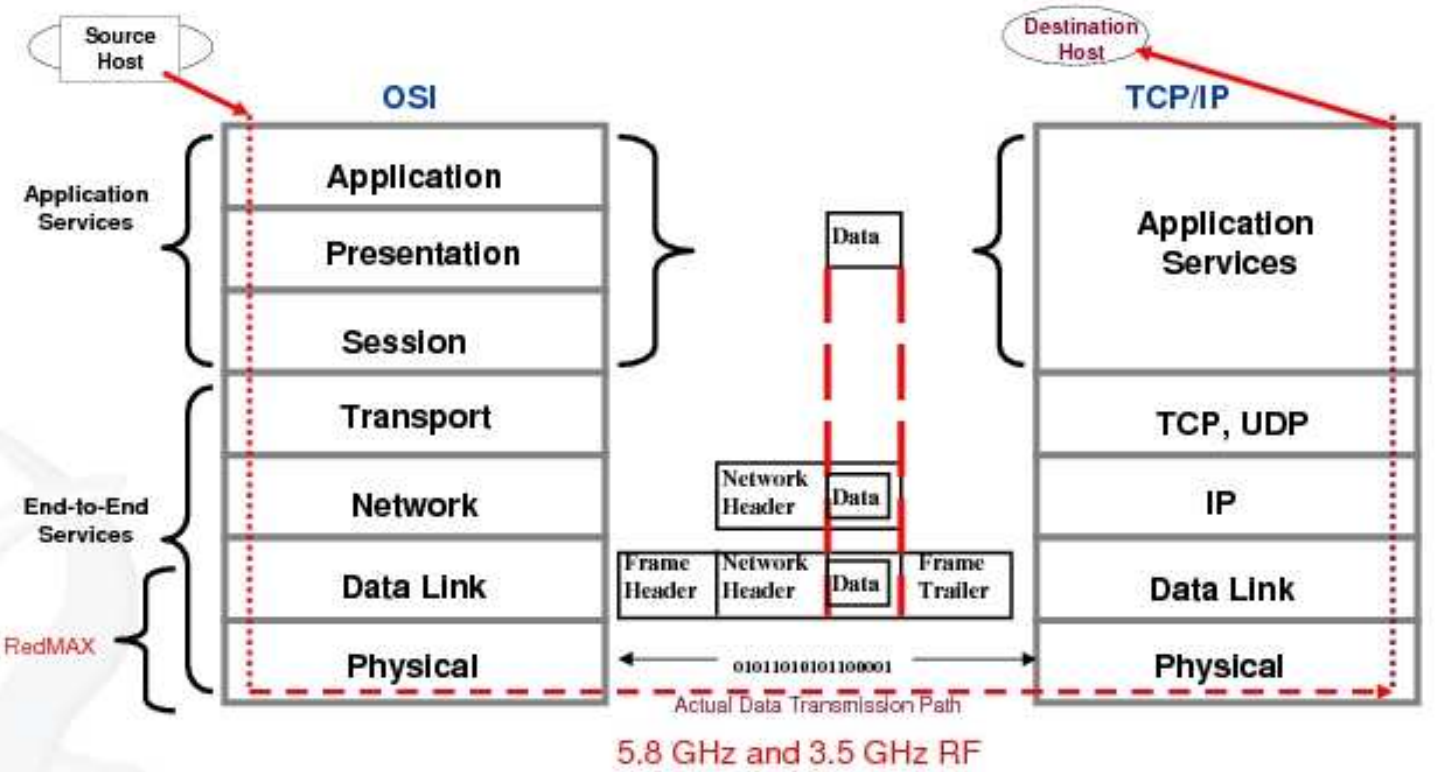
WiMAX ambition

WiMAX was established to enable very high data rate broadband wireless access in variety of deployment: Urban, Rural or even indoor.

Moreover the terminal could have full mobility, implying all problems of pathloss, shadowing and fading effects.

The standard is designed to be as scalable as possible.

OSI layers



Ethernet Header	IP Header (20)	TCP/UDP Header (20/8)	Data	Ethernet Trailer

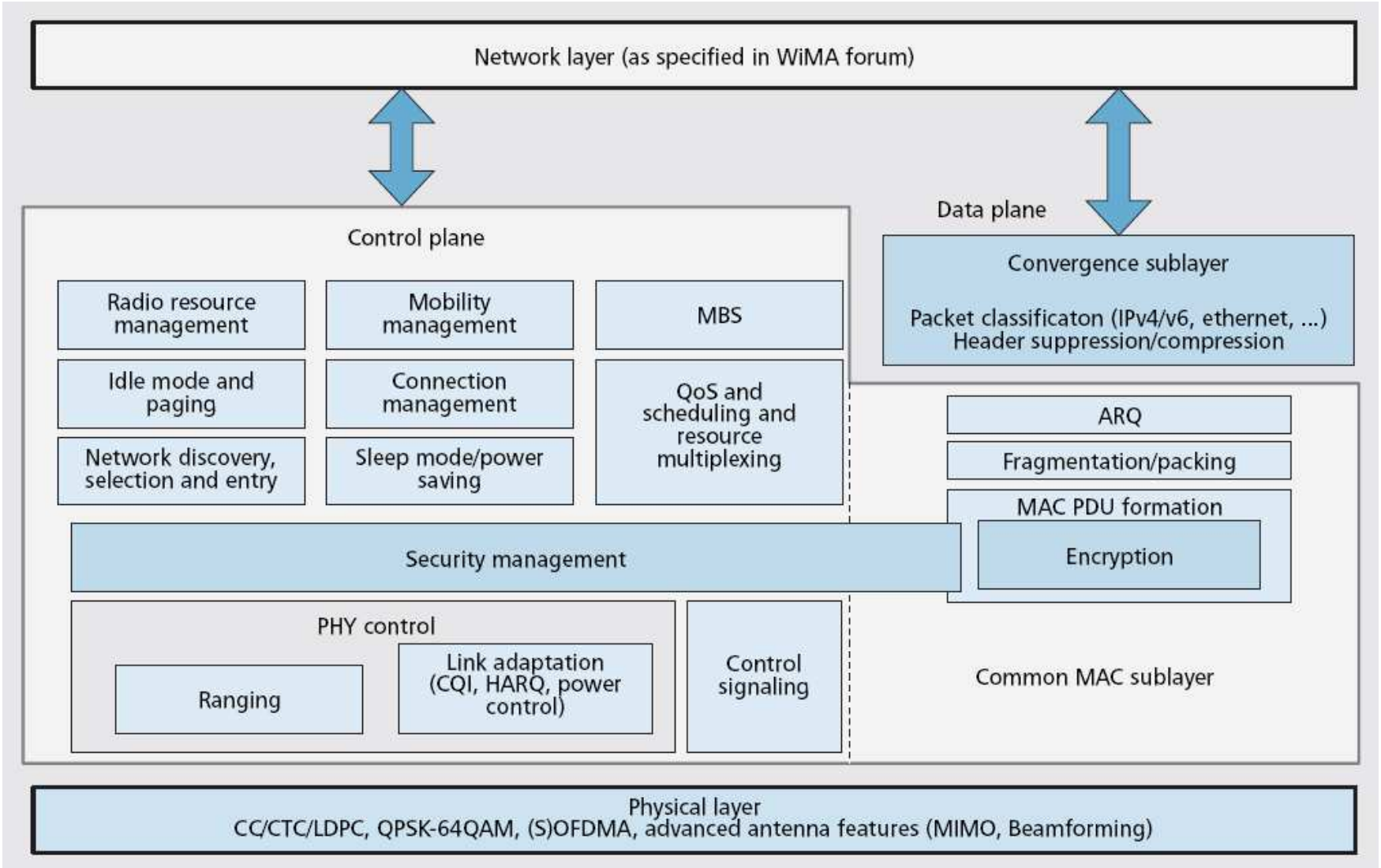
MAC/PHY

A common MAC layer applicable with different PHYs

Designation	Applicability	PHY	Additional MAC requirements	Options	Duplexing alternative
WirelessMAN-SC™	10–66 GHz	8.1			TDD FDD
WirelessMAN-SCa™	Below 11 GHz licensed bands	8.2		AAS (6.3.7.6) ARQ (6.3.4) STC (8.2.1.4.3)	TDD FDD
WirelessMAN-OFDM™	Below 11 GHz licensed bands	8.3		AAS (6.3.7.6) ARQ (6.3.4) Mesh (6.3.6.6) STC (8.3.8)	TDD FDD
WirelessMAN-OFDMA	Below 11 GHz licensed bands	8.4		AAS (6.3.7.6) ARQ (6.3.4) STC (8.4.8)	TDD FDD
WirelessHUMAN™	Below 11 GHz license-exempt bands	[8.2, 8.3, or 8.4] and 8.5	DFS (6.3.15)	AAS (6.3.7.6) ARQ (6.3.4) Mesh (6.3.6.6) (with 8.3 only) STC (8.2.1.4.3/8.3.8/ 8.4.8)	TDD

802.16d (2004) : fixed
802.16e (2005) : mobile

Air interface



source IEEE Communications Magazine

Main PHY features

LOS and NLOS environments
Licensed and un-licensed bands below 11 GHz
Flexible channel bandwidths: 1.5 to 20 MHz
TDD and FDD

Three physical layer technologies:
- *Single carrier*
- *OFDM with 256 point FFT (currently adopted by ETSI HiperMAN and (fixed) WiMAX)*
- *OFDMA with 128..2048 point FFT (dominant evolution in IEEE 802.16e with scalability of the FFT size according to the channel BW)*

Support of Adaptive Modulation and Smart Antennas

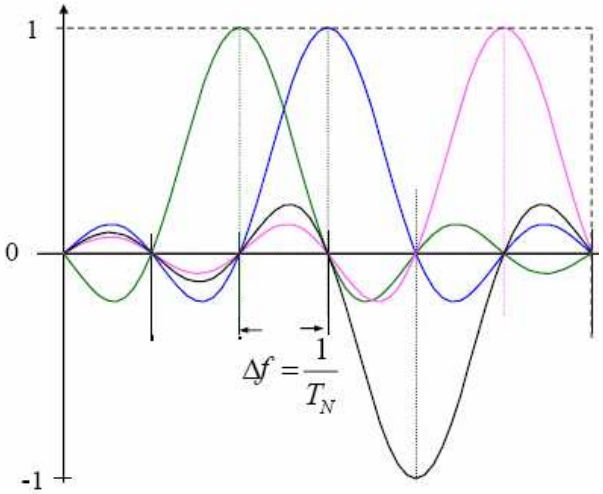
Main PHY features

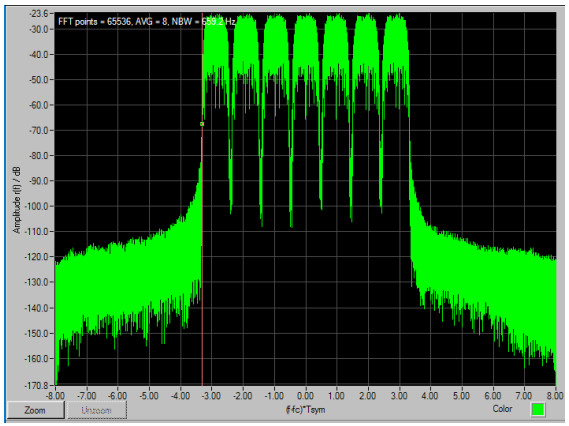
High theoretical spectral efficiency: up to 3.75 bps/Hz (Adaptive Modulation)

But dimensioning in real NLOS case in the range of 2 bps/Hz

Cell radius very dependant on the environment (NLOS, LOS, Urban, Rural), LOS up to 30km, NLOS 1 - 3 km

OFDM

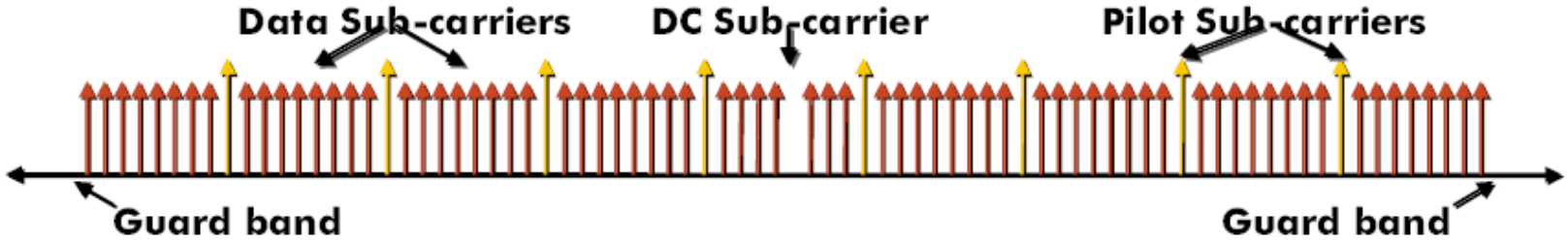




Robustness to multi-path / selective fading

Low complexity modulator / demodulator (iFFT/FFT) and equalizer

Spectrum efficiency



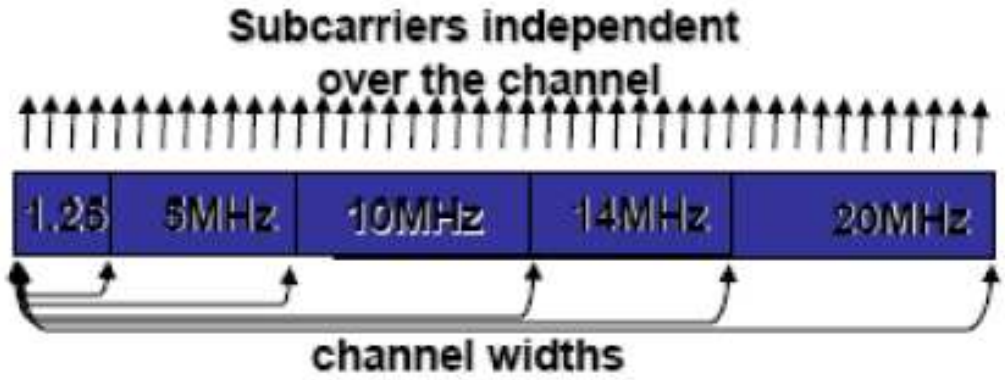
Scalability

Modulation scheme and power adjustable per sub-channel

WiMAX PHY/MAC improves OFDM with:

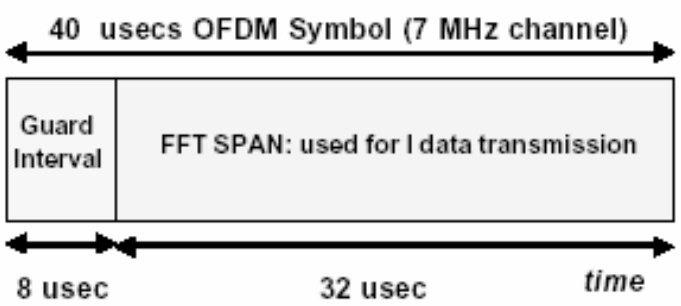
- *Robust transmission by use of error correction codes and interleaving*
- *Can recover data even in case of frequency-selective fading and narrow-band interference*

Scalable FFT size

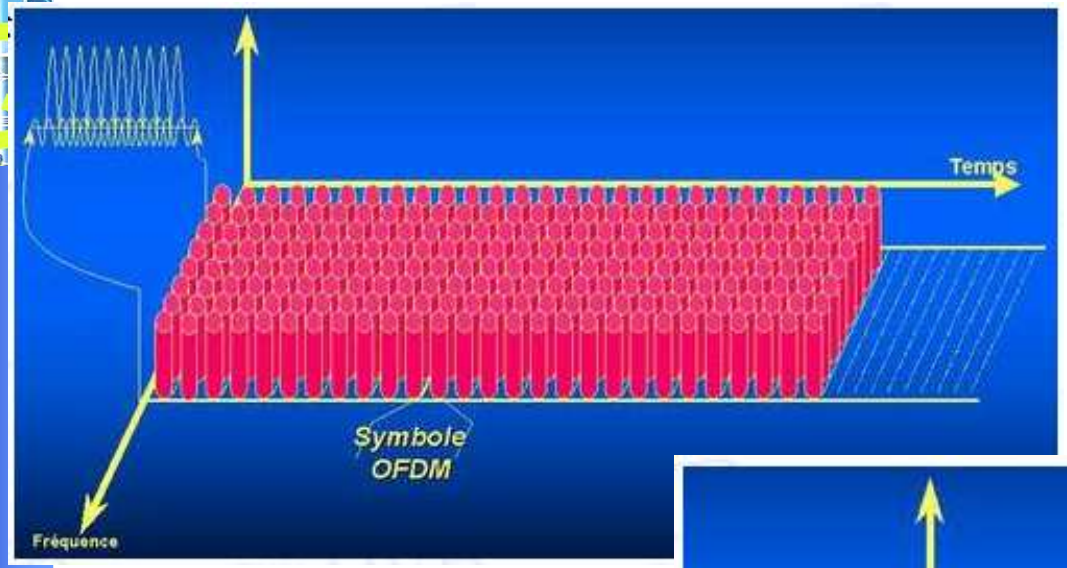


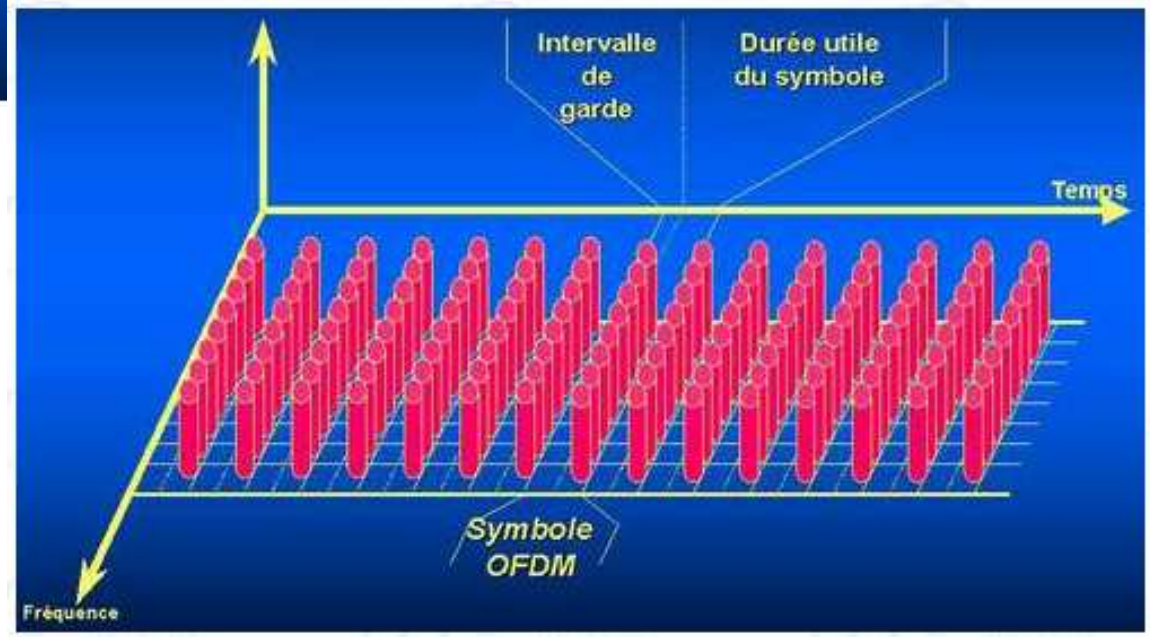
OFDM symbol

- *Pilot subcarriers inserted for channel estimation*
- *Guard Interval (GI=CP : Cyclic Prefix) at the beginning of each OFDM symbol*
- *CP : 1/4 , 1/8 , 1/16 , 1/32*
- *High CP increases robustness against multi-path*
- *CP must be longer than maximum path delay*



BW [MHz]	CP	OFDM Symbol [us]
14	1/4	20
	1/32	16.50
7	1/4	40
	1/32	33
3.5	1/4	80
	1/32	66


Temps
Symbole
OFDM
Fréquence

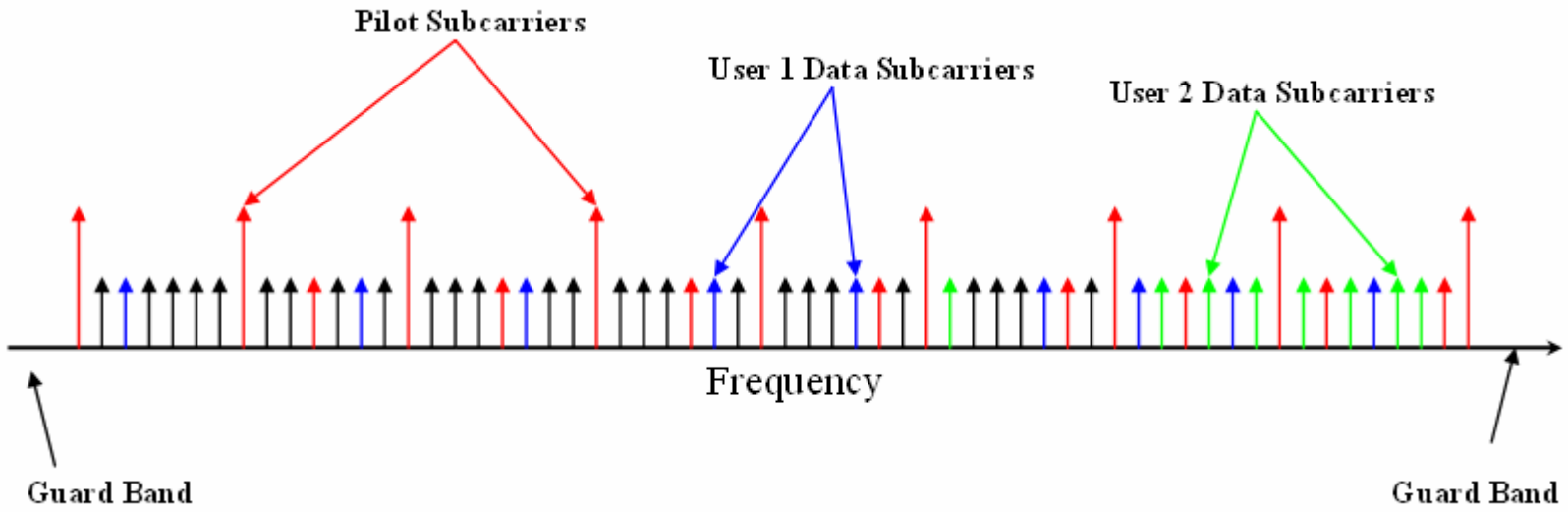

Intervalle
de
garde
Durée utile
du symbole
Temps
Symbole
OFDM
Fréquence

Modulation and Data rates

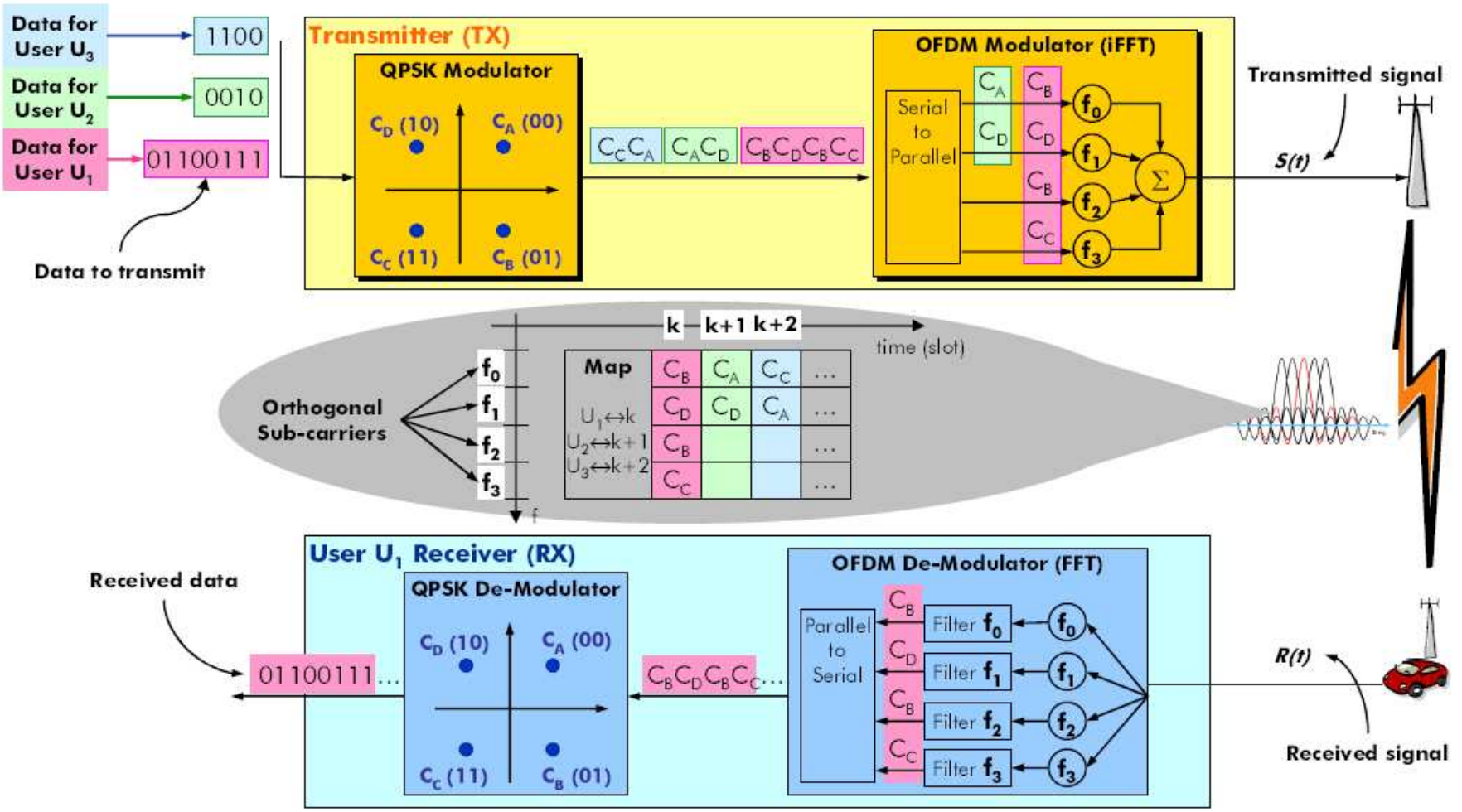
Channel BW [MHz]	Guard time	OFDM symbol duration [us]	Over the Air bit rate [Mbps]—PHY Layer				Uncoded Bit Rate [Mbps] – MAC Layer						
			BPSK	QPSK	16QAM	64QAM	BPSK 1/2	QPSK 1/2	QPSK 3/4	16QAM 1/2	16QAM 3/4	64QAM 2/3	64QAM 3/4
7	1/4	40.00	4.80	9.60	19.20	28.80	2.40	4.80	7.20	9.60	14.40	19.20	21.60
	1/8	36.00	5.33	10.67	21.33	32.00	2.67	5.33	8.00	10.67	16.00	21.33	24.00
	1/16	34.00	5.65	11.29	22.59	33.88	2.82	5.65	8.47	11.29	16.94	22.59	25.41
	1/32	33.00	5.82	11.64	23.27	34.91	2.91	5.82	8.73	11.64	17.45	23.27	26.18
3.5	1/4	80.00	2.40	4.80	9.60	14.40	1.20	2.40	3.60	4.80	7.20	9.60	10.80
	1/8	72.00	2.67	5.33	10.67	16.00	1.33	2.67	4.00	5.33	8.00	10.67	12.00
	1/16	68.00	2.82	5.65	11.29	16.94	1.41	2.82	4.24	5.65	8.47	11.29	12.71
	1/32	66.00	2.91	5.82	11.64	17.45	1.45	2.91	4.36	5.82	8.73	11.64	13.09

OFDMA

The OFDM principle is used to share the resource between users. Subcarriers are assigned to different users at the same time. S-OFDMA allows FFT-size scalability.

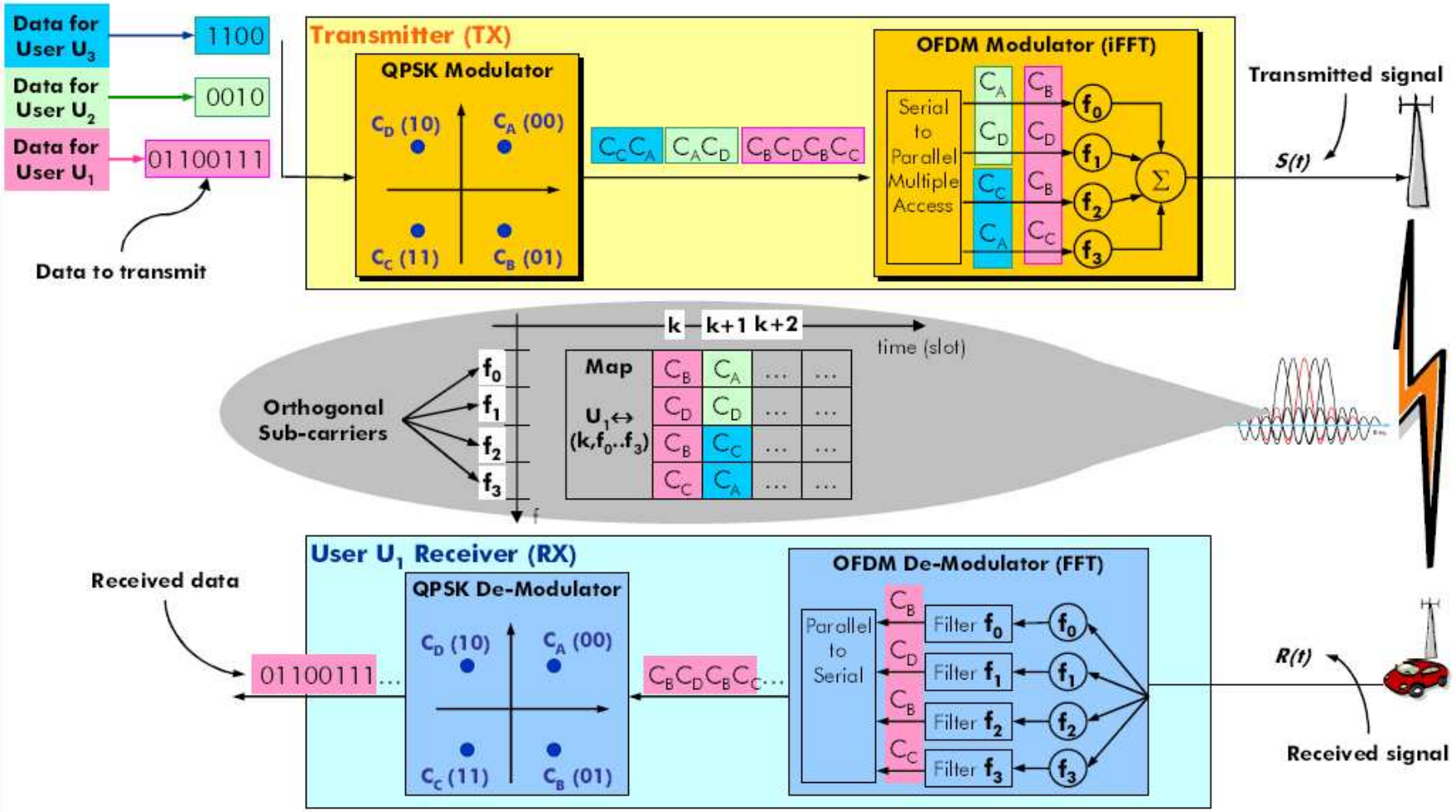


OFDM

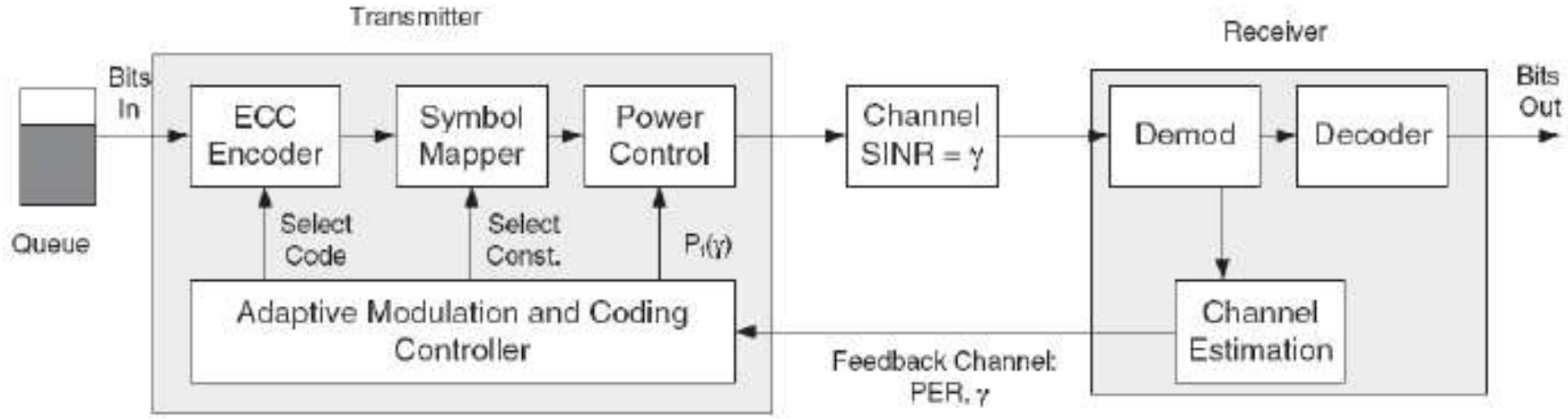


source Alcatel-Lucent

S-OFDMA


Data for User U_3
1100
Data for User U_2
0010
Data for User U_1
01100111
Data to transmit
Transmitter (TX)
QPSK Modulator
C_D (10)
C_A (00)
C_C (11)
C_B (01)
C_CC_A C_AC_D $C_BC_DC_BC_C$
OFDM Modulator (iFFT)
Serial to Parallel Multiple Access
f_0 f_1 f_2 f_3
Transmitted signal
S(t)
k k+1 k+2
time (slot)
Orthogonal Sub-carriers
Map
$U_1 \leftrightarrow (k, f_0..f_3)$
R(t)
Received signal
User U_1 Receiver (RX)
Received data
01100111...
QPSK De-Modulator
$C_BC_DC_BC_C$...
OFDM De-Modulator (FFT)
Parallel to Serial
Filter f_0
Filter f_1
Filter f_2
Filter f_3

Adaptive Modulation and Coding

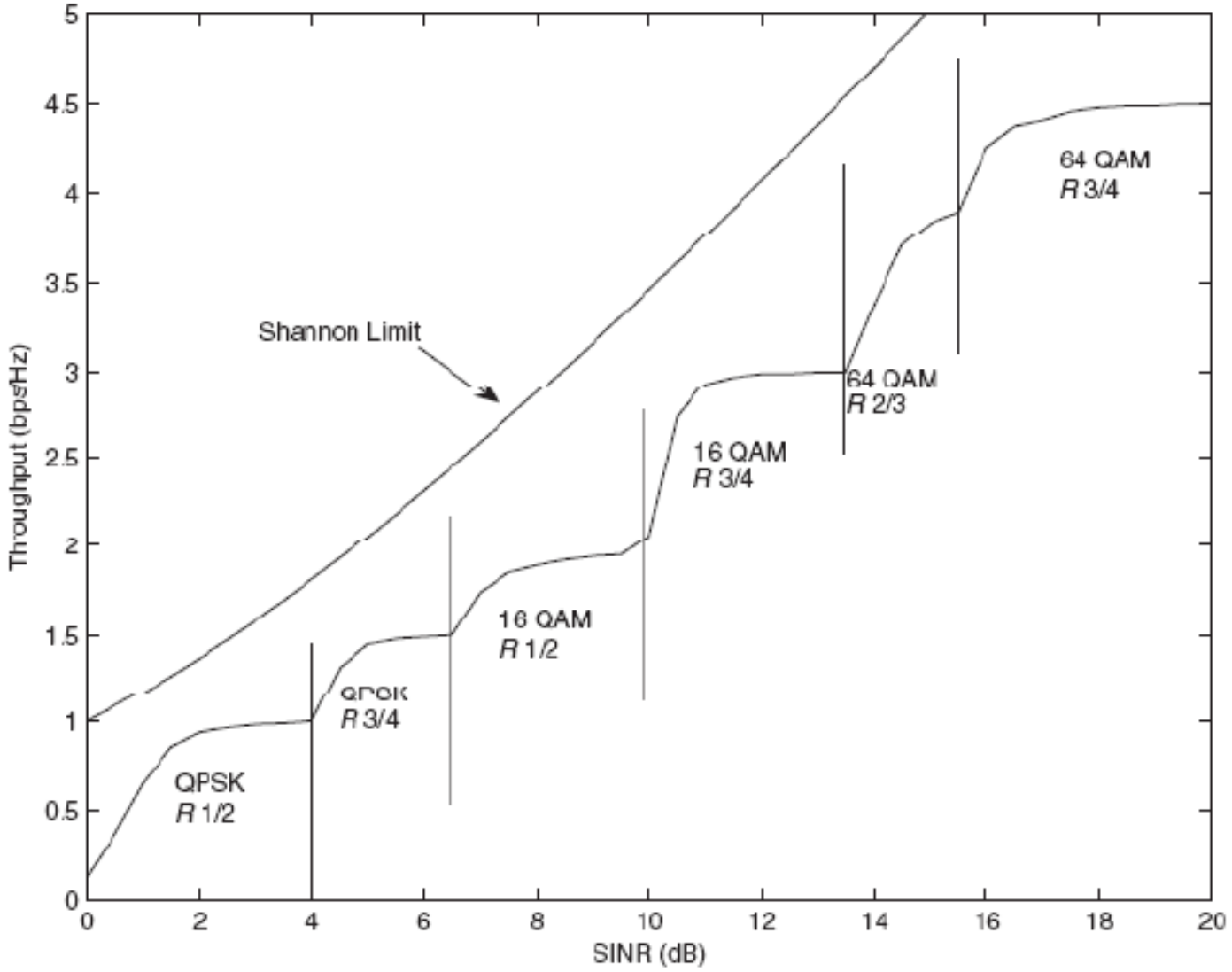


Adaptive Modulation and Coding (AMC) is used to adjust modulation order and coding rate to the channel conditions in order to optimize the data rate.

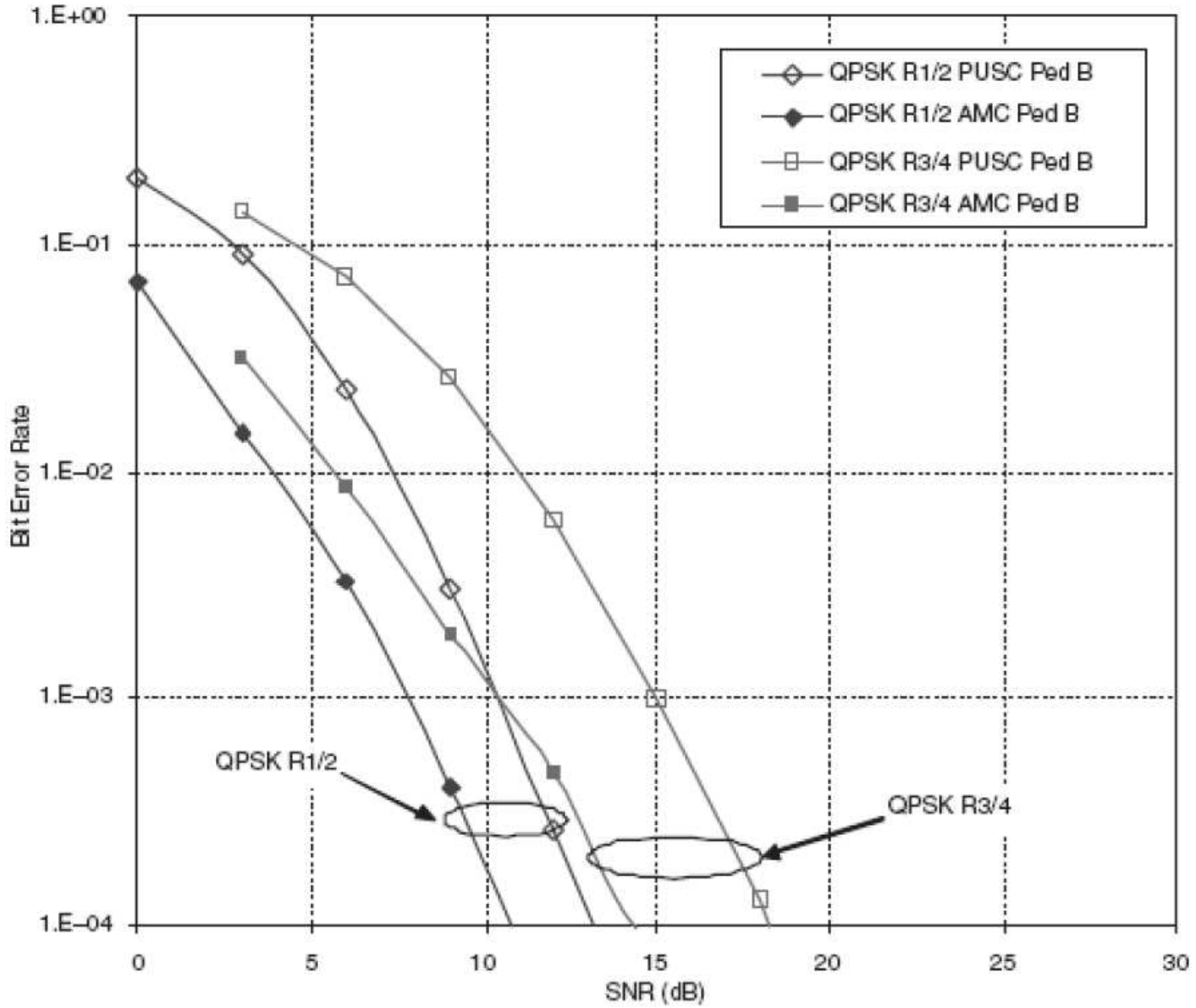
Modulation and Coding rates

Modulation	Code rate	5 MHz channel		10 MHz channel	
		Downlink rate (Mb/s)	Uplink rate (Mb/s)	Downlink rate (Mb/s)	Uplink rate (Mb/s)
QPSK	1/2 CTC, 6x	0.53	0.27	1.06	0.56
	1/2 CTC, 4x	0.79	0.41	1.59	0.84
	1/2 CTC, 2x	1.59	0.82	3.17	1.68
	1/2 CTC, 1x	3.17	1.63	6.34	3.36
	3/4 CTC	4.75	2.45	9.50	5.04
16-QAM	1/2 CTC	6.34	3.26	12.67	6.72
	3/4 CTC	9.50	4.90	19.01	10.08
64-QAM	1/2 CTC	9.50	4.90	19.01	10.08
	2/3 CTC	12.67	6.53	25.34	13.44
	3/4 CTC	14.26	7.34	28.51	15.12
	5/6 CTC	15.84	8.16	31.68	16.80

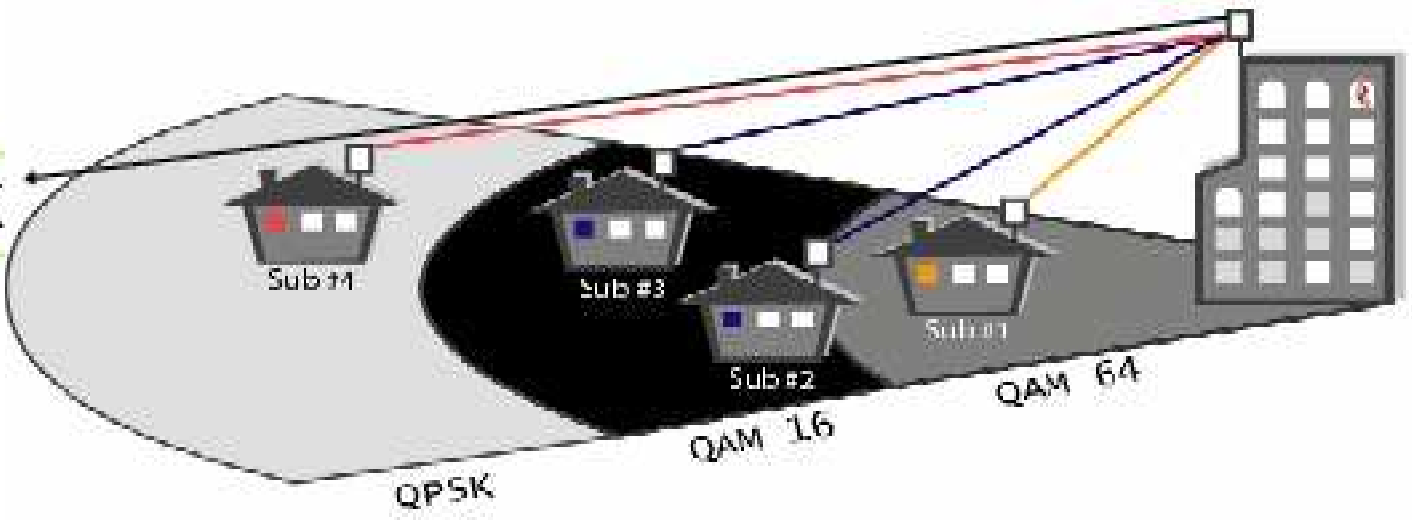
Channel capacity

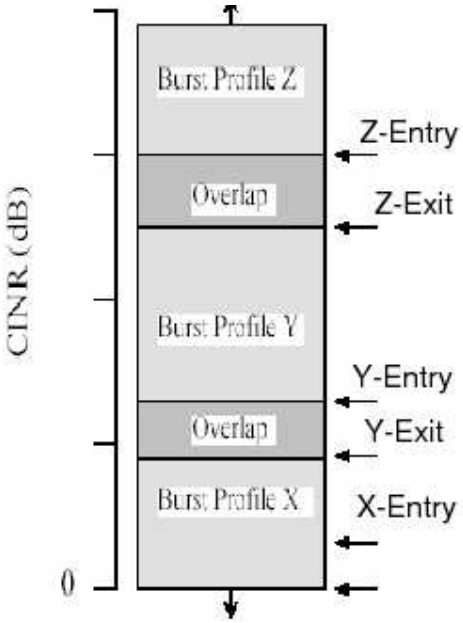


Example at pedestrian speed



Rate zones



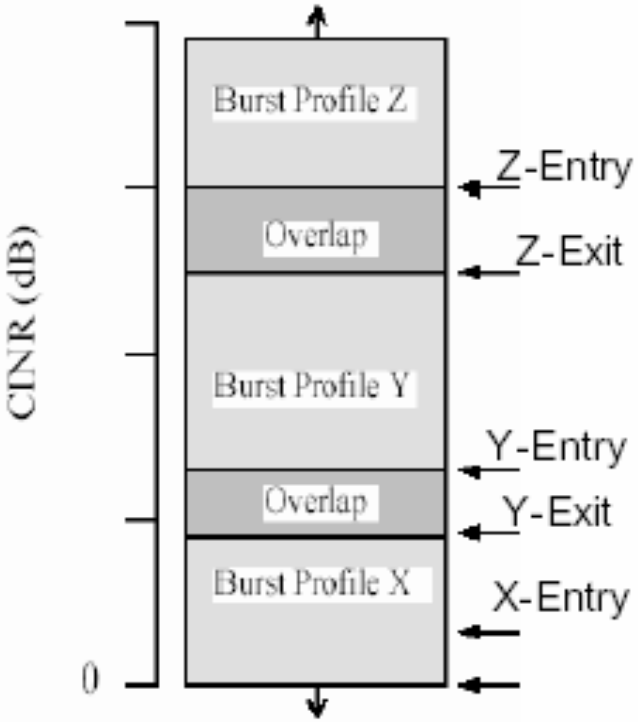


Modulation	Coding rate	CINR (dB)
BPSK	1/2	3
QPSK	1/2	6
QPSK	3/4	8.5
16QAM	1/2	11.5
16QAM	3/4	15
64QAM	2/3	19
64QAM	3/4	21

Decision threshold

Each rate has two thresholds: one to enter in this rate, the other to decide to change rate.

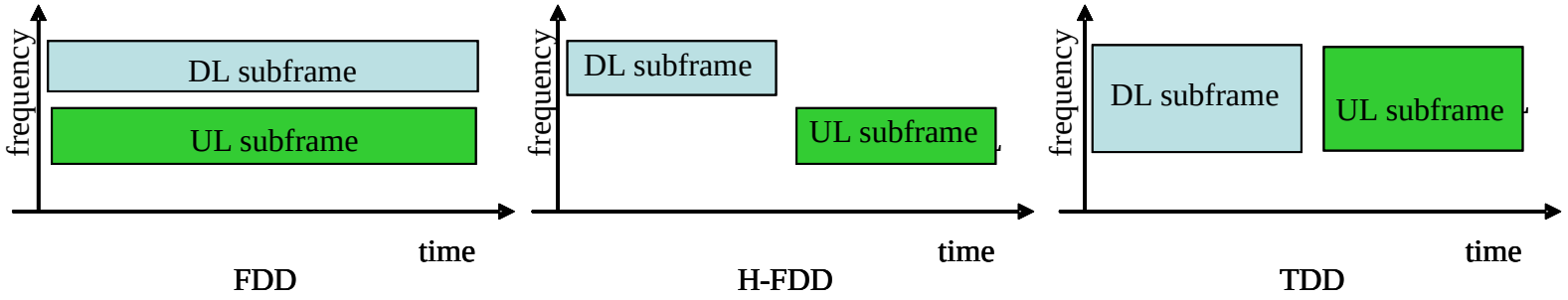
64QAM(3/4)=>64QAM(2/3)	23.25	=	64QAM(3/4)<=64QAM(2/3)	24.00
64QAM(2/3)=>16QAM(3/4)	19.13	=	64QAM(2/3)<=16QAM(3/4)	19.88
16QAM(3/4)=>16QAM(1/2)	16.50	=	16QAM(3/4)<=16QAM(1/2)	17.25
16QAM(1/2)=>QPSK(3/4)	11.25	=	16QAM(1/2)<=QPSK(3/4)	12.00
QPSK(3/4) =>QPSK(1/2)	8.63	=	QPSK(3/4) <=QPSK(1/2)	9.38



Duplexing

TDD:
Frame duration is fixed.
Frame contain a DL subframe and an UL subframe with variable duration.

FDD:
A fixed duration of frame for DL and UL
H-FDD mode: SS can not transmit and receive at the same time.



WiMAX bands

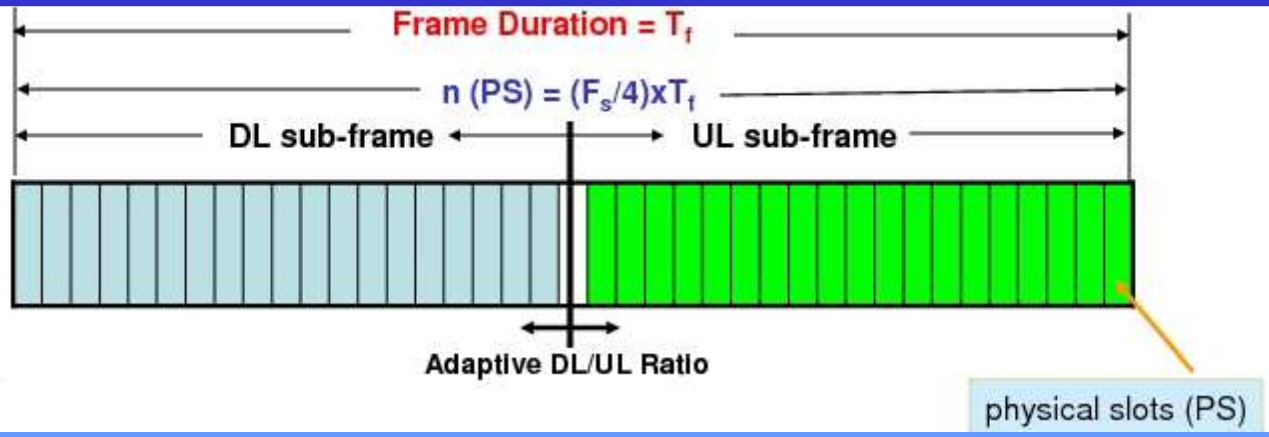
Profile	Band	Channel BW*	Duplex	License
700*	Upper 700 MHz Band	5 MHz	TDD	Yes
2.3T1*	WCS Band	5 MHz	TDD	Yes
2.5T1	MDS (BRS-EBS Band)	5 MHz	TDD	Yes
3.5T1	3.5 GHz Band	7 MHz	TDD	Yes
3.5F1	3.5 GHz Band	3.5 MHz	FDD	Yes
5.8T1	5.8 GHz ISM/UNII	10 MHz	TDD	No

* future potential WiMAX bands & channels

Frame subdivisions

Main frame characteristics:

- *Physical Slot (PS) : shortest unity of time dimensioned with respect to sampling frequency (0.5 ms @BW=7MHz)*
- *Time slot or Burst: time dedicated to one user (in PS unity)*
- *Symbol: duration depending on the number of subcarriers and frequency band (between 17 to 160 ms OFDM and 92 to 112 ms OFDMA)*
- *DL subframe: BS transmit to all MS*
- *UL subframe: shared between MS depending on CIR*
- *DL/UL ratio scalable*



Frame duration

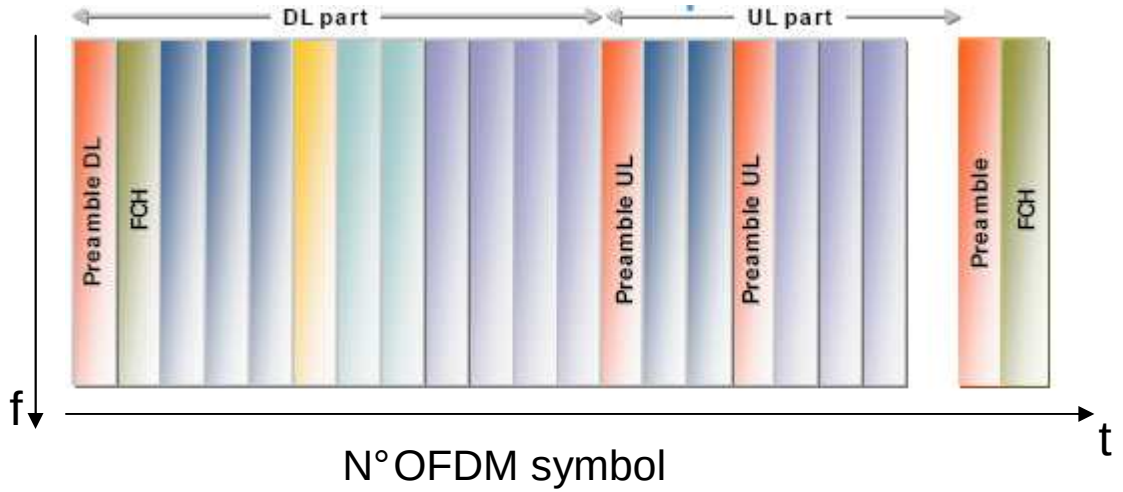
	Channel Bandwidth (MHz)			Frames/sec
Frame duration (ms)	7	3.5		
2.5	X			400
4	X	X		250
5	X	X		200
8	X	X		125
10	X	X		100
12.5	X	X		80
20	X	X		50

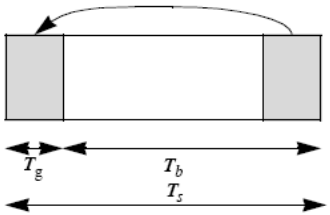
- *Frame duration related to latency and throughput*
- *Long frames increas latency*
- *Minimum latency time is equal to frame duration*
- *Maximum tolerated latency time is 1.5x frame duration*
- *Synchronized MS must use the same value*

OFDM Frame

- 256 subcarriers
- BPSK to 64QAM adaptive modulation
- Adaptive forward error coding (FEC)
- TDM multiple access
- Duplex TDD or FDD
- Space-time coding (STC)
- Beamforming (AAS)

- RF Frequency <11GHz 3.5GHz (licence)
- BW 3.5 or 7 MHz
- Frame duration 2.5-20 ms
- Effective Symbol time: Tb=64/32 us
- CP :Tg=1/4,1/8,1/16,1/32
- Total symbol time: Tg+Tb

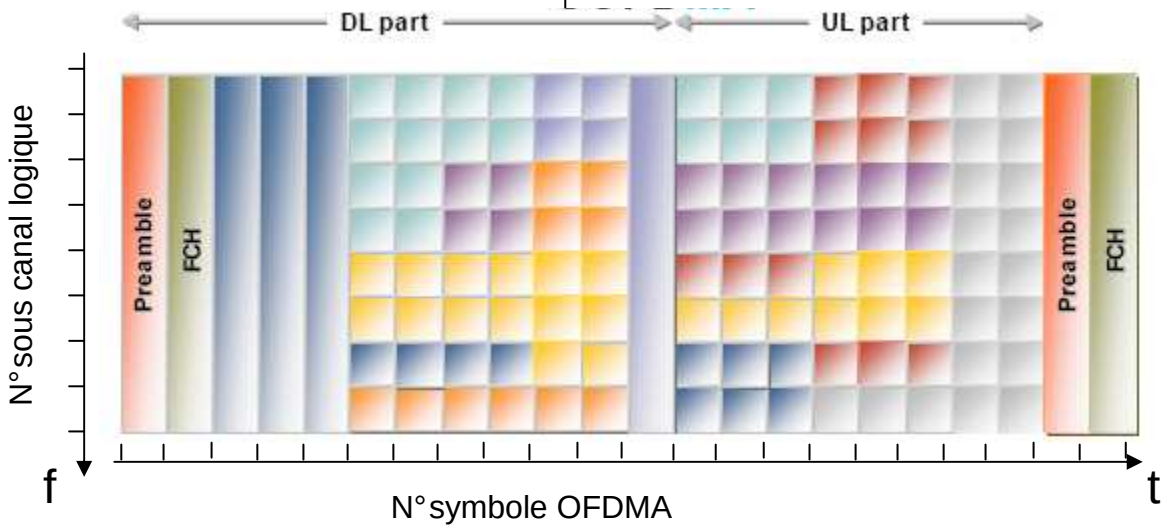




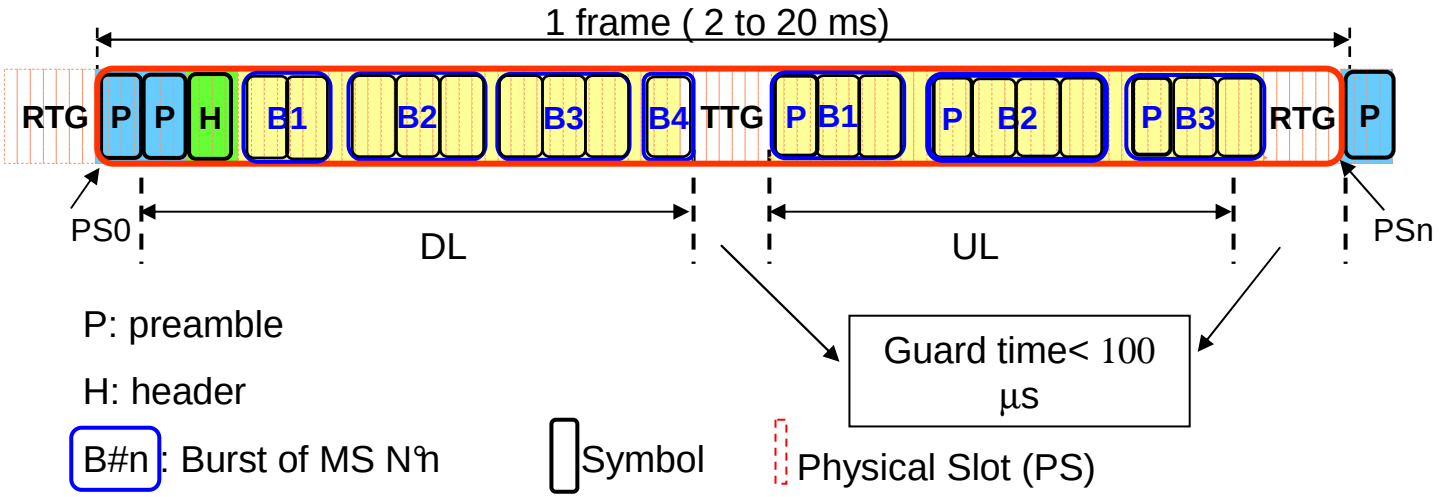
OFDMA Frame

- *128 to 2048 subcarriers (depend on BW)*
- *BPSK to 64QAM adaptive modulation*
- *Convolutional channel coding*
- *Duplex TDD or FDD*
- *Space-time coding (STC)*
- *Beamforming (AAS)*
- *Handover*

- *RF Frequency <11GHz 3.5GHz (licence)*
- *BW 1.25/5/10 or 20 MHz*
- *Frame duration 2.5-20 ms*
- *Effective Symbol time: Tb=90 us*
- *CP :Tg=1/4,1/8,1/16,1/32*
- *Total symbol time: Tg+Tb*



OFDM Frame Focus



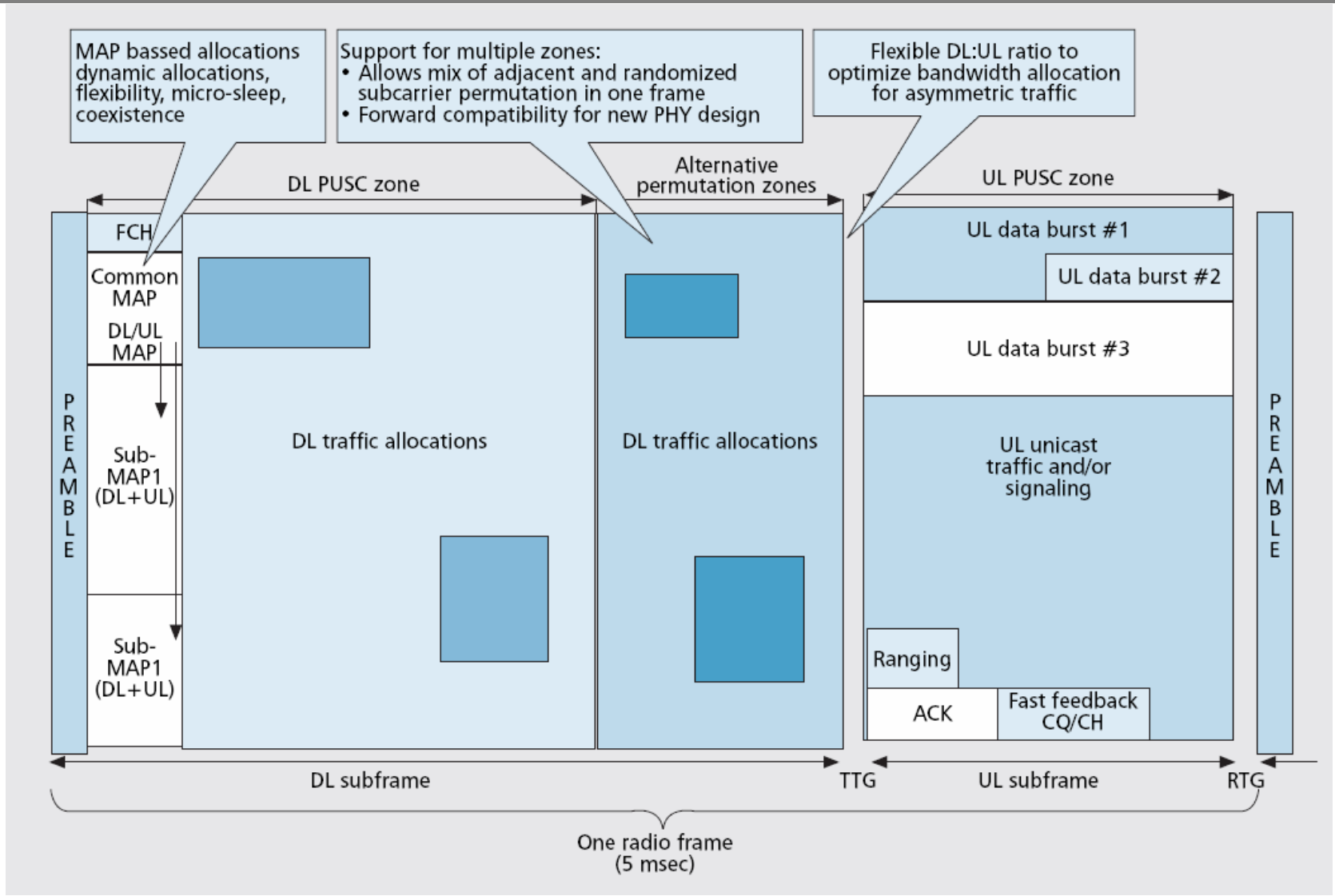
Downlink

- *Preamble : synchronization channel estimation*
- *Header: frame structure (bursts location and profile)*
- *Data to transmit to each user (TDM)*

Uplink

- *TDMA*
- *Preamble : synchronization*

OFDMA Frame Focus



OFDM symbol:102.9 us, 48 symbols by frame

Important fields

- *Preamble*

Used for:

- *Time frequency synchronization*
- *Initial channel estimation*
- *Identify the segment used by the cell*
- *Identify the cell*

Occupies all subchannels of the first OFDMA symbol
Must be received and decoded by all MSs
Modulation BPSK + transmission power +3dB w.r.t. DL bursts
Use orthogonal codes (i.e. modulate on disjoint sets of subcarriers)

- *Frame Control Header (FCH)*

In each frame, provides information about the frame and the related MAPs

- *Used sub-channels in the segment*
- *DL MAP length …*

Positioned immediately after the preamble (in the specific segment)

Broadcast information

DL MAP and UL MAP

Provide information on resource allocation for DL and UL respectively

The "description" of the bursts present in the frame (i.e. modulation and coding, based on so called DIUC)

The position and size of each burst in the OFDM matrix (Offset in frequency x time, Size in terms of symbols and subchannels)

The list of connection ID of each burst

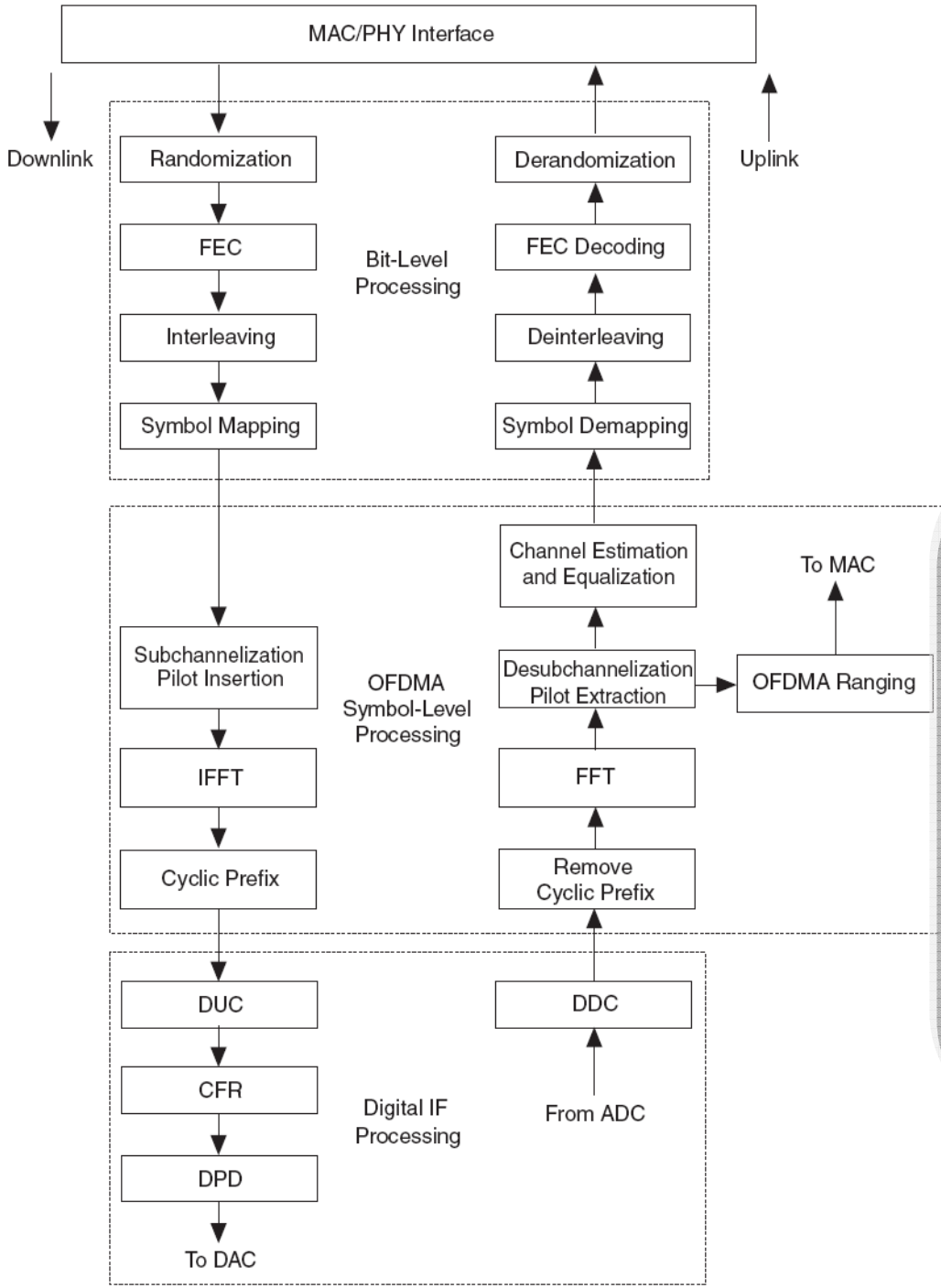
DL Channel Descriptor (DCD) & UL Channel Descriptor (UCD)

- *Provide system PHY information (BS EIRP, TTG / RTG, Paging Group ID, BS ID, Frame number, Contention access details…)*
- *Provide the physical transmission characteristics for each Burst Profile (DIUC used in the DL/UL MAP, Associated PHY characteristics (FEC code type): modulation & coding scheme)*
- *Transmitted at periodic interval of maximum 10 seconds*

Some values

Parameter	Mobile WiMAX		WiBRO
Nominal bandwidth	10 MHz*	7 MHz	8.75 MHz
Subcarrier spacing	10.9375 kHz*	7.8125 kHz	9.7656 kHz
Useful symbol time (Ts = 1/subcarrier spacing)	91.4 µs	128 µs	102.4 µs
Guard Time (Tg = Ts/8)	11.4 µs	16 µs	12.8 µs
OFDMA symbol duration (Ts + Tg)	102.9 µs	144 µs	115.2 µs
Number of symbols in frame	47	33	42
TTG+RTG	464 PS*	496 PS	404 PS
Frame length	5 ms	5 ms	5 ms
Sampling frequency (Fs = FFT points x subcarrier spacing)	11.2 MHz*	8 MHz	10 MHz
Physical slot (PS) (4/Fs)	357.14 ns	500 ns	400 ns

source Agilent



source Altera

Baseband processing

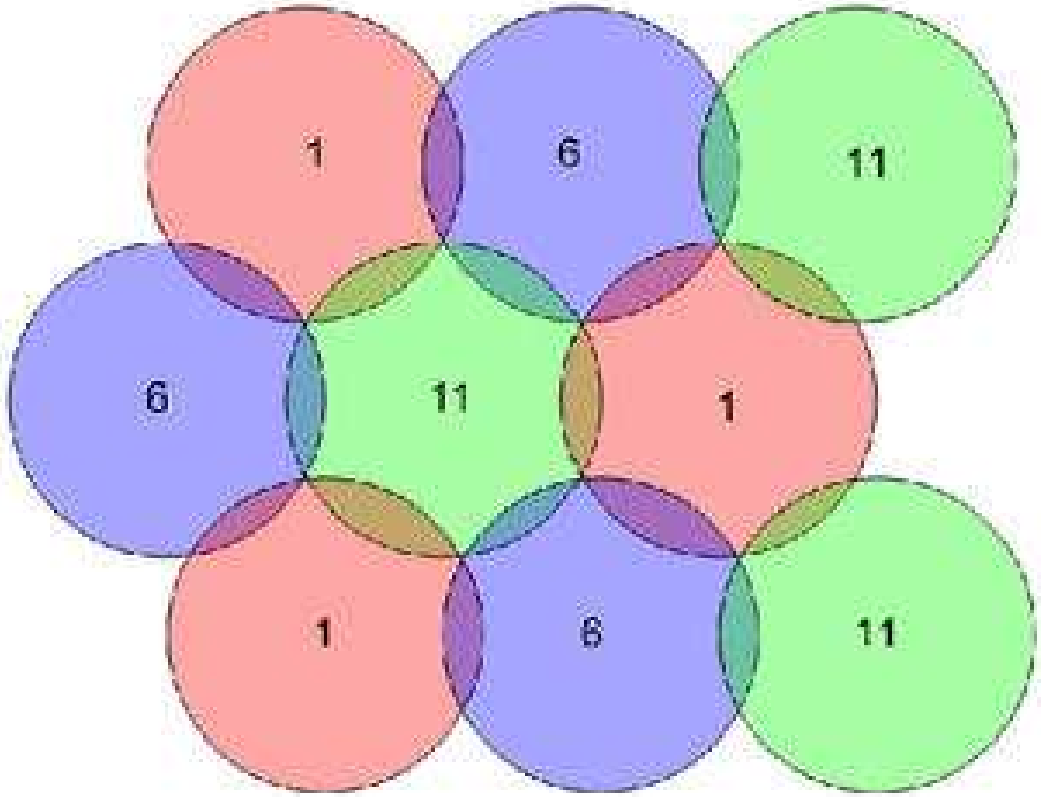
The digital IF processing blocks include single antenna and multiantenna digital up converter (DUC) and digital down converter (DDC)
reference designs, and advanced crest factor reduction (CFR) and digital predistortion (DPD)

Complementary techniques

- *HARQ (hybrid automatic repeat request):*
  - *– adaptive retransmission to cope with high error probabilities*
  - *– soft recombination*
- *CQICH : Channel quality indicator channel*
  - *– consumes uplink bandwidth*
  - *– feedback reduction is an up to date problem*

Cellular extension

In case of large scale deployment, a frequency planning must be performed in order to reduce inter-cell interference.

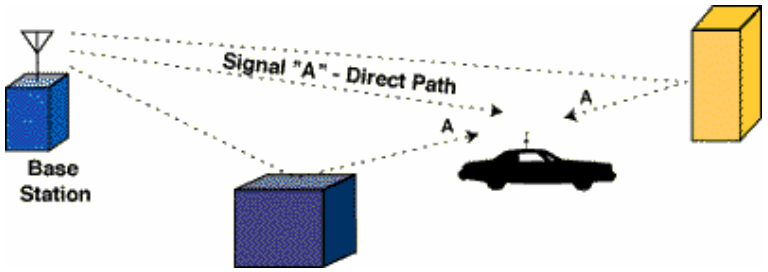


Multiple Antenna Systems

Diversity principle

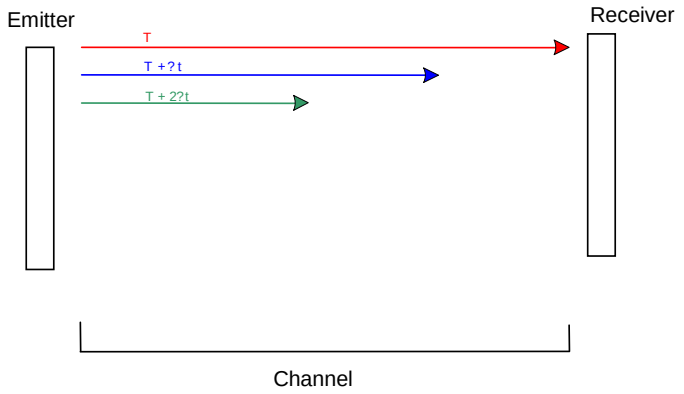
Diversity corresponds to degrees of freedom of the channel.
We could consider four main degrees of diversity:

- *Time*
- *Frequency*
- *Polarization*
- *Space*

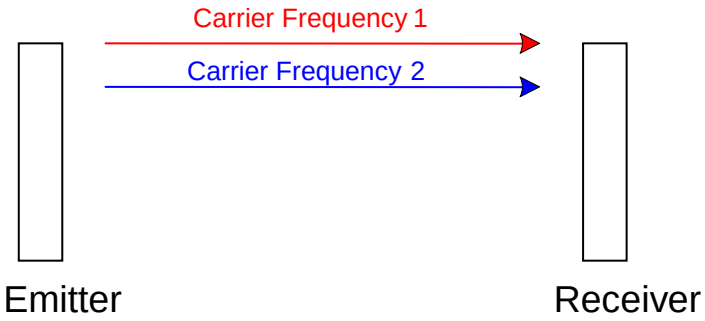


Diversity domains

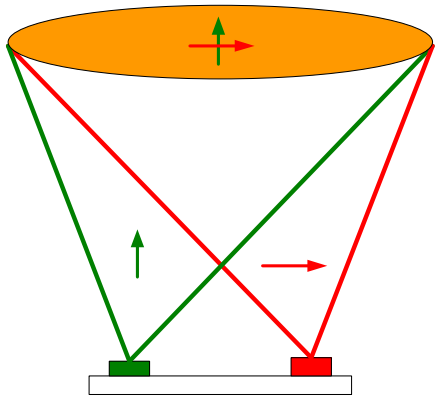
Time Diversity



Frequency Diversity



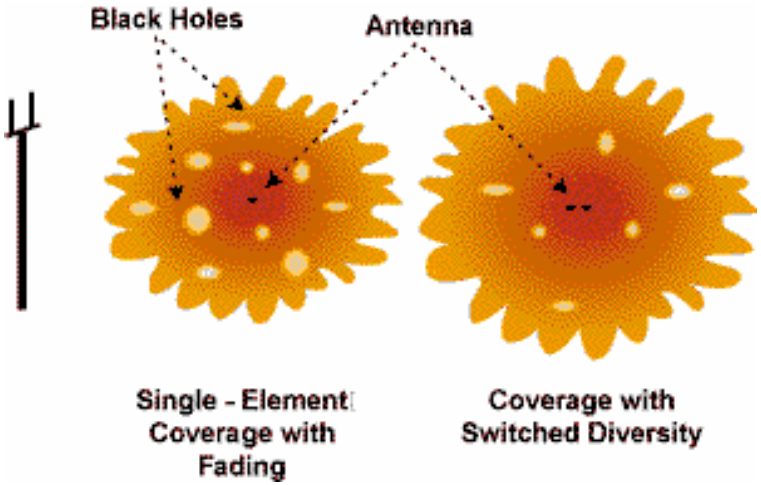
Polarization Diversity

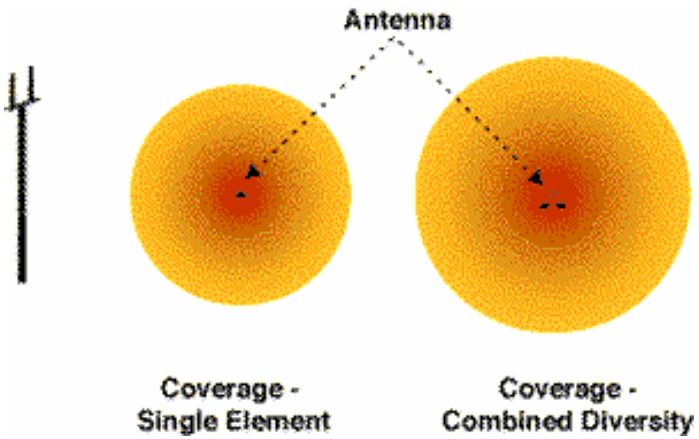


Spatial Diversity

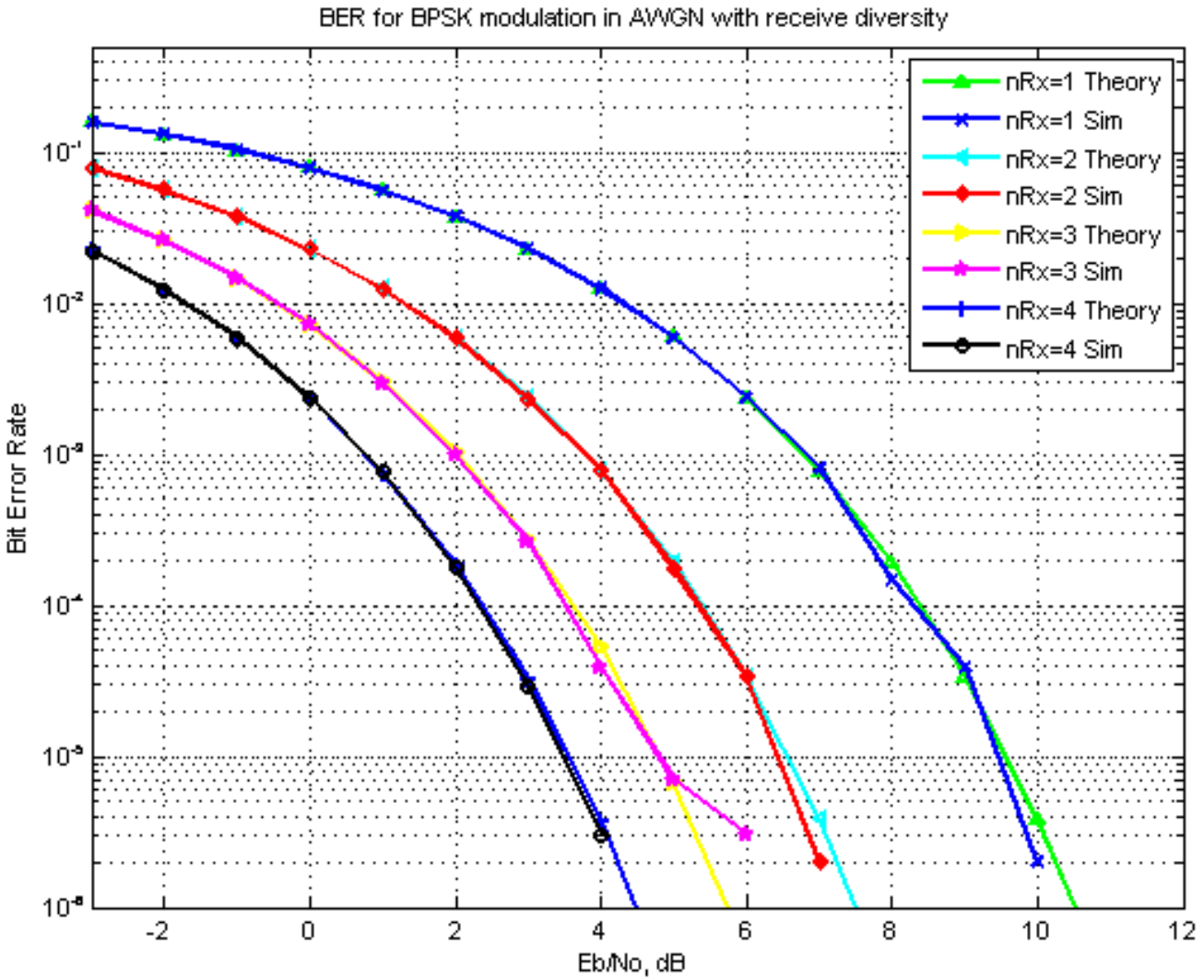
Diversity in space location :

The use of two antennas with space diversity allows to mitigate multi-path fading effect.





Receive diversity



SISO to MIMO

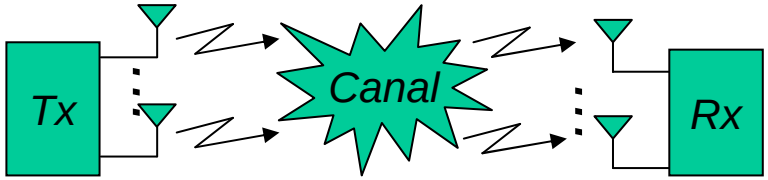
Main techniques :

- SISO : Single Input Single Output
  - Old fashion radio link

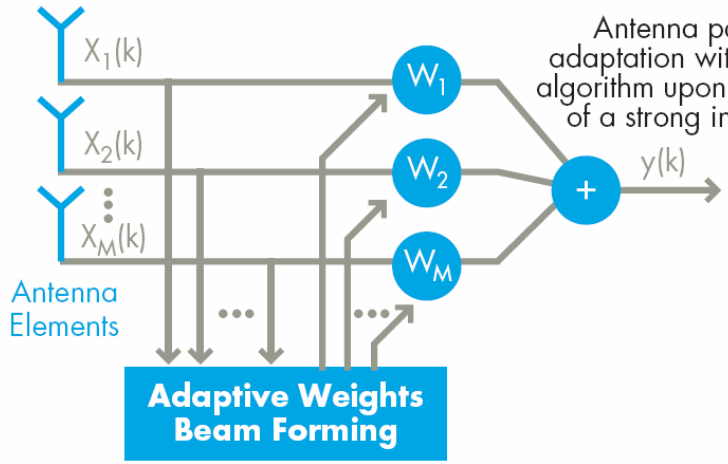
- SIMO : Single Input Multiple Output
  - Most mature
  - Different implementations

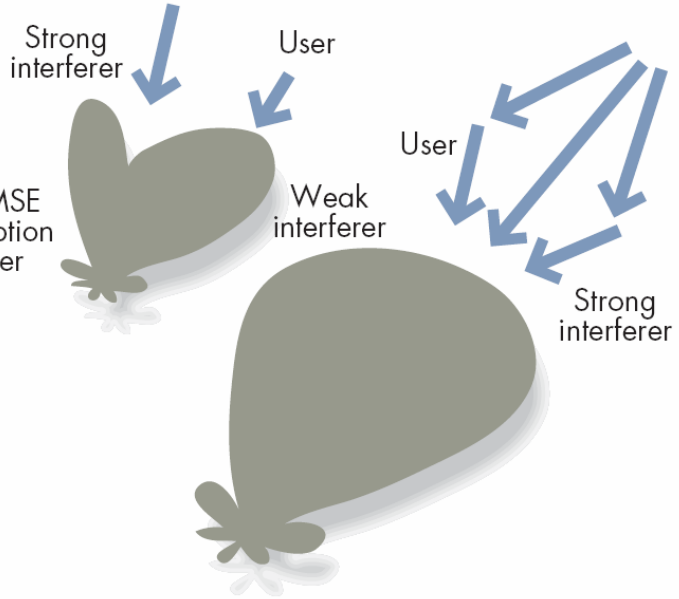
- MISO : Multiple Input Multiple Output
  - Beamforming
  - Diversity, coding

- MIMO : Multiple Input Multiple Output
  - Spatial Multiplexing
  - STBC, STTC

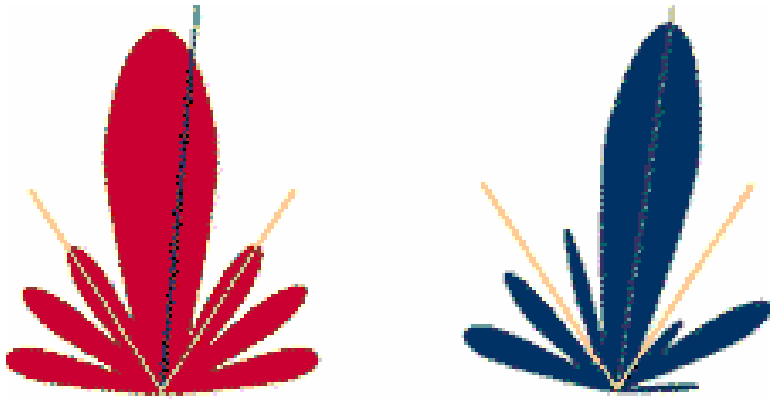


SIMO or MISO





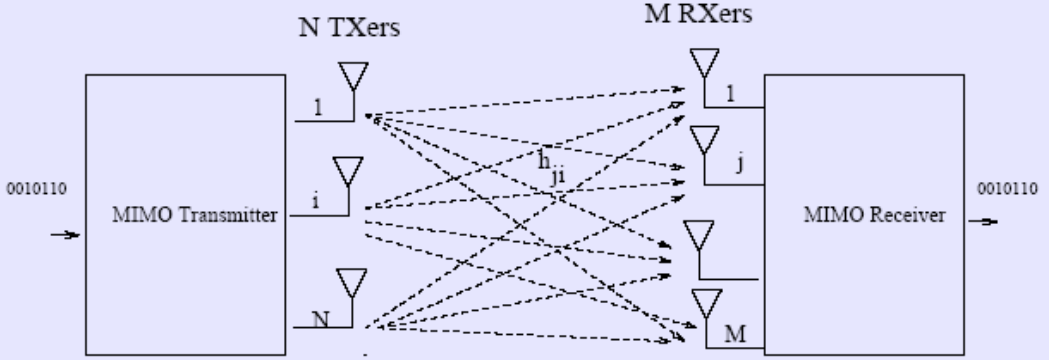
By combining several antennas at Tx or Rx, the system could take part of diversity (and mitigate interference).
Different complexity:
-switching
-EGC
-MRC
-TX Beamforming



Switched Strategy

Adaptive Strategy

MIMO



Example for 3×4 system:

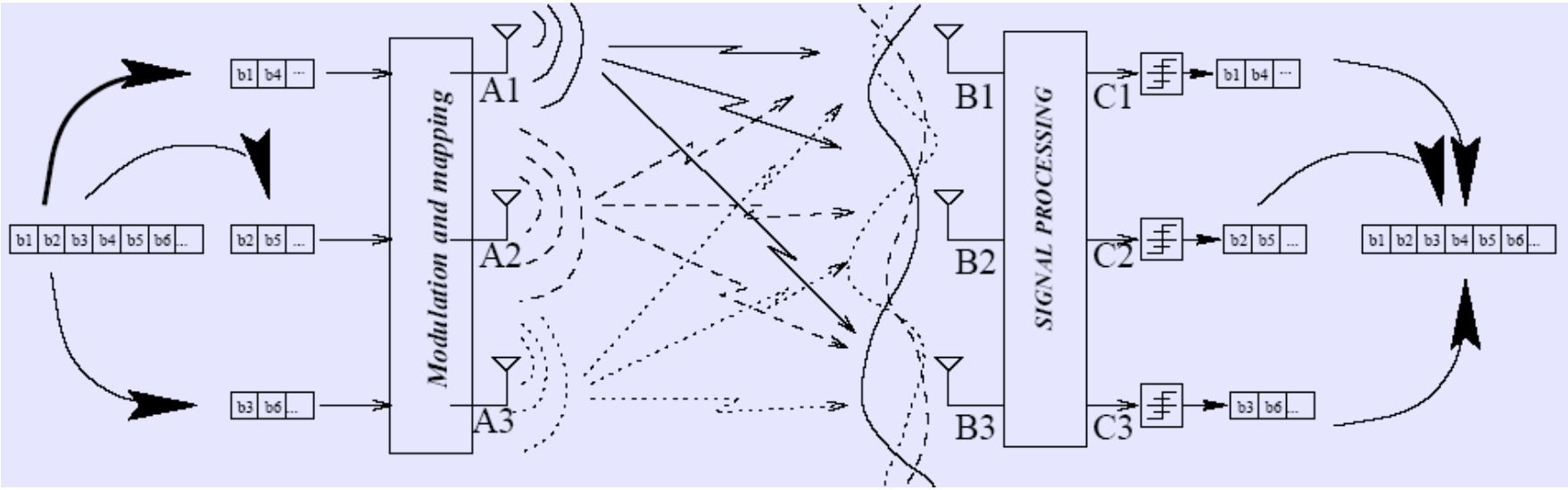
$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \\ h_{41} & h_{42} & h_{43} \end{bmatrix}$$

When we use several antennas at the Tx, each antenna becomes a singular source for the receiving array.

Diversity increases

MIMO- SM

Spatial Multiplexing :



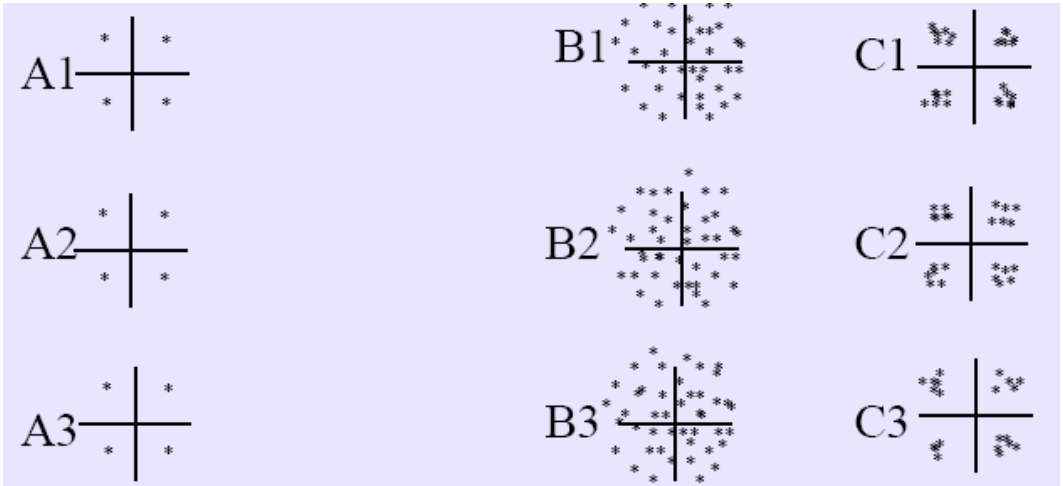
Data is divided on as many flows as Tx antennas

Throughput increases linearly with number of Tx antennas

Space-Time decoding at Rx (need at least as many antennas)

MIMO- keypoint

Matrix inversion :



$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \underbrace{\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}}_{\mathbf{H}} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} + \text{Noise}$$

$$\begin{bmatrix} \hat{b}_1 \\ \hat{b}_2 \\ \hat{b}_3 \end{bmatrix} = \mathbf{H}^{-1} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

Emitted signal — Received signal — Decoded signal

Decoding ease depends on matrix inversibility

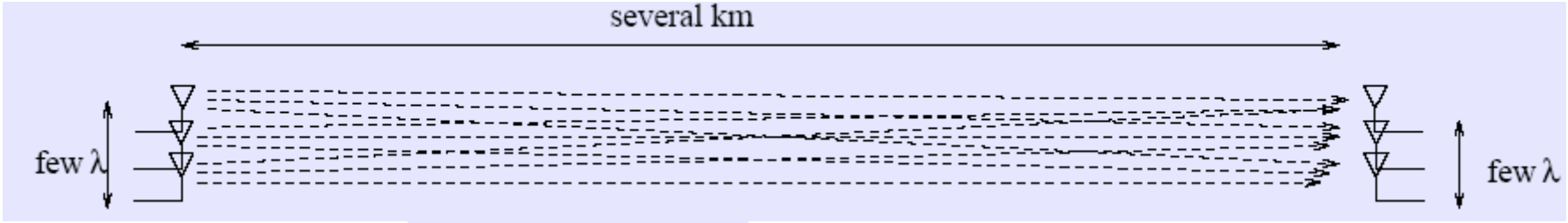
MIMO- conditions

Invertible Matrix:

Matrix inversion depends on correlation of received signals on all antennas:

- related to distance between antennas

- also to angular spread.



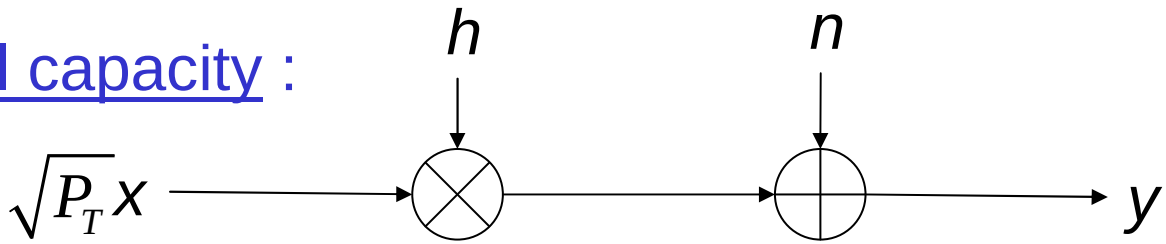
$$\mathbf{H} \approx \alpha \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

rank 1 (non inversible !)

An important spacing between antennas is required or important multi-path (perfect in indoor).

Channel Capacity

SISO channel capacity :



$$y = \sqrt{P_T}xh + n$$

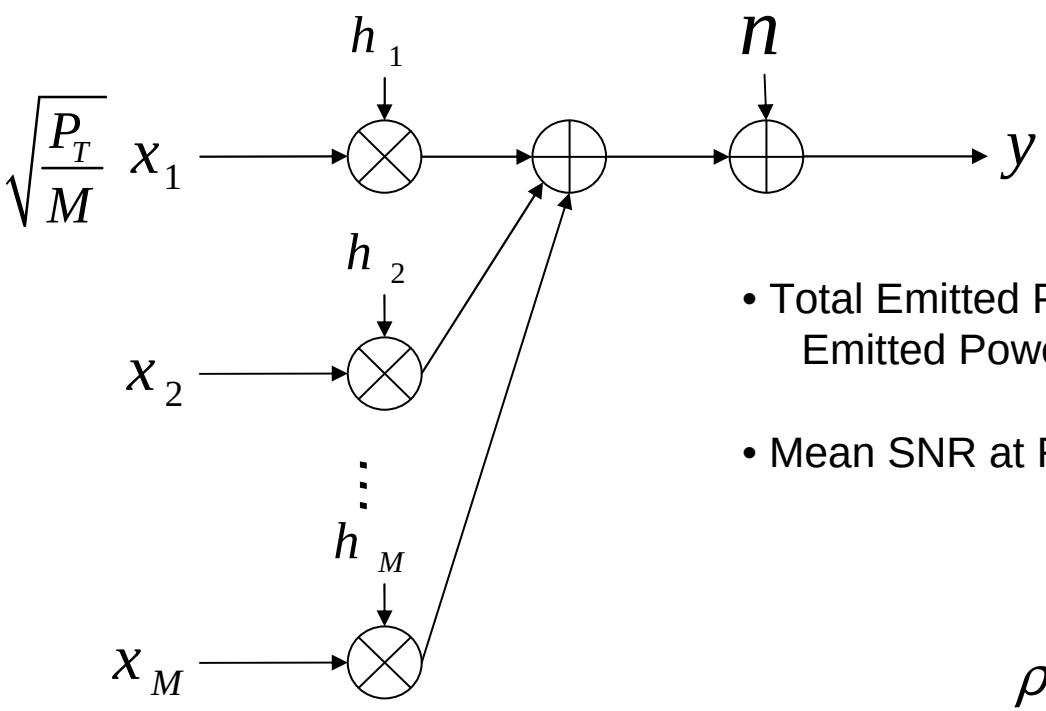
- h : complex channel gain
  - Non frequency selective (1 coefficient)
  - Time selectivity :
    - h independent of time => non selective in time,
    - h changes from a symbol to another,
    - h varies slowly
- If ρ is the mean SNR at Rx :

$$\rho = \frac{S}{B} = \frac{P_T E\left(|h|^2\right)}{\sigma^2} \quad \rho = \frac{P_T}{\sigma^2} \; si \; E\left(|h|^2\right) = 1$$

- SISO channel capacity without CSI:

$$C = \log_2\left(1 + \rho|h|^2\right) \quad bits/s/Hz$$

MISO Channel Capacity

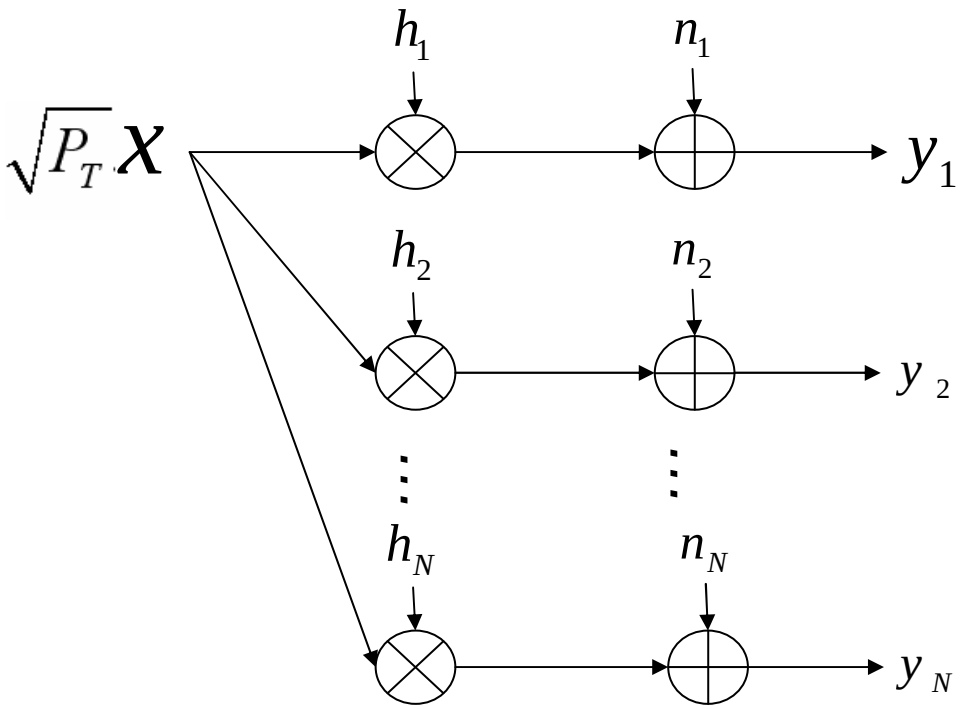


- Total Emitted Power kept constant.
  Emitted Power by antenna : $\rightarrow \frac{P_T}{M}$
- Mean SNR at Rx:

$$\rho = \frac{\frac{P_T}{M}\sum_i E\left(|h_i|^2\right)}{\sigma^2} = \frac{P_T}{\sigma^2}$$

$$C = \log_2\left(1 + \frac{\rho}{M}\sum_{i=1}^{M}|h_i|^2\right) \quad bits/s/Hz$$

SIMO Channel Capacity

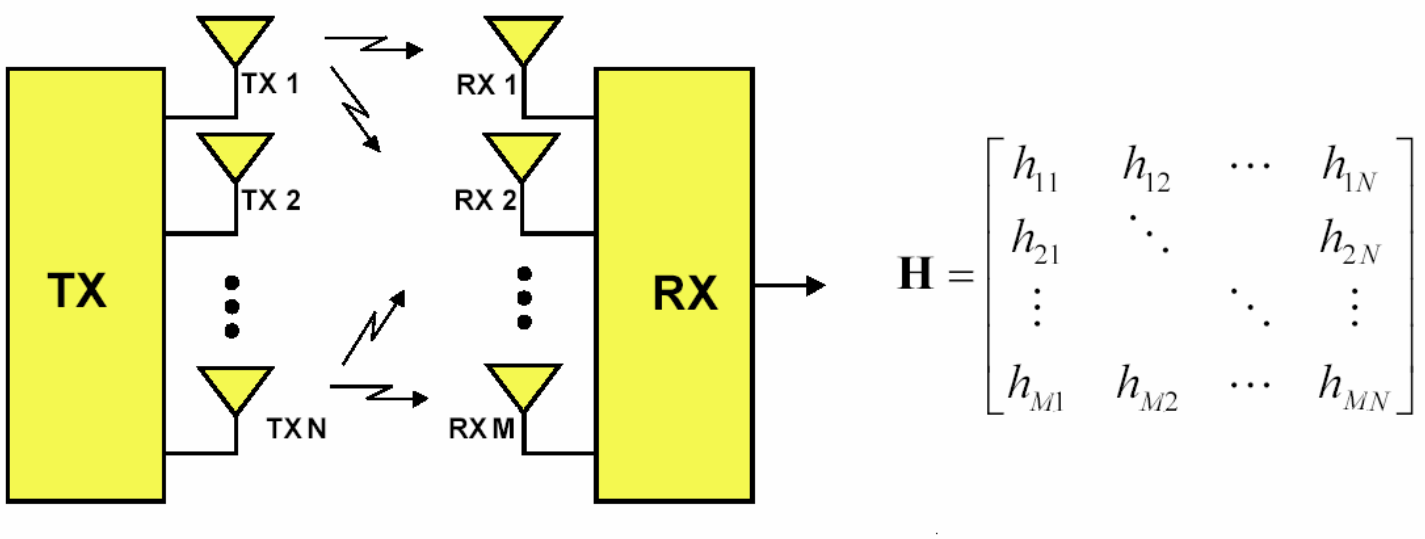


$$\rho_i = \frac{P_T E\left(|h_i|^2\right)}{\sigma_i^2} = \frac{P_T}{\sigma_i^2}$$

$$C = \log_2\left(1 + \rho \sum_{i=1}^{N} |h_i|^2\right) \quad bits/s/Hz$$

Logarithmic increase with receiving antenna number

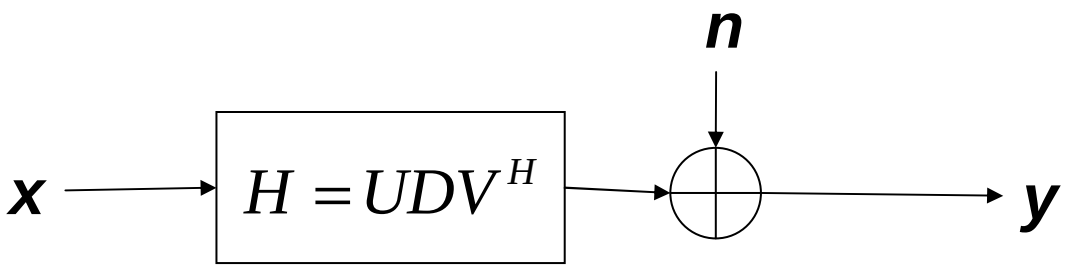
MIMO - Channel Capacity



$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N} \\ h_{21} & \ddots & & h_{2N} \\ \vdots & & \ddots & \vdots \\ h_{M1} & h_{M2} & \cdots & h_{MN} \end{bmatrix}$$

- MIMO : N Tx antennas and M reiceving antennas
- h_{ij} is channel complex gain of j^{th} emitting antenna and i^{th} receiving antenna

$$y = Hx + n$$



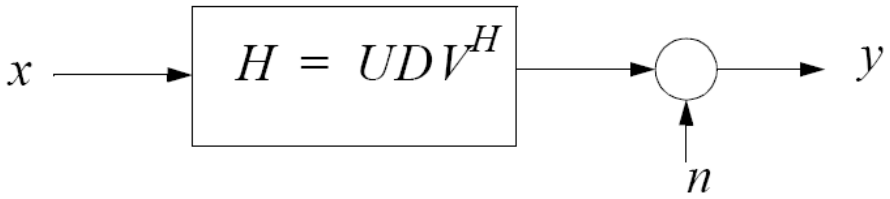
- With $x = [x_1 \quad \dots \quad x_N]^T$ and $y = [y_1 \quad \dots \quad y_M]^T$
- SVD of H :

$$\underbrace{H}_{M\times N} = \underbrace{U}_{M\times m}\ \underbrace{D}_{m\times m}\ \underbrace{V}_{m\times N}^{H} \qquad m = \min(M, N)$$

- U and V unitary : $UU^{*t} = VV^{*t} = I$
- D diagonal matrix which non-null elements are singular values of H

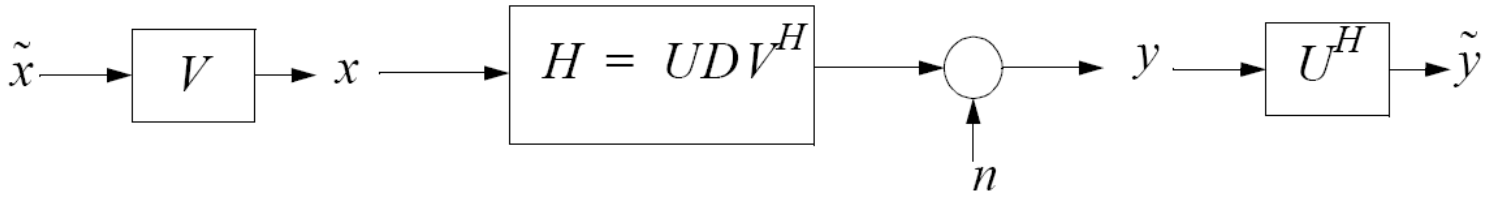
$$D = diag(\lambda_i)$$

Virtual channels

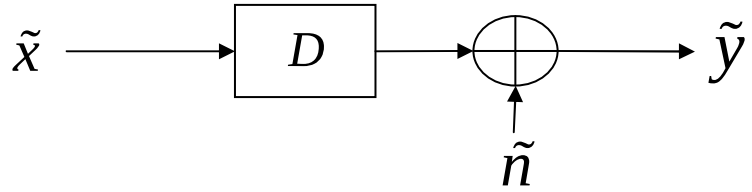


• **Goal** : the system Output must be linked to the Input by a diagonal matrix

• **Idea** : A linear pre-coding is applied to data to transmit associated to a decoding at the receiver.



$$\tilde{y} = U^H(UDV^H)V\tilde{x} + U^H n = D\tilde{x} + \tilde{n}$$



➡ m independent channels

- Capacity of a sub-channel (emitted power P_T/N) :

$$C_i = \log_2\left(1+\frac{\rho}{N}\left|\lambda_i\right|^2\right)$$

- MIMO system capacity :

$$C = \sum_{i=1}^{m} C_i \quad \textit{if m independent channels}$$

$$C = \sum_{i=1}^{m} \log_2\left(1+\frac{\rho}{N}\left|\lambda_i\right|^2\right)$$

- Generally written:

$$C = \log_2 \det\left[\underline{\underline{I}}_M + \frac{\rho}{N}\underline{\underline{H}}\,\underline{\underline{H}}^H\right]$$

➡ Linear increase corresponding to **min(N , M)**

Channel State Information

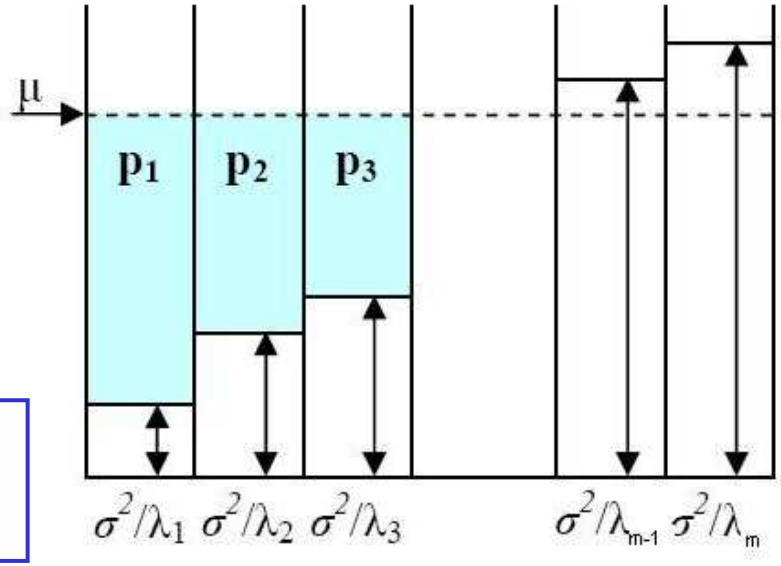
CSI at the emitter:

Knowning channel state at the receiver is ease with training sequences, but at the emitter it requires feedback.

- **Case without information (no CSI)** :

Same power allowed to each Tx antenna (BLAST strategy)

$$C = \log_2 \det\left[\underline{\underline{I}}_M + \frac{\rho}{N} \underline{\underline{H}}\,\underline{\underline{H}}^H \right]$$

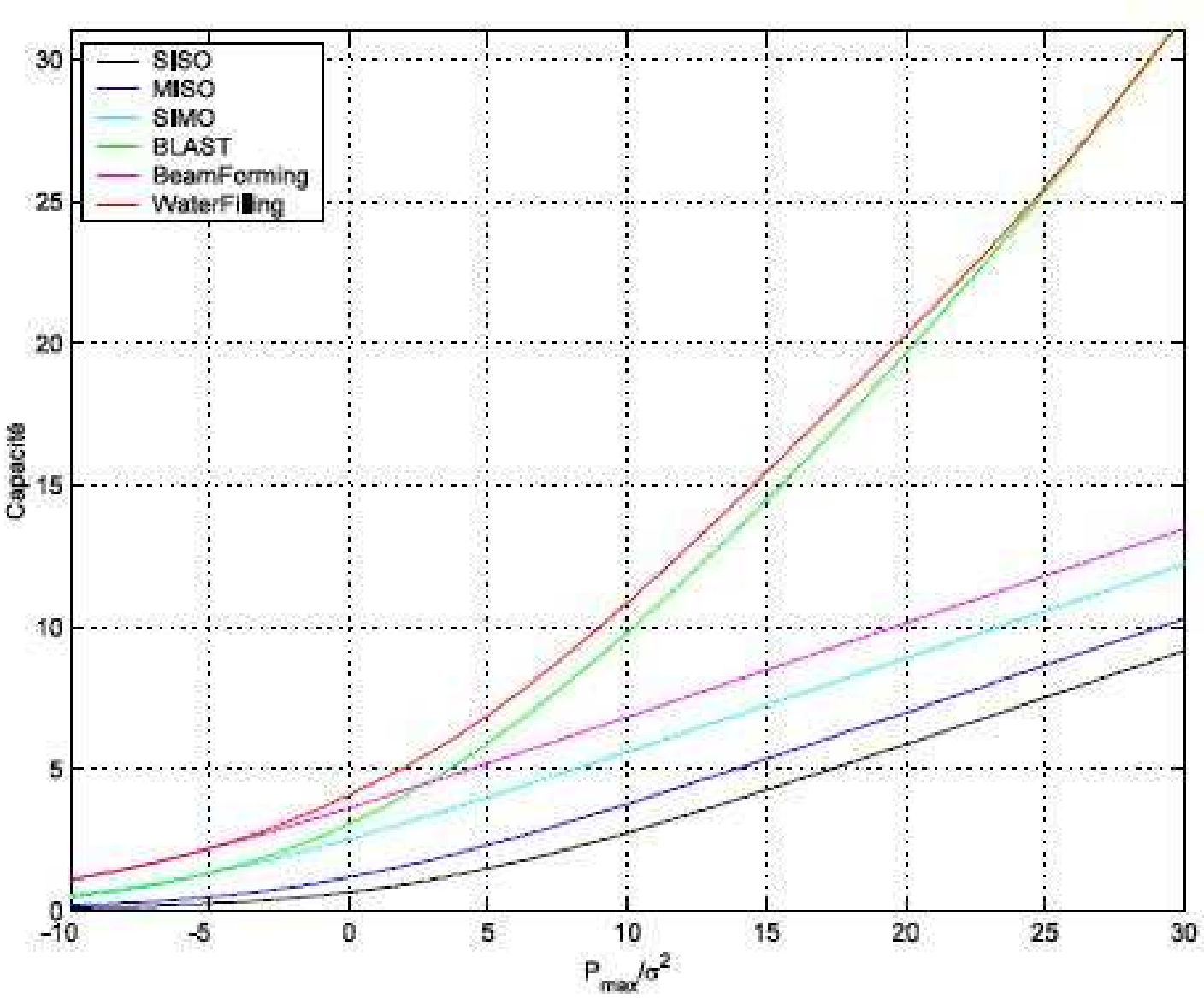


- **Case with information (CSI)** :

Emitted power optimally dispatched (WATERFILLING)

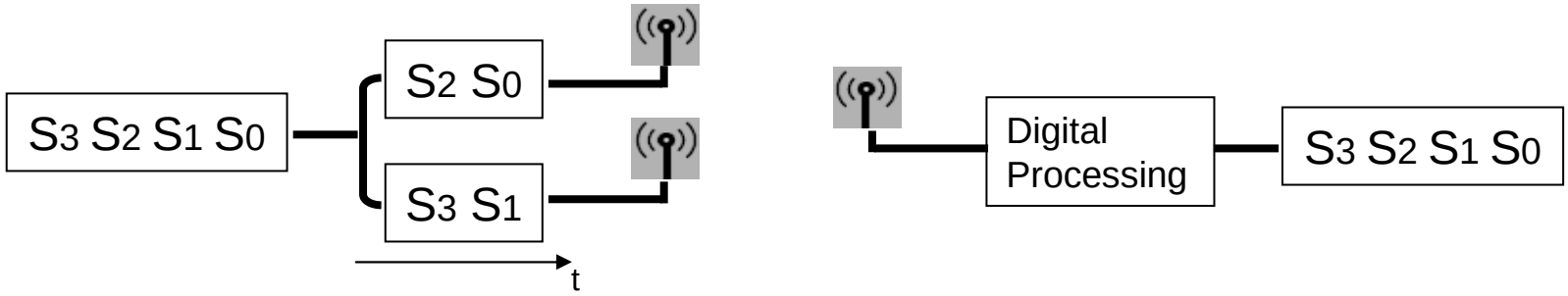
$$C = \max_{\mathbf{Q}:trace(\mathbf{Q})=P_T} \log_2 \det\left[\boldsymbol{I}_M + \boldsymbol{H}\mathbf{Q}\boldsymbol{H}^H \right]$$

Capacity Comparison

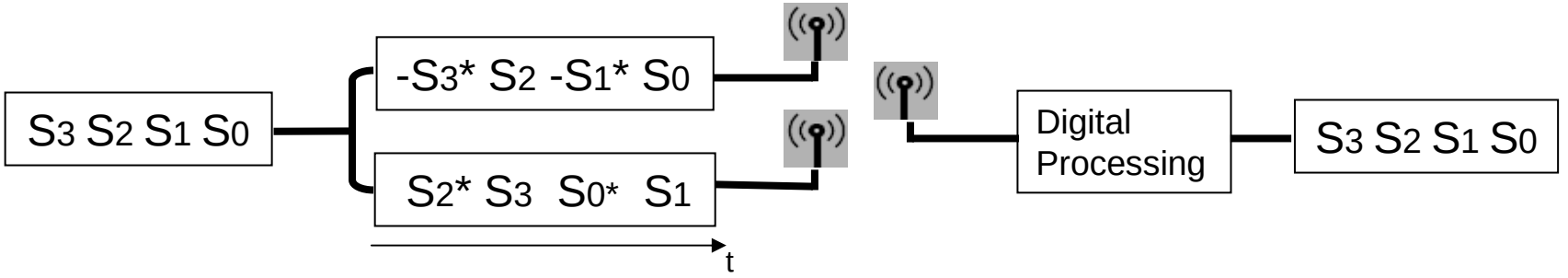


Different techniques

Spatial Multiplexing: increases throughput



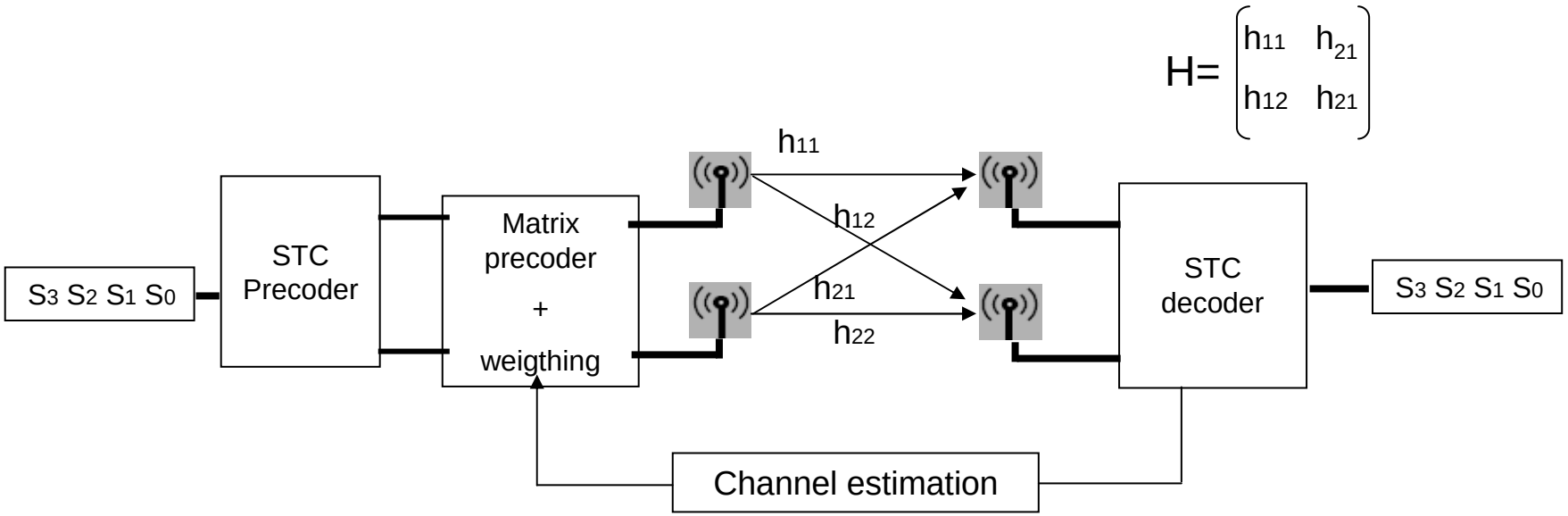
Space-Time Code: increases link robustness



Interest: no CSI needed

Different techniques

Pre-coding: knowledge of CSI at emitter side to pre-code data and optimize transmission



Increases capacity and robustness
More complex to implement

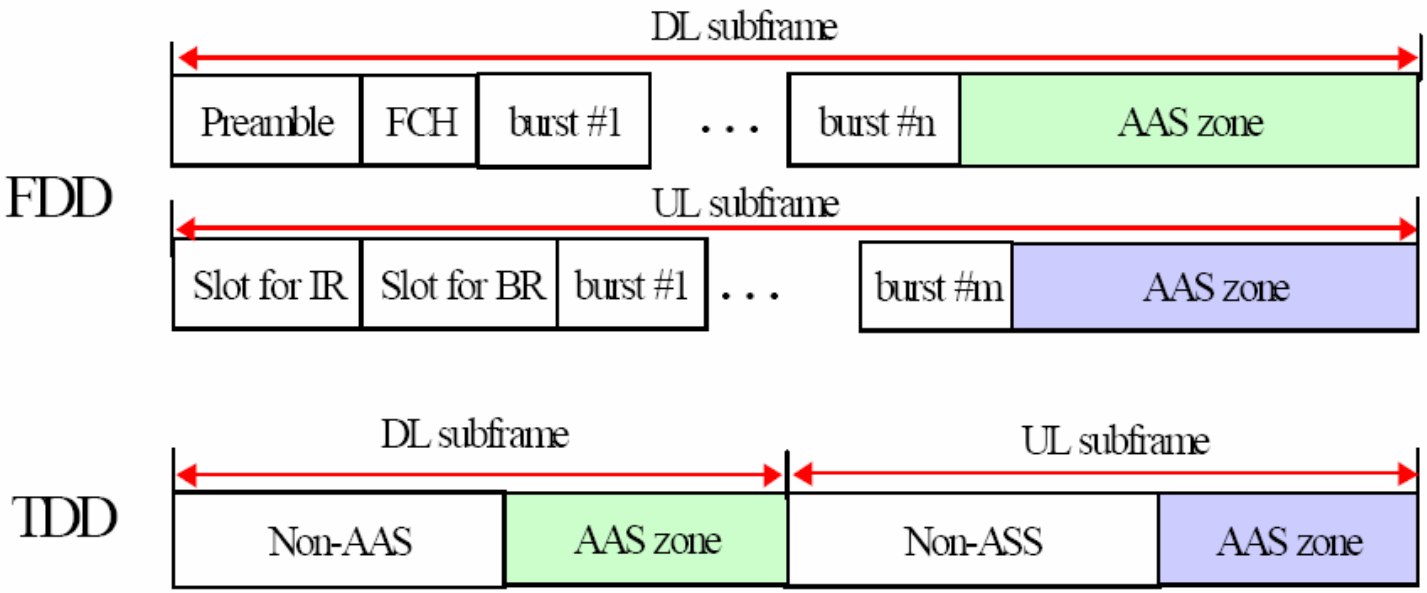
Multi-antenna in WiMAX

AAS (Adaptative Antenna System) :

Possibility of forming a beam from BS to MS (if compatible).

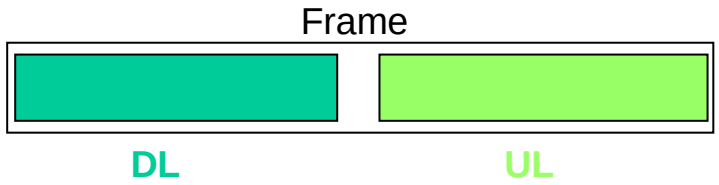
Only one antenna at MS.

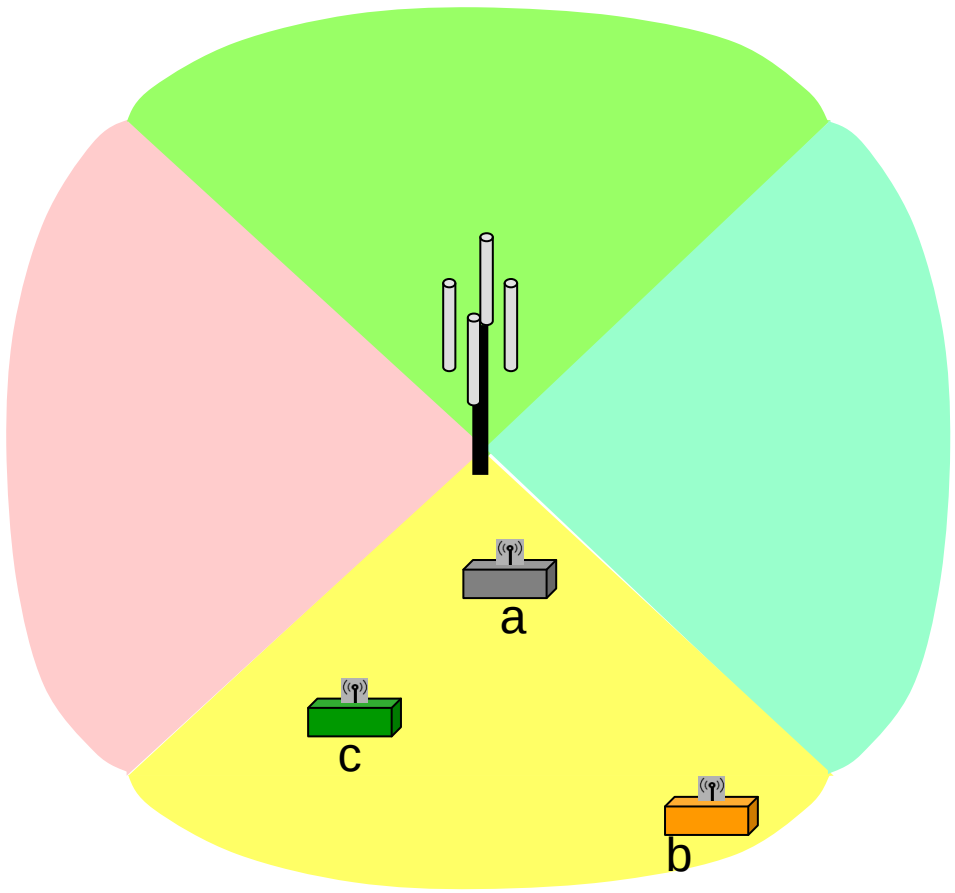
Needs feedback information on each antenna element (DOA).



WiMAX implementation

Classical sectorial topology: sectorial antennas at the BS



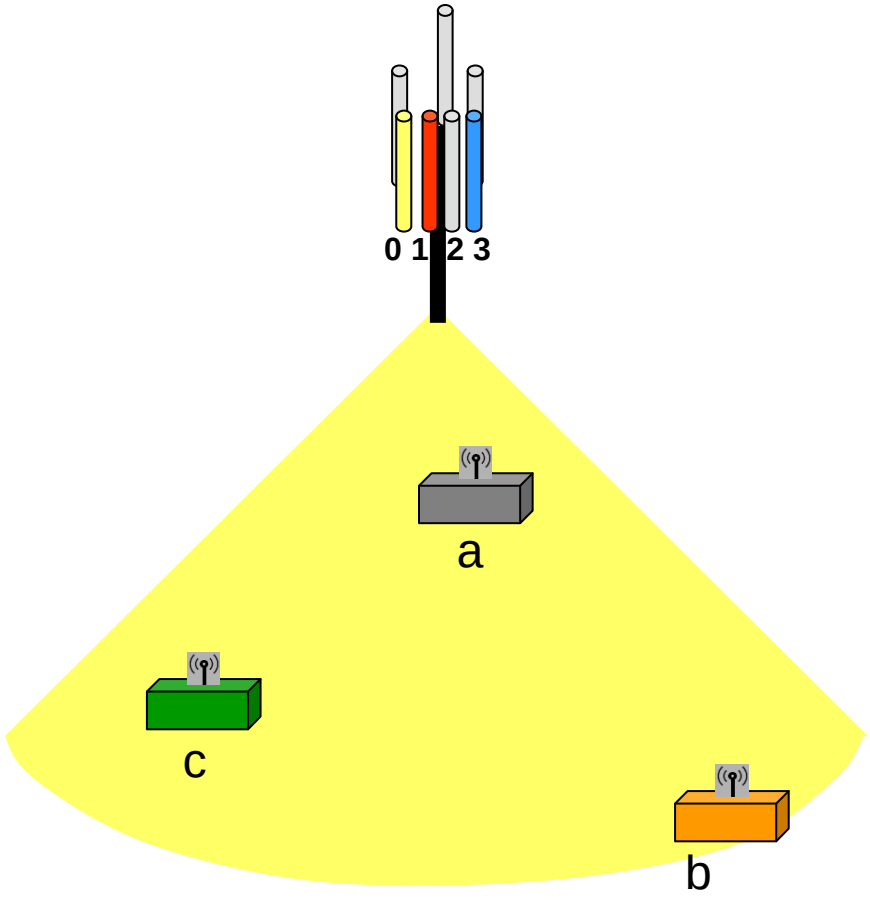


Initializing mechanism for a new user in the network:

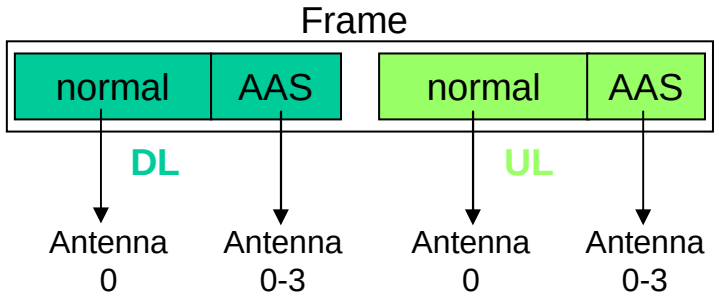
- scan of DL channel to synchonize with BS.
- send request to BS
- BS calculates transmission parameters (UCD)
- BS send authorization and BW allocation

AAS system

Up to 4 antennas on a sector



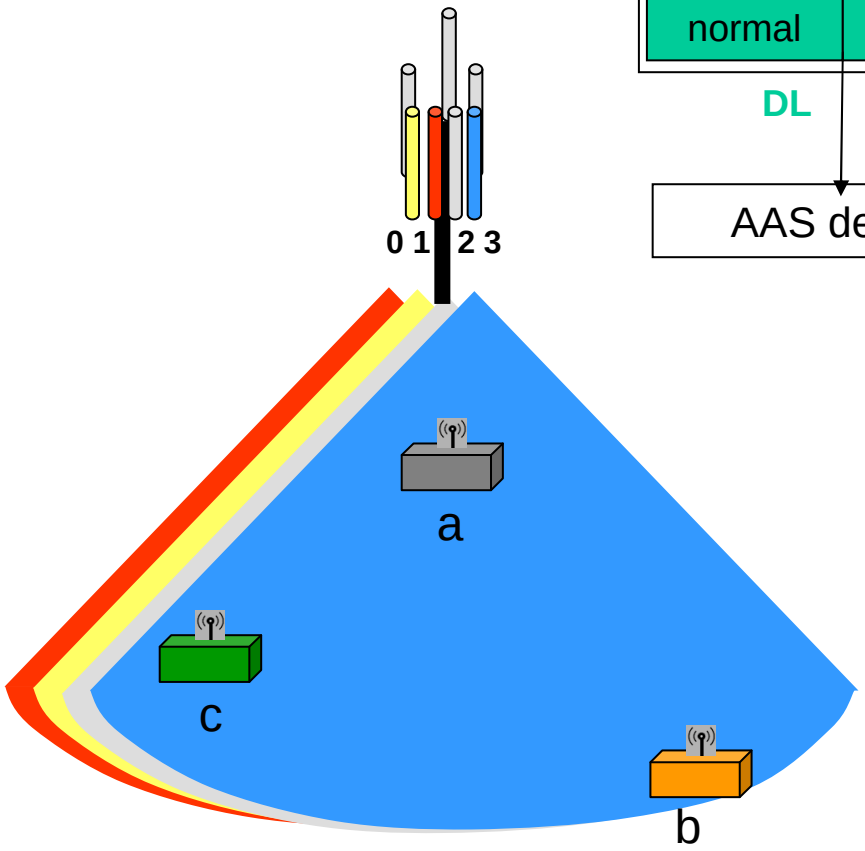
- AAS is optional
- Beamforming at the BS
- Only with implemented terminals
- Subframes divided in two parts

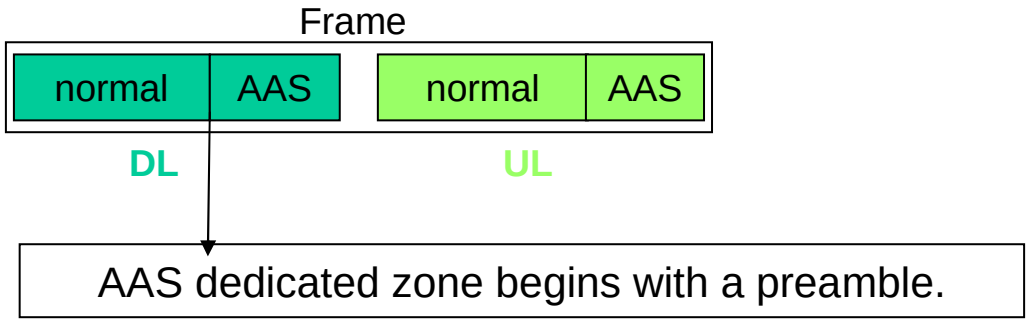


a without AAS

b and c with AAS

AAS mechanism





Each 4 antennas must cover the sector.

Each antenna send a preamble.

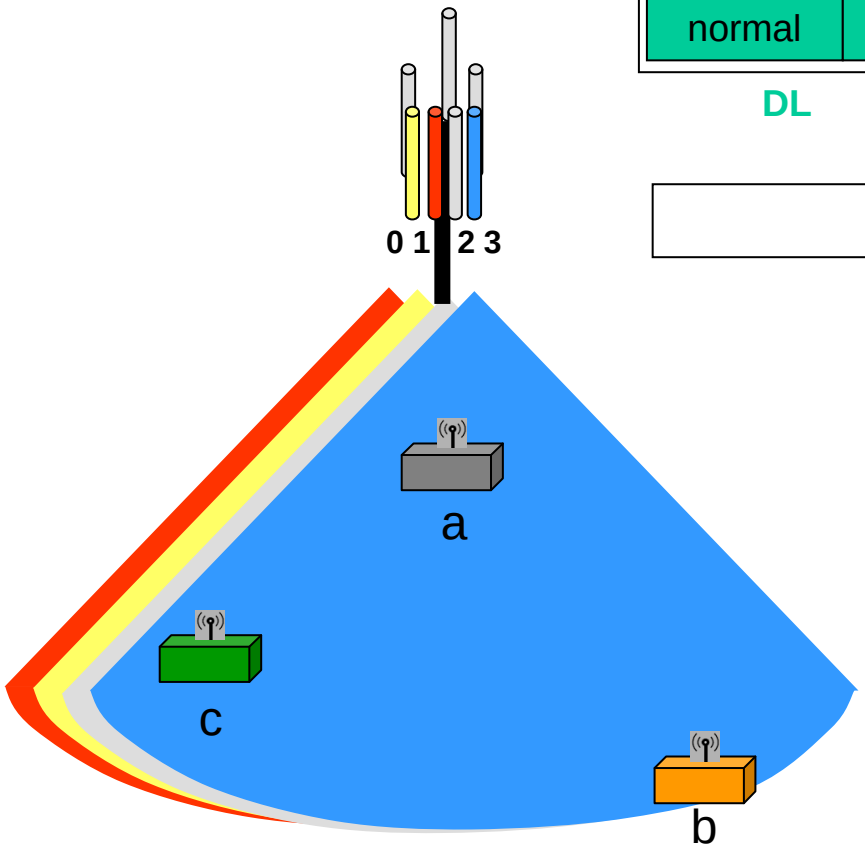
Different Subcarriers (SC) for different beams :

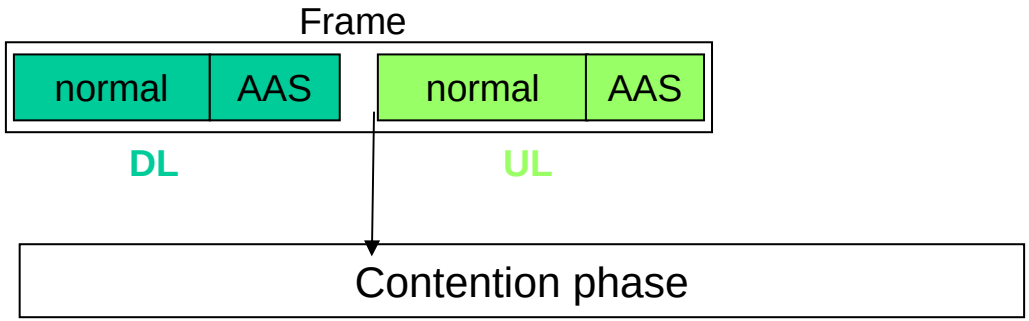
antenna 0 SC[-100;-96;…;96;100]

antenna 1 SC[-99;-95;…;95;99]

antenna 2 SC[-98;-94;…;94;98]

antenna 3 SC[-97;-93;…;93;97]



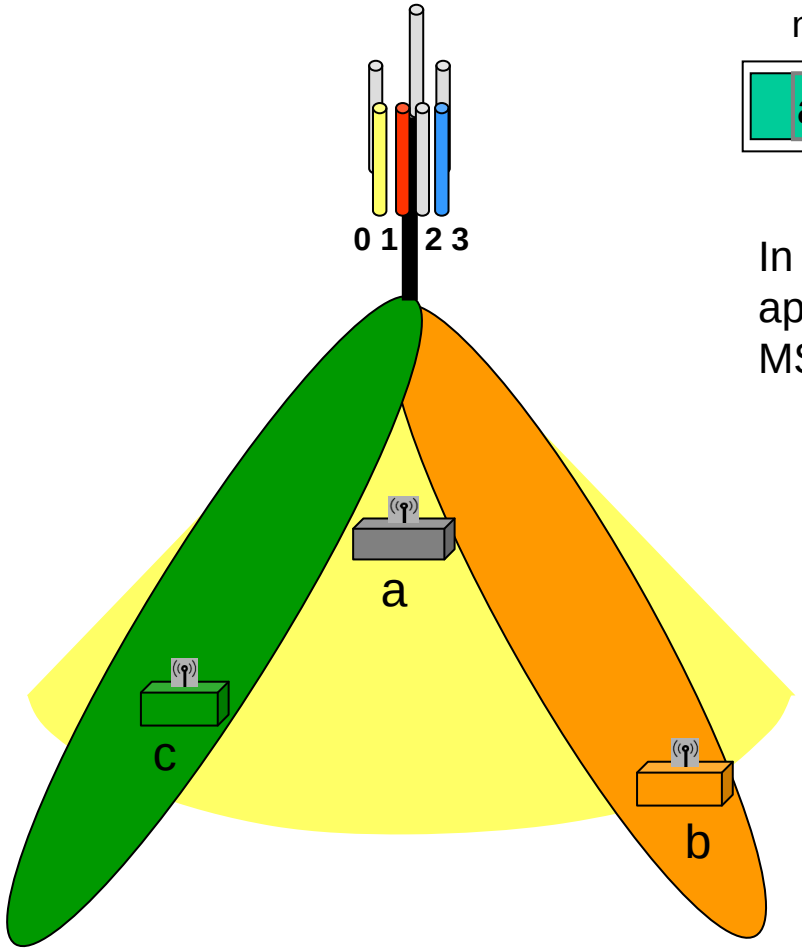


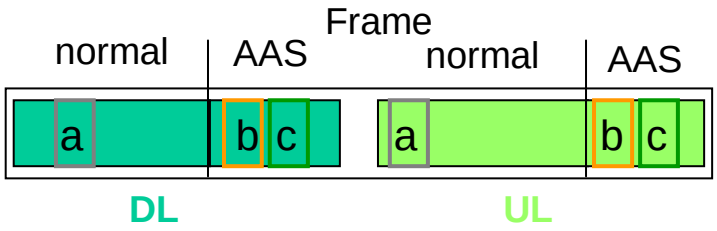
One MS with AAS send a BW request.

During next frame, BS send a request to estimate channel state (one sequence by Tx antenna).

Replying to this request, MS sends CINR, RSSI, amplitude and phase of each SC.

AAS beamforming





In the AAS zone, weightings are directly applied on BB signals for beamforming in MS direction.

At MAC level: messages management for channel estimation…

At PHY level: preamble, CSI, weigths…

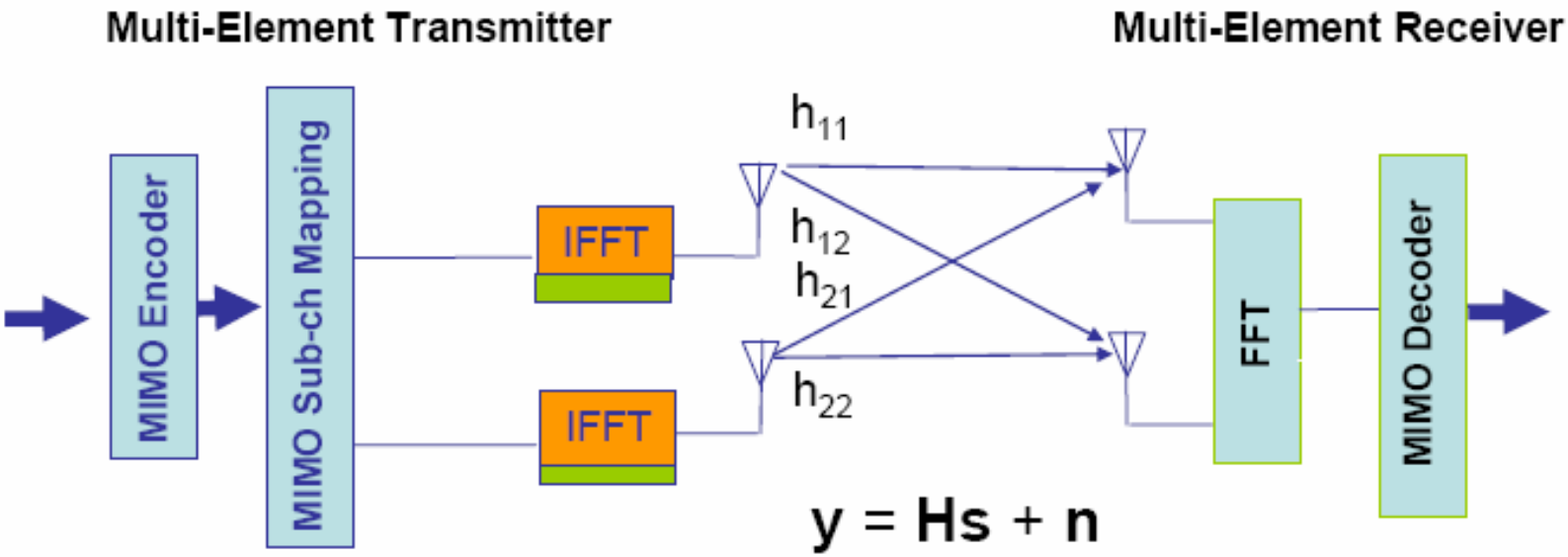
Digital processing algorithms are not described in the standard.

AAS increases link budget (antenna gain, interference mitigation) and the cell range.

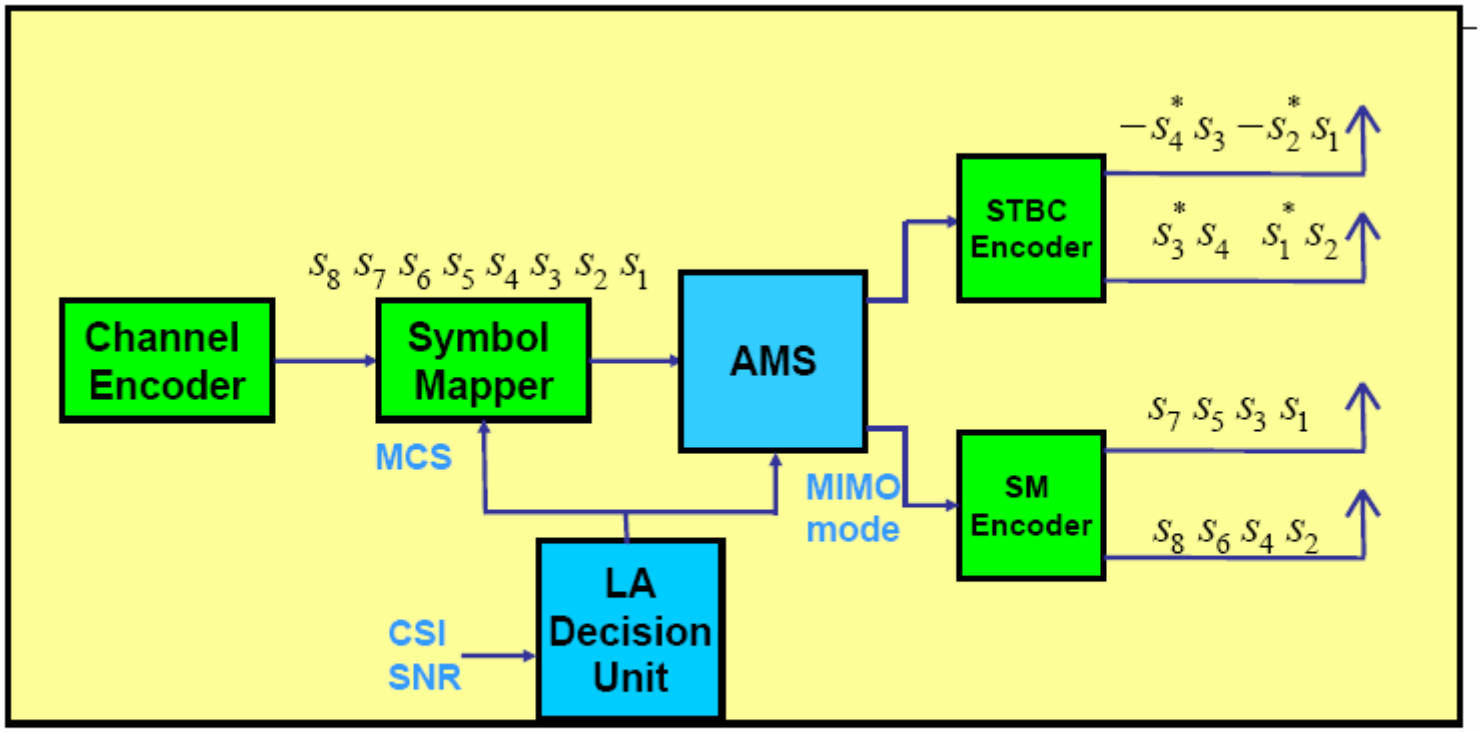
MIMO operation on frequency domain

- Flat subcarriers - h_{ij} is scalar
- Simple frequency domain equalizer
- Scalable with bandwidth

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{bmatrix}$$

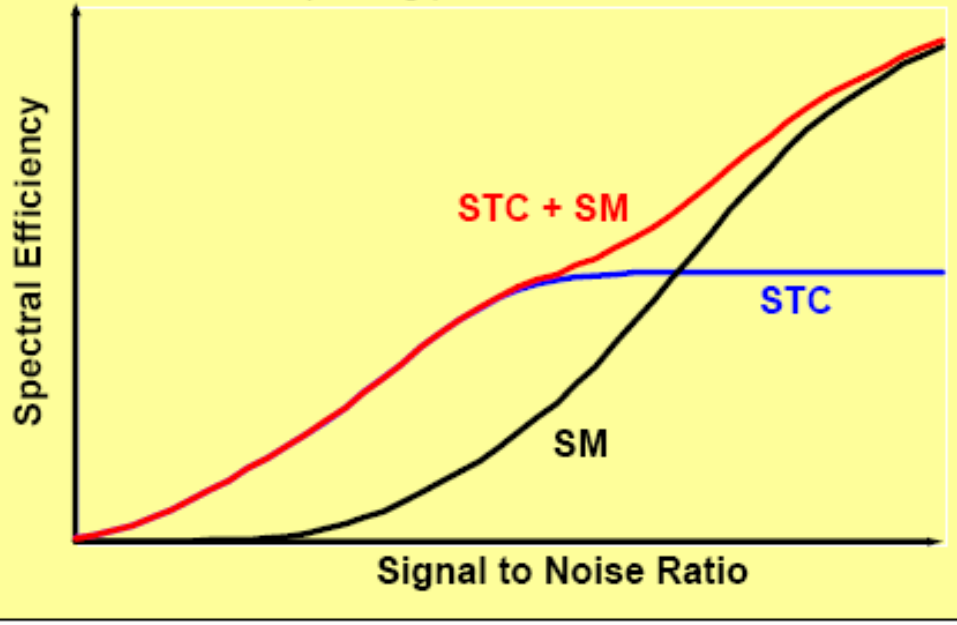


DL Adaptive MIMO Switching (AMS)



MCS: Modulation and Coding Scheme
LA: Link Adaptation
CSI: Channel State Information
SNR: Signal-to-Noise Ratio

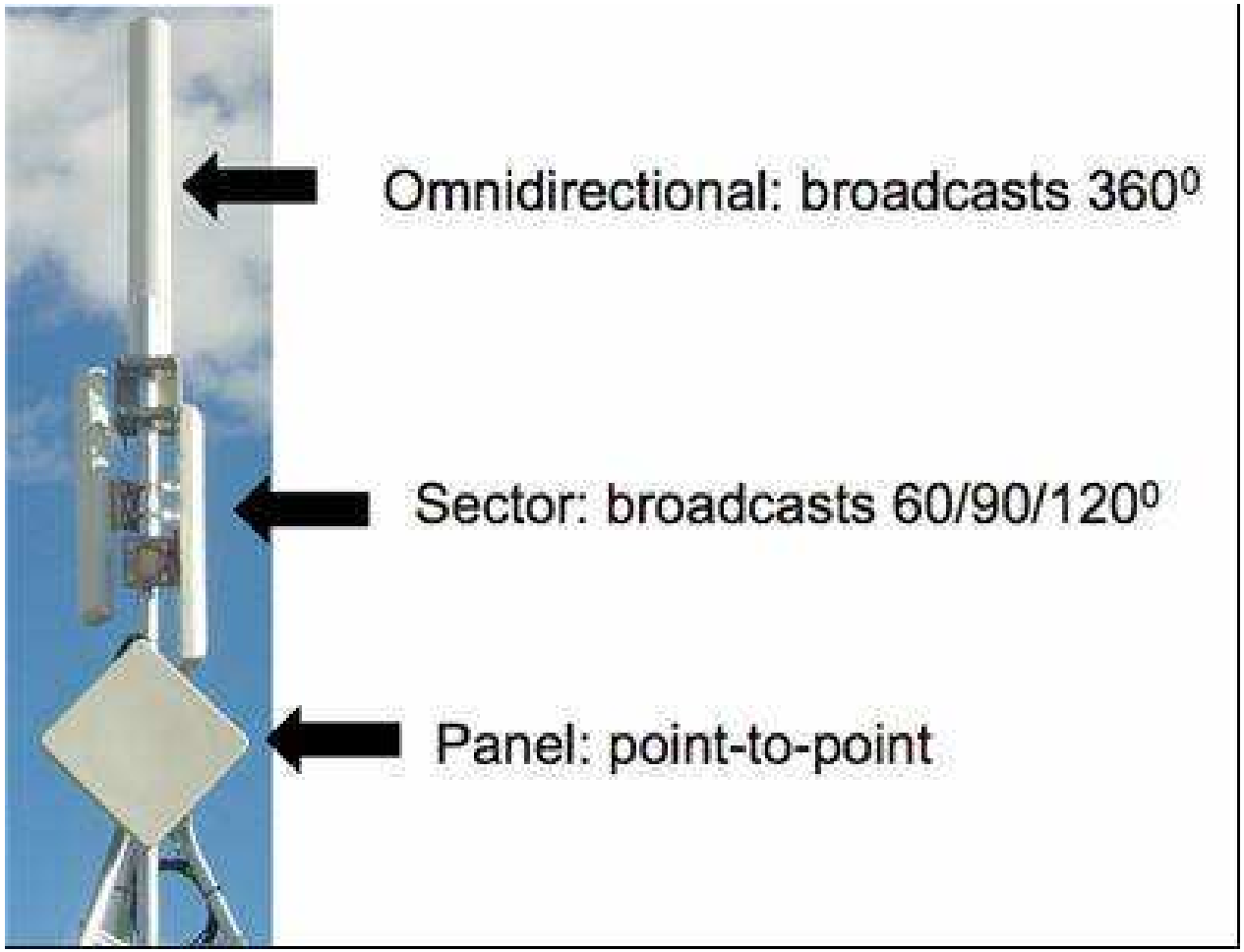
- STC: Improving coverage regardless channel condition.
- SM: Improving peak data rate



AMS overcomes the deficiencies of STBC and SM and leads to spectral efficiency very close to the ideal one at both low and high SNR regions

Some examples of existing materials

Base station antennas



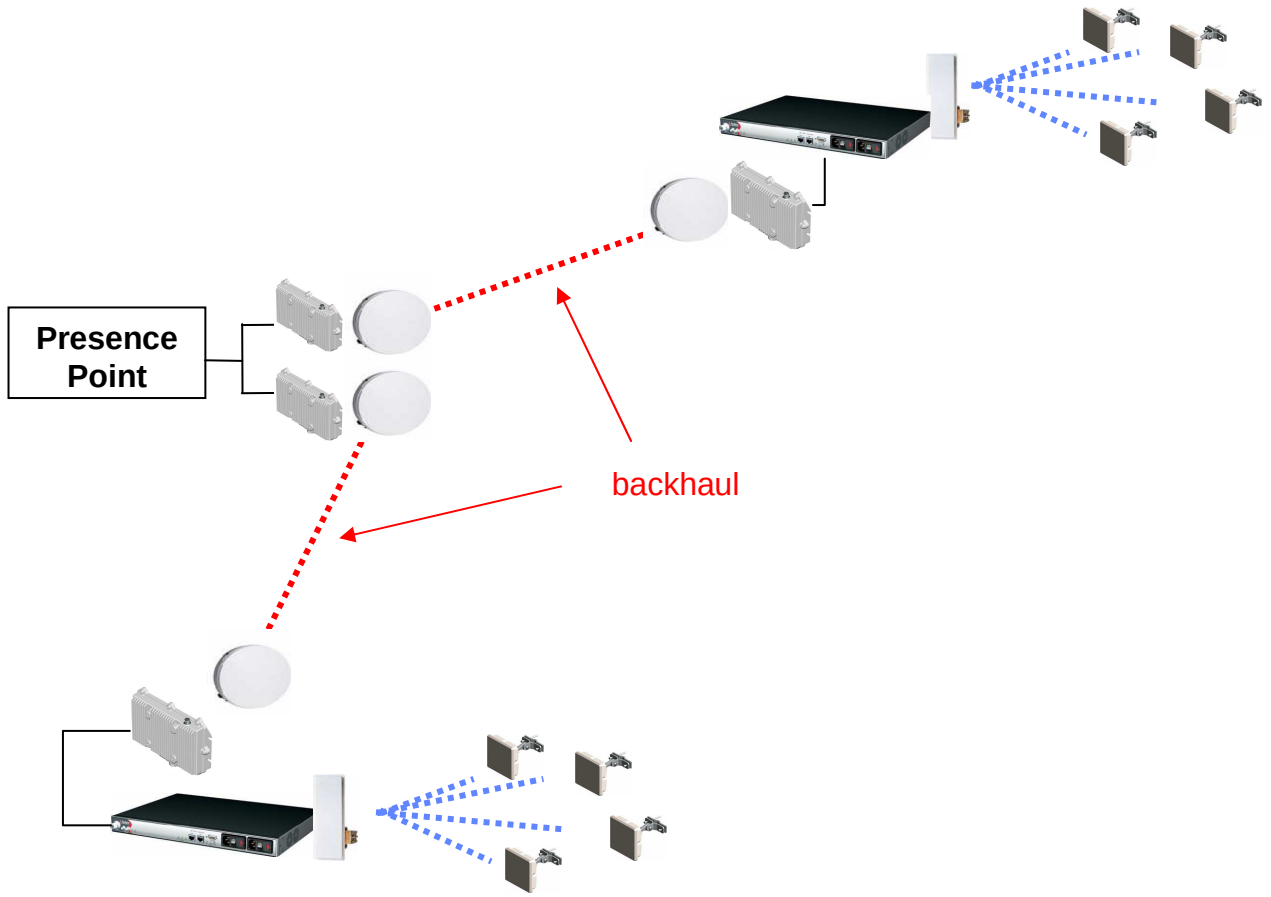
source C. Townsend

Subscribers antennas

Indoor (omnidirectional) or outdoor (directional) antennas for fixed subscribers

source Airspan

RedMAX



RedMAX deployment : backhaul AN80i and Basestation AN100U

SC and SU-O are Wimax Certified.

SU-O RF

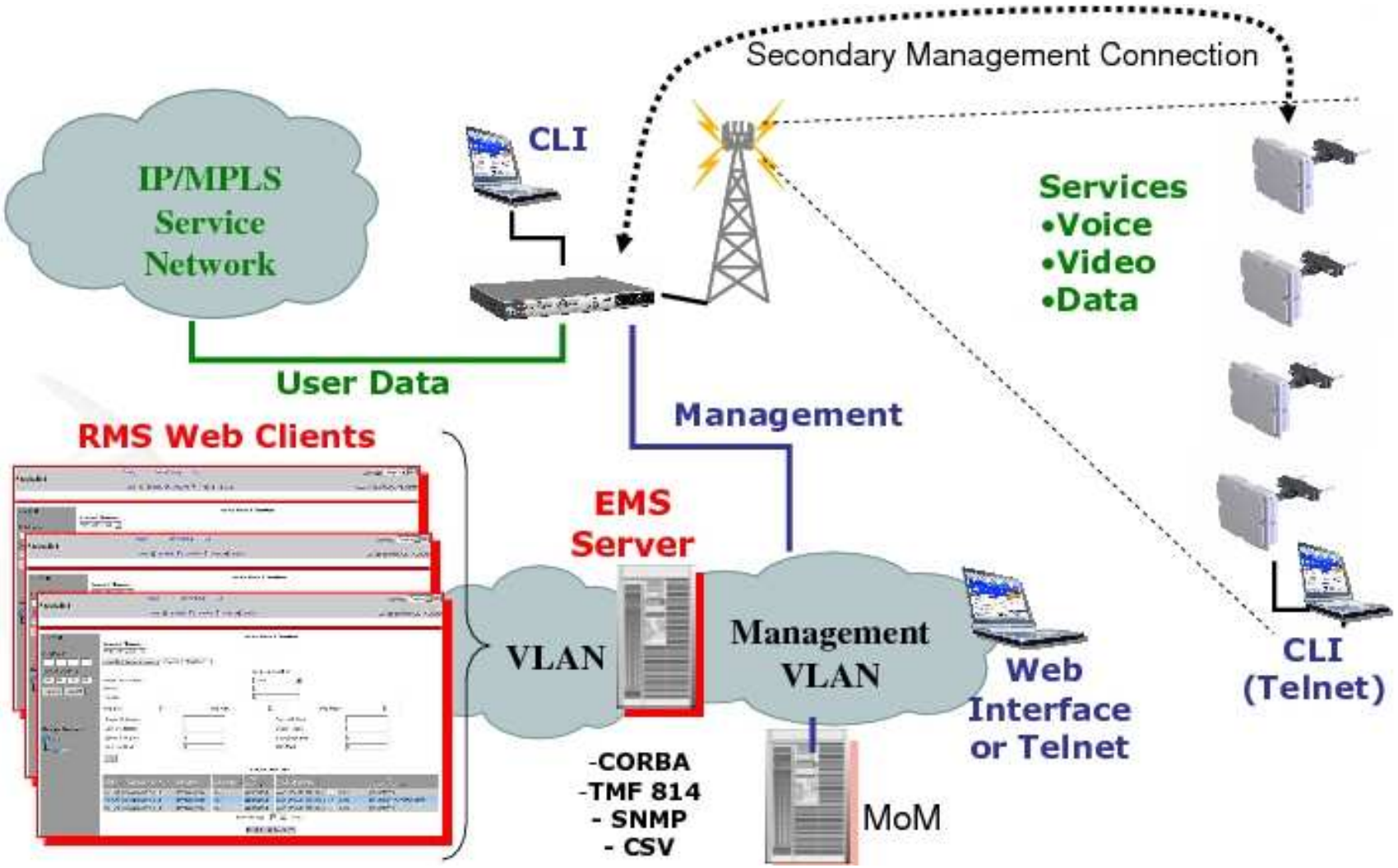
SU-O IA

100U split architecture (IDU/ODU)
(Sector Controller or a "premium grade" subscriber unit)

RedMAX Subscriber Unit - Outdoor

SU-I

RedMAX Subscriber Unit - Indoor


Secondary Management Connection
IP/MPLS
Service
Network
CLI
Services
•Voice
•Video
•Data
User Data
Management
RMS Web Clients
EMS
Server
VLAN
Management
VLAN
Web
Interface
or Telnet
CLI
(Telnet)
-CORBA
-TMF 814
- SNMP
- CSV
MoM

Examples of Base station products

Software Defined Radios, many degrees of freedom

source Airspan

		HiperMAX	MacroMAX
RF Interface	RF Multiple Access Scheme	OFDM (SDR software upgradable to SOFDMA)	OFDM (SDR software upgradable to SOFDMA)
	Frequency Bands	3.4-3.6GHz initially + subsequent additional WiMAX bands	3.4-3.6GHz initially + subsequent additional WiMAX bands
	Channel Size	1.75MHz, 3.5MHz, 5MHz, 7MHz, 10MHz	1.75MHz, 3.5MHz, 5MHz
	FFT	256 (SDR software upgradeable to 512 and 1024)	256 (SDR software upgradeable to 512 and 1024)
	Duplex Method	FDD + TDD	FDD + TDD
	Sector Angle	60, 90, 120, 180, omni	60, 90, 120, 180, omni
	Modulations Supported	64QAM , 16QAM, QPSK, BPSK	64QAM , 16QAM, QPSK, BPSK
	WiMAX Profiles Supported	3.5F1, 3.5F2, 3.5T1, 3.5T2	3.5F1, 3.5F2, 3.5T1, 3.5T2
	Standards Compliance	IEEE 802.16-2004 (Software upgradeabe to 802.16e)	IEEE 802.16-2004 (Software upgradeabe to 802.16e)
	Tx Power	Up to +32dBm per antenna element	Up to +37dBm per antenna
	Rx Sensitivity	-115dBm (1/16), -100dBm (1/1)	-115dBm (1/16), -100dBm (1/1)
	AAS & Diversity Gains (Downlink/Uplink)	Up to 18dB / 13dB	Up to 5dB / 5dB
RF Interface Options	Adaptive Antenna System (AAS) Support	Yes	No
	Multi Channel Tx Diversity	Yes	Yes
	Nth Order Rx Diversity	Yes	Yes
	Space Division Multiple Access (SDMA) Support	Yes, by software upgrade	No
	Spatial Frequency Interface Rejection (SFIR) Support	Yes, by software upgrade	No
	Uplink Sub-Channelisation Support	1/2, 1/4, 1/8, 1/16 (+1/32 with software upgrade)	1/2, 1/4, 1/8, 1/16 (+1/32 with software upgrade)
	Dynamic Frequency Selection (DFS) Support	N/A	N/A
	Turbo Coding Supported	Yes, by software upgrade	Yes, by software upgrade
	Configurable Cyclic Prefix	1/4, 1/8, 1/16, 1/32	1/4, 1/8, 1/16, 1/32
	Configurable Frame Duration	2.5, 4, 5, 8, 10, 12.5, 20ms	2.5, 4, 5, 8, 10, 12.5, 20ms
	GPS Clock Synch Supported	Yes	Yes

Examples of subscriber products

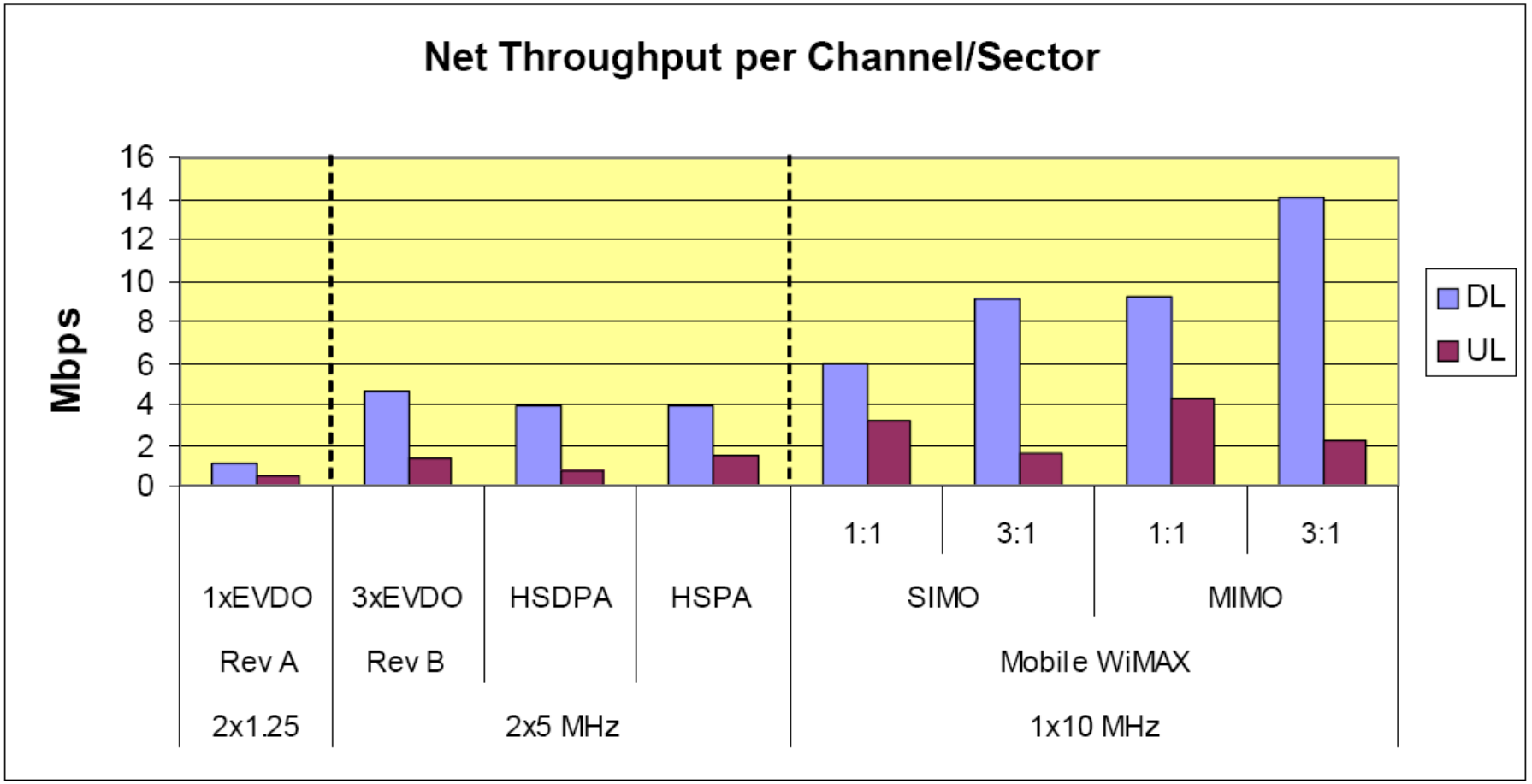
Lower cost, lower performances… the cost is at the BS

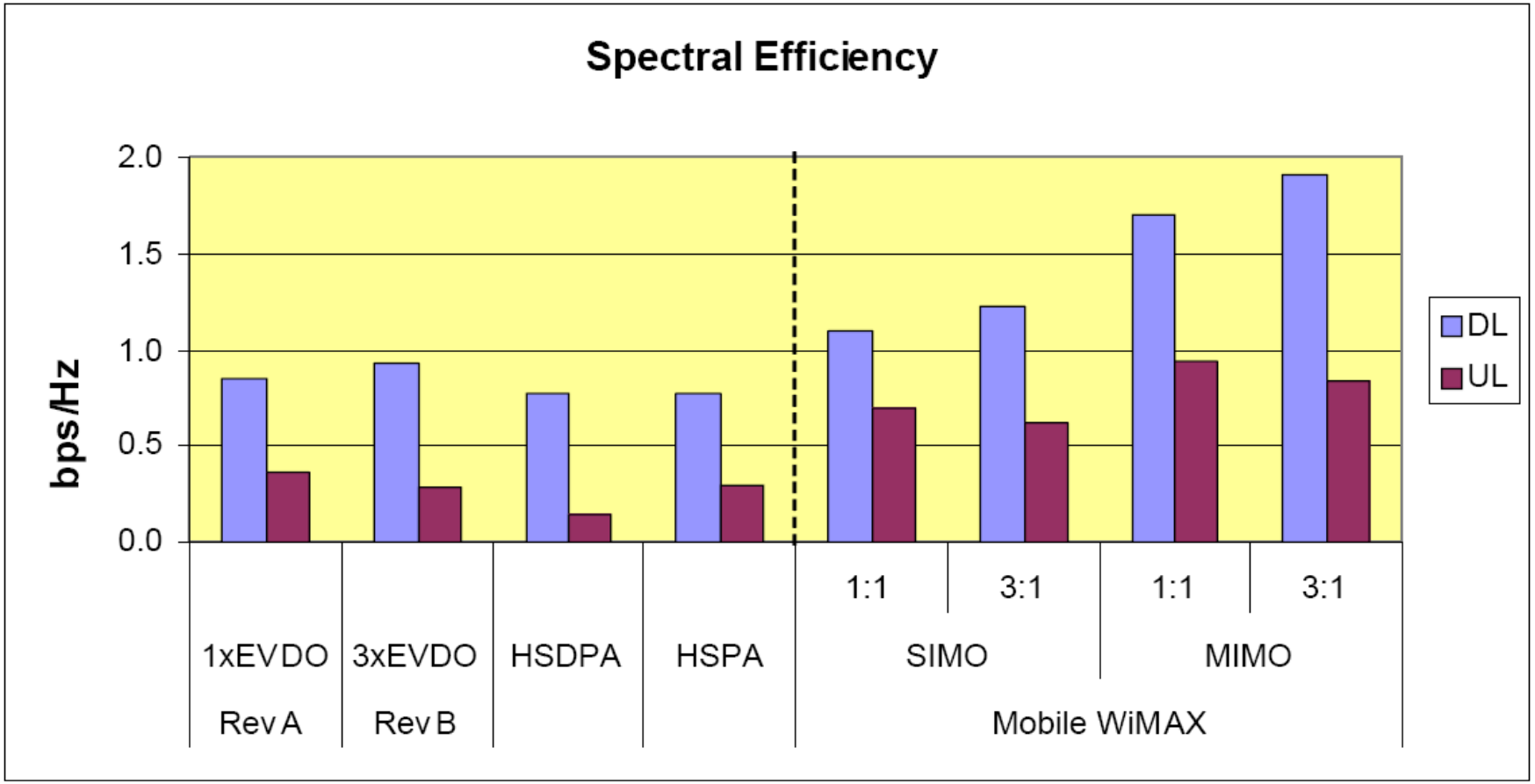
source Airspan

		PrimeMAX	EasyST	ProST
RF Interface	RF Multiple Access Scheme	OFDM	OFDM (future release supports SOFDMA)	OFDM (future release supports SOFDMA)
	Frequency Bands	3.4-3.6GHz, 5.8GHz	3.4-3.6GHz, 5.8GHz initially + subsequent additional WiMAX bands	3.4-3.6GHz, 5.8GHz initially + subsequent additional WiMAX bands
	Channel Size	7MHz, 10MHz, 14MHz, 20 MHz	1.75MHz, 3.5MHz, 7MHz, 10MHz	1.75MHz, 3.5MHz, 7MHz, 10MHz
	FFT	256	256 (future release supports 512)	256 (future release supports 512)
	Duplex Method	TDD (plus HD-FDD)	HFDD + TDD	HFDD + TDD
	Sector Angle	60 + others with external antenna	N/A	N/A
	Modulations Supported	64QAM , 16QAM, QPSK	64QAM , 16QAM, QPSK, BPSK	64QAM , 16QAM, QPSK, BPSK
	WiMAX Profiles Supported	3.5T1, 5.8T	3.5F1, 3.5F2, 3.5T1, 3.5T2, 5.8T	3.5F1, 3.5F2, 3.5T1, 3.5T2, 5.8T
	Standards Compliance	IEEE 802.16-2004	IEEE 802.16-2004 (future release to support 802.16e)	IEEE 802.16-2004 (future release to support 802.16e)
	Tx Power	+23dBm	+24dBm	Up to +23dBm
	Rx Sensitivity	-90dBm	-98 dBm	-98 dBm
	AAS & Diversity Gains (Downlink/Uplink)	-	-	-
RF Interface Options	Adaptive Antenna System (AAS) Support	No	Yes	Yes
	Multi Channel Tx Diversity	No	Yes	Yes
	Nth Order Rx Diversity	No	Yes	Yes
	Space Division Multiple Access (SDMA) Support	No	Yes	Yes
	Spatial Frequency Interface Rejection (SFIR) Support	No	Yes	Yes
	Uplink Sub-Channelisation Support	No	Yes	Yes
	Dynamic Frequency Selection (DFS) Support	N/A	Yes (at 5.8HGz)	Yes (at 5.8HGz)
	Turbo Coding Supported	No	No	No
	Configurable Cyclic Prefix	N/A	N/A	N/A
	Configurable Frame Duration	N/A	N/A	N/A
	GPS Clock Synch Supported	N/A	N/A	N/A

A performance comparison performed between WiMAX and 3G

Channel Model	# of Paths	Speed	Fading	# of Users per Sector
Model A	1	3 km/hr	Jakes	3 (30%)
Model B	3	10 km/hr	Jakes	3 (30%)
Model C	2	30 km/hr	Jakes	2 (20%)
Model D	1	120 km/hr	Jakes	1 (10%)
Model E	1	0, $f_{Doppler}$ = 1.5 Hz	Rician Factor K = 10 dB	1 (10%)
			Total Users per Sector	10
			Total Users per Cell	30


Net Throughput per Channel/Sector
Mbps
16
14
12
10
8
6
4
2
0
DL
UL
1:1
3:1
1:1
3:1
1xEVDO
Rev A
3xEVDO
Rev B
HSDPA
HSPA
SIMO
MIMO
Mobile WiMAX
2x1.25
2x5 MHz
1x10 MHz


Spectral Efficiency
bps/Hz
2.0
1.5
1.0
0.5
0.0
DL
UL
1:1
3:1
1:1
3:1
1xEVDO
Rev A
3xEVDO
Rev B
HSDPA
HSPA
SIMO
MIMO
Mobile WiMAX