Resource Management & Scheduling

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Resource Management: Why is it so important?

Resources ? (Visible - invisible)

Wireless Technologies (LTE, LTE-A, WiMAX, WiMAX2)

QoS in modern wireless networks

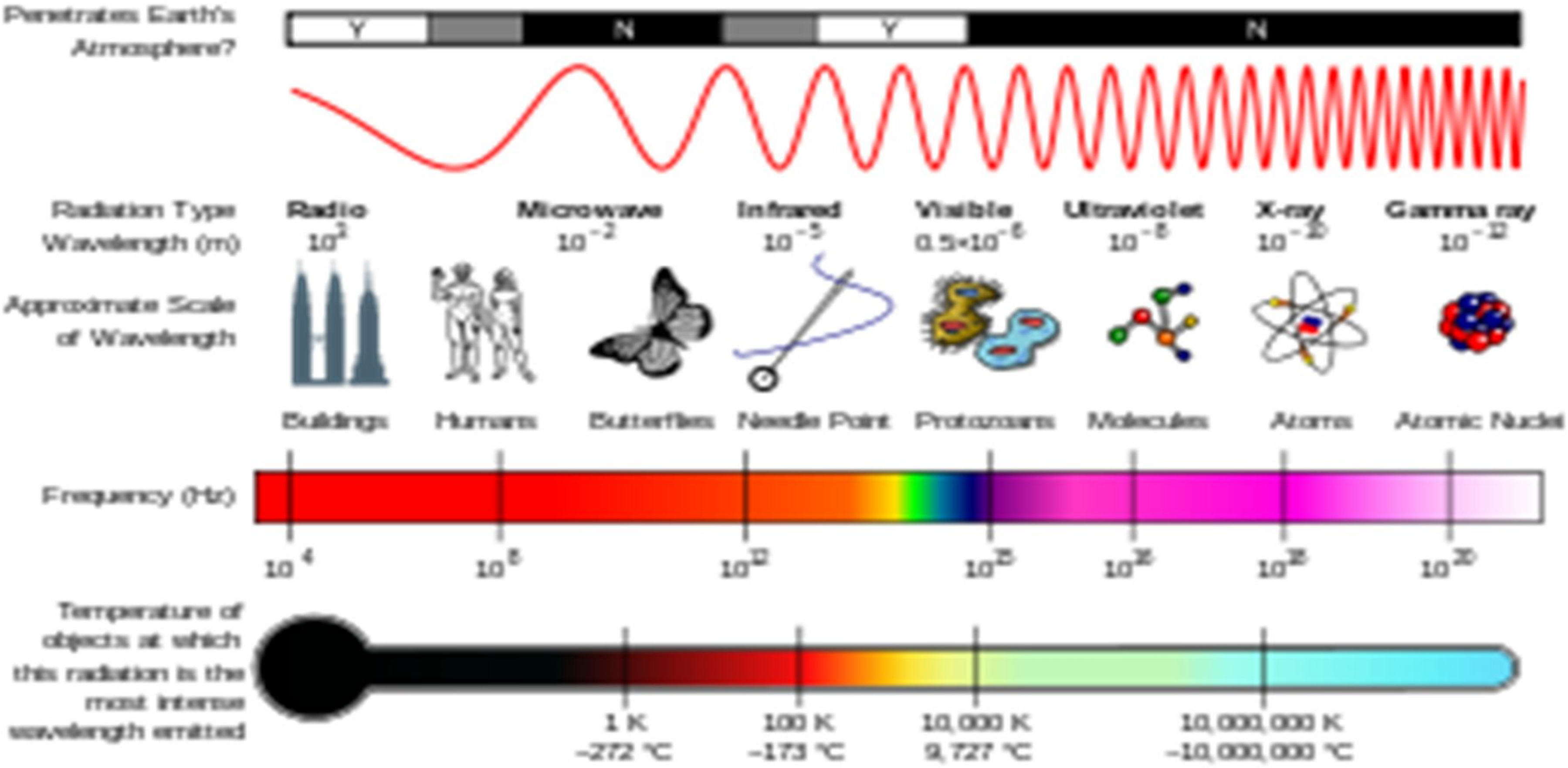
Traditional & Modern Scheduling Algorithms

Case Study: WiMAX (Co-FRTS)

PMP - MESH

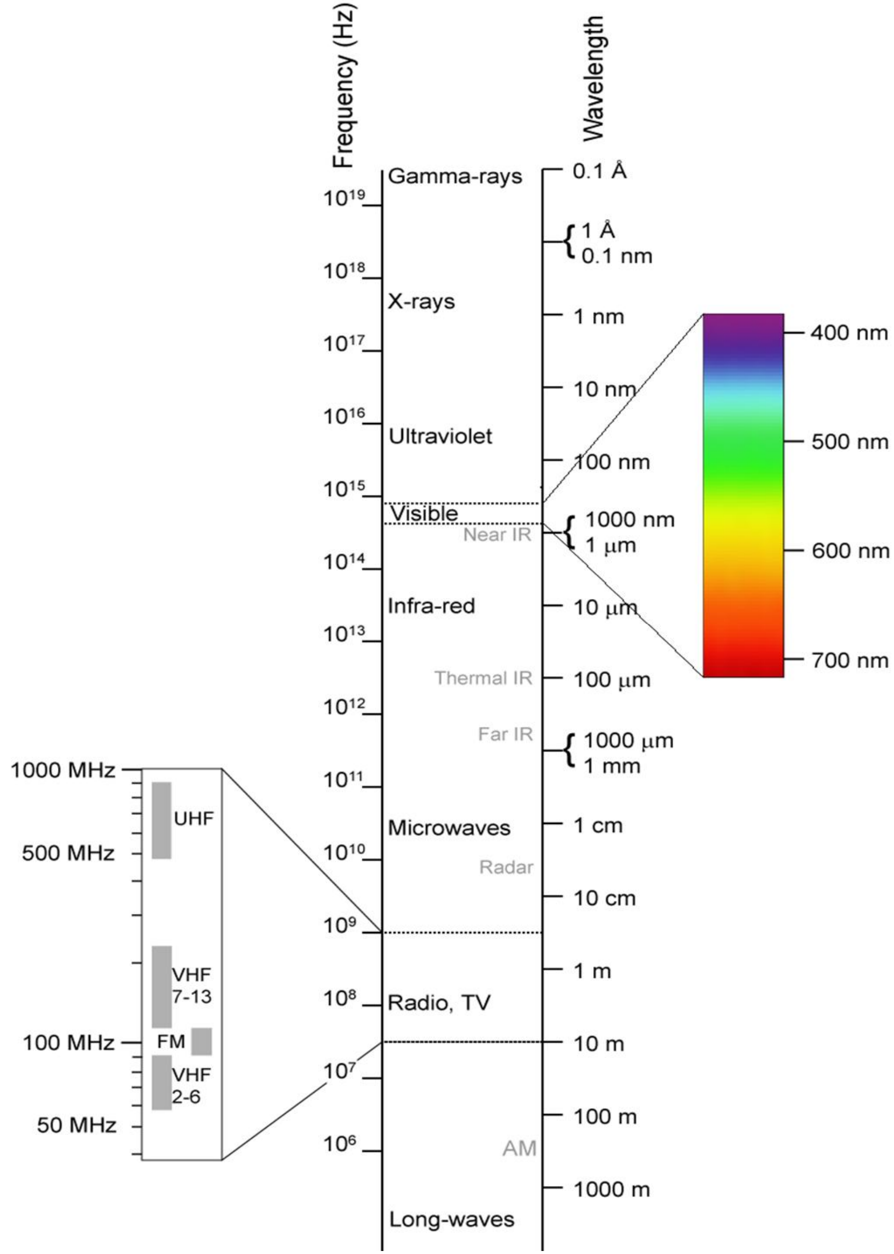
Simulation Environments

Resources (invisible) – Electromagnetic Spectrum



Resources (invisible) – Electromagnetic Spectrum

CLASS	FREQUENCY	WAVELENGTH	ENERGY
Y	300 EHz	1 pm	1.24 MeV
HX	30 EHz	10 pm	124 keV
	3 EHz	100 pm	12.4 keV
SX	300 PHz	1 nm	1.24 keV
EUV	30 PHz	10 nm	124 eV
NUV	3 PHz	100 nm	12.4 eV
NIR	300 THz	1 μm	1.24 eV
MIR	30 THz	10 μm	124 meV
FIR	3 THz	100 μm	12.4 meV
EHF	300 GHz	1 mm	1.24 meV
SHF	30 GHz	1 cm	124 μeV
UHF	3 GHz	1 dm	12.4 μeV
VHF	300 MHz	1 m	1.24 μeV
HF	30 MHz	10 m	124 neV
MF	3 MHz	100 m	12.4 neV
LF	300 kHz	1 km	1.24 neV
VLF	30 kHz	10 km	124 peV
VF/ULF	3 kHz	100 km	12.4 peV
SLF	300 Hz	1 Mm	1.24 peV
ELF	30 Hz	10 Mm	124 feV
	3 Hz	100 Mm	12.4 feV



Resources (visible) – Equipment

- User Equipment

- ISP Infrastructure

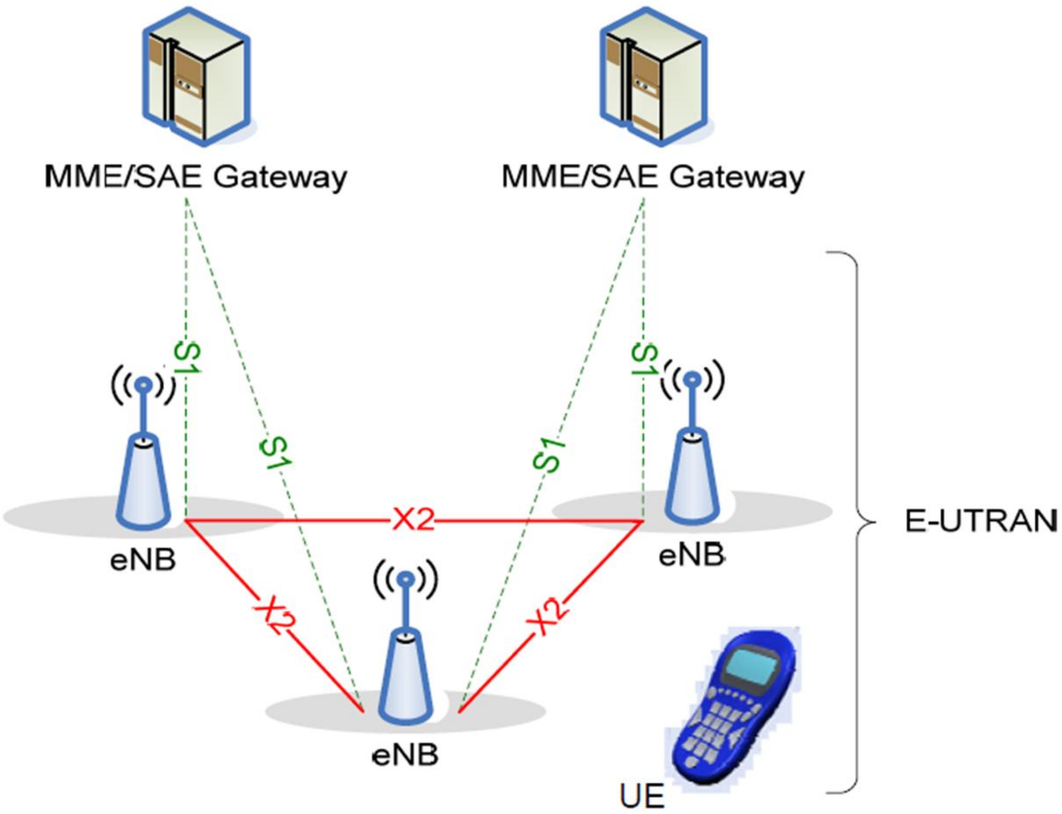
- Common type of hardware – different scale
  - Process Power
  - Memory
  - Antenna(s)
  - Transmission Power

Resource Management Role

- Efficiently use spectrum
- According to Wireless System should take into consideration:
  - Architecture (LTE, LTE-A, WiMAX, WiMAX 2 etc)
  - Point-to-multipoint & Mesh architectures
  - PHY (Transmission scheme, Multiple Access Scheme, Modulations etc)
  - MAC → QoS
  - Interference
  - Target (Throughput, QoE, QoS, scale economy, etc)
- According to the equipment should take into consideration:
  - Available Process Power
  - Memory
  - Power
  - Mobility

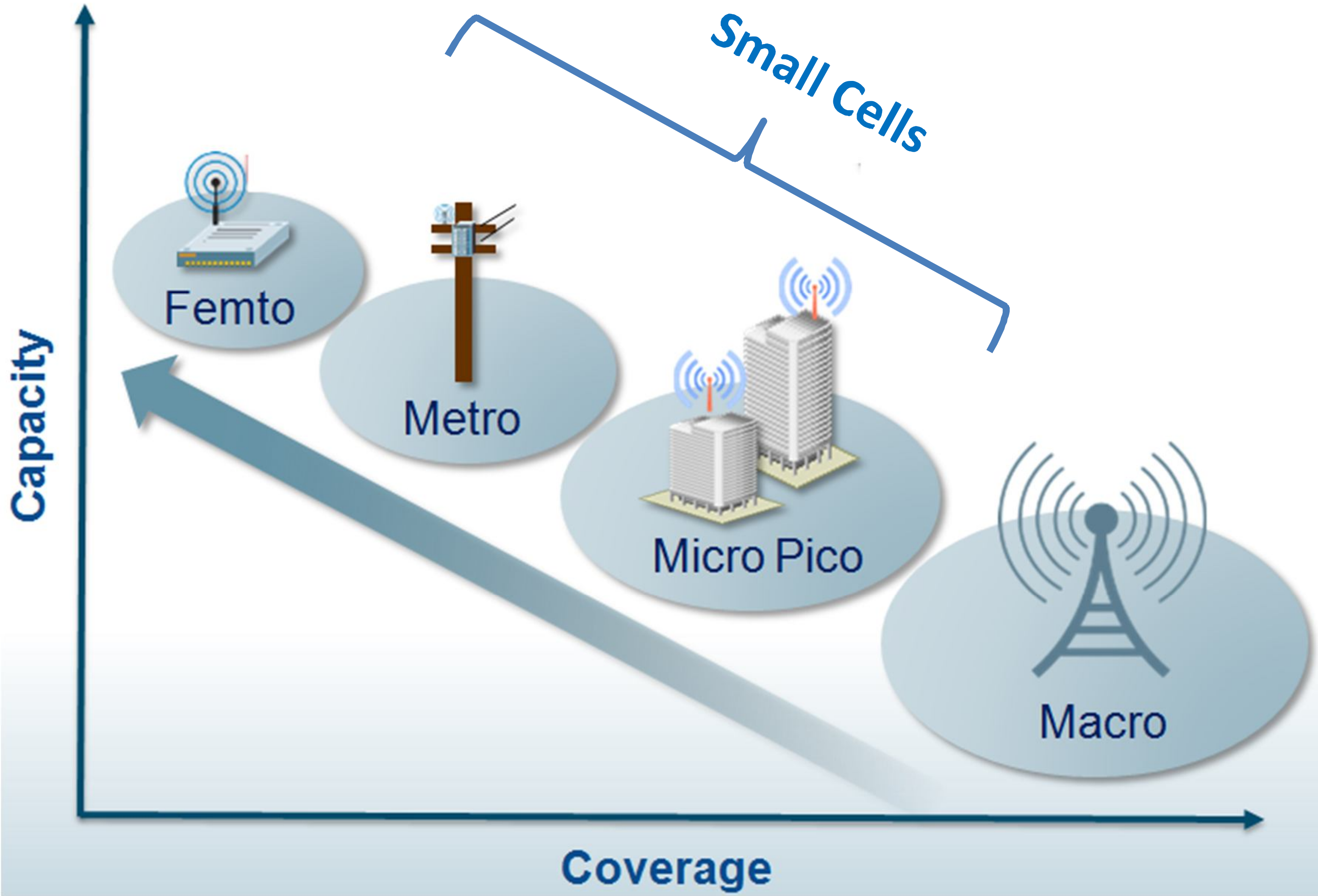
LTE / LTE-A
Architecture &
other major characteristics

LTE Architecture

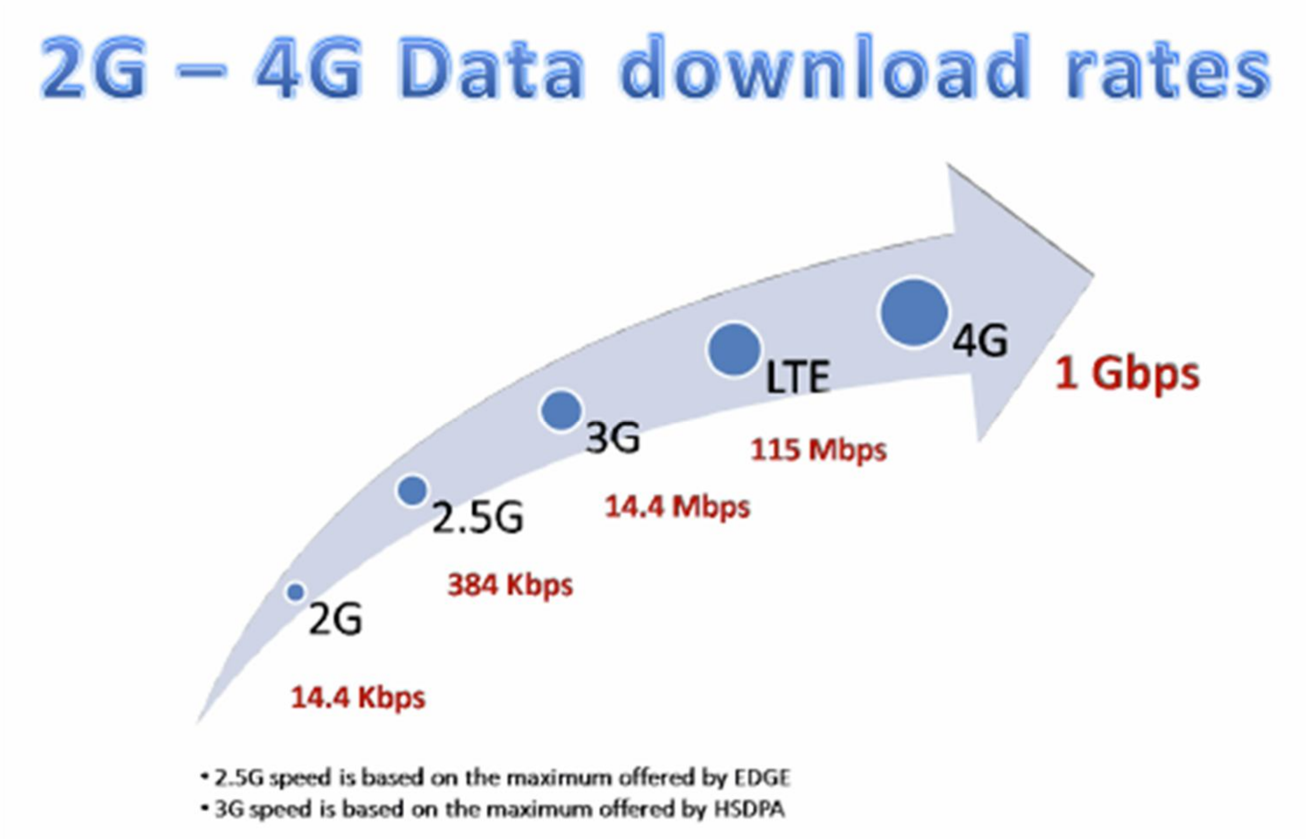


- **eNB**: Enhanced Node B, or base station
- **UE**: User Equipment
- **EPC**: Evolved Packet Core
  - **MME**: Mobility Management Entity (Control Plane)
  - **SAE**: System Architecture Evolved (User Plane)
- **E-UTRAN**: Evolved Universal Terrestrial Radio Access Network

Heterogeneous networks in LTE-A



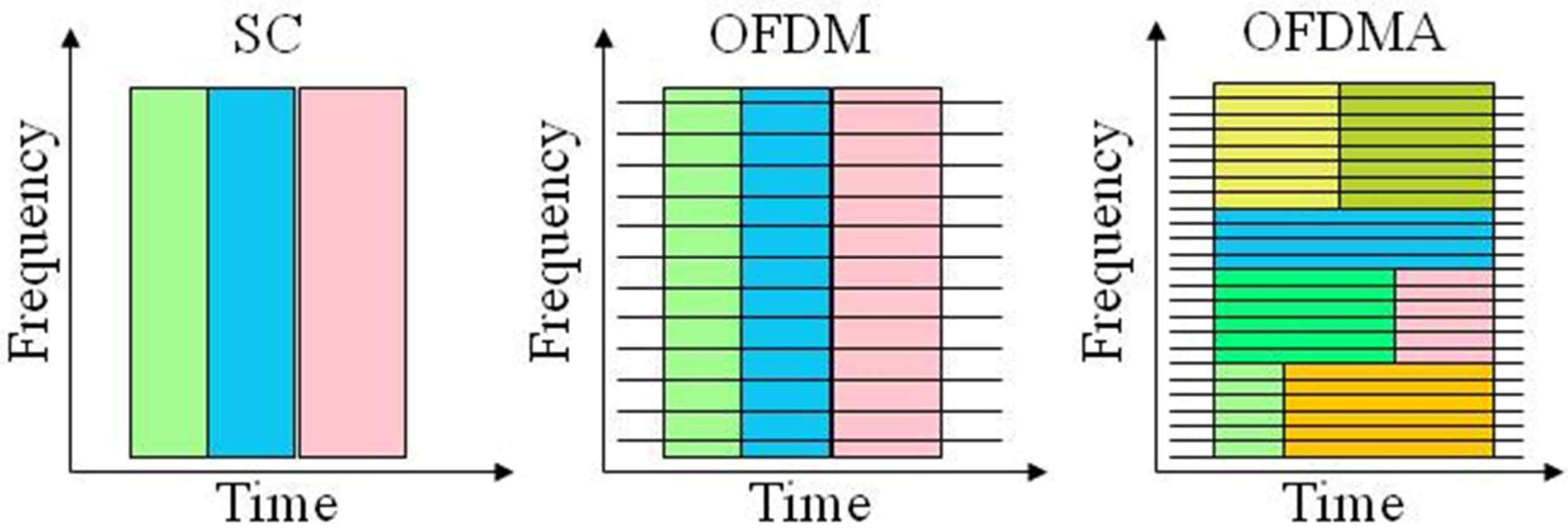
Comparison of LTE Speed



Key features of LTE

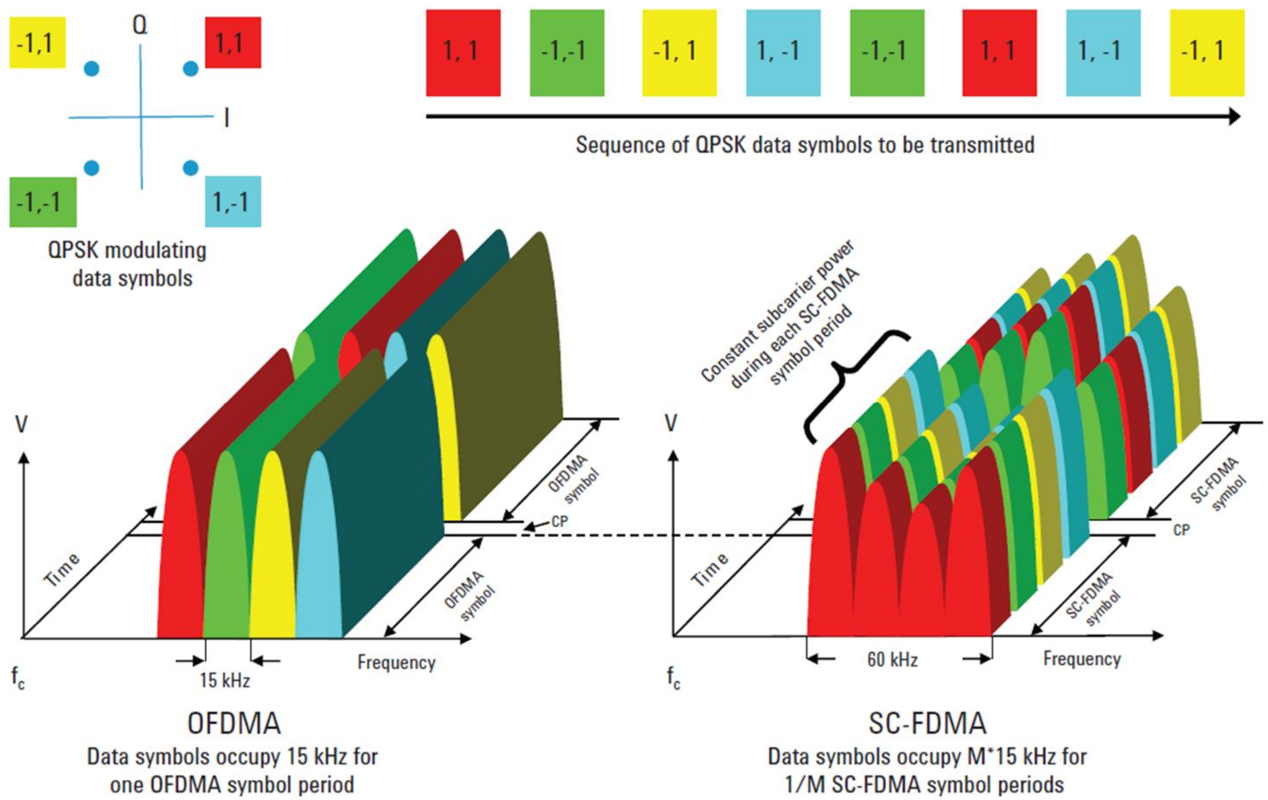
- **Multiple access scheme**
  - *DL: OFDMA*
  - *UL: Single Carrier FDMA (SCFDMA)*
- **Adaptive modulation & Coding**
  - *DL/UL modulations: QPSK, 16QAM & 64QAM*
  - *Convolutional code & Rel-6 turbo code*
- **Advanced MIMO spatial multiplexing techniques**
  - *(2 or 4)x(2 or 4) downlink & uplink supported*
  - *Multi-user MIMO also supported*
- **Support for both FDD & TDD**
- **H-ARQ, mobility support, rate control, security & etc**

SC/OFDM/OFDMA



LTE Uplink (SC-FDMA)

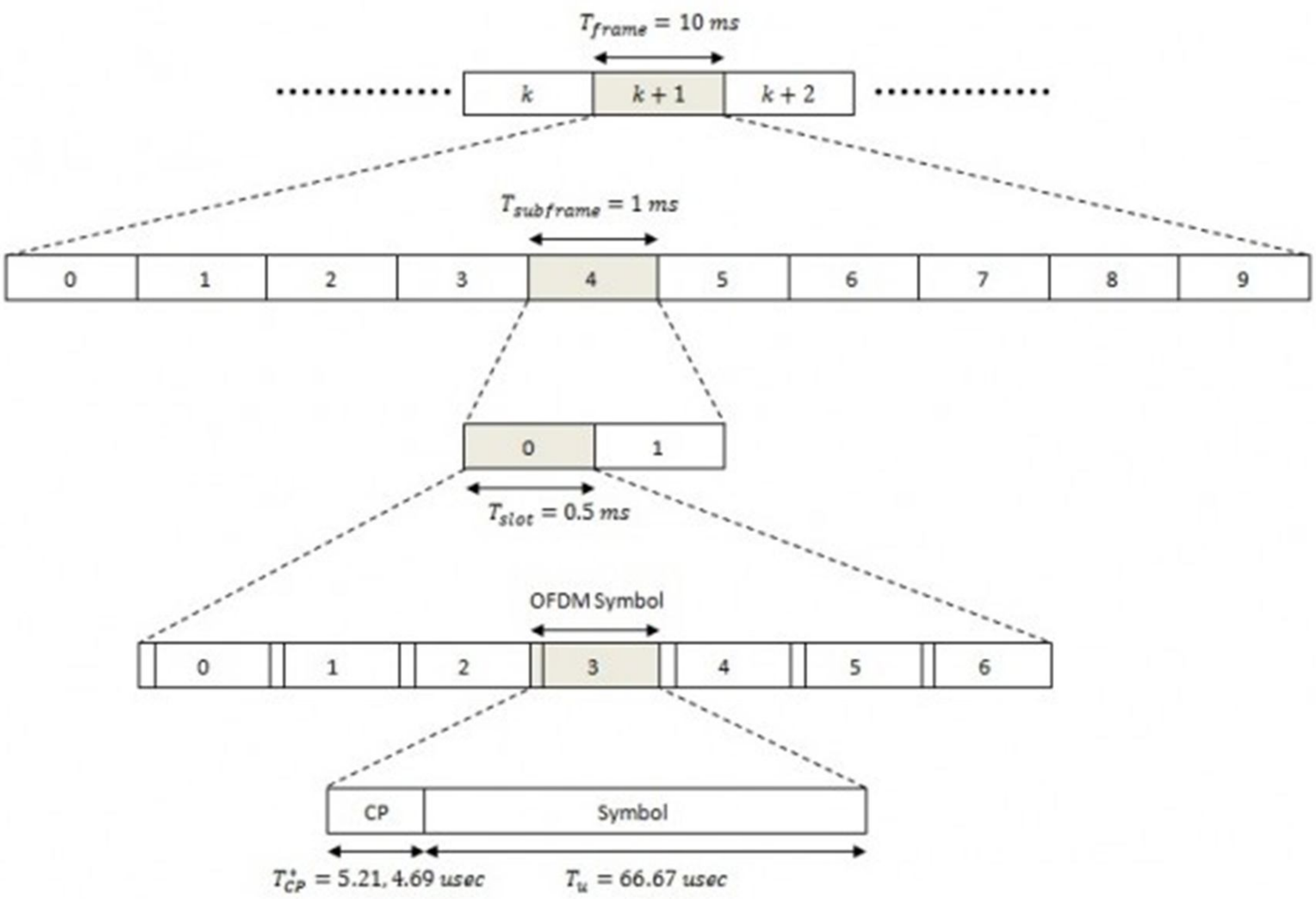
- SC-FDMA is a new single carrier multiple access technique which has similar structure and performance to OFDMA
- More complex, but consumes ***less power***



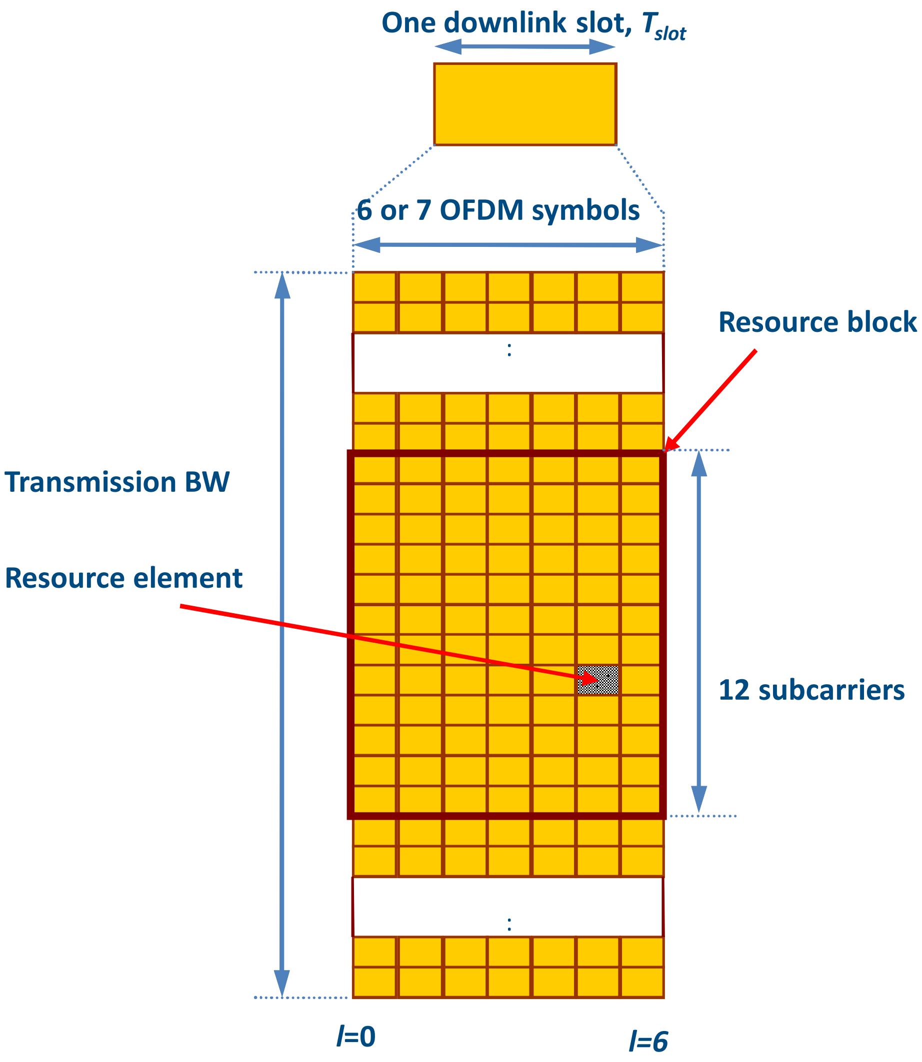
Peak data rates of LTE

Downlink peak data rates (64 QAM)			
Antenna configuration	SISO	2x2 MIMO	4x4 MIMO
Peak data rate Mbps	100	172.8	326.4
Uplink peak data rates (single antenna)			
Modulation	QPSK	16 QAM	64 QAM
Peak data rate Mbps	50	57.6	86.4

Generic Frame Structure

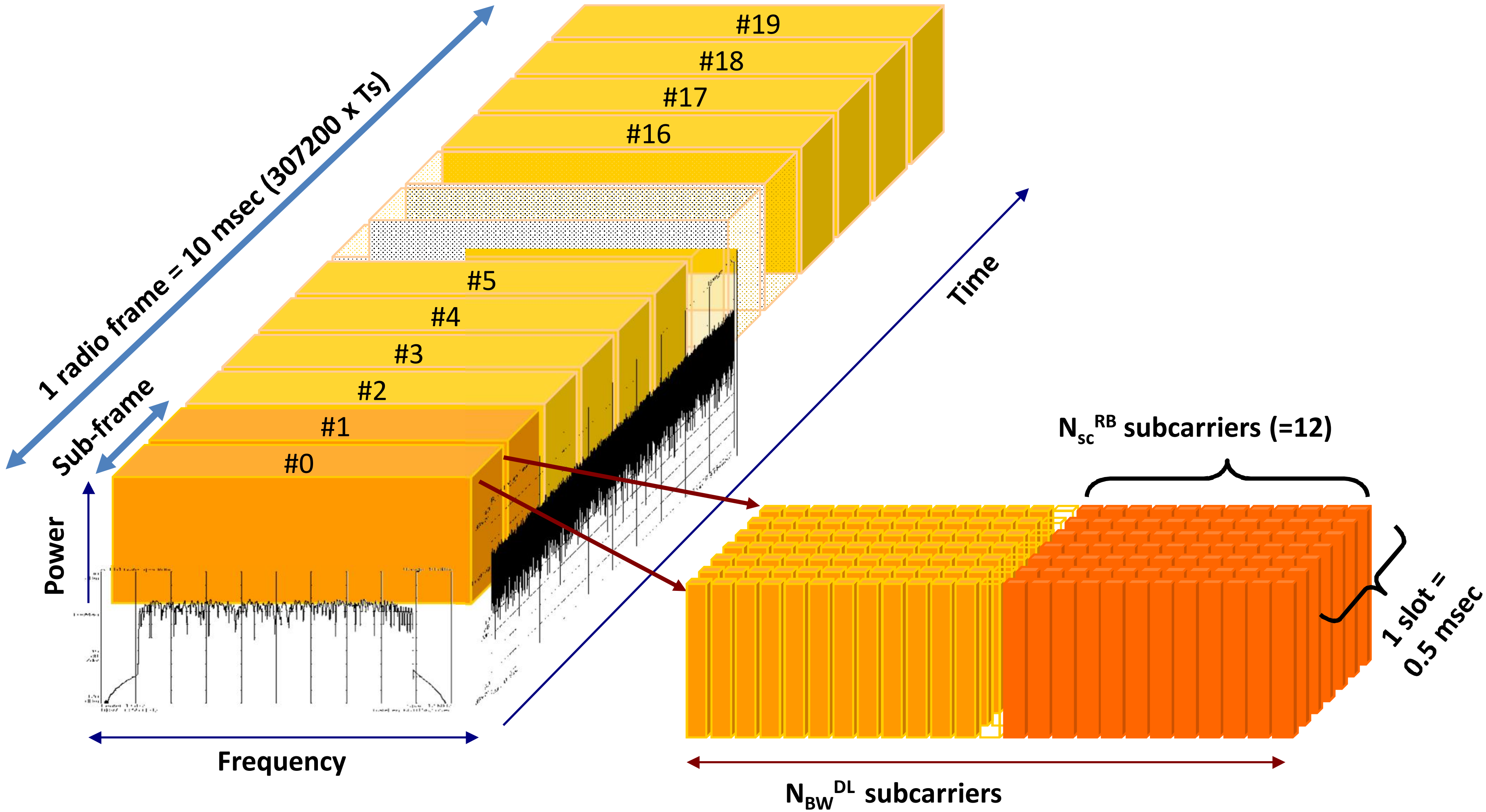


Resource Grid

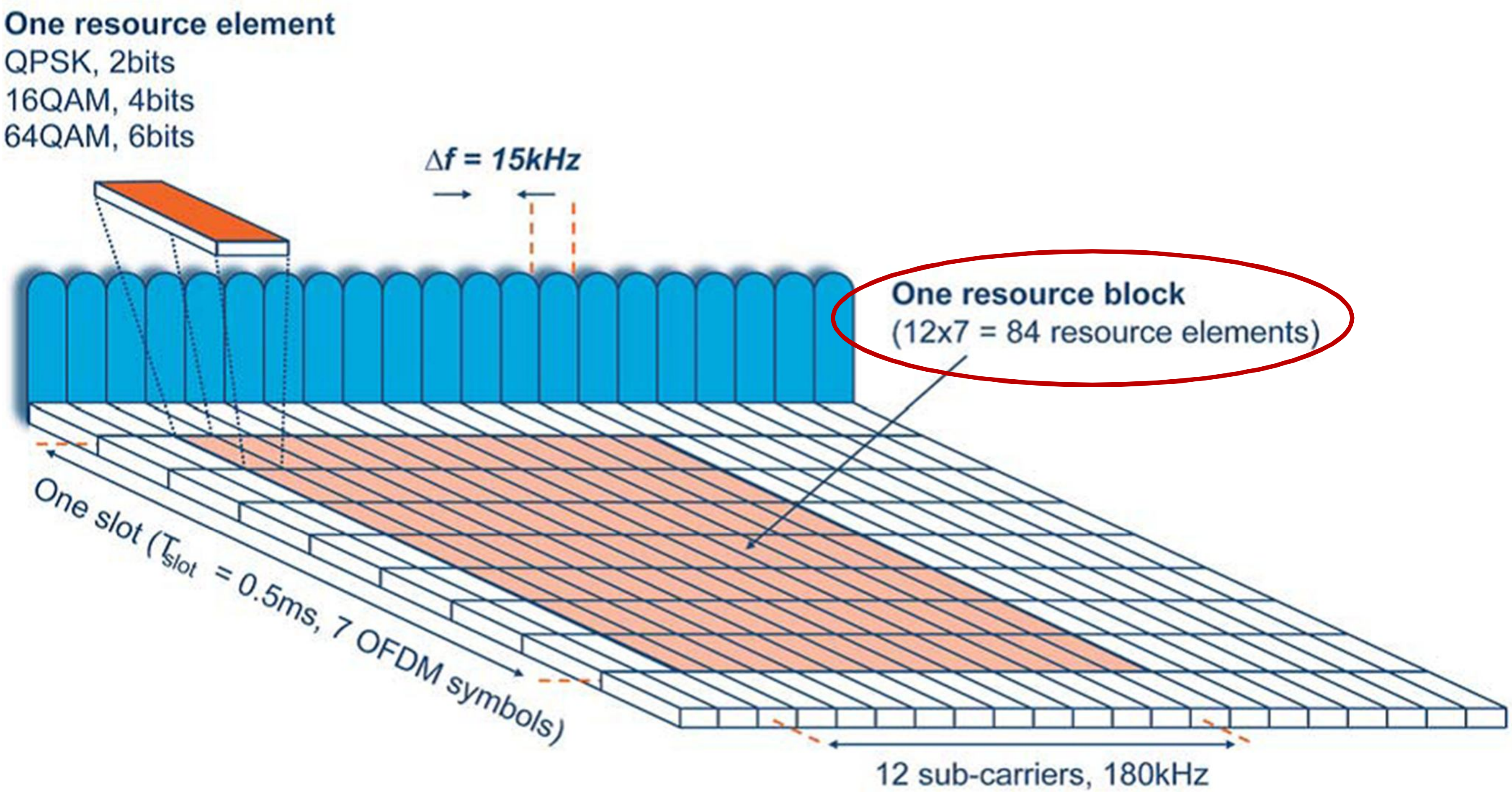


- 6 or 7 OFDM symbols in 1 slot
- Subcarrier spacing = 15 kHz
- Block of 12 SCs in 1 slot = 1 RB
  - *0.5 ms x 180 kHz*
  - Smallest unit of allocation

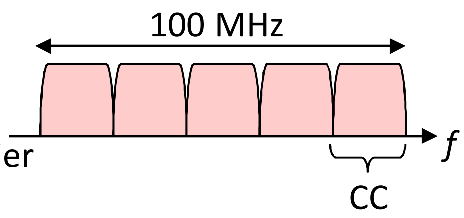
Resource grid 2D



Allocation of physical resource blocks (PRBs) is handled by a scheduling function at the 3GPP base station (eNodeB)



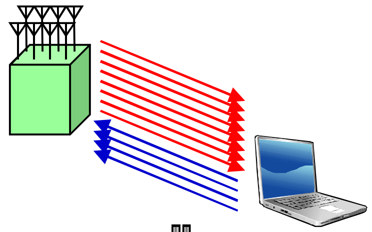
LTE-A main features



Support of Wider Bandwidth(Carrier Aggregation)

- Use of multiple component carriers(CC) to extend bandwidth up to 100 MHz
- Common physical layer parameters between component carrier and LTE Rel-8 carrier

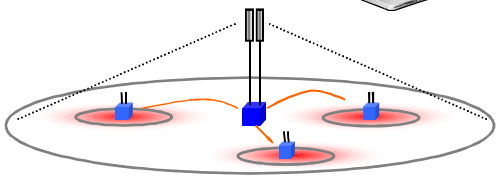
➔ Improvement of peak data rate, backward compatibility with LTE Rel-8



Advanced MIMO techniques

- Extension to up to 8-layer transmission in downlink
- Introduction of single-user MIMO up to 4-layer transmission in uplink
- Enhancements of multi-user MIMO

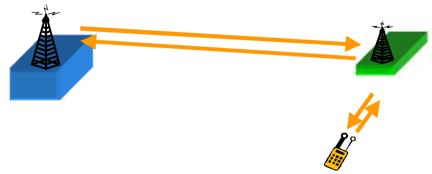
➔ Improvement of peak data rate and capacity



Heterogeneous network and eICIC (enhanced Inter-Cell Interference Coordination)

- Interference coordination for overlaid deployment of cells with different Tx power

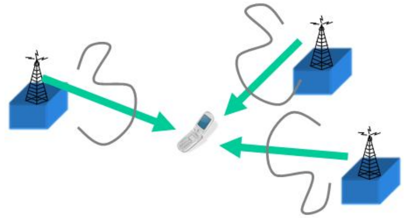
➔ Improvement of cell-edge throughput and coverage



Relay

- Supports radio backhaul and creates a separate cell and appear as Rel. 8 LTE eNB to Rel. 8 LTE UEs

➔ Improvement of coverage and flexibility of service area extension



Coordinated Multi-Point transmission and reception (CoMP)

- Support of multi-cell transmission and reception

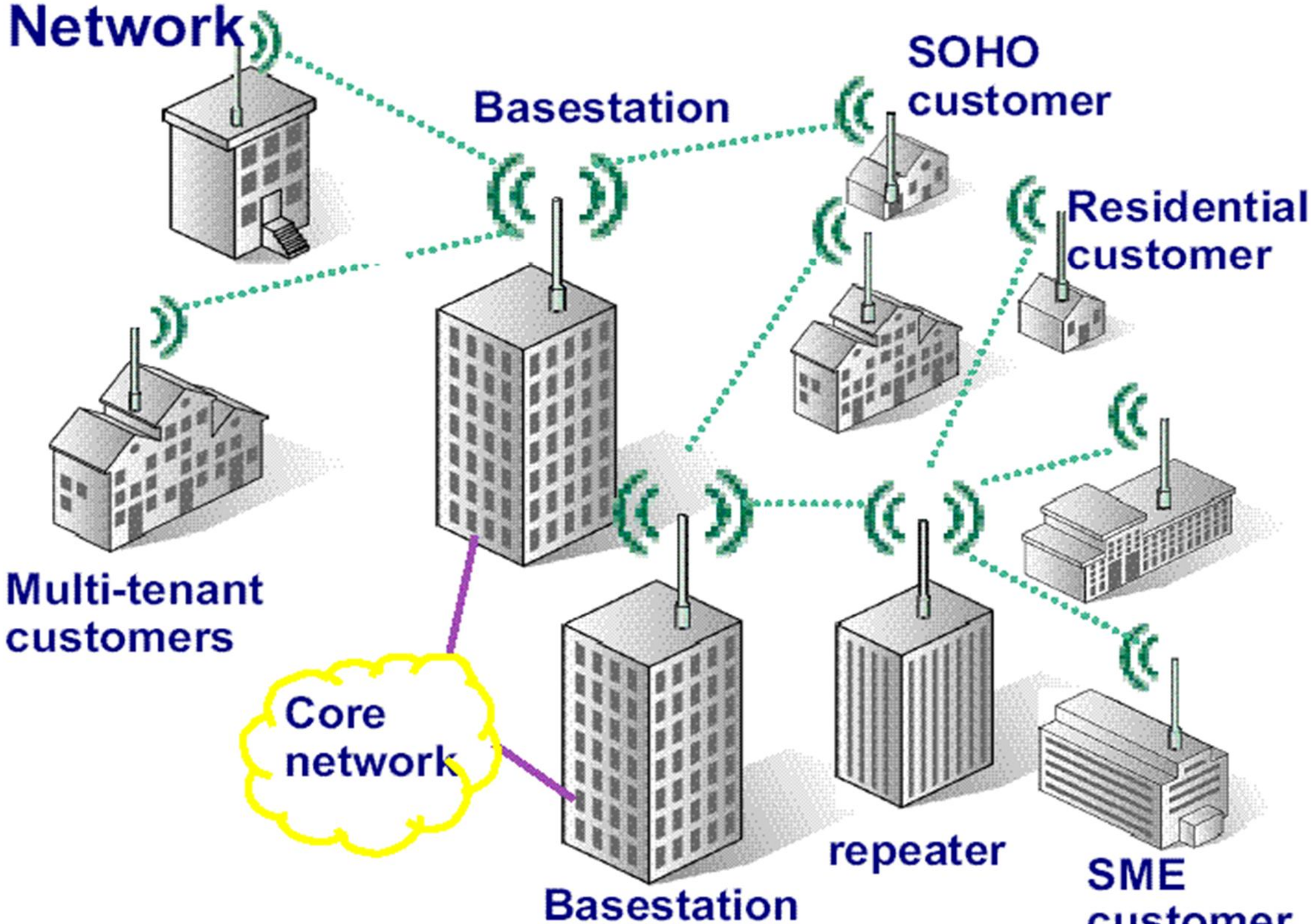
➔ Improvement of cell-edge throughput and coverage

LTE / LTE-A comparison

Technology	LTE	LTE--A
Peak data rate Down Link (DL)	150 Mbps	1 Gbps
Peak data rate Up Link (UL)	75 Mbps	500 Mbps
Transmission bandwidth DL	20MHz	100 MHz
Transmission bandwidth UL	20MHz	40 MHz (requirements as defined by ITU)
Mobility	Optimized for low speeds(<15 km/hr) High Performance At speeds up to 120 km/hr Maintain Links at speeds up to 350 km/hr	Same as that in LTE
Coverage	Full performance up to 5 km	a) Same as LTE requirement b) Should be optimized or deployment in local areas/micro cell environments.
Scalable Band Widths	1.3,3, 5, 10, and 20 MHz	Up to 20–100 MHz
Capacity	200 active users per cell in 5 MHz.	3 times higher than that in LTE

IEEE 802.16
WiMAX / WiMAX 2 / 2.1
Architecture &
other major characteristics

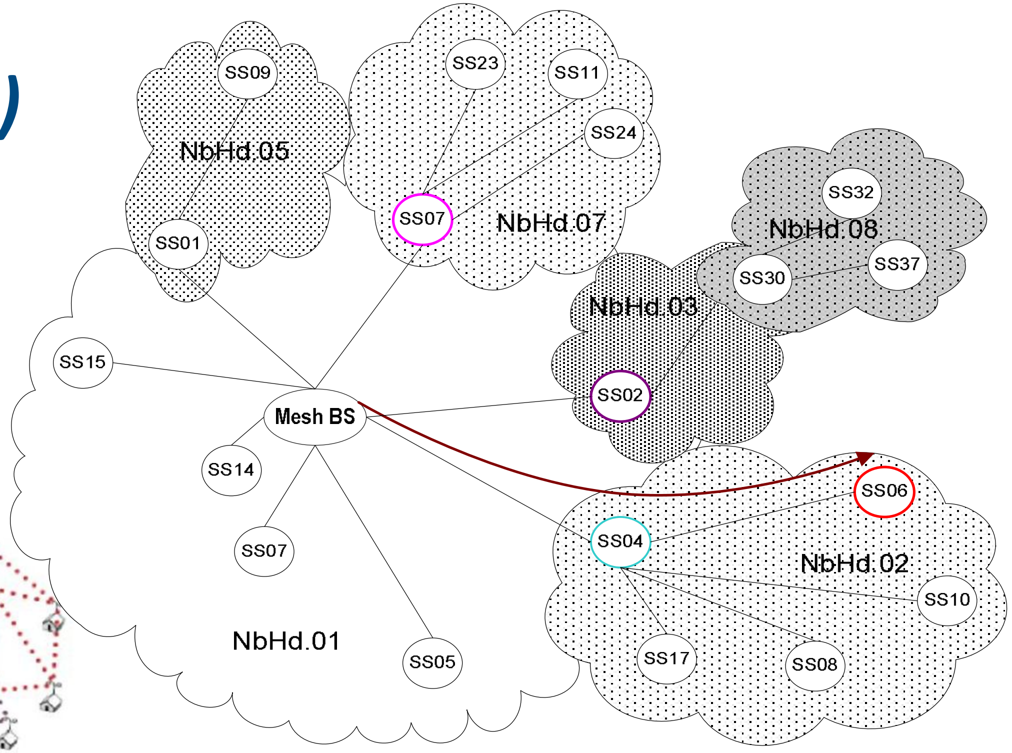
WirelessMAN: Wireless Metropolitan Area Network

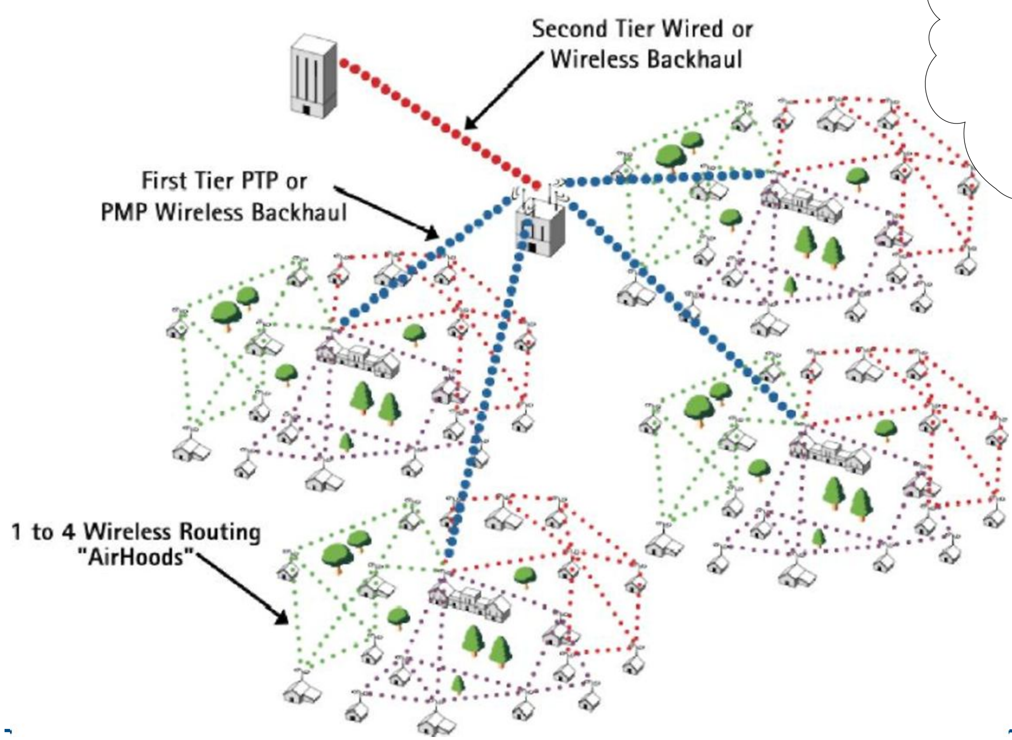


Source: Nokia Networks

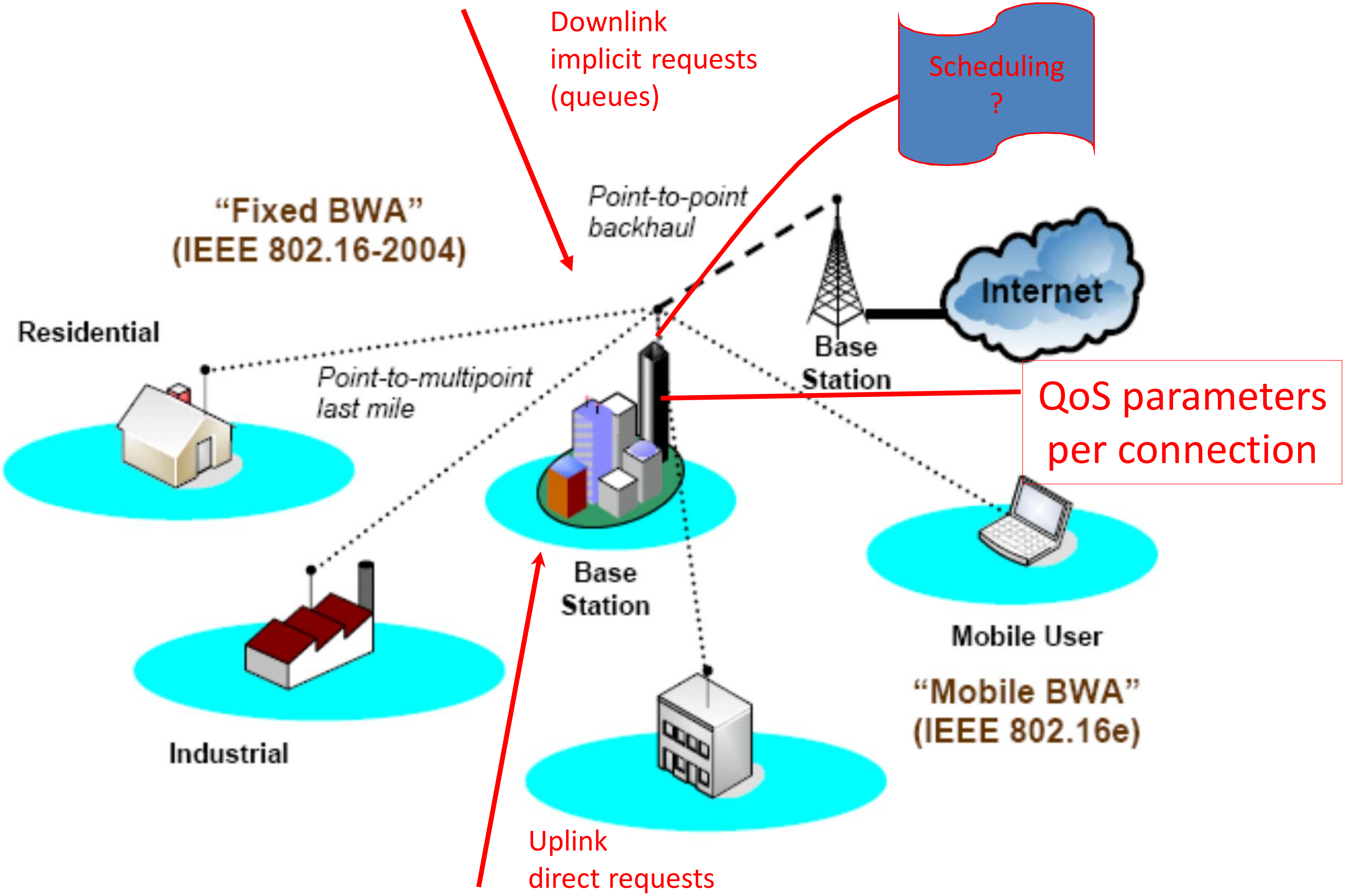
IEEE 802.16-2004 Topologies

- ***Point-to-Multipoint (PMP)***
- ***Centralized Mesh mode***
- Distributed Mesh mode

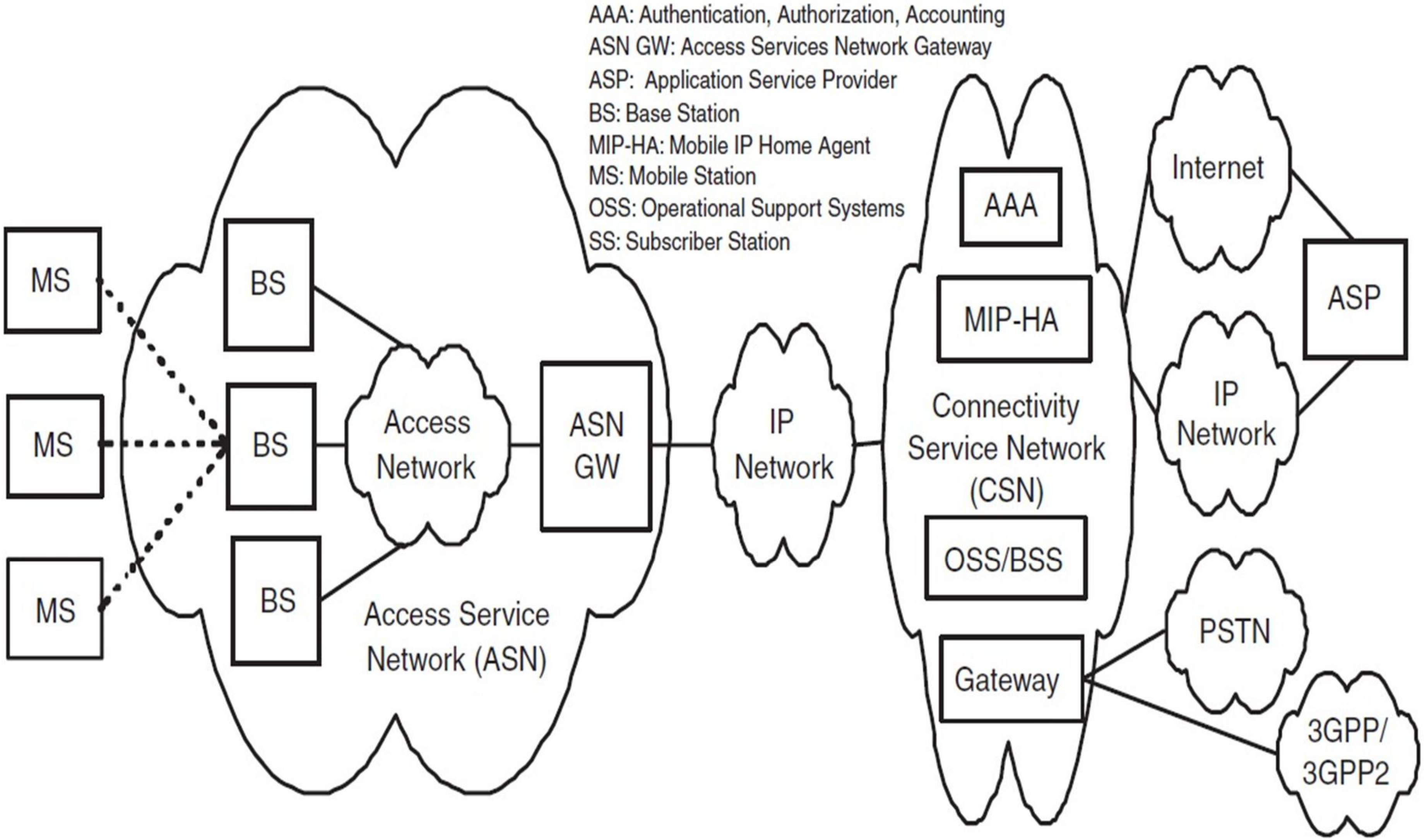




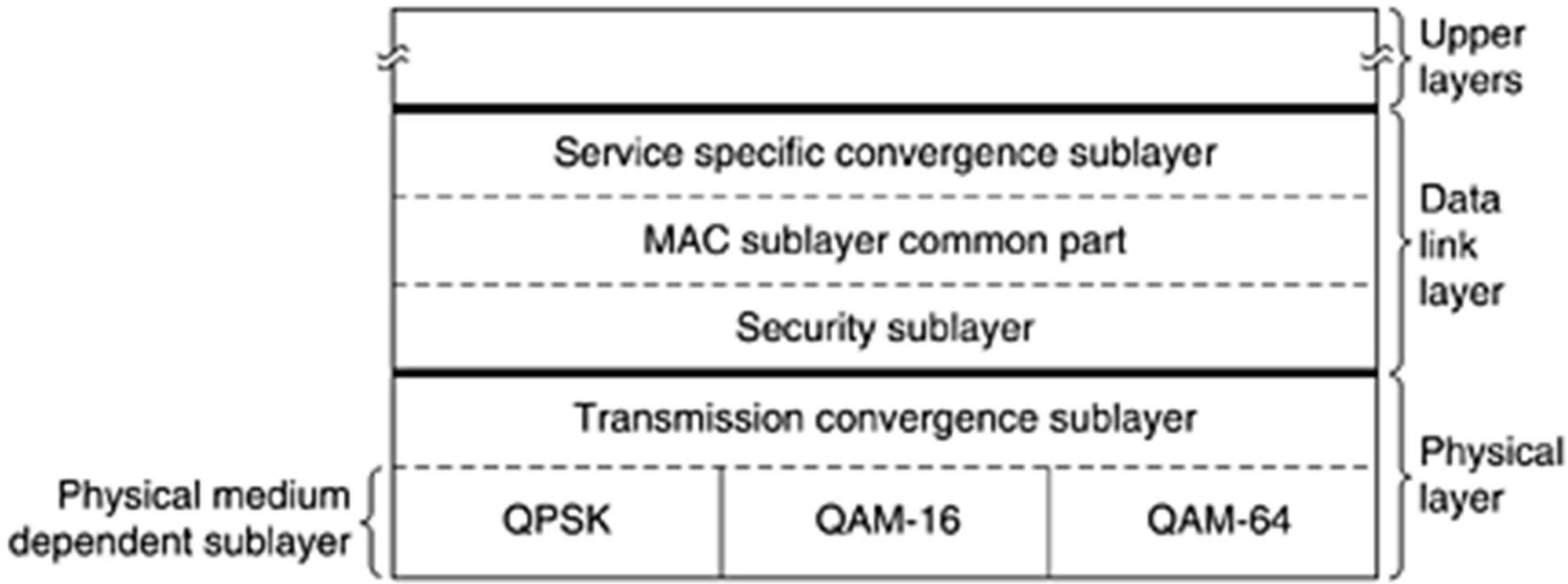
Bandwidth request & allocation



WiMAX Architecture



WiMaX Layers



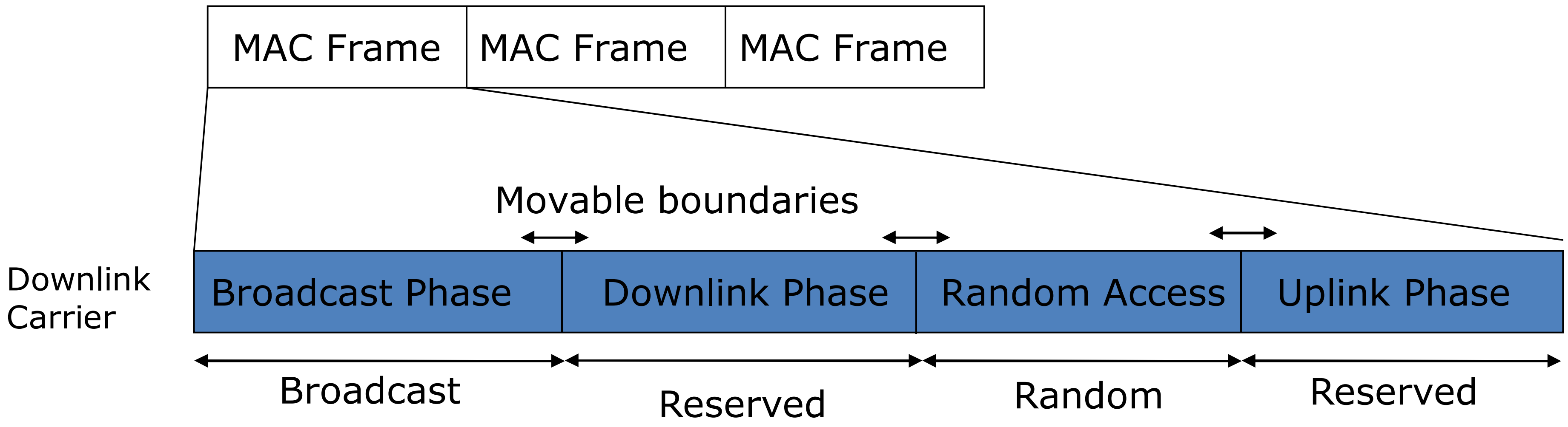
Extensions in 802.16e

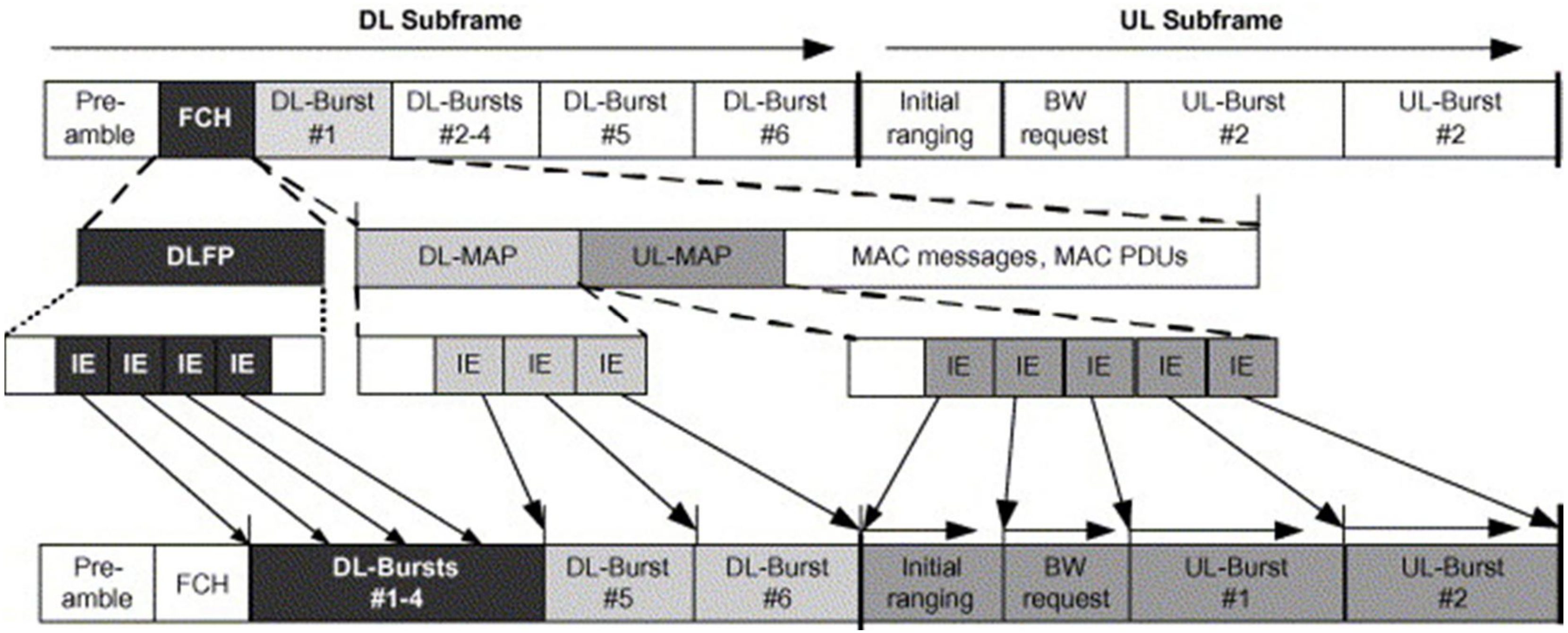
- Mobility support
- Orthogonal time division multiple access (OFDMA)

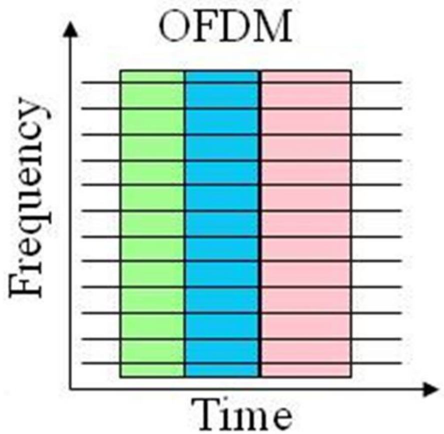
Media Access Control (MAC)

- **Connection oriented μετάδοση**
  - ***Connection ID (CID)***
  - ***Uni-directional***
- **Channel access:**
  - ***UL-MAP***
    1. Includes reservation information for the uplink
    2. Who transmits (to the Base Station) & when
  - ***DL-MAP***
    1. Includes reservation information for the downlink
    2. Who receives (from the Base Station) & when
  - ***UL-MAP & DL-MAP are transmitted at the beginning of each time frame (broadcasting).***

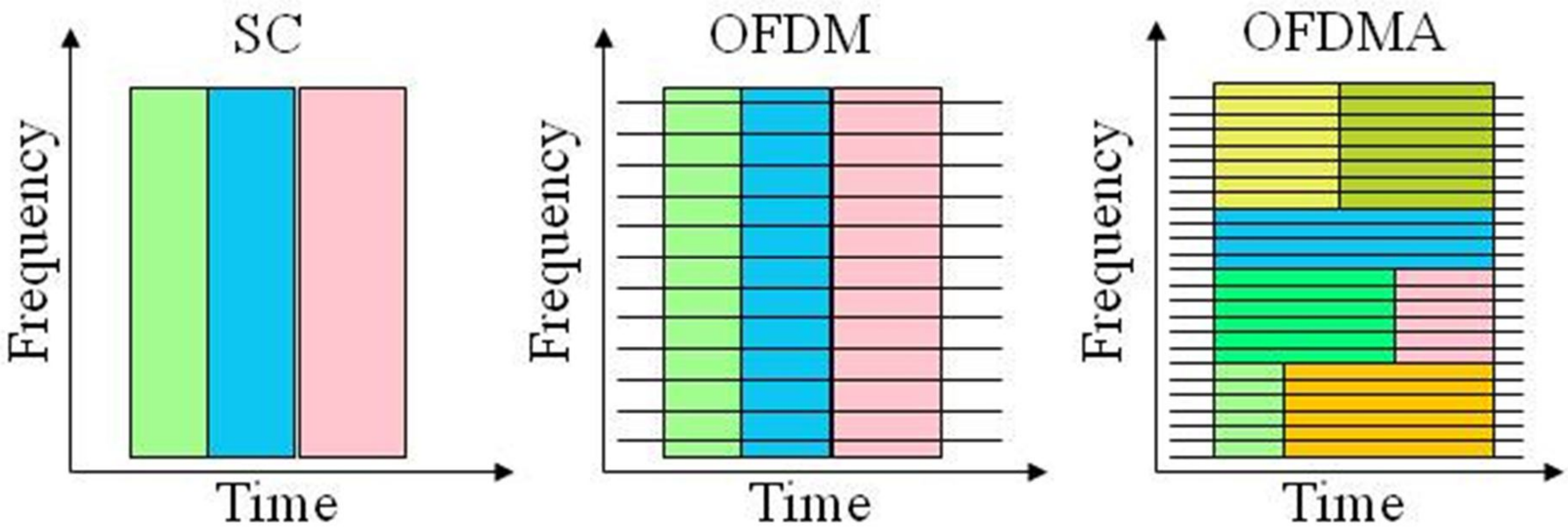
Time Division Duplexing (TDD)



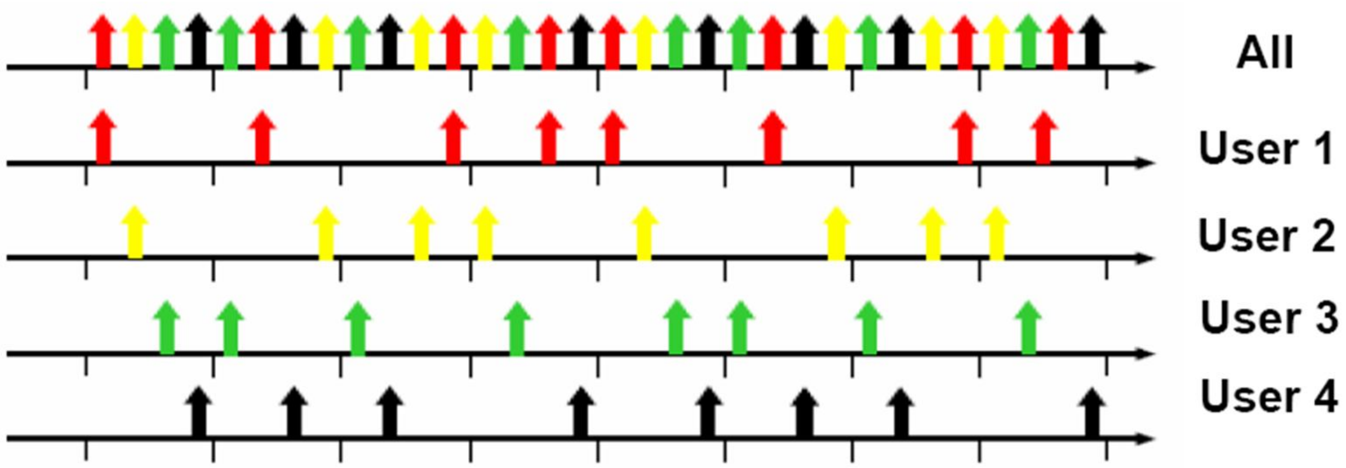

DL Subframe
UL Subframe
Pre-amble
FCH
DL-Burst #1
DL-Bursts #2-4
DL-Burst #5
DL-Burst #6
Initial ranging
BW request
UL-Burst #2
UL-Burst #2
DLFP
DL-MAP
UL-MAP
MAC messages, MAC PDUs
IE
Pre-amble
FCH
DL-Bursts #1-4
DL-Burst #5
DL-Burst #6
Initial ranging
BW request
UL-Burst #1
UL-Burst #2

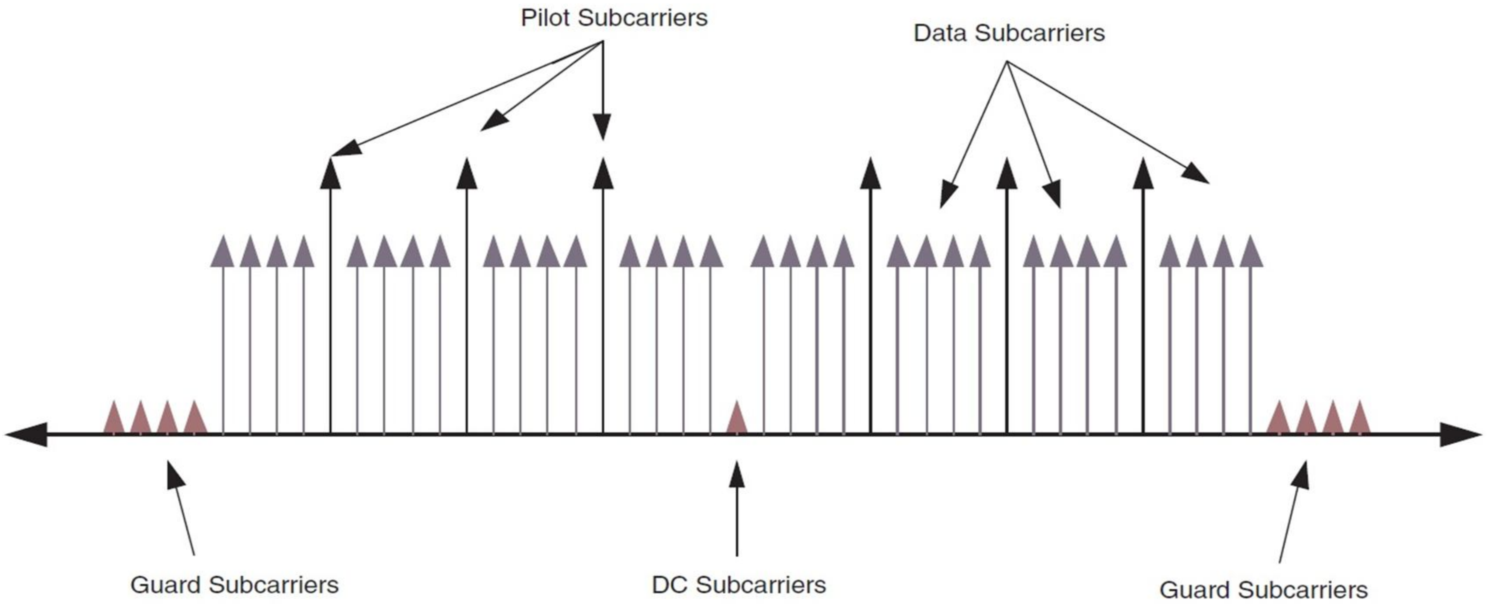

OFDM
Frequency
Time

SC/OFDM/OFDMA



OFDMA & OFDM symbol example





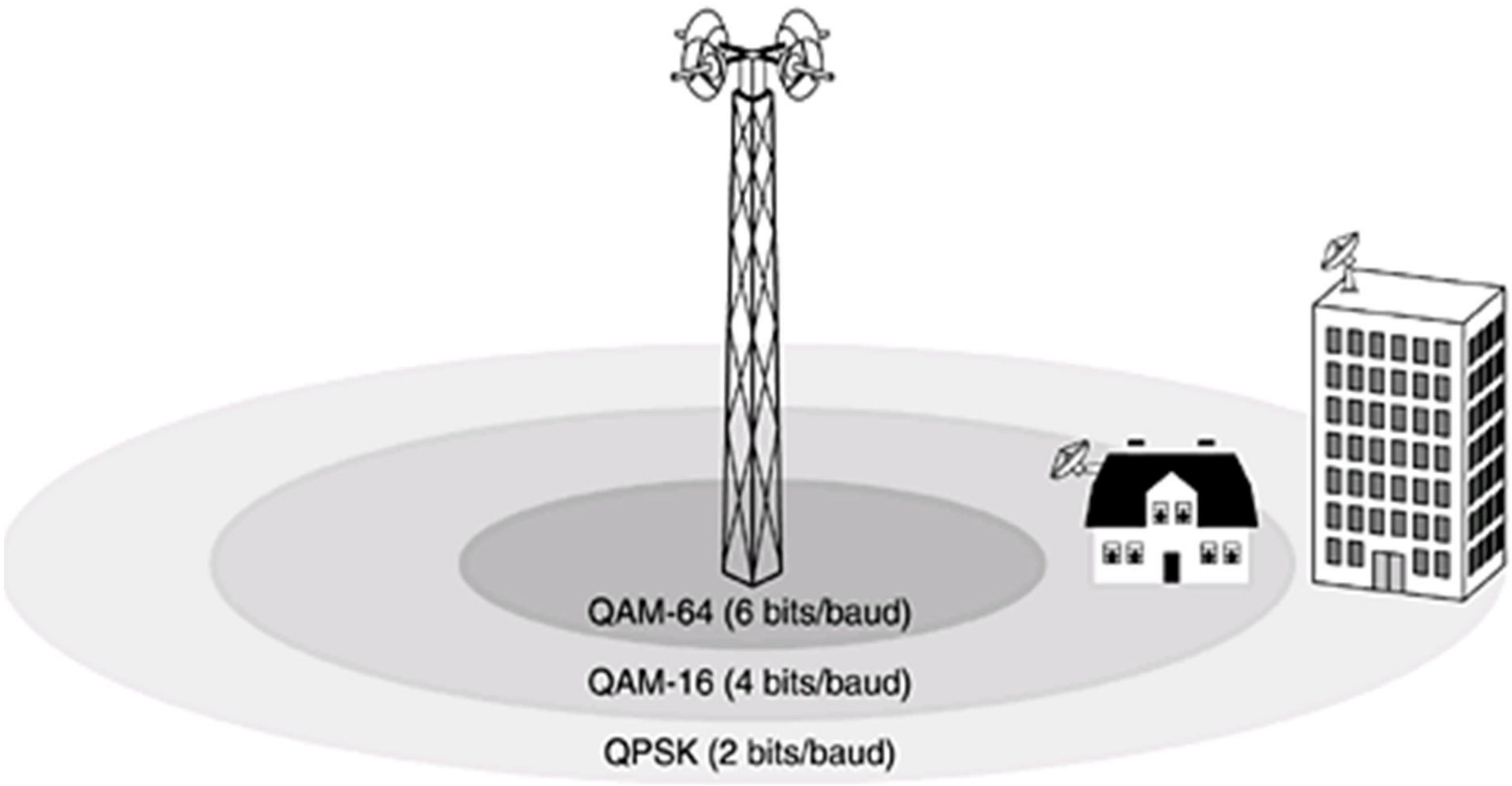
Advantages of OFDMA

- More flexible allocation of the available spectrum.
- Avoid transmission in low quality carriers (e.g., due to interference).
- Lower maximum transmission power for users.
- Higher overall throughput.
- Allows simultaneous transmissions from several users.
- Lower delay variance.
- Averaging interferences from neighboring cells, by using different carriers when possible.

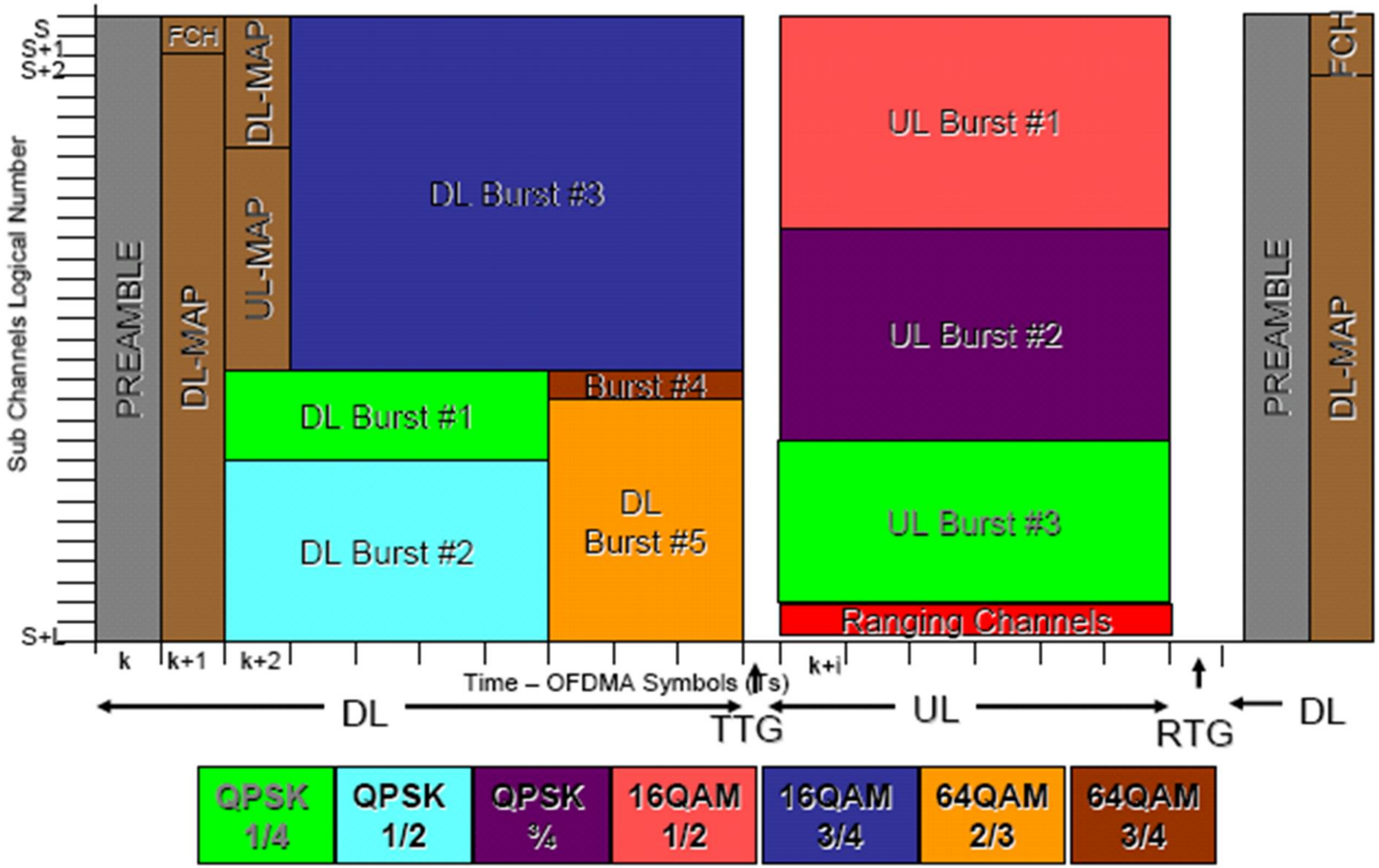
Disadvantage

- Considerably complex in design & implementation

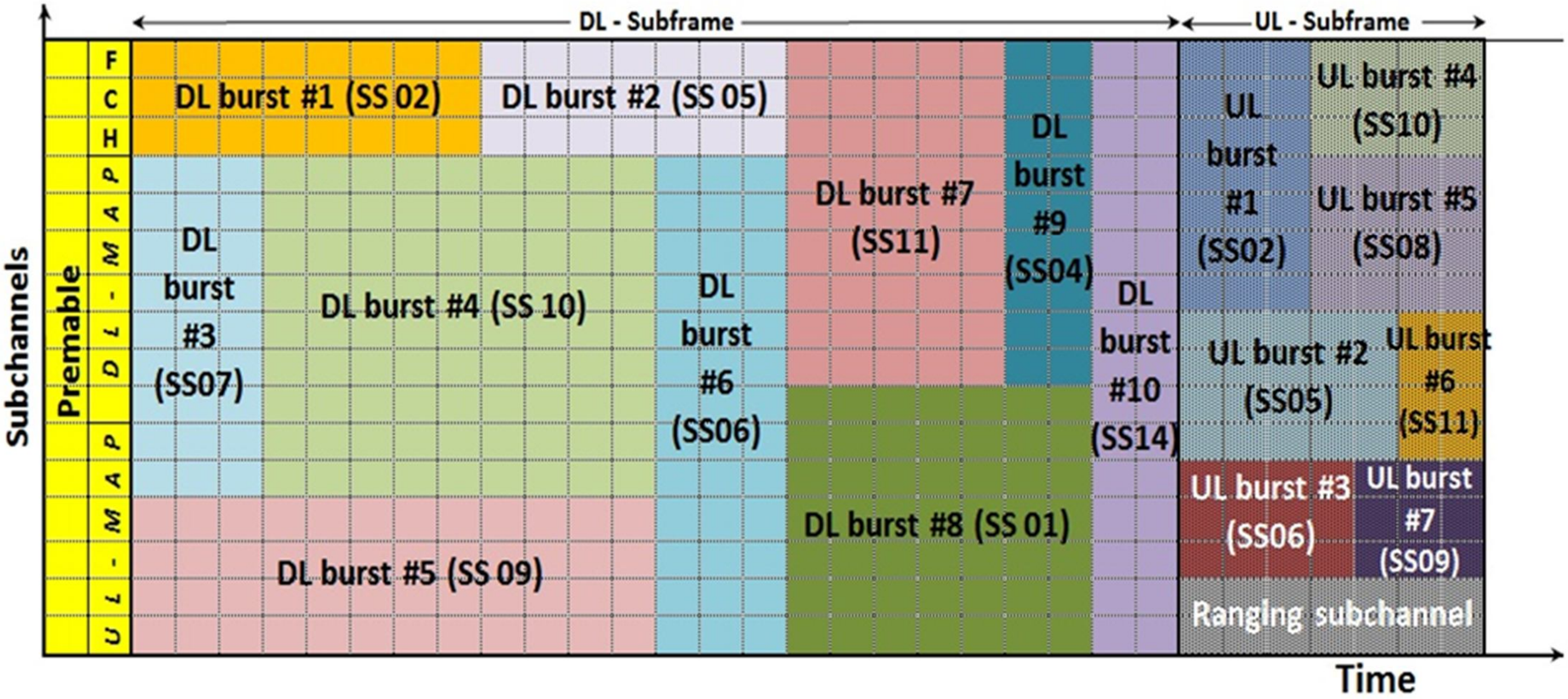
Adaptive modulation



OFDMA/TDD structure



OFDMA/TDD structure



OFDM symbol parameters in frequency domain

Parameters	Fixed WiMAX OFDMA-PHY	Mobile WiMAX Scalable OFDMA-PHY[a]			
FFT Size	256	128	512	1024	2048
Number of data subcarriers to be used[b]	192	72	360	720	1440
Number of pilot subcarriers	8	12	60	120	240
Number of null/guardband subcarriers	56	44	92	184	368
Cyclic prefix or guard time (Tg/Tb)	1/32, 1/16, 1/8, 1/4				
Oversampling Rate (in Fs/BW)	Considering BW: 7/6 for 256 OFDM, 8/7 for multiples of 1.75MHz, & 28/25 for multiples of 1.25MHz, 2MHz, ή 2.75MHz				
Channel BW in MHz	3.5	1.25	5	10	20
Subcarriers' Frequency spacing (in KHz)	15.625	10.94			
Useful symbol time(σε μs)	64	91.4			
Guard Time (Considering 12,5% in μs)	8	11.4			
OFDM symbol duration (in μs)	72	102.9			
Number of OFDM symbols in 5ms Timeframe	69	48.0			

Downlink Full Usage of Subcarriers

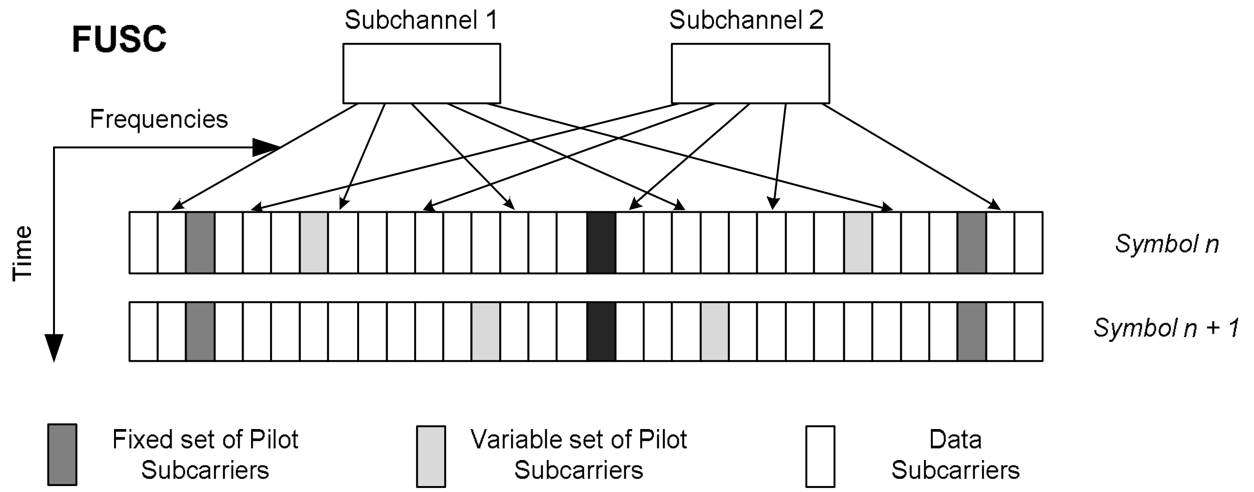


Figure: FUSC subchannelization

Table: FUSC subchannelization parameters

	128	256[a]	512	1024	2048
Subcarriers per subchannel	48	N/A	48	48	48
Number of subchannels	2	N/A	8	16	32
Number of data subcarriers	96	192	384	768	1536
Number of Pilot subcarriers constant set	1	8	6	11	24
Number of Pilot subcarriers variable set	9	N/A	36	71	142
Left guard subcarriers (left-guard)	11	28	43	87	173
Right guard subcarriers (right-guard)	10	27	42	86	172

Downlink Partial Usage of Subcarriers

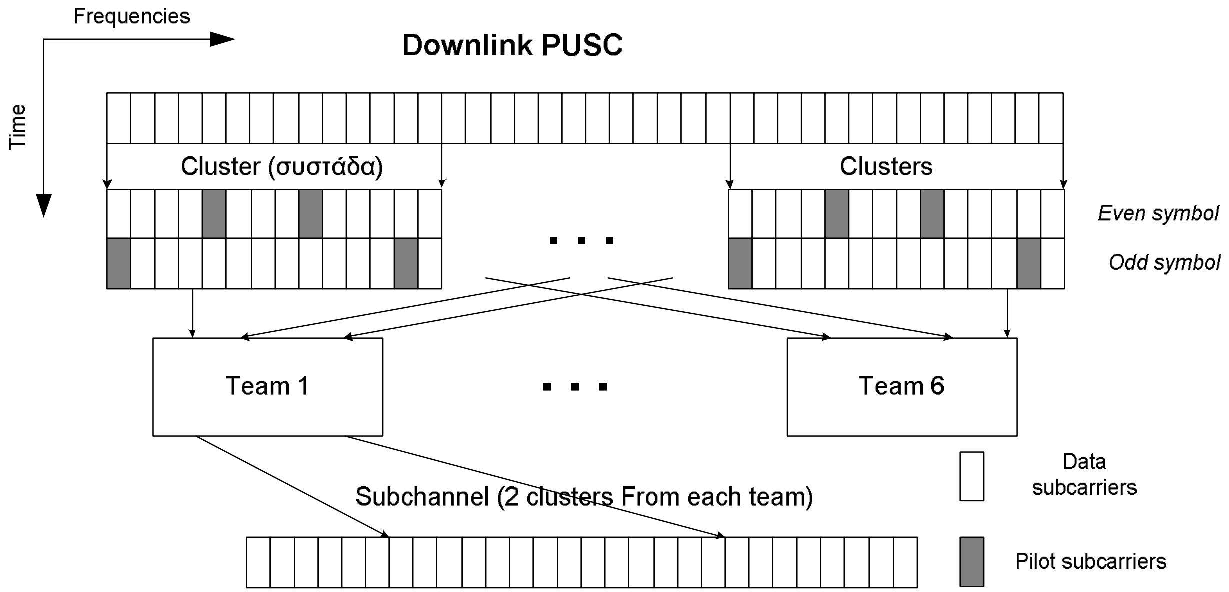
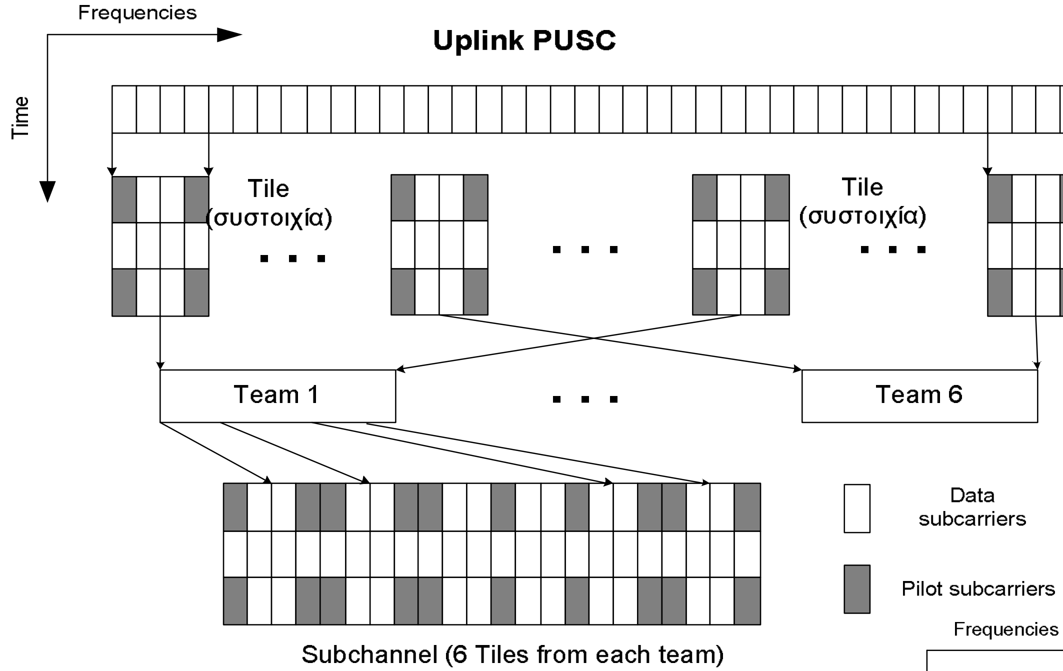
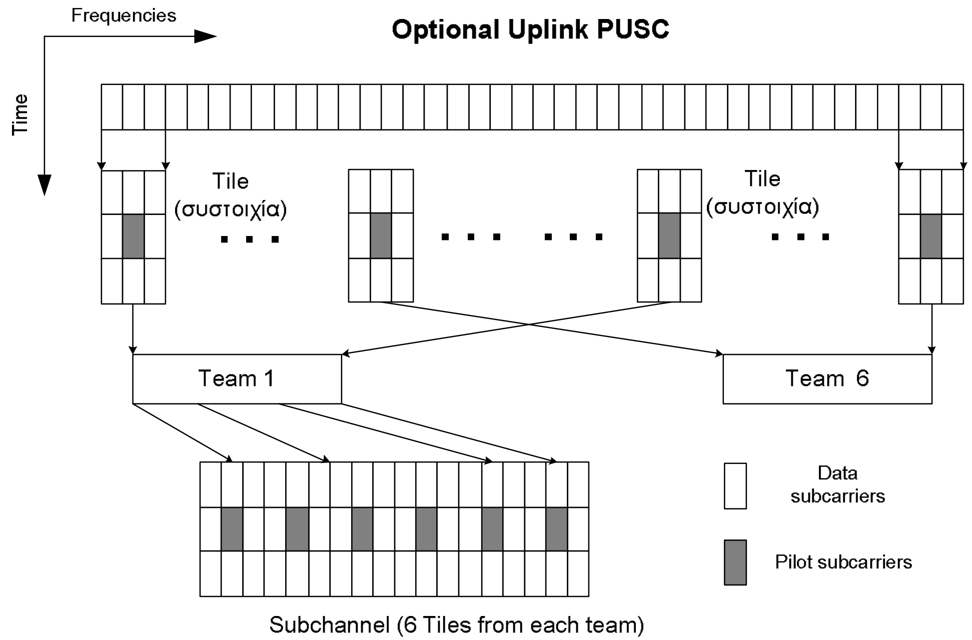


Figure: PUSC subchannelization

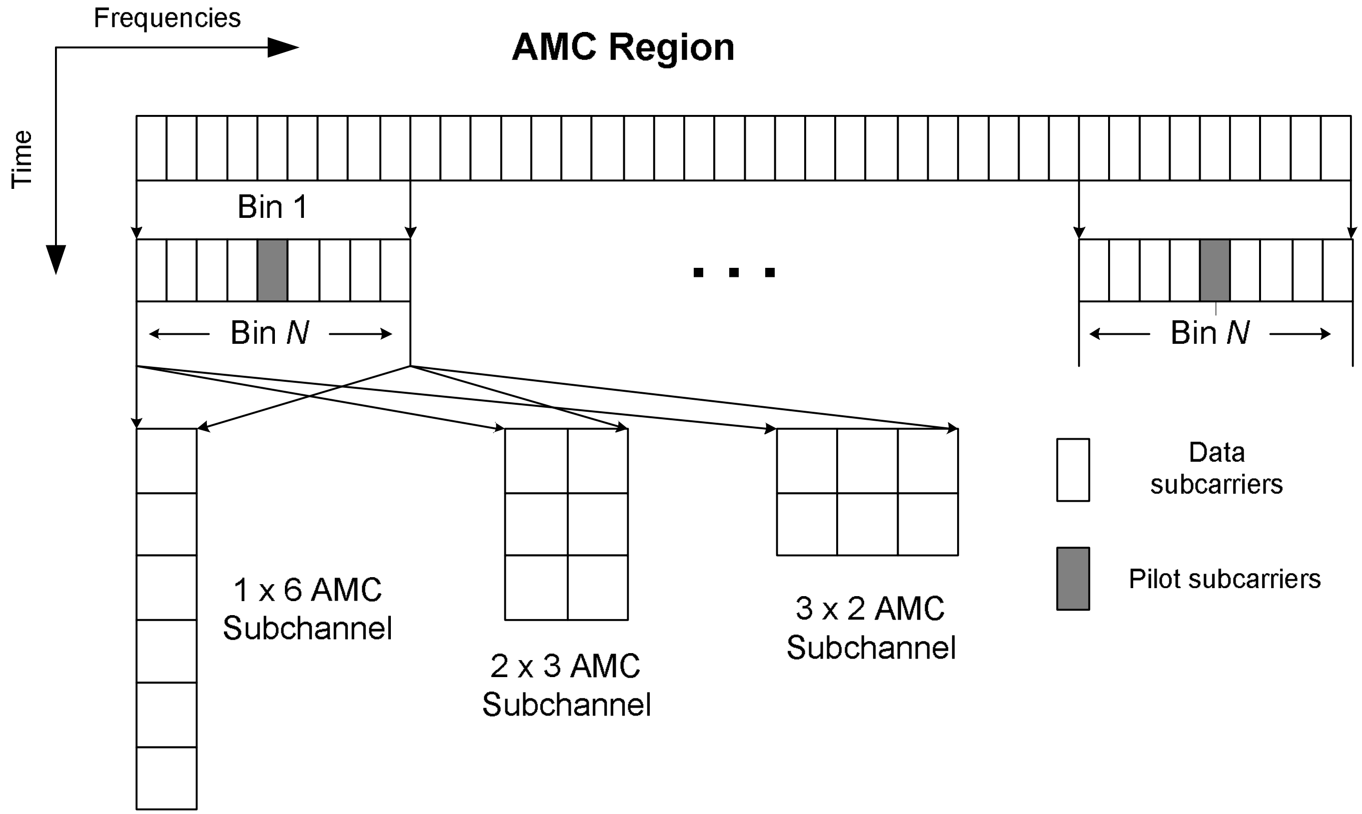
Table: PUSC subchannelization parameters

	128	512	1024	2048
Subcarriers per subchannel	14	14	14	14
Number of subchannels	3	15	30	60
Number of data subcarriers	72	360	720	1440
Number of Pilot subcarriers constant set	12	60	120	240
Left guard subcarriers (left-guard)	22	46	92	184
Right guard subcarriers (right-guard)	21	43	91	183


Frequencies
Time
Uplink PUSC
Tile
(συστοιχία)
Tile
(συστοιχία)
Team 1
Team 6
Data
subcarriers
Pilot subcarriers
Subchannel (6 Tiles from each team)


Frequencies
Time
Optional Uplink PUSC
Tile
(συστοιχία)
Tile
(συστοιχία)
Team 1
Team 6
Data
subcarriers
Pilot subcarriers
Subchannel (6 Tiles from each team)

Band Adaptive Modulation and Coding



Data rate Mbps

Bandwidth	10 MHz with 1024 FFT size							
Subchannelization Method	FUSC / Band AMC				PUSC			
Number of data subcarriers	768 for downlink				720 for downlink & 560 for uplink			
Cyclic Prefix	1/4	1/8	1/16	1/32	1/4	1/8	1/16	1/32
QPSK R1/2 DL	3.920	4.356	4.612	4.752	3.675	4.083	4.324	4.455
QPSK R1/2 UL	1.260	1.400	1.482	1.527	919	1.021	1.081	1.114
QPSK R3/4 DL	5.880	6.533	6.918	7.127	4.900	5.444	5.765	5.939
QPSK R3/4 UL	1.890	2.100	2.224	2.291	1.225	1.361	1.441	1.485
16QAM R1/2 DL	7.840	8.711	9.224	9.503	5.513	6.125	6.485	6.682
16QAM R1/2 UL	2.520	2.800	2.965	3.055	1.378	1.531	1.621	1.670
16QAM R3/4 DL*	11.760	13.067	13.835	14.255	7.350	8.167	8.647	8.909
16QAM R3/4 UL	3.780	4.200	4.447	4.582	1.838	2.042	2.162	2.227
64QAM R2/3 DL	15.680	17.422	18.447	19.006	9.800	10.889	11.529	11.879
64QAM R2/3 UL	5.040	5.600	5.929	6.109	2.450	2.722	2.882	2.970
64QAM R3/4 DL	17.640	19.600	20.753	21.382	11.025	12.250	12.971	13.364
64QAM R3/4 UL	5.670	6.300	6.671	6.873	2.756	3.063	3.243	3.341
64QAM R5/6 DL	19.600	21.778	23.059	23.758	11.025	12.250	12.971	13.364
64QAM R5/6 UL	6.300	7.000	7.412	7.636	2.756	3.063	3.243	3.341

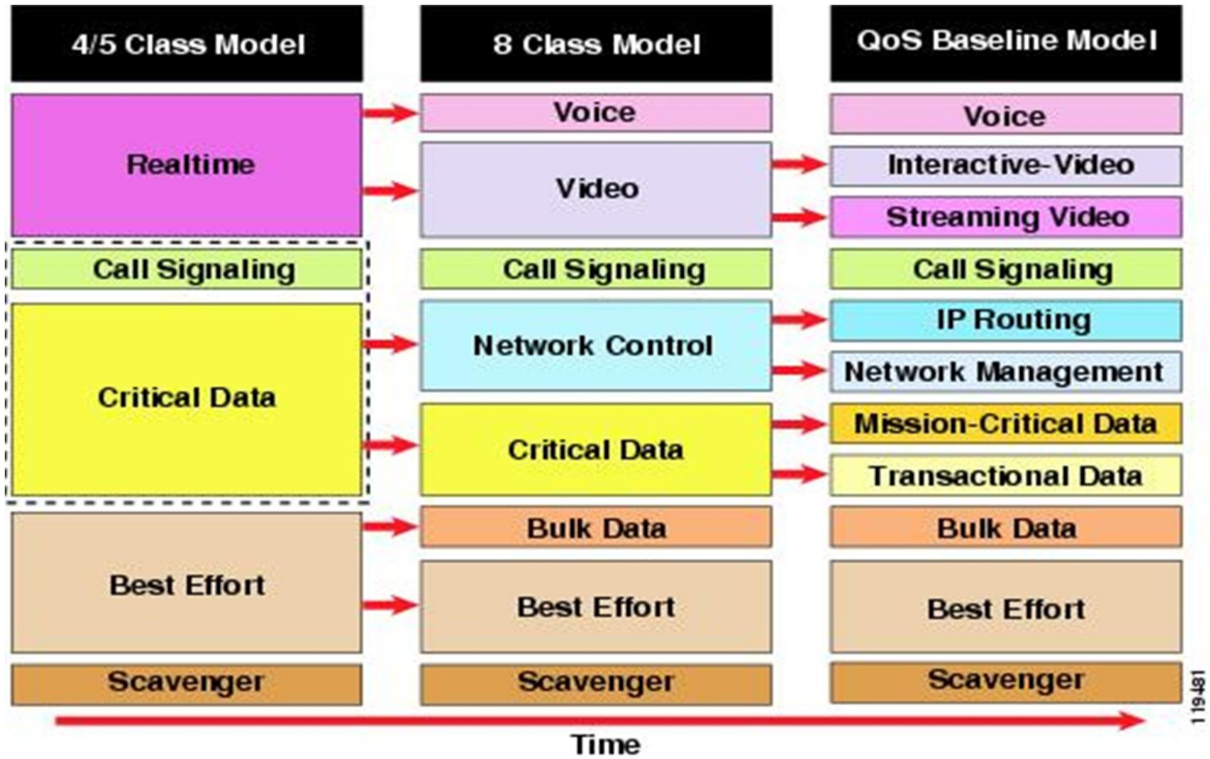
Ρυθμοί μετάδοσης Mbps

Bandwidth	20 MHz with 2048 FFT size							
Subchannelization Method	FUSC / Optional UL PUSC / Band AMC				PUSC			
Number of data subcarriers	1536 for downlink & for uplink				1440 for downlink & 1120 for uplink			
Cyclic Prefix	1/4	1/8	1/16	1/32	1/4	1/8	1/16	1/32
QPSK R1/2 DL	7.840	8.711	9.224	9.503	7.350	8.167	8.647	8.909
QPSK R1/2 UL	2.520	2.800	2.965	3.055	1.838	2.042	2.162	2.227
QPSK R3/4 DL	11.760	13.067	13.835	14.255	11.025	12.250	12.971	13.364
QPSK R3/4 UL	3.780	4.200	4.447	4.582	2.756	3.063	3.243	3.341
16QAM R1/2 DL	15.680	17.422	18.447	19.006	14.700	16.333	17.294	17.818
16QAM R1/2 UL	5.040	5.600	5.929	6.109	3.675	4.083	4.324	4.455
16QAM R3/4 DL*	23.520	26.133	27.671	28.509	22.050	24.500	25.941	26.727
16QAM R3/4 UL	7.560	8.400	8.894	9.164	5.513	6.125	6.485	6.682
64QAM R2/3 DL	31.360	34.844	36.894	38.012	29.400	32.667	34.588	35.636
64QAM R2/3 UL	10.080	11.200	11.859	12.218	7.350	8.167	8.647	8.909
64QAM R3/4 DL	35.280	39.200	41.506	42.764	33.075	36.750	38.912	40.091
64QAM R3/4 UL	11.340	12.600	13.341	13.745	8.269	9.188	9.728	10.023
64QAM R5/6 DL	39.200	43.556	46.118	47.515	36.750	40.833	43.235	44.545
64QAM R5/6 UL	12.600	14.000	14.824	15.273	9.187	10.208	10.809	11.136

QoS in LTE / LTE-A

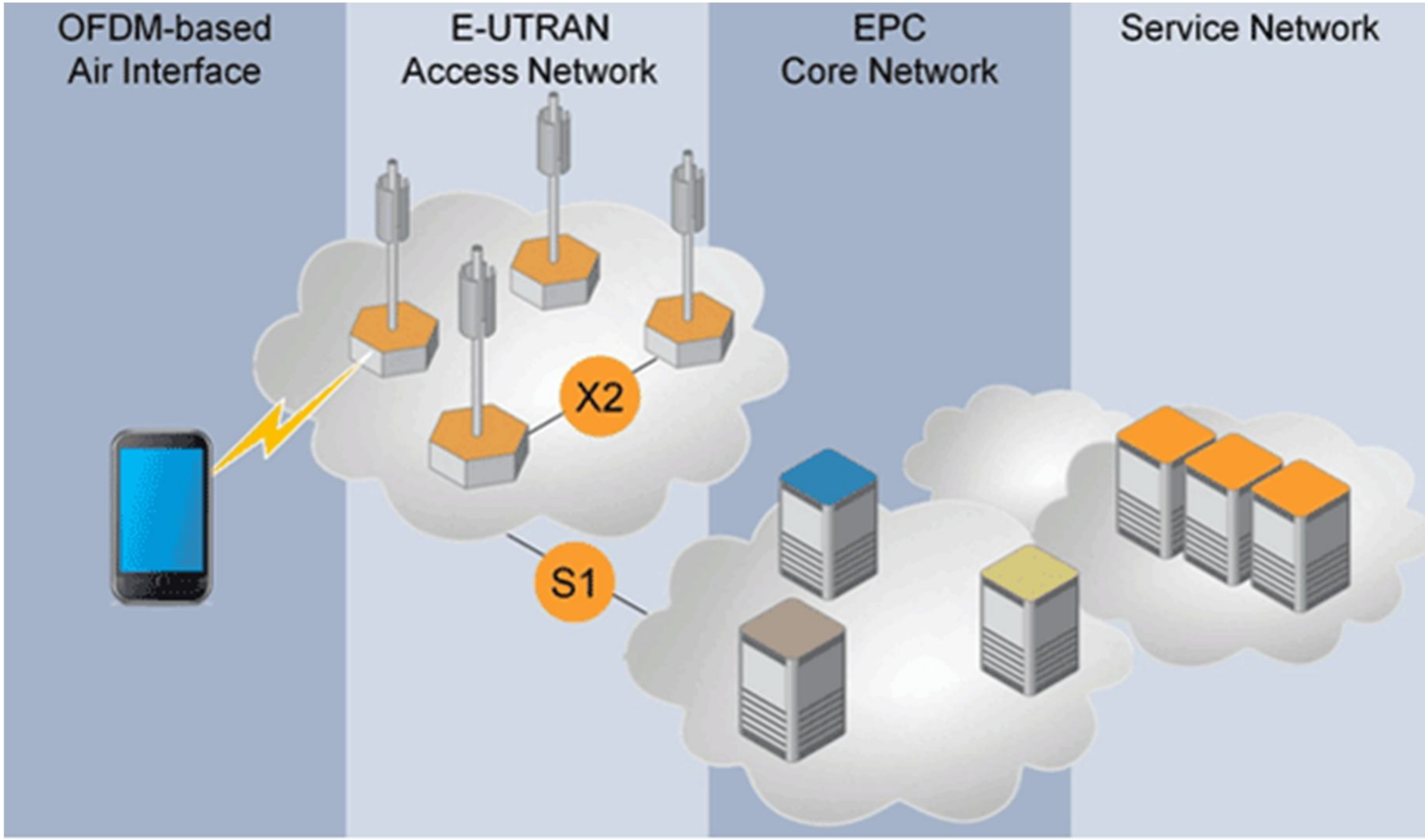
Quality of Service (QoS)

- QoS classes
  - Different services - different QoS parameters
  - Resources are not infinite! Thus, guaranteeing different QoS levels is a fundamental procedure in any system.



QoS in LTE/LTE-A

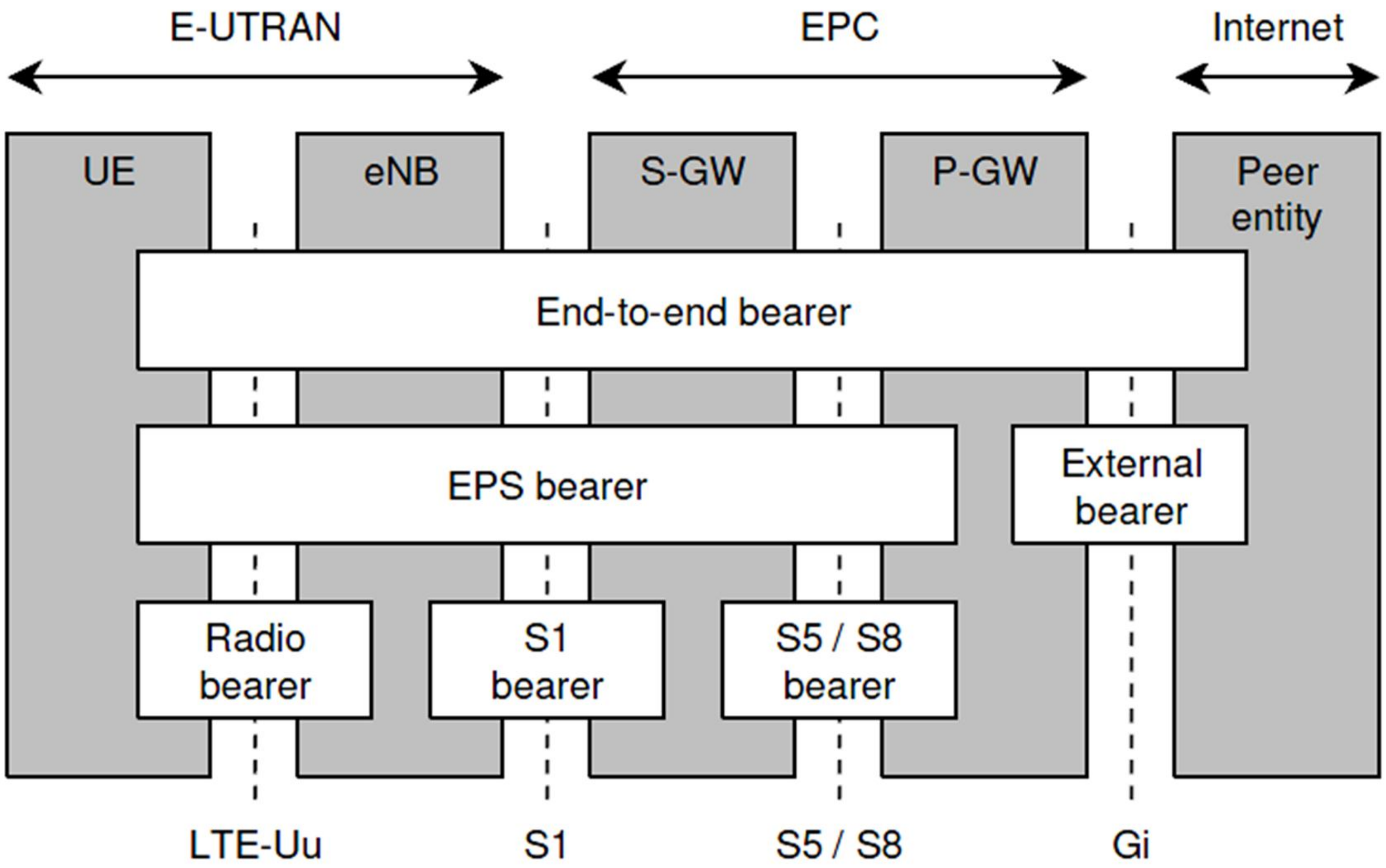
- LTE-A network Architecture



LTE Architecture

QoS in LTE/LTE-A

- EPS-bearer



QoS in LTE/LTE-A

- Each EPS bearer is associated with the following QoS parameters:
  - QoS class identifier (QCI): This is a number which describes the error rate and delay that are associated with the service.
  - Allocation and retention priority (ARP): This determines whether a bearer can be dropped if the network gets congested, or whether it can cause other bearers to be dropped. Emergency calls might be associated with a high ARP, for example.

QoS in LTE/LTE-A

- There are a few different types of EPS bearer. One classification refers to quality of service:
  - A GBR bearer has a guaranteed bit rate (GBR) amongst its quality-of-service parameters. A GBR bearer would be suitable for a conversational service, such as a voice call.
  - A non-GBR bearer does not have a guaranteed bit rate. A non-GBR bearer would be suitable for a background service, such as Email.

QoS in LTE/LTE-A

QCI	Resource type	Priority	Packet delay budget	Packet error loss rate	Example services
1	GBR	2	100 ms	10^{-2}	Conversational voice
2		4	150 ms	10^{-3}	Conversational video (live streaming)
3		3	50 ms	10^{-3}	Real time gaming
4		5	300 ms	10^{-6}	Non-conversational video (buffered streaming)
5	Non-GBR	1	100 ms	10^{-3}	IMS signaling
6		6	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100 ms	10^{-6}	Voice, Video (live streaming), Interactive gaming
8		8	300ms	10^{-3}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9		9		10^{-6}	

*IP Multimedia Subsystem (IMS)

QoS in LTE/LTE-A

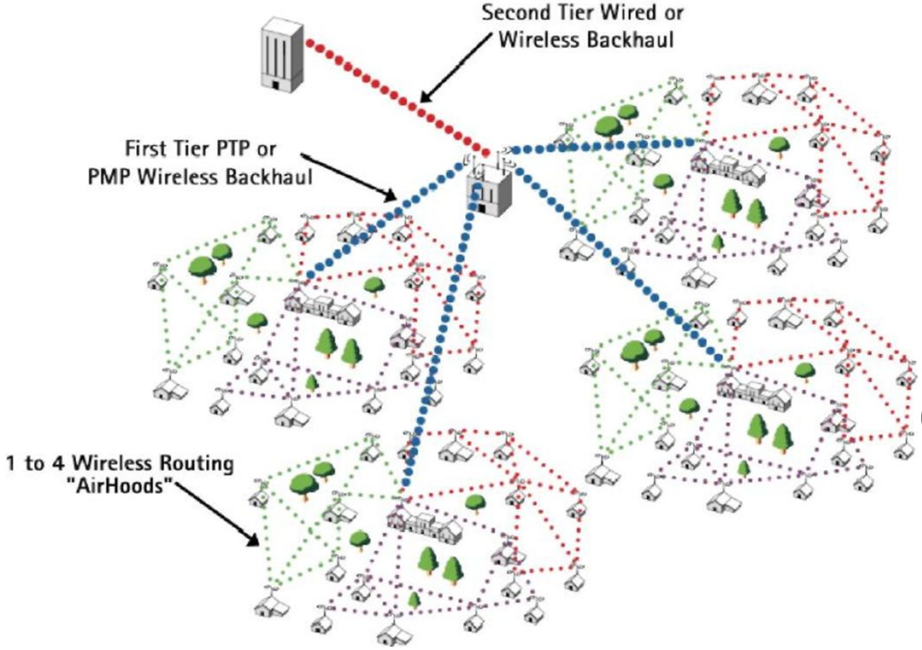
To summarize…

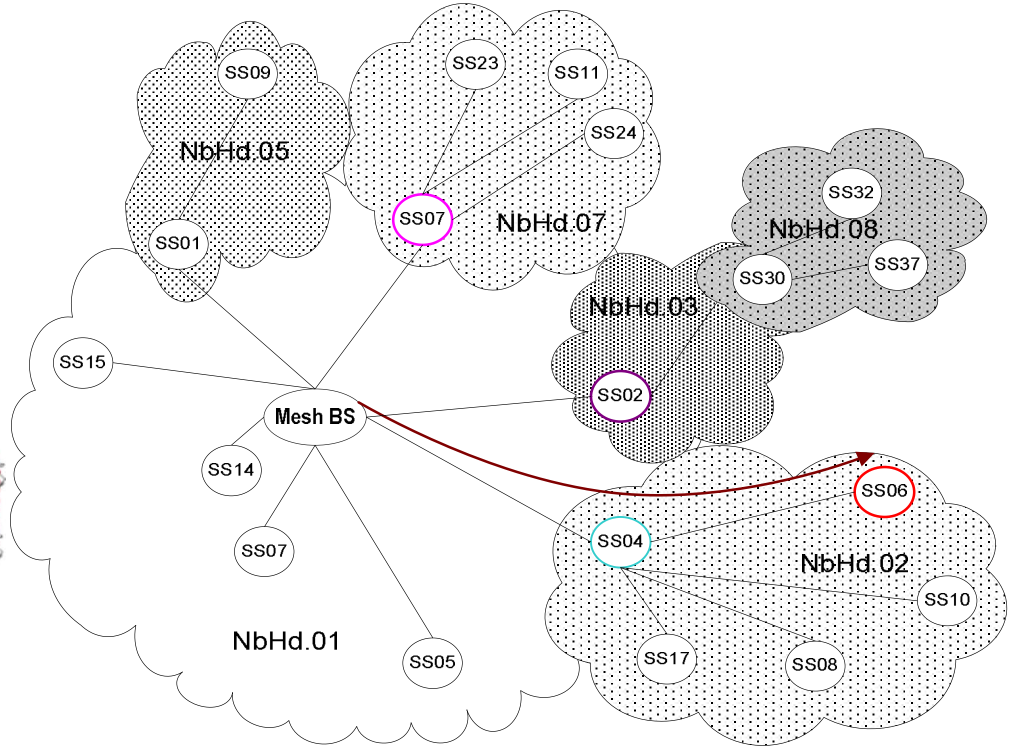
- Guaranteeing different QoS levels is a fundamental procedure in any system.
- QoS in LTE/LTE-A system
  - LTE/LTE-A network use bearers to carry information from one part of the system to the other
  - Data are carried by EPS – bearers
  - There are different EPS – bearers for different **QoS**
  - A QoS-based classification is: GBR and non-GBR EPS – bearers

The question which arises is whether guaranteeing QoS is enough?

QoS in
WiMAX / WiMAX2

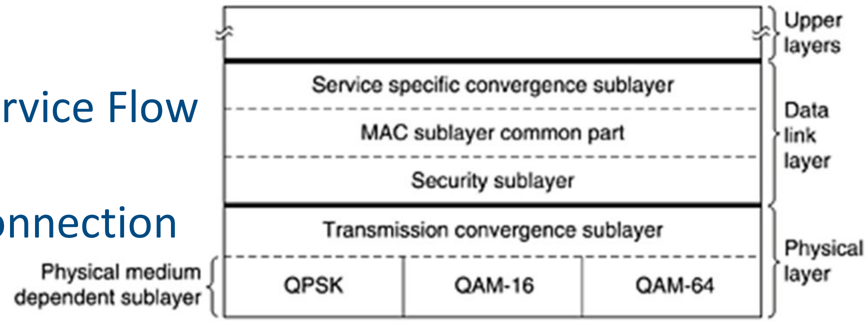
Service Flow vs Connection





Service Flow

Connection



Most important QoS parameters

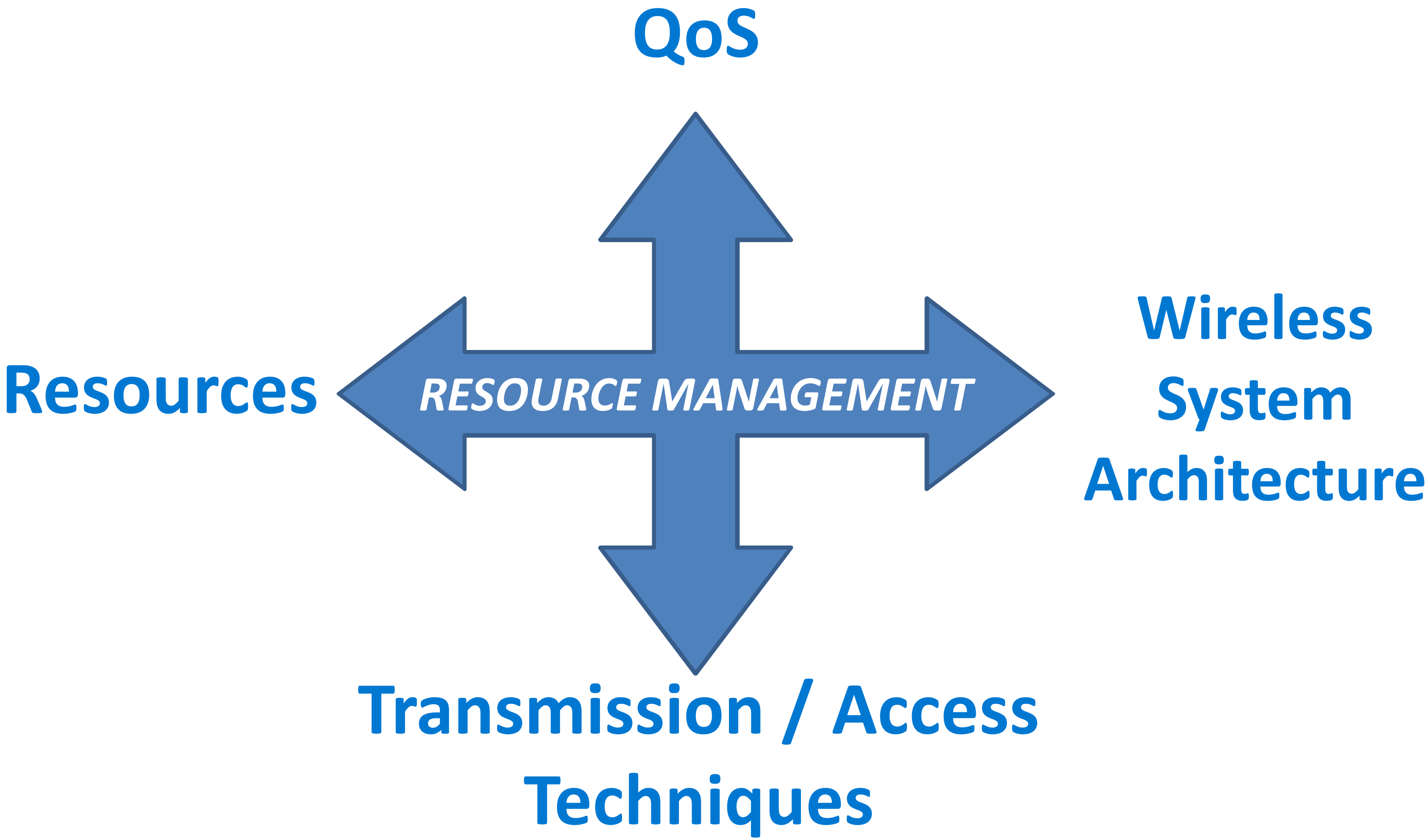
1. ***Minimum Reserved Traffic Rate - mrtr (in bits/sec)***
2. ***Maximum Sustained Traffic Rate - mstr (in bits/sec)***
3. ***Maximum Latency (in ms)***
4. *Uplink grant scheduling type*
5. ***Tolerated Jitter (minimum delay in ms)***
6. ***GrantSize_primary (aGP: !=6B→ rtPS, =6B→ ertPS)***
7. *Traffic Priority (range 0-7, with 7 the highest)*
8. *Unsolicited Grant Interval*
9. *Unsolicited Polling Interval*
10. *Request/Transmission Policy (range 0-7)*

QoS Types & their parameters

QoS Types	Applications	QoS parameters	
UGS Unsolicited Grant Service *(Αυτόκλητη Υπηρεσία Εκχώρησης)*	Voice over IP (VoIP) without silence suppression	• *Max Sustained Traffic Rate,* • *Maximum Latency,* • *Tolerated Jitter,*	• *Uplink grant scheduling type,* • *Unsolicited Grant Interval,* • *Request/Transmission Policy*
rtPS Real-Time Packet Service	Streaming audio & video, MPEG (Motion Picture experts Group) encoded	• *Max Sustained Traffic Rate,* • *Min Reserved Traffic Rate,* • *Maximum Latency,*	• *Uplink grant scheduling type,* • *Unsolicited Polling Interval* • *Request/Transmission Policy*
ertPS Extended Real-Time Packet Service	VoIP with silence suppression	• *Max Sustained Traffic Rate,* • *Min Reserved Traffic Rate,* • *Maximum Latency,* • *Tolerated Jitter,*	• *Uplink grant scheduling type,* • *Unsolicited Grant Interval,* • *Request/Transmission Policy*
aGP* Adaptive granting and polling service	VoIP with or without silence suppression	• *Max Sustained Traffic Rate,* • *Min Reserved Traffic Rate,* • *Maximum Latency,* • *Tolerated Jitter,*	• *GrantSize_primary,* • *Uplink grant scheduling type,* • *Unsolicited Grant Interval,* • *Request/Transmission Policy*
nrtPS Non-Real-Time Packet Service	File Transfer Protocol (FTP)	• *Max Sustained Traffic Rate,* • *Min Reserved Traffic Rate,* • *Traffic Priority*	• *Uplink grant scheduling type,* • *Unsolicited Polling Interval,* • *Request/Transmission Policy*
BE Best Effort Service	Data transfer, Web Browsing, e.t.c.	• *Max Sustained Traffic Rate,* • *Traffic Priority*	• *Uplink grant scheduling type,* • *Unsolicited Polling Interval,* • *Request/Transmission Policy*

Resource Allocation / Scheduling Algorithms

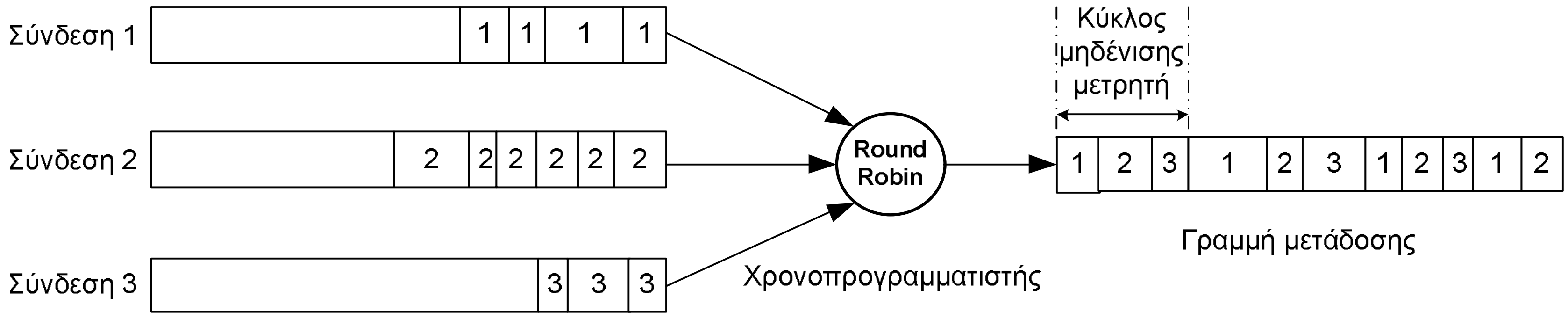
Scheduler/RA's role



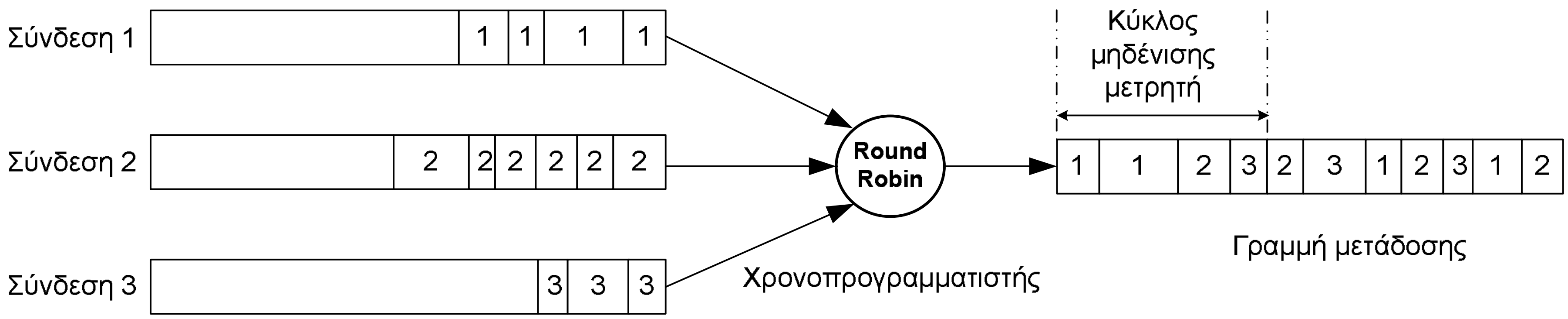
Scheduler/RA's role

- *Who* transmits / receives
- *What* is transmitted by whom
- *When* each one transmits / receives
  - *For Single Carrier (e.g. TDD): in which timeslots*
- *Which (sub)carriers will be used*
  - *For OFDM: in which carriers*
  - *For OFDMA: in which time slots or resource blocks*
    - *For SC-FDMA with what power*
- *All in specific (very small amount of) time*
- *Number of users (UEs)*
- *Throughput or goodput ?*

Round Robin

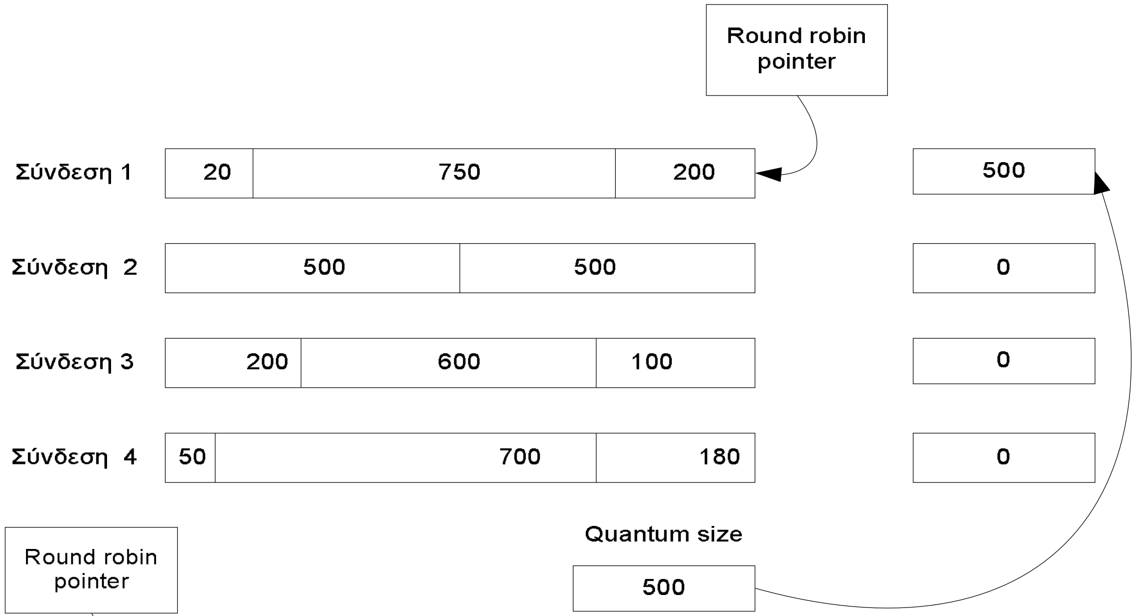


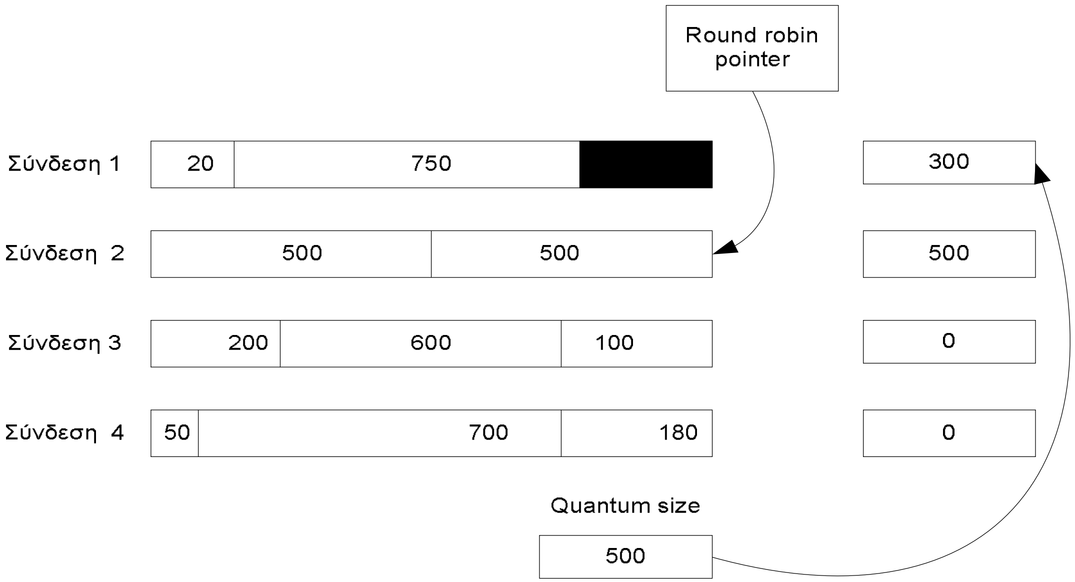
Weighted Round Robin



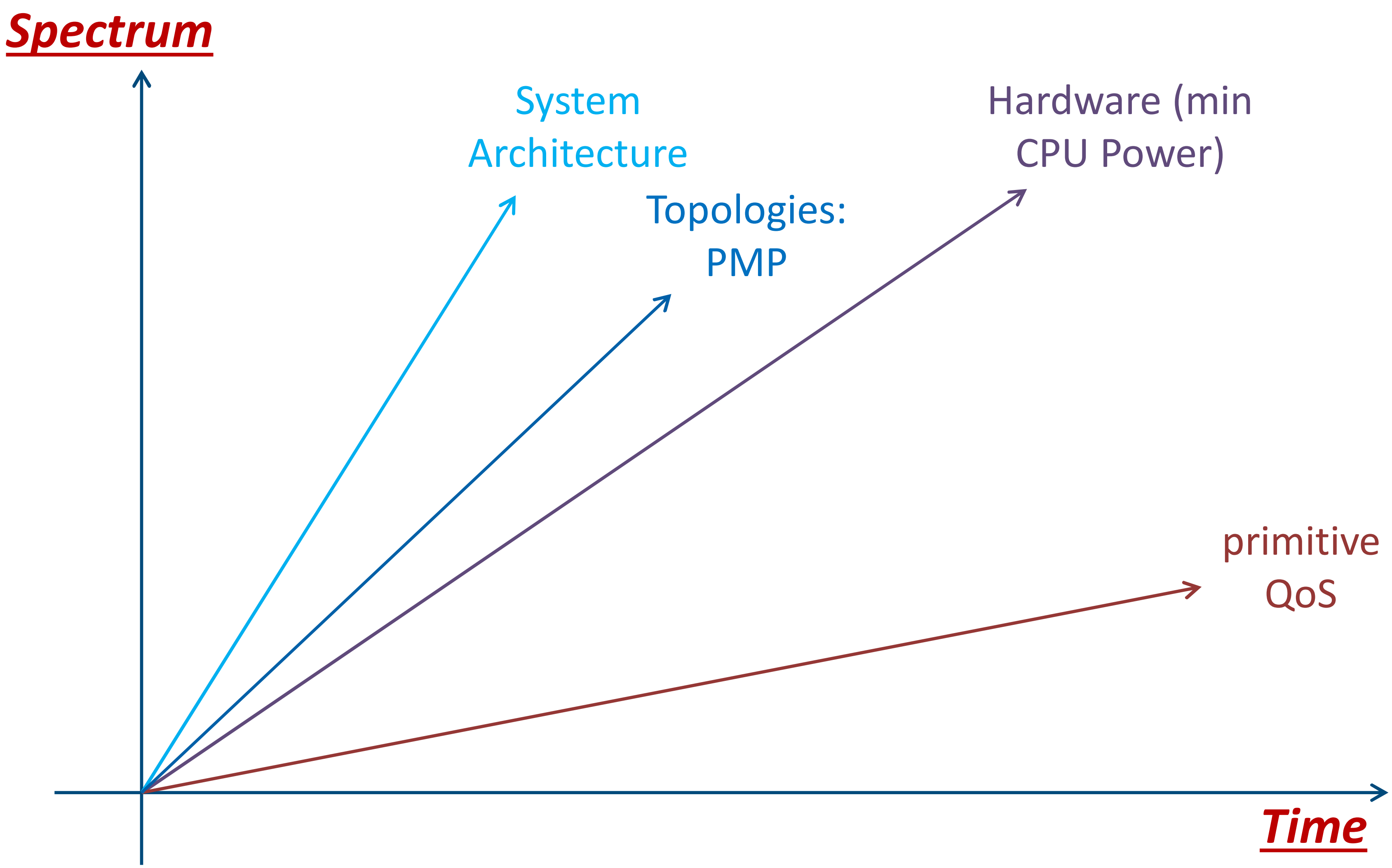
Deficit Round Robin

- For each connection:
  - Deficit counter
  - Quantum size





Dimensionize Resource Management



Weighted Fair Queue (WFQ) -1

- Packets from each queue categorized in different logical queues
- A ideal scheduler (GPS) is responsible to serve not empty queues (bypassing empty ones)
- Computes *necessary time* for serving each packet
- In each scan uses a very small amount of data from each queue
- In certain period of time should have visited each queue at least once
- Serves packets in ascending order of expiration time

In other words: WFQ simulates a GPS Scheduler, using simulation results to specify the sequence of future served packets

Weighted Fair Queue (WFQ) -2

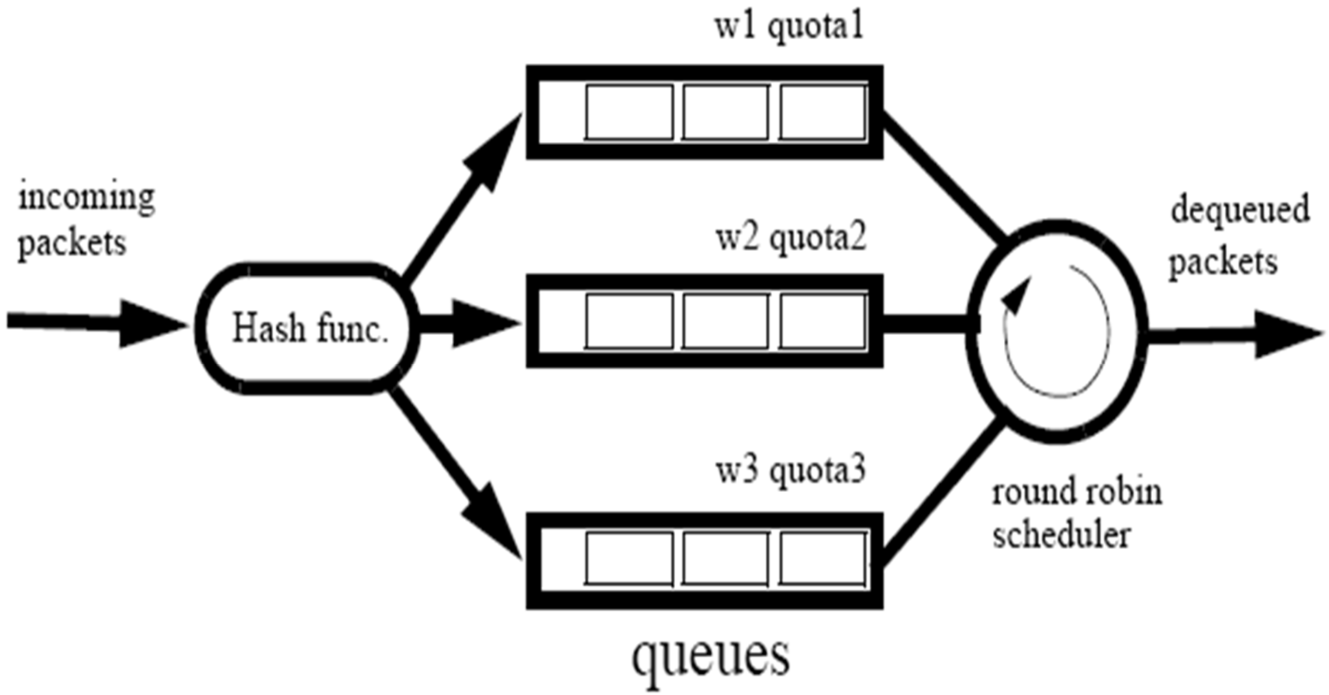
WFQ computes packets' expiration time using the following variables:

- ***R(t)*** : Round number in time t (# rounds that bit-by-bit Round Robin Scheduler has completed
- ***P(i,k,t)*** : Length of packet ***k,*** comes in queue ***i*** in time ***t***
- ***F(i,k,t)*** : Expiration time of packet ***k,*** comes in queue ***i*** in time ***t***
- ***W(i)*** : Weight of ***i*** connection
- ***Active queue***: A queue with packets' greatest expiration time (F(i,k,t)) being larger than current Round Number (R(t))

Round length (serve 1bit from each queue)is relative to the number of active queues

$$\mathrm{F(i,k,t)} = \max\{\mathrm{F(i,k-l,t), R(t)}\} + \frac{\mathrm{P(i,k,t)}}{W(i)}$$

Weighted Fair Queue (WFQ) -3



Modified Earliest Deadline First (MEDF)-1

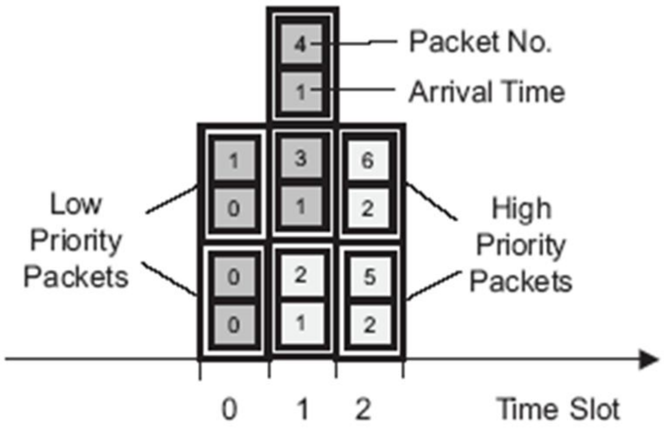
- Modifies appropriately EDF
- Packets are stored in ***n*** queues using FIFO
- Each packet is marked with a expiration time limit

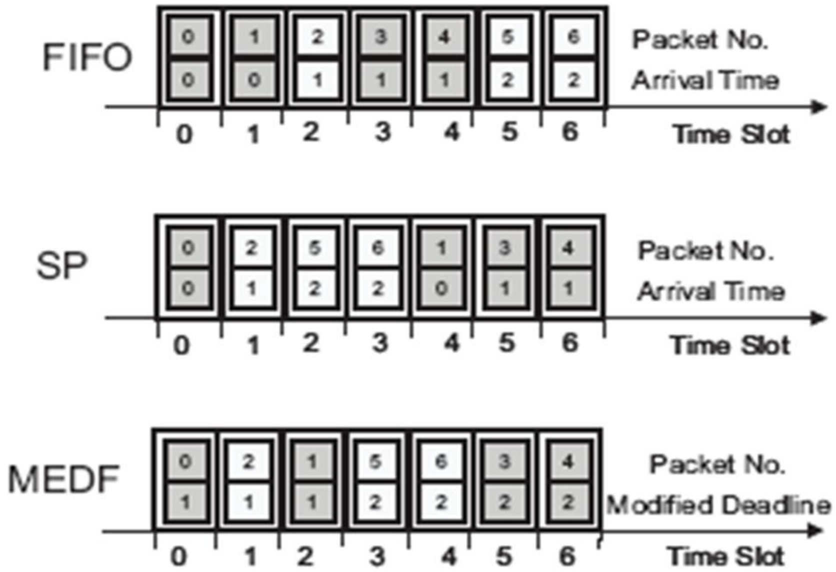
  ETL = Arrival_Time + M_i , $0 \leq i < n$ (M_i characteristic $\forall$ TSC)

In other words:

- ***MEDF does a local re-sorting in a FIFO queue***
- ***The maximum latency limit between two queues specifies when a re-sorting will happen, & must be less than latency***

Modified Earliest Deadline First (MEDF)-2

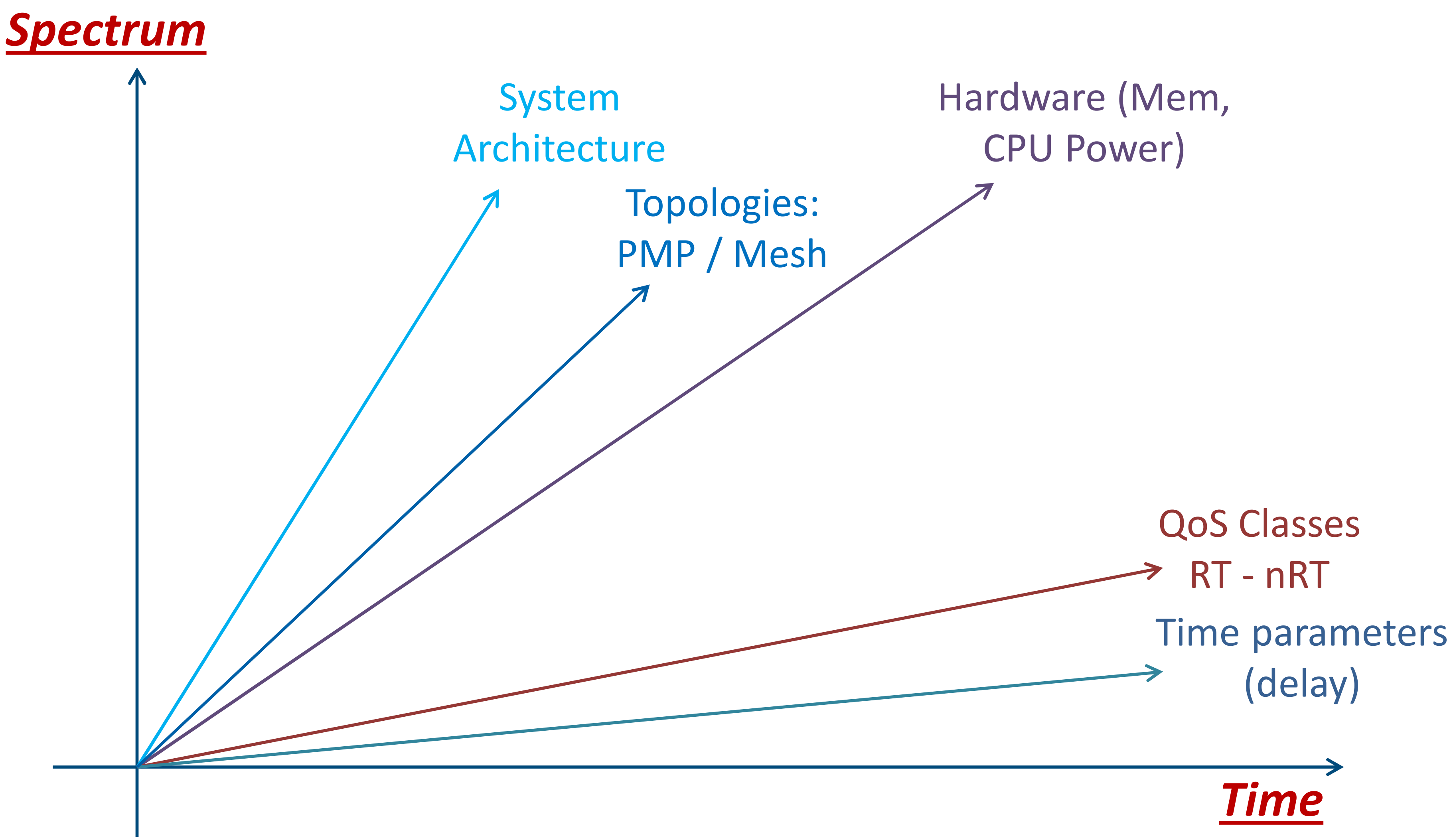




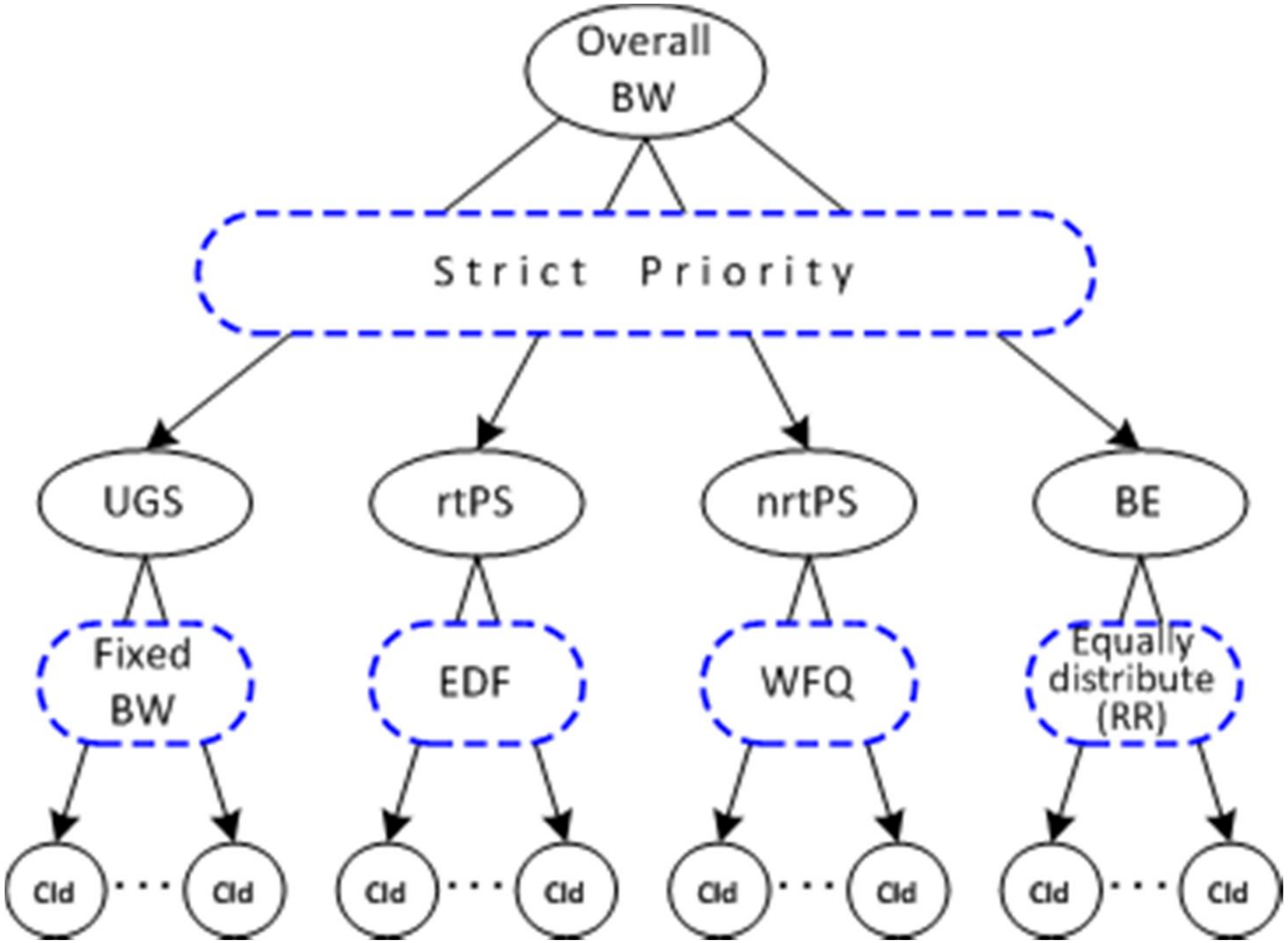
MEDF :

- ***Has better performance than FIFO, SP, WRR under any circumstances***
- ***Compared to WFQ, does not need overall network traffic knowledge***

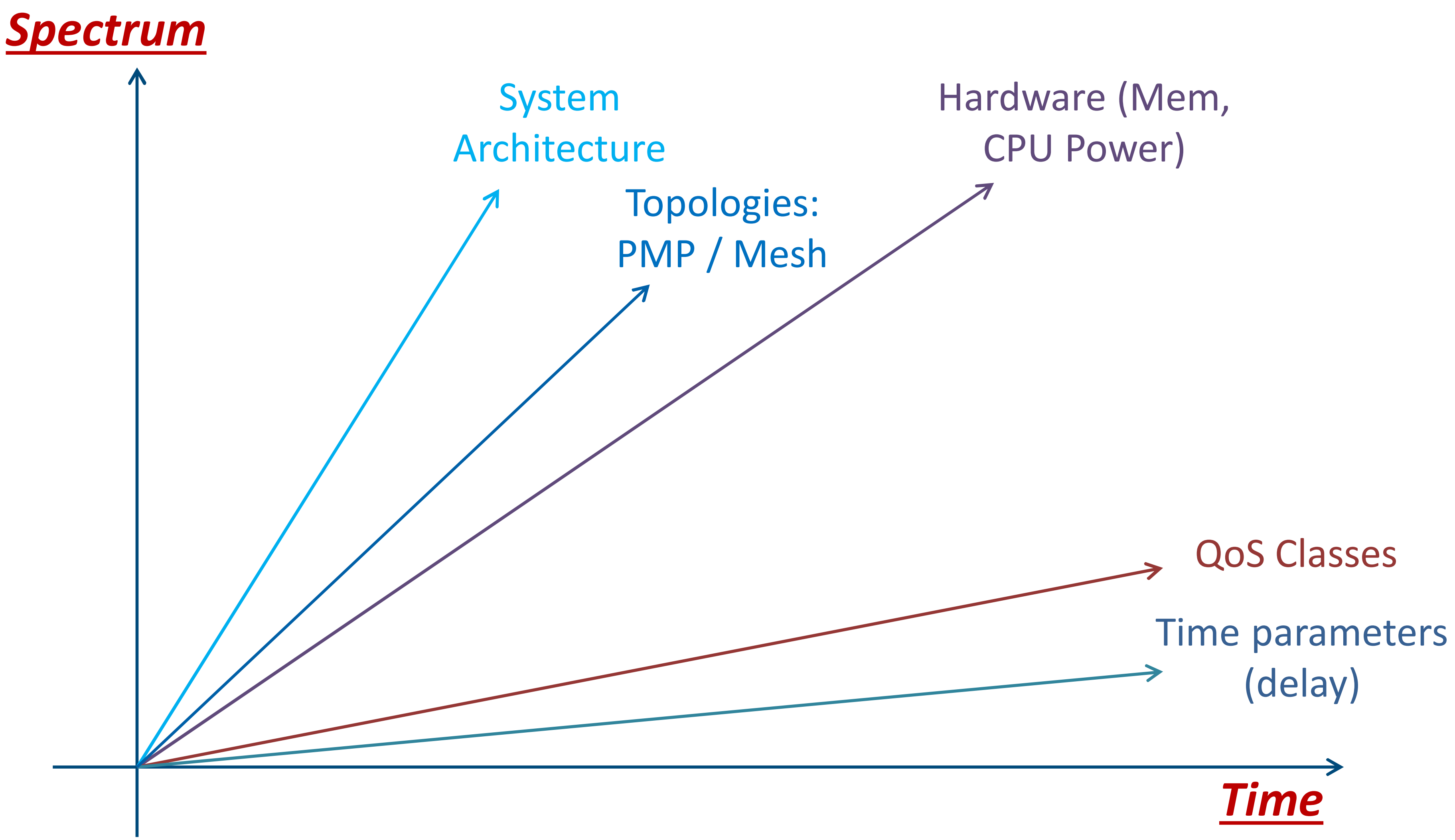
Dimensionize Resource Management



"Packet scheduling for QoS support in IEEE 802.16 broadband wireless access systems"



Dimensionize Resource Management

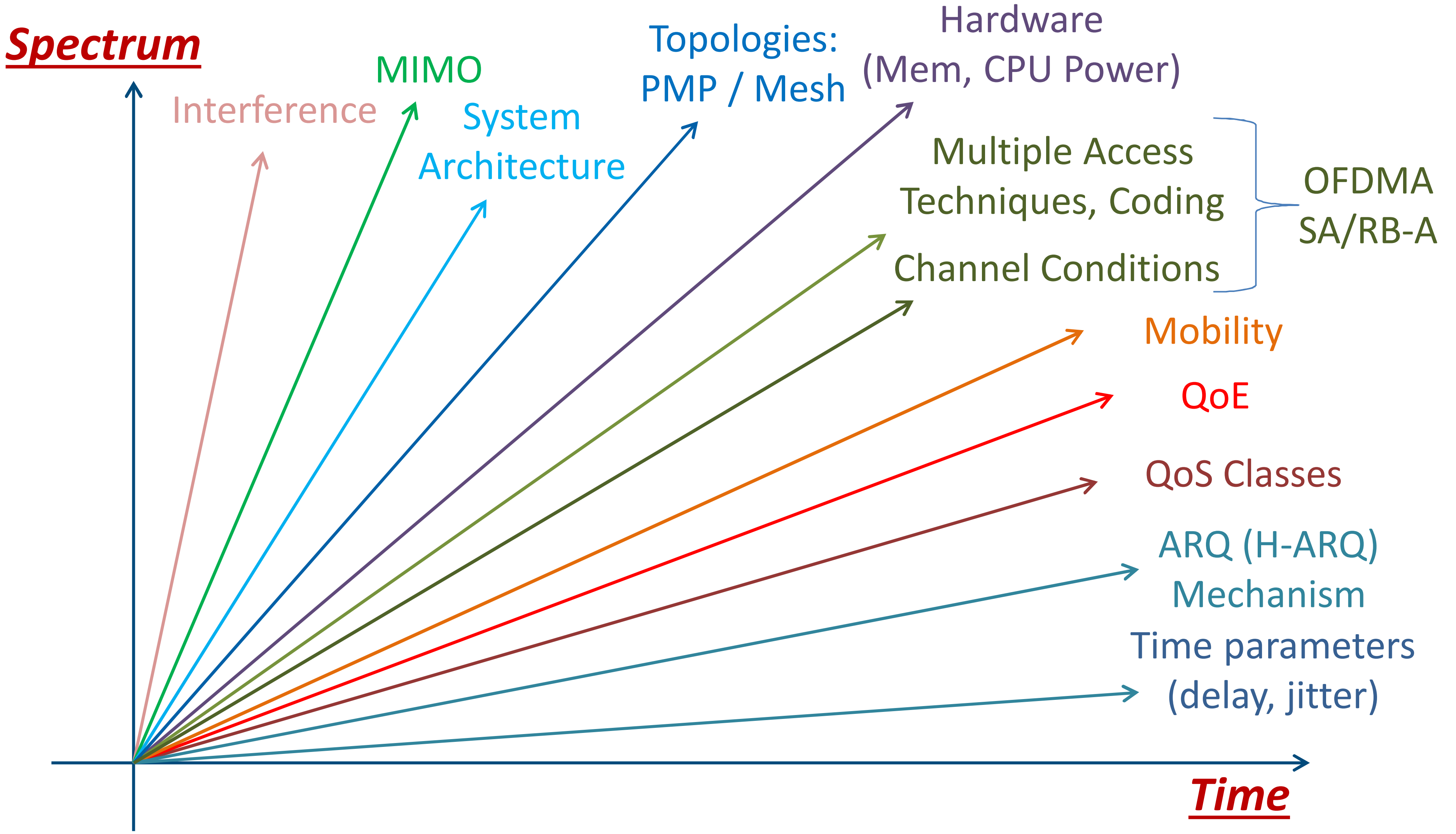


α/α	Paper	Aim		SC	OFDMA	AMC	PMP	Mesh	Link		QoS Classes					Delay	Jitter	ARQ	Compl. Eval.	Simul. Tool
		M.T.	Fairness						DL	UL	UGS	ertPS	rtPS	nrtPS	BE					
1	[8]	√	√	√	—	—	√	—	—	√	√	—	√	√	√	—	—	—	—	C++
2	[16]	Εκτίμηση		√	—	—	√	—	√	√	√	√	√	—	—	—	—	—	—	—
3	[17]	√	—	√	—	—	√	—	—	√	—	—	—	—	√	—	—	—	—	NS-2
4	[19]	√	—	√	—	—	√	—	√	√	—	√	—	—	√	—	—	—	√	—
5	[20]	√	—	√	—	—	√	—	—	√	—	—	—	√	—	—	—	—	—	—
6	[21]	√	√	√	—	—	√	—	√	√	√	√	√	√	√	√	—	—	—	—
7	[22]	√	—	√	—	—	√	—	√	√	√	—	√	√	√	—	—	—	—	NS-2
8	[23]	—	√	√	—	—	√	—	—	√	√	—	√	√	√	√	√	—	—	Opnet
9	[24]	√	√	√	—	—	√	—	√	√	√	√	√	√	√	—	—	—	—	Opnet
10	[26]	√	—	√	—	—	√	—	√	—	√	√	√	√	√	—	—	—	√	NS-2
11	[27]	√	—	√	—	—	√	—	√	√	—	—	√	—	√	√	—	—	—	—
12	[28]	√	√	√	—	—	√	—	—	√	√	√	√	√	√	√	—	—	—	Matlab
13	[29]	√	—	√	—	—	√	—	√	√	—	—	√	√	√	√	—	—	—	C++
14	[29]	√	√	√	—	—	√	—	√	—	√	√	√	√	√	√	√	—	—	NS-2
15	[32]	—	√	√	—	—	√	—	—	√	√	√	√	√	√	√	—	—	√	NS-2
16	[43]	—	√	—	√	—	√	—	√	—	—	—	—	—	—	—	—	√	—	—
17	[44]	√	—	—	√	—	√	—	—	√	—	—	—	—	—	—	—	—	√	—
18	[45]	√	—	—	√	—	√	—	√	—	—	—	—	—	—	—	—	—	√	—
19	[48]	√	√	—	√	—	√	—	√	√	—	—	—	—	—	—	—	—	—	—
20	[49]	√	√	—	√	—	√	—	—	√	—	—	√	√	√	√	√	—	—	—
21	[47]	√	—	—	√	—	√	—	√	—	—	—	—	—	—	—	—	—	√	—
22	[50]	√	√	—	√	—	√	—	√	—	—	—	—	—	—	√	—	—	—	—
23	[51]	—	√	—	√	√	√	—	√	√	—	—	—	—	—	—	—	—	—	—
24	[52]	√	√	—	√	—	√	—	√	—	—	—	—	—	—	—	√	√	√	—
25	[53]	√	—	—	√	—	√	—	√	—	—	—	—	—	—	—	—	—	√	C++
26	[54]	√	—	—	√	√	√	—	√	—	—	—	—	—	—	—	—	—	√	C++
27	[59]	√	√	√	√	√	√	—	√	√	√	√	√	√	√	√	—	—	—	—
28	[60]	√	—	√	√	—	—	—	√	—	—	—	√	√	—	—	—	—	—	—
29	[61]	√	—	—	√	—	√	—	—	√	—	√	—	—	—	—	—	—	—	Opnet
30	[62]	√	—	—	√	√	√	—	√	—	—	—	—	√	√	—	—	—	—	—
31	[63]	√	—	—	√	—	√	—	—	√	—	√	—	—	√	—	—	—	—	—
32	[64]	√	—	—	√	√	√	—	√	√	—	—	—	√	—	—	—	√	—	—
33	[65]	√	—	—	√	—	√	—	—	√	√	—	—	—	—	—	—	—	—	—
34	[66]	√	√	√	√	√	√	—	√	√	—	—	√	√	√	—	—	—	—	—
34	[67]	—	√	—	√	√	√	—	√	—	√	—	√	√	√	—	—	—	—	—
35	[68]	√	—	—	√	√	√	—	√	—	√	—	√	√	√	—	—	—	—	—
36	[69]	√	—	—	√	—	√	√	√	√	√	√	√	√	√	—	—	—	—	—
37	[70]	√	√	—	√	√	√	—	√	—	—	—	√	√	√	√	—	√	—	—
38	[71]	√	√	—	√	—	√	—	—	√	√	—	√	√	√	√	—	—	√	—
39	[72]	√	√	—	√	—	√	—	—	√	√	√	√	√	√	√	—	—	√	C++

LTE / LTE-A comparison

Technology	LTE	LTE--A
Peak data rate Down Link (DL)	150 Mbps	1 Gbps
Peak data rate Up Link (UL)	75 Mbps	500 Mbps
Transmission bandwidth DL	20MHz	100 MHz
Transmission bandwidth UL	20MHz	40 MHz (requirements as defined by ITU)
Mobility	Optimized for low speeds(<15 km/hr) High Performance At speeds up to 120 km/hr Maintain Links at speeds up to 350 km/hr	Same as that in LTE
Coverage	Full performance up to 5 km	a) Same as LTE requirement b) Should be optimized or deployment in local areas/micro cell environments.
Scalable Band Widths	1.3,3, 5, 10, and 20 MHz	Up to 20–100 MHz
Capacity	200 active users per cell in 5 MHz.	3 times higher than that in LTE

Dimensionize Resource Management



State the problem of RA/OFDMA SA (2)

- Assignment Problem is one basic combinatorial optimization problems
- Could be reduced to finding a maximum weight matching
- In its most generic form, correlated to OFDMA SA we can consider:

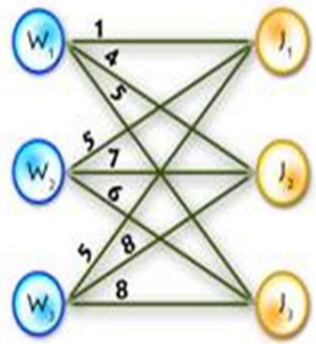
An amount of resources that have to be allocated to number of Users

Any user can use any resource creating a profit, which is proportional to couple (resource-user)

It is requested the allocation of all resources, by allocating exactly one user to each resource, so as a profit maximization occurs.

In some of its forms this problem could be reduced to a Linear Assignment Problem which can be solved by ***Hungarian algorithm*** with ***O(N⁴)*** computational complexity.

$$\begin{pmatrix} 1 & 4 & 5 \\ 5 & 7 & 6 \\ 5 & 8 & 8 \end{pmatrix} \Leftrightarrow$$

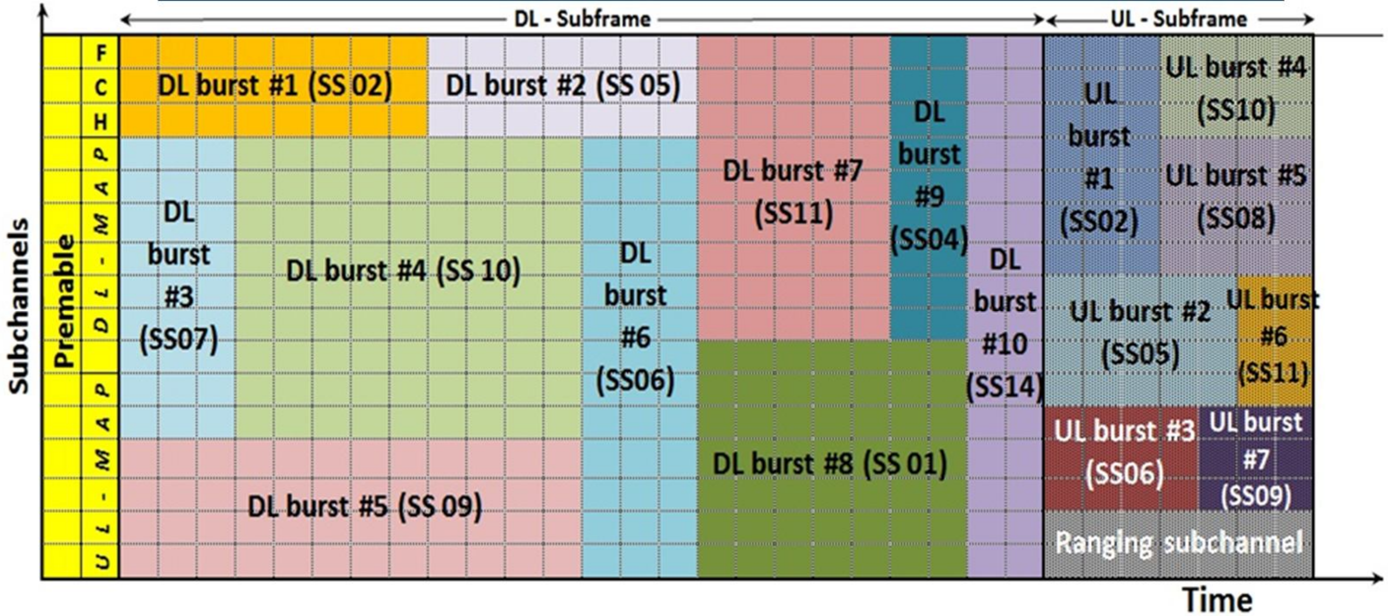


State the problem of RA/OFDMA SA

- OFDMA-SA can be reduced to "MAXIMUM CONSTRAINED PARTITION" problem, a well known NP-Hard problem.
- Thus Y. B.-Shimol, I. Kitroser and Y. Dinitz have prove in:

[52] Y. B.-Shimol, I. Kitroser and Y. Dinitz, "Two-Dimensional Mapping for Wireless OFDMA Systems" IEEE TRANSACTIONS ON BROADCASTING, VOL. 52, NO. 3, SEPTEMBER 2006

that OFDMA-SA is also a NP-Hard problem



Case Study : WiMAX

- Ideal Scheduler Characteristics
- Recently proposed solutions
- An advanced solution for WiMAX/OFDMA with demanding QoS
    - Complexity vs Memory Usage
    - Basic operations
    - The use of an advanced Tree Structure as complexity leverage
    - Subtrees
    - Simulations

Colored OFDMA Frame Registry Tree Scheduler (CO-FRTS)

Ideal Scheduler Characteristics

→ Organize data in time (deadline, jitter, ARQ mechanism etc)

→ Organize transmissions per User (MS), considering recent measurements:

i. *available modulations & coding schemes,*

ii. *subchannels with SINR greater than a threshold,*

iii. *total & per User power control,*

→ Data transmissions should be complied with:

i. *Each packet deadline (arrival time + maximum latency),*

ii. *Jitter (minimum required latency),*

iii. *Minimum & maximum traffic rates ∀ connection,*

iv. *ARQ mechanism used (e.g. H-ARQ).*

→ Organize transmissions of different QoS types with certain priority

(e.g. $Priority_{UGS}$>$Priority_{ertPS}$>$Priority_{rtPS}$>$Priority_{nrtPS}$>$Priority_{BE}$)

→ Required operations & necessary computational complexity, should be limited (DL-MAP & UL-MAP)

→ All actions should lead to throughput maximization, (after complying with as many QoS parameters as possible)

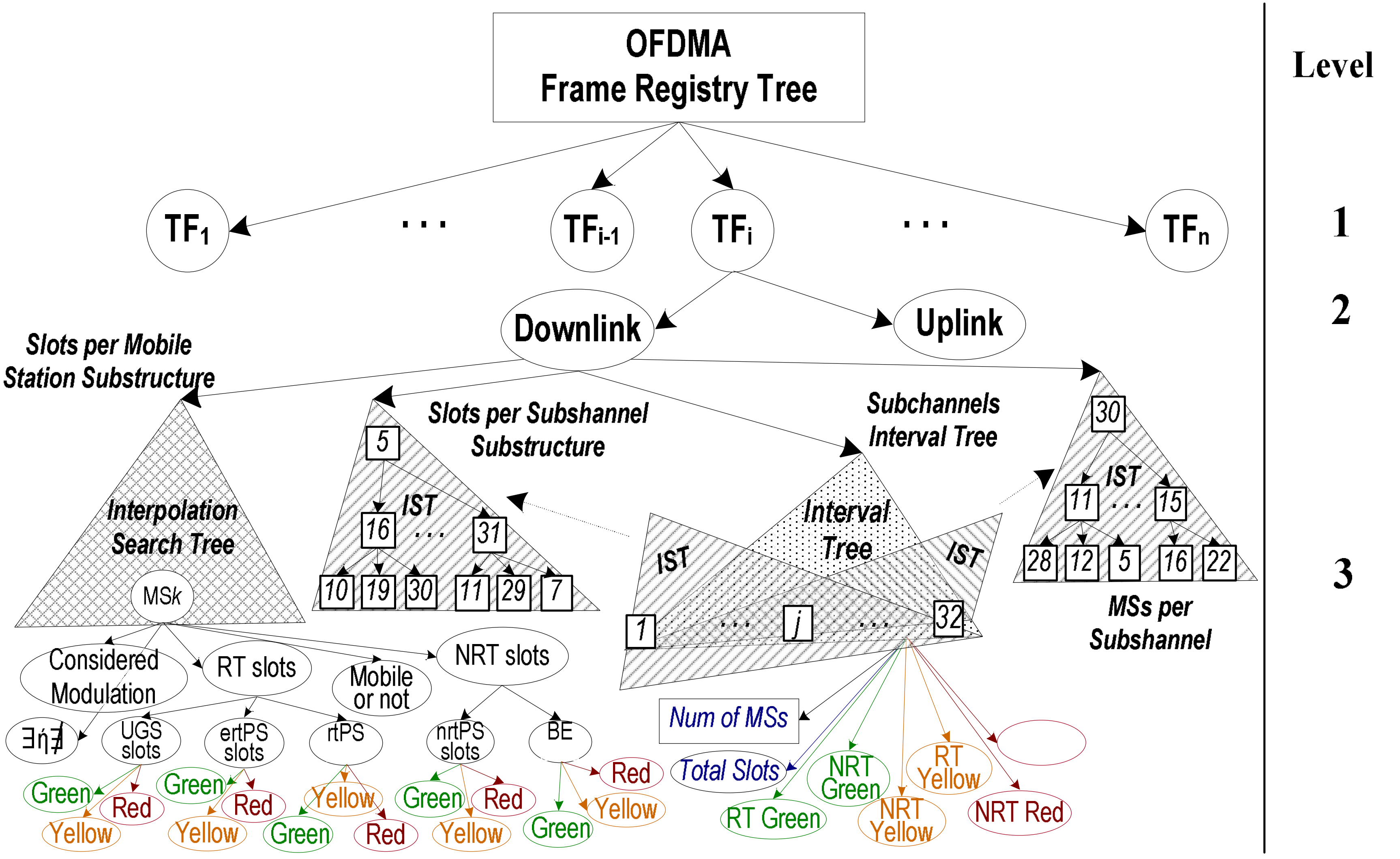
(by organizing transmissions by modulation (max e.g. 256QAM to BPSK)

→ Any modification in Users' basic characteristics should :

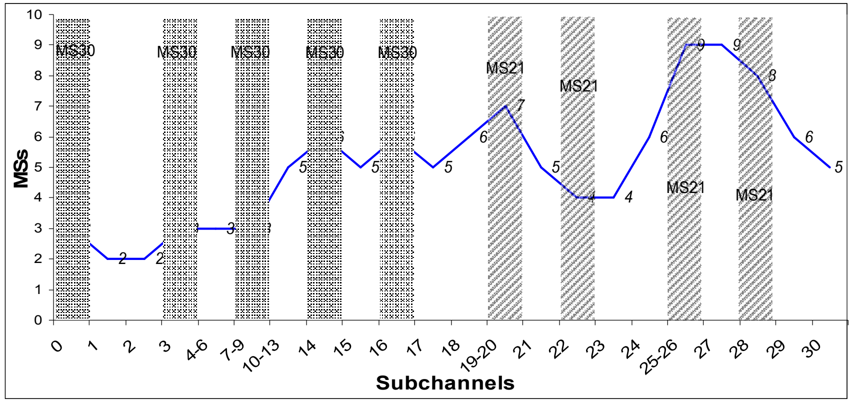
i. *the effect on scheduler' s operations should be limited*

ii. *aggravate minimum computational complexity*

Colored OFDMA Frame Registry Tree



CO-FRTree Example

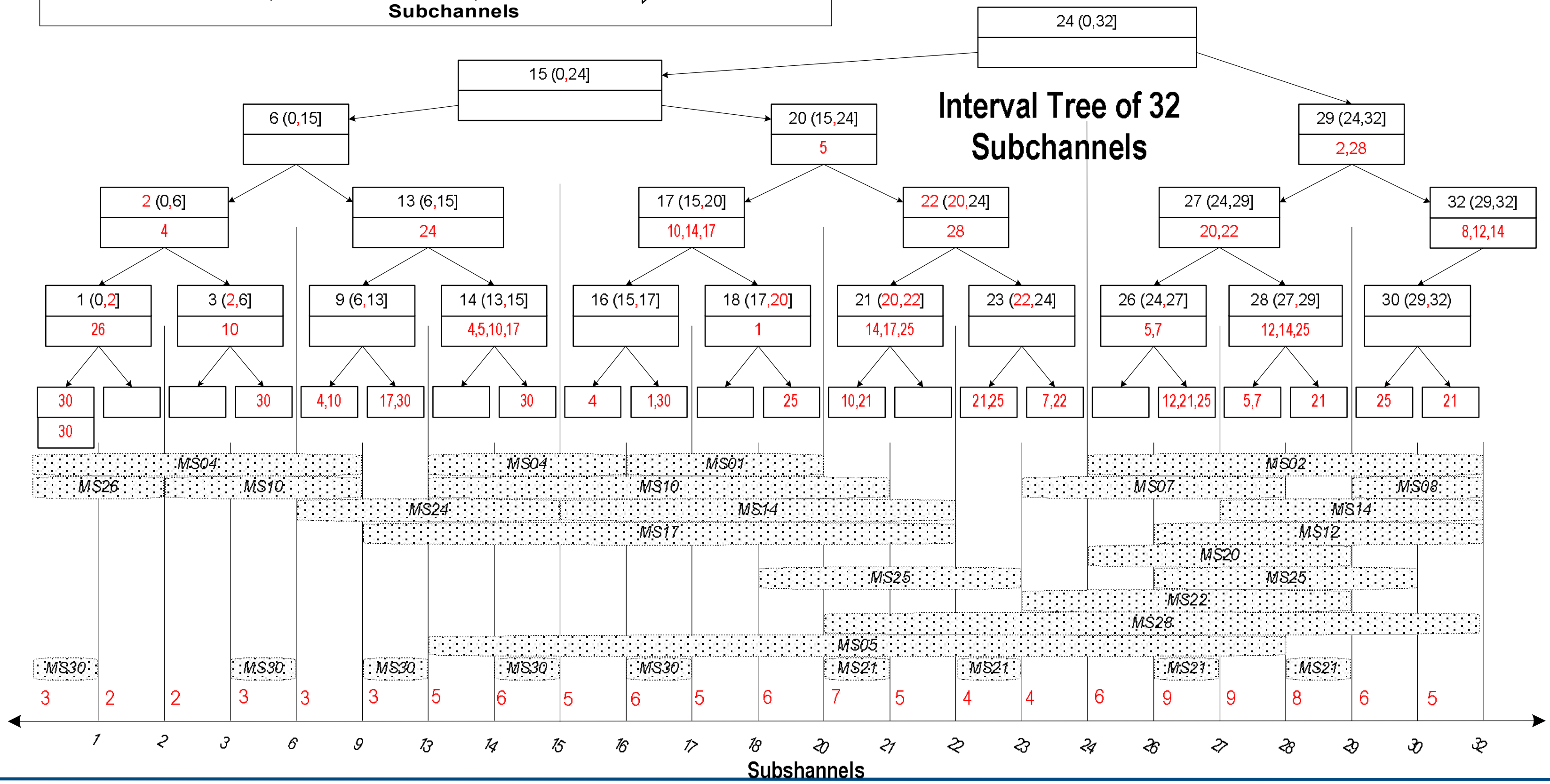


MS01→ [17,20] ≡ (16,20]
MS02→ [25,32] ≡ (24,32]
MS04→ [1,9] U [14,16] ≡ (0,9] U (13,16]
MS05→ [14, 28] ≡ (13,28]
MS07→ [24,28] ≡ (23,28]
MS08→ [30,32] ≡ (29,32]
MS10→ [3,9], [14,21] ≡ (2,9] U (13,21]
MS12→ [27,32] ≡ (26,32]
MS14→ [16,22] U [28,32] ≡ (15,22] U (27,32]

MS17-> [10,22] ≡ (9,22]
MS20-> [25,29] ≡ (24,29]
MS21-> 21 U 23 U 27 U 29 ≡
(20,21] U (22,23] U (26,27] U (28,29]
MS22-> [24,29] ≡ (23,29]
MS24-> [7,15] ≡ (6,15]
MS25-> [19,23] U [27,30] ≡ (18,23] U (26,30]
MS26-> [1,2] ≡ (0,2]
MS28-> [21,32] ≡ (20,32]
MS30-> 1 U [4-6] U [10-13] U 15 U 17 ≡
(0,1] U (3,6] U (9,13] U (14,15] U (16,17]

Nodes (all left open edges except zero with all right closed edges):
1,2,3,6,9,13,14,15,16,17,18,20,21,22,23,24,26,27,28,29,30,32

22 intervals:
1, 2, 3, 4-6, 7-9, 10-13, 14, 15, 16, 17, 18, 19-20, 21, 22, 23, 24, 25-26, 27, 28, 29, 30, 31-32



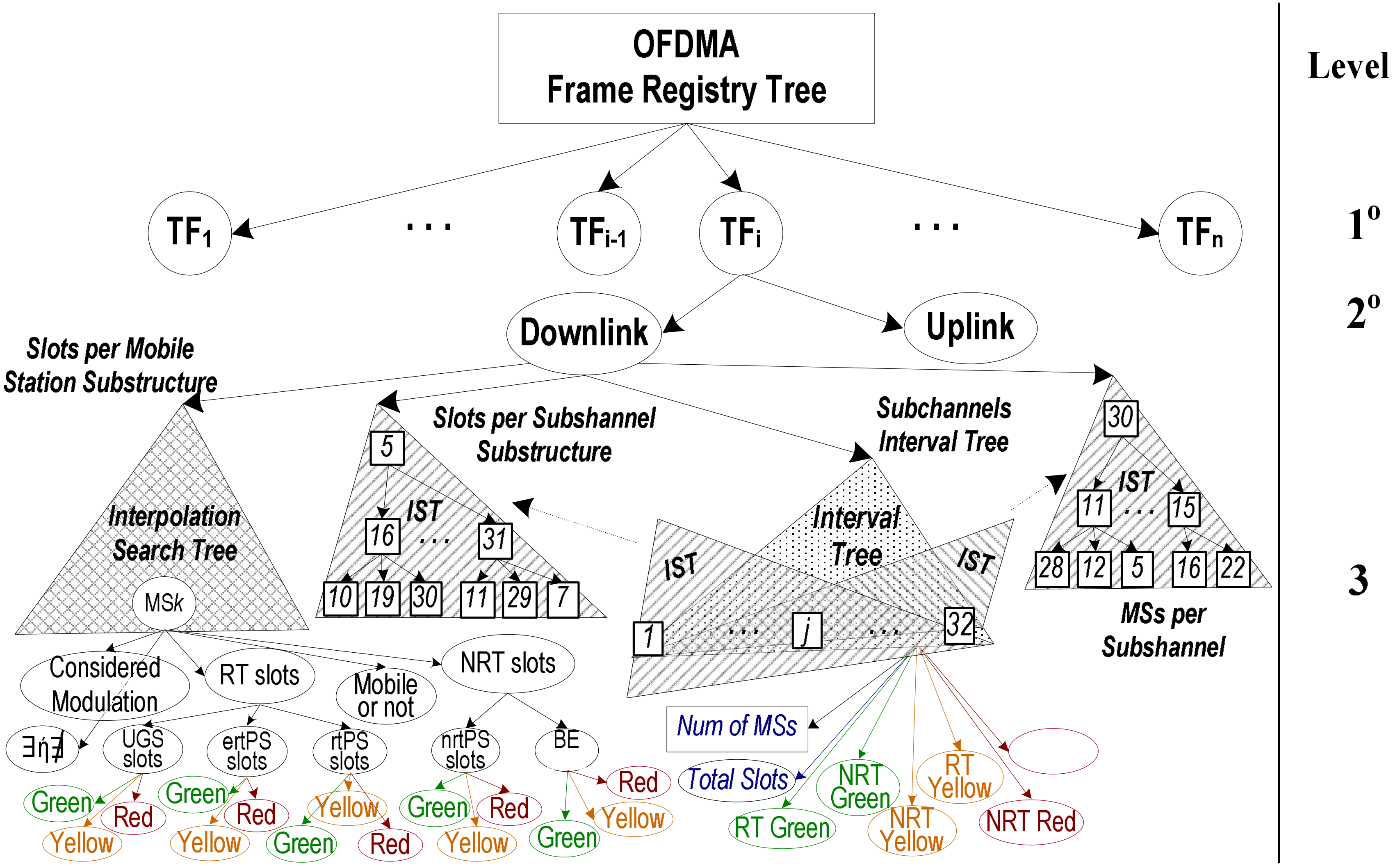
"Slots per Mobile Station" Primary Subtree

- ***Interpolation Search Tree or Van Emde Boas Tree, thus ∀ <u>K</u> MS,***
  1. needs ***O(K)*** space,
  2. ***O(loglogK)*** depth,
  3. any process (search or update) costs ***O(loglogK)*** expected time with high probability
- ***Each node has at least***:
  1. an identification ∀ MS,
  2. time slots needed for the transmission of incoming packets ∀ specific timeframe (considering Modulation & Coding Scheme),
  3. timeslots are separated in five (5) categories (UGS, ertPS, rtPS, nrtPS, BE).
- ***Can answer in O(loglogK) time questions like:***
  1. *"How many slots MS_k requires for the transmission of non real time data?"*
  2. *"How many slots MS_k requires for the transmission of real time data packets, corresponding to data rate greater than the agreed **mrtr** (**minimum reserved traffic rate**)?"*

"Subchannels Interval Tree" Primary Subtree

- ***Interval Tree, thus for N subchannels:***
  1. requires ***O(NlogN)*** space
  2. has ***O(logN)*** depth
  3. needs ***O(NlogN)*** building time
  4. Its leaves need ***O(N)*** space
- ***Each leaf contains the number of slots needed by all active users in corresponding time interval***
- ***Each internal node "spans" to the whole interval defined by two groups of subchannels***
- ***For the interval [a, b] defined by active subchannels of MS_k, MS_k is stored in node x if and only if:***
  - i. interval [a,b] fully contains ***span(x)***
  - ii. interval [a,b] does not fully contain ***span(parent(x))***, (e.g. ***span(6) = [2,13],*** MS_5: [14,28], will be stored in nodes 14, 20, 26 & 28left).
- ***For a specified interval of N' subchannels, any MS with active interval of subchannels in that interval, can be found in O(N'+logN) time, consequently O(N).***
- ***Update of an MS_k active subchannels costs O(N) time, whereas in combination of "Slots per Mobile Station" subtree it costs O(loglogN)***
- ***Can answer in O(N) time questions like:***
  - i. *"Which MSs can reliably transmit at interval [a,b]?"*
  - ii. *"How many slots have been counted for transmission at interval [a,b]?"*
  - iii. In combination with "Slots per Mobile Station": *"How many slots that have been counted for transmission at interval [a,b], correspond to non real time BW, according to mrtr & mstr;"*

Colored OFDMA Frame Registry Tree



"Slots per Subchannel" Secondary Subtree

- ***Interpolation Search Tree ή Van Emde Boas Tree, thus for N intervals:***
  i. needs ***O(N)*** space
  ii. has ***O(loglogN)*** depth
  iii. any process (search or update) costs ***O(loglogN)*** expected time with high probability
- ***Subtree "Slots per Subchannel":***
  i. its nodes are the leaves of "Subchannels Interval Tree"
  ii. keeps them sorted by the number of slots correspond to each interval
  iii. gives access to each leaf "Subchannels Interval Tree" in ***O(loglogN)*** time, for ***N*** intervals
  iv. each update costs ***O(1)*** for given position, ***O(loglogN)*** at average & in worst case ***O(logN)***
  v. required space limited in interconnection pointers
- ***Can answer in O(loglogN) time questions like :***
  i. "Which is the first empty slot in the interval [a,b]?" or
  ii. "Which is the elementary interval [a,b] with the least traffic?".

“MSs per Subchannel” Secondary Subtree

- ***Interpolation Search Tree ή Van Emde Boas Tree, οπότε για N διαστήματα,***
  1. needs ***O(N)*** space,
  2. has ***O(loglogN)*** depth
  3. any process (search or update) costs ***O(loglogN)*** expected time with high probability
- ***Subtree “Mobile Stations per Subchannel”:***
  1. its nodes are the leaves of “Subchannels Interval Tree”
  2. keeps them sorted by the each MS Id that can reliably transmit in each interval
  3. each update costs ***O(loglogN)*** at average & in worst case ***O(logN),***
  4. required space limited in interconnection pointers
- ***Can answer in O(loglogN) time questions like :***
  1. “Among all available elementary intervals (1,32), which is the one [a,b], that the minimum number of MSs can reliably transmit?”

Space evaluation of Colored OFDMA Frame Registry Tree

For *K* MSs, *N* subchannels, & *c* stored timeframes :

TotalStorage = NumberOfFrames{Storage(Slots_per_MS) +*

Storage(Subchannels_Interval_Tree) +

Storage(Slots_per_Subchannel) +

Storage(MSs_per_Subchannels)} ⇔

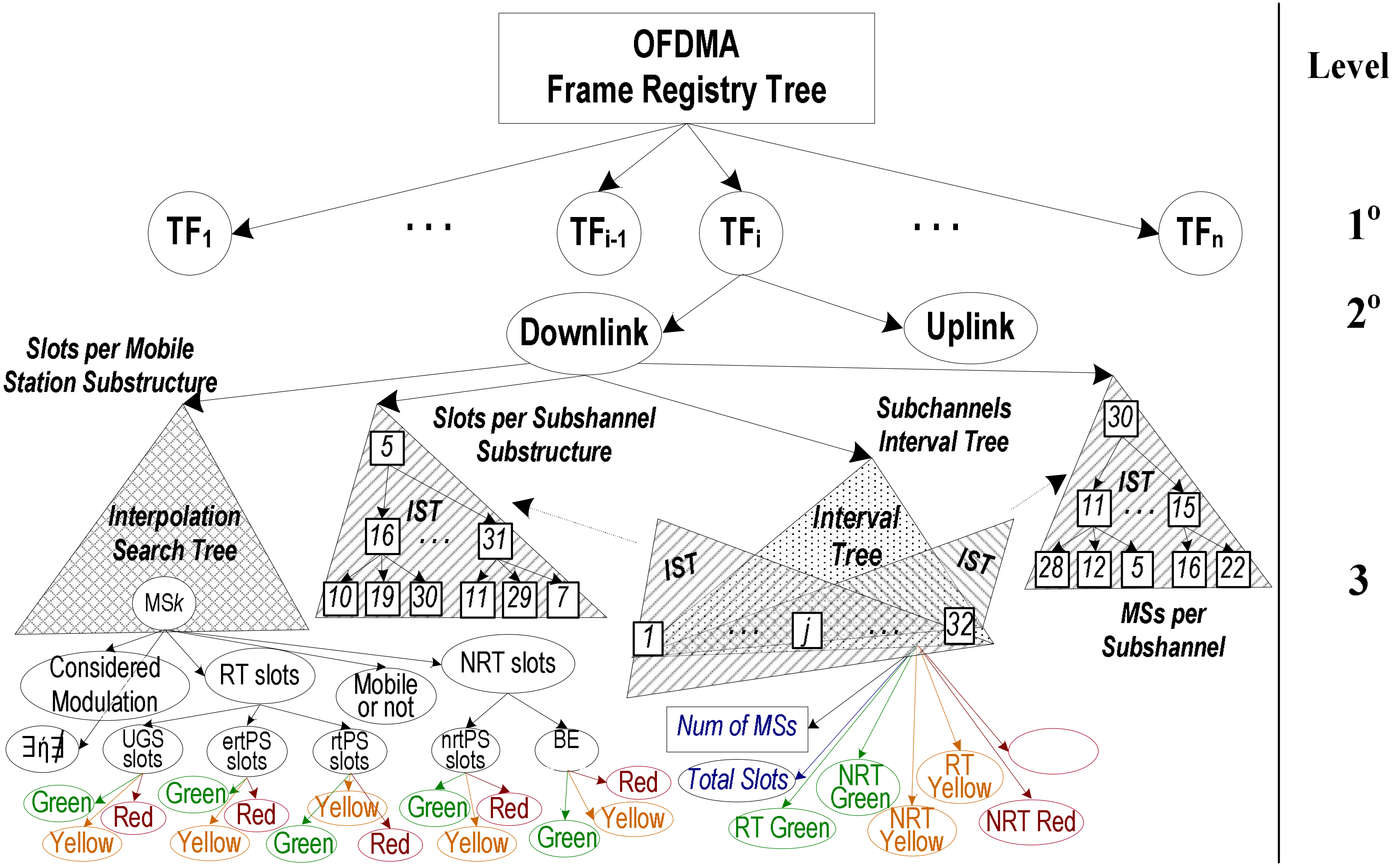
TotalStorage = c{O(K)+O(NlogN)+O(NlogN)+ O(NlogN)} ⇔

*TotalStorage = c*O(K+NlogN)*

TotalStorage = O(c[K+NlogN])

e.g., IF max(max_delay)=100ms AND frame_size= 5 ms, THEN c=20.

Colored OFDMA Frame Registry Tree



CO-FRTS basic operations

1. **Packet /request for transmission / Grant arrival & insertion in CO-Frame Registry Tree**
   i. *Deadline(P_{ij})=ArrivalTime(P_{ij})+MaxLatency(P_{ij}) calculation,*
   ii. *SL_{ij} = f(Mod_k,SizeInBytes(P_{ij})) calculation, with C_j the connection it belongs,*
   iii. ***Thr(P_{ij})<?>mrtr(C_j), mstr(C_j)** check, & coloring,*
   iv. *primary subtrees insertion (**SL_{ij}/q** for [a,b], q=b-a+1 at Interval Tree),*
   v. *insertion / update at secondary subtrees.*
2. **Timeframe creation - Frame Map Creation Procedure (DL/UL MAP)**
   i. *Timeframe Preparation Procedure*
      - Choose transmission interval ∀ MS (IMF)
      - Cut excess slots – fulfill empty ones
      - counterbalance traffic among subchannels
   ii. *Timeframe Construction Procedure*
3. **User characteristics modification**

Packet /request for transmission / Grant arrival & insertion in CO-FRTree

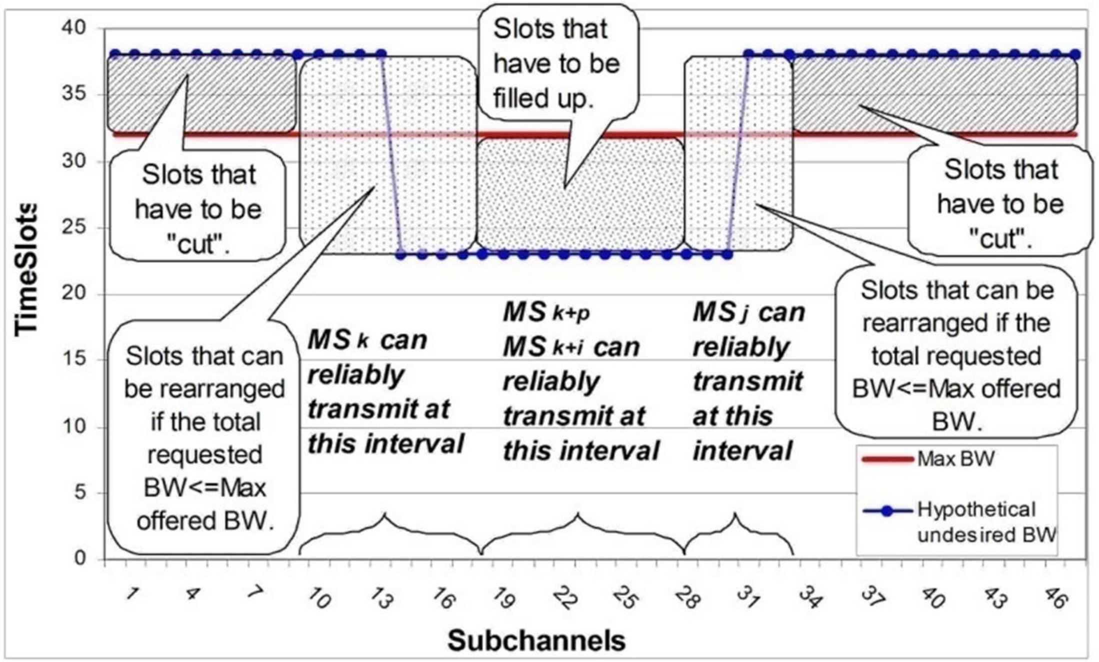
- Calculate packet deadline :

  $Deadline(P_{ij})=ArrivalTime(P_{ij})+MaxLatency(P_{ij})$, with C_j the connection it belongs
- Calculate :

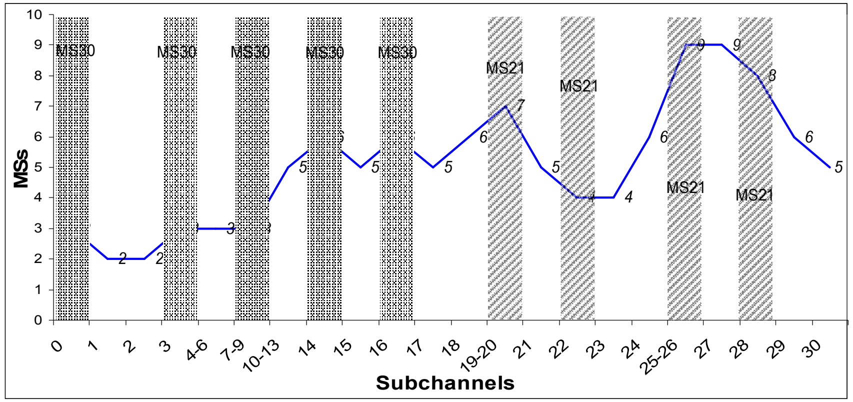
  $SL_{ij} = f(Mod_k, SizeInBytes(P_{ij}))$
- Search/find MS_k at “Slots per Mobile Station” subtree & update it according to the follwing:
  - if $Thr(P_{ij})<mrtr(C_j)$, green node of ST_j is increased by SL_{ij}.
  - if $mrtr(C_j)\leq Thr(P_{ij})\leq mstr(C_j)$, yellow node of ST_j is increased by SL_{ij}.
  - if $Thr(P_{ij})>mstr(C_j)$, red node of ST_j is increased by SL_{ij}.
- At “Subchannels Interval Tree”:
  - if MS_k can reliably transmit μπορεί at interval [a,b], q=b-a+1 subchannels,
  - balanced increment, meaning nodes between a & b are incremented by SL_{ij}/q

Timeframe Preparation Procedure

- ***Aim: proper preparations of next timeframe for transmission (TF_1)***
- ***Three major problems:***
  1. Existence of more than one intervals of subchannels, that some MSs can transmit with the same reliability (same SINR, probably single subchannels)
     - *Only one interval of subchannels, e.g. MS_5, MS_{28},*
     - *Single subchannels, e.g. MS_{21},*
     - *More than one intervals with more than one subchannel each, e.g. MS_4, MS_{10}, MS_{30}.*
  2. Abnormally distributed traffic with possible gaps or excess slots
  3. Data areas ∀ MS should form a rectangle, (slots / subchannels → integer).



CO-FRTree Example



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MS30-> 1 U [4-6] U [10-13] U 15 U 17 ≡
(0,1] U (3,6] U (9,13] U (14,15] U (16,17]

Nodes (all left open edges except zero with all right closed edges):
1,2,3,6,9,13,14,15,16,17,18,20,21,22,23,24,26,27,28,29,30,32

22 intervals:
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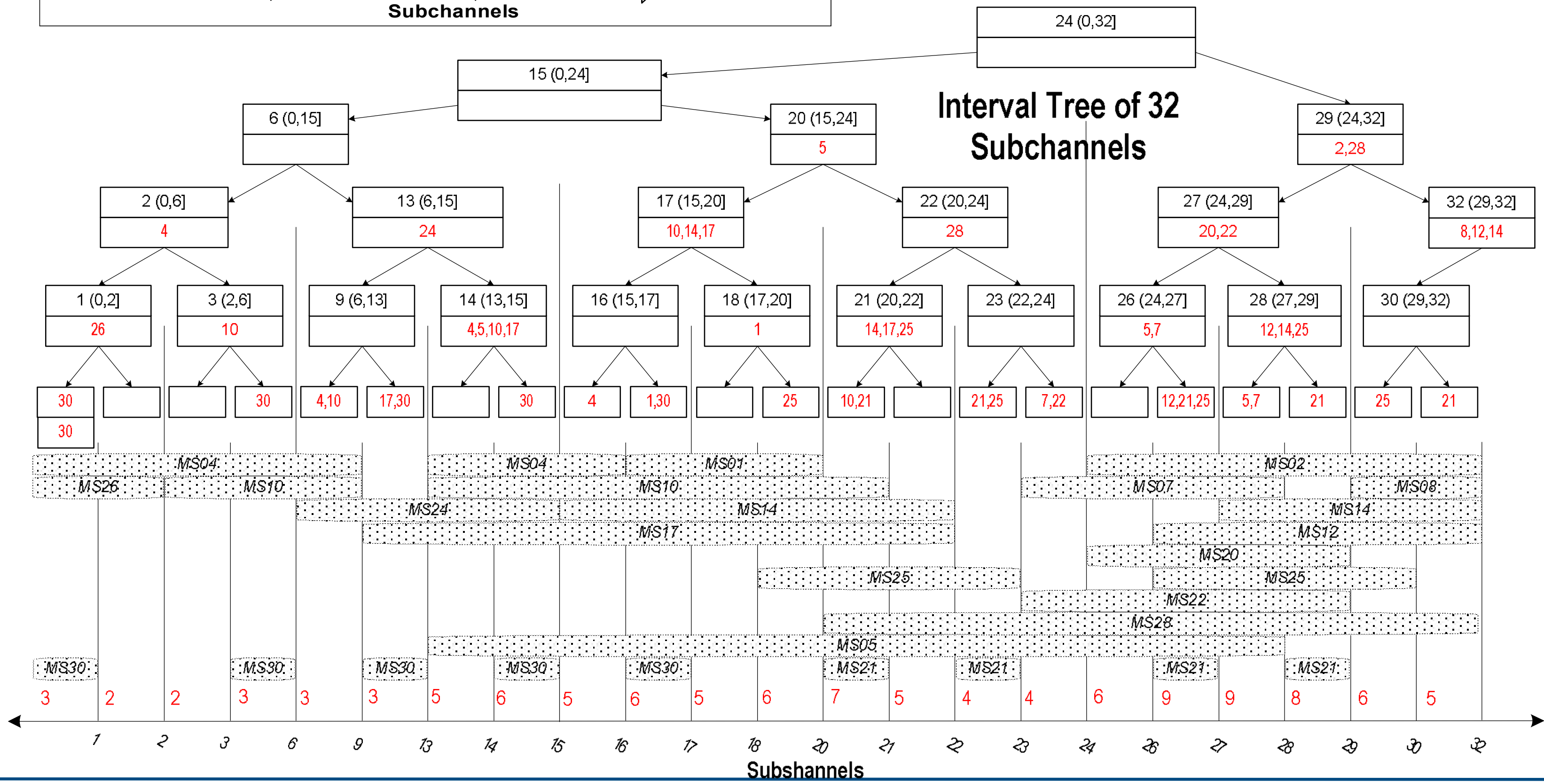


Solution for choosing interval ∀ MS

Considering that MS_k has to receive SL_k slots at m intervals i=[α,β], ii=[γ,δ] with (β<γ).

Importance Factor (IMF) of MSk at [α,β] IMFk,[a,b] is given by :

$$IMF_{k,[a,b]} = \frac{Number\_Of\_Slots\_Assigned\_By\_MS_k\_At[a,b]}{Total\_Number\_Of\_Slots\_Assigned\_By\_All\_MSs\_At[a,b]} \Leftrightarrow$$

$$IMF_{k,[a,b]} = \frac{SL_k}{TSL_{[a,b]}} \Leftrightarrow$$

$$IMF_{k,[a,b]} = \frac{SL_k}{TSL_1 + .. + TSL_y + .. + TSL_m}, TSL_y : 1 \leq y \leq m \leq N'$$

*where **m** are the elementary intervals of subchannels, as they occur & **TSL_y** is the corresponding number of slots that have been allocated in each interval μ by all MSs with this interval active.*

Cost: O(NK)+ O(KlogN)= O(KN)

Solution for cut excess slots – fill in the gaps

- ***From "Slots per Subchannel", find interval with excess slots***
- ***Combining "Subchannels Interval Tree", search/find MS with worst Modulation & Coding Scheme***
- ***"Cut" slots with colored order:***

  $(CutPriority_{GREEN} < CutPriority_{YELLOW} < CutPriority_{RED}) \cup$

  $(CutPriority_{UGS} < CutPriority_{ertPS} < CutPriority_{rtPS} < CutPriority_{nrtPS} < CutPriority_{BE})$
- ***Fill empty slots with opposite priority from next timeframes:***

  $(TransPriority_{GREEN} > TransPriority_{YELLOW} > TransPriority_{RED}) \cup$

  $(TransPriority_{UGS} > TransPriority_{ertPS} > TransPriority_{rtPS} > TransPriority_{nrtPS} > TransPriority_{BE})$
- ***Possible traffic balance***

Total complexity evaluation for CO-FRTS

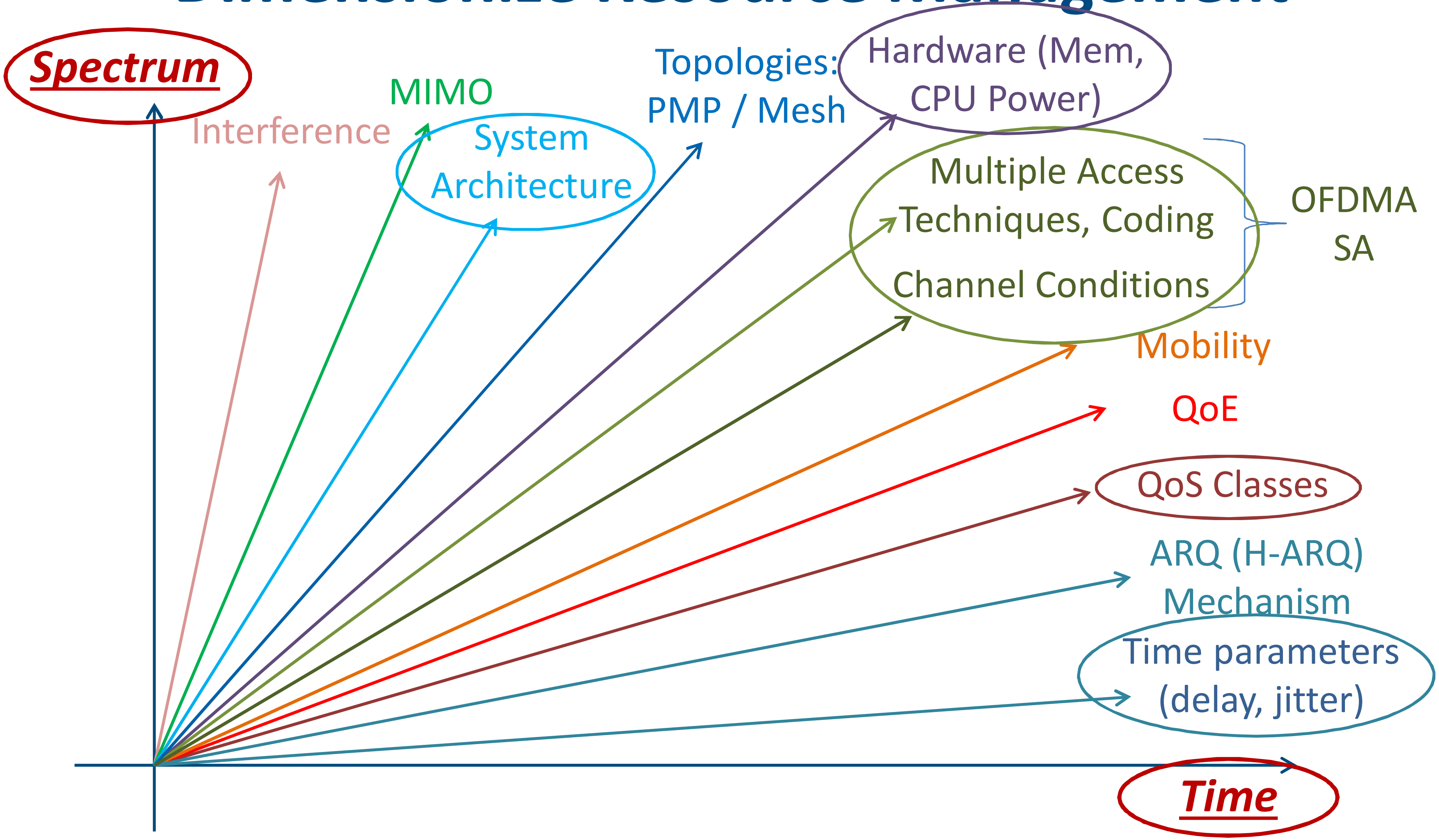
For *N* subchannels & *K* Mobile Stations					
	Structure	**Mobile Stations Structure-IST**	**Interval Tree of Subchannels -MSs**	**Subchannels Structure -IST**	**Total Cost in Time**
Action					
MS's Interval & Data Insertion	mean				
	max	O(log log K)	O(N)	$O(\log^2 \log N)$	$O(N+\log^2 \log N)$
MS's Data Insertion	mean				
	max	O(log log K)	O(N)	$O(\log^2 \log N)$	$O(N+\log^2 \log N)$
MS Search	mean				
	max	O(log log K)	O(1)	-	O(loglogK)
Interval Update	mean	-		O(1)	
	max	-	O(1)	O(NloglogN)	O(NloglogN)
Elementary Interval Search	mean	-		O(1)	
	max	-	O(logN)	O(loglogN)	O(loglogN)

TotalCost = $O(N+\log^2 \log N)+O(N+\log^2 \log N)+O(K\log\log K)+O(N\log\log N)+O(N\log\log N)+O(KN)$ ⇔

TotalCost = $O(N) + O(K\log\log K) + O(N\log\log N) + O(KN)$ ⇔

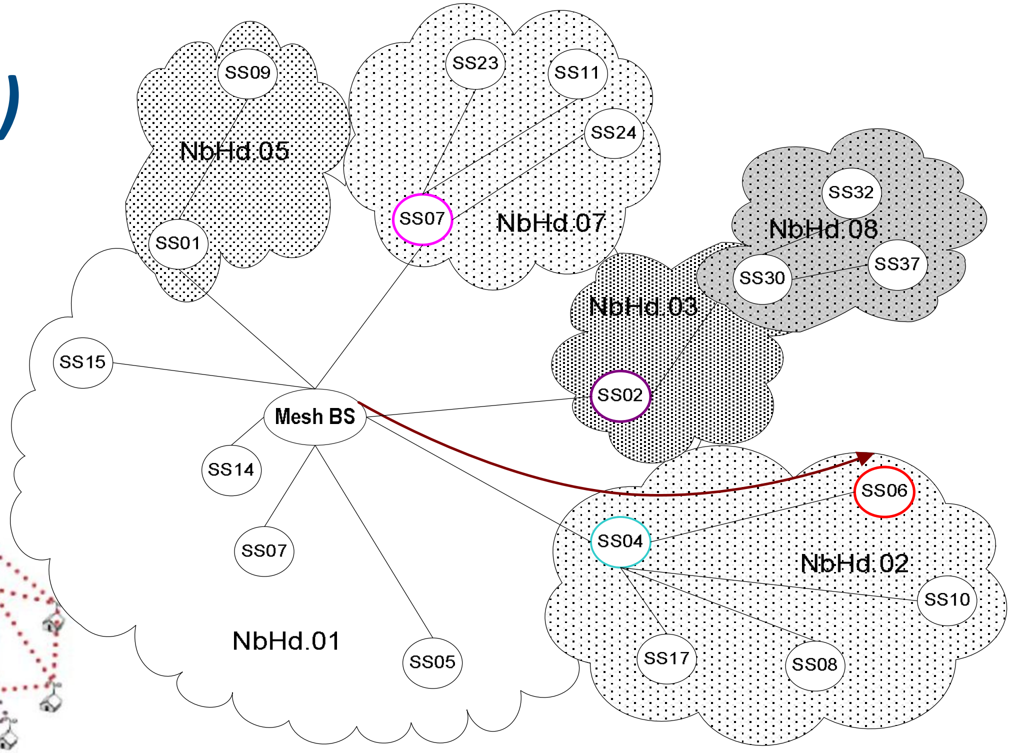
TotalCost = O(KN + KloglogK + NloglogN)

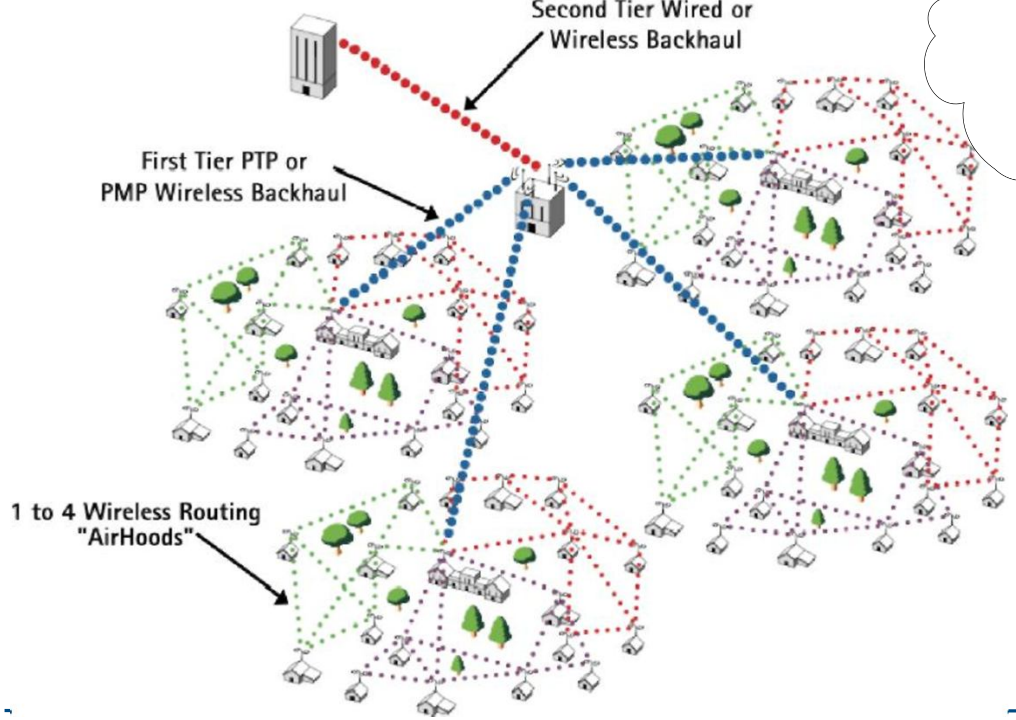
Dimensionize Resource Management



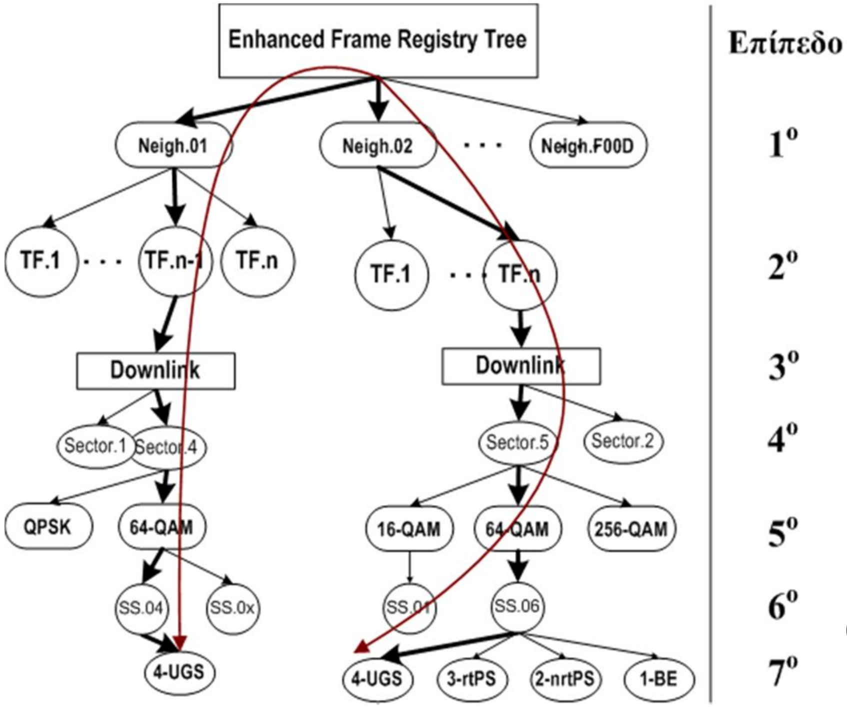
IEEE 802.16-2004 Topologies

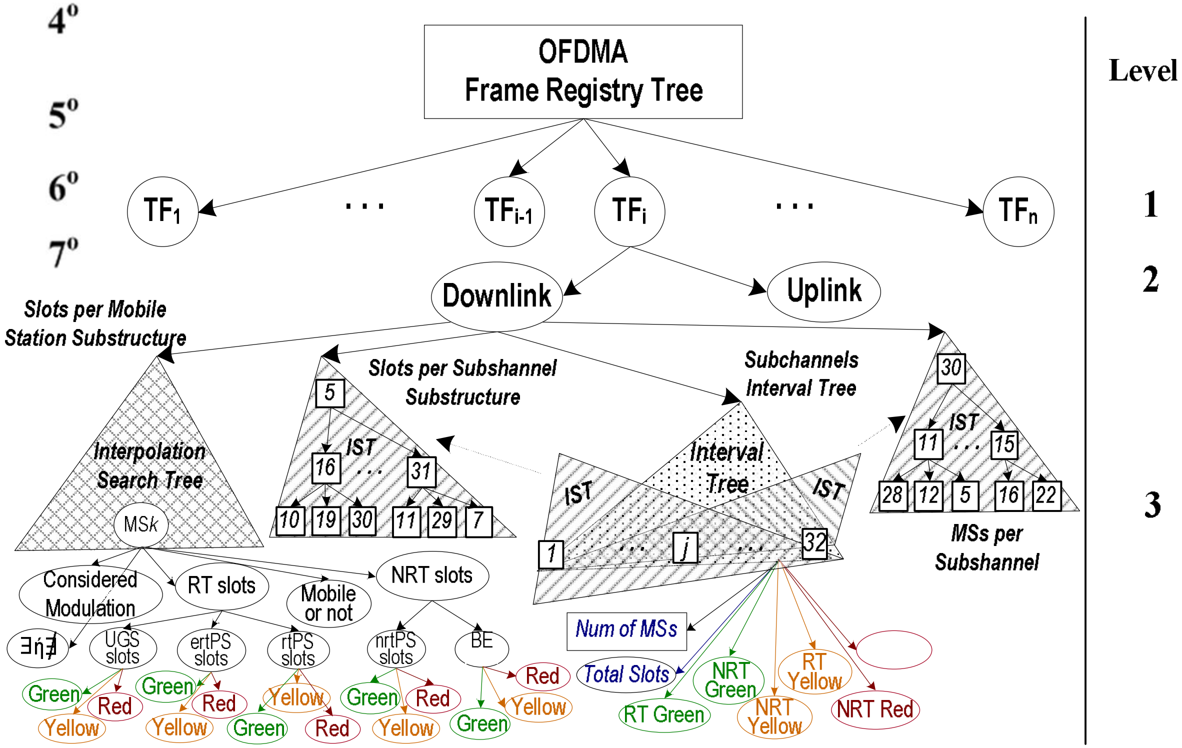
- ***Point-to-Multipoint (PMP)***
- ***Centralized Mesh mode***
- Distributed Mesh mode





Enhanced Frame Registry Tree - CoFRTS





Simulation Platform

Widely used simulation platforms

- *Opnet :*
  - → *supports Release 8 of the 3GPP LTE standard*
  - → *supports the IEEE 802.16-2004 & IEEE 802.16e-2005 (not 802.16m-2011)*
  - → *not free (very expensive)*
- *NS-3*
  - → *evolution of NS-2*
  - → *freeware*
  - → *integration environment almost only in Linux*
  - → *built using C++ & Python, scripting available with both languages*
  - → *supports the 3GPP LTE standard (not LTE-A)*
  - → *supports the IEEE 802.16-2004 & IEEE 802.16e-2005 (not 802.16m-2011)*
- *GloMoSim (Global Mobile Information System Simulator)*
- *OMNeT++*
- *NetSim*
- *NCTUNS*
- *Matlab*

Need for our simulation environment (1)

All available simulation tools are either:

→ *expensive (Opnet)*

→ *not so user friendly, inflexible, thus awkward (NS-2/3)*

→ *built for generic use*

→ *very slow in adaptation of new technologies (LTE-A, WiMAX2 etc)*

→ *lack of support for complicated structures & programming entities (objects - Matlab)*

→ *very slow (Matlab - cause of Java)*

Need for our simulation environment (2)

→ *Easy integration (windows, MS Visual Studio 2005 or newer)*

→ *Freeware*

→ *Run in normal PC*

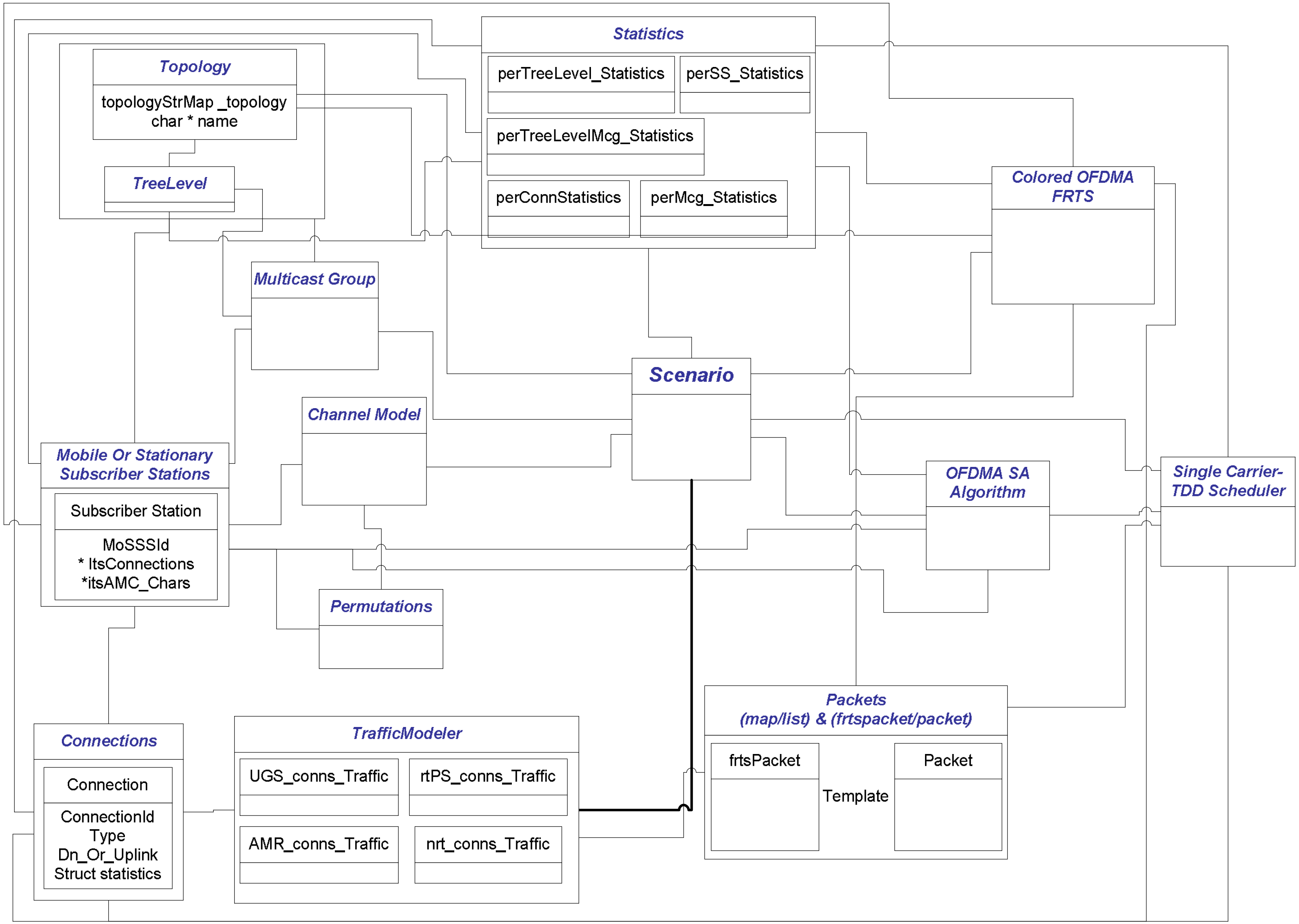
→ *Group design, development & evolution (GAIN team work)*

→ *Based in C++ for best memory and process usage and control*

→ *Can support any modern and easily extent to future technologies*

→ *Extracts results in xls file for best usage (matlab etc)*

Basic Entities of Simulation Platform



Main characteristics of the Simulation Platform

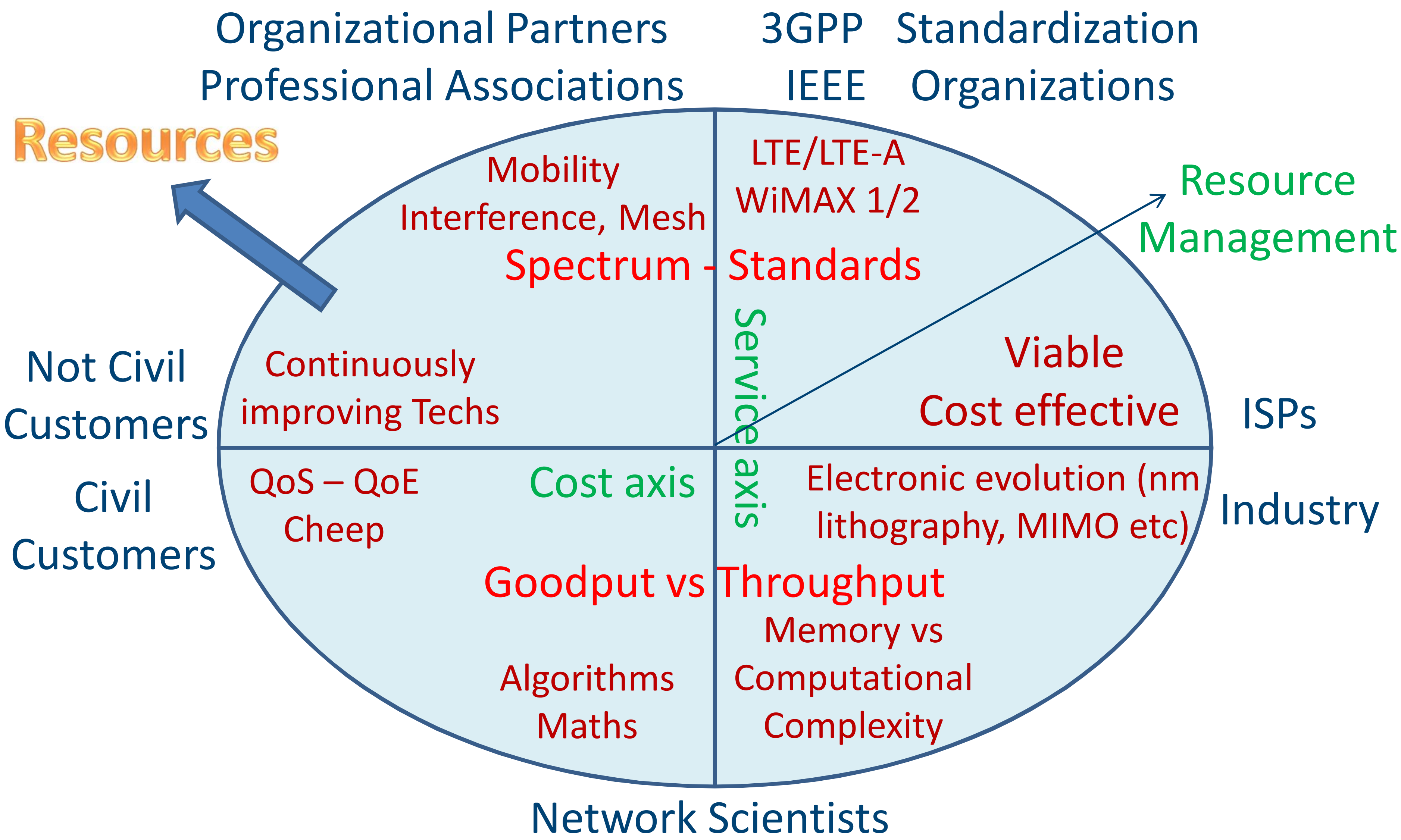
- Uses libraries: MAP, MULTIMAP, SET, MULTISET &LIST (B+ Trees)
- "Scenario": definition of parameters by #define (e.g. #define scenario_PHY _OFDMA)
- "Topology": can simulate very complicated tree topologies (e.g. n-nary tree or even more complicated)
- "Channel Model": can use file created with Matlab ("channelEstimation.bin")
- "Traffic Modeler": → AMR according to 3GPP TS 26.071 v5.0.0
  → packet size 54, 66, 70, 80, 92, 102 & 114 bytes
  → sophisticated traffic model considering mrtr & mstr
  → video traffic from trace files (25 or 30 fps)
- "Statistics": extraction of extensive results in ".xls / .xlsx" files.

Possible future extensions

- "Scenario": need for GUI
  - → for parameters definition
  - → for realtime simulation observation
- "Channel Model": develop / integration in c++ models for
  - → path-loss
  - → multipath fading effect,
  - → dynamic channel conditions creation
- "Traffic Modeler": integration of
  - → enrichment of traffic vreation models
- Integration of a number of modern RA algorithms (library creation)

Conclusions

Resource Management trade-offs



Resource Allocation what we have seen so far

Resources ? (Visible - invisible)

Wireless Technologies (LTE, LTE-A, WiMAX, WiMAX2)

QoS

Traditional & Modern Scheduling Algorithms

Case Study: WiMAX (Co-FRTS)

PMP - MESH

Simulation Environments

Thank you for your attention!

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