System Level Simulations with WiSE

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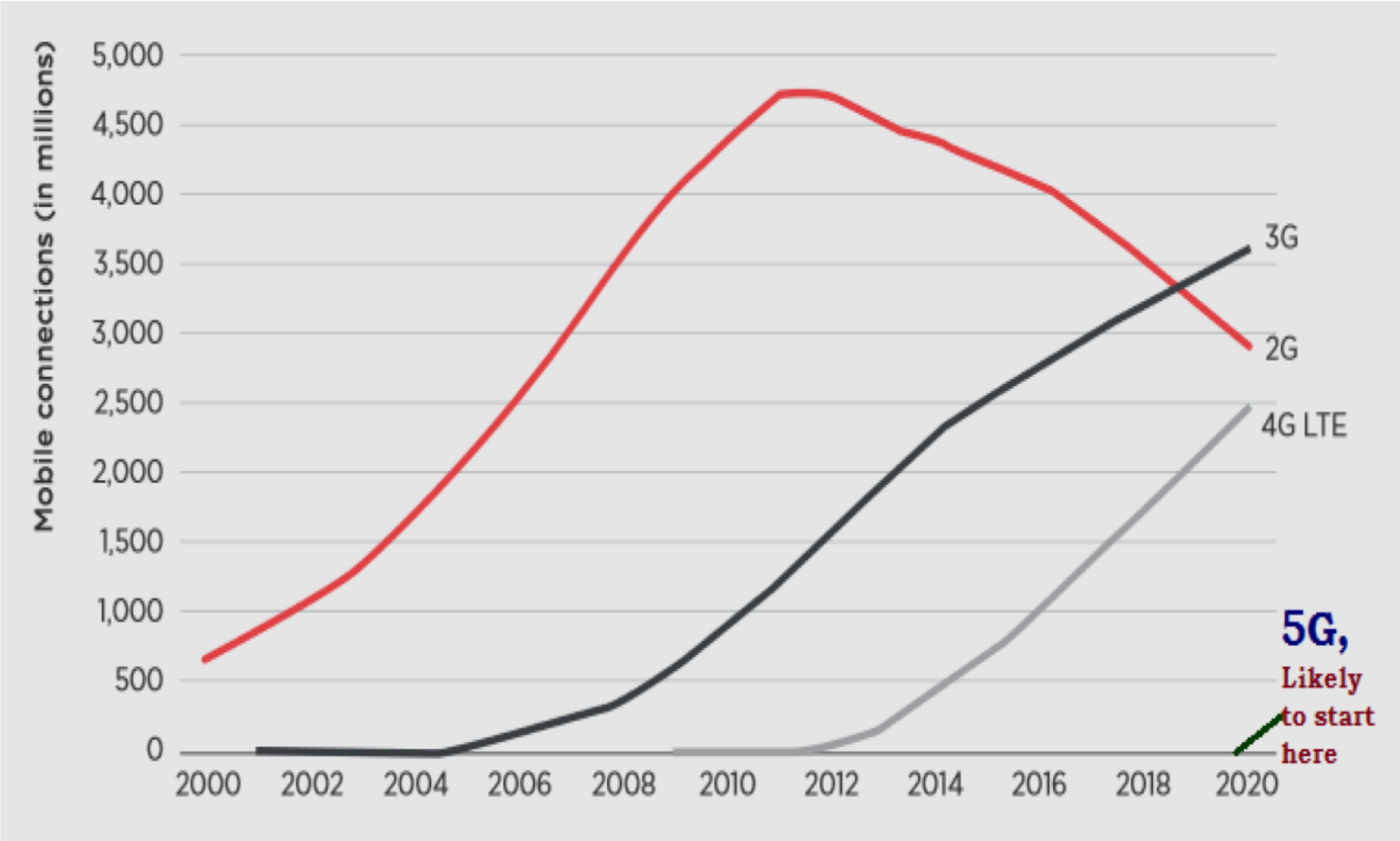
Content

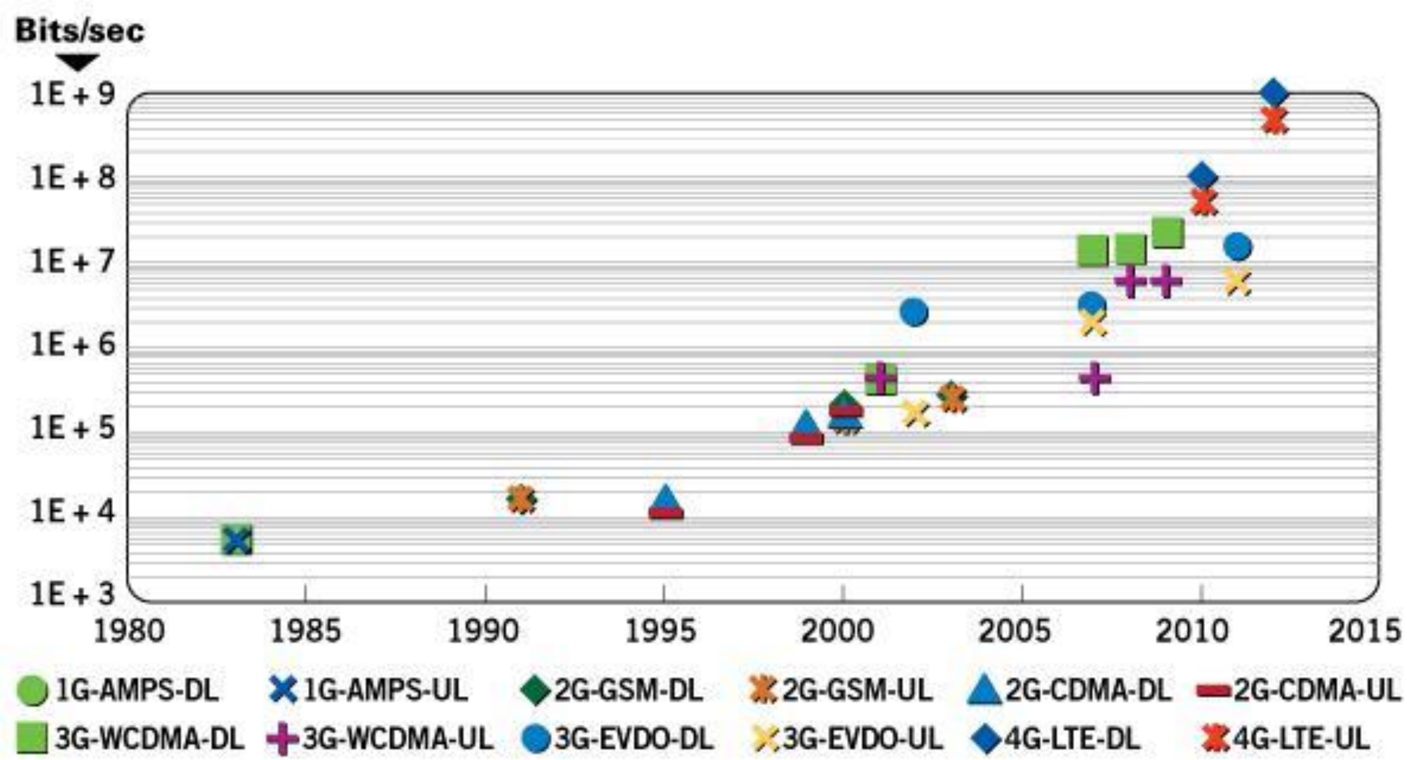
I. Introduction to 5G

- Wireless communication has experienced a rapid growth and evolution since 1980s (1G, …4G, or now 5G).

- Evolution:


Mobile connections (in millions)
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
3G
2G
4G LTE
5G,
Likely
to start
here

- Data rate enhancement:



  – In just 30 years, wireless data rate has been increased by more than 100,000 times!

- What is 5G?
  - 5G is the fifth generation technology, and it has many advanced features potential enough to change our life dramatically.

- Targets:

https://5g-ppp.eu/#

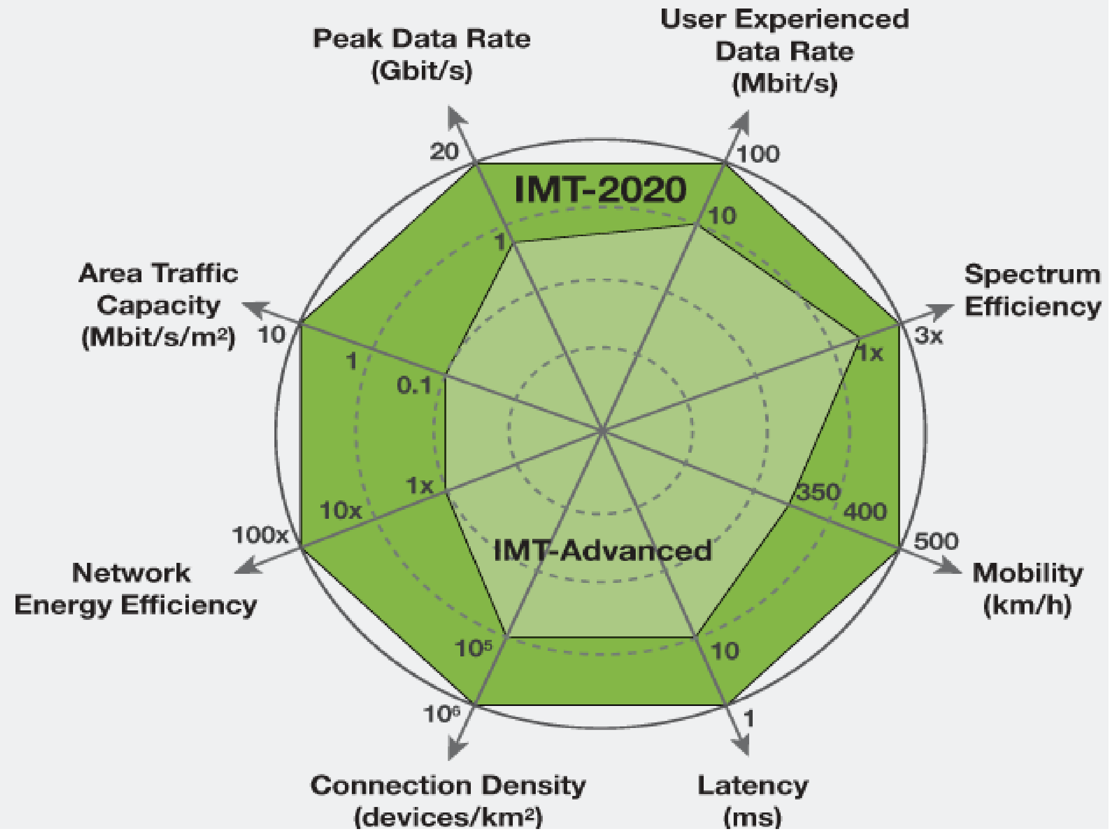
- Features:
  - High increased peak bit rate
  - Larger data volume per unit area
  - High capacity
  - Lower battery consumption
  - Better connectivity irrespective of the geographic region
  - Larger number of supporting devices
  - Lower cost of infrastructural development
  - Higher reliability of the communications

- How to increase the capacity by 1000 times?

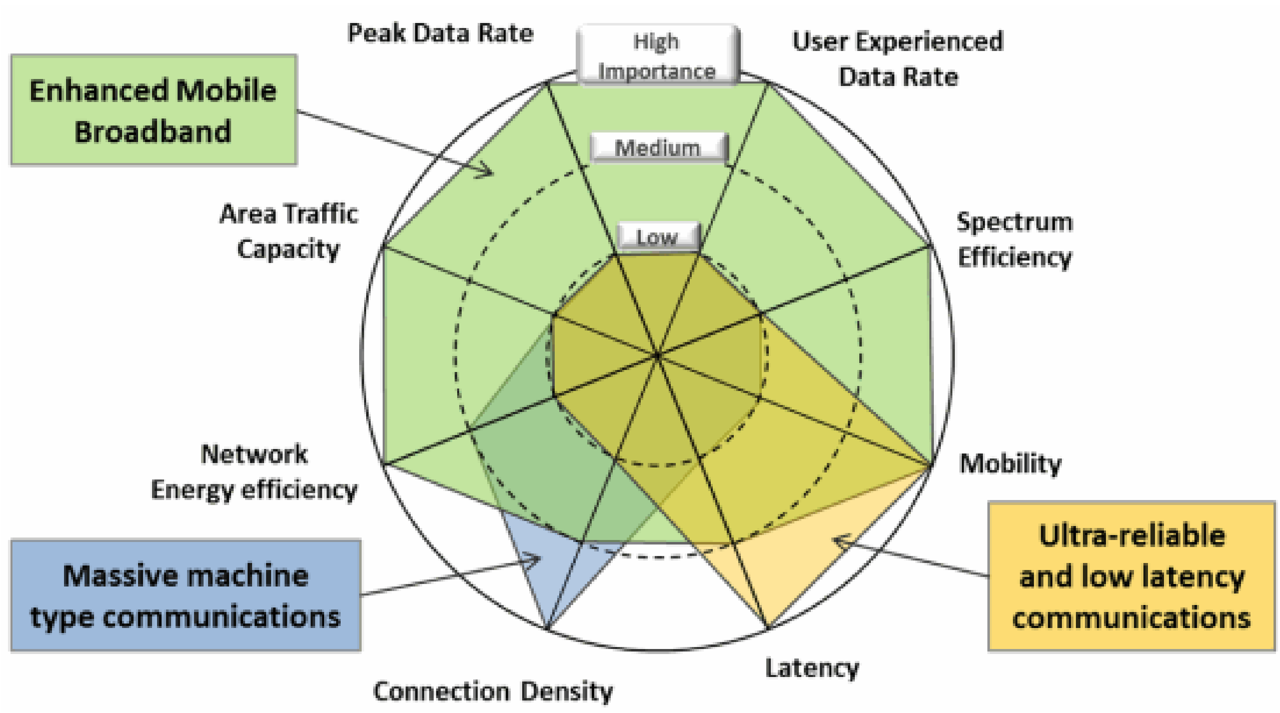
- Better spectral efficiency (4):
  - Spectral efficiency: 30 bps/Hz → ?
  - Key enabling technology, MIMO, …
- Larger spectrum (5):
  - Carrier bandwidth Increase: 100MHz → 500MHz/1GHz
  - Spectrum availability?
    - Higher band: millimeter wave (mmWave)
    - Spectrum sharing
    - Unlicensed bands
- More cells, network densification (50):
  - Greatly reduce the coverage of a cell, i.e., dramatically increase the cell number.
  - Key enabling technology: ultra-dense small cells

- Technology challenges:
  - Authorized shared access
  - Unlicensed bands
  - mmWave
  - Massive MIMO
  - Phase antenna array
  - Beam-forming and beam-tracking
  - Small cell
  - Interference management
  - Full duplex radios
  - SDN and NFV
  - …

- ITU has defined three usage scenarios in 5G
  - Enhanced mobile broadband
  - Massive machine type communications
  - Ultra-reliable and low latency communications
- Key features:



- Three scenarios:

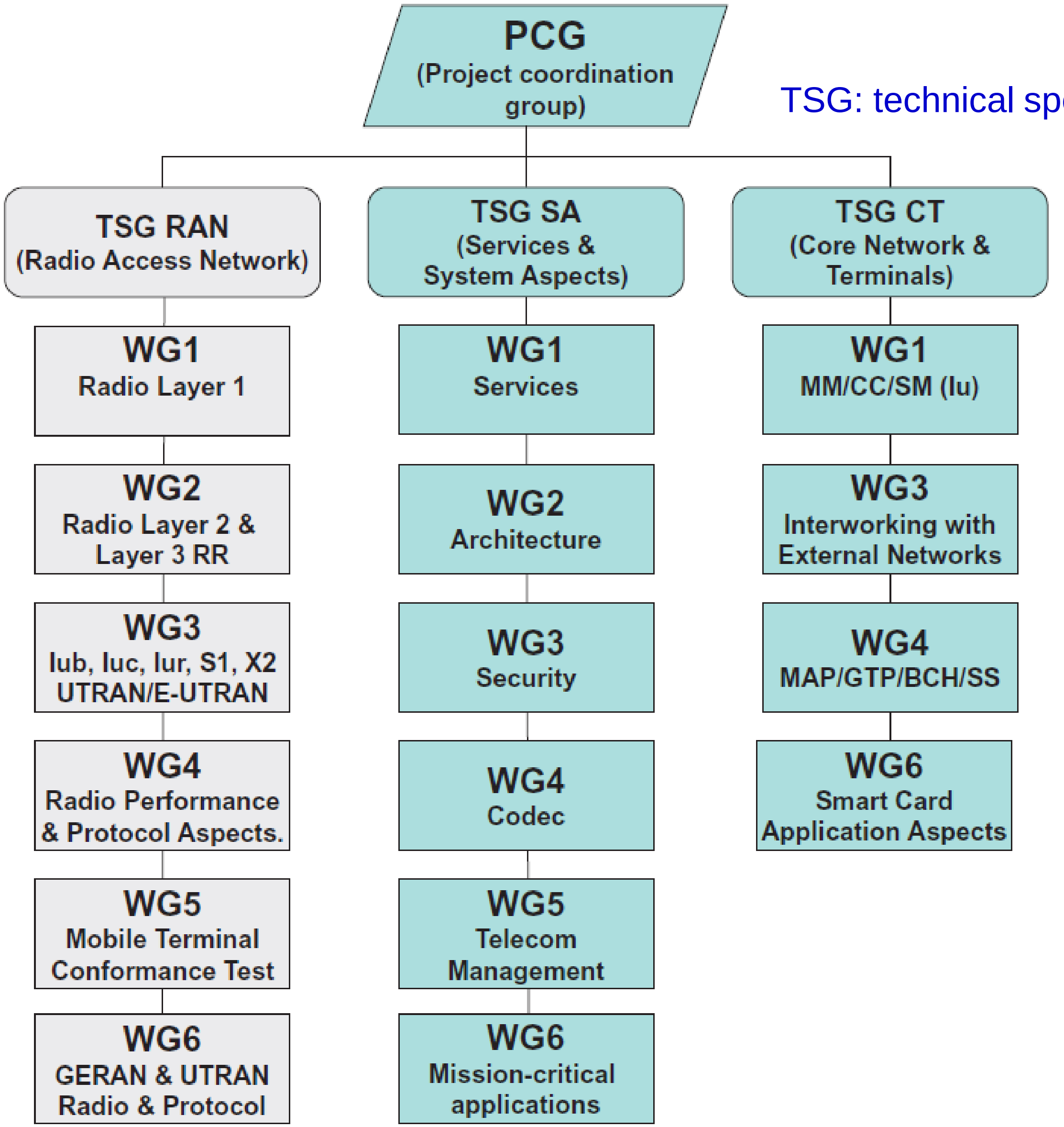


II. Introduction to WiSE

1. Introduction

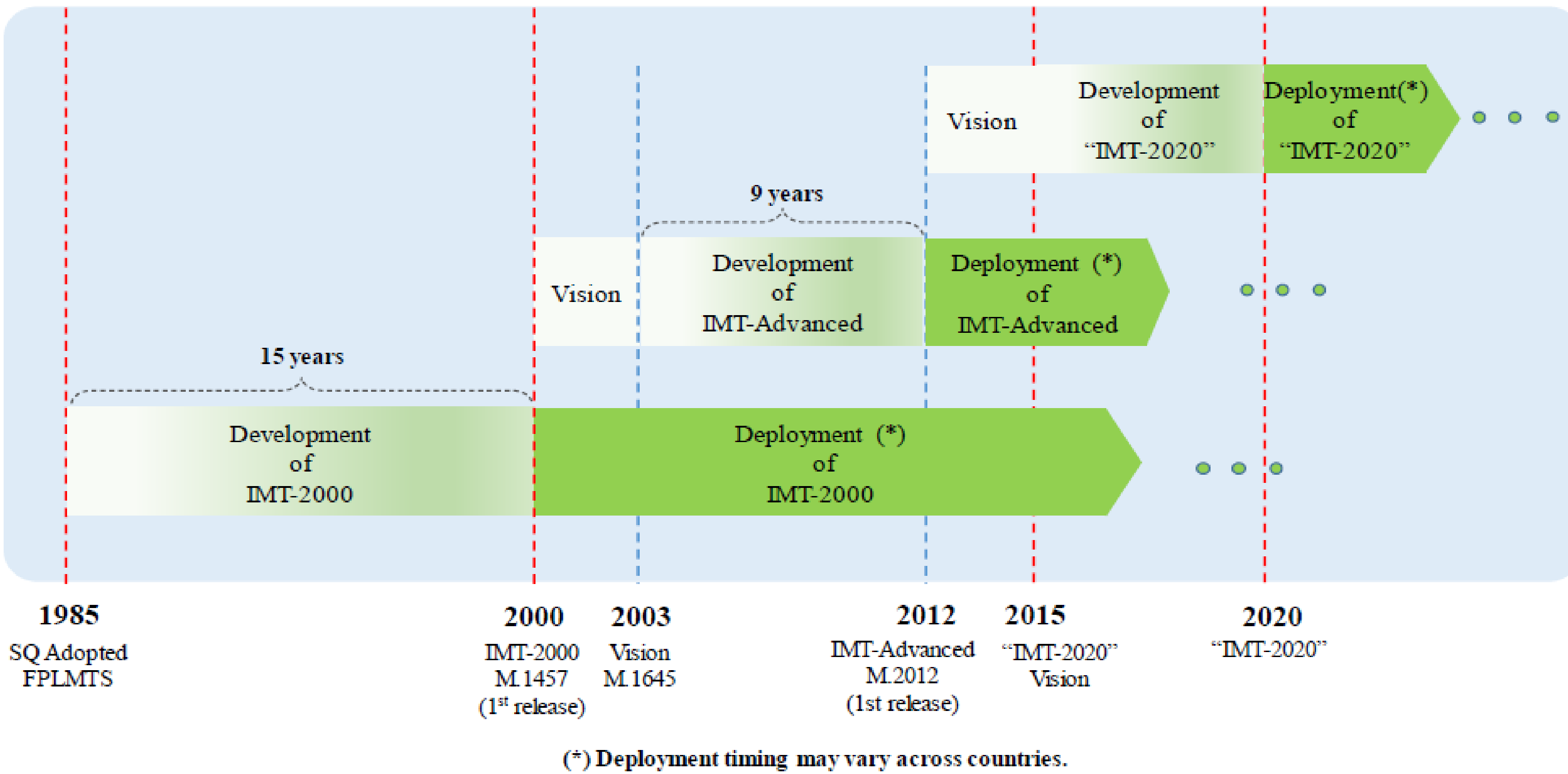
- The 3rd generation partnership project (3GPP) is an umbrella term for a number of standards organizations which develop protocols for mobile telecommunications.
  - GSM and related 2G and 2.5G standards, including GPRS and EDGE
  - UMTS and related 3G standards, including HSPA and HSPA+
  - LTE and related 4G standards, including LTE Advanced and LTE Advanced Pro
  - 5G NR and related 5G standards
- 3GPP is a partnership project formed by the standards bodies ETSI, ARIB, TTC, TTA, CCSA, and ATIS.
- The project was established in December 1998 with the goal of developing a specification for a 3G mobile phone system based on the 2G GSM system.

- Project architecture:



TSG: technical specification group

- IMT development:

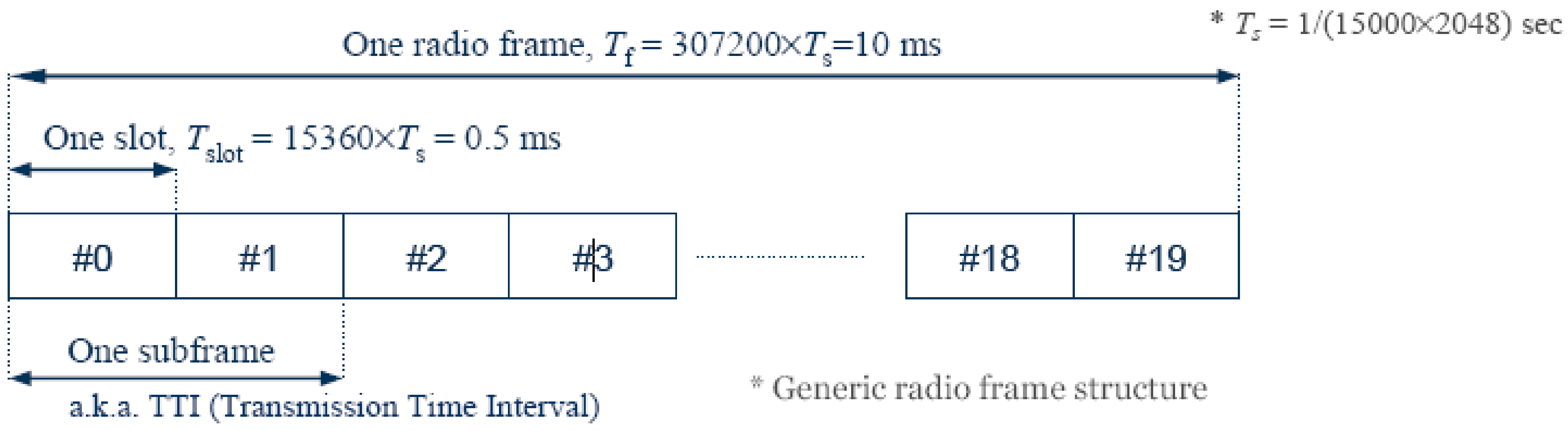


IMT-2000: 3G
IMT-Advanced: 4G
IMT-2020: 5G
issued by the ITU Radio communication Sector (ITU-R)
of the International Telecommunication Union (ITU)

IMT: International Mobile Telecommunications

- Key features of LTE:
  - Multiple access scheme
    - Downlink: orthogonal frequency division multiple access (OFDMA)
    - Uplink: single carrier FDMA (SC-FDMA)
  - Adaptive modulation and coding
    - DL modulations: QPSK, 16QAM, and 64QAM
    - UL modulations: QPSK and 16QAM
  - Bandwidth scalability for efficient operation in differently sized allocated spectrum bands
  - Multiple antenna (MIMO) technology for enhanced data rate and performance
  - Support for both FDD and TDD
  - Channel dependent scheduling & link adaptation for enhanced performance

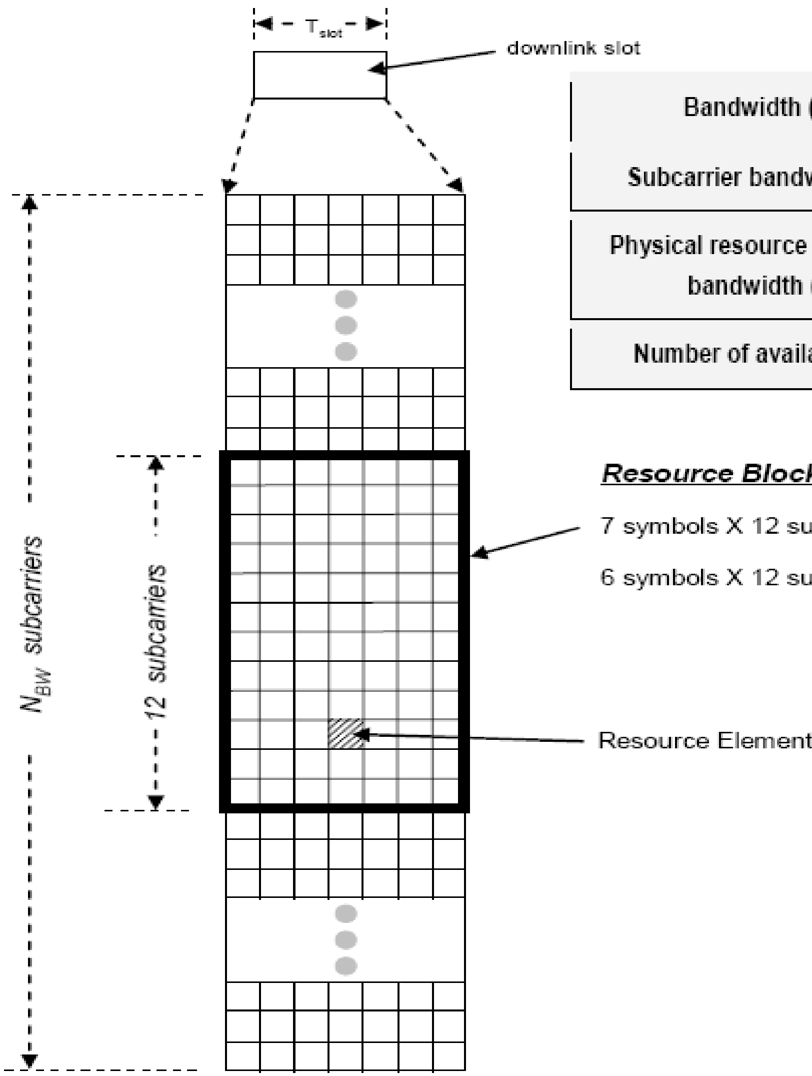
- Frame structure:



  – LTE frames are 10 ms in duration.
  – They are divided into 10 subframes, each subframe being 1.0 ms long.
  – Each subframe is further divided into two slots, each of 0.5 ms duration.
  – Slots consist of either 6 or 7 OFDM symbols, depending on whether the normal or extended cyclic prefix is employed.

- # Frame structure:

Available Downlink Bandwidth is Divided into Physical Resource Blocks (RBs)

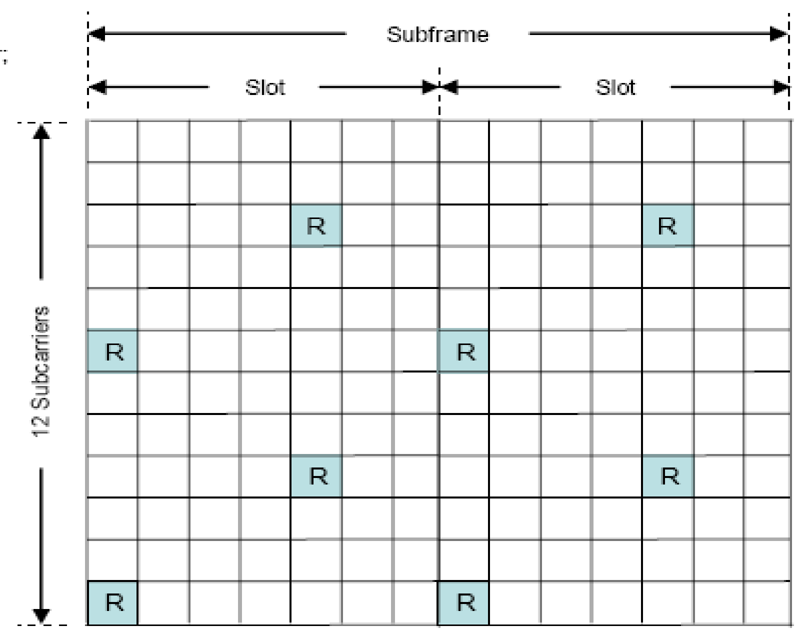


Bandwidth (MHz)	1.25	2.5	5.0	10.0	15.0	20.0
Subcarrier bandwidth (kHz)	15					
Physical resource block (PRB) bandwidth (kHz)	180					
Number of available PRBs	6	12	25	50	75	100

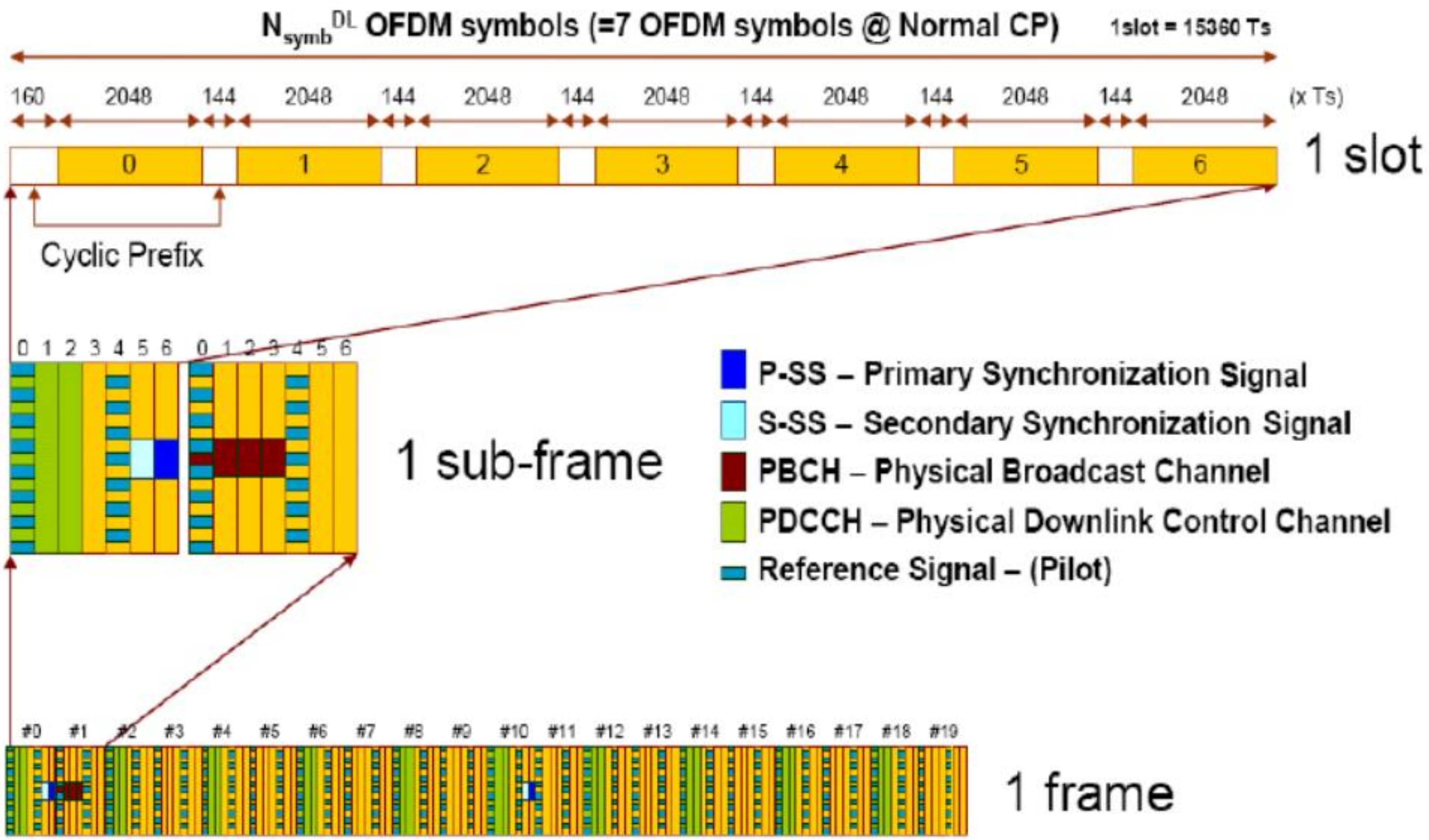
Resource Block:

7 symbols X 12 subcarriers (short CP), or;

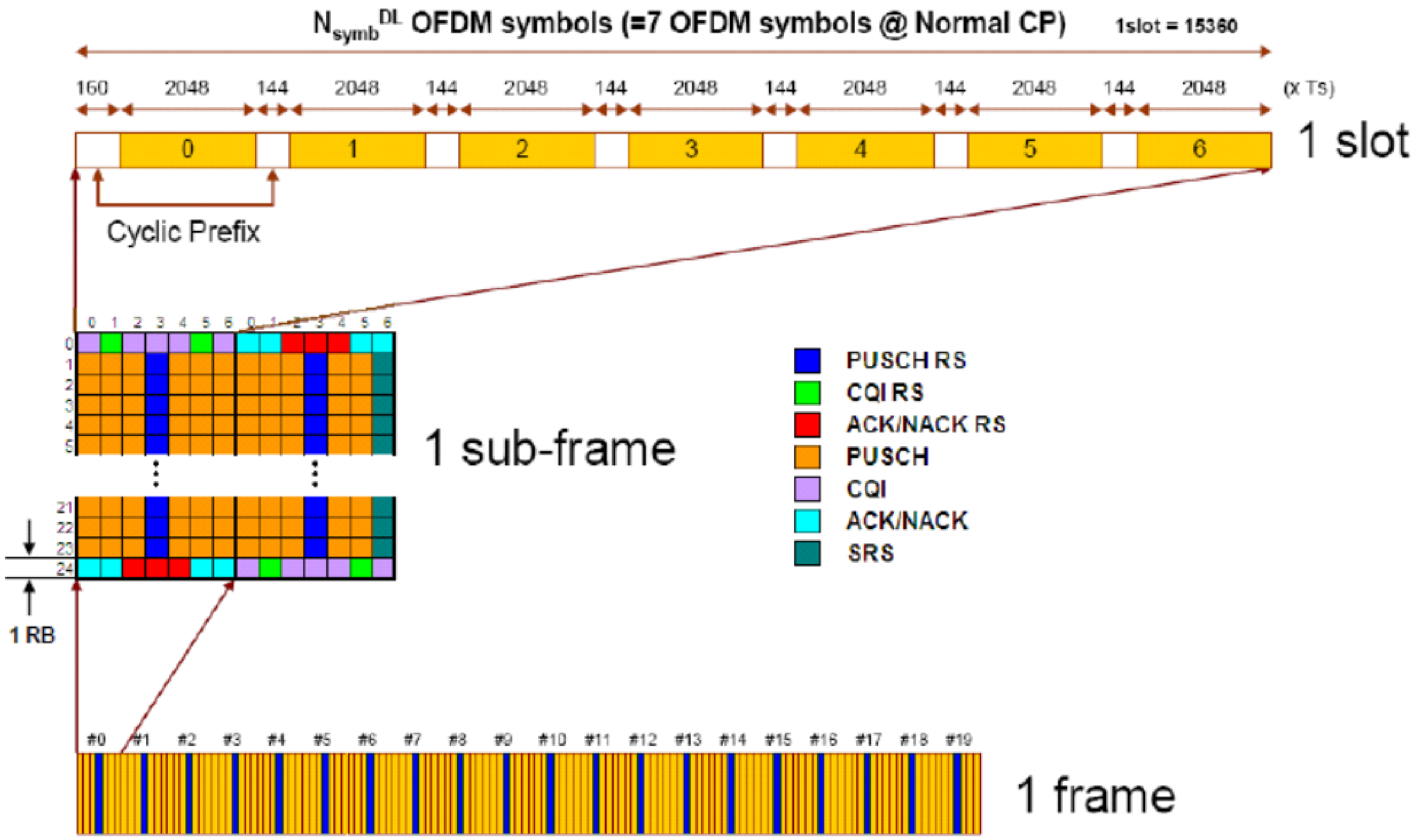
6 symbols X 12 subcarriers (long CP)



- DL frame structure:



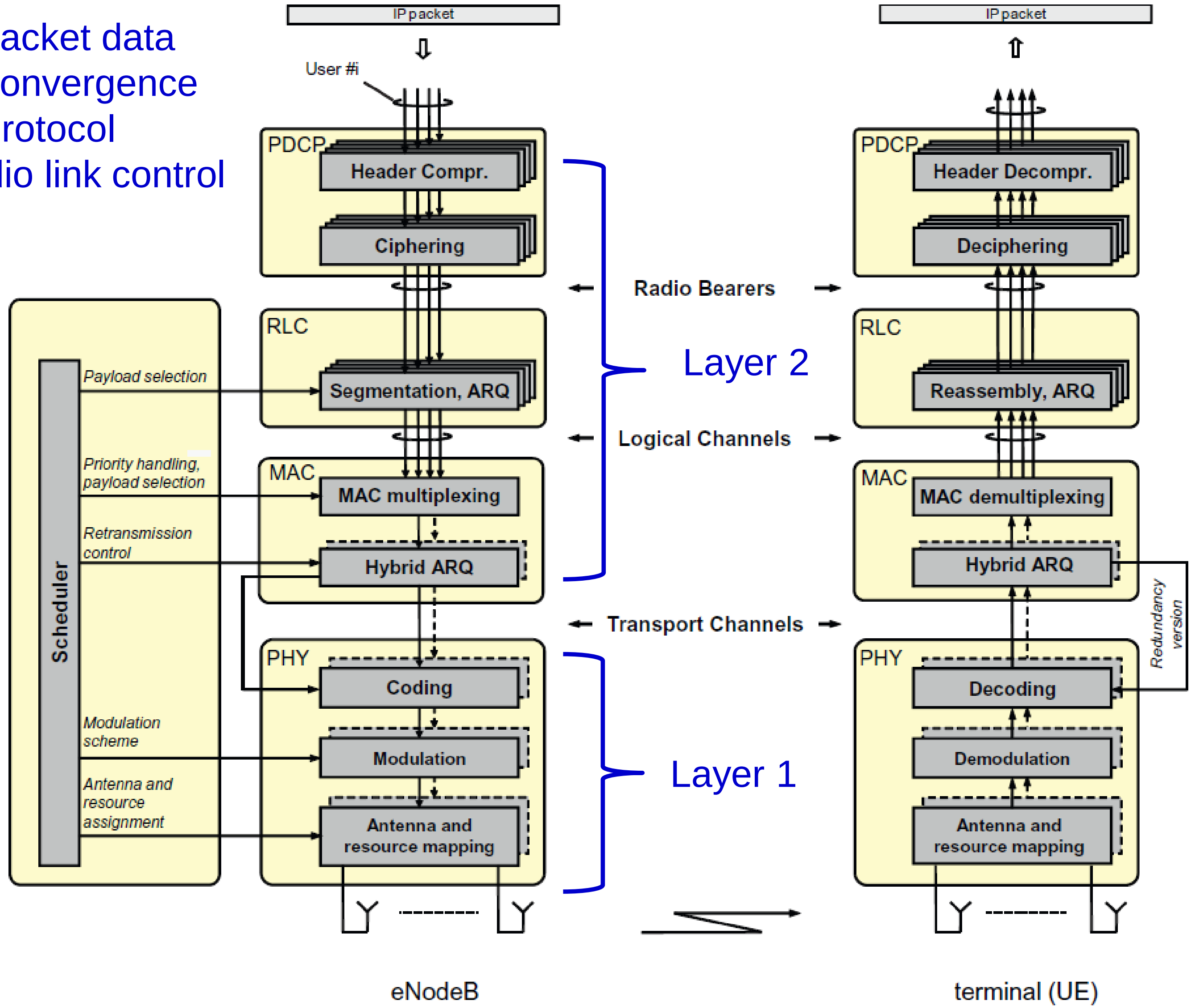
- UL frame structure:



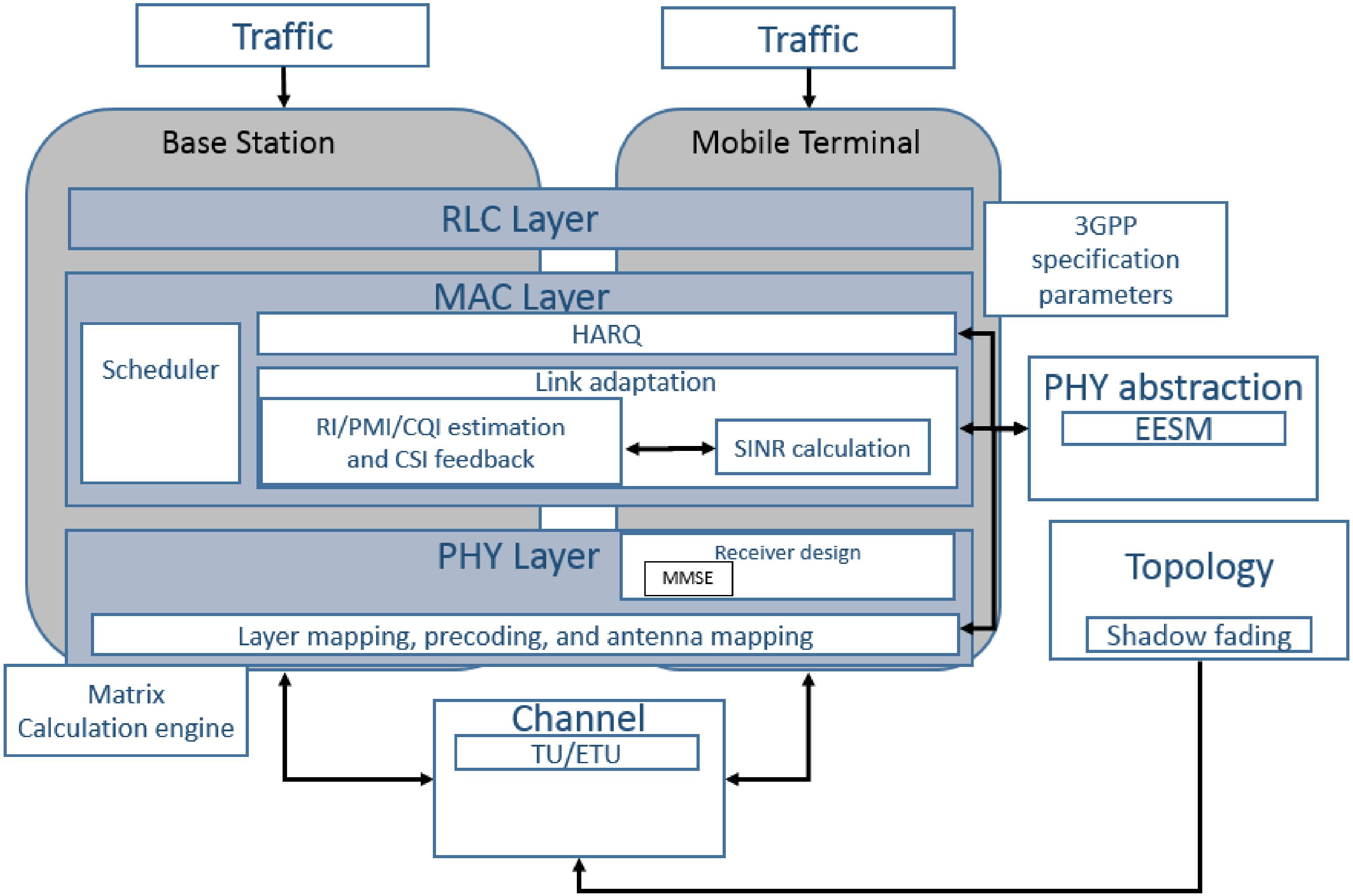
- LTE protocol architecture (DL):

From upper layer: service data unit (SDU)
To lower layer: protocol data unit (PDU)

PDCP: packet data convergence protocol
RLC: radio link control

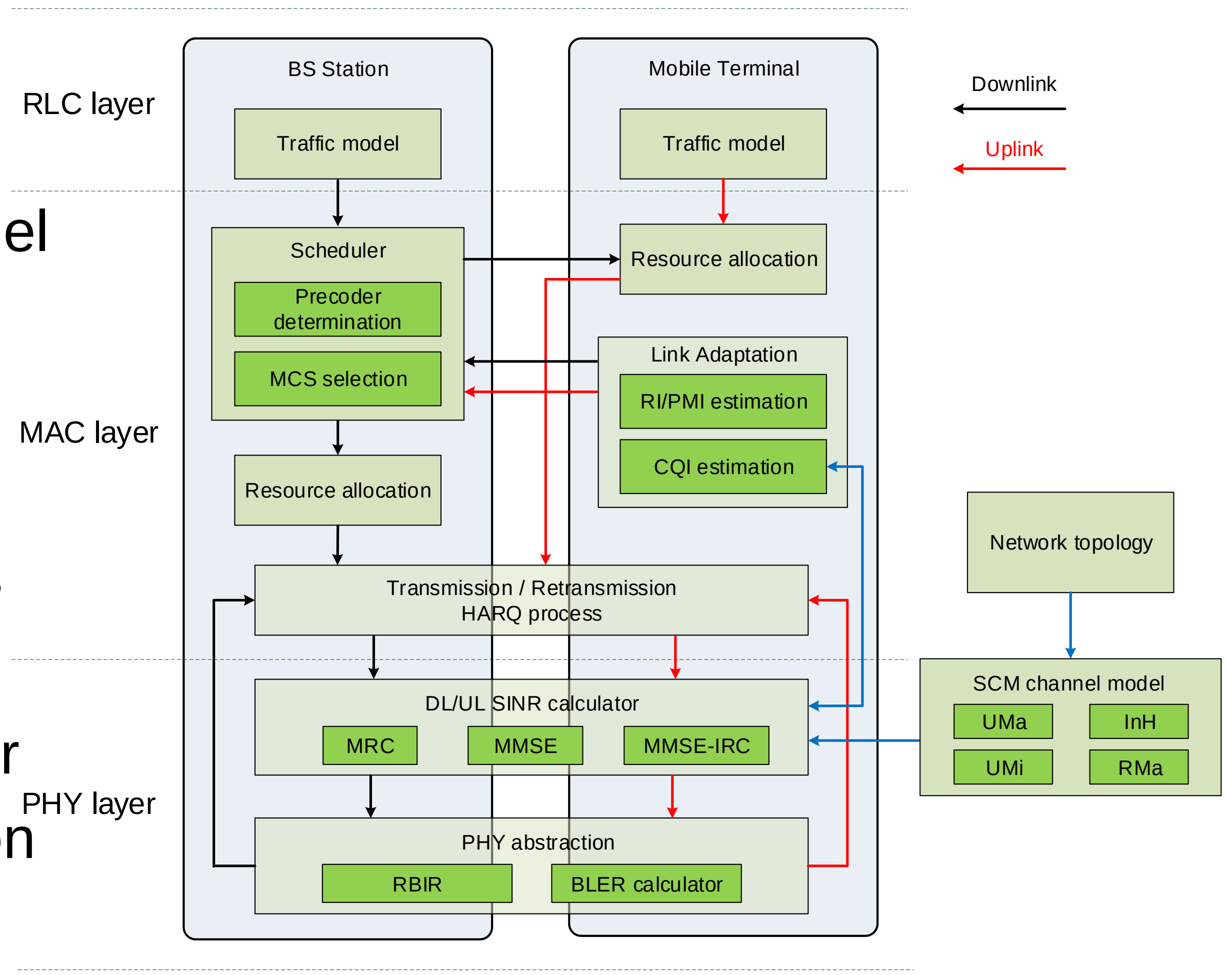


- WiSE SLS architecture:



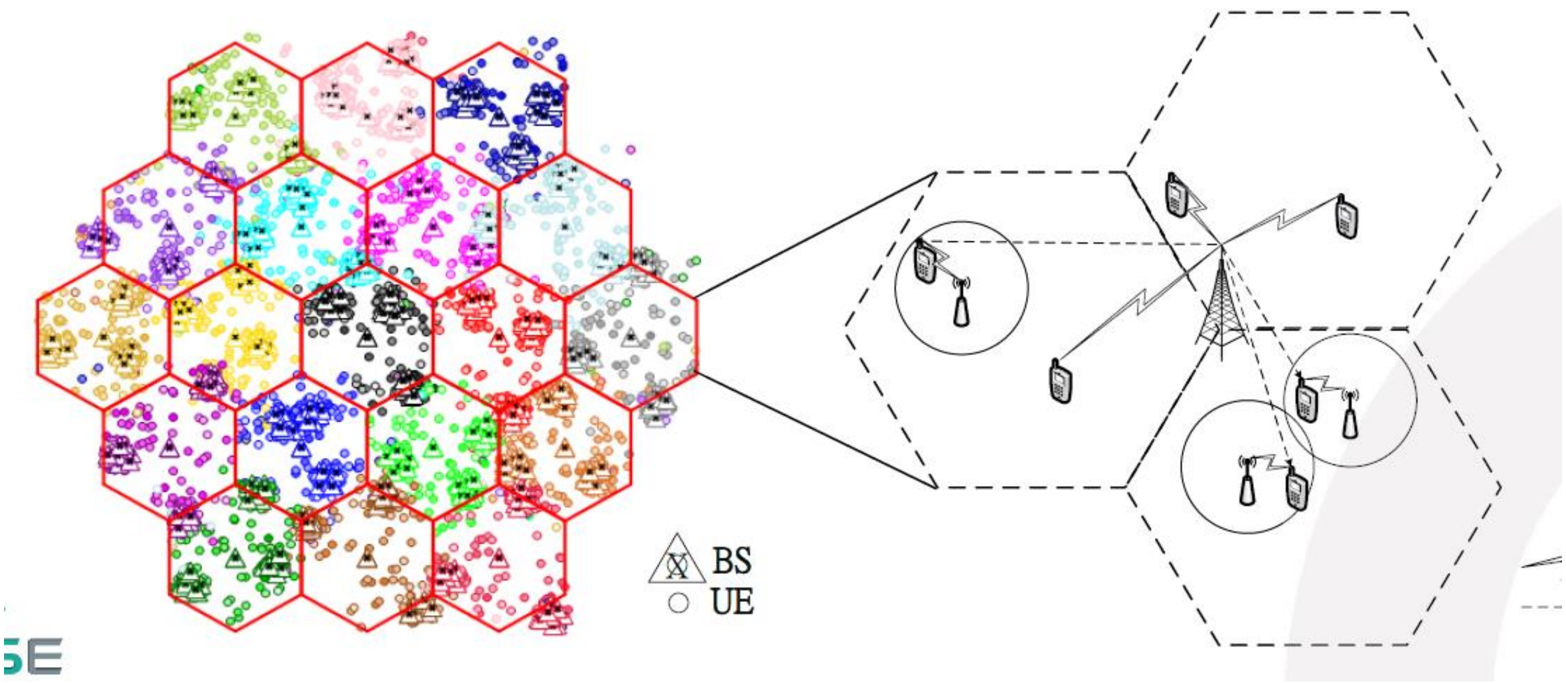
WiSE functional blocks:

- RLC layer
  - Traffic model
  - FTP model
  - Full buffer model
  - VoIP model
- MAC layer
  - Scheduler
  - HARQ process
- PHY layer
  - SINR calculator
  - PHY abstraction



IRC: interference rejection combing

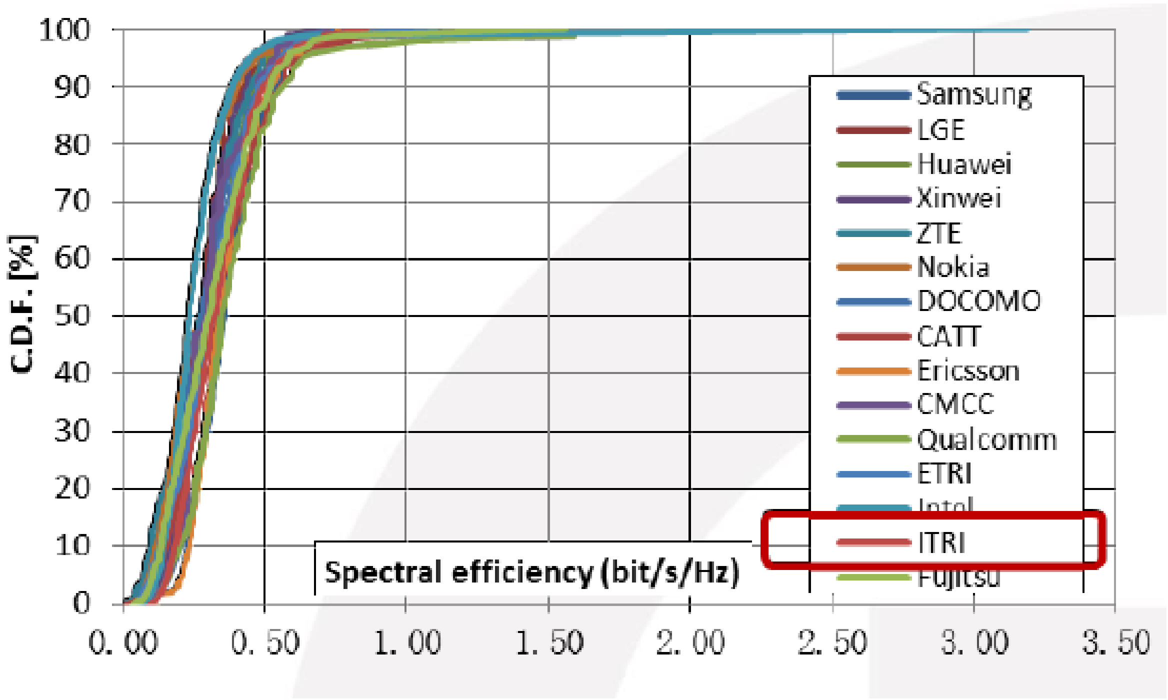
- System level simulator (SLS) is designed to simulate the communication performance between a large number of BSs and UEs (cellular systems).
- Traffic models, scheduling algorithms, CSI feedbacks and interference managements etc. are all considered in SLS.



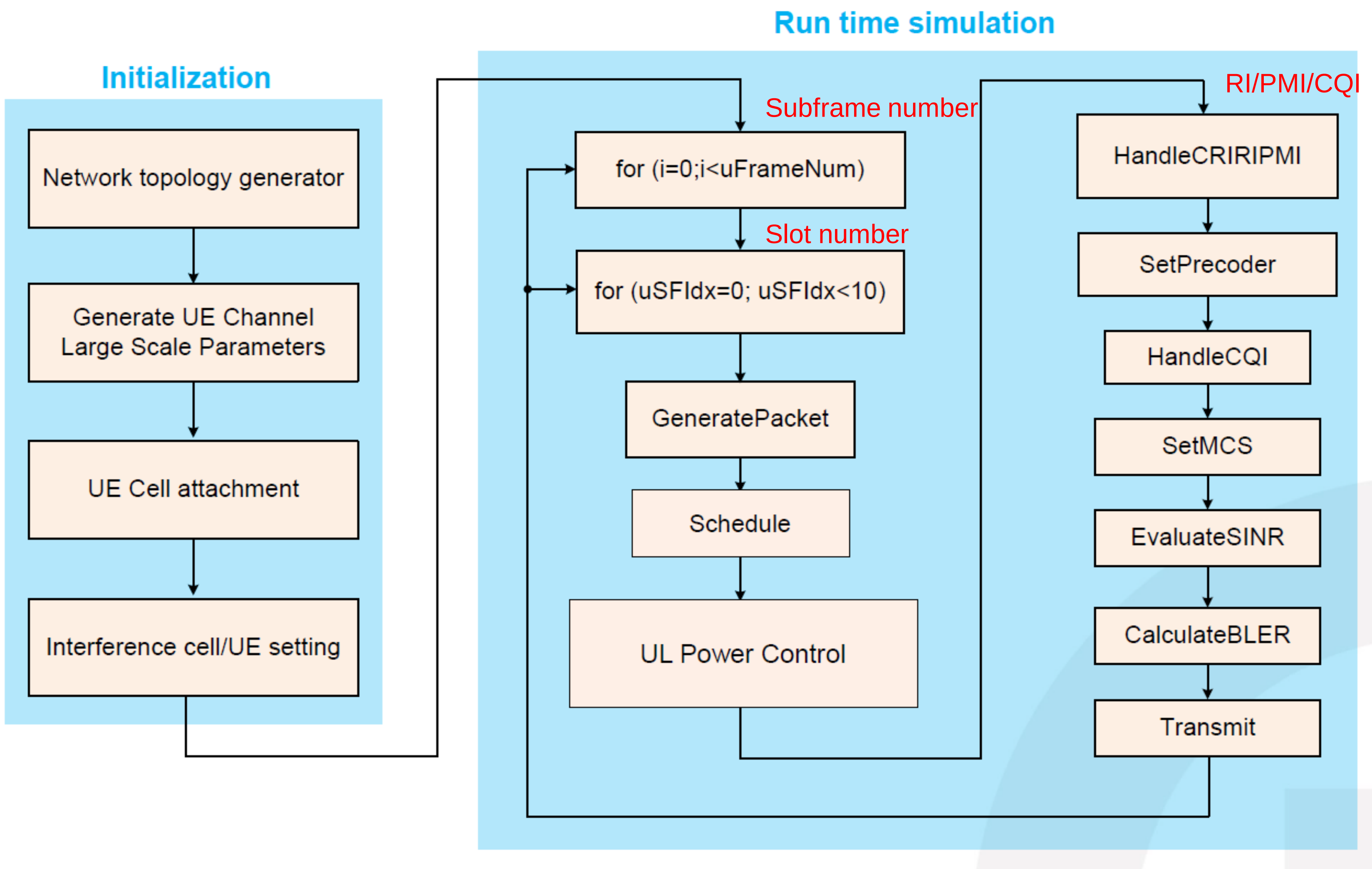
Performance metrics:

- System throughput
  - Average data rate
  - Cell average packet throughput
  - UE average packet throughput
- Spectrum efficiency
  - Cell spectrum efficiency
  - Cell edge user spectrum efficiency
- Avg. packet retransmission number
- Packet drop rate
- Packet transmission latency
- Fairness metric

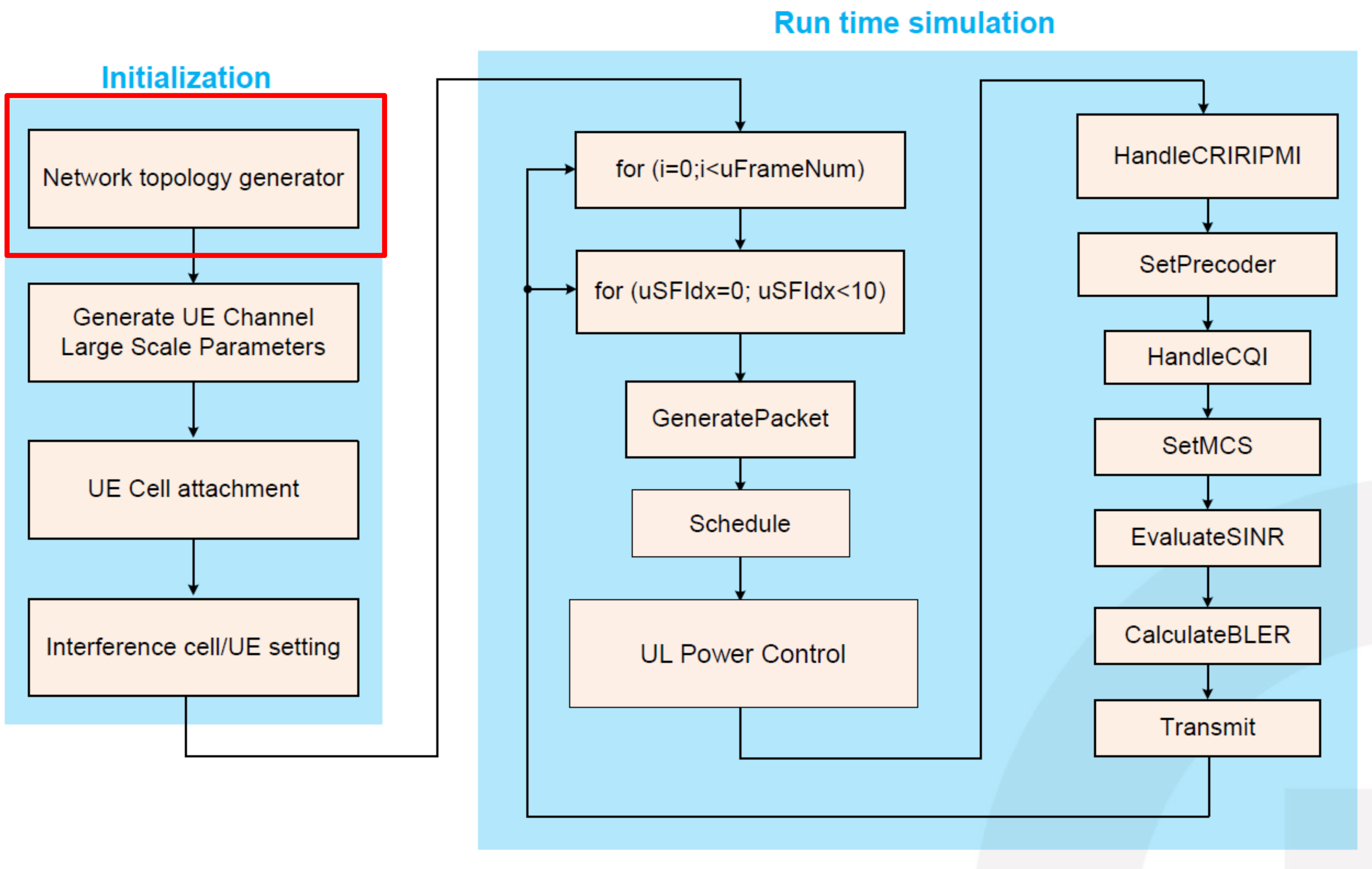
- Those metrics can be used to
  - evaluate system performance,
  - conduct calibrations, and
  - check if systems satisfy specification requirements.



- WiSE program flow:



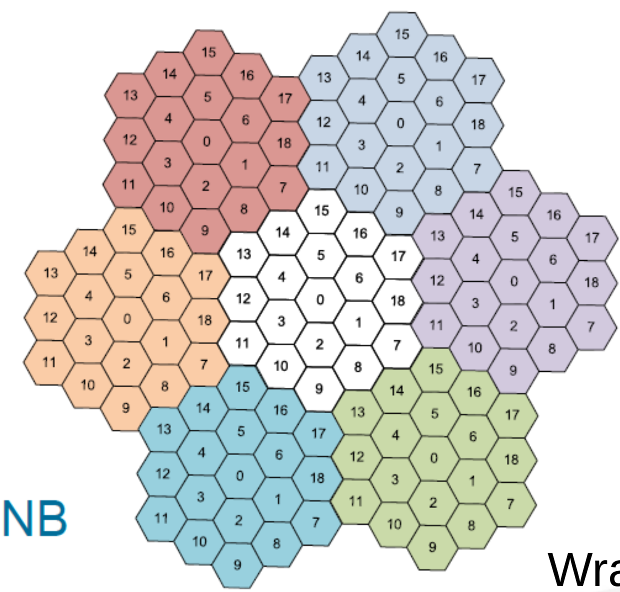
- WiSE program flow:



Network topology generator

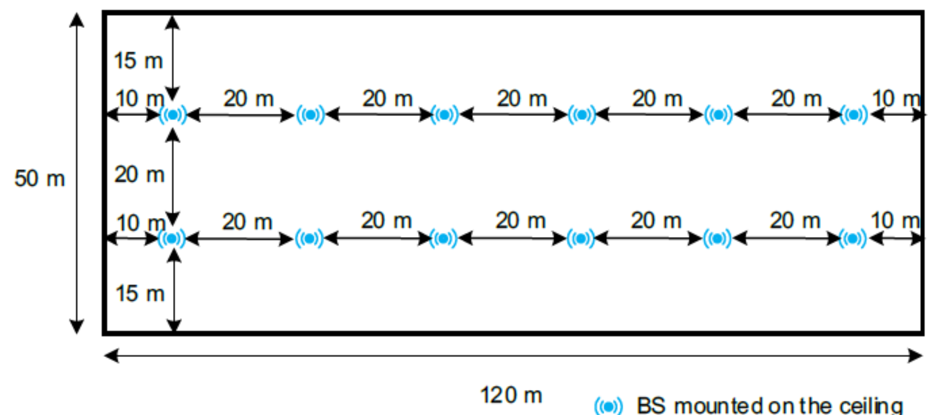
InH: indoor hotspot
UMa: urban macro
UMi: urban micro

- 3GPP setting:
  - InH: 12 gNB
  - UMa: 19 gNB, ISD:200m or 500m
  - RMa: 19 gNB, ISD:1732m or 6000m
- User setting:
  - Users can flexibly adjust the position of gNB

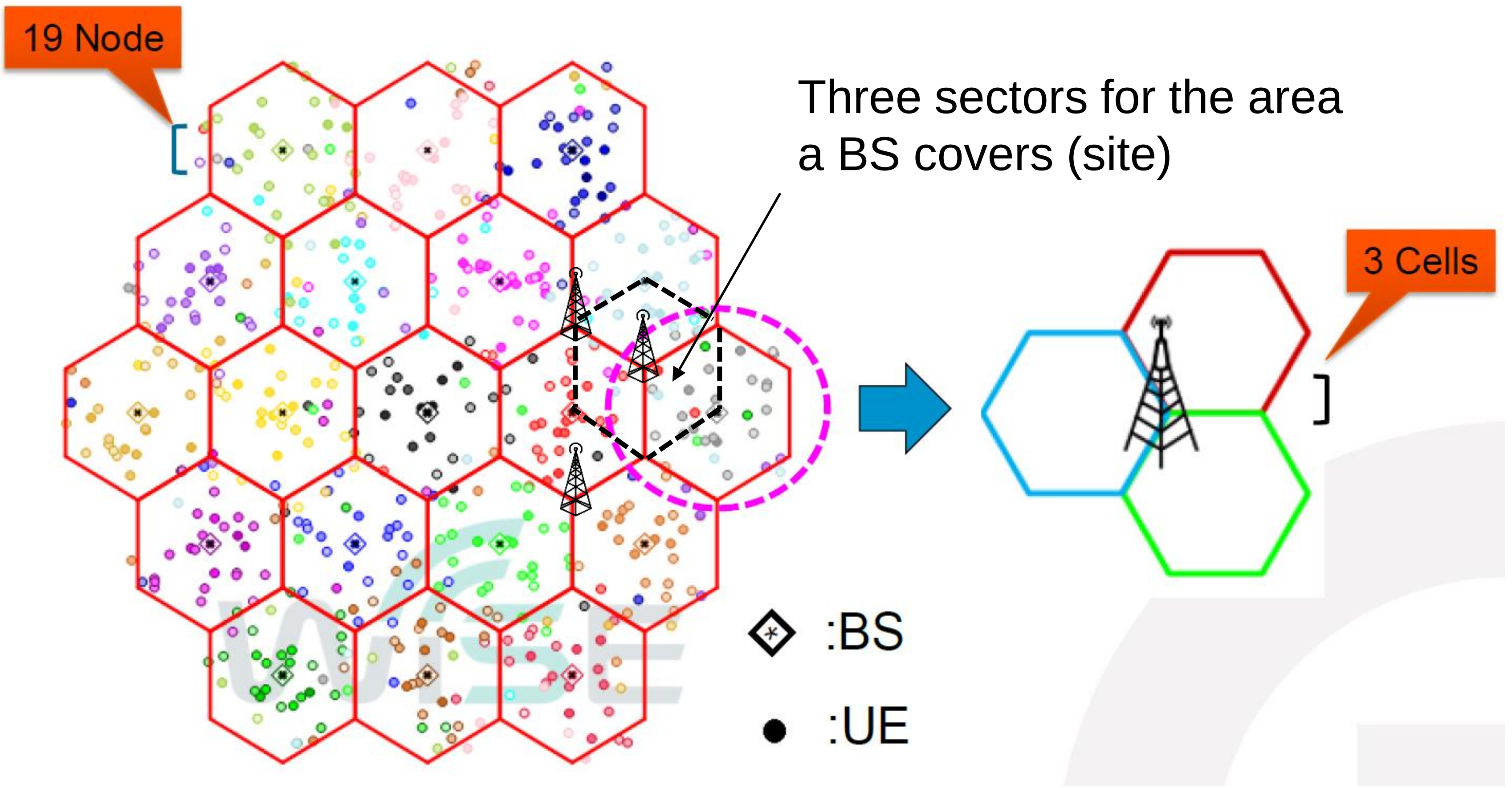


gNB

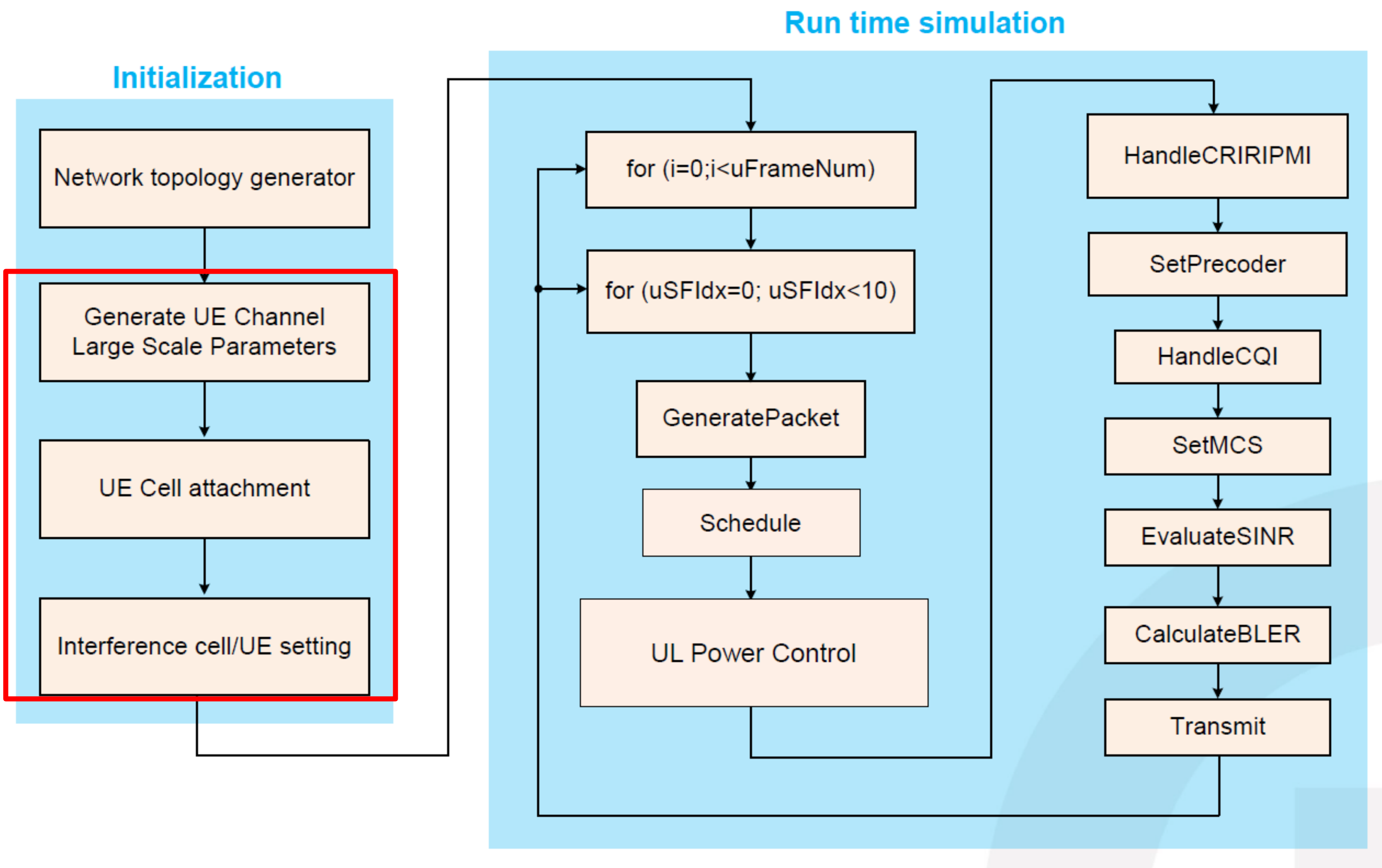
Wrapped around



- A common cellar topology:



- WiSE program flow:



- WiSE channel model:
  - InH Model A , Model B
  - UMa Model A , Model B
  - UMi Model A , Model B
  - RMa Model A , MoelB
- Channel model selection:
  - TR 38.802 Table A.2.1-11

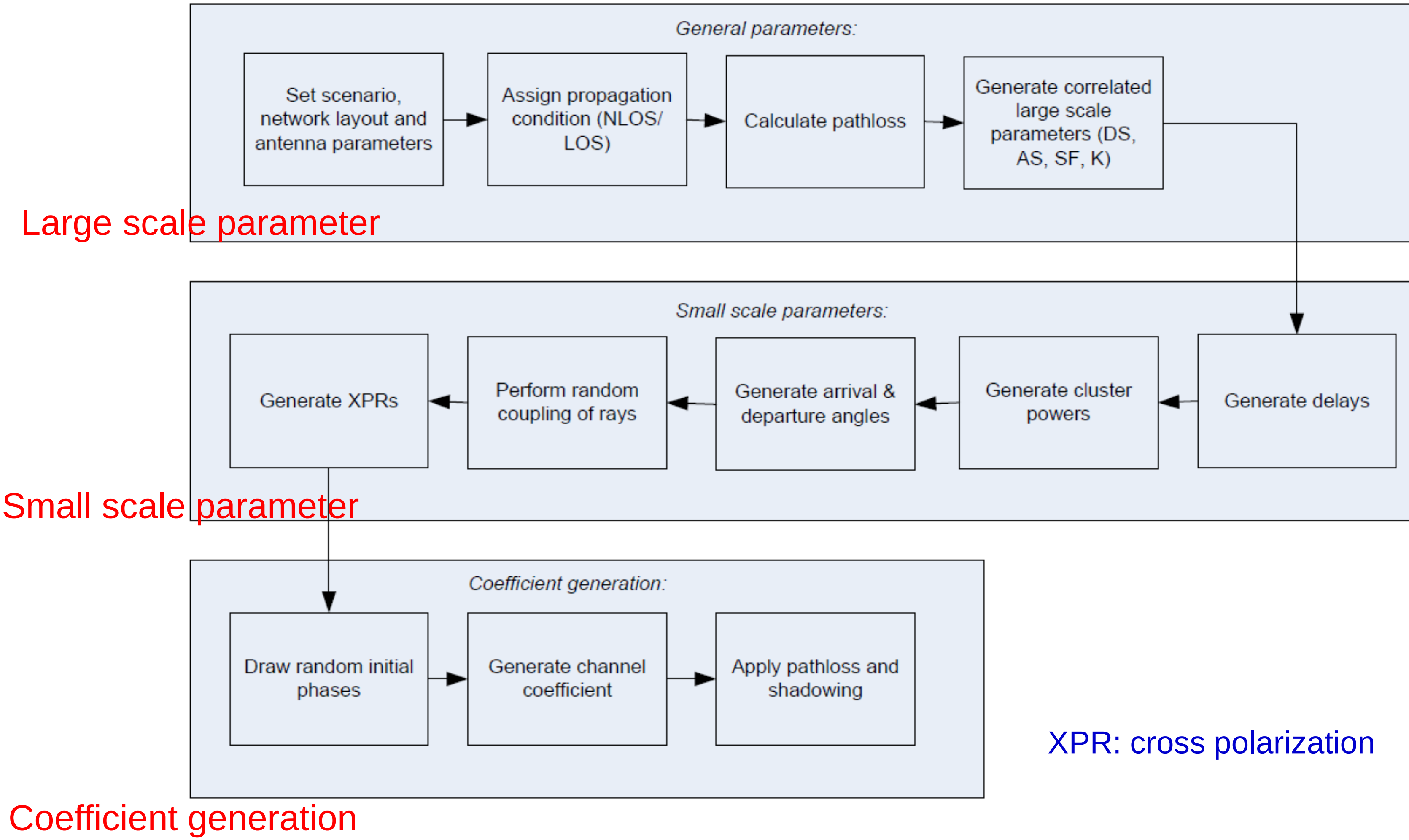
InH: indoor hotspot
UMa: urban macro
UMi: urban micro

Model A	**0.5GHz<f<6GHz**
	6GHz<f<100GHz
Model B	**0.5GHz<f<100GHz**

Parameter	Dense Urban	Urban Macro	Indoor Hotspot
channel parameters	Below 6GHz: - Macro-to-UE: 3D UMa - Micro-to-UE: 3D UMi - Macro-to-Macro: 3D UMa (h_UE=25m) - Macro-to-Micro: 3D UMa (h_UE=10m) - Micro-to-Micro: 3D UMi (h_UE=10m) - UE-to-UE: A.2.1.2 in TR36.843(***), penetration loss between UEs follows Table A.2.1-13 Above 6GHz: - Macro-to-UE: 5GCM UMa - Micro-to-UE: UMi-Street canyon - Macro-to-Macro: 5GCM UMa (h_UE=25m) - Macro-to-Micro: 5GCM UMa (h_UE=10m) - Micro-to-Micro: UMi-Street canyon (h_UE=10m) - UE-to-UE: UMi-Street canyon (h_BS=1.5m ~ 22.5m), penetration loss between UEs follows Table A.2.1-12		Below 6GHz: - TRP-to-UE: ITU InH - TRP-to-TRP: ITU InH (h_UE=3m) - UE-to-UE: A.2.1.2 in TR36.843 Above 6GHz: - TRP-to-UE: 5GCM Indoor-office - TRP-to-TRP: 5GCM Indoor-office (h_UE=3m) - UE-to-UE: 5GCM Indoor-office (h_BS=1.5m)

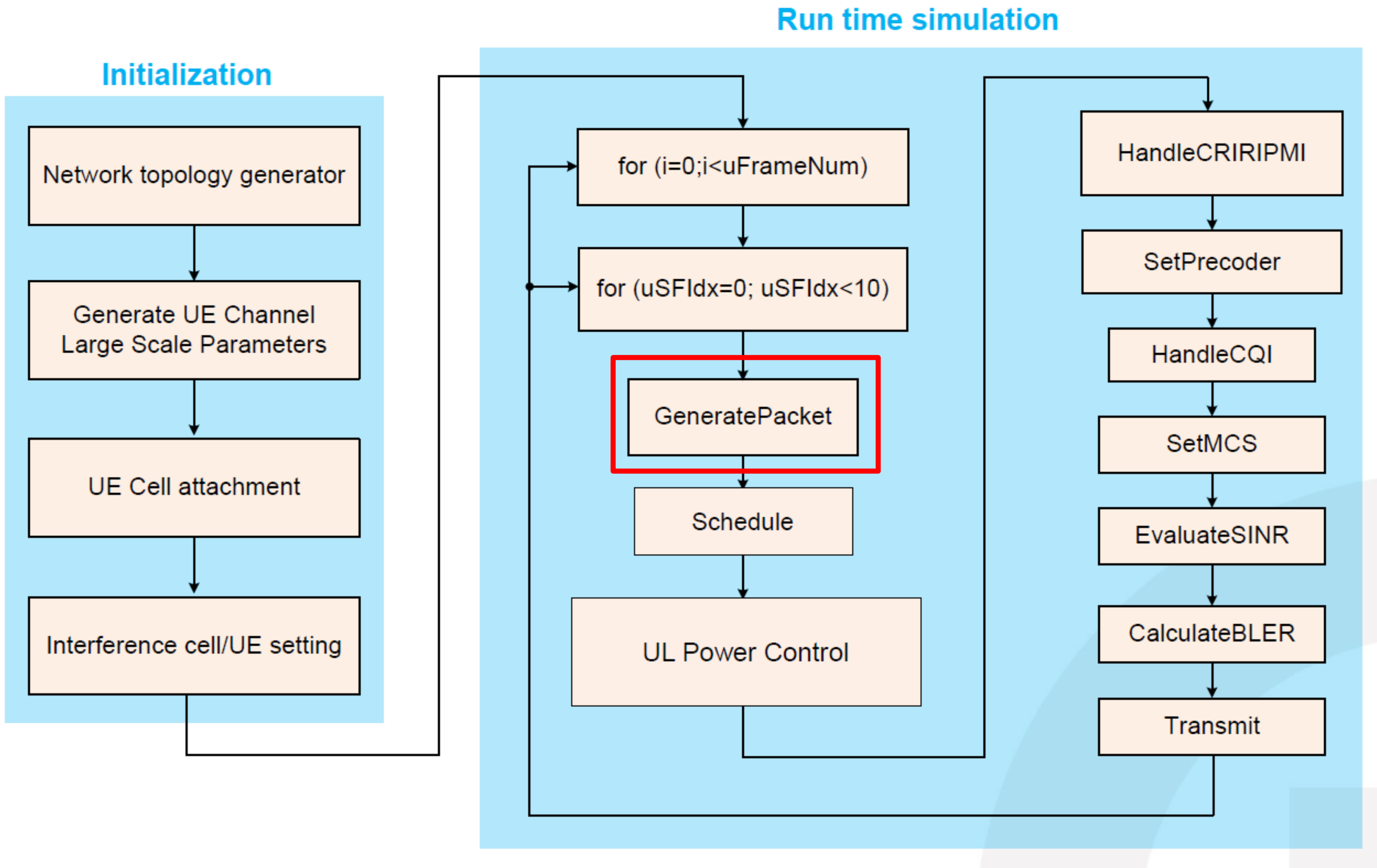
Channel generation

TR 38.901 Figure 7.5-1 Channel coefficient generation procedure

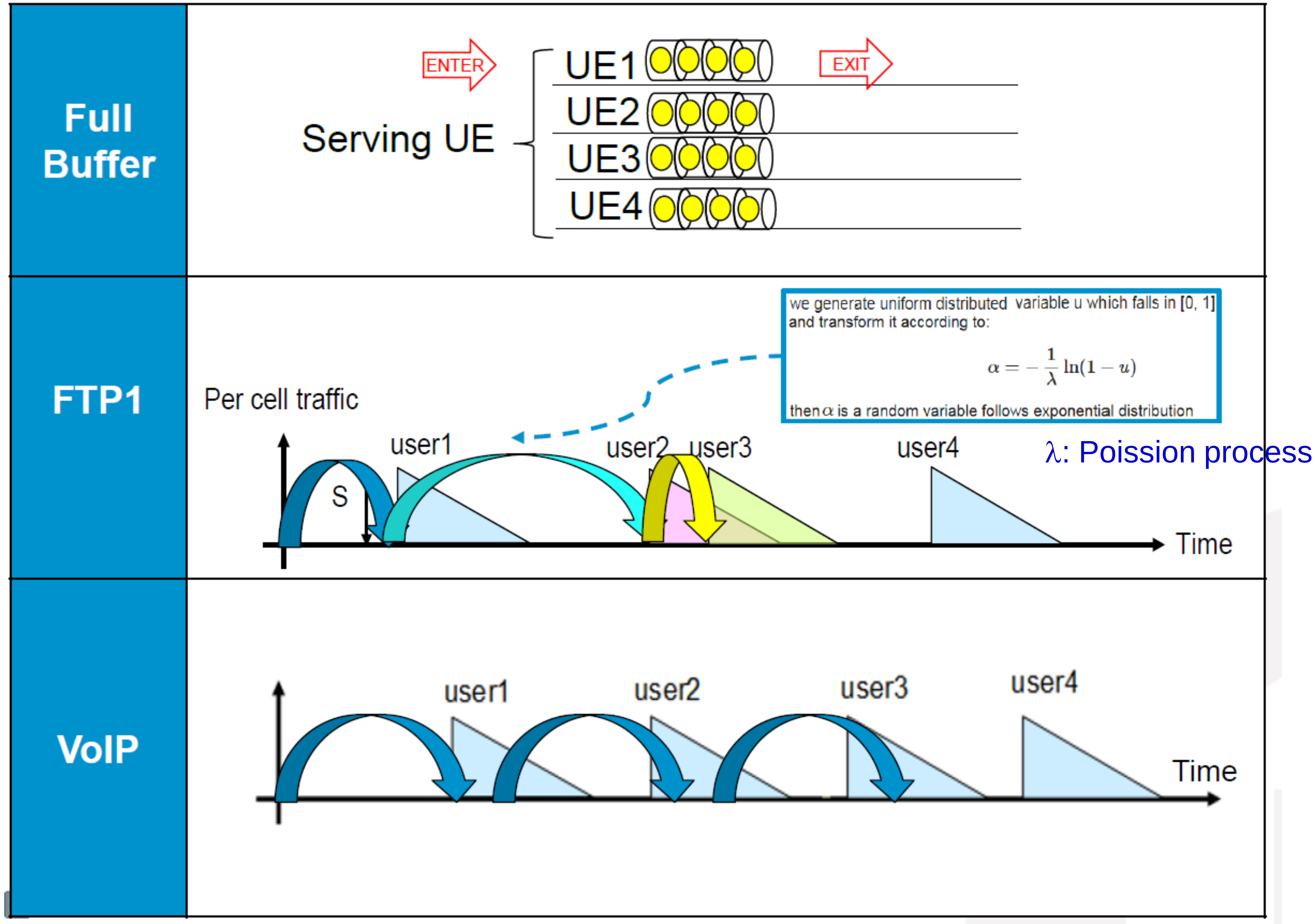


XPR: cross polarization

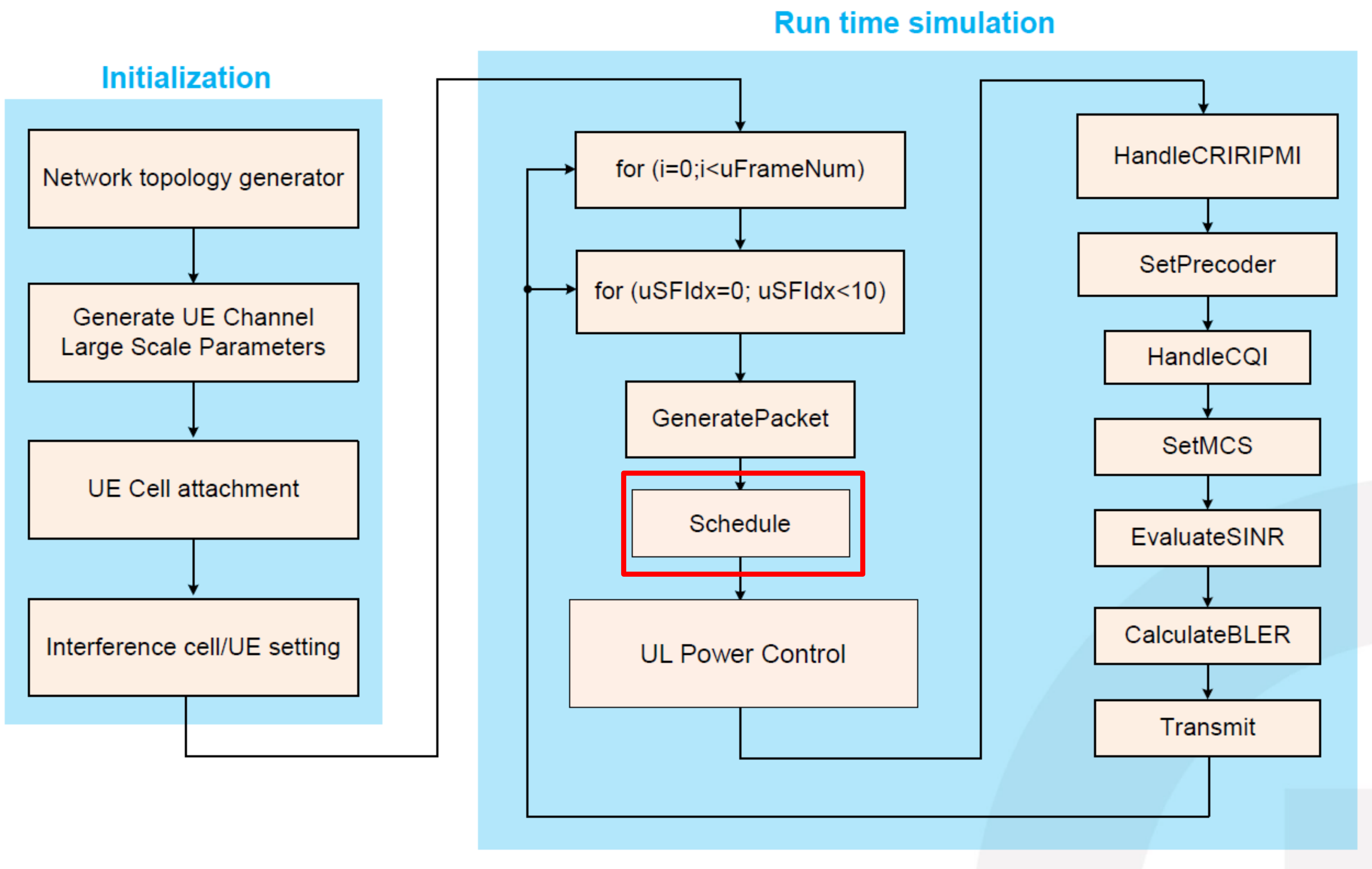
Packet generation



- Traffic model (packet generation):

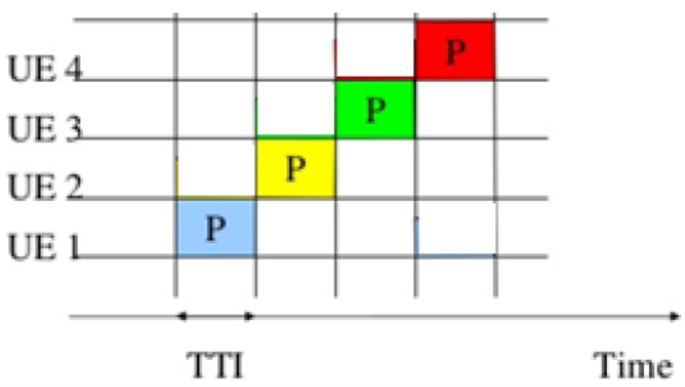


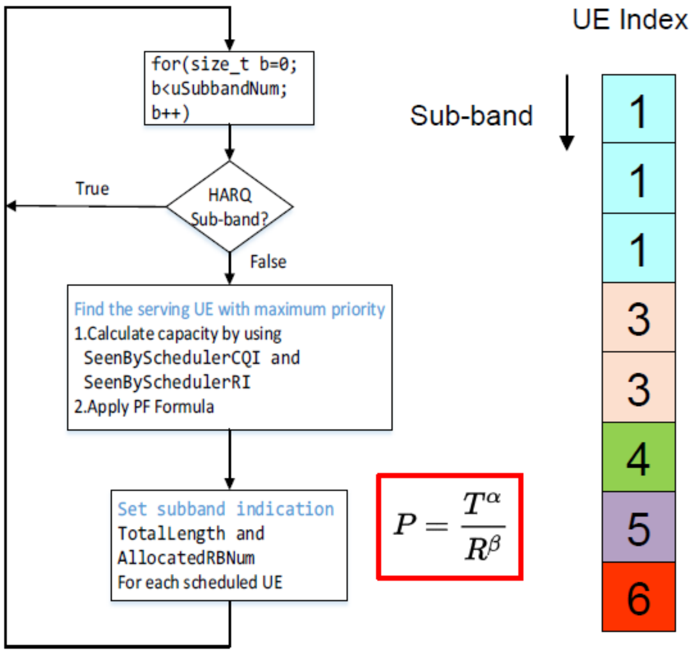
Scheduling


Initialization
Network topology generator
Generate UE Channel Large Scale Parameters
UE Cell attachment
Interference cell/UE setting
Run time simulation
for (i=0;i<uFrameNum)
for (uSFIdx=0; uSFIdx<10)
GeneratePacket
Schedule
UL Power Control
HandleCRIRIPMI
SetPrecoder
HandleCQI
SetMCS
EvaluateSINR
CalculateBLER
Transmit

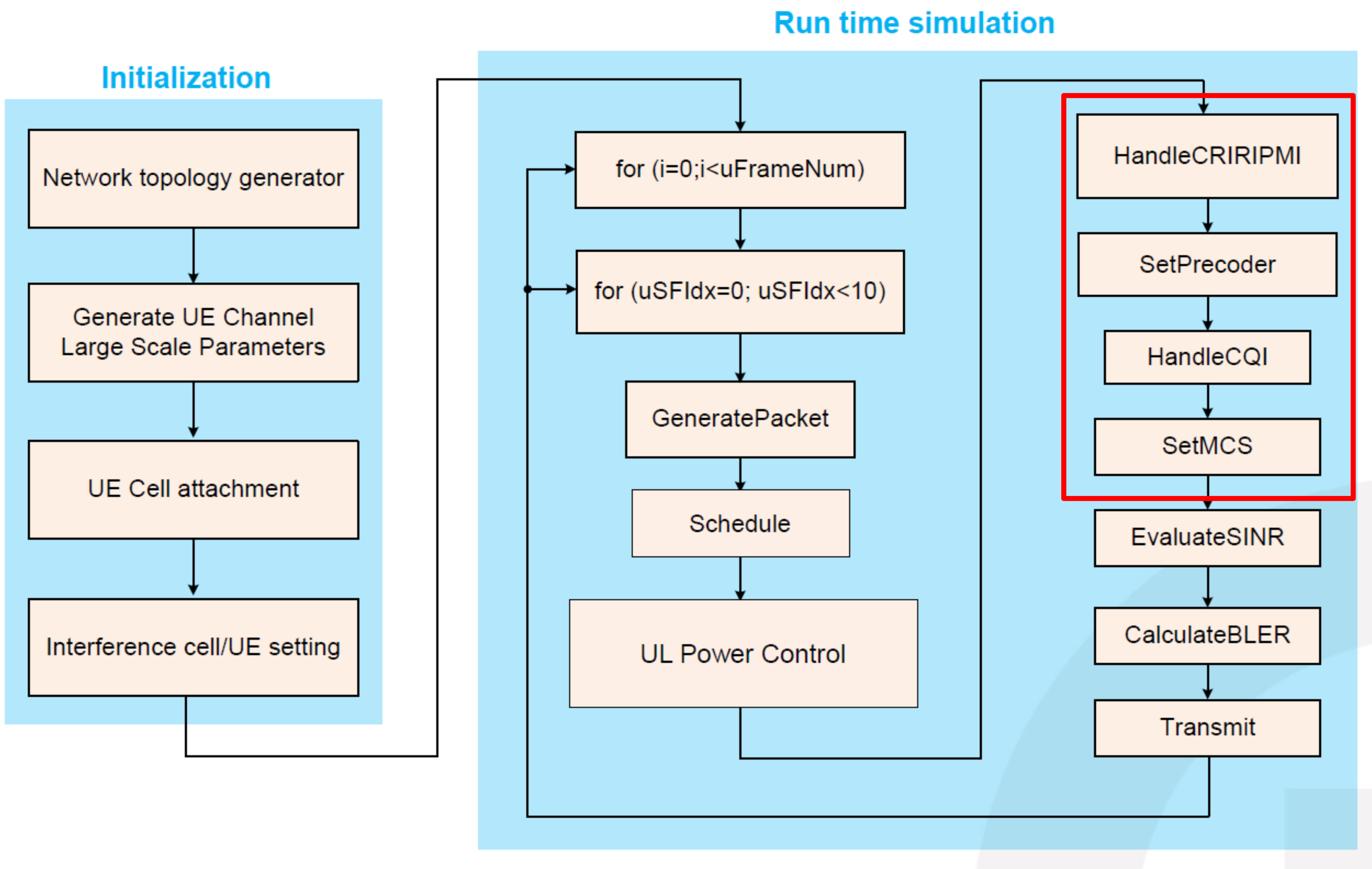
- Scheduler:

Round-Robin	Proportional Fairness

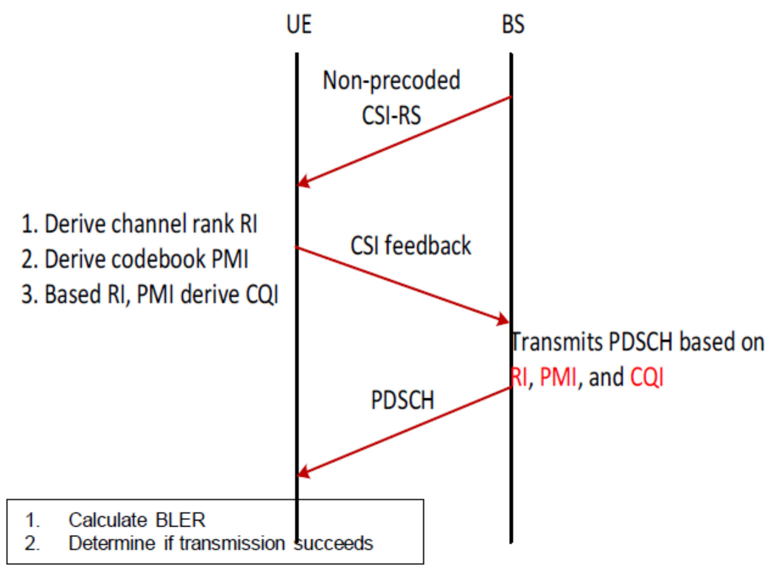
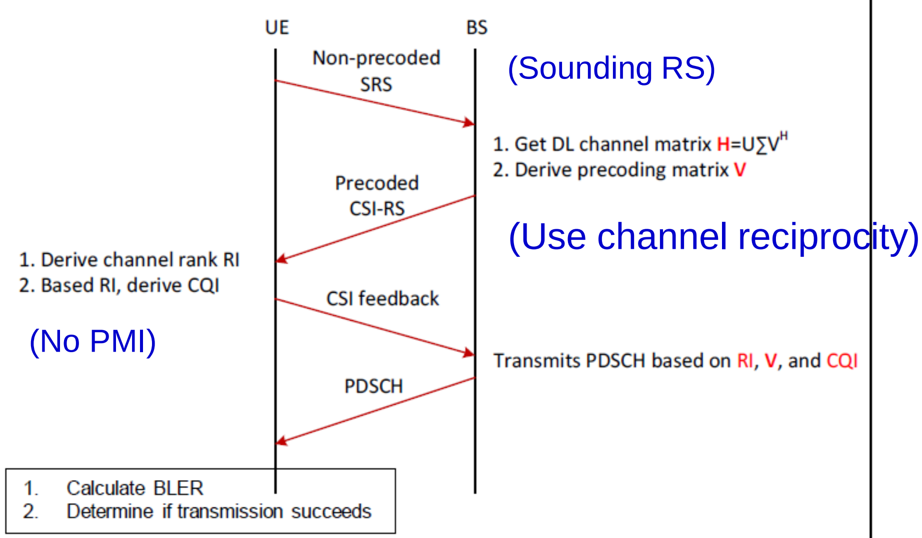




CSI feedback

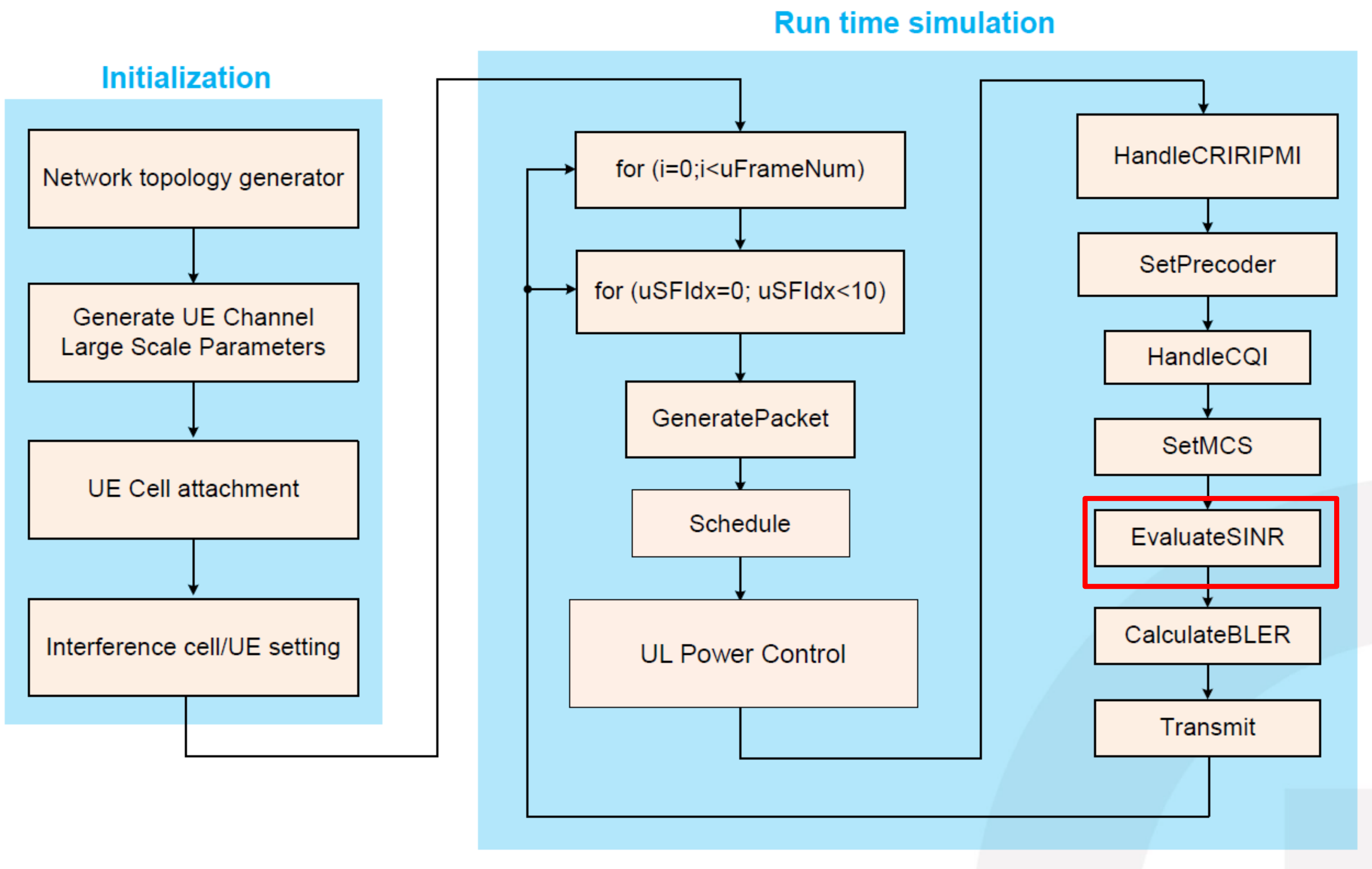


- CSI feedback in FDD and TDD:

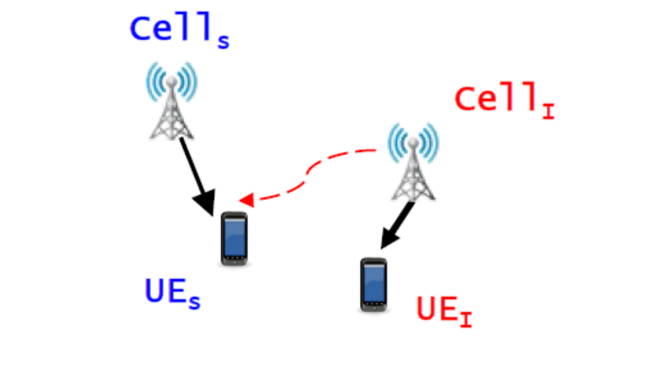
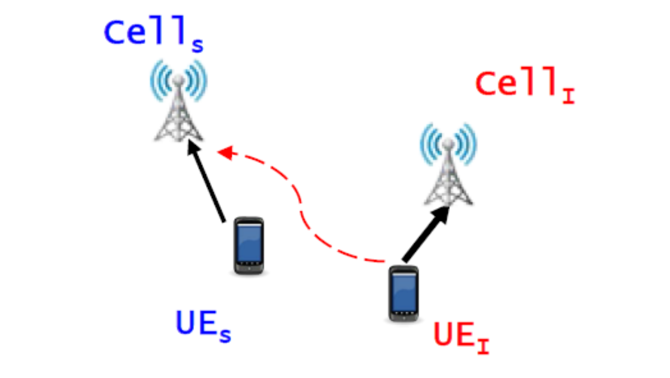
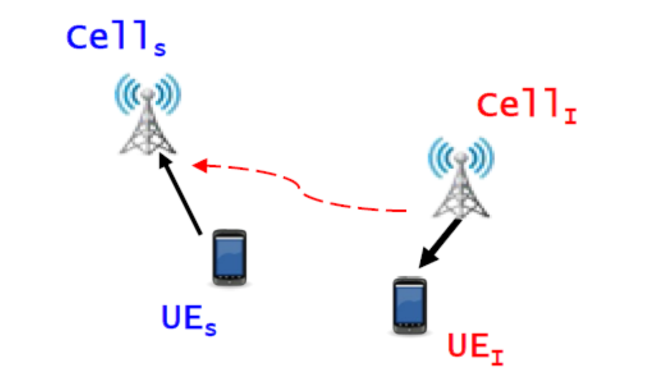
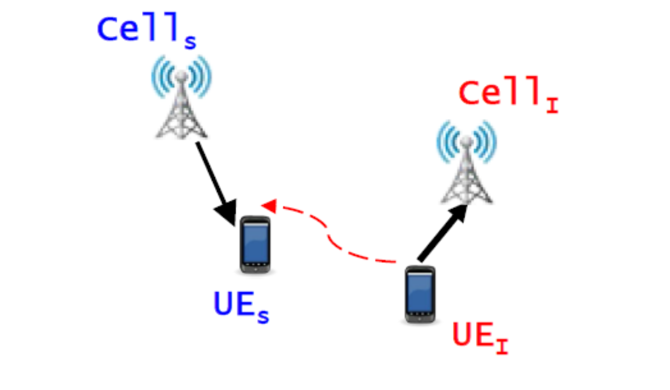
Codebook-based Transmission (FDD)	Non-codebook-based Transmission (TDD)
	

SRS: sounding reference signal

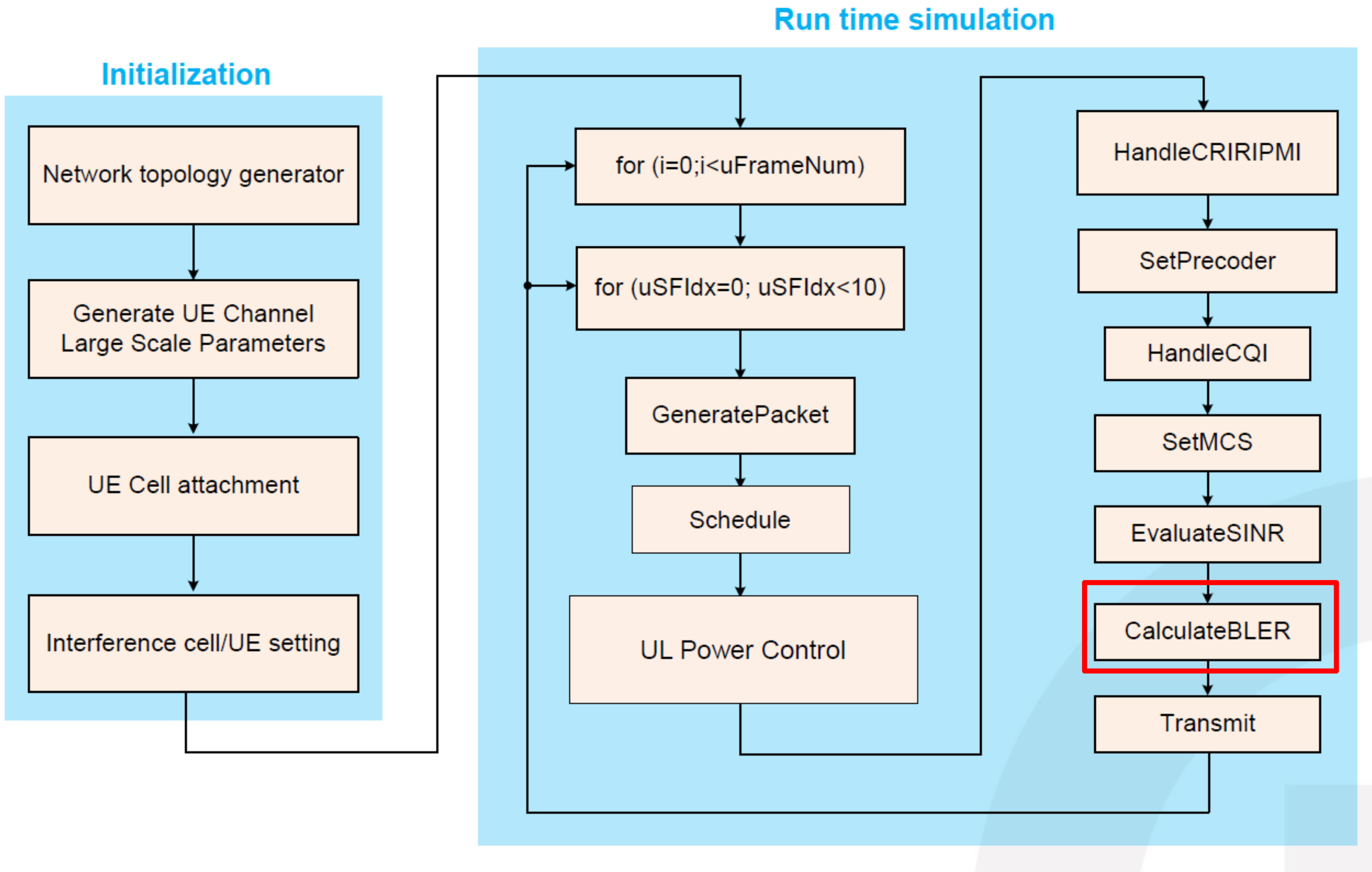
SINR evaluation



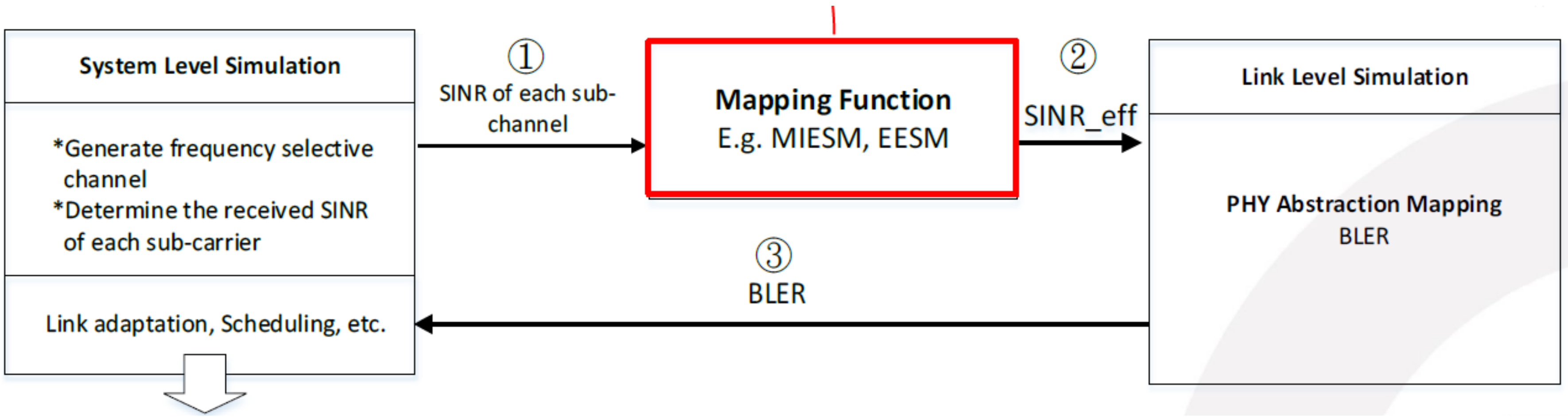
- Interference:

Cell to UE	UE to Cell
	
Cell to Cell	**UE to UE**
	

BLER calculation



- PHY layer abstraction:



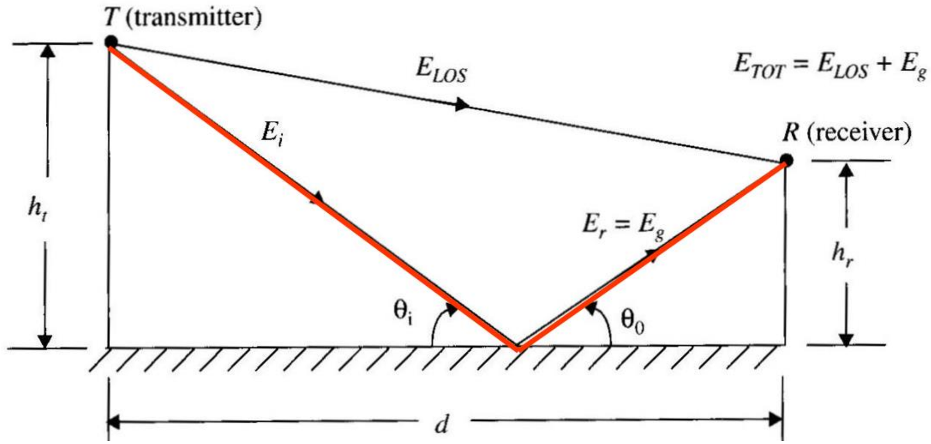
Throughput, Packet error rate, etc.

- Exponential Effective SINR Mapping (EESM)
- Mutual Information Effective SINR Mapping (MIESM)

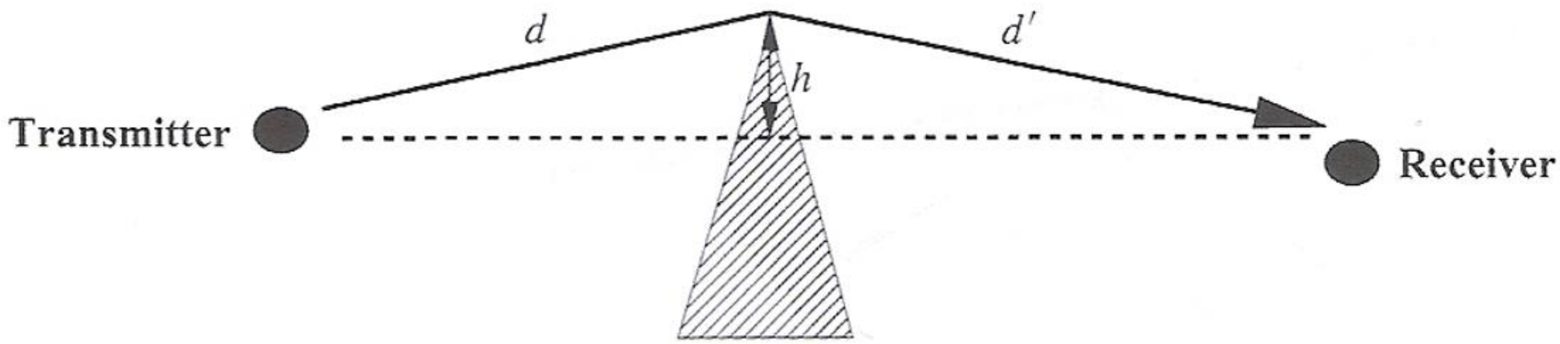
II. Introduction to WiSE
2. 5G SCM channel model

- Channel: ground radio waves generally propagate according to three mechanisms:
  - Reflection
  - Diffraction
  - Scattering
- The transmitted radio signal is not only susceptible to noise and interference (in additive manner), but also distorted by the propagation channel.
- "Fading" is used to describe the variations in received power with time caused by changes of the propagation channel.
  - Large-scale fading
  - Small-scale fading

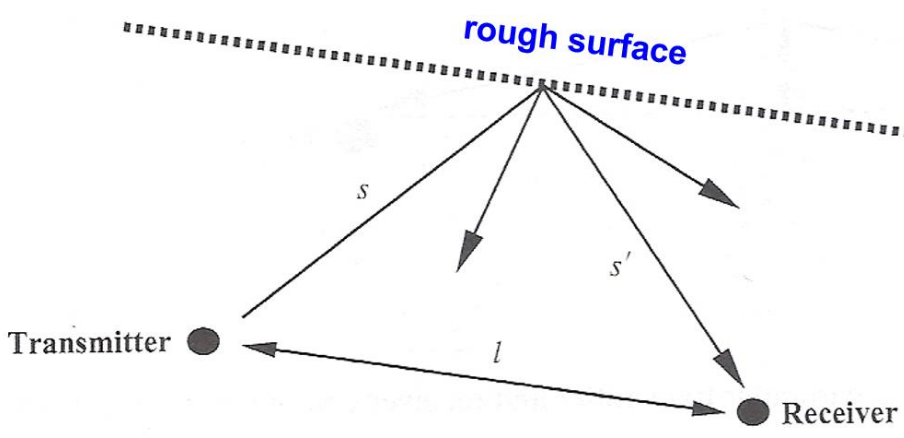
- Reflection:



- Diffraction:

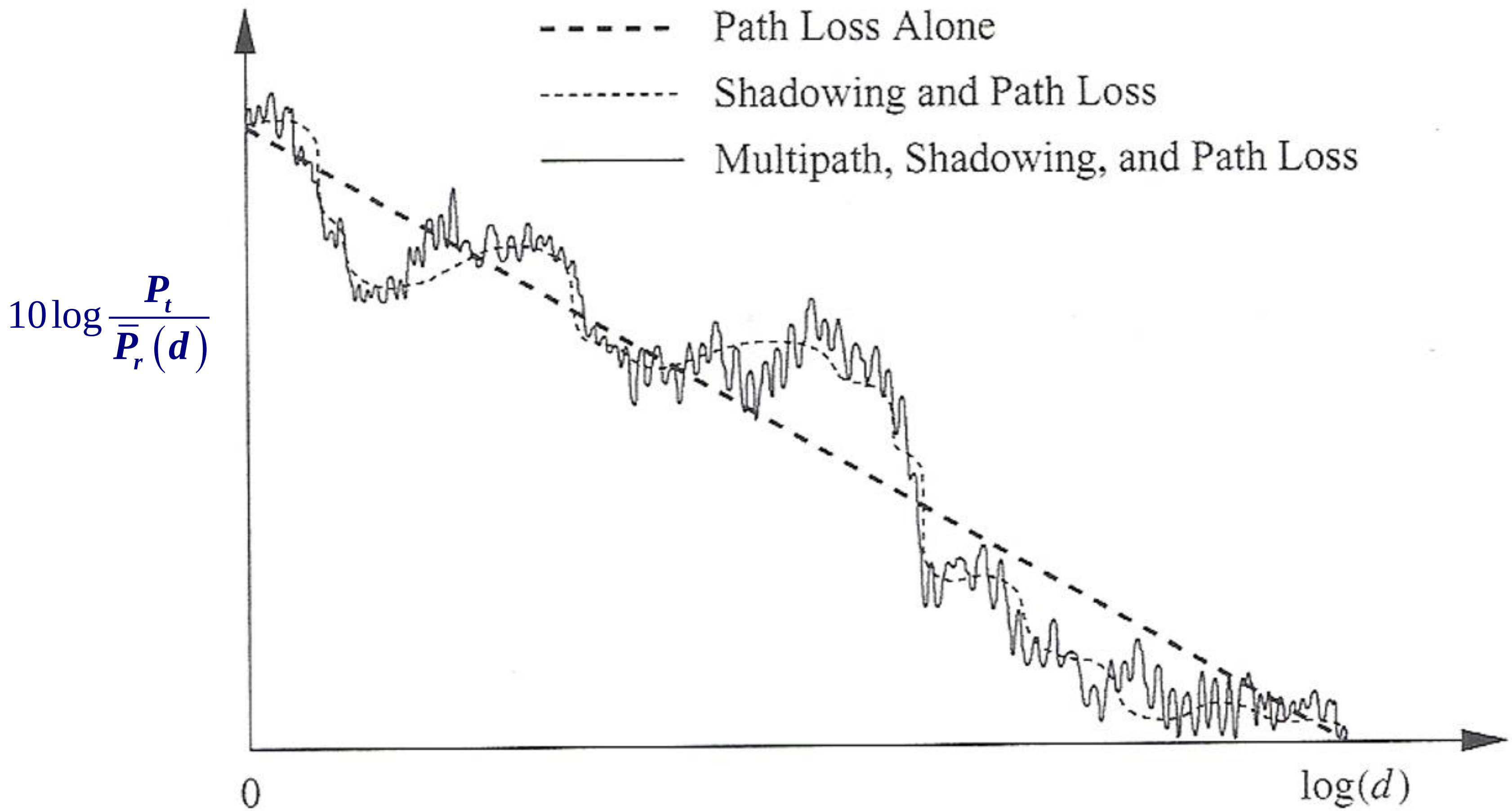


- Scattering:



- Large-scale fading:
  - The variation in received signal power over relatively large distances due to path loss and shadowing
    - "Path loss" is the reduction in power (attenuation) of an electromagnetic wave as it propagates through space.
    - "Shadowing" is the attenuation of an electromagnetic radio signal by obstacles.
- Small-scale fading:
  - The variation in received signal power occurs over very short distances (on the order of the signal wavelength)
    - e.g., f_c=1GHz, $\lambda = 3\times10^8$ (m/s) / $10^9 = 0.3$m

- Channel model:

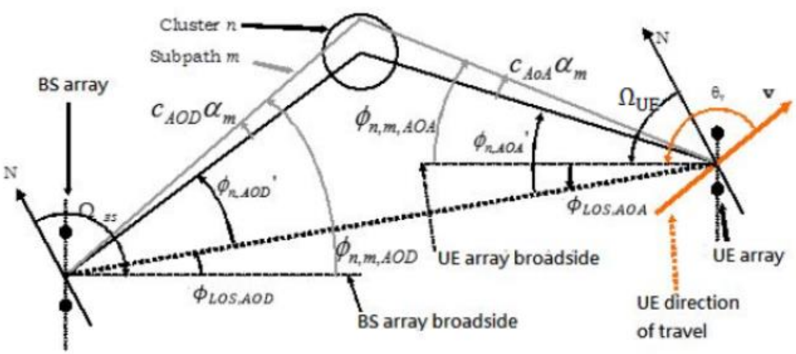


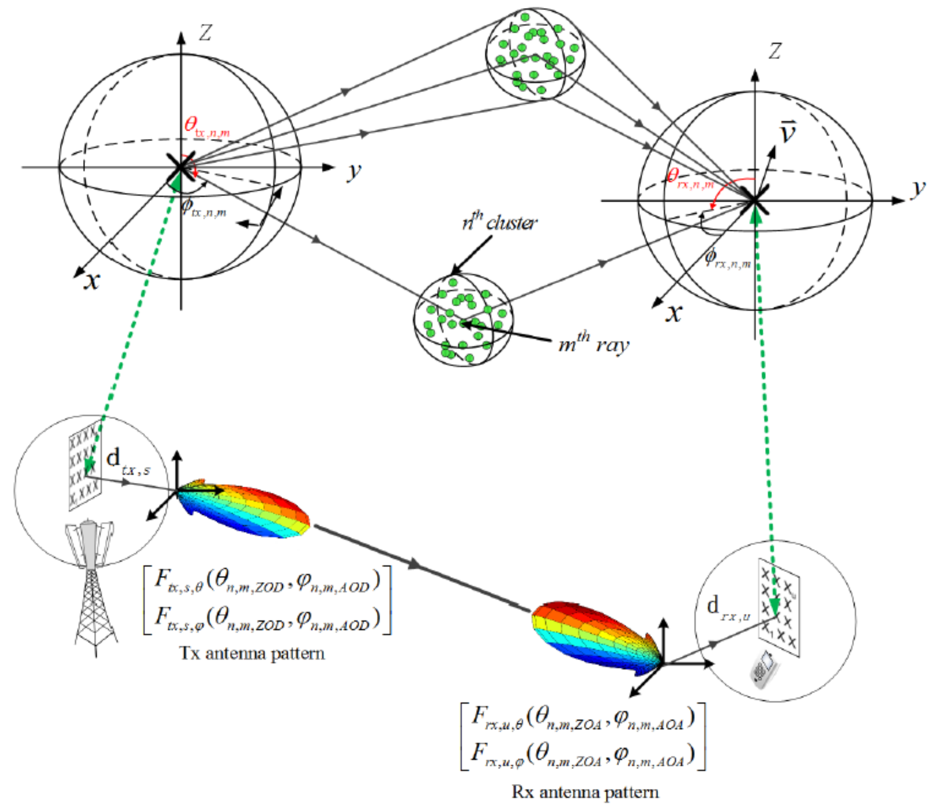
- Free space model: $P_r(d)=\frac{P_tG_tG_r\lambda^2}{(4\pi d)^2}\propto\frac{1}{d^2},\frac{1}{f^2},\lambda^2.$

- 3D channel model:
  - Spatial channel model for multiple-input-multiple-output
  - Cluster based

SCM

TR 25.996 Spatial channel model
for Multiple Input Multiple Output simulation





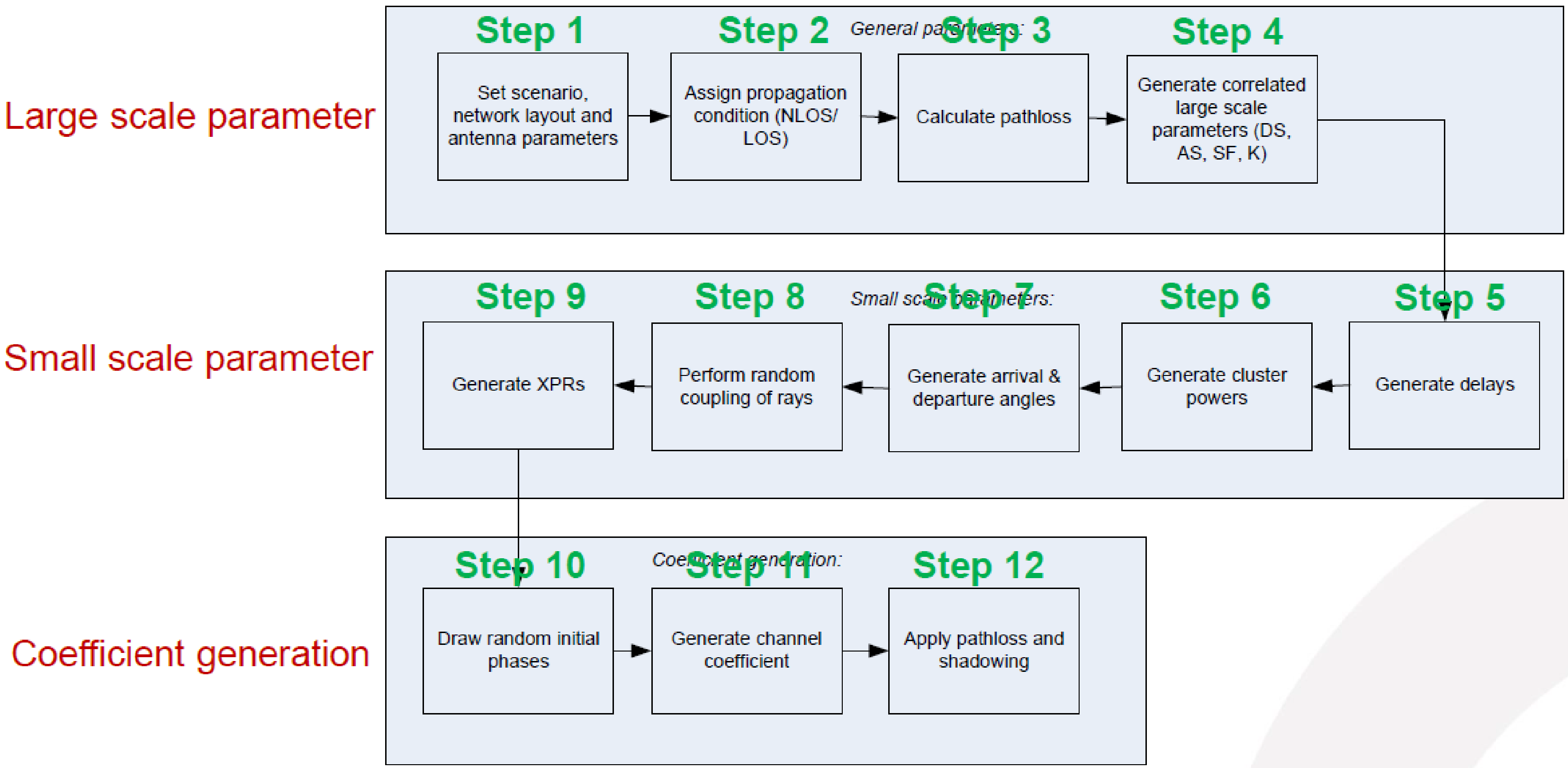
- 5G channel model:

ITU-R M.2412 Table A1-1
The mapping of channel models to the test environments

Test environment	Indoor Hotspot – eMBB	Dense urban – eMBB	Rural – eMBB	Urban macro - mMTC	Urban macro - URLLC
Channel model	InH_A, InH_B	Macro layer: UMa_A, UMa_B Micro layer: UMi_A, UMi_B	RMa_A, RMa_B	UMa_A, UMa_B	UMa_A, UMa_B

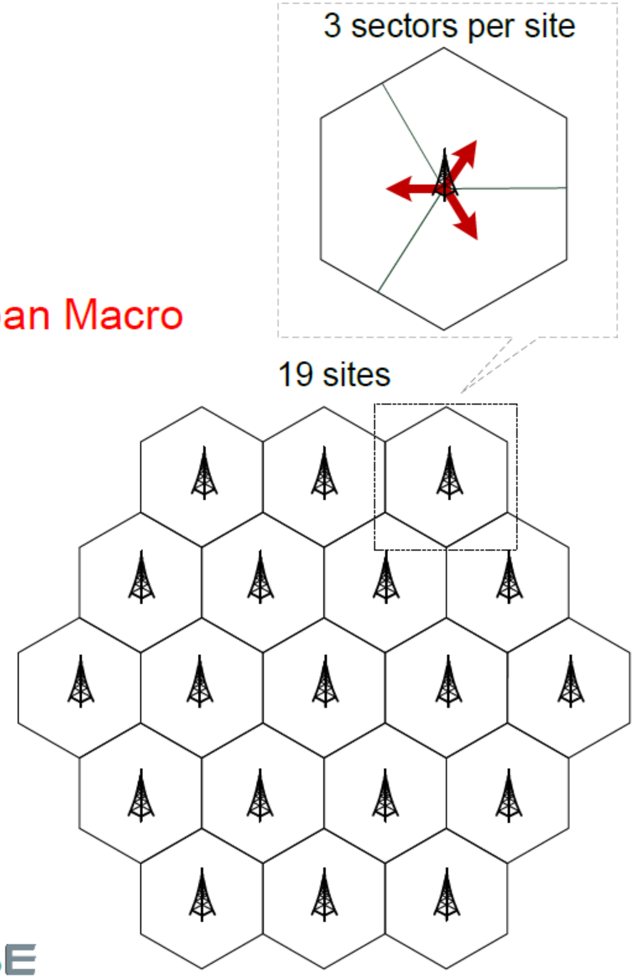
InH: indoor hotspot
UMa: urban macro
UMi: urban micro

- 3D channel generation procedure:

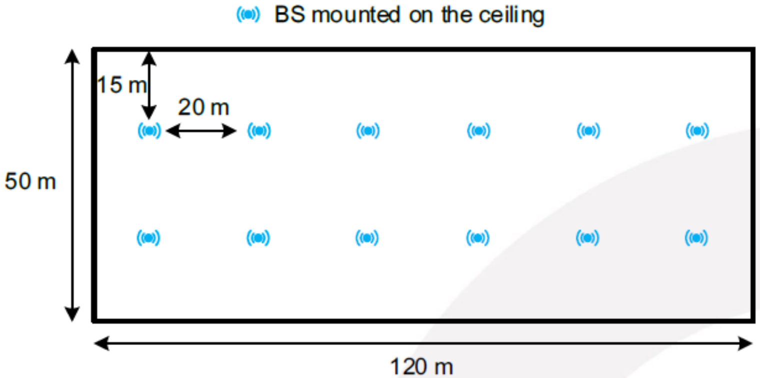


- Scenario/network layout:

Urban Macro

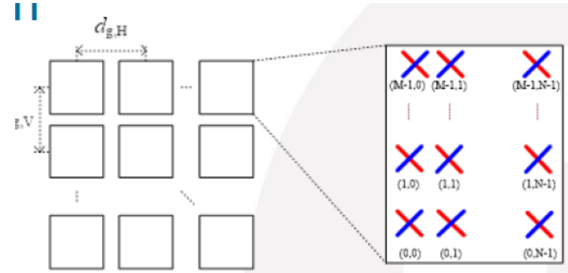


Indoor Hotspot



- Antenna parameters:

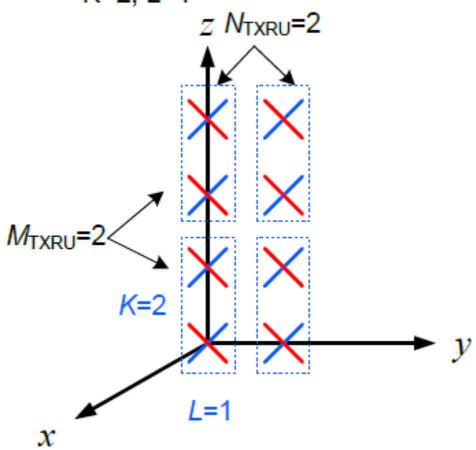
* Different panels can be put in different locations, facing different directions.



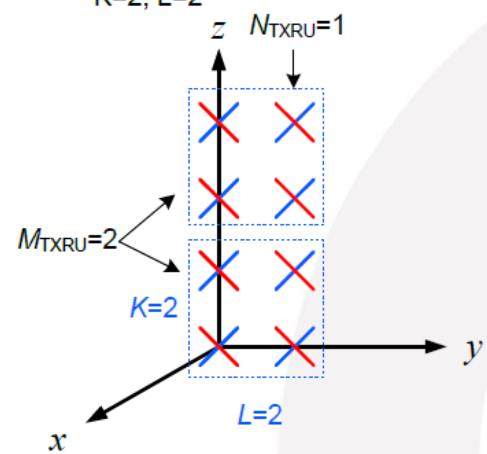
  - M: the number of rows per polarization per panel
  - N: the number of columns per polarization per panel
  - M_{TXRU} (M_p) : the number of TXRU per column per polarization per panel
  - N_{TXRU} (N_p) : the number of TXRU per row per polarization per panel
  - Polarization flag: 0: V-polarization, 1: X-polarization
  - K: the number of virtualization weight per columns for each TXRU
  - L: the number of virtualization weight per rows for each TXRU
  - d_H: horizontal antenna element spacing
  - d_V: vertical antenna element spacing
  - Mg, Ng: number of panels in row and column

* V (vertical) polarization : no polarization

XploFlag=1
M=4, N=2, Mg=1, Ng=1
M_{TXRU}=2, N_{TXRU}=2
K=2, L=1

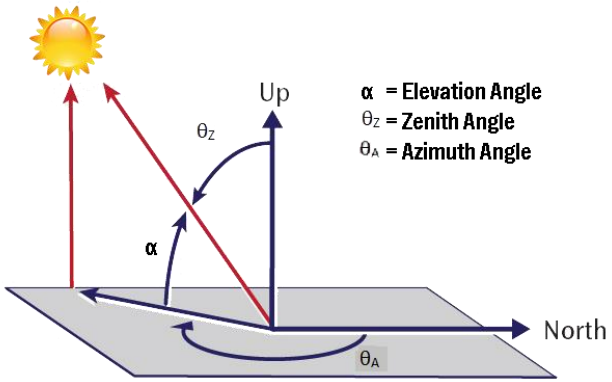


XploFlag=1
M=4, N=2, Mg=1, Ng=1
M_{TXRU}=2, N_{TXRU}=1
K=2, L=2

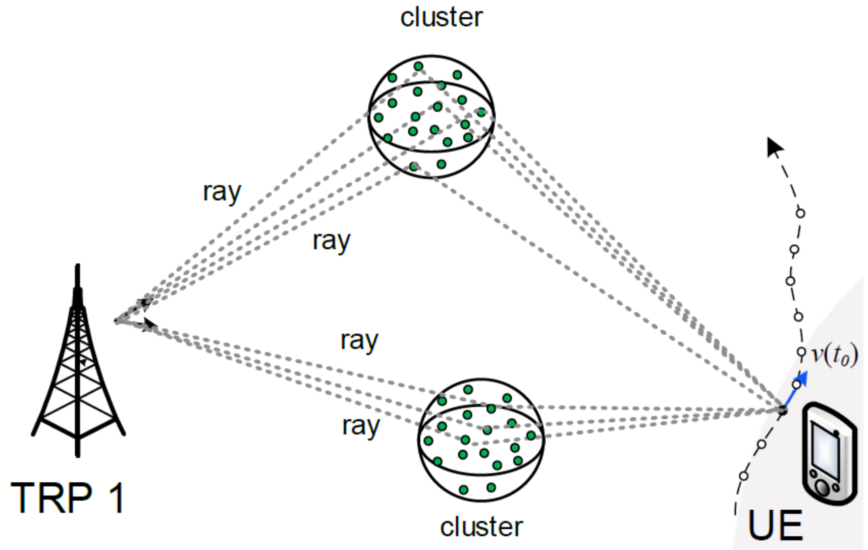


- Channel parameters:
  - Large-scale parameters
    - DS - rms Delay Spread
    - ASD – rms Azimuth Spread of Departure
    - ASA – rms Azimuth Spread of Arrival
    - ZSD – rms Zenith Spread of Departure
    - ZSA – rms Zenith Spread of Arrival
    - SF - shadow fading
    - K - Ricean K-factor

2

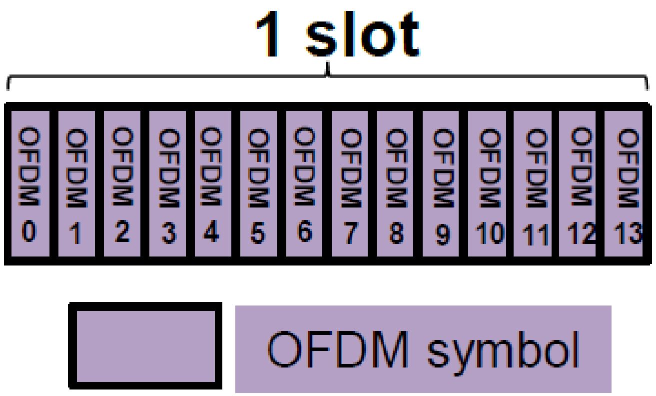


  - Small-scale parameters
    - Delay, power, AOA, AOD, ZOA, ZOD



II. Introduction to WiSE
3. Scheduler and HARQ

- 5G NR frame, subframe, and slot:



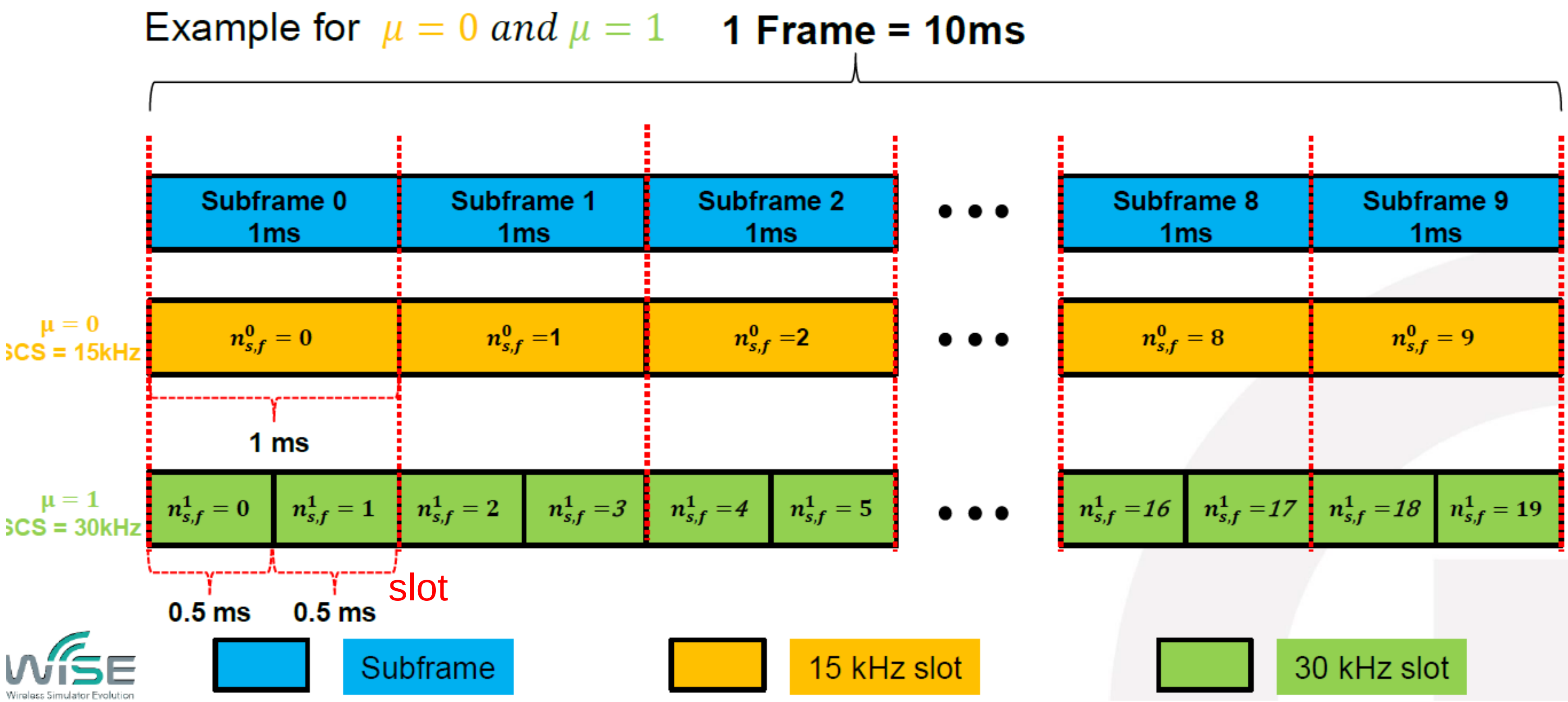
Supported transmission numerologies

μ	$\Delta f = 2^{\mu} \cdot 15[\text{kHz}]$	**Cyclic prefix**
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal

Number of OFDM symbols per slot, slots per frame, and slots per subframe for normal cyclic prefix.

μ	$N_{\text{symb}}^{\text{slot}}$	$N_{\text{slot}}^{\text{frame},\mu}$	$N_{\text{slot}}^{\text{subframe},\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16

- Example:

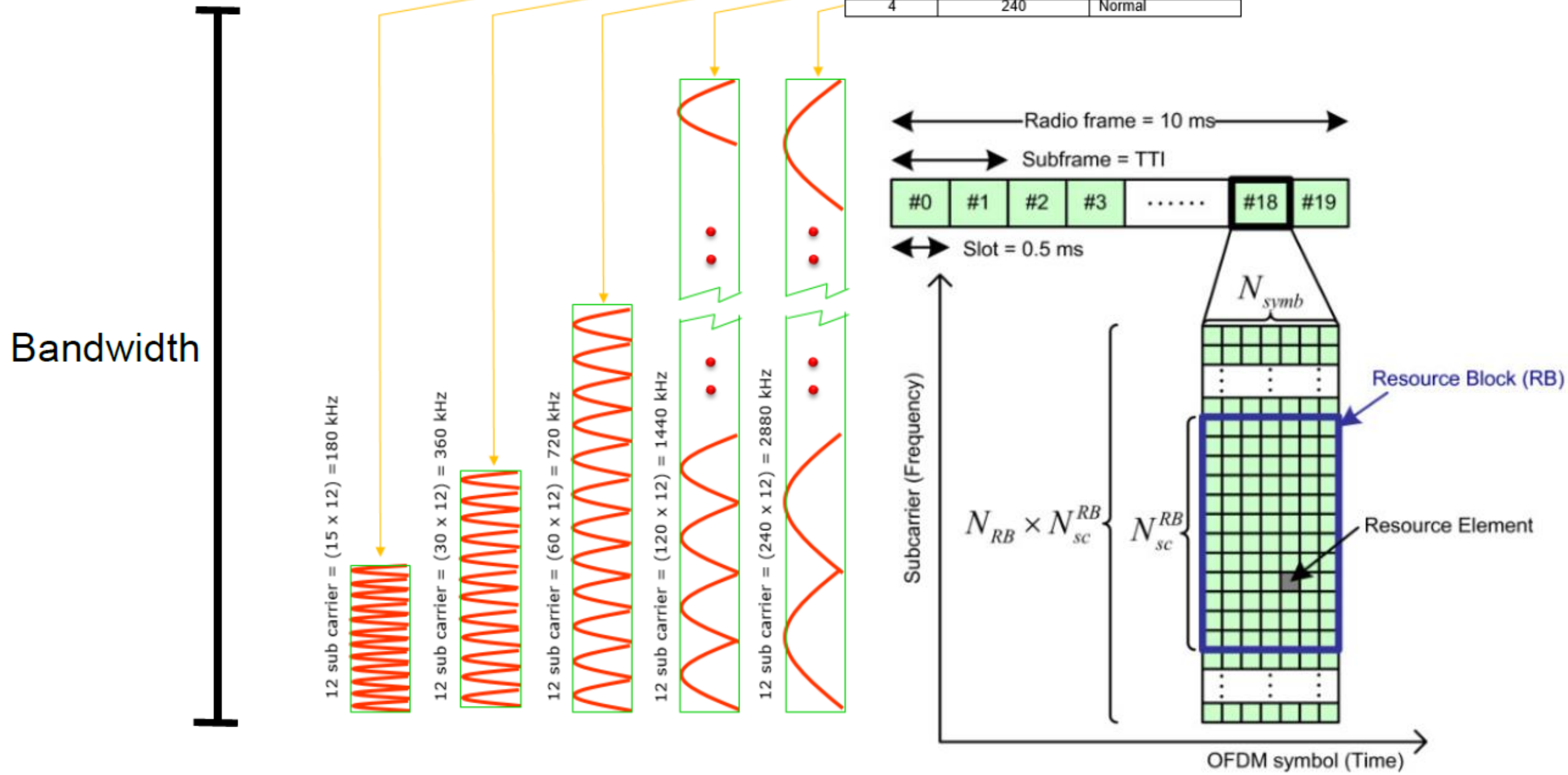


* Subcarrier spacing is higher, bandwidth is higher and sampling rate is higher.

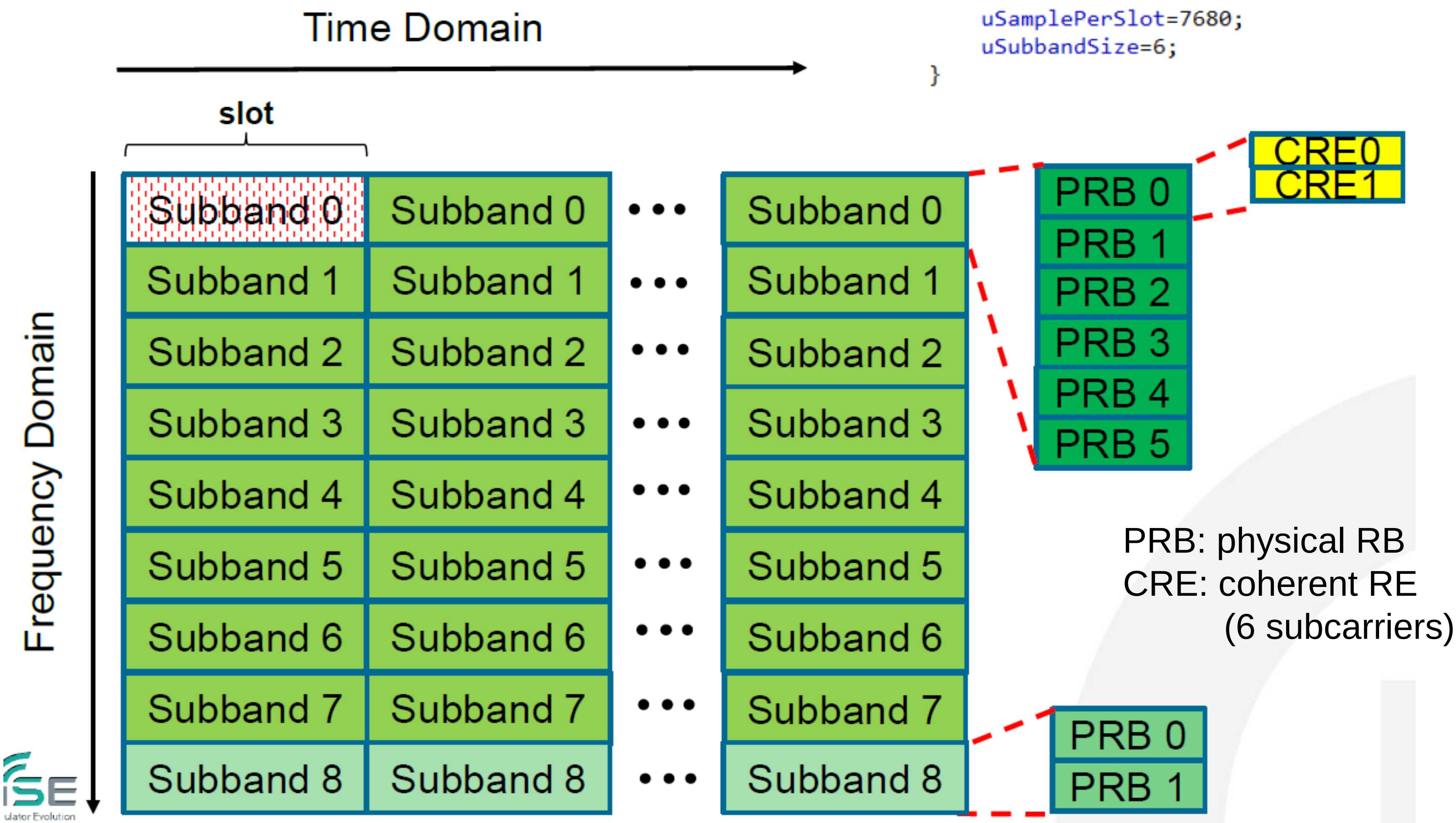
- Occupied bandwidth:

38.211 Table 4.2-1

μ	$\Delta f = 2^{\mu} \cdot 15\,[\text{kHz}]$	Cyclic prefix
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal



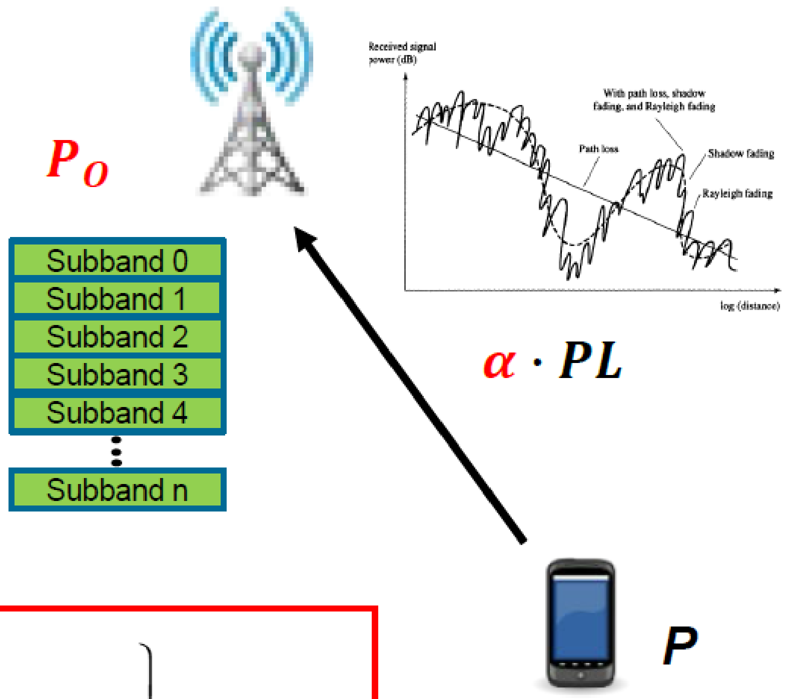
- In WiSE:
  - Scheduling unit: subband



* Subband partition is different for different μ.

Example for $\mu = 0\ (15kHz)\ ; Bandwidth = 10MHz$

- UE power control:



$$P = \min \left\{ \begin{matrix} P_{\mathrm{CMAX}}, \\ P_{\mathrm{O}} + 10\log_{10}(2^{\mu} \cdot M_{RB}) + \alpha \cdot PL \end{matrix} \right\} [dBm]$$

P_{CMAX} : UE configured maximum output power

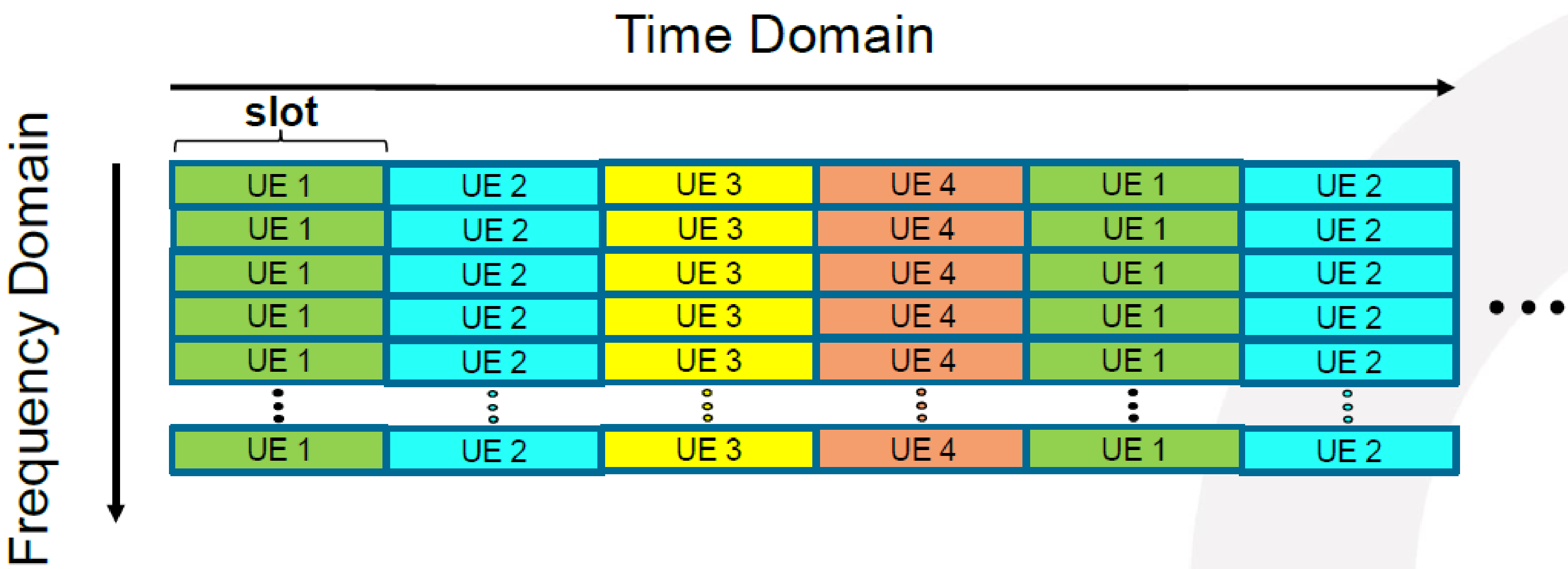
P_{O} : target received power

M_{RB} : number of resource blocks for UL transmission

α : pathloss compensation factor

PL : pathloss between the UE and its serving base station

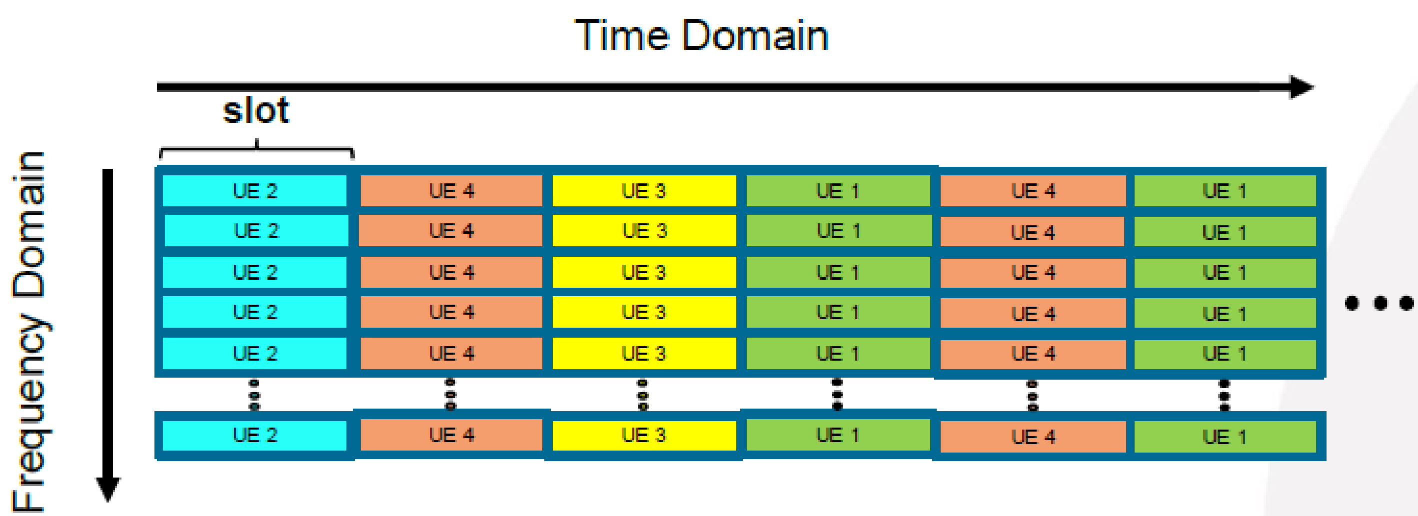
- Round robin (RR) scheduling:
  - RR scheduling uses equal bandwidth for all UEs without accounting priority and channel condition.
  - RR scheduling is simple, easy to implement, and starvation free.
  - In WiSE, each UE obtains a whole OFDM symbol for transmission periodically.



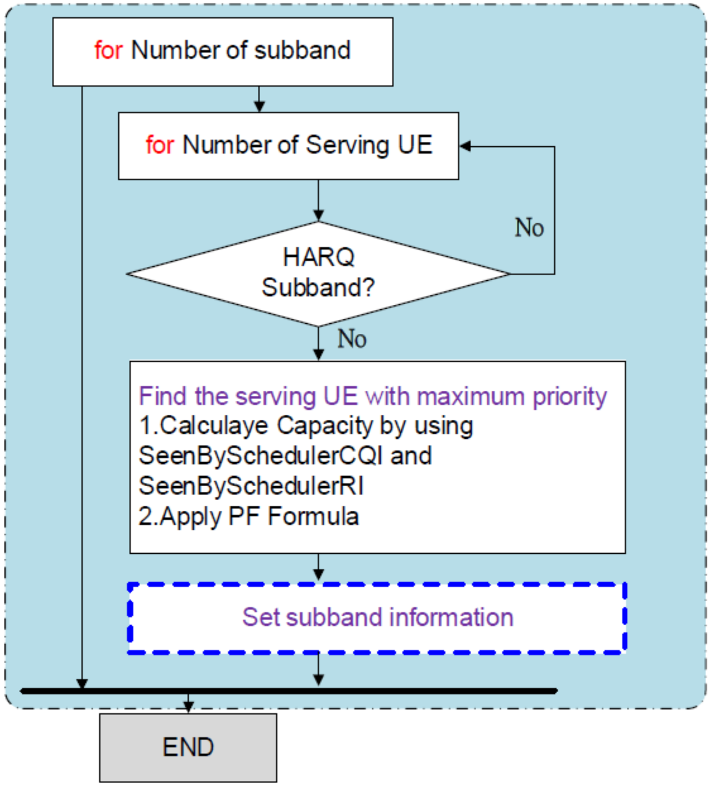
- Proportional fairness (PF) scheduling:
  - PF tries to balance QoS and total throughput for each UE.
  - Schedule the channel for the UE having the highest priority function, *P*.

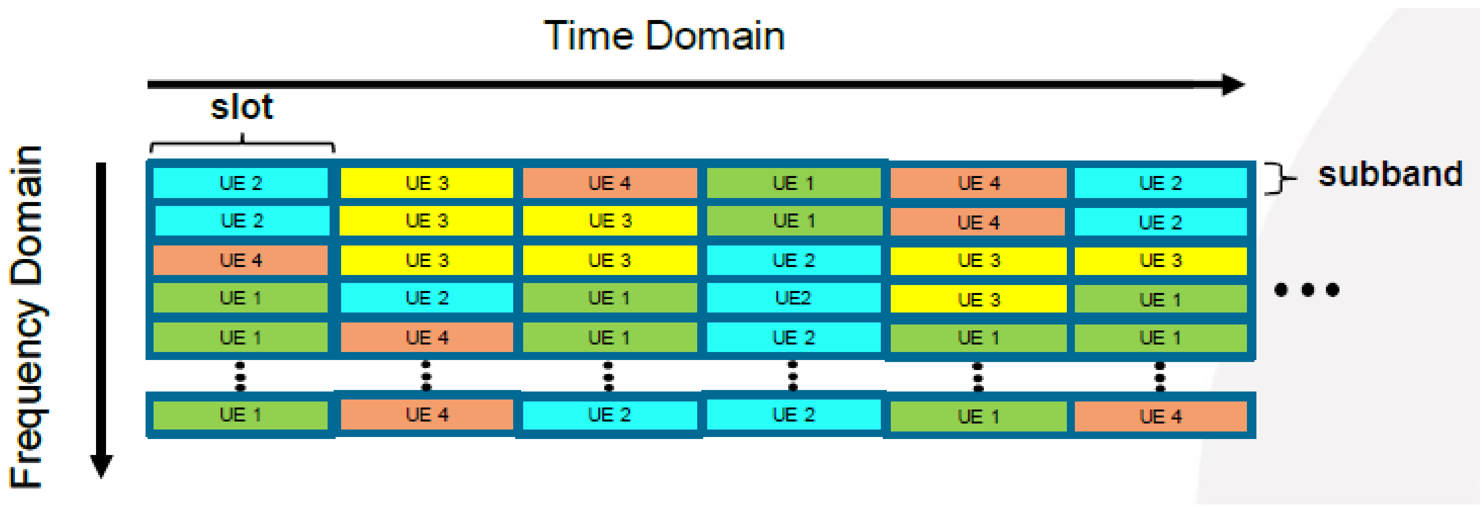
$$P = \frac{T^{\alpha}}{R^{\beta}}$$

- T denotes the data rate potentially achievable for the station in the present time slot.
- R is the historical average data rate of this station.
- α and β tune the "fairness" of the scheduler.

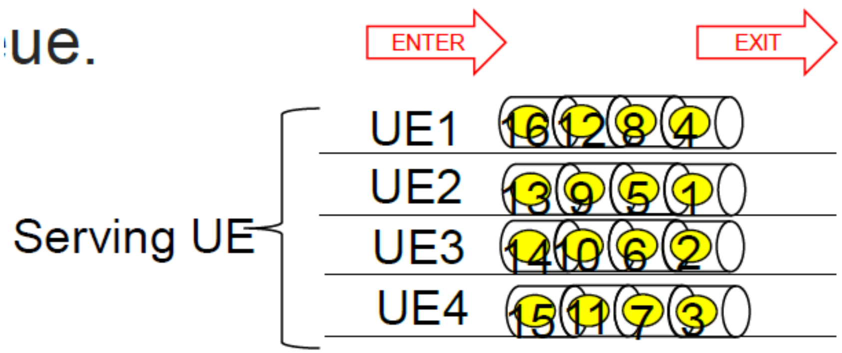


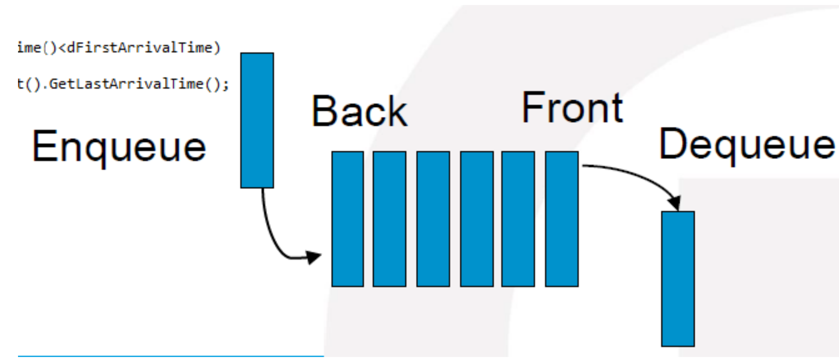
- Subband based:

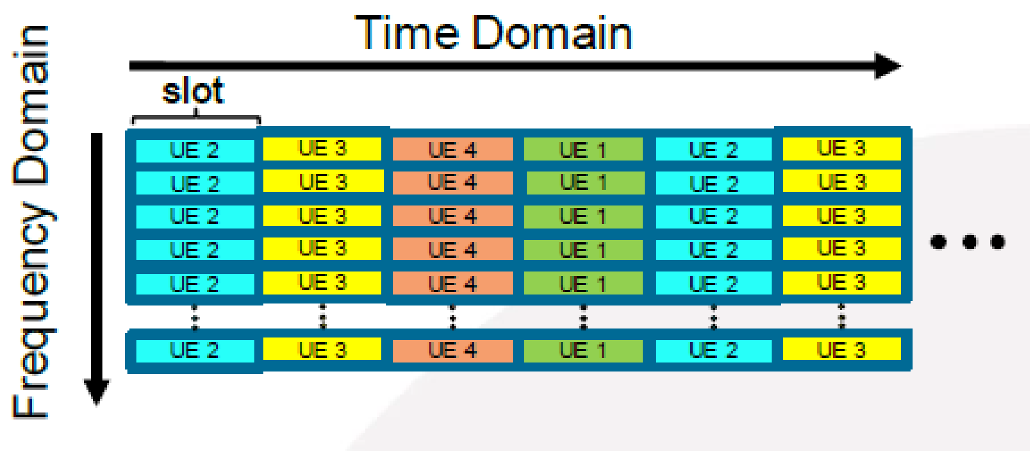




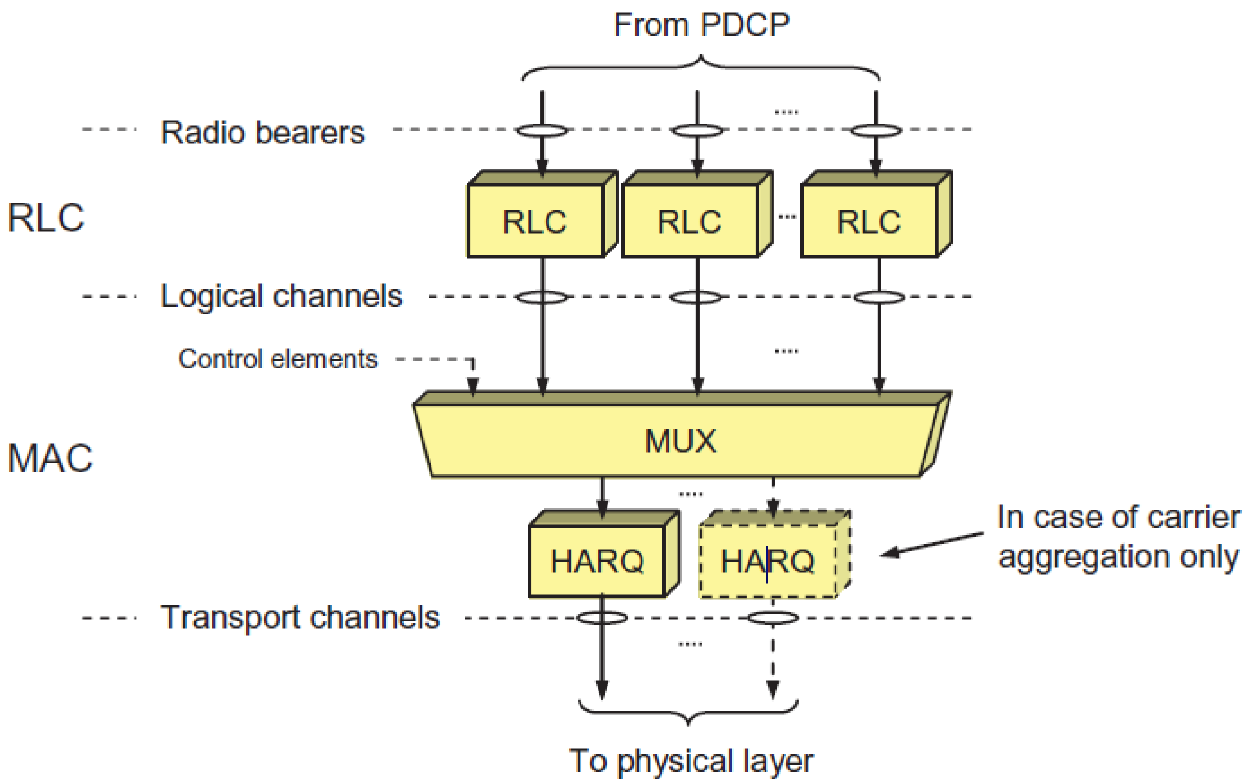
- First-in-first-out (FIFO) scheduling:



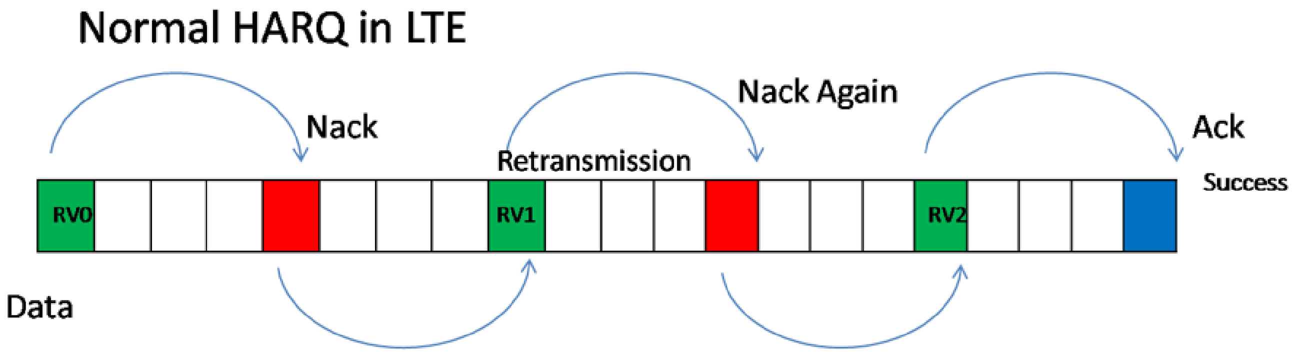




- ARQ (automatic repeat request) / hybrid ARQ (HARQ) :
  - The ARQ functionality provides error correction by retransmissions in acknowledged mode at Layer 2.
  - The HARQ functionality ensures delivery between peer entities at Layer 1.



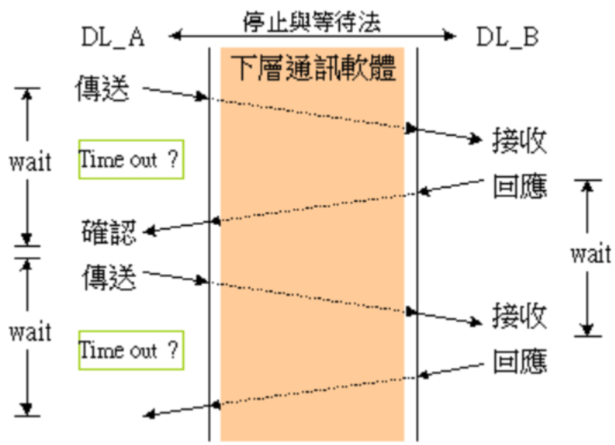
- HARQ with soft combining provides robustness against transmission errors
- HARQ protocol is part of the MAC layer, while the actual soft combining is handled by the physical layer



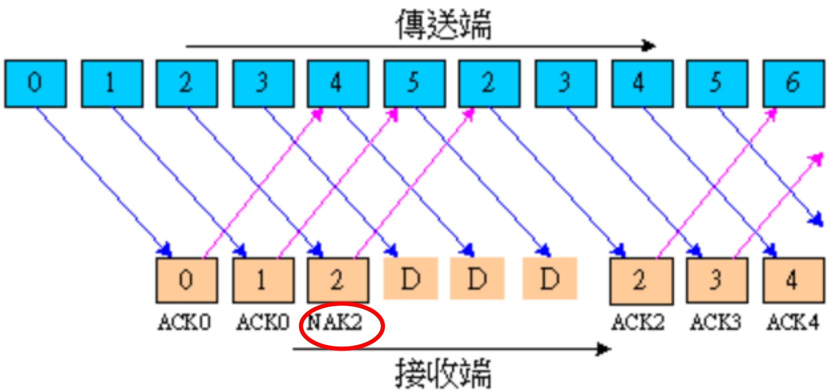
- Two types of HARQ combining:
  - Chase combining (CC)
    - Combine information of multiple codewords
  - Incremental redundancy (IR):
    - Combing information of multiple partial codewords

- Types of HARQ:

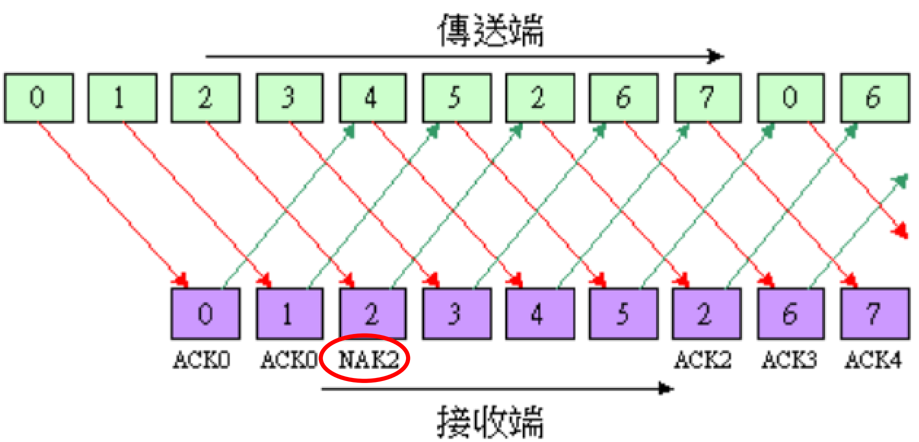
Stop-and-wait



Go-back-N



Selective-repeat



II. Introduction to WiSE
4. Codebook and CSI feedback

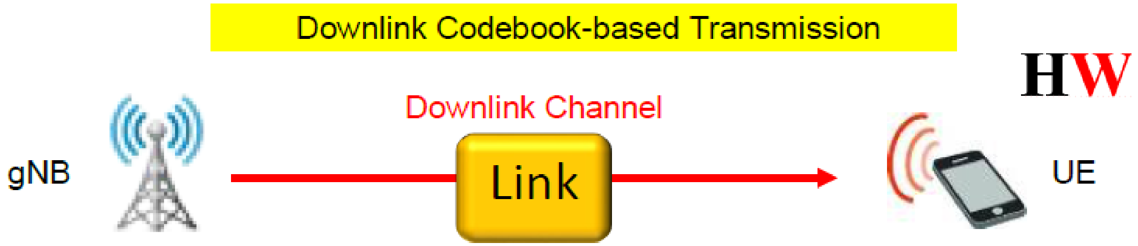
- Channel state information (CSI):
  - An indicator shows how good or bad the channel is at a specific time.
- Precoding:
  - For MIMO systems, transmitting signal vectors can be multiplied by a matrix to optimize the performance.

$$\mathbf{y}_{\mathrm{M}\times 1}=\mathbf{H}_{M\times N}\mathrm{x}_{N\times 1}+\mathrm{v} \;\Rightarrow\; \mathbf{y}=\mathbf{H}\mathbf{W}\mathbf{x}+\mathbf{v}$$

Precoder

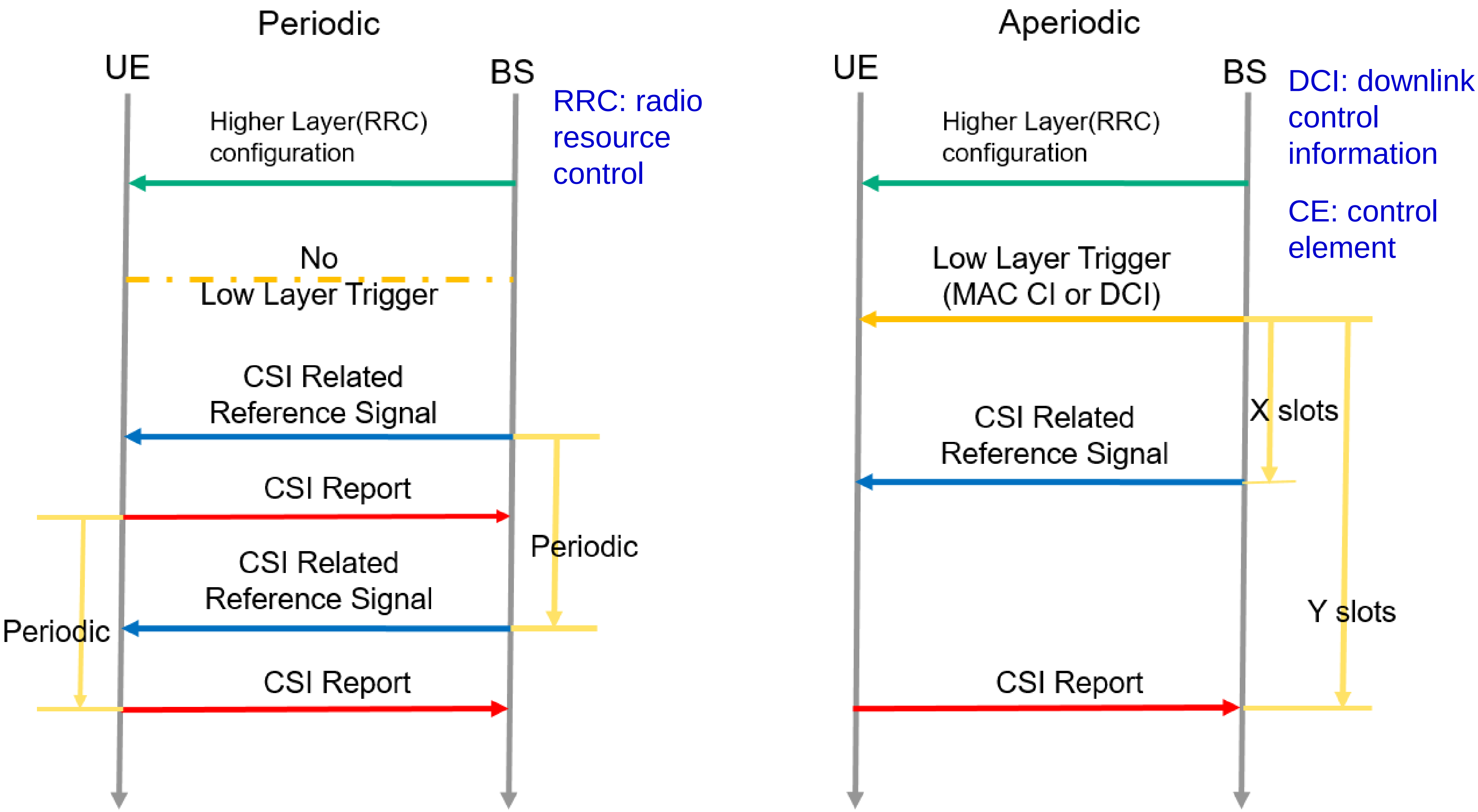
- CSIs:
  - Rank indicator (RI)
  - Precoding matrix index (PMI)
  - Channel quality indicator (CQI)

* If **H** is full rank, min(M,N) layers signals can be transmitted



- NR supports three types of CSI reporting:
  - Aperiodic CSI reporting
    - Delivered when explicitly requested by the network by means of the channel-state request flag included in uplink scheduling grants.
  - Periodic CSI reporting
    - It can be configured by higher layer. higher-layer configuration includes at least reporting periodicity and timing offset.
  - Semi-persistent CSI reporting
    - Configuration of CSI reporting can be activated or de-activated.

- Periodic and aperiodic:



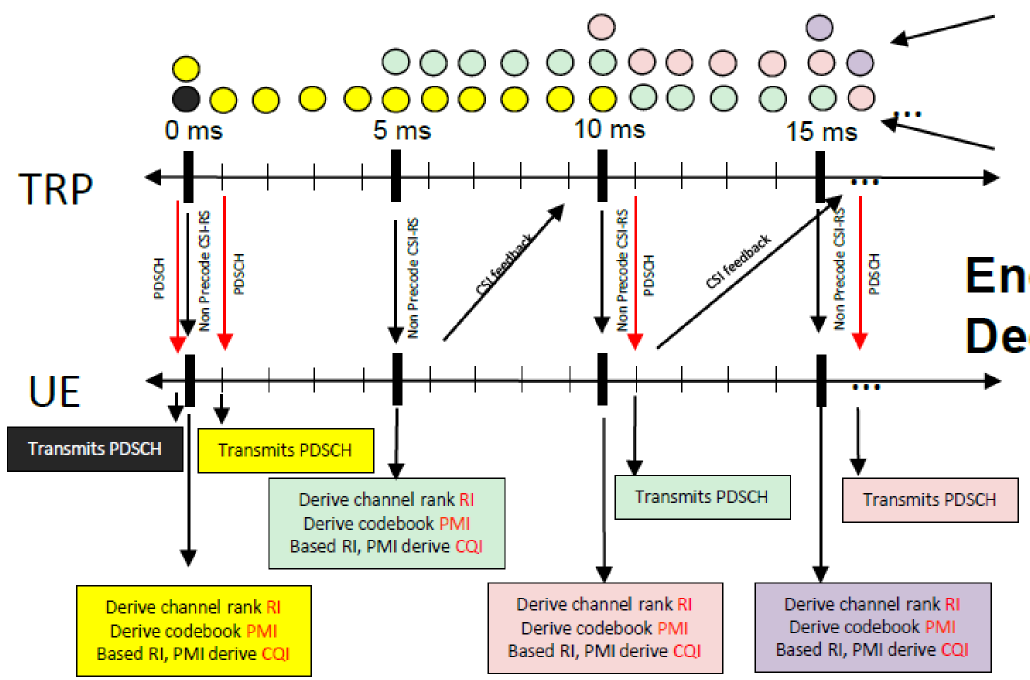
- The period for CSI reporting (5G NR) is 5ms.
  – CSI feedback delay is 6ms, meaning that the estimation is used after 6ms.
- Difference in TDD and FDD:
  – In TDD, UL and DL frames are not ideally allocated such that longer CSI delay will be resulted.
  – No problem with FDD.

Uplink-downlink configuration	Downlink-to-Uplink Switch-point periodicity	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

S: special subframe for DL and UL switch
DwPTS: DL pilot time slot
GP: guard period
UpPTS: UL pilot time slot

DwPTS	GP	UpPTS

- WiSE periodic feedback:
  - CSI feedback delay = 6
  - CSI periodicity =5



Queue rear

Queue front

Enqueue: TTI 0, 5,10, 15……

Dequeue: TTI 0, 11, 16, 21, 26….

TTI: Transmission Time Interval

TRP: transmission receiption point

- RI, providing a recommendation on the number of layers that should preferably be used for downlink transmission to the terminal.
- RI only needs to be reported when configured to be in one of the spatial-multiplexing transmission modes.
- RI estimation
  - Using the different number of the transmission rank (layer) cause the different capacities
  - The higher number of the transmission rank (layer) is, the larger inter-layer interference is.
- The capacity of a MIMO channel can be written as

$$C = \log_2 \left\{ \det \left[\mathbf{I}_n + \mathrm{SINR}(\mathbf{H}\mathbf{H}^H) \right] \right\}$$

- WiSE SLS estimates the capacity of different RI and chooses the best capacity’s RI for transmission.

- How many signal streams can be sent for a MIMO channel?

$$\max(\mathrm{RI})=\min(N_t,N_r)$$

- Ex:

Case1: Tx=3	Rx=3	Maximum Rank = 3
Case2: Tx=4	Rx=2	Maximum Rank = 2
Case3: Tx=4	Rx=8	Maximum Rank = 4

- If RI< $\min(N_t,N_r)$, it means that at least two antennas are fully correlated.

- Capacity for the ith stream:

* Conduct MMSE equalization first
* Treat each layer independently
* Equal power allocation

$$C_i^{MMSE} = \log_2\left(\frac{1}{[(\mathbf{I}_r + \mathrm{SINR}_r\mathbf{H}_r^H\mathbf{H}_r)^{-1}]_{i,i}}\right)$$

- RI estimation:

$$\underset{n\times m}{\mathbf{H}_b} = \underset{n\times m}{\mathbf{U}}\,\underset{m\times m}{\mathbf{\Sigma}}\,\mathbf{V}^H$$

$$\mathbf{H}_b \rightarrow SVD \rightarrow \mathbf{V}_b$$

$$\mathbf{H}_{eq(r,b)} = \mathbf{H}_b\mathbf{V}_{b,r} \quad , r = 1,\ldots,\text{max rank}$$

$$C_{r,b} = \log_2\left(\frac{1}{\left[\left(\mathbf{I}_r + \mathrm{SINR}_r\mathbf{H}^H_{eq(r,b)}\mathbf{H}_{eq(r,b)}\right)^{-1}\right]_{i,i}}\right)$$

$$C_r = \sum_b C_{r,b}$$

$$\left[\hat{R}\right] = \arg\max_r \ C_r$$

$$\begin{cases} b : \text{subband index} \\ \mathbf{H}_b : \text{Average channel in subband } b \\ \mathbf{H}_{eq(r,b)} : \text{equivalent channel of channel } \mathbf{H}_b \text{ with precoder } \mathbf{V}_{b,r} \\ \mathrm{SINR}_r : \text{ Wideband SINR in Rank } r \\ C_{r,b} : \text{subband MMSE capacity of equivalent channel } \mathbf{H}_{eq(r,b)} \\ C_r : \text{wideband MMSE capacity} \\ \hat{R} : \text{decision of RI} \end{cases}$$