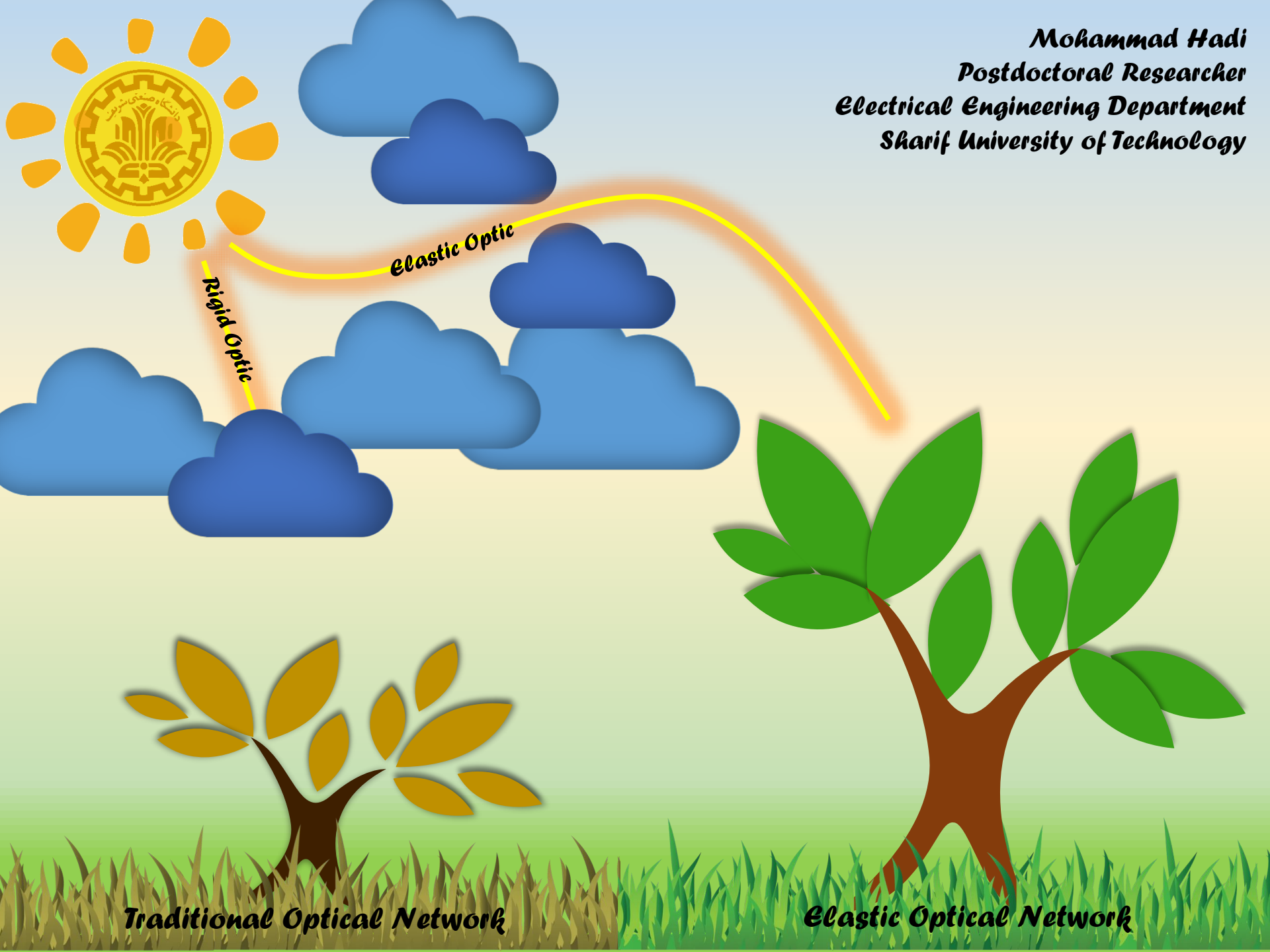
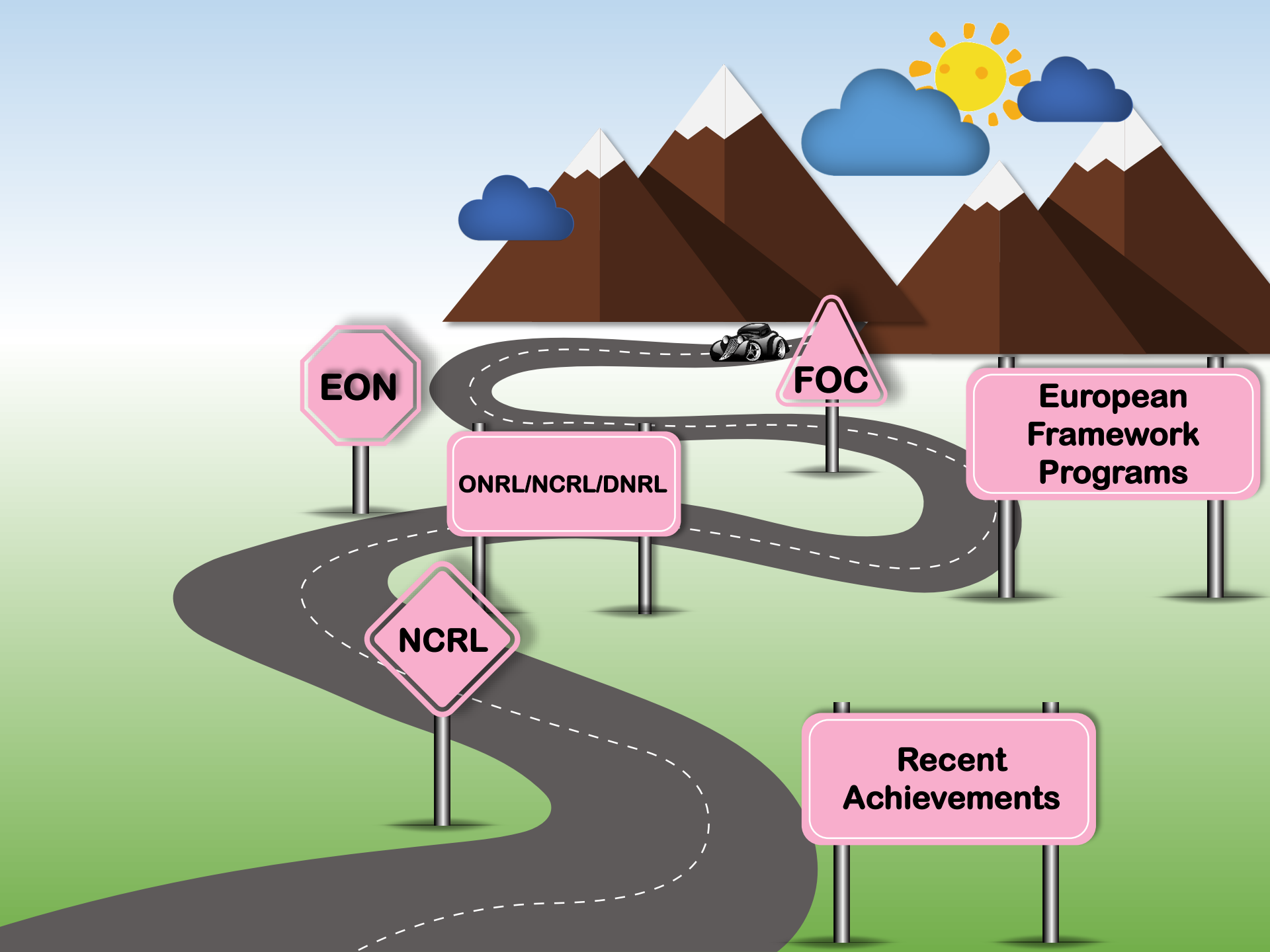
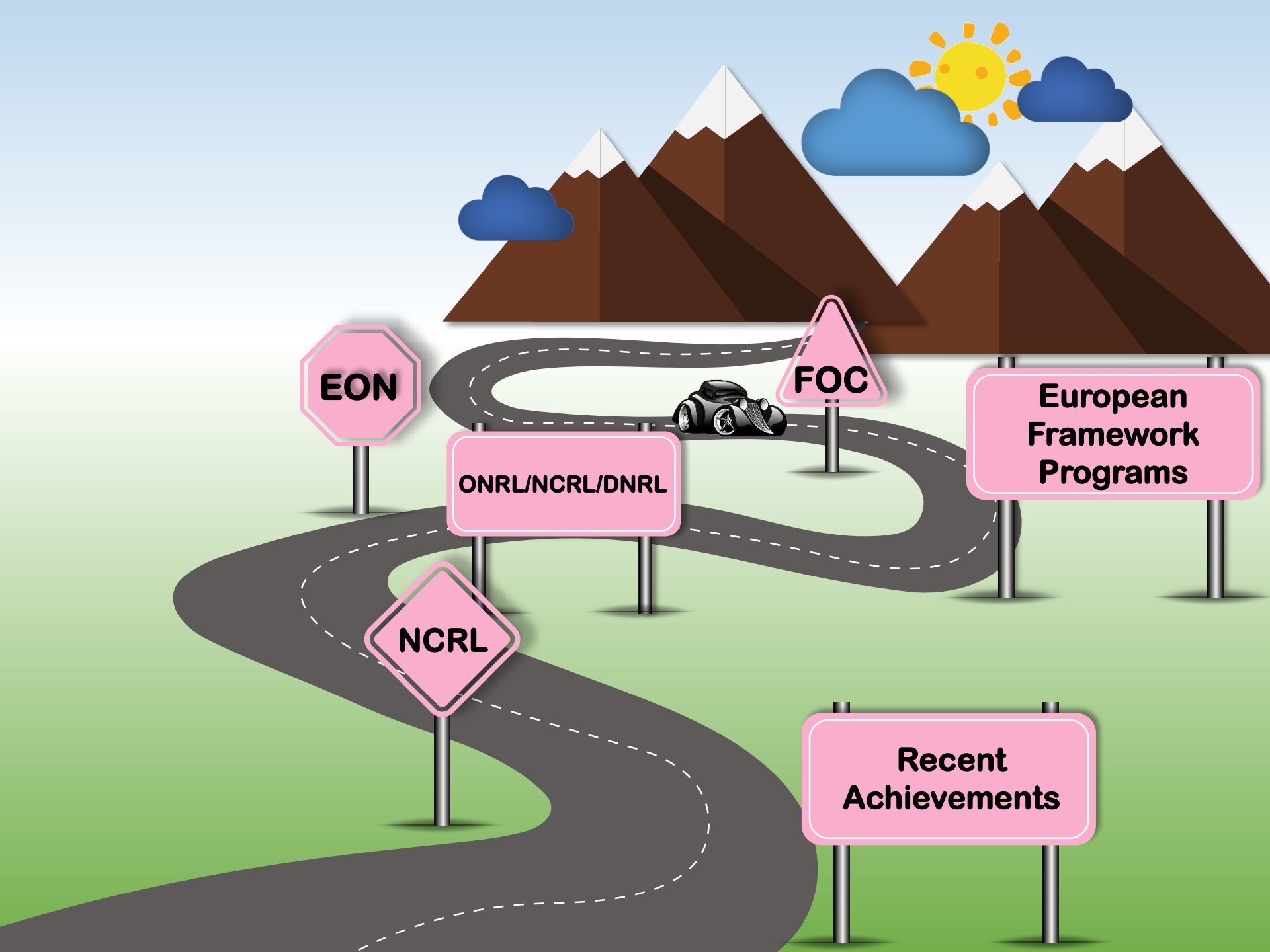
Mohammad Hadi
Postdoctoral Researcher
Electrical Engineering Department
Sharif University of Technology




EON
FOC
European Framework Programs
ONRL/NCRL/DNRL
NCRL
Recent Achievements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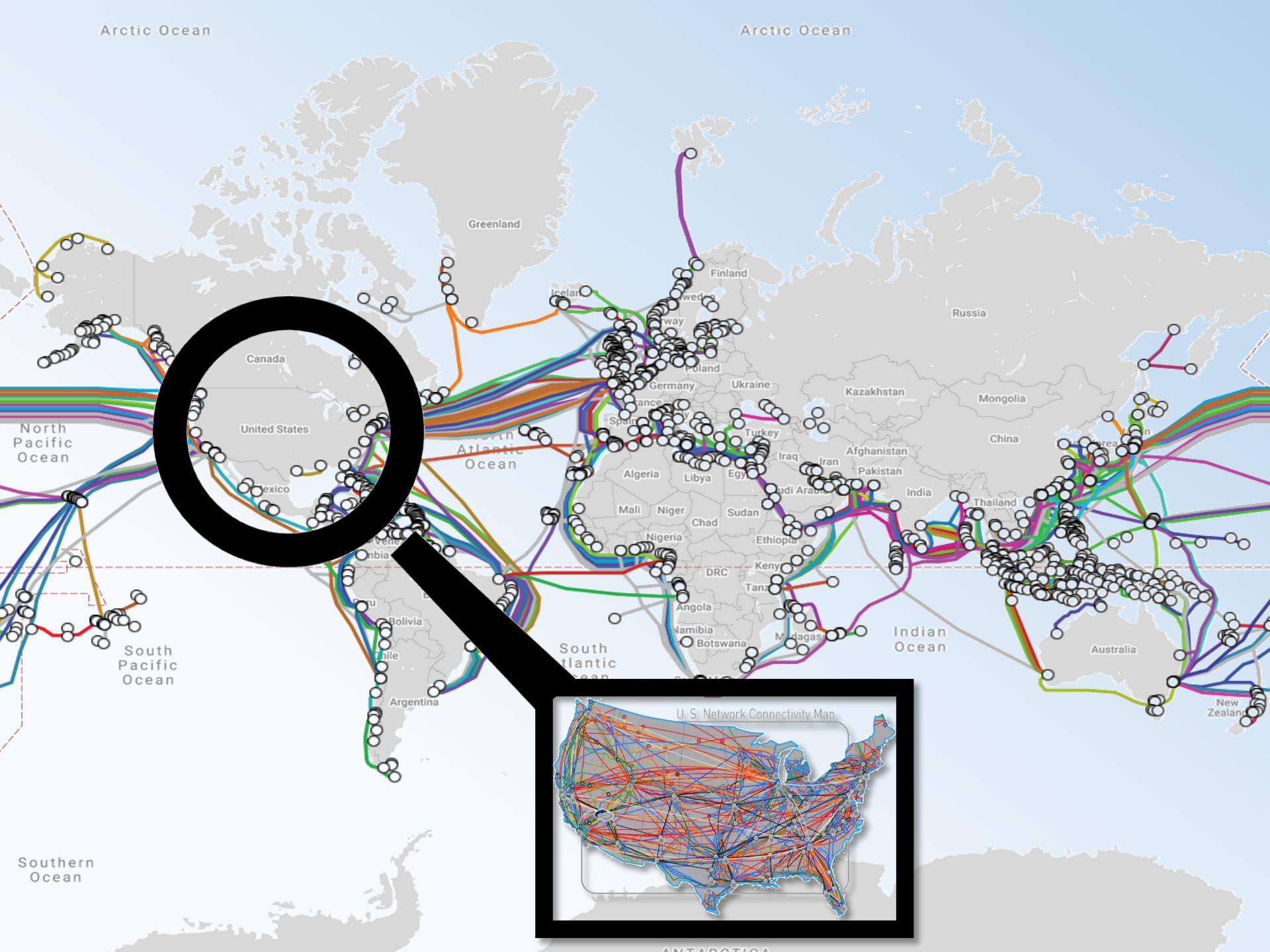
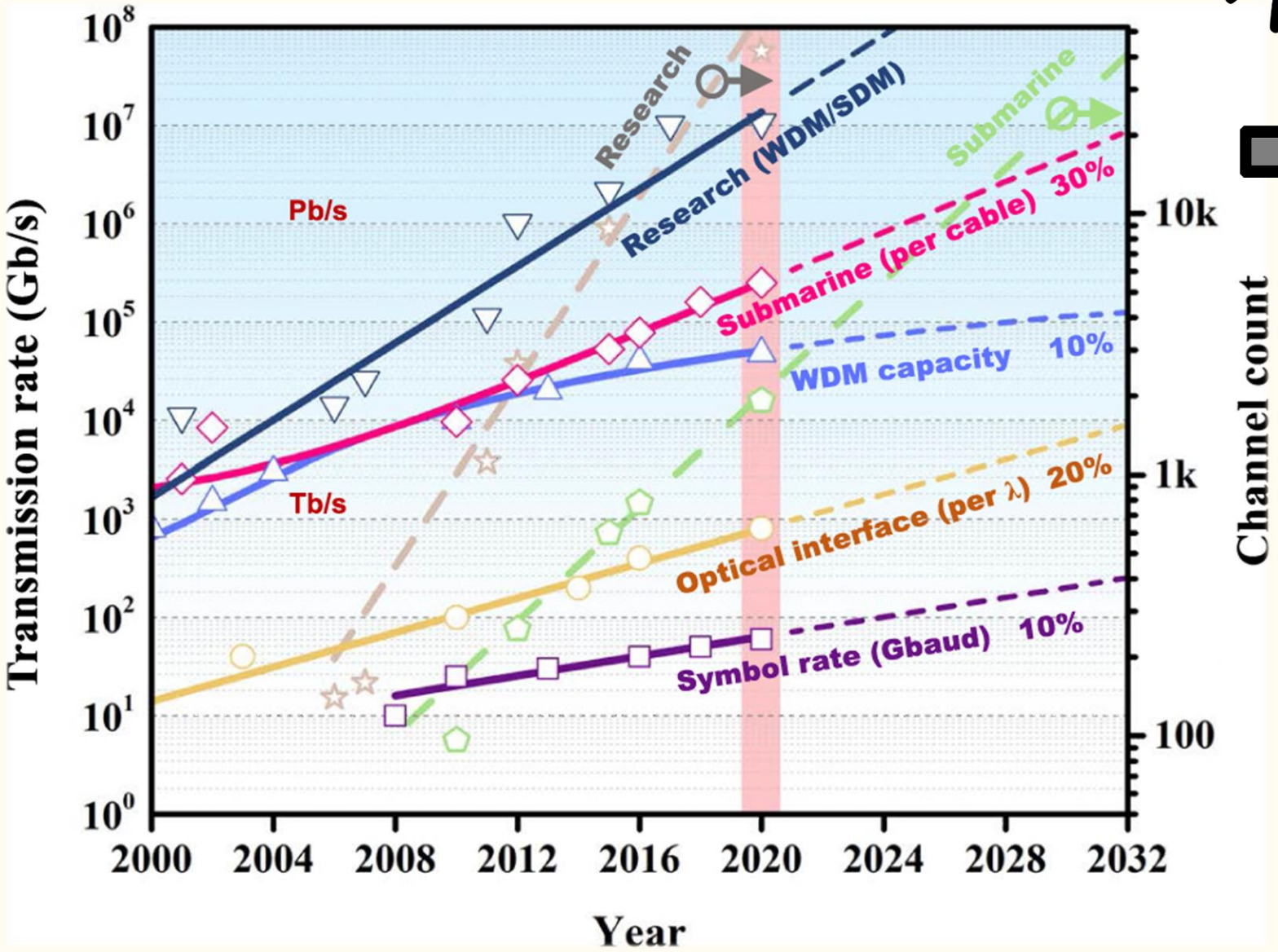
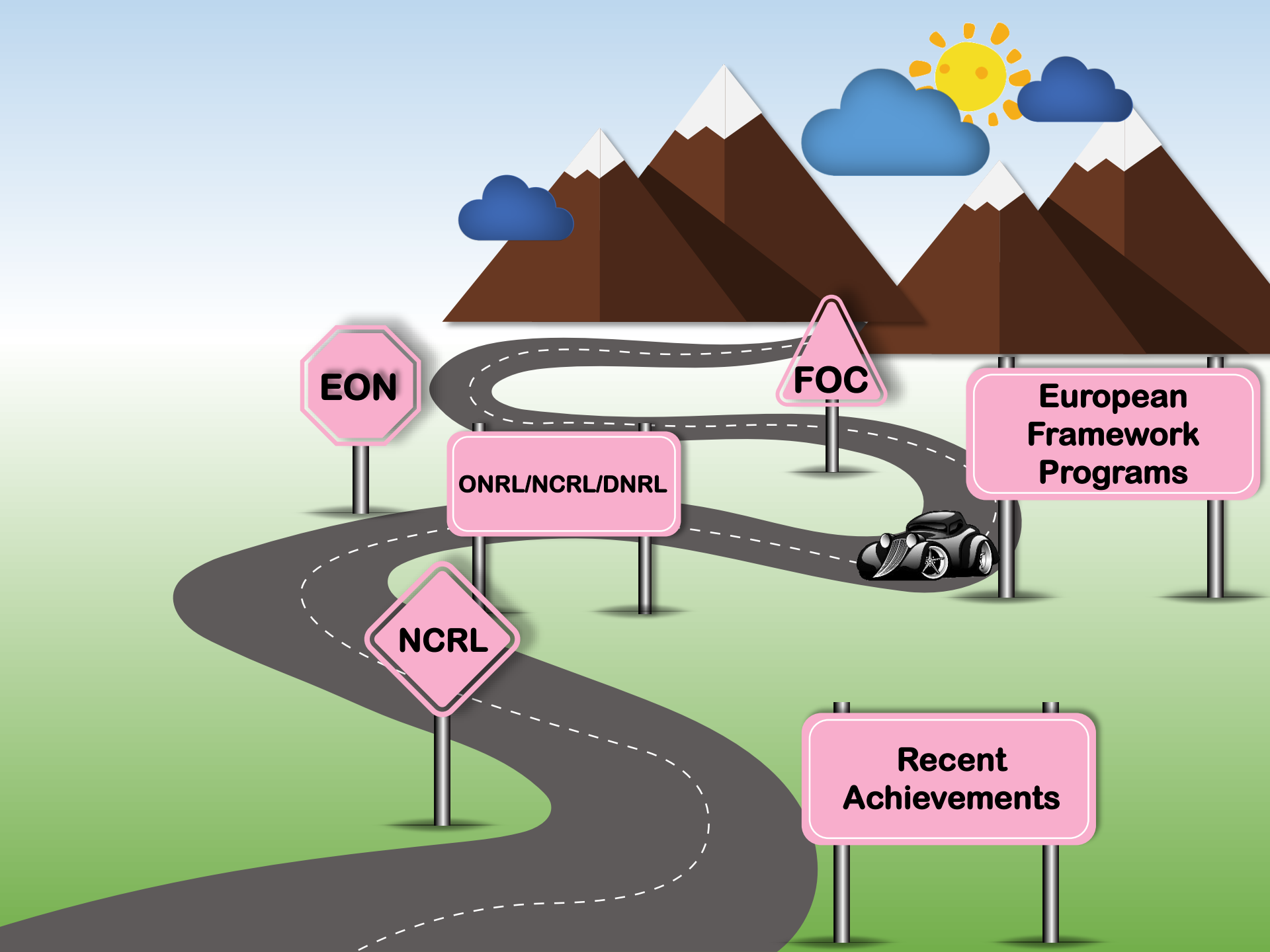
Recent Achievements


Arctic Ocean
Arctic Ocean
Greenland
Canada
United States
North Pacific Ocean
North Atlantic Ocean
Finland
Russia
Germany
Ukraine
Kazakhstan
Mongolia
China
Turkey
Iraq
Iran
Afghanistan
Pakistan
India
Thailand
Algeria
Libya
Mali
Niger
Chad
Sudan
Nigeria
Ethiopia
DRC
Angola
Namibia
Botswana
Indian Ocean
Australia
New Zealand
South Pacific Ocean
Bolivia
Argentina
South Atlantic Ocean
Southern Ocean
U. S. Network Connectivity Map


Transmission rate (Gb/s)
Channel count
Year
Pb/s
Tb/s
Research
Research (WDM/SDM)
Submarine
Submarine (per cable) 30%
WDM capacity 10%
Optical interface (per λ) 20%
Symbol rate (Gbaud) 10%
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10k
1k
100
2000
2004
2008
2012
2016
2020
2024
2028
2032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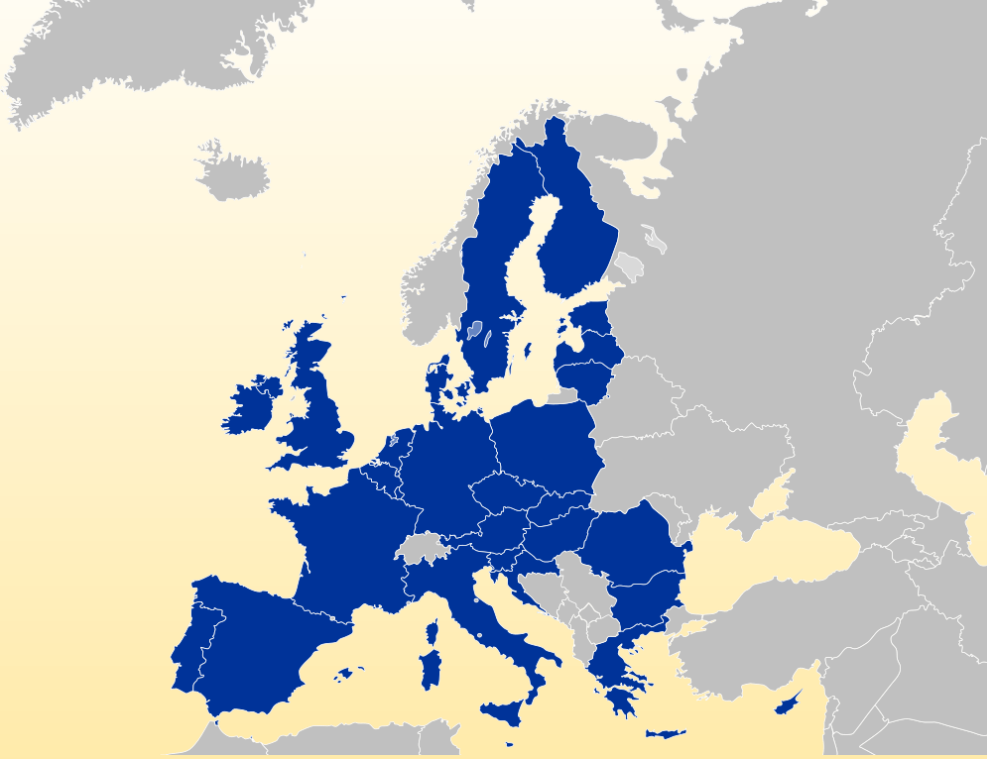
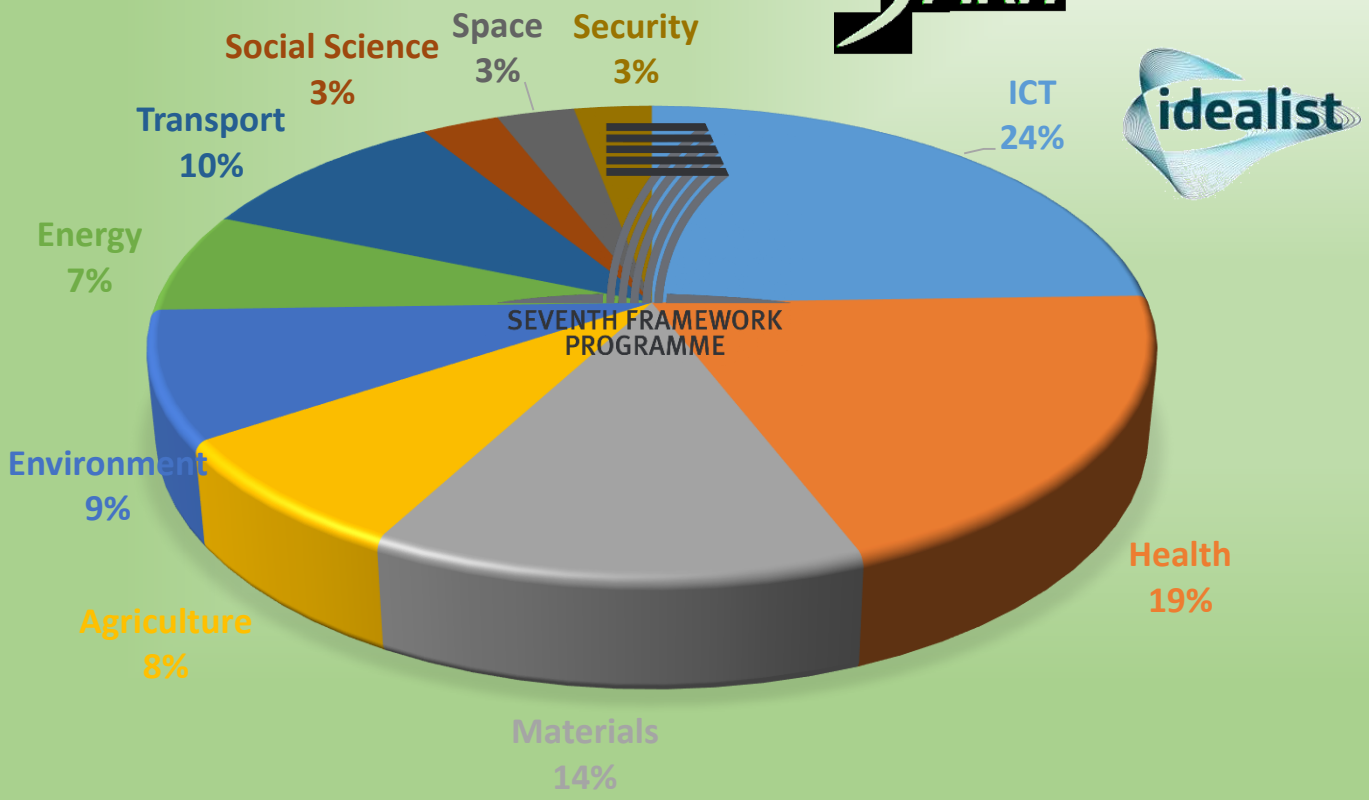
Recent Achievements

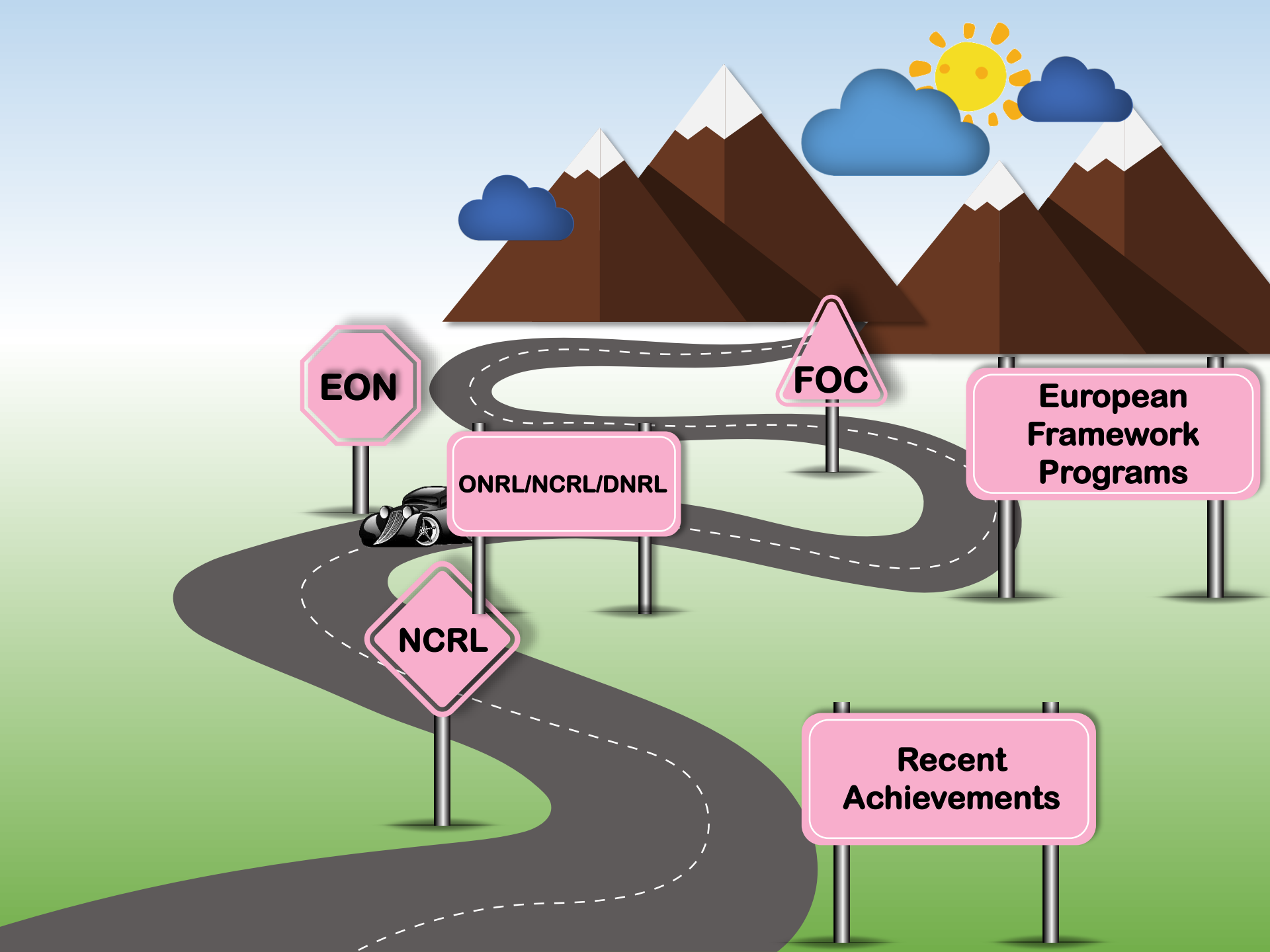


FP7

Horizon 2020

Horizon Europe


Social Science
3%
Space
3%
Security
3%
Transport
10%
ICT
24%
Energy
7%
SEVENTH FRAMEWORK
PROGRAMME
Environment
9%
Health
19%
Agriculture
8%
Materials
14%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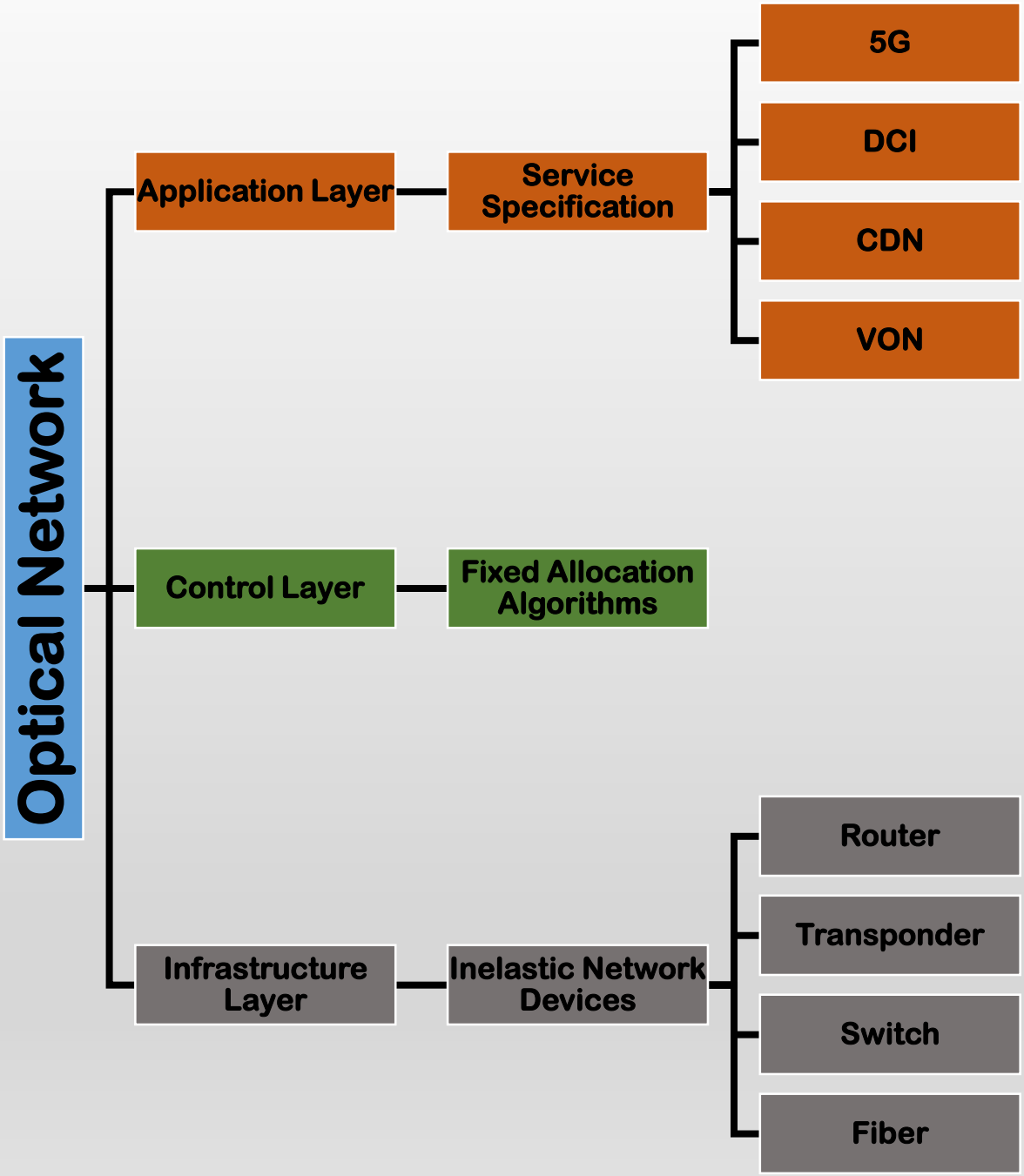
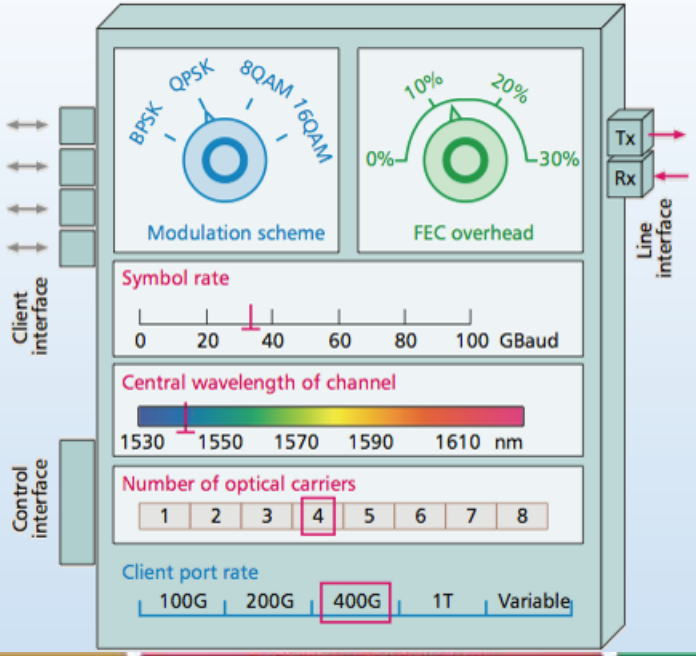
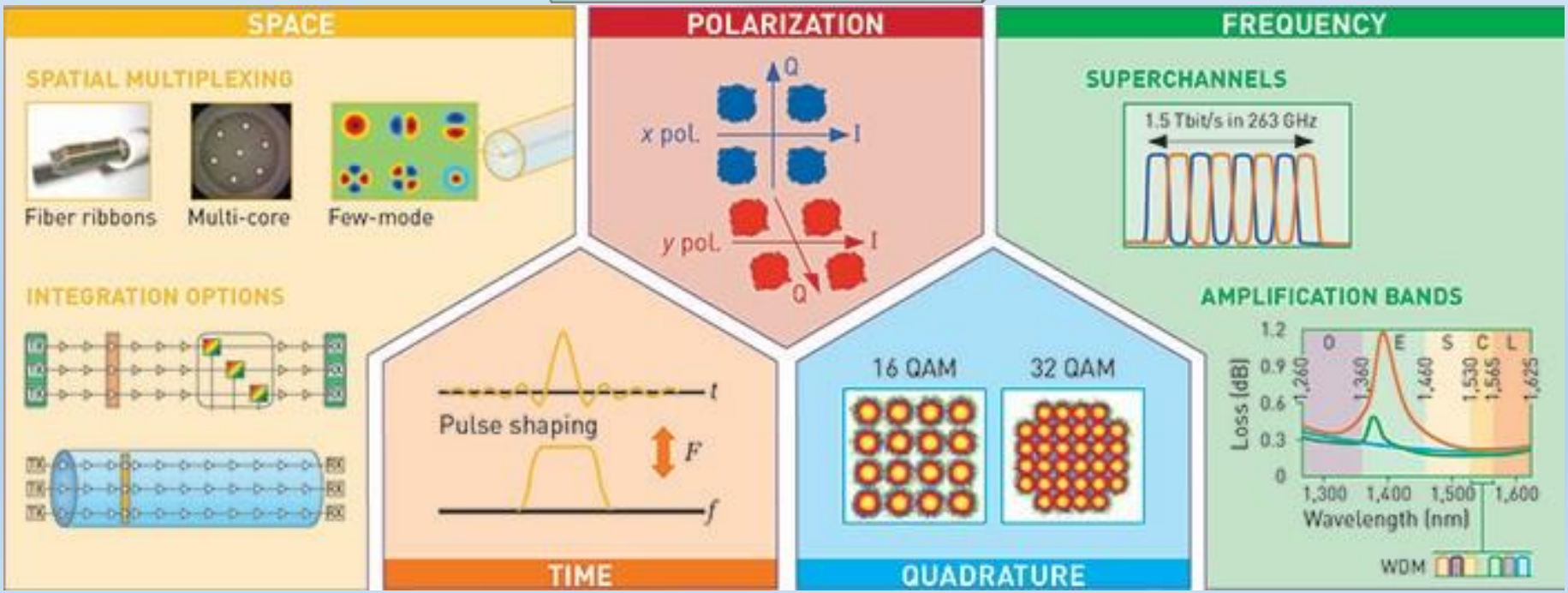
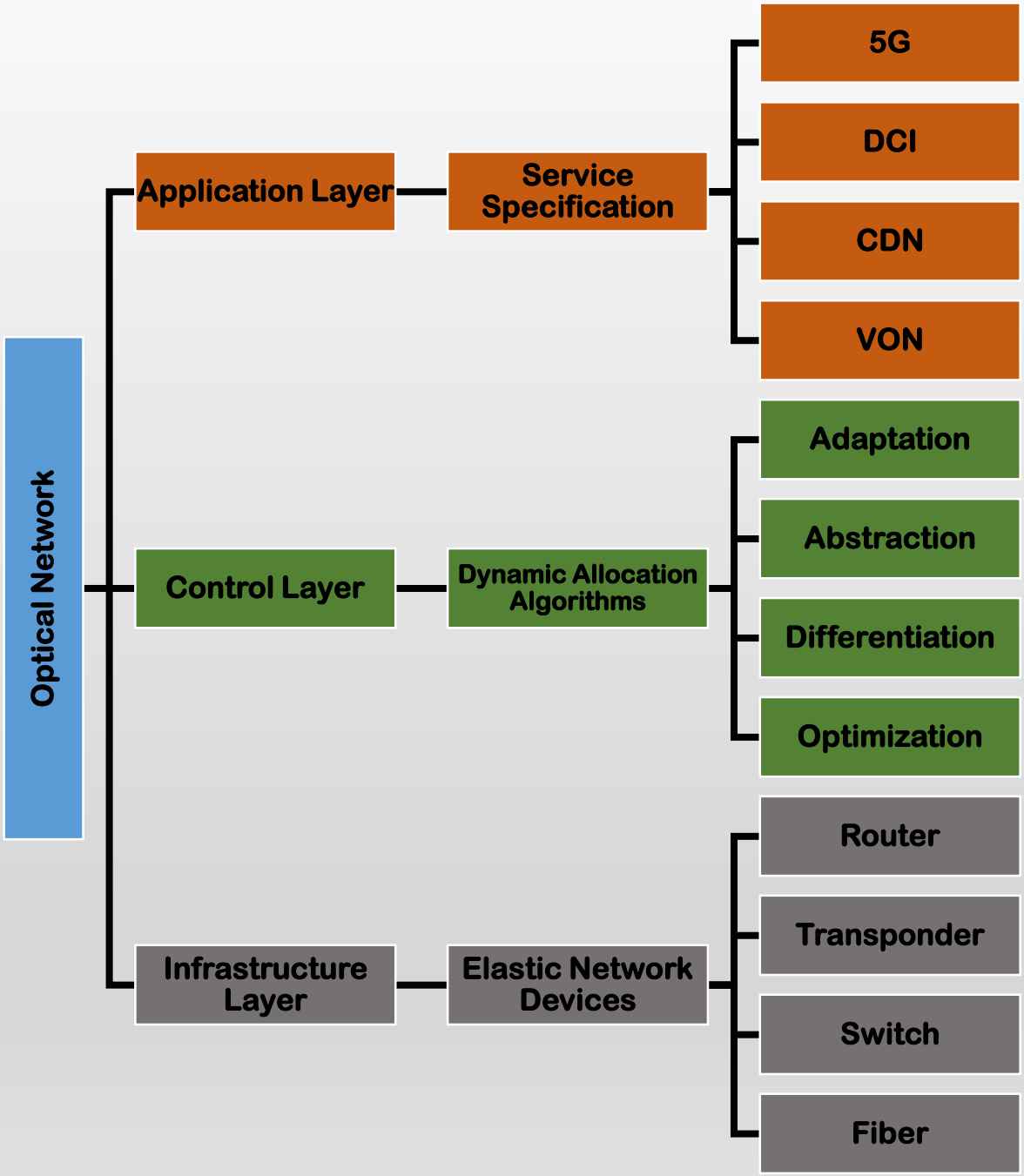
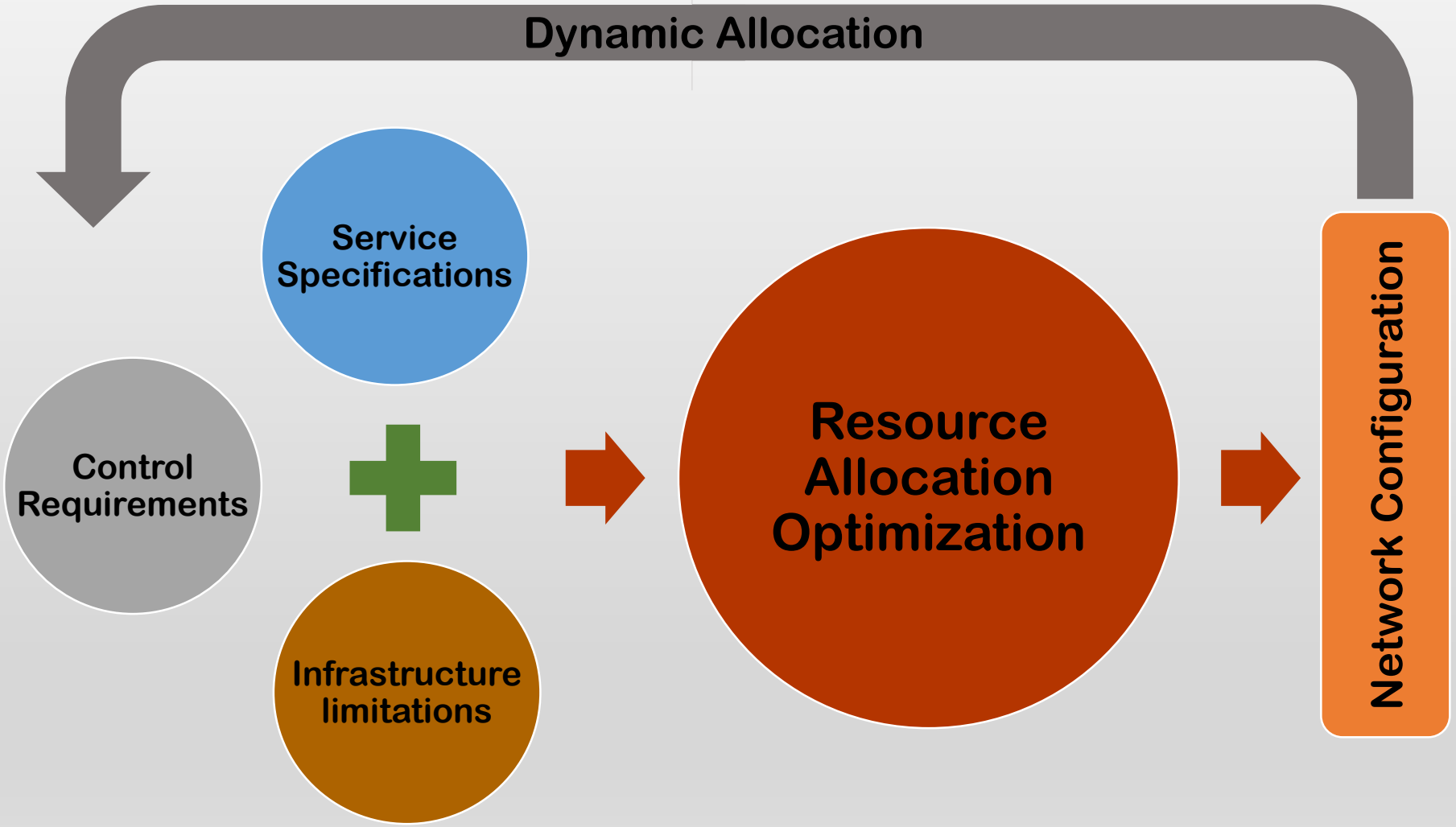
Recent Achievements

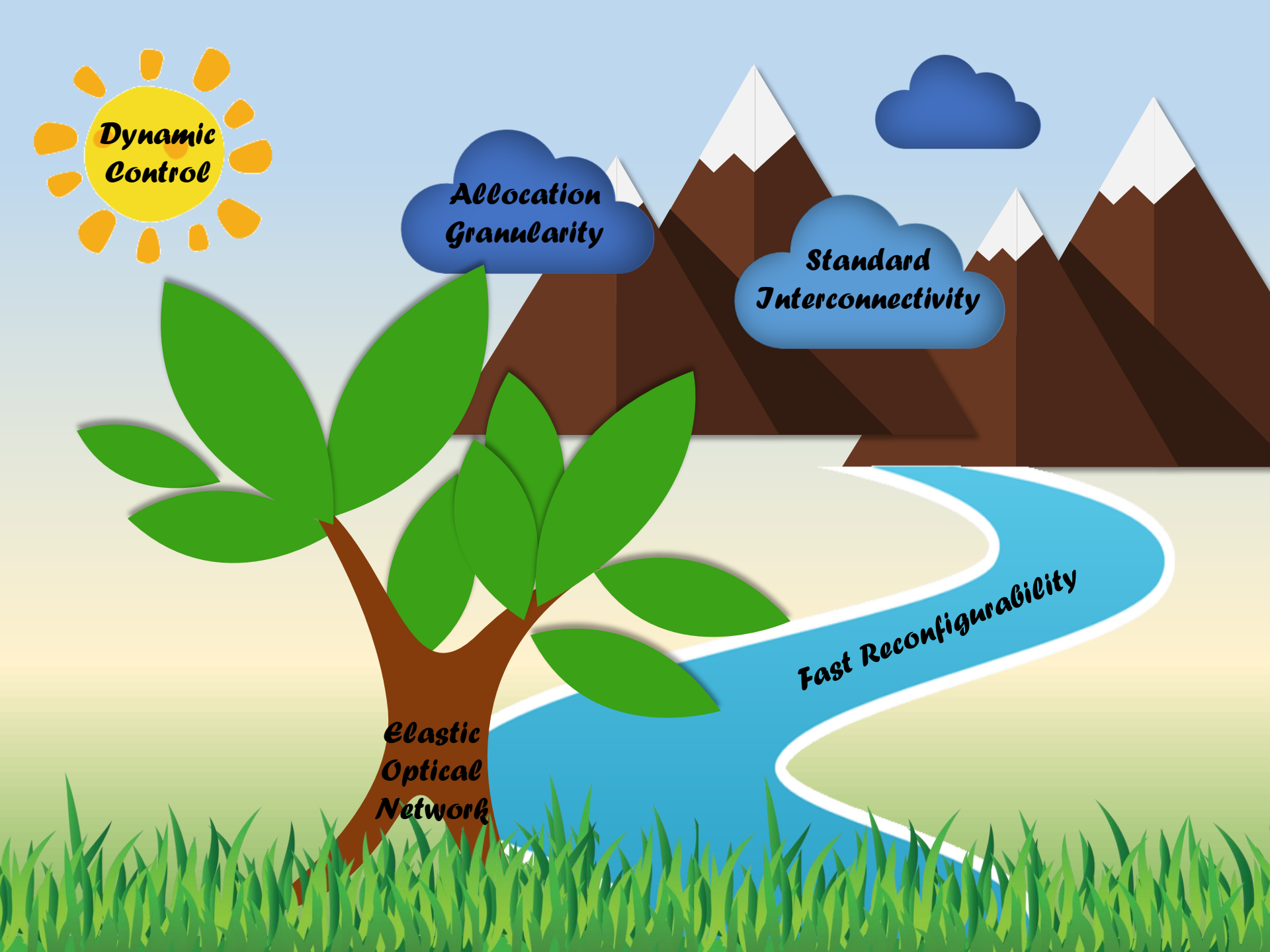

Optical Network
Application Layer
Service Specification
5G
DCI
CDN
VON
Control Layer
Fixed Allocation Algorithms
Infrastructure Layer
Inelastic Network Devices
Router
Transponder
Switch
Fiber

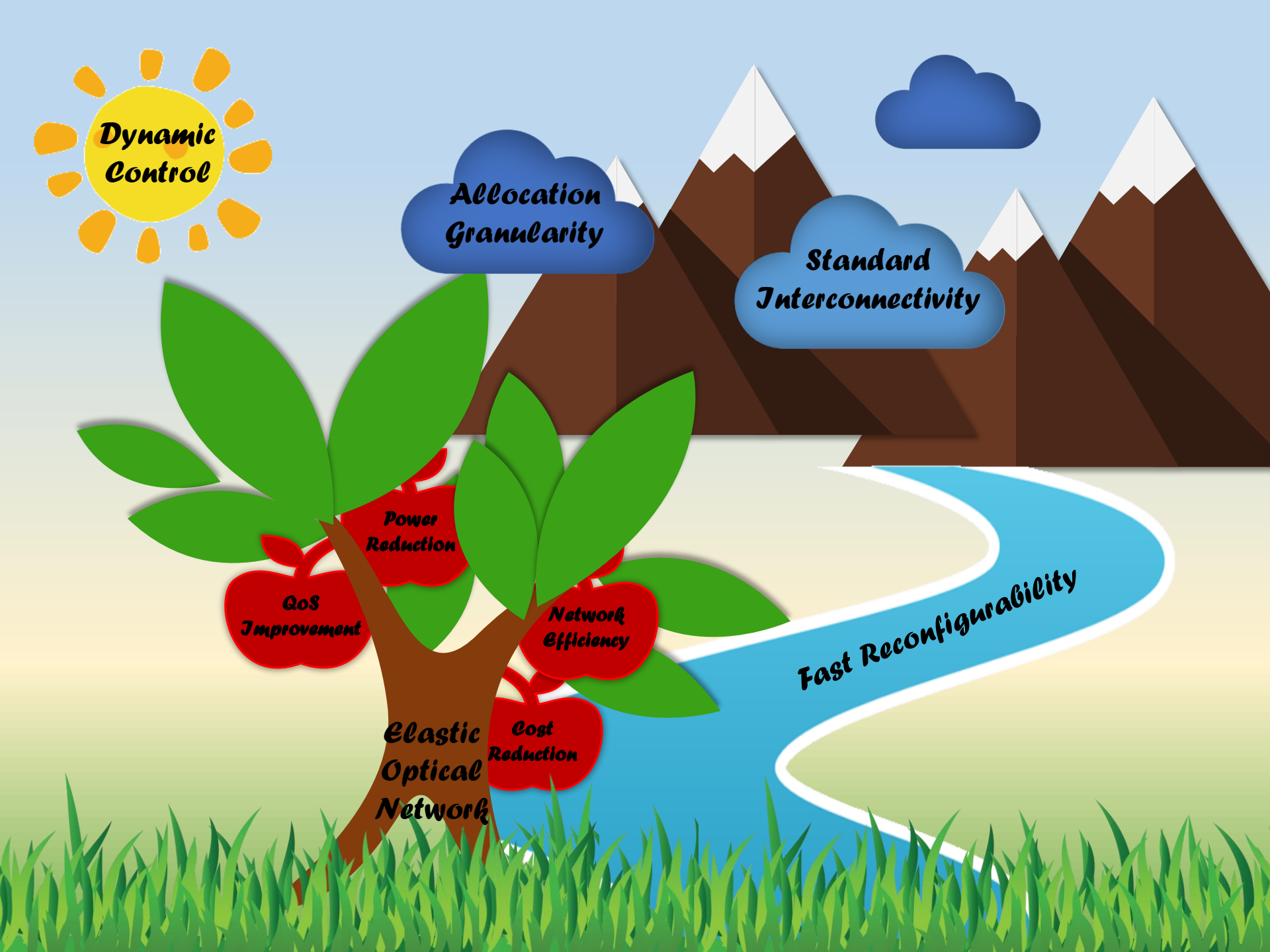

BPSK
QPSK
8QAM
16QAM
Modulation scheme
10%
20%
0%
30%
FEC overhead
Tx
Rx
Line interface
Client interface
Symbol rate
0 20 40 60 80 100 GBaud
Central wavelength of channel
1530 1550 1570 1590 1610 nm
Control interface
Number of optical carriers
1 2 3 4 5 6 7 8
Client port rate
100G 200G 400G 1T Variable

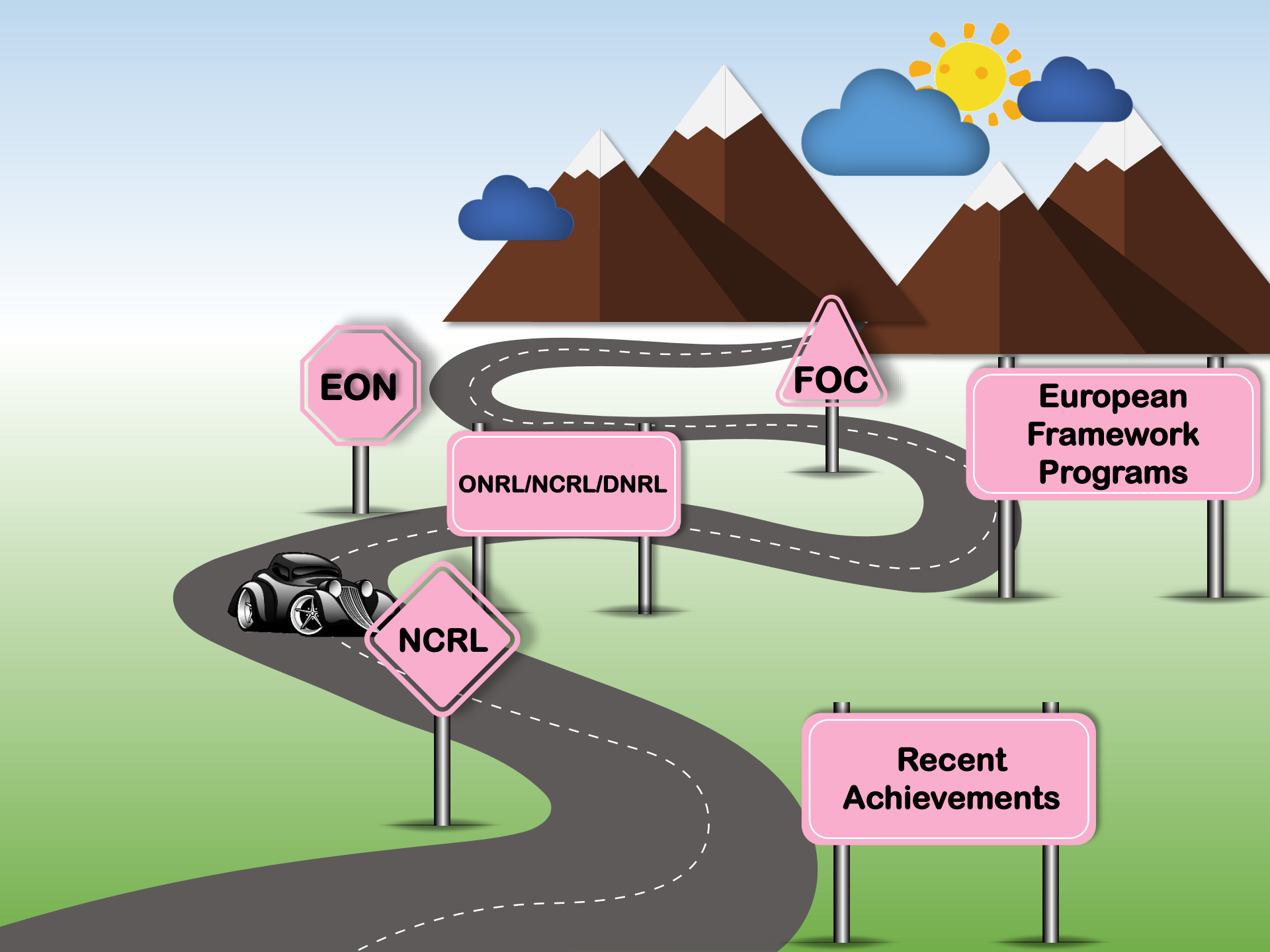

SPACE
SPATIAL MULTIPLEXING
Fiber ribbons
Multi-core
Few-mode
INTEGRATION OPTIONS
POLARIZATION
Q
x pol.
I
y pol.
I
Q
FREQUENCY
SUPERCHANNELS
1.5 Tbit/s in 263 GHz
AMPLIFICATION BANDS
Loss (dB)
1.2
0.9
0.6
0.3
0
O
E
S
C
L
1,260
1,360
1,440
1,530
1,565
1,625
1,300 1,400 1,500 1,600
Wavelength (nm)
WDM
Pulse shaping
t
F
f
TIME
16 QAM
32 QAM
QUADRATURE


Optical Network
Application Layer
Service Specification
5G
DCI
CDN
VON
Control Layer
Dynamic Allocation Algorithms
Adaptation
Abstraction
Differentiation
Optimization
Infrastructure Layer
Elastic Network Devices
Router
Transponder
Switch
Fiber


Dynamic Allocation
Service Specifications
Control Requirements
Infrastructure limitations
Resource Allocation Optimization
Network Configuration


Dynamic Control
Allocation Granularity
Standard Interconnectivity
Fast Reconfigurability
Elastic Optical Network


Dynamic Control
Allocation Granularity
Standard Interconnectivity
Power Reduction
QoS Improvement
Network Efficiency
Cost Reduction
Elastic Optical Network
Fast Reconfigurability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FOC
European Framework Programs
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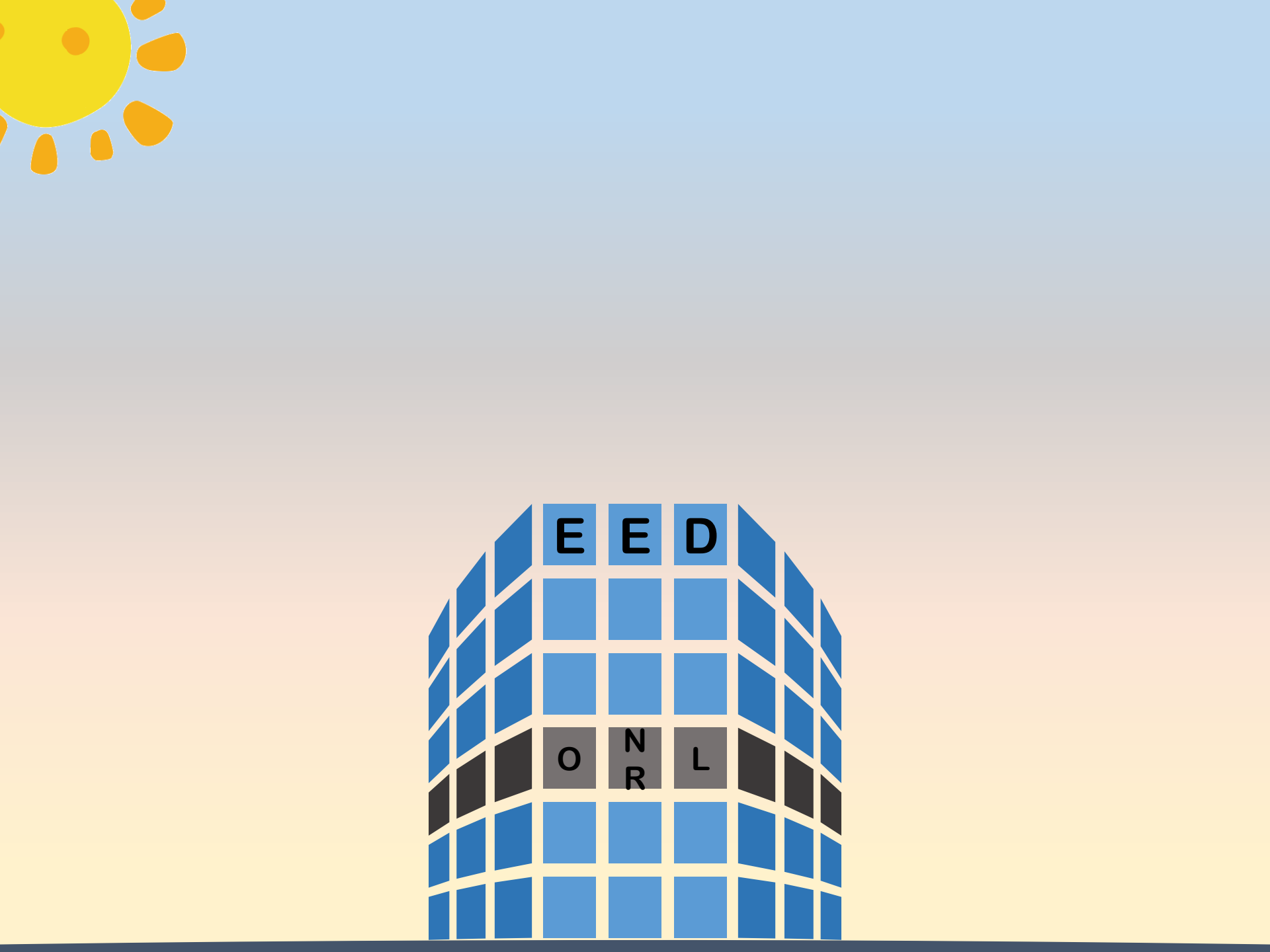
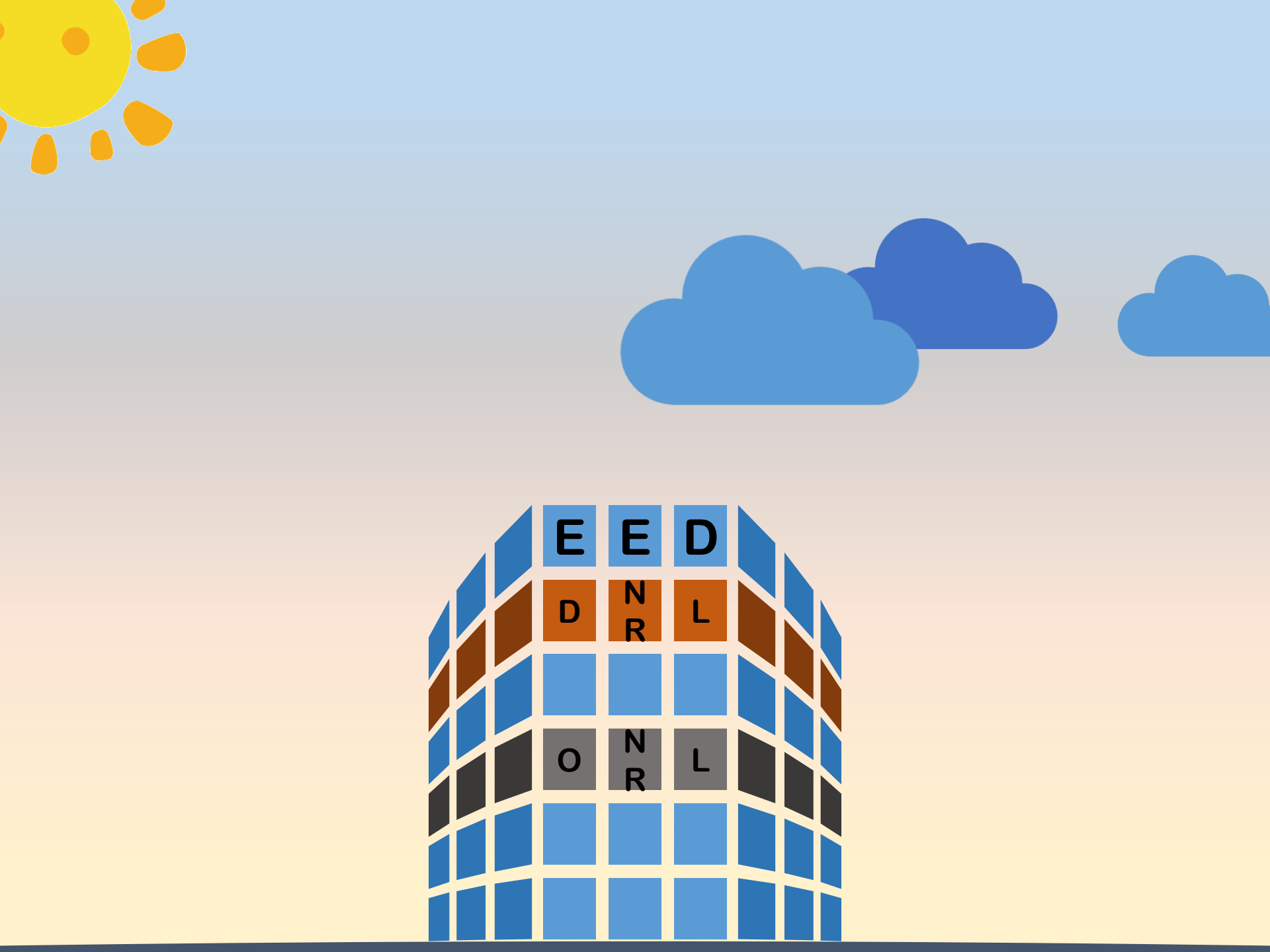
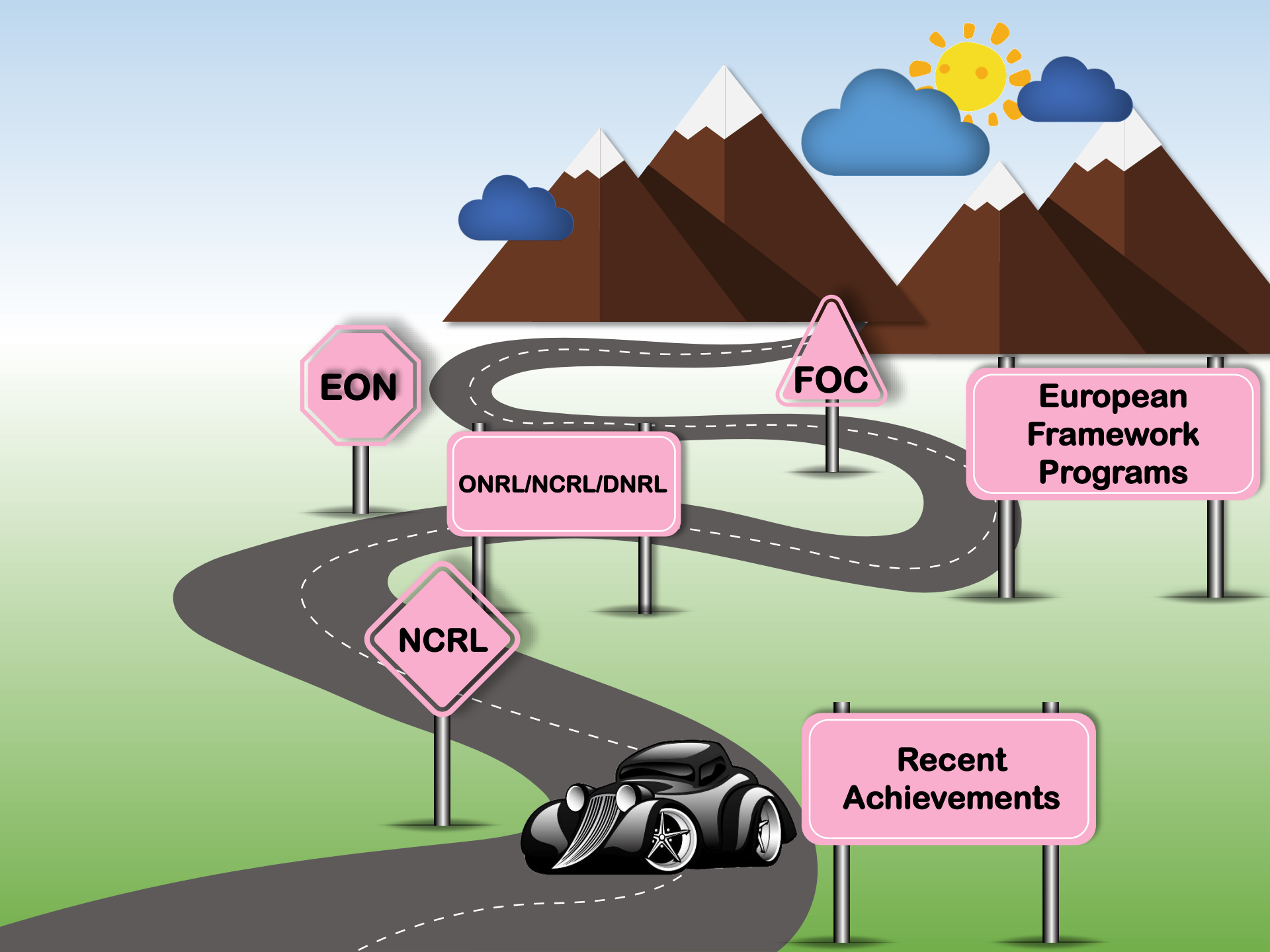
NCRL
Recent Achievements


E E D
O N L
R


E E D
D N L
R
O N L
R


E E D
D N L
N C L
O N L
R R R

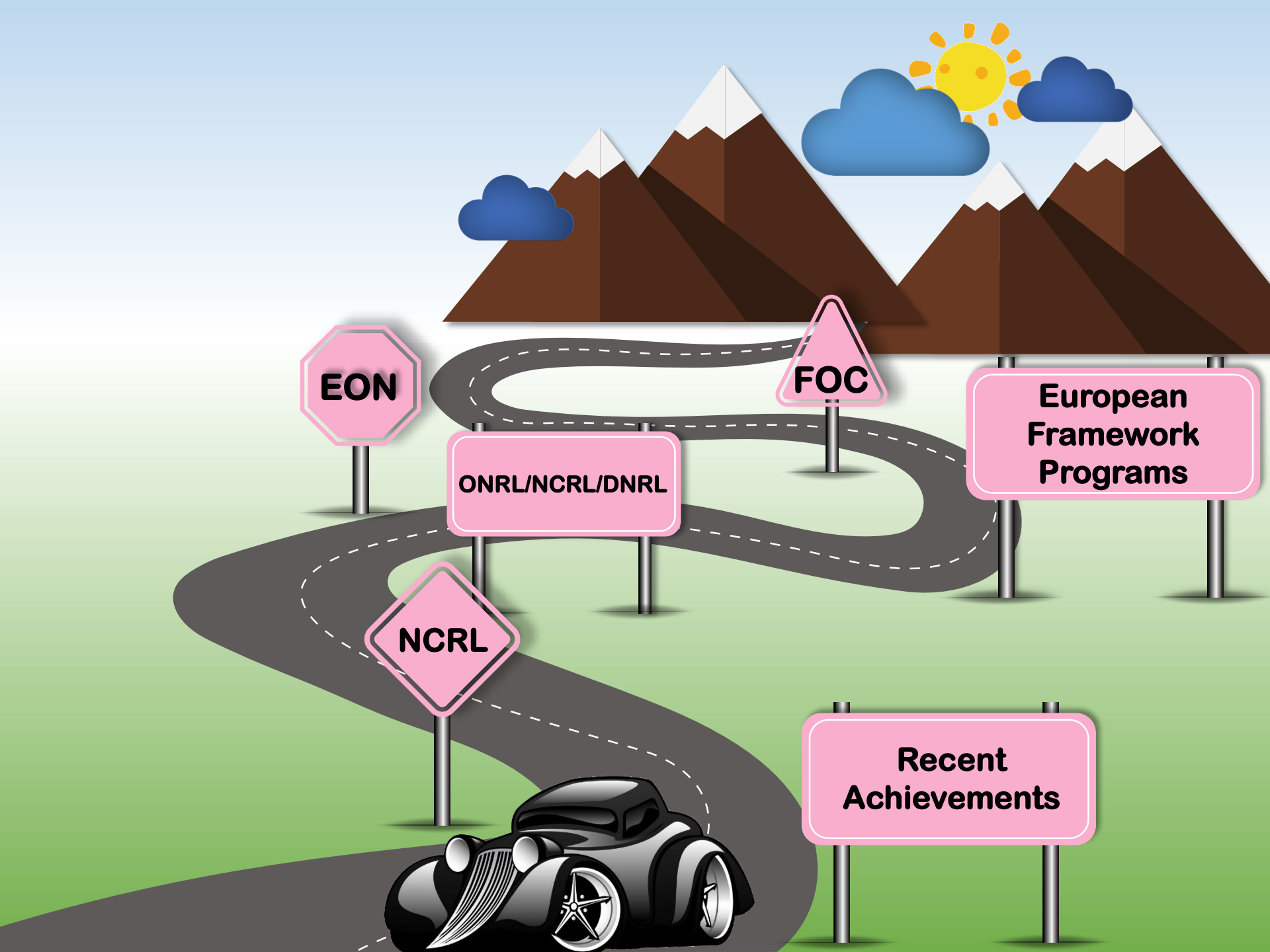

EON
FOC
European Framework Programs
ONRL/NCRL/DNRL
NCRL
Recent Achievements

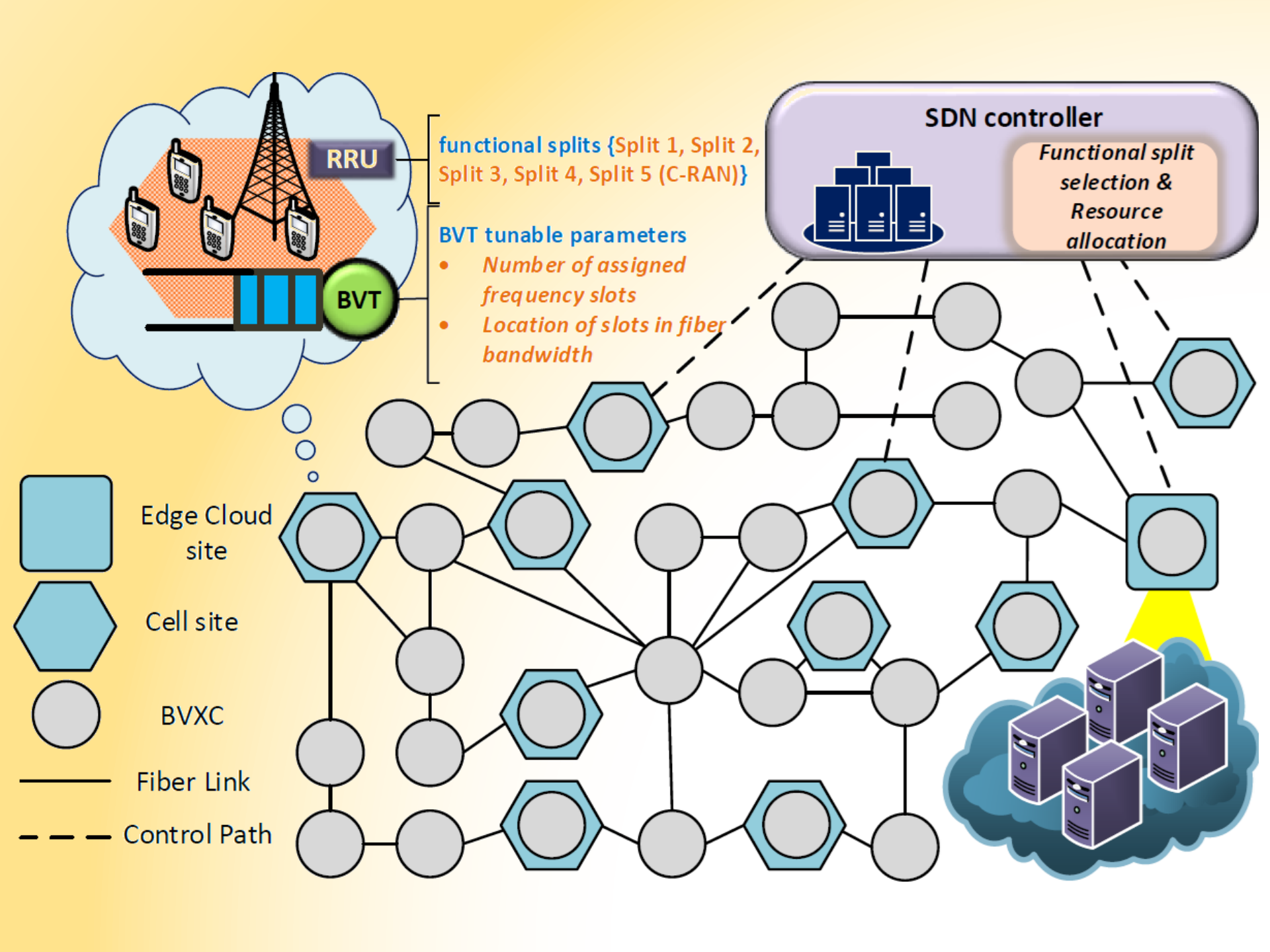

MED
TIC
EED
DNRL
NCRL
ONRL
FORCE
IED


MED
T I C
ED


MED
T I C
E E
D
N
O
F O R


Publications
Virtual Lab
Industrial Collaboration
Workshops
International Collaboration
Multi-disciplinary


EON
FOC
European Framework Programs
ONRL/NCRL/DNRL
NCRL
Recent Achievements


RRU
BVT
functional splits {Split 1, Split 2, Split 3, Split 4, Split 5 (C-RAN)}
BVT tunable parameters
Number of assigned frequency slots
Location of slots in fiber bandwidth
SDN controller
Functional split selection & Resource allocation
Edge Cloud site
Cell site
BVXC
Fiber Link
Control Path

$$\min_{\substack{\boldsymbol{x}[n],\boldsymbol{y}[n],\boldsymbol{t}[n]\\ \boldsymbol{b}[n],\boldsymbol{h}[n]}} \quad \overline{p} \quad \text{s.t.} \tag{3a}$$

$$\overline{a_i} \leqslant \overline{s_i}, \qquad i \in \mathbb{Z}_1^N \tag{3b}$$

$$h_i[n] + b_i[n] \leqslant M, \qquad i \in \mathbb{Z}_1^N \tag{3c}$$

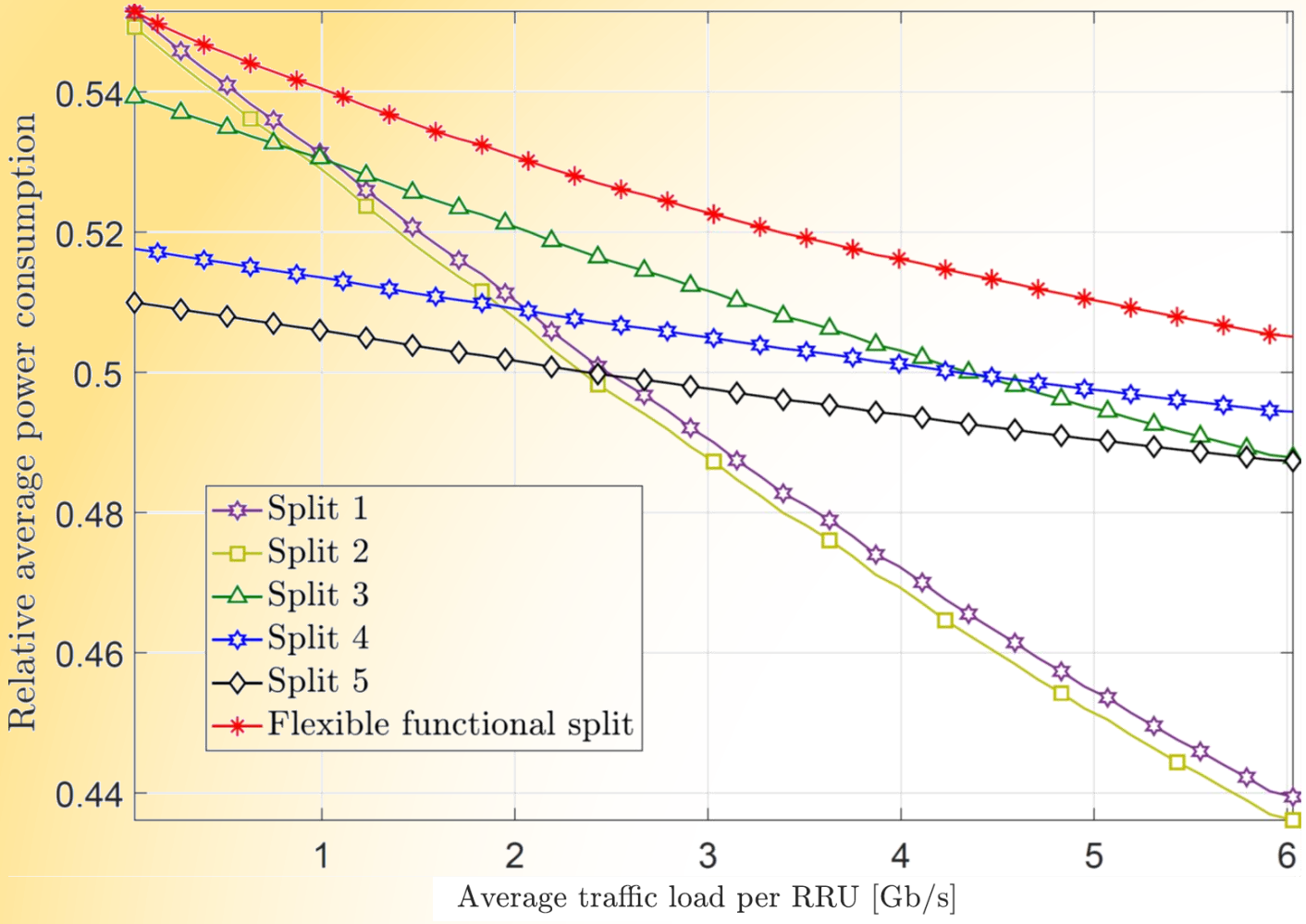
$$a_i[n] - b_i[n] \leqslant D, \qquad i \in \mathbb{Z}_1^N \tag{3d}$$

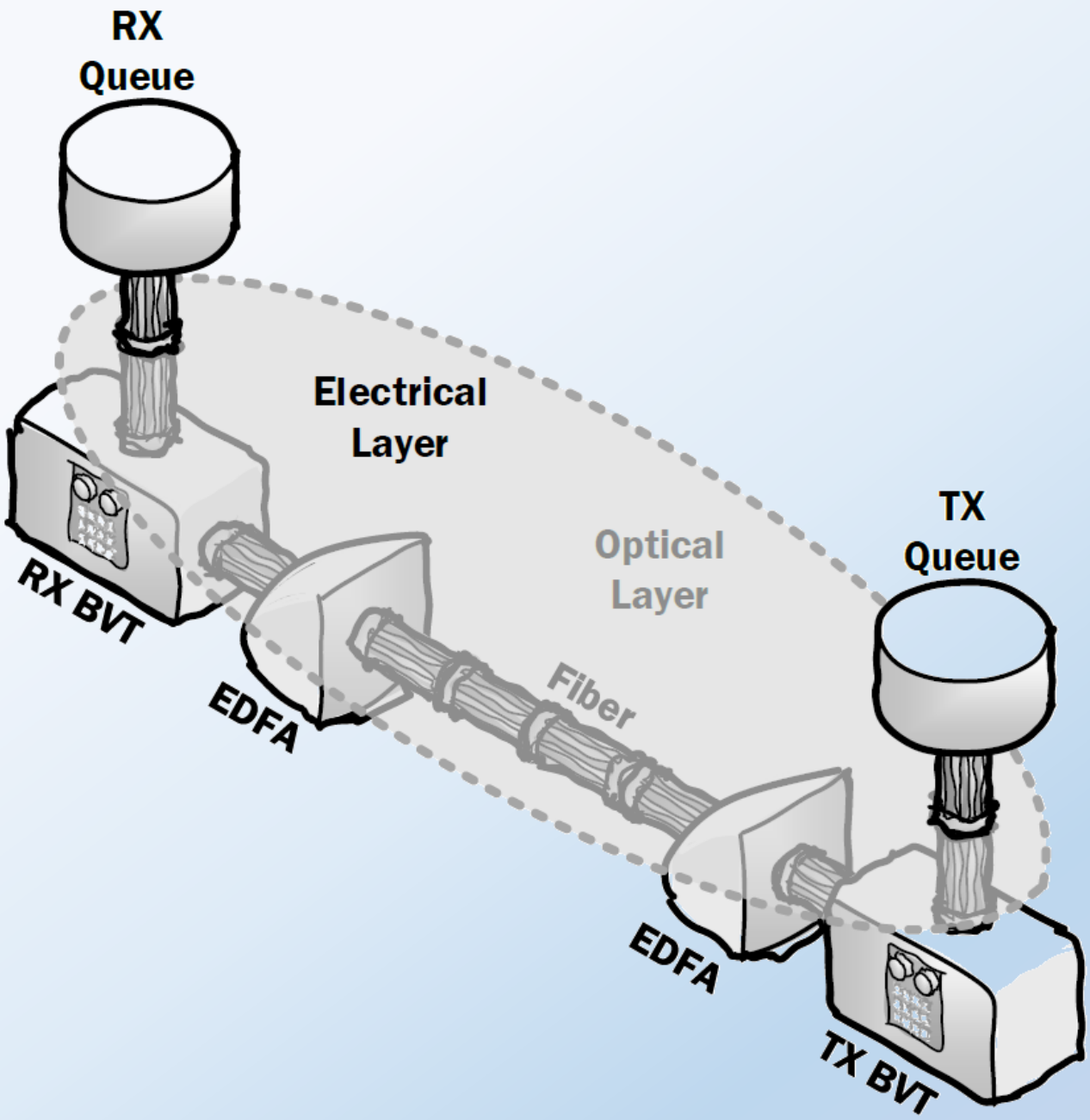
$$\sum_{k=1}^{K} x_{i,k}[n] = 1, \qquad i \in \mathbb{Z}_1^N \tag{3e}$$

$$b_i[n] \leqslant M y_i[n], \qquad i \in \mathbb{Z}_1^N \tag{3f}$$

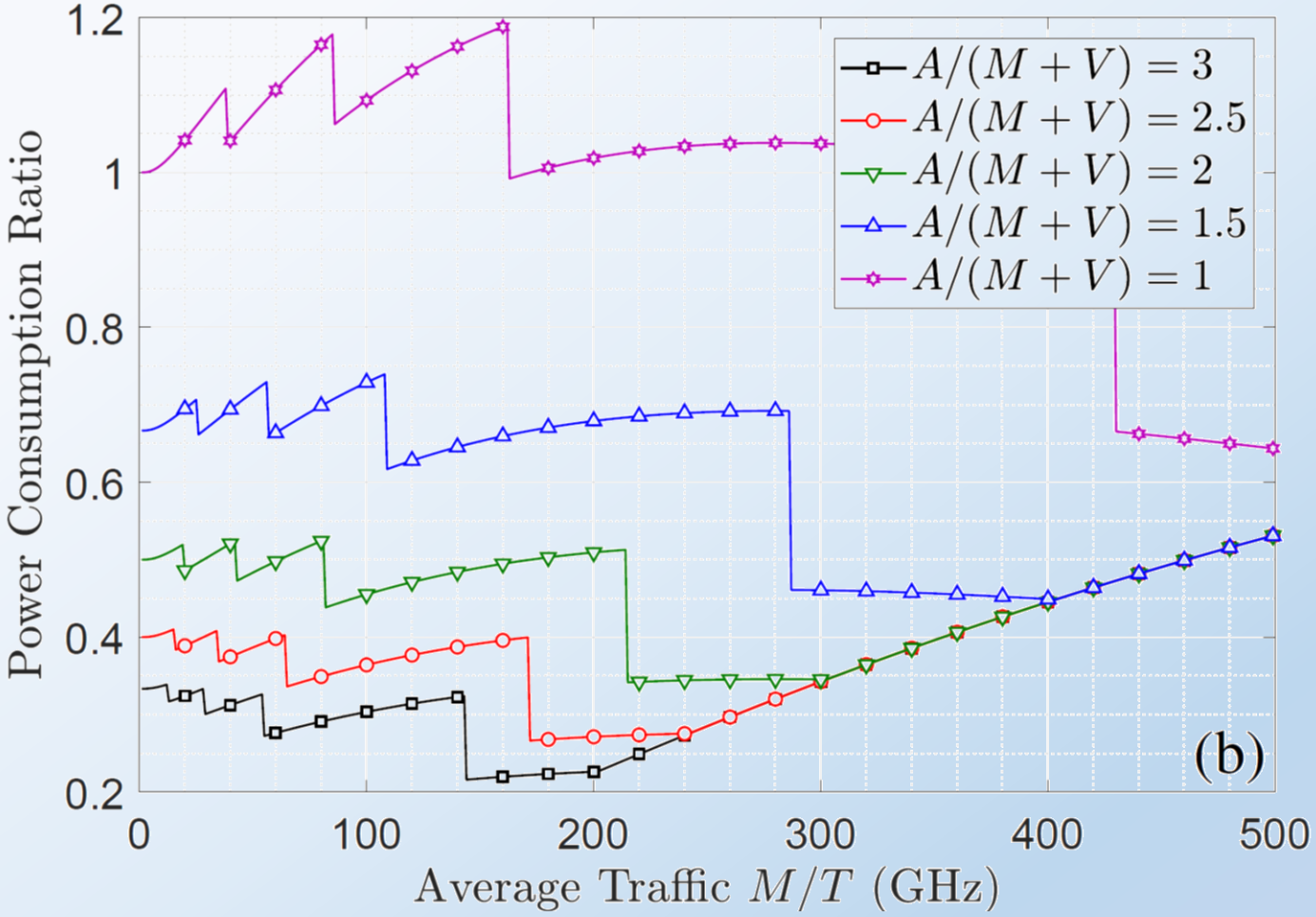
$$h_i[n] + b_i[n] + G \leqslant h_{i'}[n] + N\Big(3 - t_{i,i'}[n] - y_i[n] - y_{i'}[n]\Big), \quad i, i' \in \mathbb{Z}_1^N : \mathbf{P}_i \cap \mathbf{P}_{i'} \neq \varnothing \tag{3g}$$

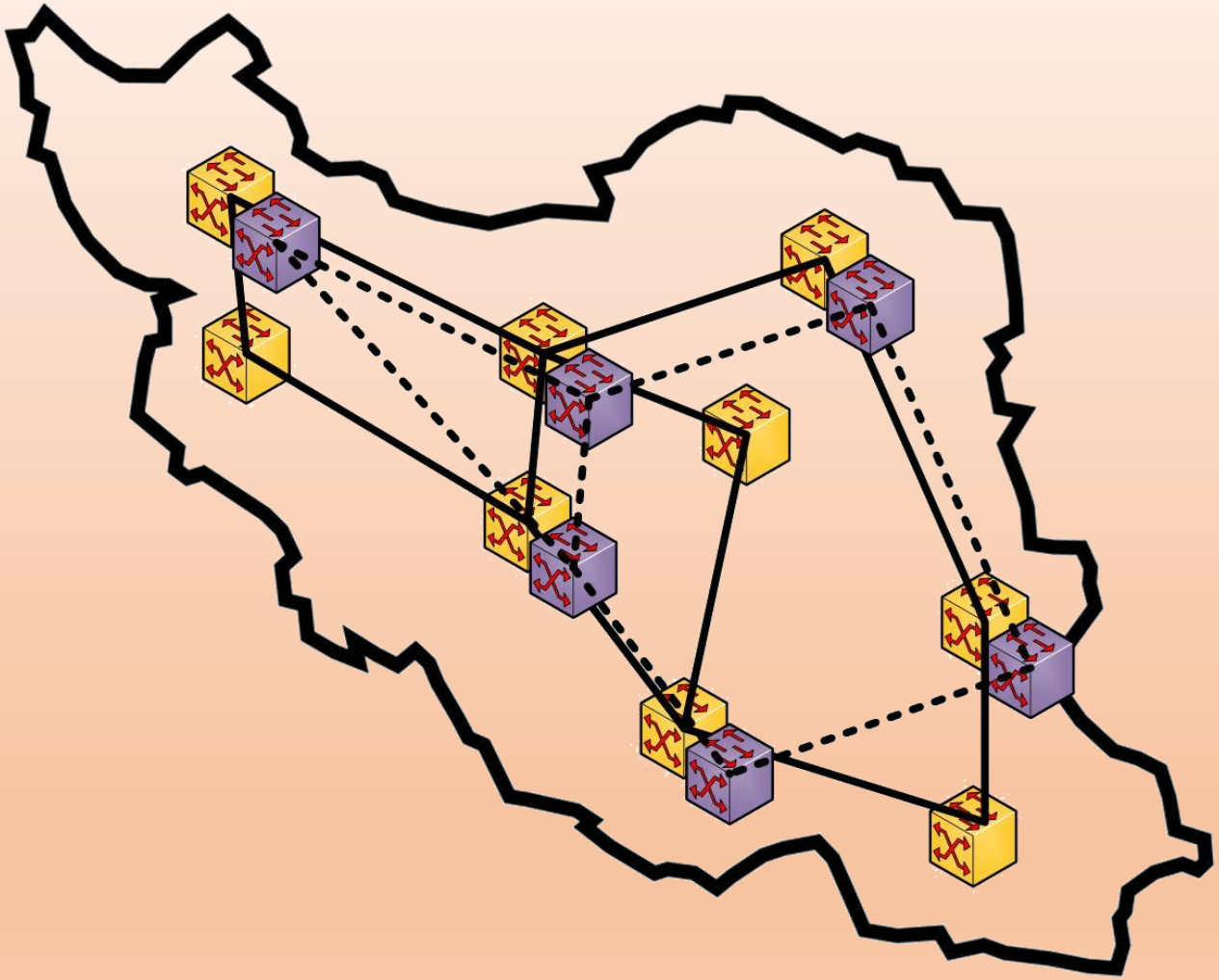
$$t_{i,i'}[n] + t_{i',i}[n] = 1, \quad i, i' \in \mathbb{Z}_1^N : i \neq i', \tag{3h}$$

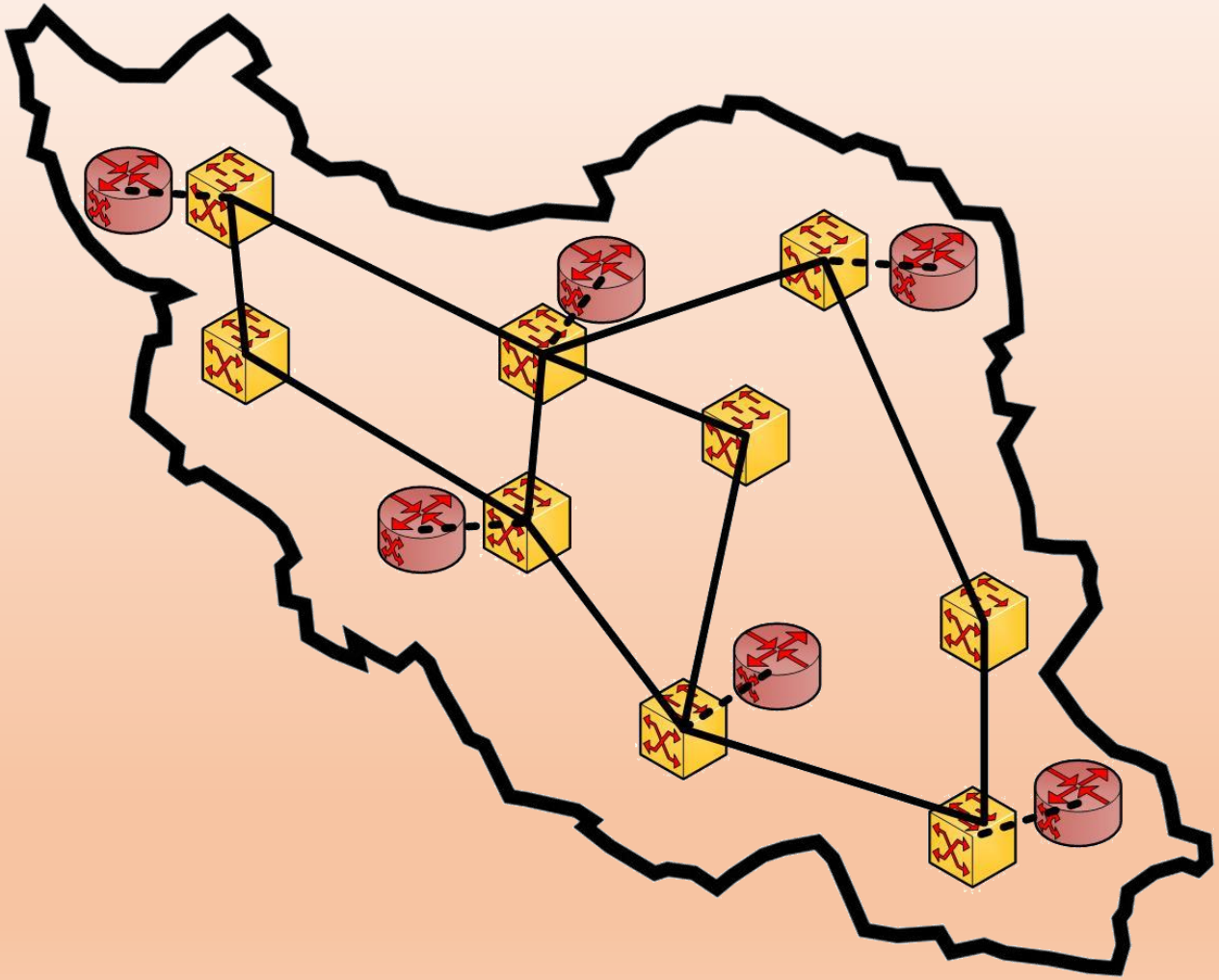

Relative average power consumption
0.54
0.52
0.5
0.48
0.46
0.44
1
2
3
4
5
6
Average traffic load per RRU [Gb/s]
Split 1
Split 2
Split 3
Split 4
Split 5
Flexible functional split

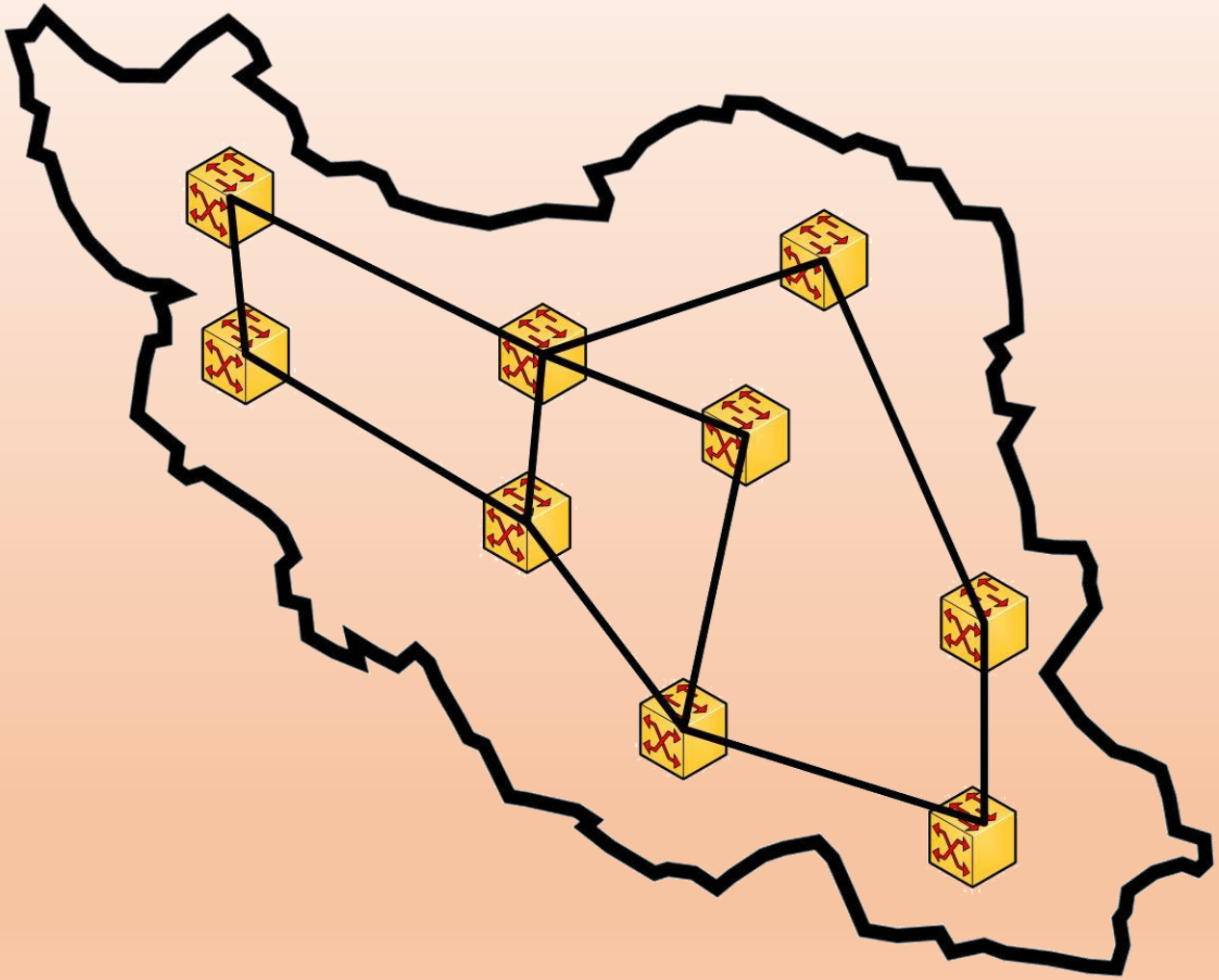

RX
Queue
Electrical
Layer
Optical
Layer
TX
Queue
RX BVT
EDFA
Fiber
EDFA
TX BVT

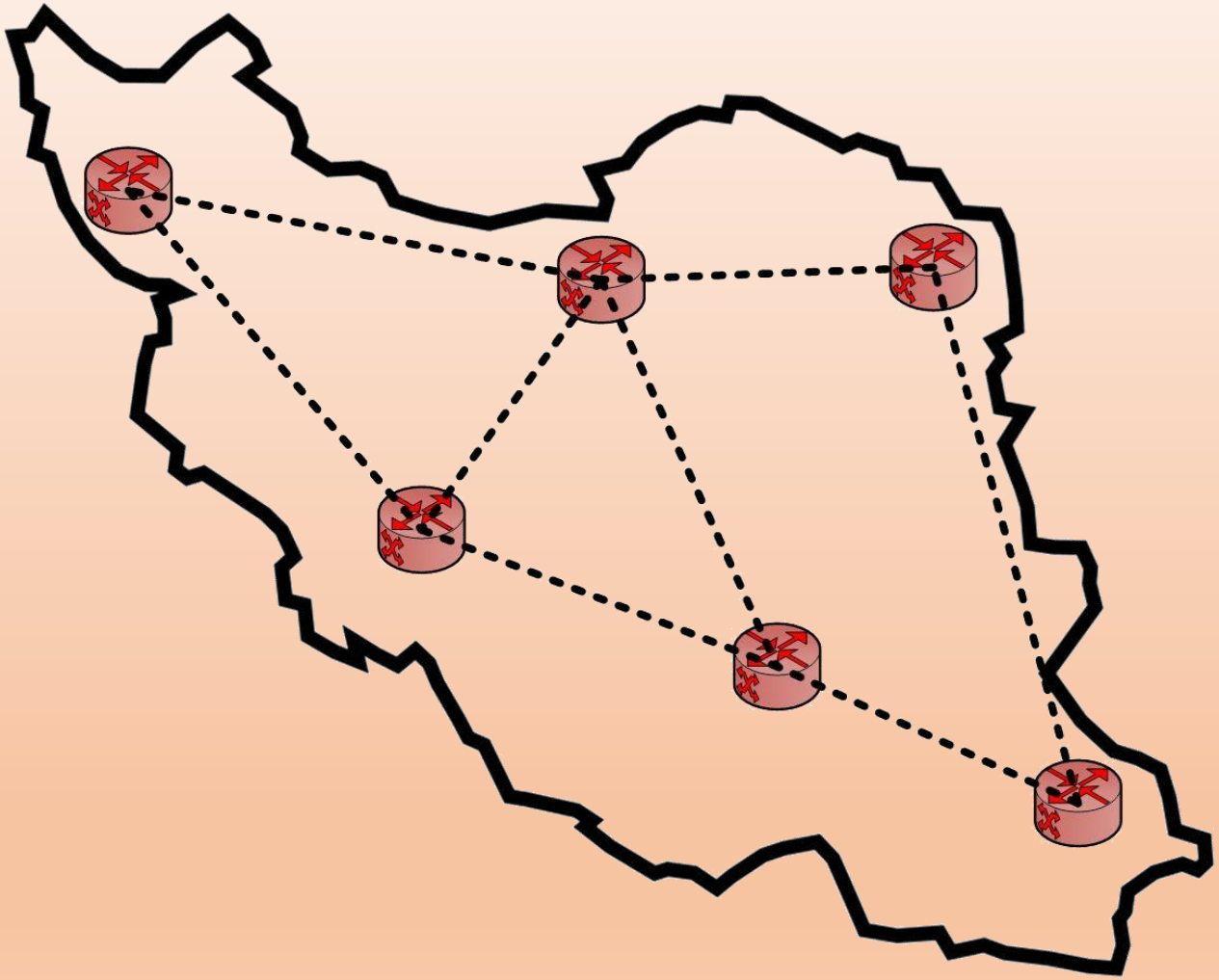
Scenario	Performance Metrics	
Lasing-Limited Rigid Configuration $C_k = 2k$ $R_k = \lfloor T\Delta C_k \rfloor$	$\bar{c} = C_K$	(3a)
	$\bar{d} = \left[M\mathrm{U}(\frac{MR_K}{N^2}, \infty) - R_K\mathrm{U}(\frac{R_K}{M}, \infty)\right]\mathrm{V}(R_K, \infty) + \left[M\mathrm{U}(\frac{MA}{N^2}, \infty) - A\mathrm{U}(\frac{A}{M}, \infty)\right]\mathrm{V}(0, R_K)$	(3b)
	$\bar{s} = \frac{R_K}{TC_K}\mathrm{V}(R_K, \infty) + \frac{A}{TC_K}\mathrm{V}(0, R_K)$	(3c)
	$\bar{p} = \frac{R_K(E+FC_K)}{TC_K}\mathrm{V}(R_K, \infty) + \frac{A(E+FC_K)}{TC_K}\mathrm{V}(0, R_K)$	(3d)
Lasing-Limited Elastic Configuration $C_k = 2k$ $R_k = \lfloor T\Delta C_k \rfloor$	$\bar{c} = C_K$	(3e)
	$\bar{d} = M\mathrm{U}(\frac{MR_K}{N^2}, \infty) - R_K\mathrm{U}(\frac{R_K}{M}, \infty)$	(3f)
	$\bar{s} = \frac{R_K}{TC_K}\mathrm{U}(\frac{R_K}{M}, \infty) + \frac{M}{TC_K}\mathrm{U}(0, \frac{MR_K}{N^2})$	(3g)
	$\bar{p} = \frac{R_K(E+FC_K)}{TC_K}\mathrm{U}(\frac{R_K}{M}, \infty) + \frac{M(E+FC_K)}{TC_K}\mathrm{U}(-\infty, \frac{MR_K}{N^2})$	(3h)
SNR-Limited Rigid Configuration $C_k = 2k$ $R_k = \lfloor T\Upsilon C_k/\sqrt{\Psi_k^3} \rfloor$	$\bar{c} = C_1\mathrm{V}(R_1, \infty) + C_K\mathrm{V}(0, R_K) + \sum_{k=1}^{K-1}\frac{A}{TC_k}\mathrm{V}(R_{k+1}, R_k)$	(3i)
	$\bar{d} = \left[M\mathrm{U}(\frac{MR_1}{N^2}, \infty) - R_1\mathrm{U}(\frac{R_1}{M}, \infty)\right]\mathrm{V}(R_1, \infty) + \left[M\mathrm{U}(\frac{MA}{N^2}, \infty) - A\mathrm{U}(\frac{A}{M}, \infty)\right]\mathrm{V}(0, R_1)$	(3j)
	$\bar{s} = \frac{R_1}{TC_1}\mathrm{V}(R_1, \infty) + \frac{A}{TC_K}\mathrm{V}(0, R_K) + \sum_{k=1}^{K-1}\frac{A}{TC_k}\mathrm{V}(R_{k+1}, R_k)$	(3k)
	$\bar{p} = \frac{R_1(E+FC_1)}{TC_1}\mathrm{V}(R_1, \infty) + \frac{A(E+FC_K)}{TC_K}\mathrm{V}(0, R_K) + \sum_{k=1}^{K-1}\frac{A(E+FC_k)}{TC_k}\mathrm{V}(R_{k+1}, R_k)$	(3l)
SNR-Limited Elastic Configuration $C_k = 2k$ $R_k = \lfloor T\Upsilon C_k/\sqrt{\Psi_k^3} \rfloor$	$\bar{c} = C_1\mathrm{U}(\frac{R_1}{M}, \infty) + C_K\mathrm{U}(0, \frac{MR_K}{N^2}) + \sum_{k=1}^{K-1}C_k\mathrm{U}(\frac{MR_{k+1}}{N^2}, \frac{MR_k}{N^2})$	(3m)
	$\bar{d} = M\mathrm{U}(\frac{MR_1}{N^2}, \infty) - R_1\mathrm{U}(\frac{R_1}{M}, \infty)$	(3n)
	$\bar{s} = \frac{R_1}{TC_1}\mathrm{U}(\frac{R_1}{M}, \infty) + \frac{M}{TC_K}\mathrm{U}(0, \frac{MR_K}{N^2}) + \sum_{k=1}^{K-1}\frac{M}{TC_k}\mathrm{U}(\frac{MR_{k+1}}{N^2}, \frac{MR_k}{N^2})$	(3o)
	$\bar{p} = \frac{R_1(E+FC_1)}{TC_1}\mathrm{U}(\frac{R_1}{M}, \infty) + \frac{M(E+FC_K)}{TC_K}\mathrm{U}(0, \frac{MR_K}{N^2}) + \sum_{k=1}^{K-1}\frac{M(E+FC_k)}{TC_k}\mathrm{U}(\frac{MR_{k+1}}{N^2}, \frac{MR_k}{N^2})$	(3p)

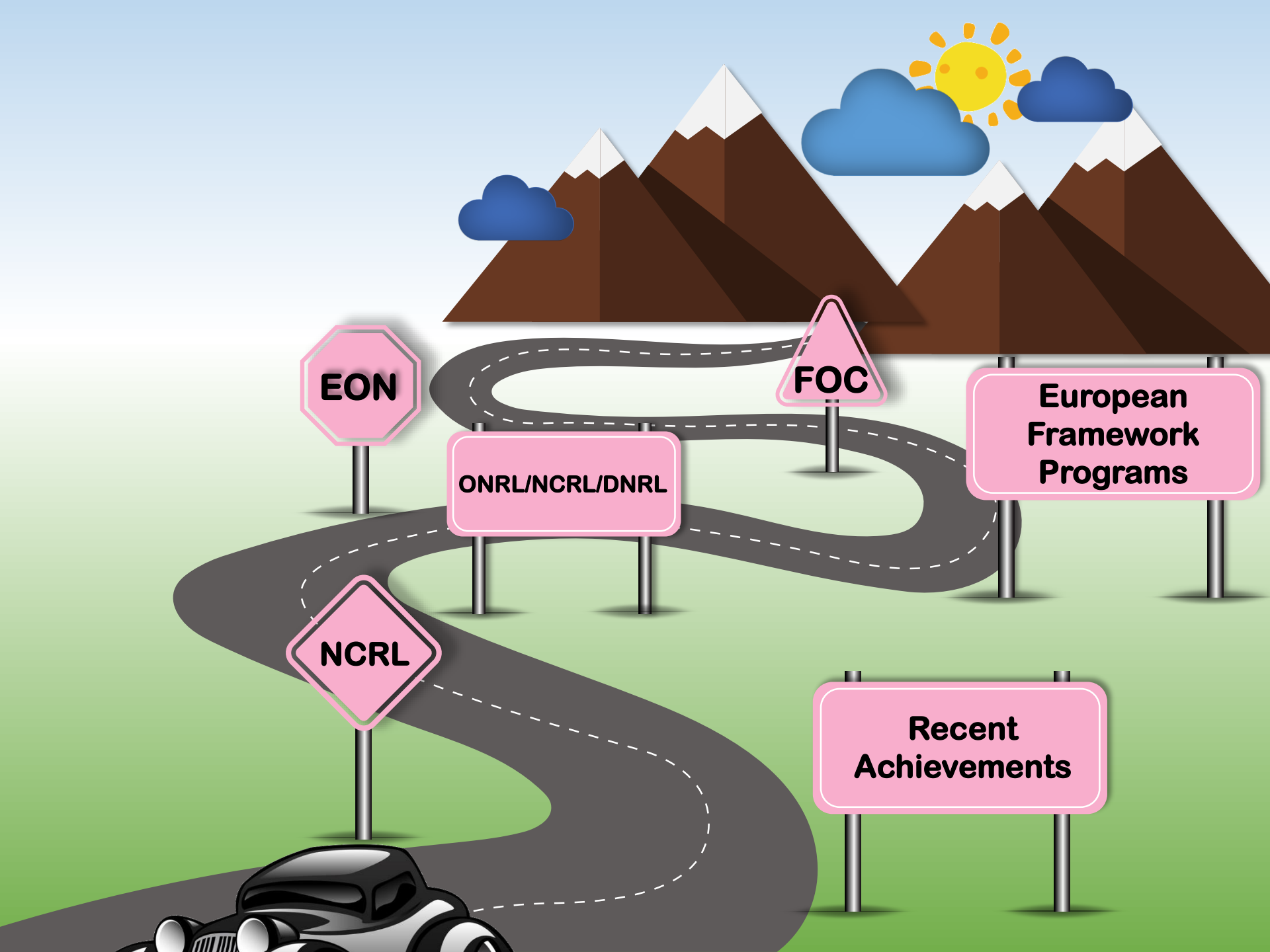

Power Consumption Ratio
1.2
1
0.8
0.6
0.4
0.2
0
100
200
300
400
500
Average Traffic M/T (GHz)
$A/(M+V) = 3$
$A/(M+V) = 2.5$
$A/(M+V) = 2$
$A/(M+V) = 1.5$
$A/(M+V) = 1$
(b)







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European Framework Programs
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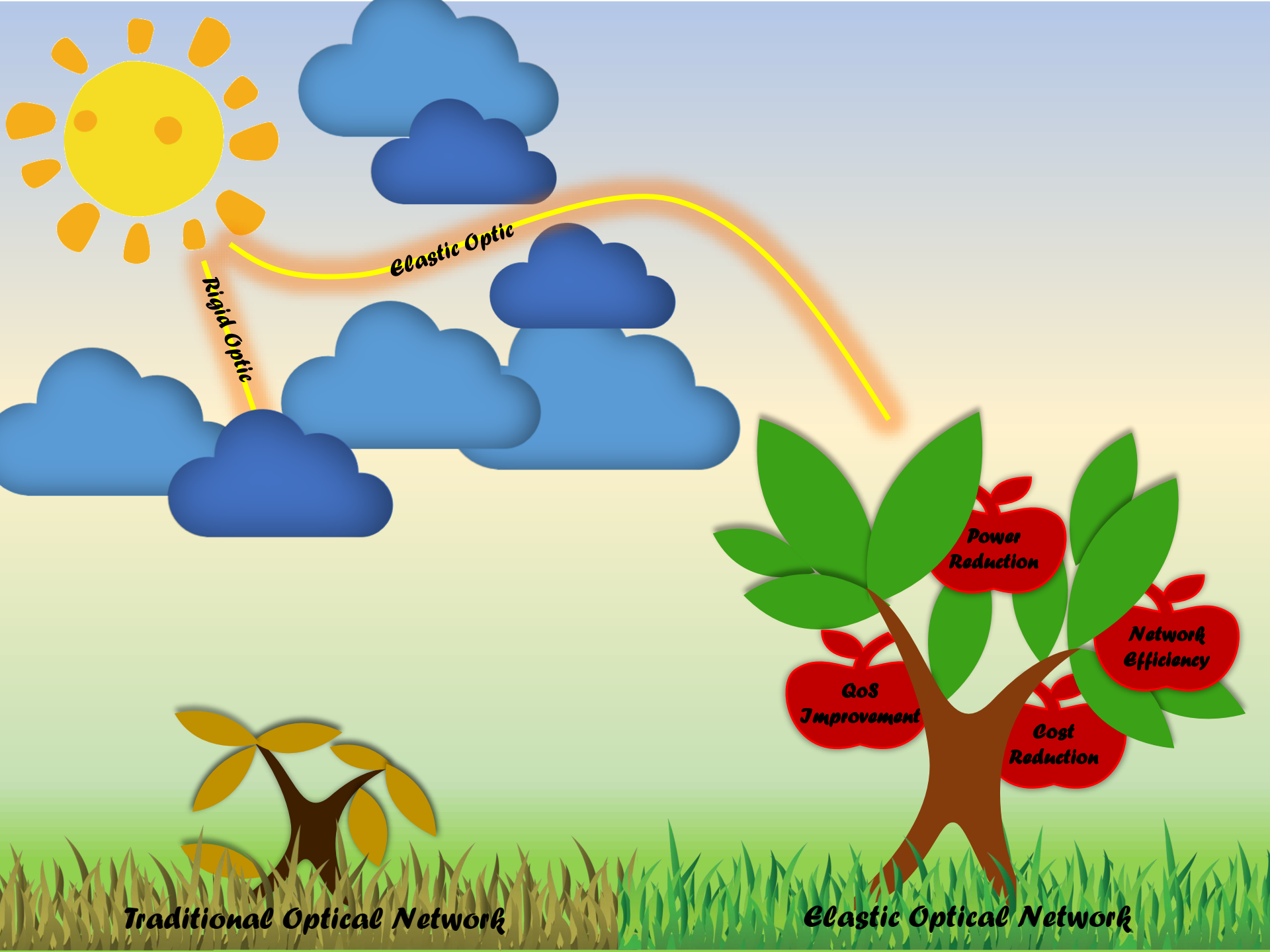
NCRL
Recent Achievements


Elastic Optic
Rigid Optic
Power Reduction
Network Efficiency
QoS Improvement
Cost Reduction
Traditional Optical Network
Elastic Optical Network