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Can 5G New Radio Sidelink Provide More Capacity To Public Safety?

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ACRONYMS

- 5G: The Fifth Generation Mobile Network
- AGC: Automatic Gain Control
- BWP: Bandwidth Part
- DM-RS: Demodulation Reference Signal
- eMBB: Enhanced Mobile Broadband
- HARQ: Hybrid Automatic Repeat Request
- LTE: Long Term Evolution
- MCS: Modulation and Coding Scheme
- MIMO: Multiple Input Multiple Output
- MMTC: Massive Machine Type Communications
- NG-RAN: Next-Generation Radio Access Network
- NR: New Radio
- PSCCH: Physical Sidelink Control Channel
- PSFCH: Physical Sidelink Feedback Channel
- PSSCH: Physical Sidelink Shared Channel
- QAM: Quadrature Amplitude Modulation
- QoS: Quality of Service
- RB: Resource Block
- RE: Resource Element
- Rx: Receive
- SCI2: 2nd-Stage Sidelink Control Information
- SCS: Subcarrier Spacing
- SINR: Signal-to-Interference-plus-Noise-Ratio
- SL: Sidelink
- Tx: Transmit
- UE: User Equipment
- URLLC: Ultra-Reliable and Low Latency Communications

OUTLINE

Overview

- Motivation
- Capacity related 5G New Radio (NR) configurations

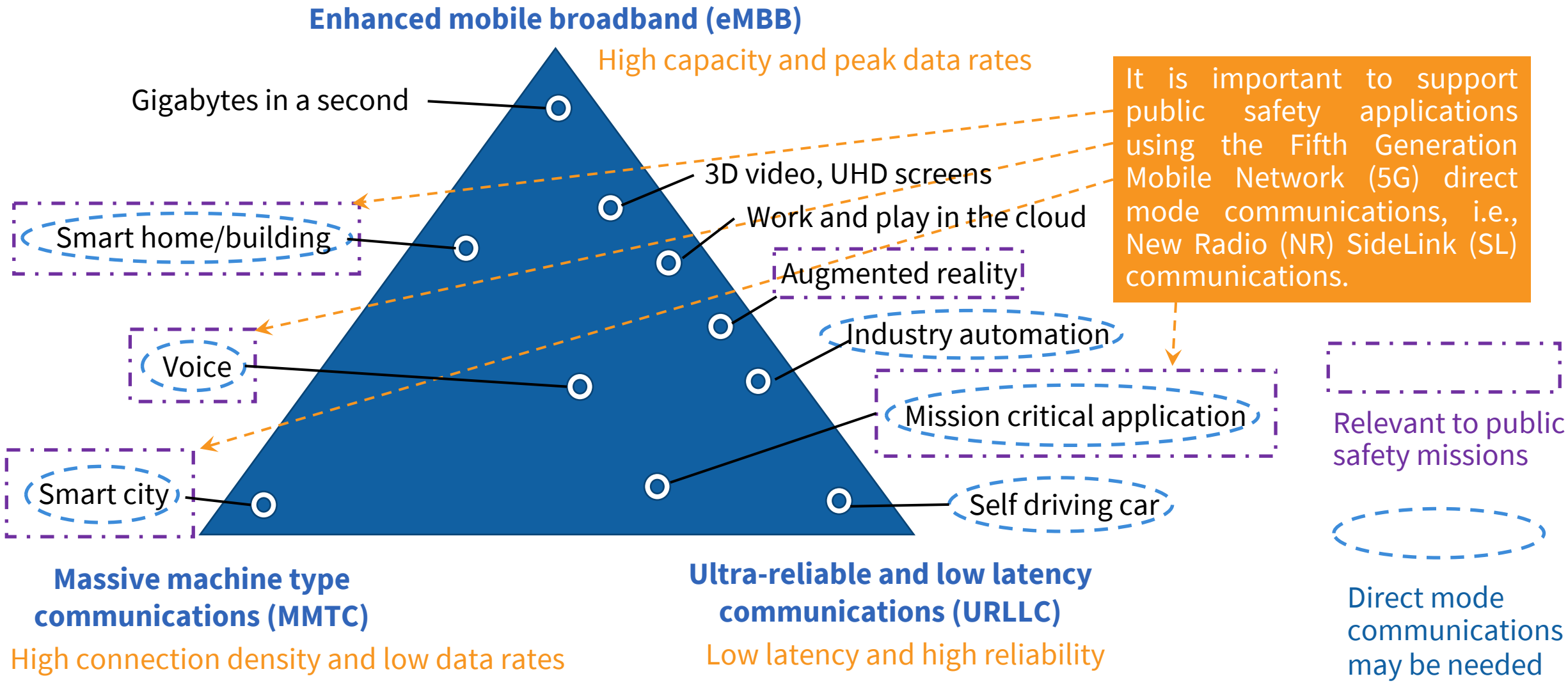
Capacity Study

- How does 5G NR sidelink capacity vary under NR's flexible configurations?
- Does NR improve capacity over LTE for public safety?
- What are the major NR features that impact its capacity and by how much?

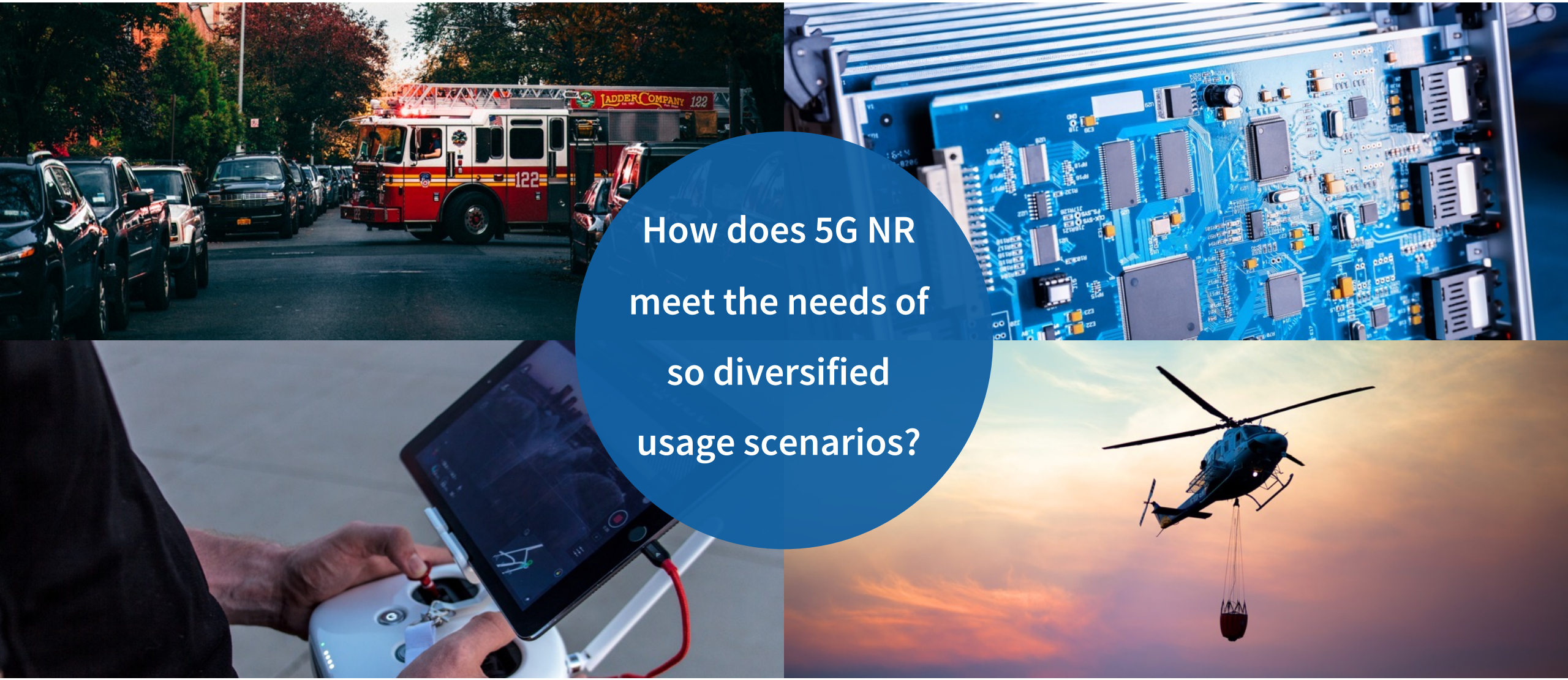
Summary

- Conclusion and next steps
- Ongoing research efforts for public safety communications

5G USAGE SCENARIOS



Ref: ITU, Rec. ITU-R M.2083-0, Figure 2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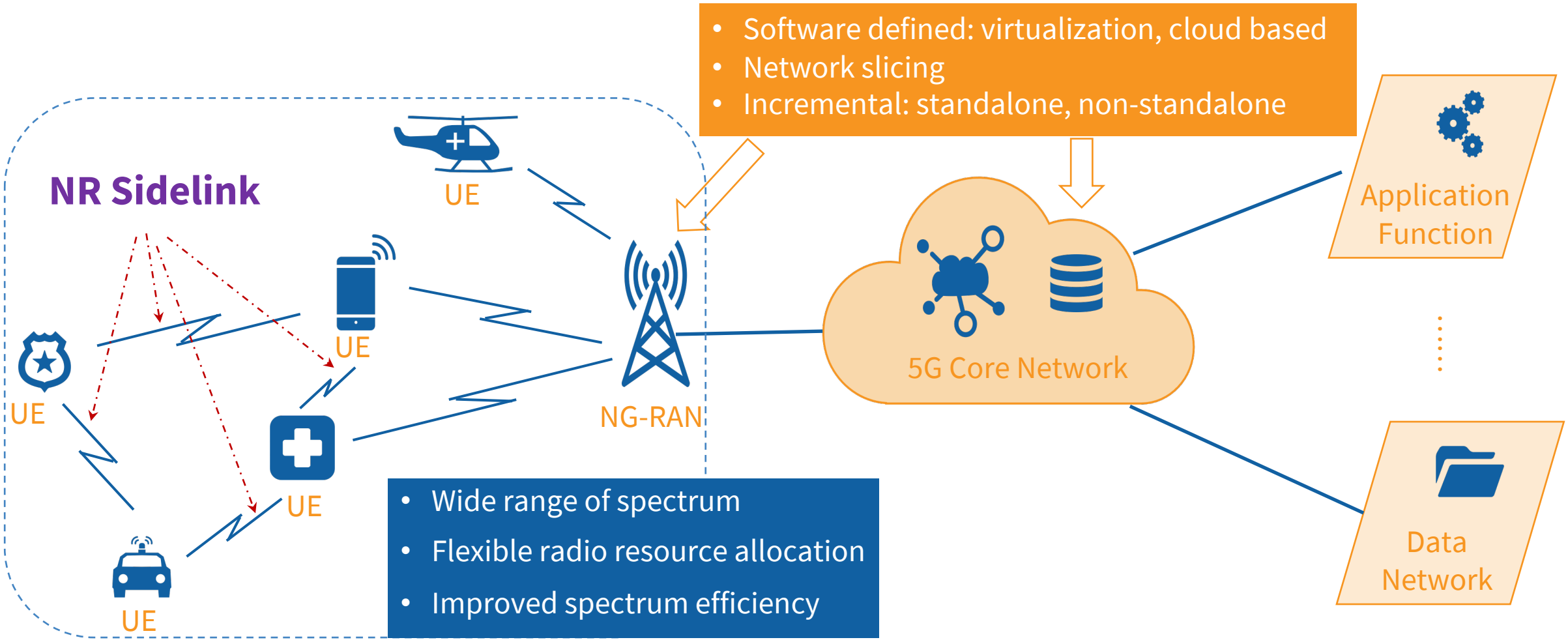
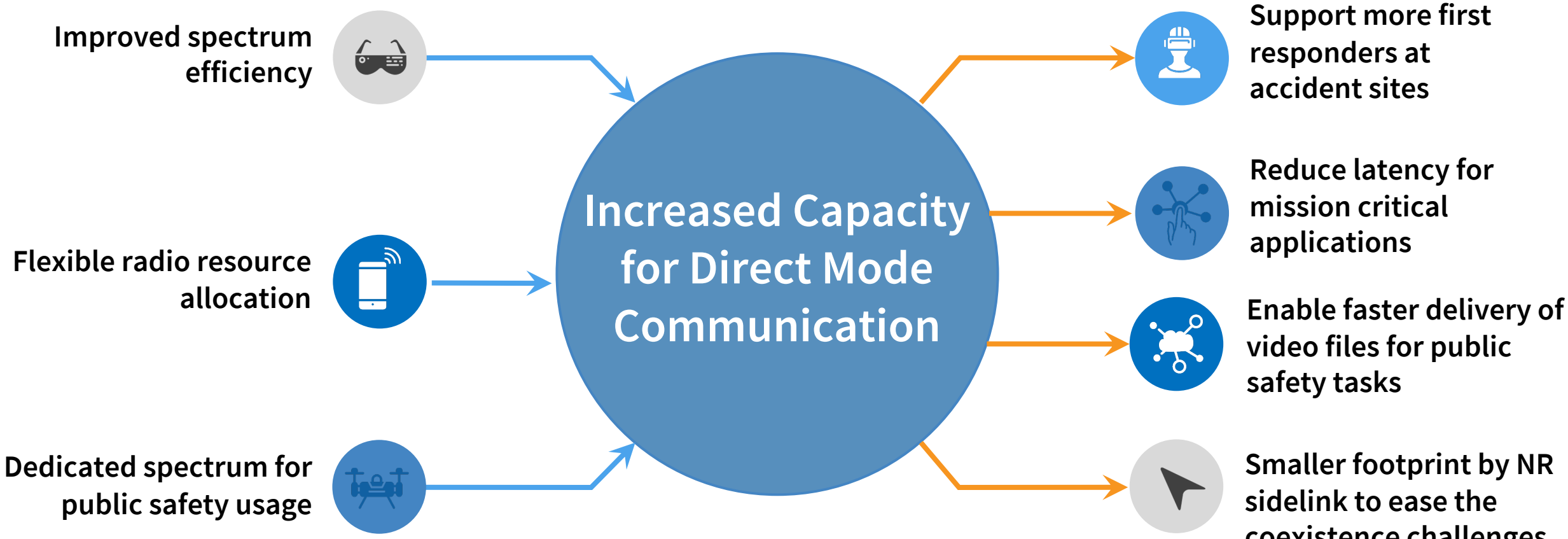
How does 5G NR meet the needs of so diversified usage scenarios?

5G NETWORK ARCHITECTURE

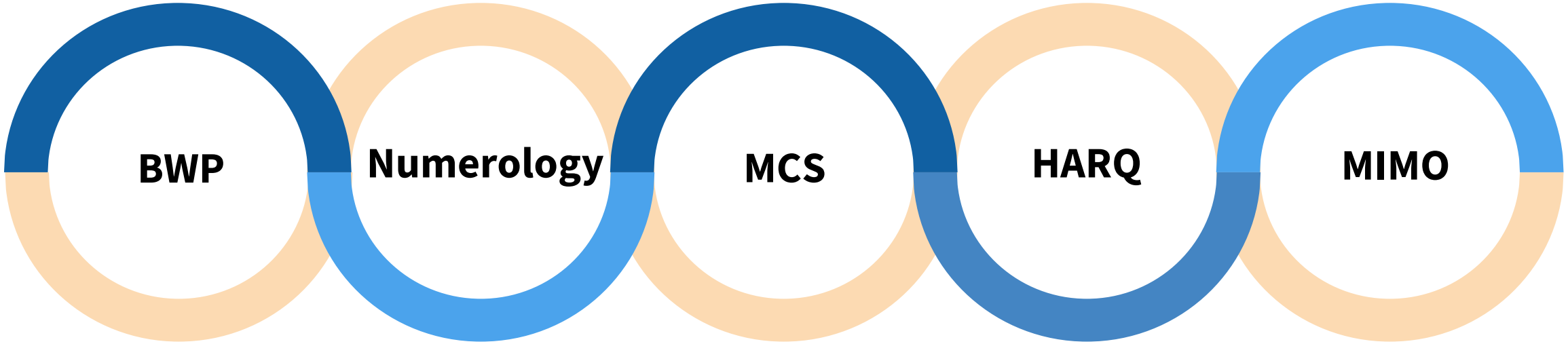


UE: User Equipment
NG-RAN: Next-Generation Radio Access Network

MOTIVATION OF CAPACITY STUDY

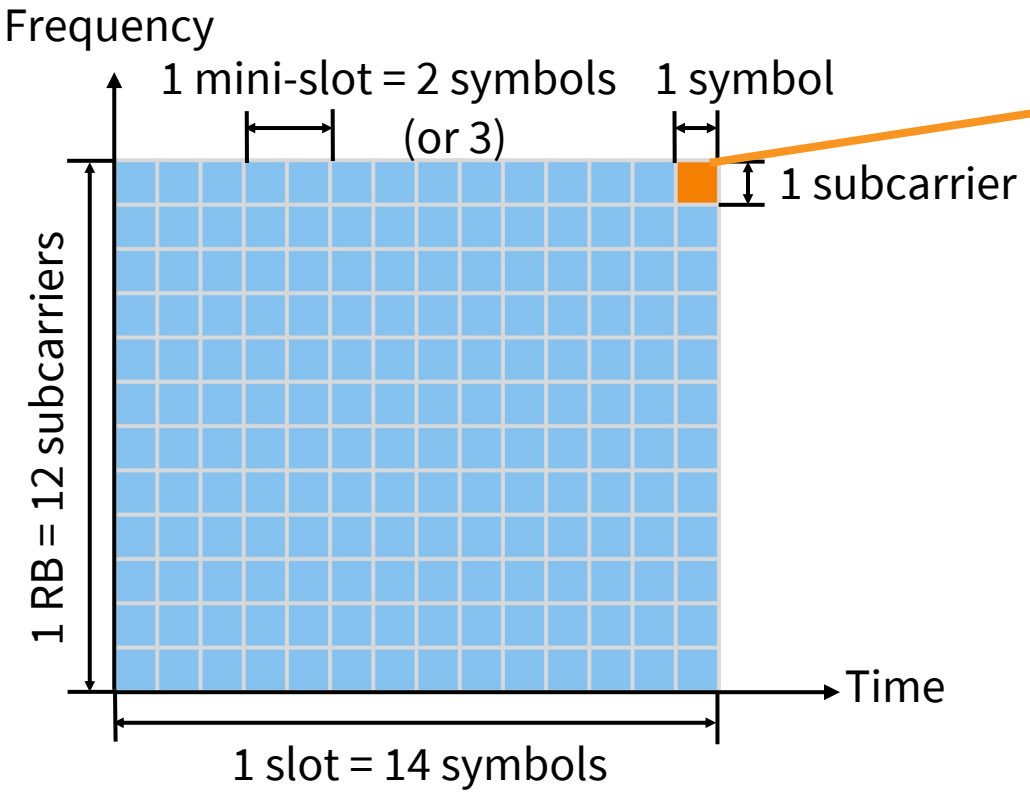


CAPACITY RELATED NR CONFIGURATIONS



- **Bandwidth Part (BWP)**
  How to specify radio resources allocated for a specific usage?
- **Numerology**
  How big is one unit of resource?
  How many resource units are available in a given BWP?
- **Modulation and Coding Scheme (MCS)**
  How much data can be carried by the allocated resources?
- **Hybrid Automatic Repeat Request (HARQ)**
  How to transmit data/information over these allocated resources efficiently and reliably?
  - Retransmission
- **Multiple-Input & Multiple-Output (MIMO)**
  - Multiple streams

RADIO RESOURCE ALLOCATION BASICS



1 RE = 1 symbol x 1 subcarrier

- Both time and frequency domain
- The basic resource unit
- The resource allocation granularity for control signal

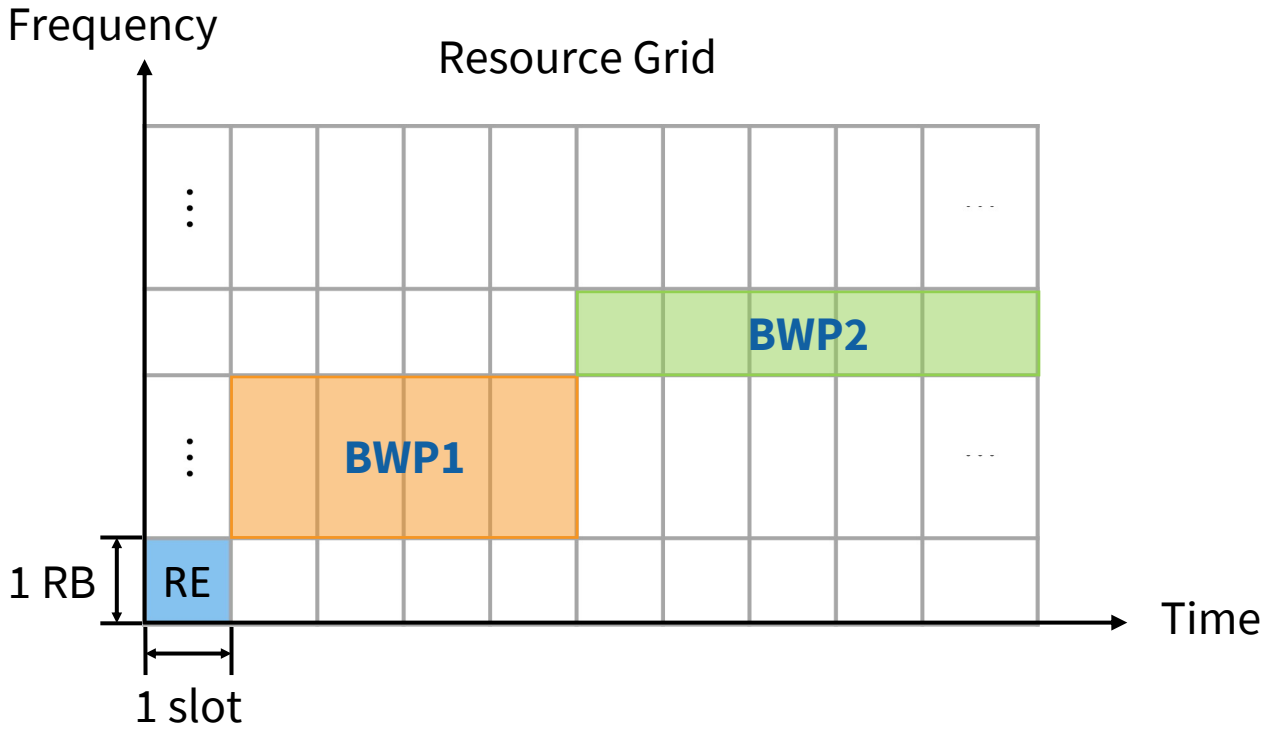
The resource allocation granularity for data:

- Frequency domain: subchannel
  - # RBs in a subchannel is configurable
- Time domain: slot or mini-slot, depending on usage scenarios

RB: Resource Block
RE: Resource Element

BANDWIDTH PART

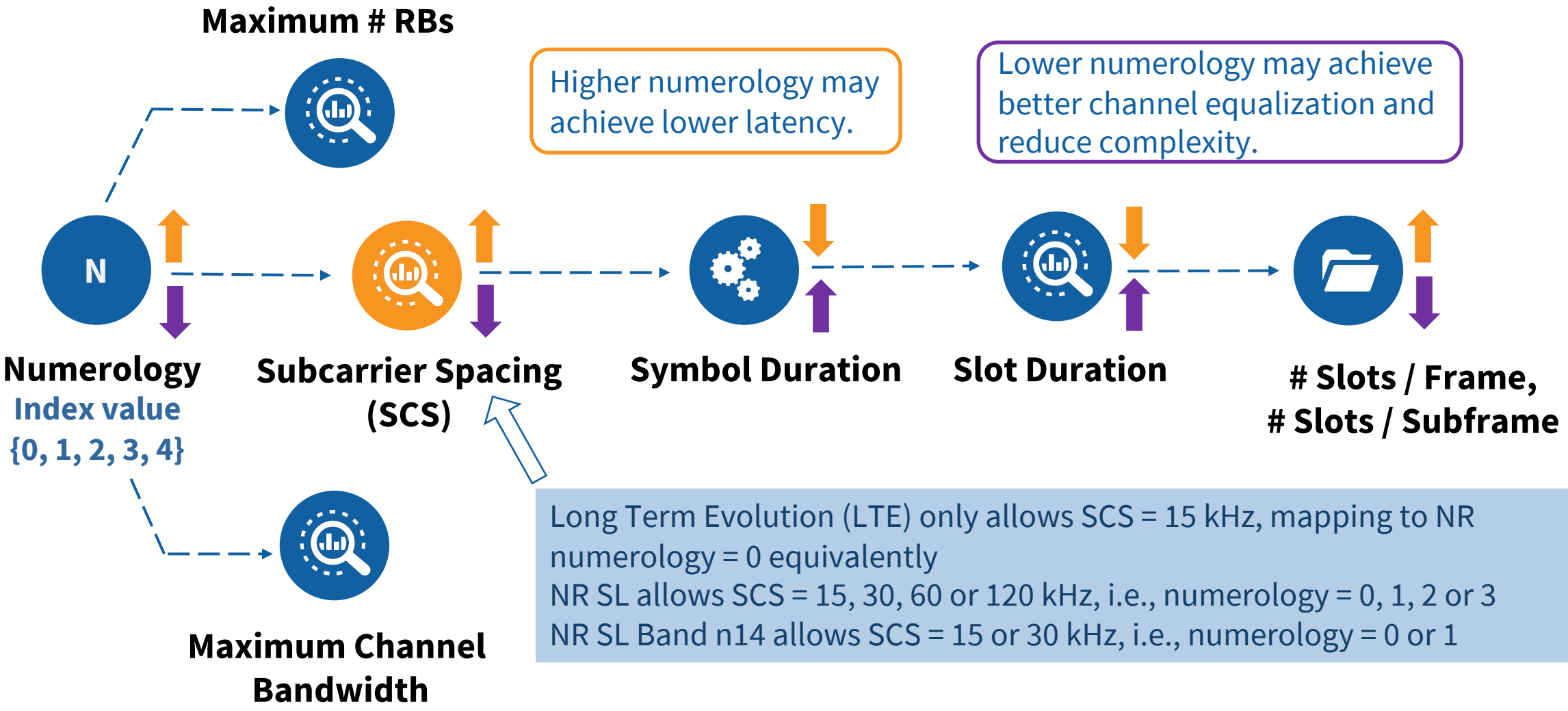
- A subset of contiguous common RBs allocated for specific usage
- Impacts # resources available for data transmission
- Up to four bandwidth parts can be configured per UE for uplink and downlink, but one active at a time
- For NR sidelink, only one bandwidth part can be configured in Release 16



In frequency domain,

- Both bandwidth part and subchannel are defined in unit of RBs
- However, within a bandwidth part, the granularity of resource allocation for data transmission is subchannel instead of RB
- Therefore, if the size of a bandwidth part in frequency domain is not a multiple of subchannel size, there will be leftover resources in the bandwidth part unallocated

NUMEROLOGY

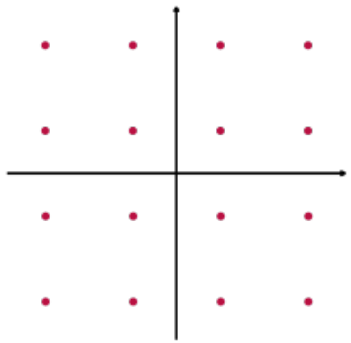

Maximum # RBs
Higher numerology may achieve lower latency.
Lower numerology may achieve better channel equalization and reduce complexity.
N
Numerology
Index value
{0, 1, 2, 3, 4}
Subcarrier Spacing (SCS)
Symbol Duration
Slot Duration
Slots / Frame,
Slots / Subframe
Maximum Channel Bandwidth
Long Term Evolution (LTE) only allows SCS = 15 kHz, mapping to NR numerology = 0 equivalently
NR SL allows SCS = 15, 30, 60 or 120 kHz, i.e., numerology = 0, 1, 2 or 3
NR SL Band n14 allows SCS = 15 or 30 kHz, i.e., numerology = 0 or 1

MODULATION AND CODING SCHEME

Modulation and coding scheme determines how many information bits can be carried by an RE:

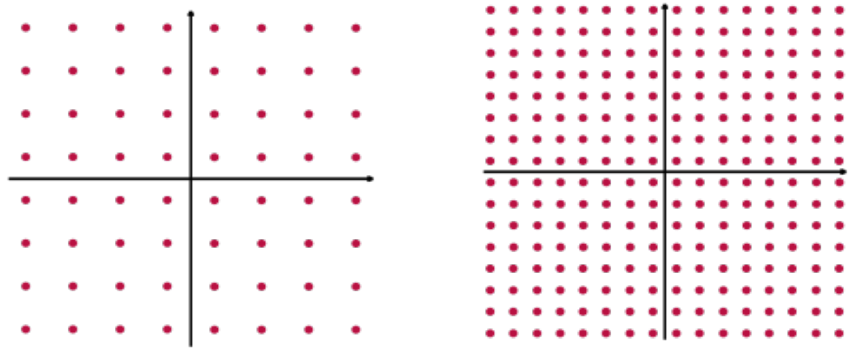
- The higher the code rate, the more efficient use of an RE:
  - NR sidelink Mode 2 can achieve higher maximal code rate than LTE sidelink Mode 2
- The higher the modulation, the more efficient use of an RE:
  - 2^N QAM modulation can carry N bits/RE

The highest modulation available for LTE sidelink Mode 2:



16 QAM (i.e., 4 bits/RE)

The highest modulation available for NR sidelink Mode 2:



64 QAM (i.e., 6 bits/RE) or 256 QAM (i.e., 8 bits/RE), depending on device capability

QAM: Quadrature Amplitude Modulation

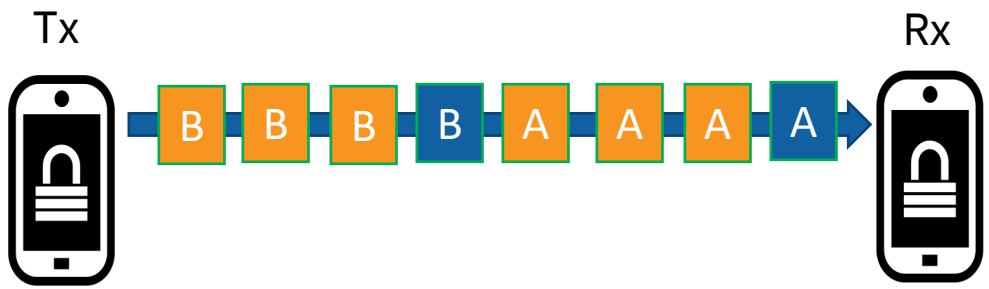
HYBRID AUTOMATIC REPEAT REQUEST

HARQ configuration may specify whether, when, and how many retransmission(s) of data is needed.

Blind (re)transmission

(+): Simple, less scheduling and feedback overhead

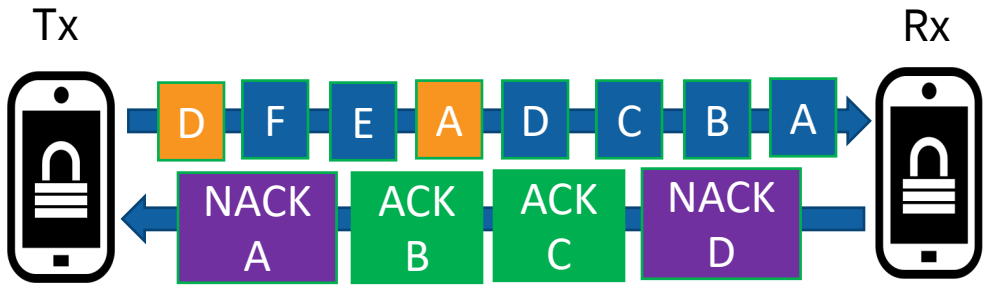
(-) : Unnecessary retransmission likely



Feedback-based (re)transmission

(+): Retransmit only if needed

(-) : Overhead for feedback and scheduling, etc.



A Initial Transmission A Retransmission ACK A Acknowledgement (ACK) NACK A Negative ACK (NACK)

LTE sidelink Mode 2 communication supports:

- Blind retransmission only
- Mandatory 4 transmissions (i.e., 3 retransmissions)

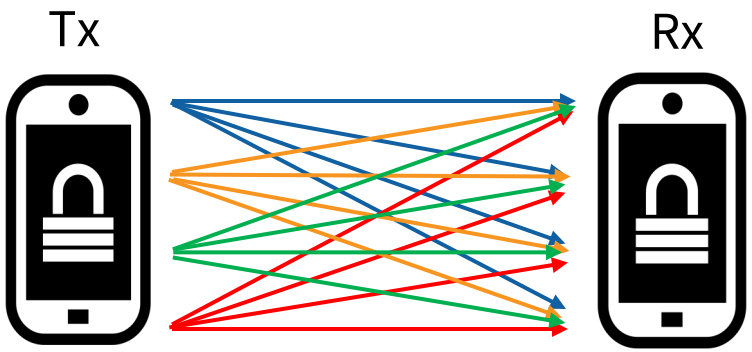
NR sidelink Mode 2 communication supports:

- Both blind retransmission and feedback based retransmission
- Number of maximum transmissions can be configured up to 32 (i.e., 31 retransmissions)

Rx: Receive, Tx: Transmit

MULTIPLE-INPUT AND MULTIPLE-OUTPUT

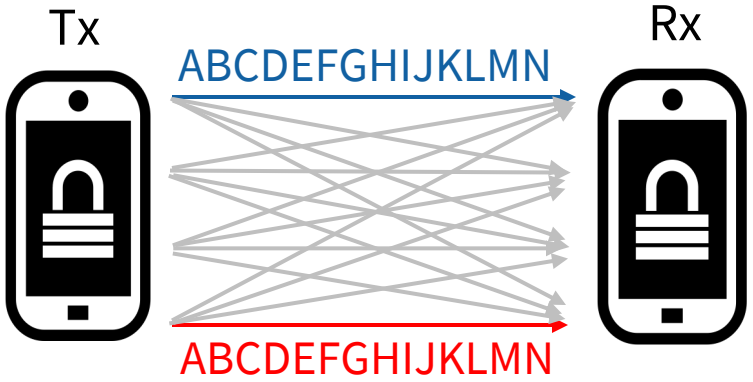
MIMO enables the simultaneous transmission of multiple streams between two devices.



Spatial multiplexing gain improves UE throughput and thus capacity.

Tx different data

Tx the same data



Diversity gain improves Signal-to-Interference-plus-Noise-Ratio and thus decoding reliability.

CAPACITY RELATED CONFIGURATION

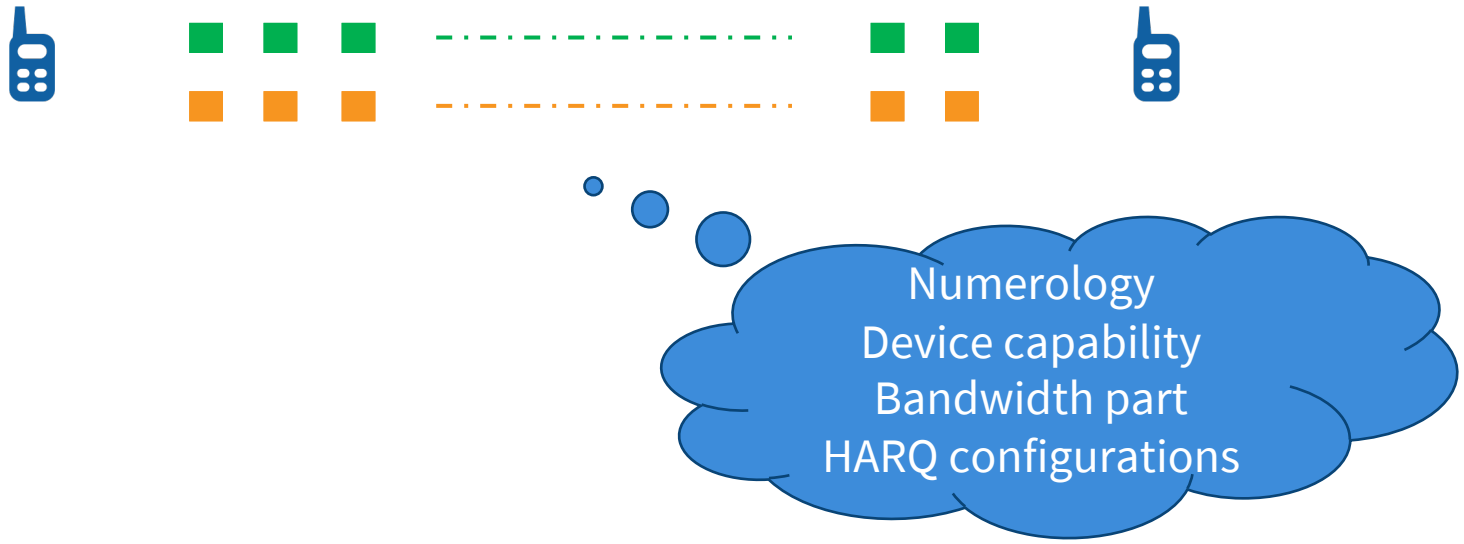
Configuration	LTE SL Mode 2	NR SL Mode 2
Numerology	0 (equivalent)	0, 1, 2, or 3
Spatial Multiplexing	1 layer	Up to 2 layers
HARQ	Blind 4 total transmissions	Configurable (blind or feedback-based) Up to 32 total transmissions
Highest MCS	16 QAM Code rate lower than NR's	64 QAM or 256 QAM depending on device capability Code rate up to 948/1024

The NR sidelink mode 2 has great potential to achieve higher capacity than LTE sidelink mode 2:

- What's the percentage of increase?
- Which feature/configuration contribute the most to the increase? – *important to implement or upgrade*

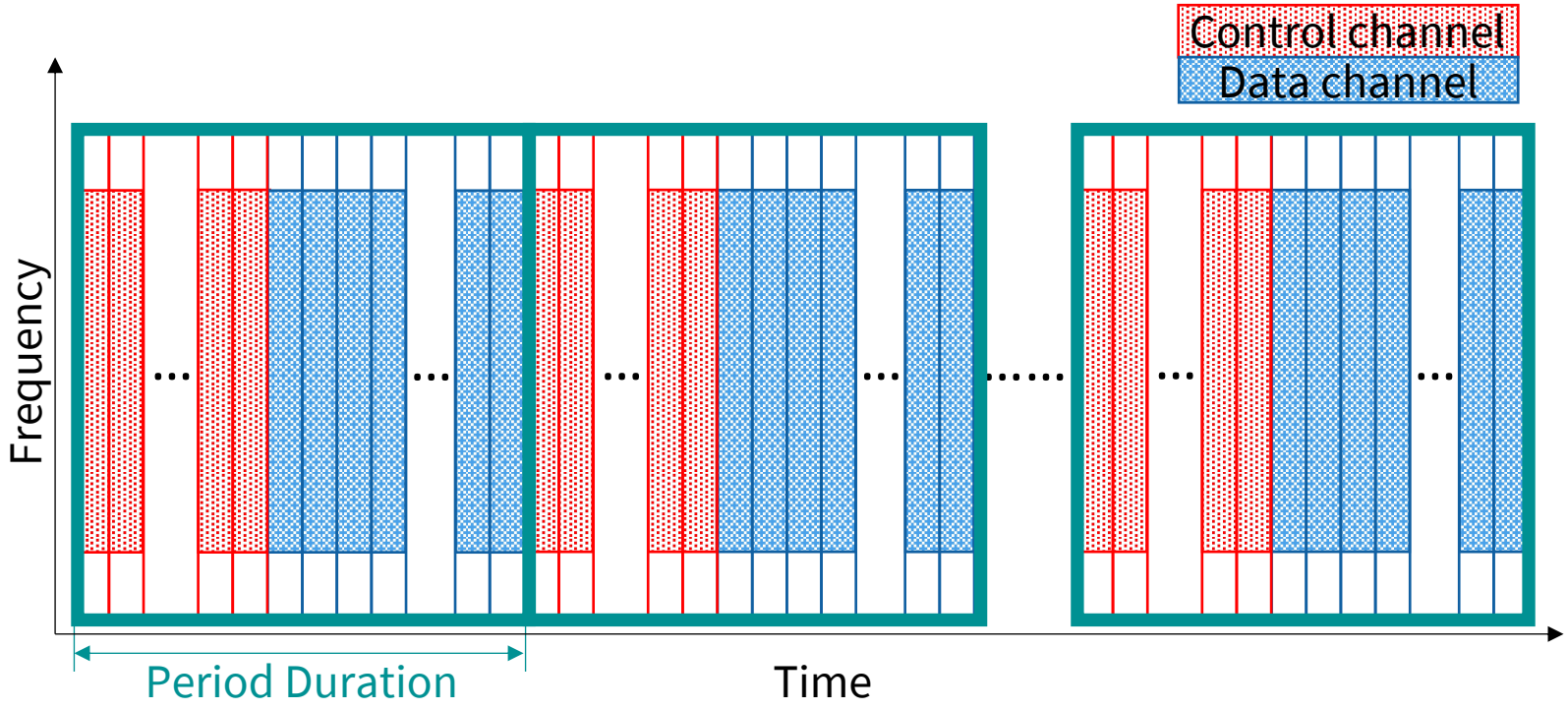
CAPACITY IN DATA RATE

Maximum achievable data rate



Study 5G NR sidelink capacity under various operational configurations.
Quantify impact of features that differentiate NR capacity from LTE.

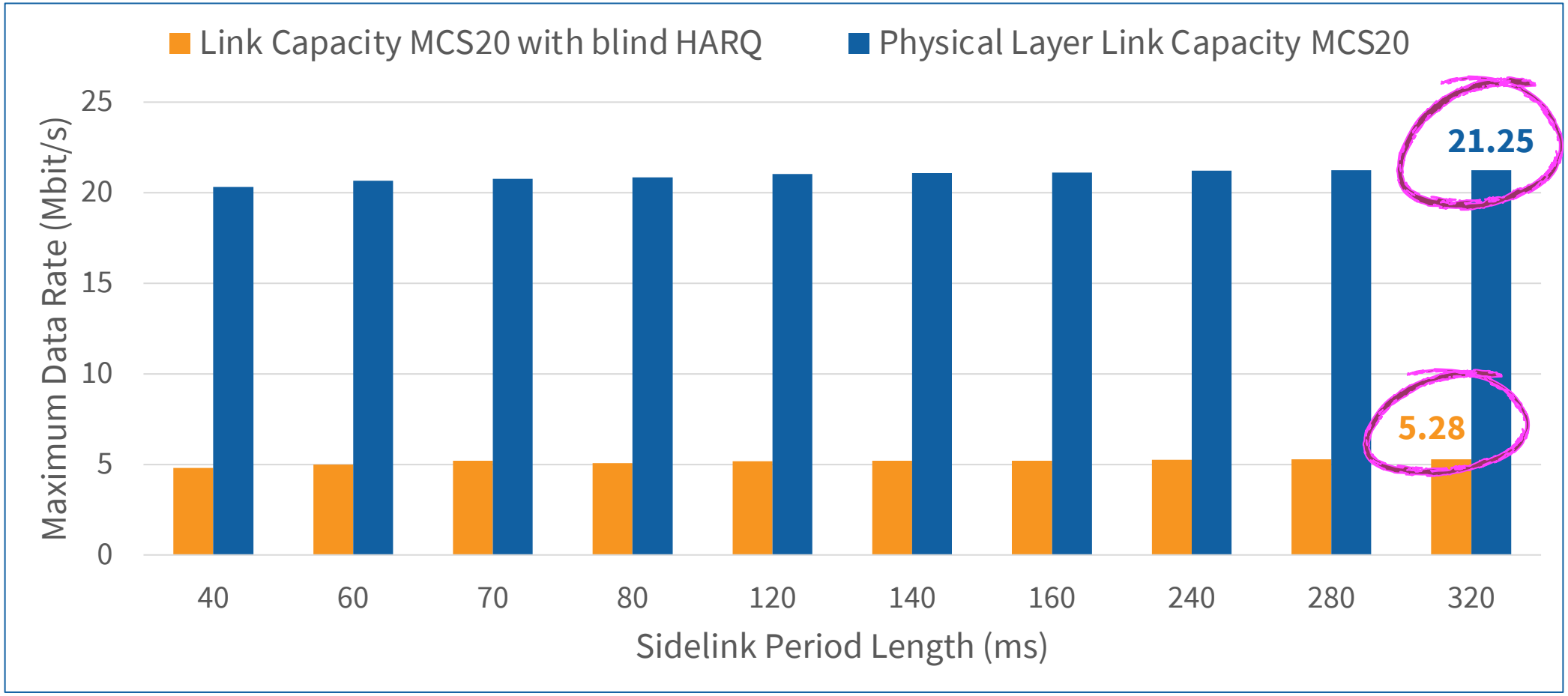
LTE - SIDELINK TRANSMISSIONS



Periodic transmission of sidelink control and data channels.

No spatial multiplexing, maximum modulation of 16 QAM.
Mandatory HARQ with four blind transmissions.

LTE - SIDELINK CAPACITY



Settings: Band 14 10 MHz bandwidth, unrestricted time pattern, 2 ms control channel every Sidelink period (lowest control overhead), MCS 20 (16 QAM, highest for Sidelink).

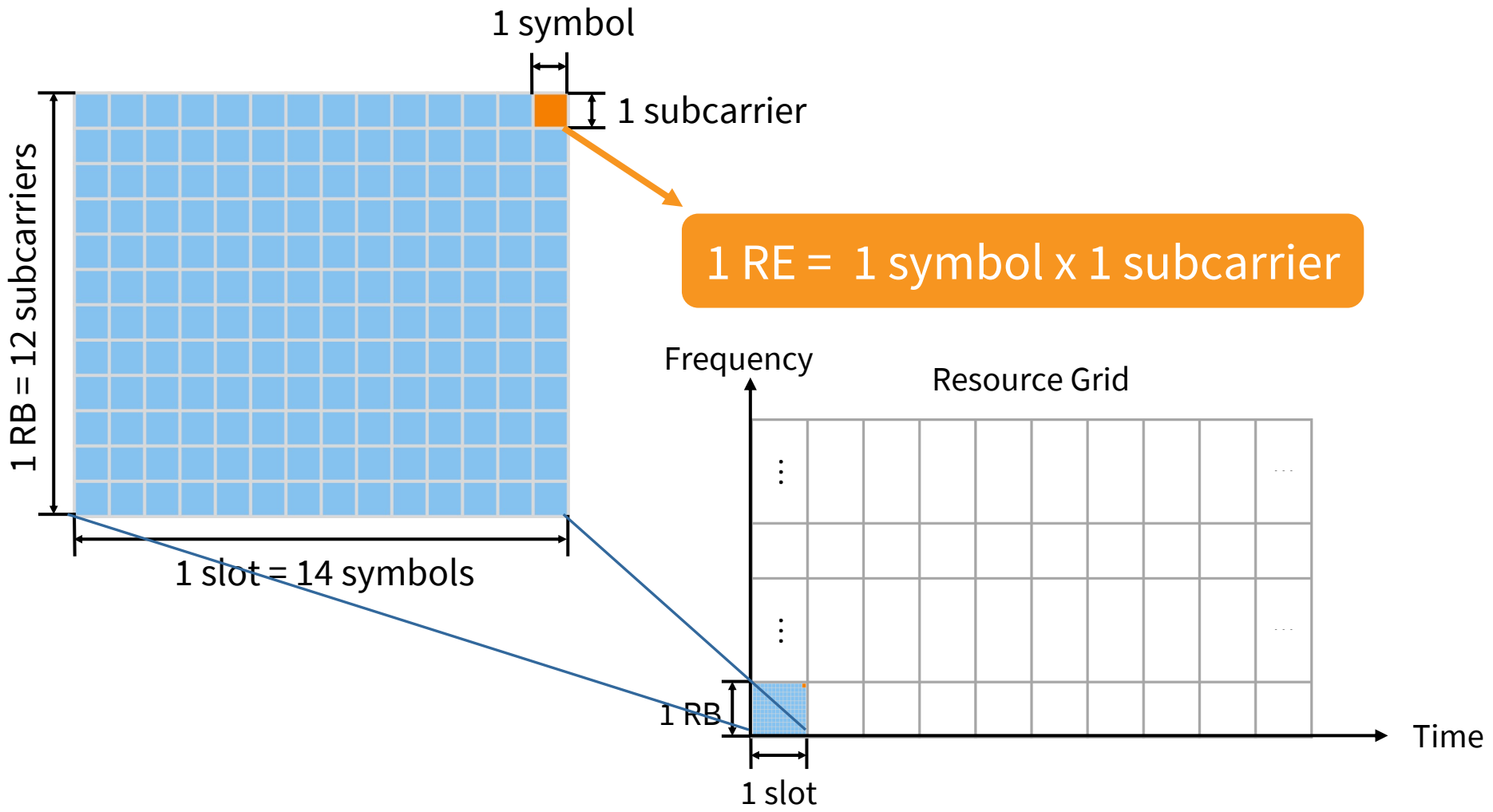
Capacity is reduced significantly with mandatory HARQ four blind transmissions.

NR CAPACITY

$$data\ rate\ (in\ Mbit/s) = 10^{-6} \cdot \nu_{layers} \cdot Q_m \cdot R_{max} \cdot \frac{N_{PRB}^{BW,\mu} \times 12}{T_s^{\mu}} \cdot (1 - OH)/N$$

Data rate = Total # resource units X # Bits / resource unit

NR RESOURCE UNIT – RESOURCE ELEMENT



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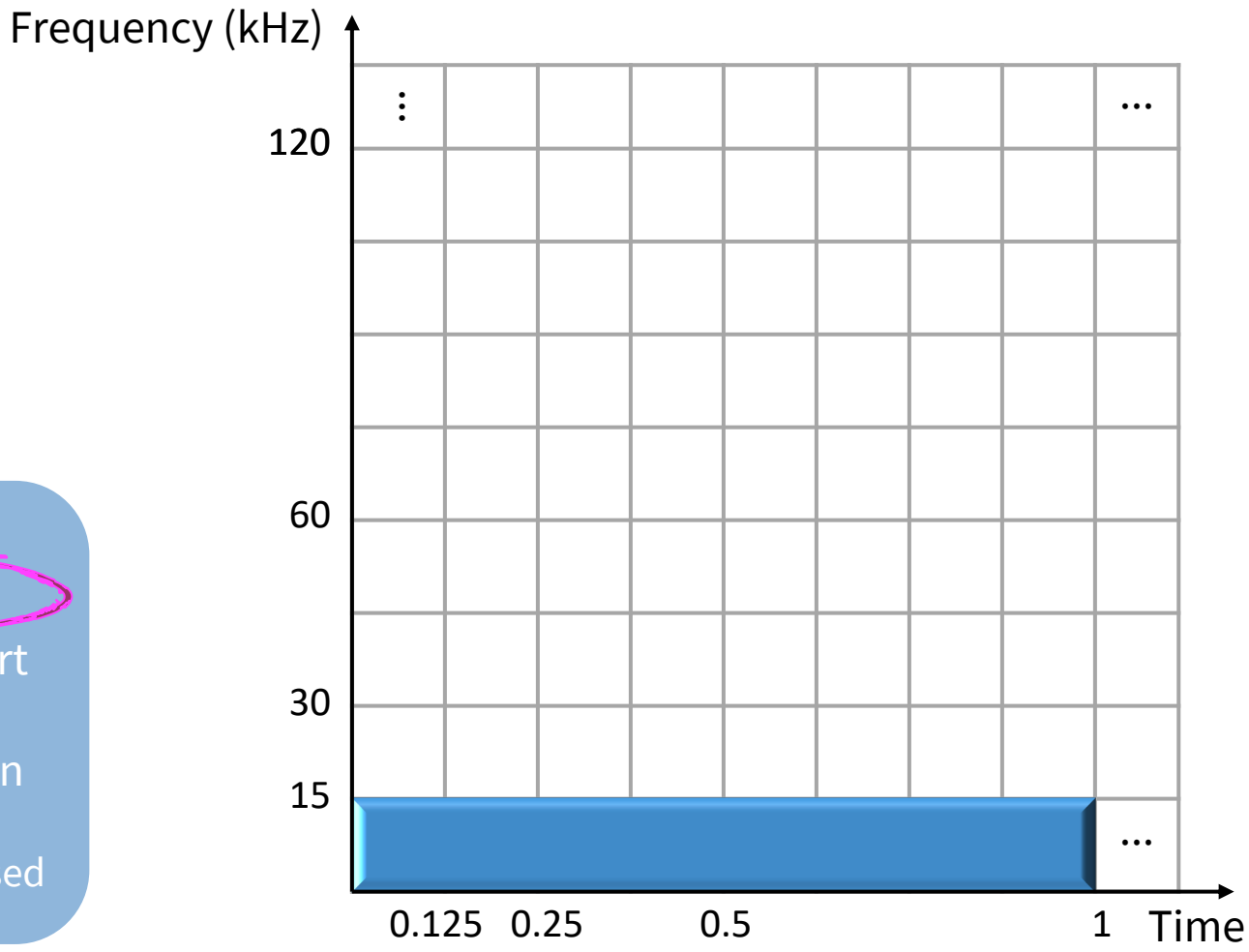
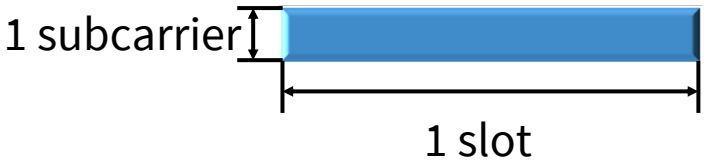
TOTAL # REs - NUMEROLOGY

Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based

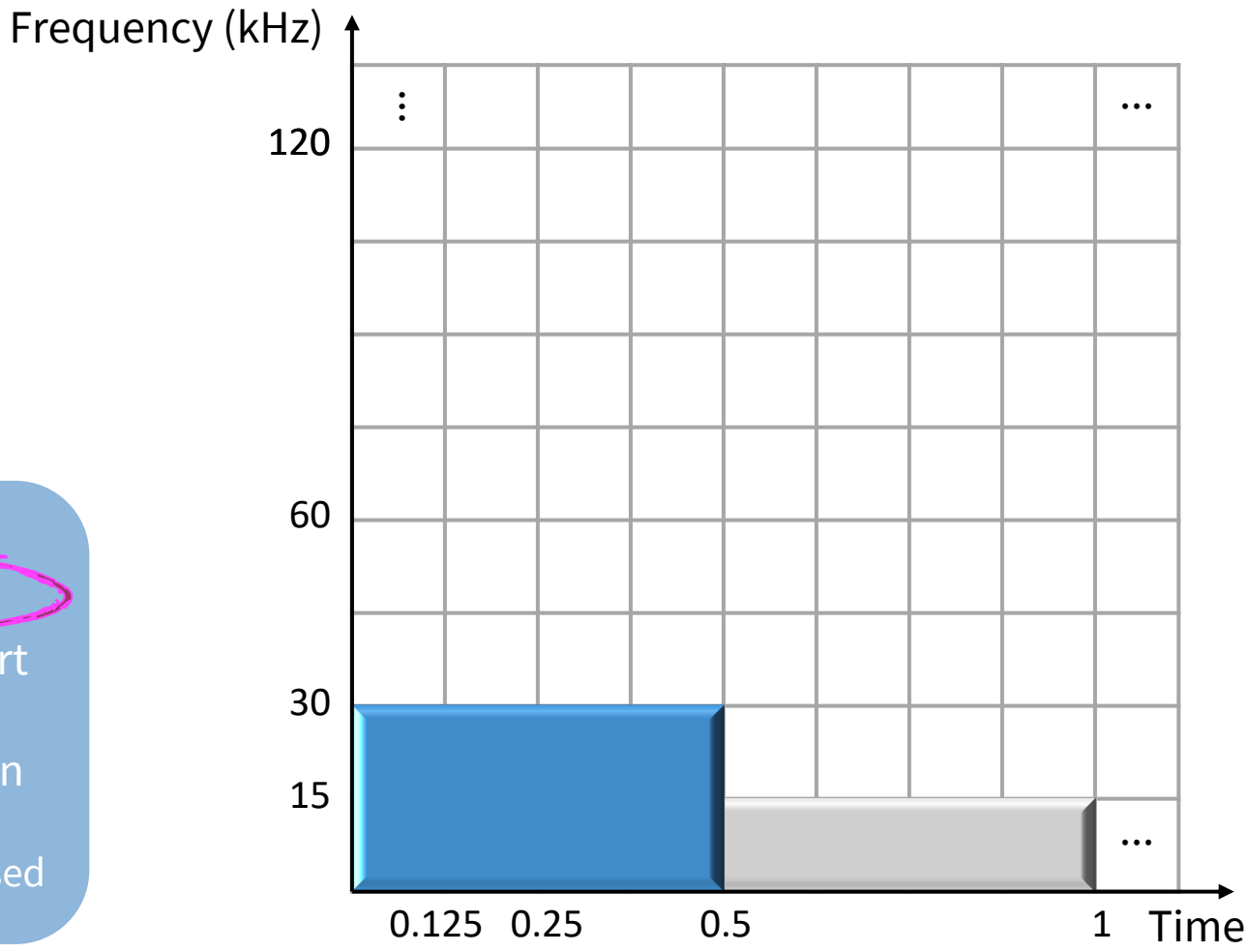


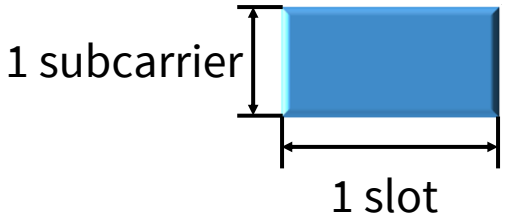


Numerology	Subcarrier (kHz)	Slot (ms)
0	15	1
1	30	0.5
2	60	0.25
3	120	0.125

TOTAL # REs - NUMEROLOGY

Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based





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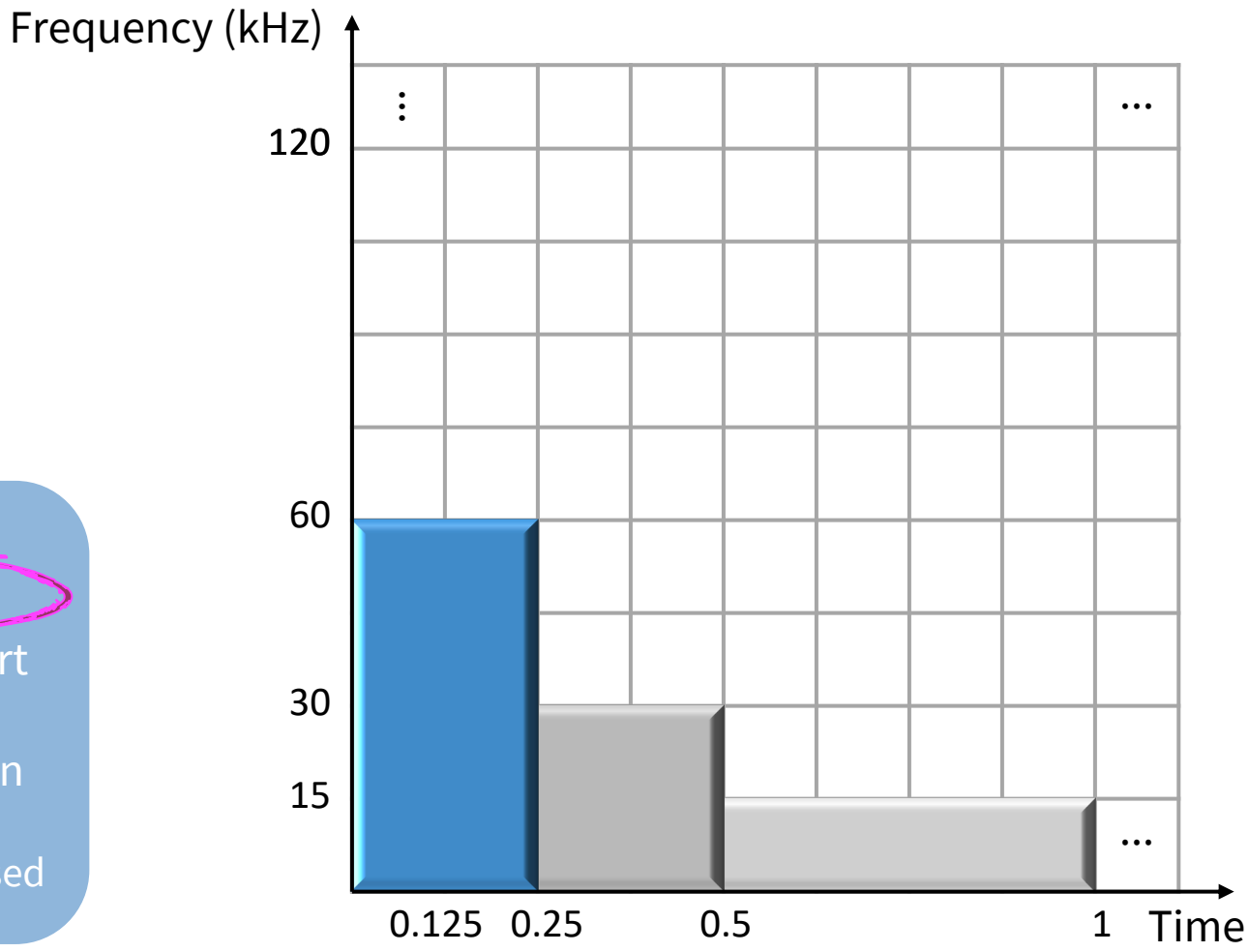

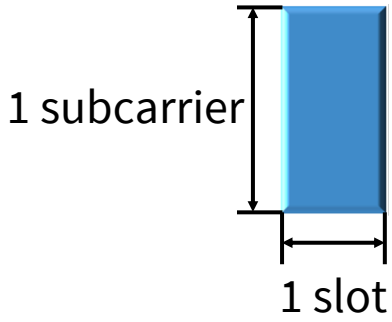

Numerology	Subcarrier (kHz)	Slot (ms)
0	15	1
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TOTAL # REs - NUMEROLOGY

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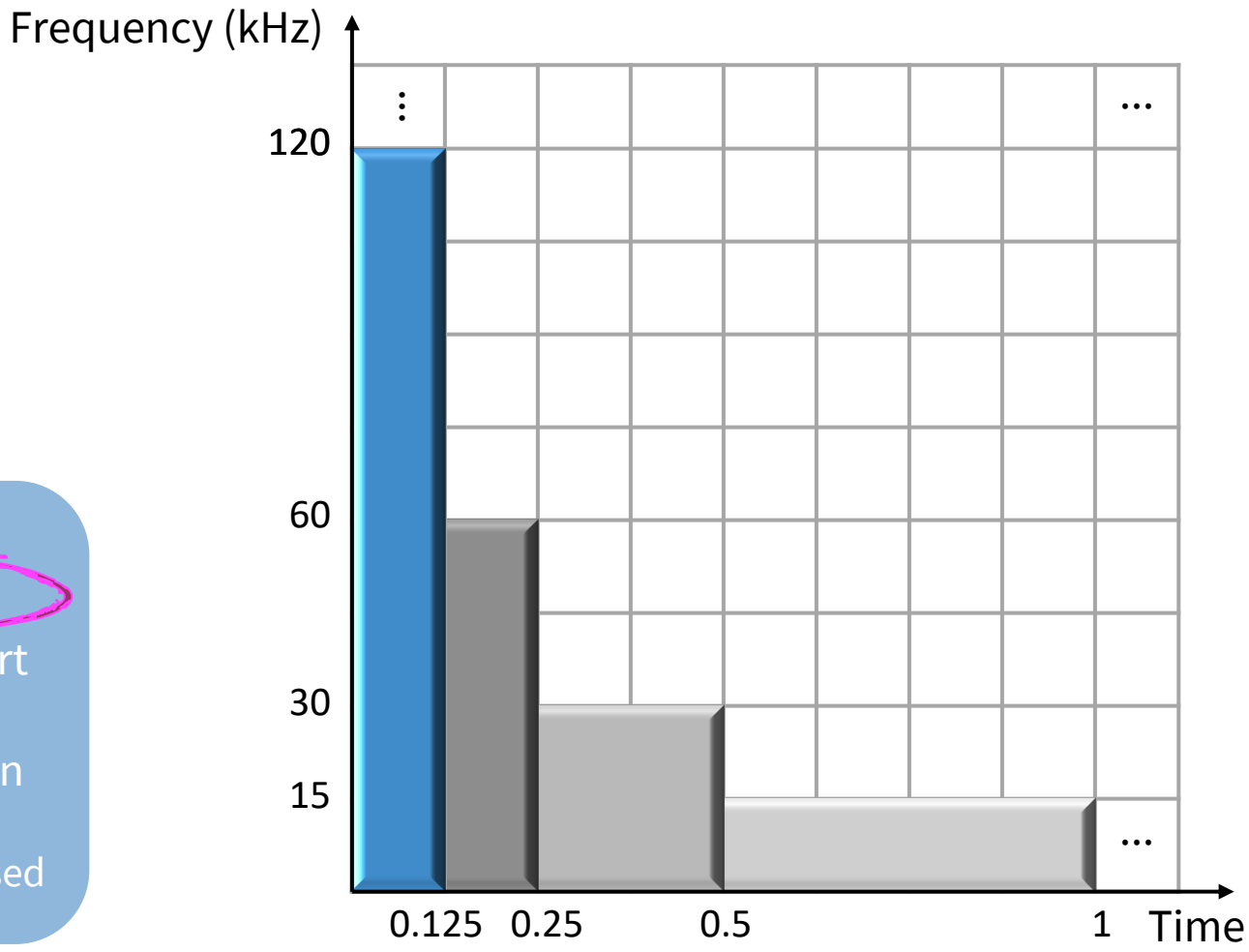

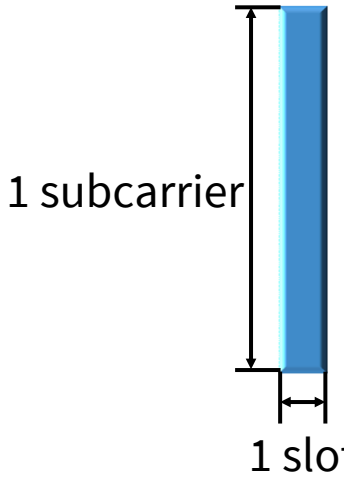

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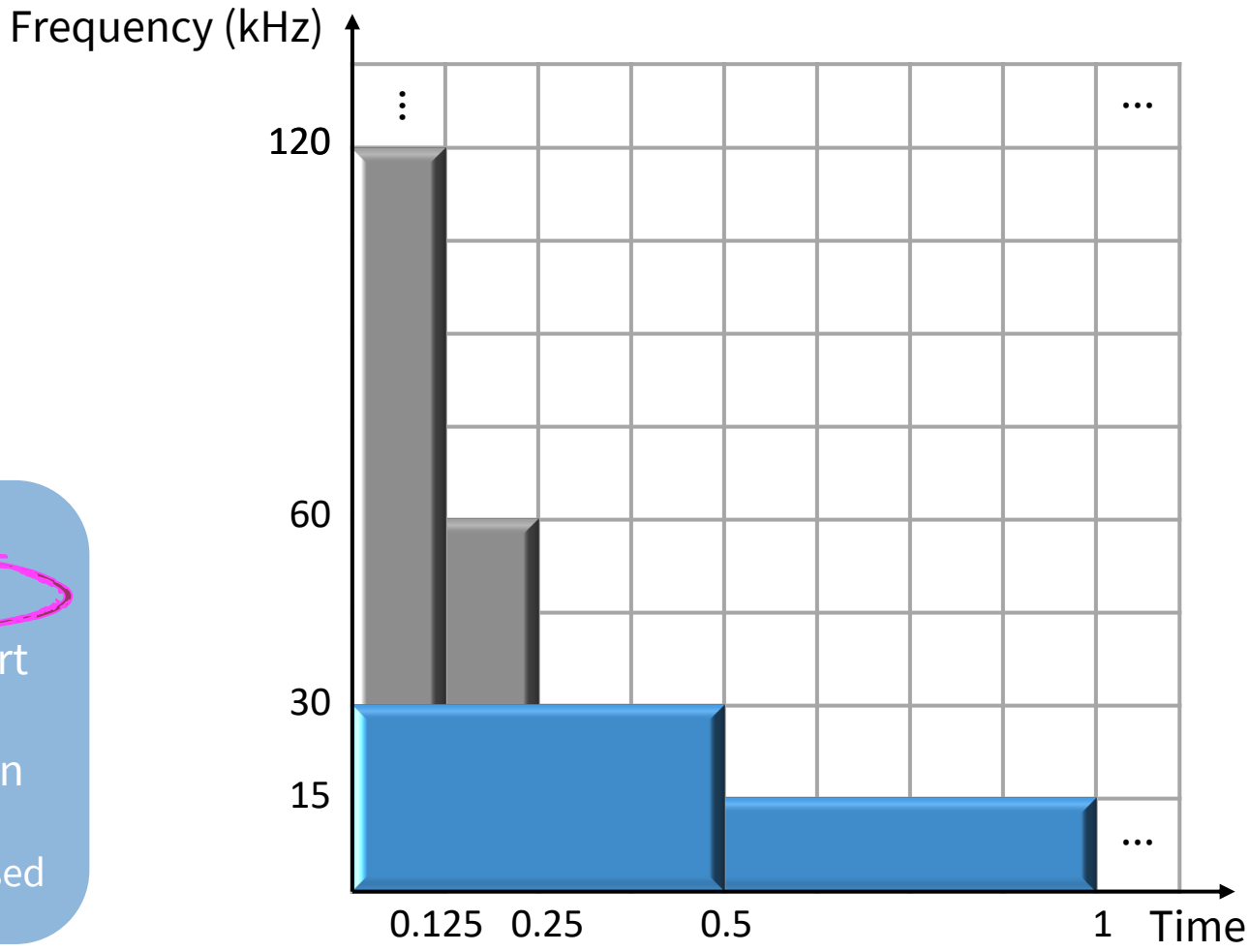


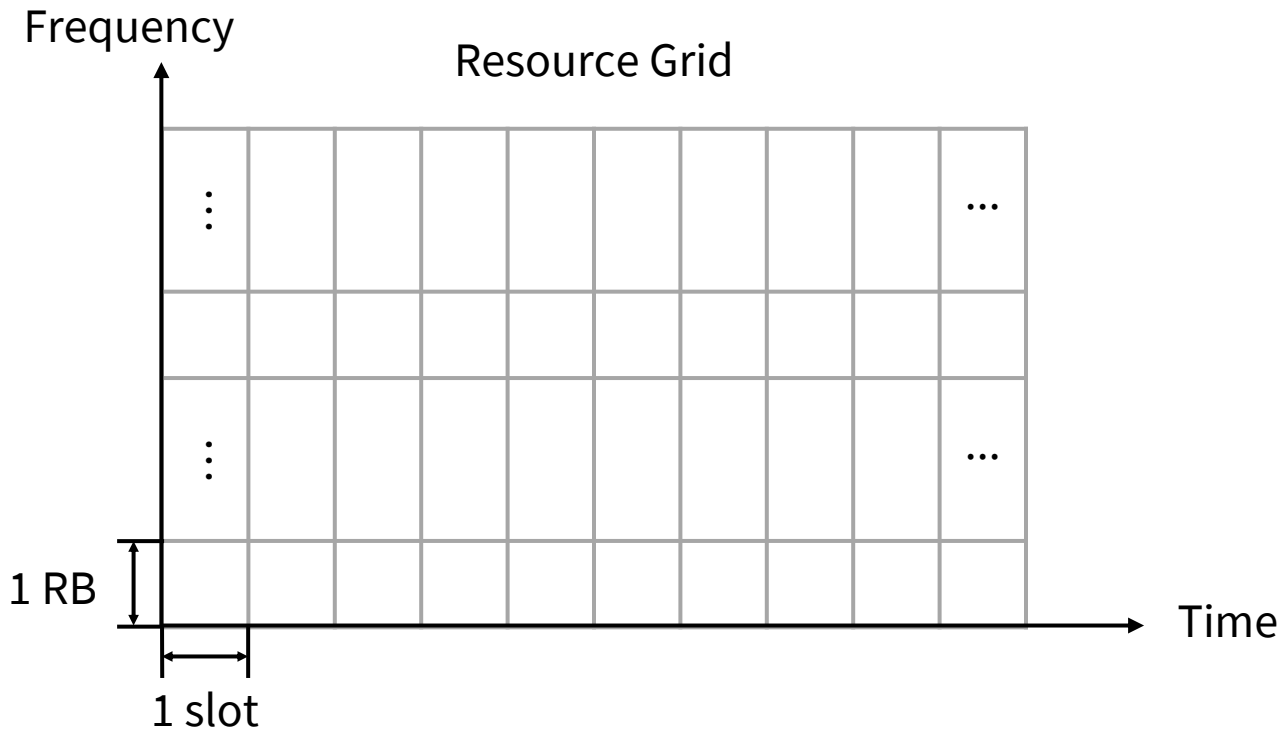
Numerology	Subcarrier (kHz)	Slot (ms)
0	15	1
1	30	0.5
2	60	0.25
3	120	0.125

Numerology 0, 1, 2, and 3 are specified for NR sidelink.
(Numerology 0 and 1 for Band n14, for numerical analysis)

TOTAL # REs – BANDWIDTH PART

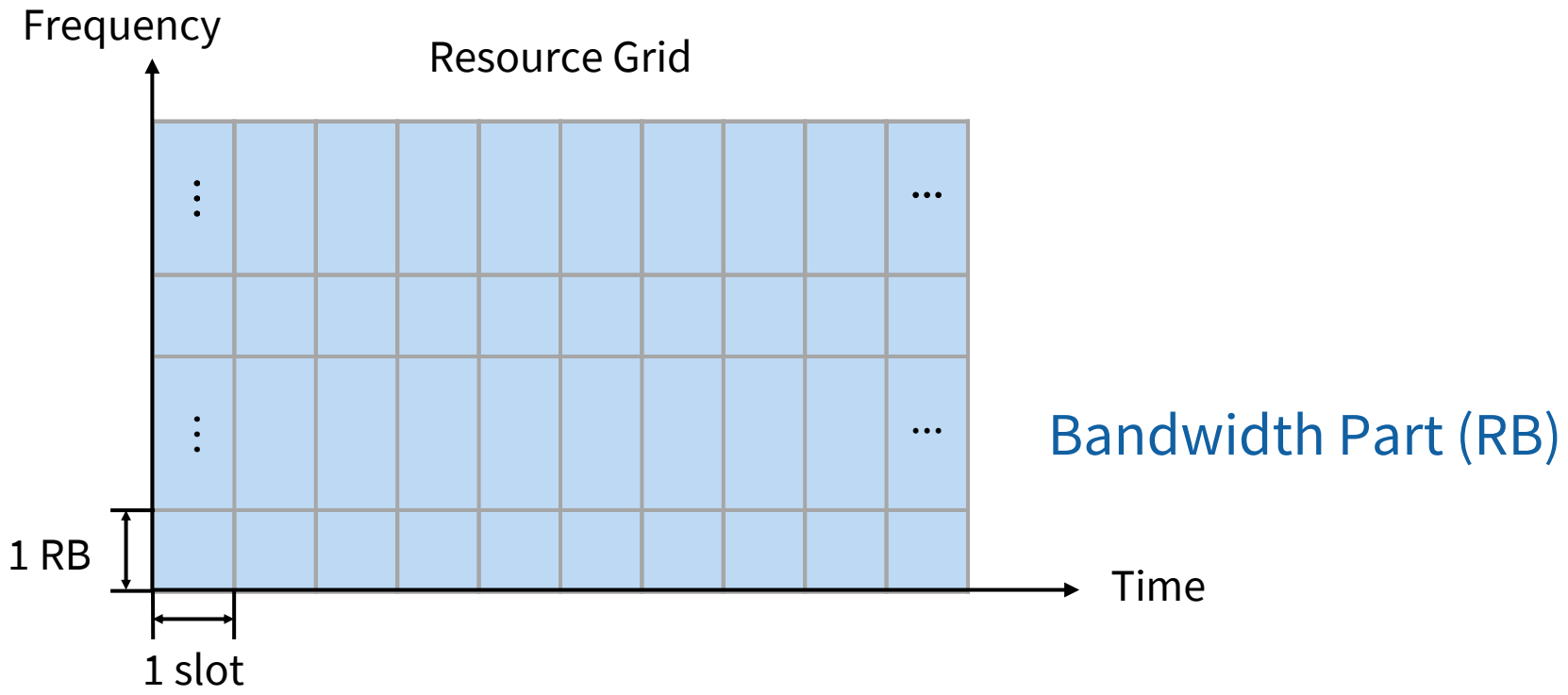
Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based

Bandwidth part in frequency domain



TOTAL # REs – BANDWIDTH PART

Bandwidth part in frequency domain



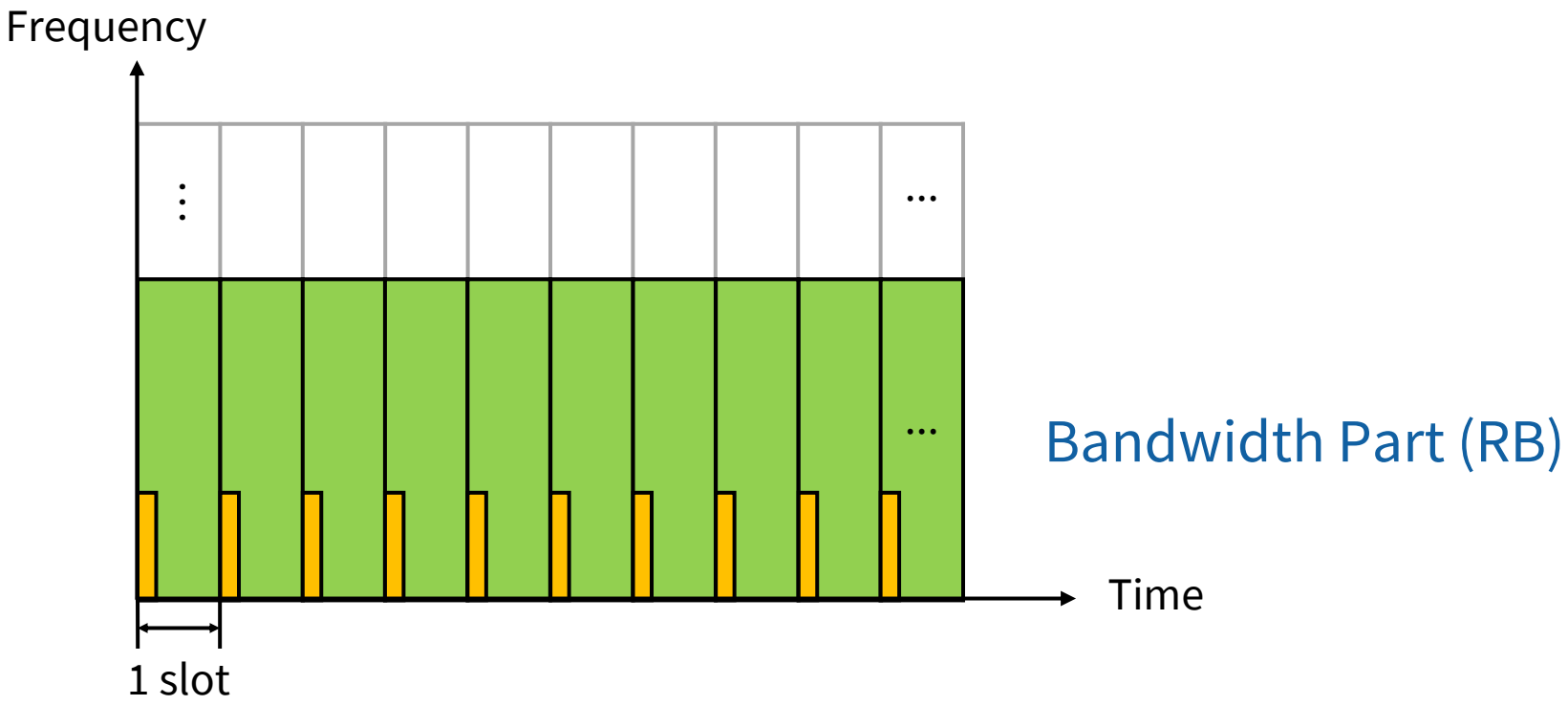
Bandwidth Part (RB)

Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based

Bandwidth Part size is up to 52 and 24 RBs for numerology 0 and 1, respectively.

TOTAL # REs – DATA CHANNEL AND OVERHEAD

Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based



TOTAL # REs – DATA CHANNEL AND OVERHEAD

Total # REs
- Numerology
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- Overhead
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  - Blind
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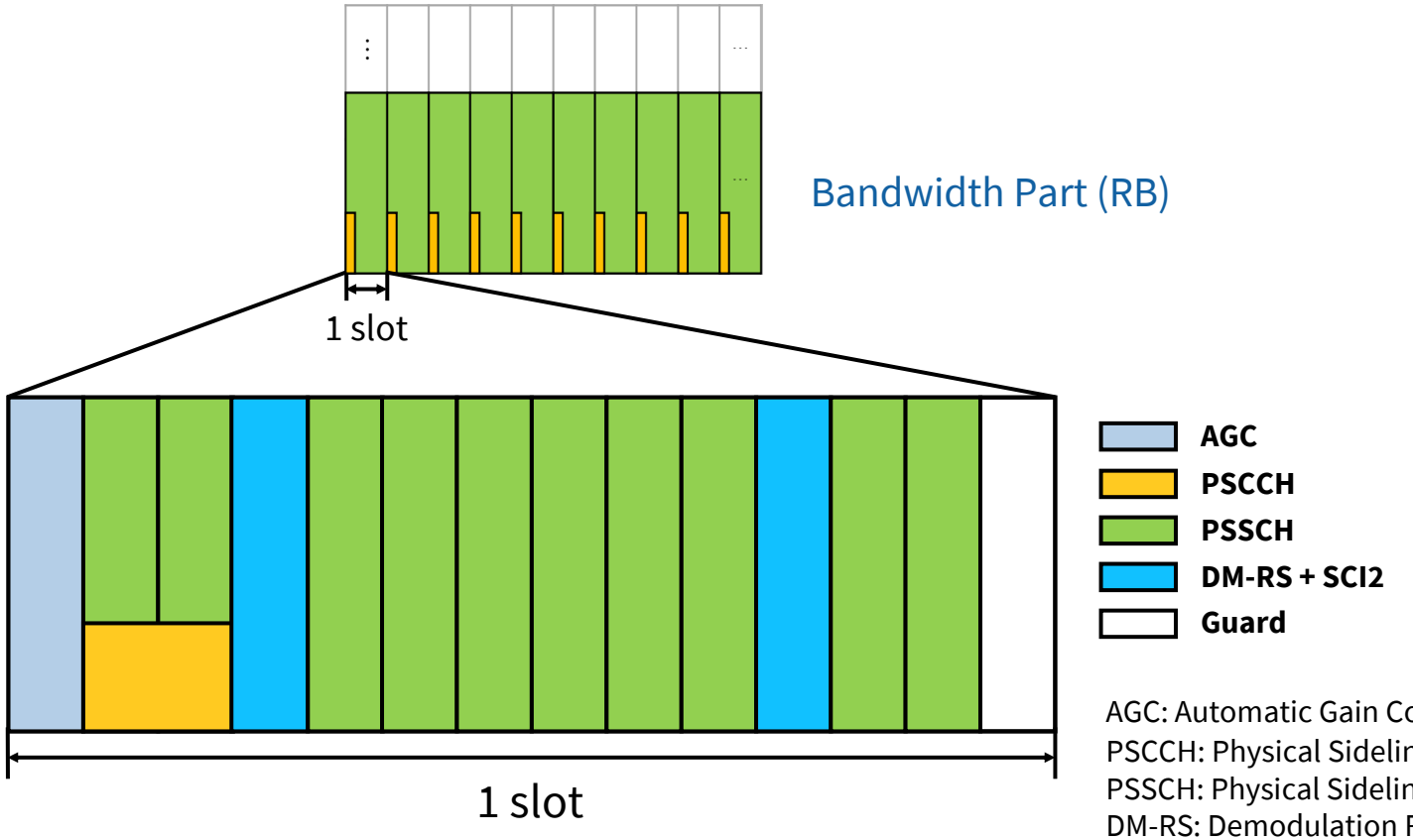
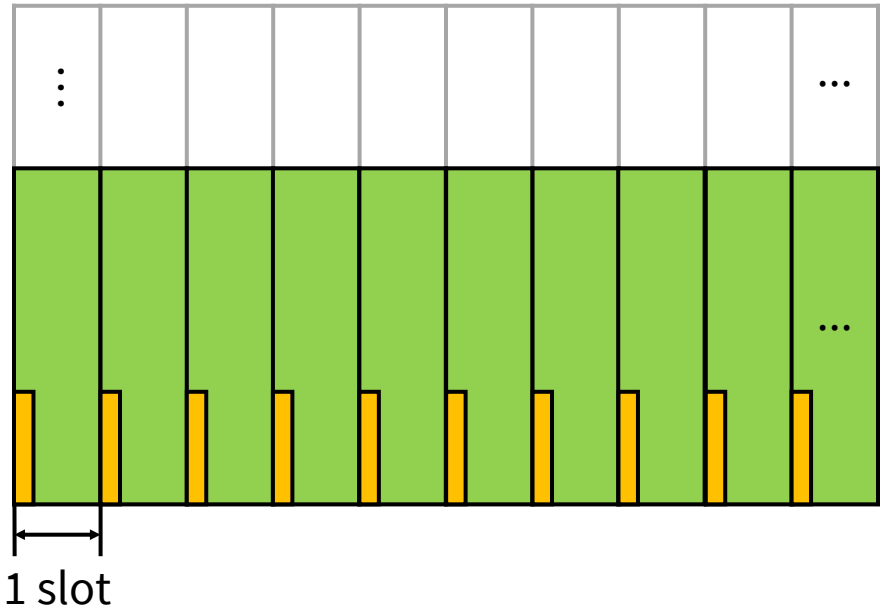


AGC: Automatic Gain Control
PSCCH: Physical Sidelink Control Channel
PSSCH: Physical Sidelink Shared Channel
DM-RS: Demodulation Reference Signal
SCI2: 2nd-Stage Sidelink Control Information

Resources in data channel contribute to capacity.

TOTAL # REs – BLIND TRANSMISSIONS

Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based



TOTAL # REs – BLIND TRANSMISSIONS

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- Numerology
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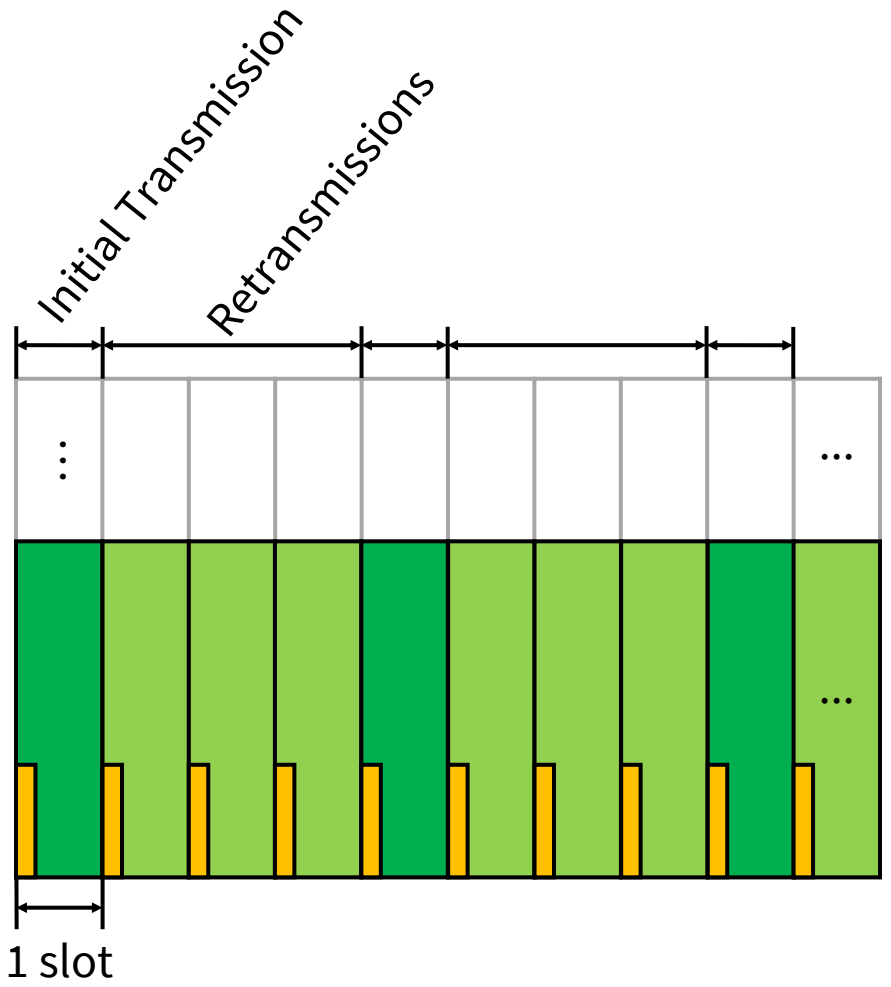


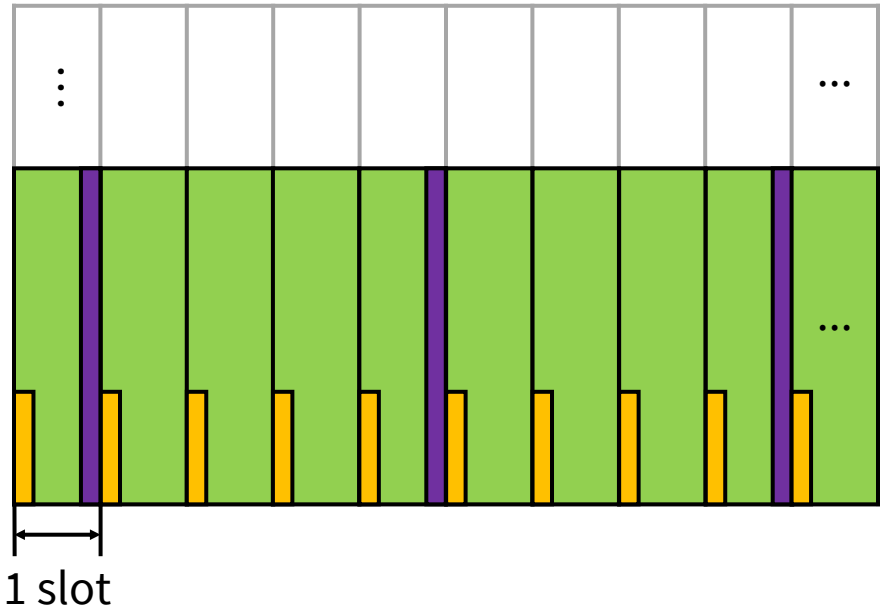
Illustration -
Four blind transmissions

Initial Transmission
Retransmission

Unnecessary blind retransmissions lead to waste of resource and capacity reduction.
Total number of transmissions is configurable from 1 to 32.

TOTAL # REs – FEEDBACK-BASED RETRANSMISSIONS

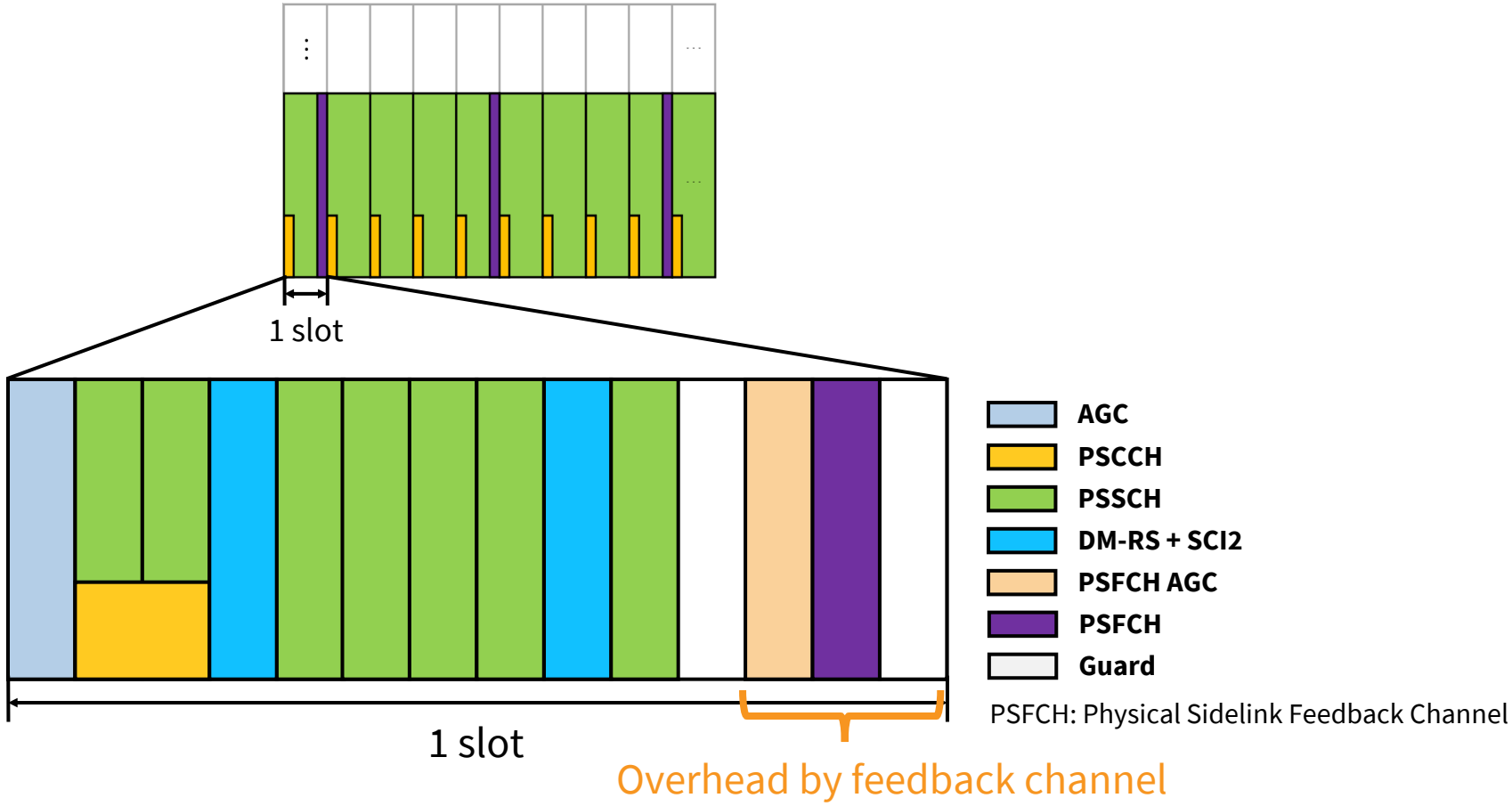
Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based



Feedback-based retransmission introduces overhead.

TOTAL # REs – FEEDBACK-BASED RETRANSMISSIONS

Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based

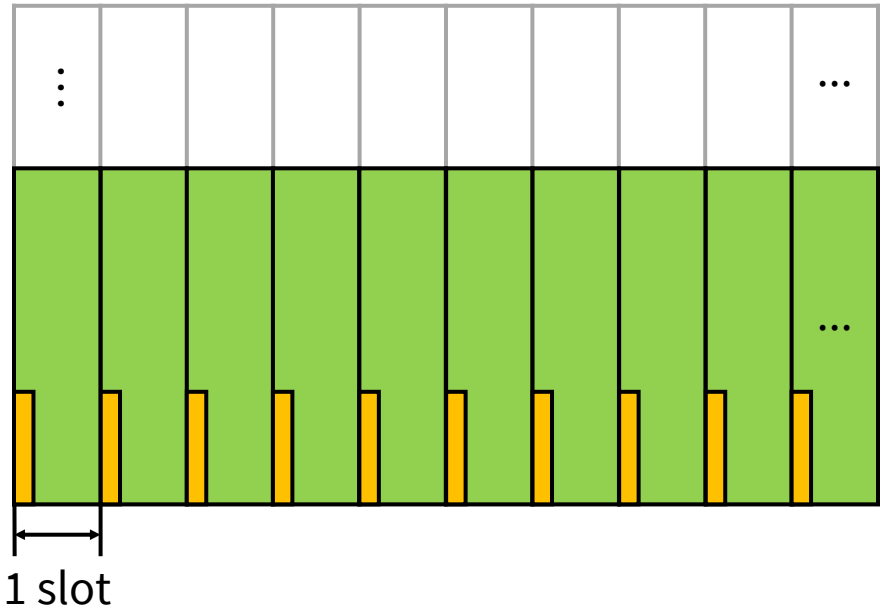


Feedback-based retransmission introduces overhead.

TOTAL # REs – FEEDBACK-BASED RETRANSMISSIONS

Feedback channel period (in slot): 0, 4, 2 or 1

Feedback channel period = 0
(0 = no feedback channel)

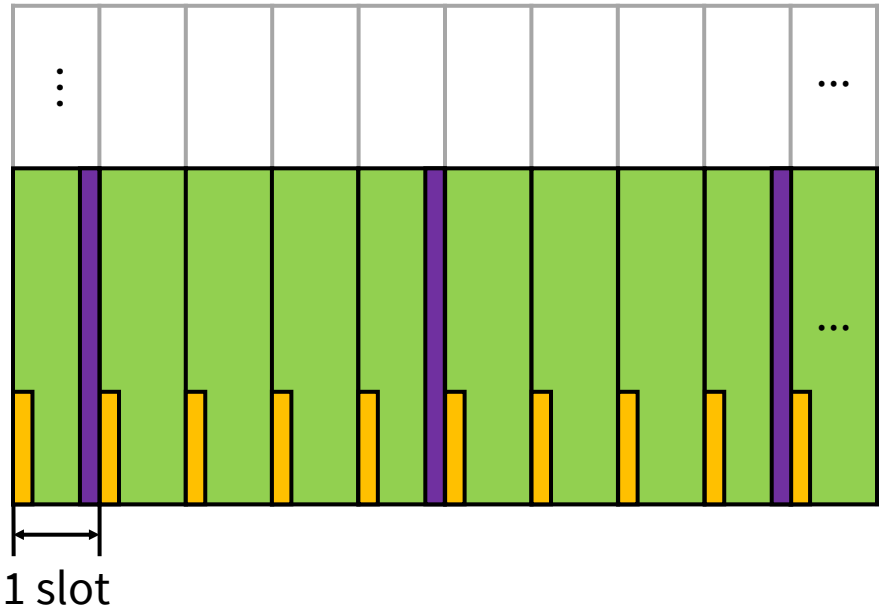


Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based

TOTAL # REs – FEEDBACK-BASED RETRANSMISSIONS

Feedback channel period (in slot): 0, 4, 2 or 1

Feedback channel period = 4

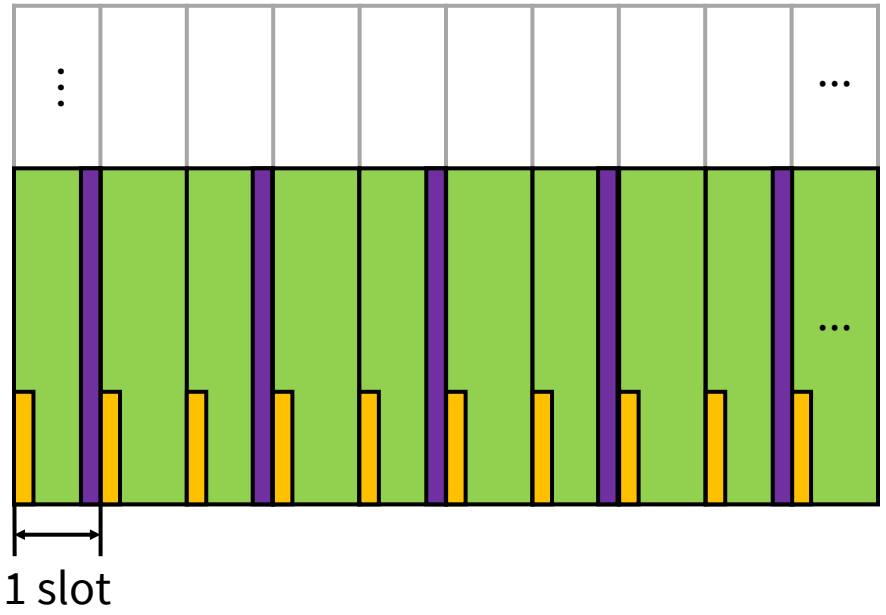


Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based

TOTAL # REs – FEEDBACK-BASED RETRANSMISSIONS

Feedback channel period (in slot): 0, 4, 2 or 1

Feedback channel period = 2

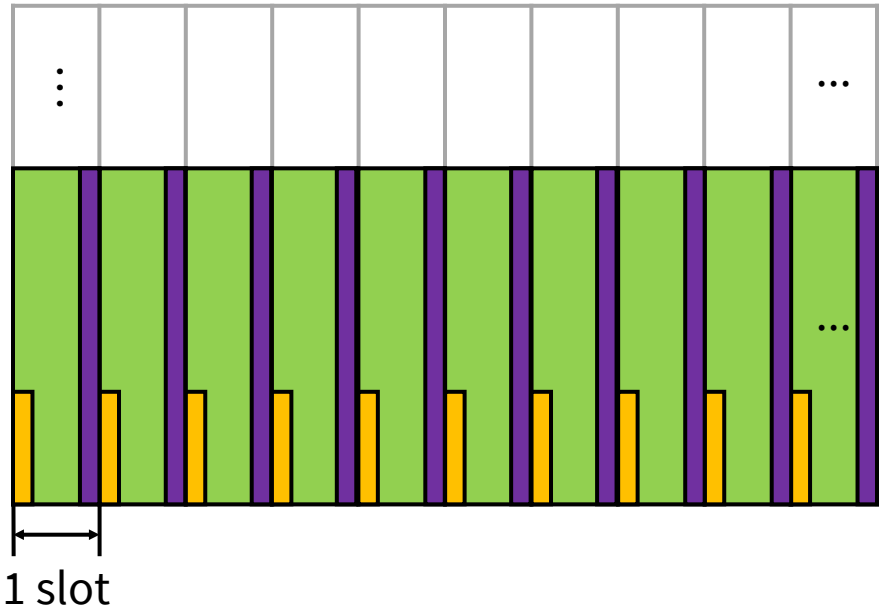


Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based

TOTAL # REs – FEEDBACK-BASED RETRANSMISSIONS

Feedback channel period (in slot): 0, 4, 2 or 1

Feedback channel period = 1



Total # REs
- Numerology
- Bandwidth part
- Overhead
- Retransmission
  - Blind
  - Feedback-based

The shorter the feedback channel period, the more the overhead.

CONFIGURATION SUMMARY

	Configuration		NR	LTE
Total # REs	Numerology		0, 1, 2, 3 for sidelink (0/1 for Band n14)	N/A
	Bandwidth part*		Up to 52 RBs under numerology 0 Up to 24 RBs under numerology 1	No definition of bandwidth part 50 RBs in total
	Overhead		Configurable	Configurable
	HARQ	Blind transmissions	Configurable 1 to 32 transmissions	Mandatory 4 blind transmissions
		Feedback-based retransmissions	Configurable feedback channel period: 0 (no feedback), 4, 2, or 1 slots	N/A

* In NR resource is allocated to data per subchannel, and there could be leftover RBs wasted in BWP due to granularity.

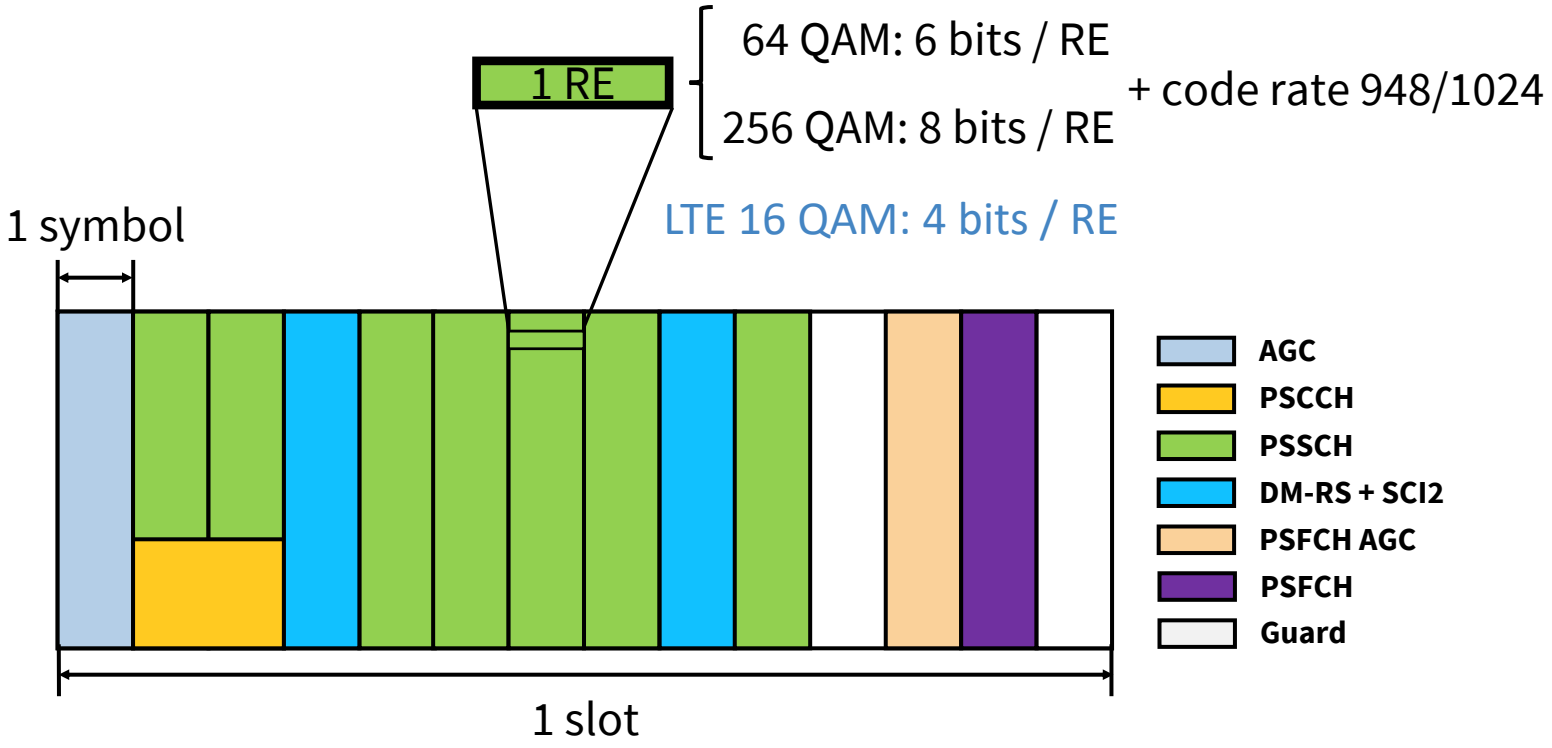
NR CAPACITY

$$data\ rate\ (in\ Mbit/s) = 10^{-6} \cdot \nu_{layers} \cdot Q_m \cdot R_{max} \cdot \frac{N_{PRB}^{BW,\mu} \times 12}{T_s^{\mu}} \cdot (1 - OH)/N$$

Data rate = Total # REs X # Bits / RE

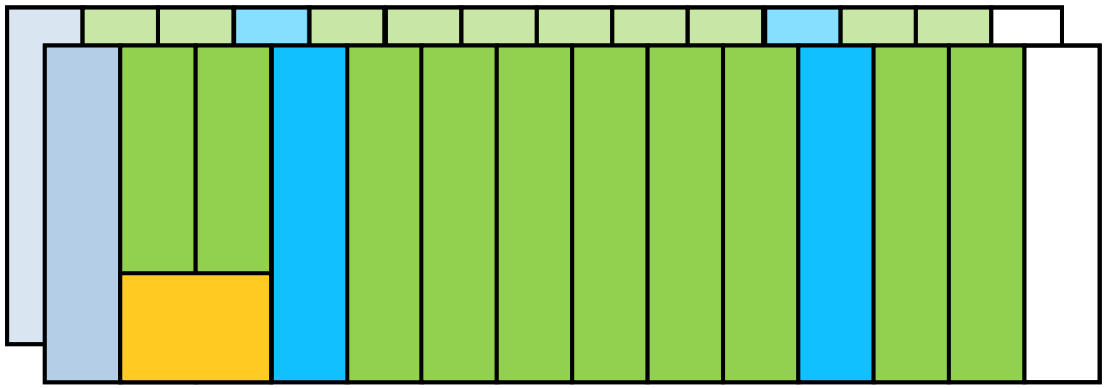
BITs PER RE – MODULATION AND CODING

- # Bits / RE
  - Modulation and coding scheme
- Spatial multiplexing



Device capability ➔ highest MCS ➔ most # bits /RE.

BITs PER RE – SPATIAL MULTIPLEXING



Bits / RE
- Modulation and coding scheme
- Spatial multiplexing

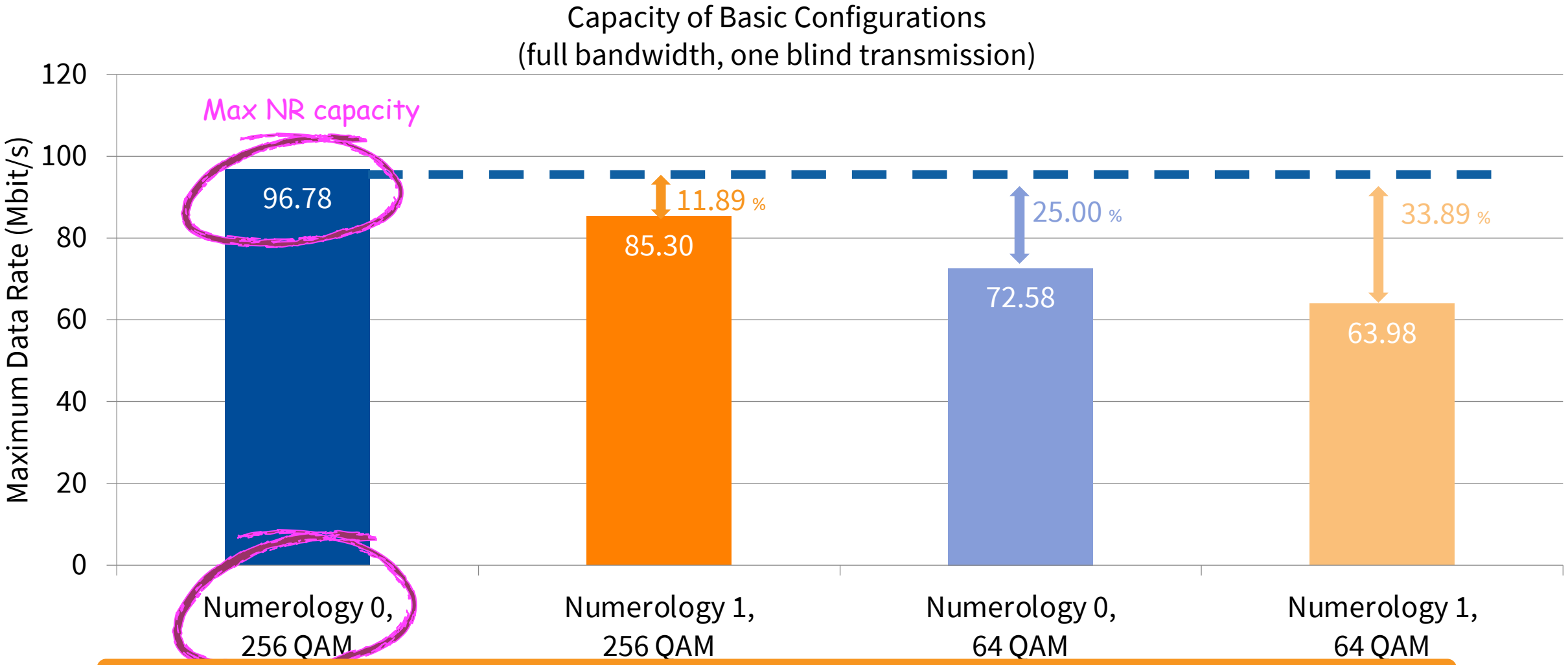
Two-layer transmission doubles #bits / RE.

CONFIGURATION SUMMARY

	Configuration		NR	LTE
Total # REs	Numerology		0, 1, 2, 3 for sidelink (0/1 for Band n14)	N/A
	Bandwidth part*		Up to 52 RBs under numerology 0 Up to 24 RBs under numerology 1	No definition of bandwidth part 50 RBs in total
	Overhead		Configurable	Configurable
	HARQ	Blind transmissions	Configurable 1 to 32 transmissions	Mandatory 4 blind transmissions
		Feedback-based retransmissions	Configurable feedback channel period: 0 (no feedback), 4, 2, or 1 slots	N/A
# Bits / RE	Modulation and coding scheme		Modulation: up to 64 or 256 QAM (depending on device capability) Code rate: maximal 948 / 1024	Modulation: up to 16 QAM
	Spatial multiplexing		Up to 2 layers	N/A

* In NR resource is allocated to data per subchannel, and there could be leftover RBs wasted in BWP due to granularity.

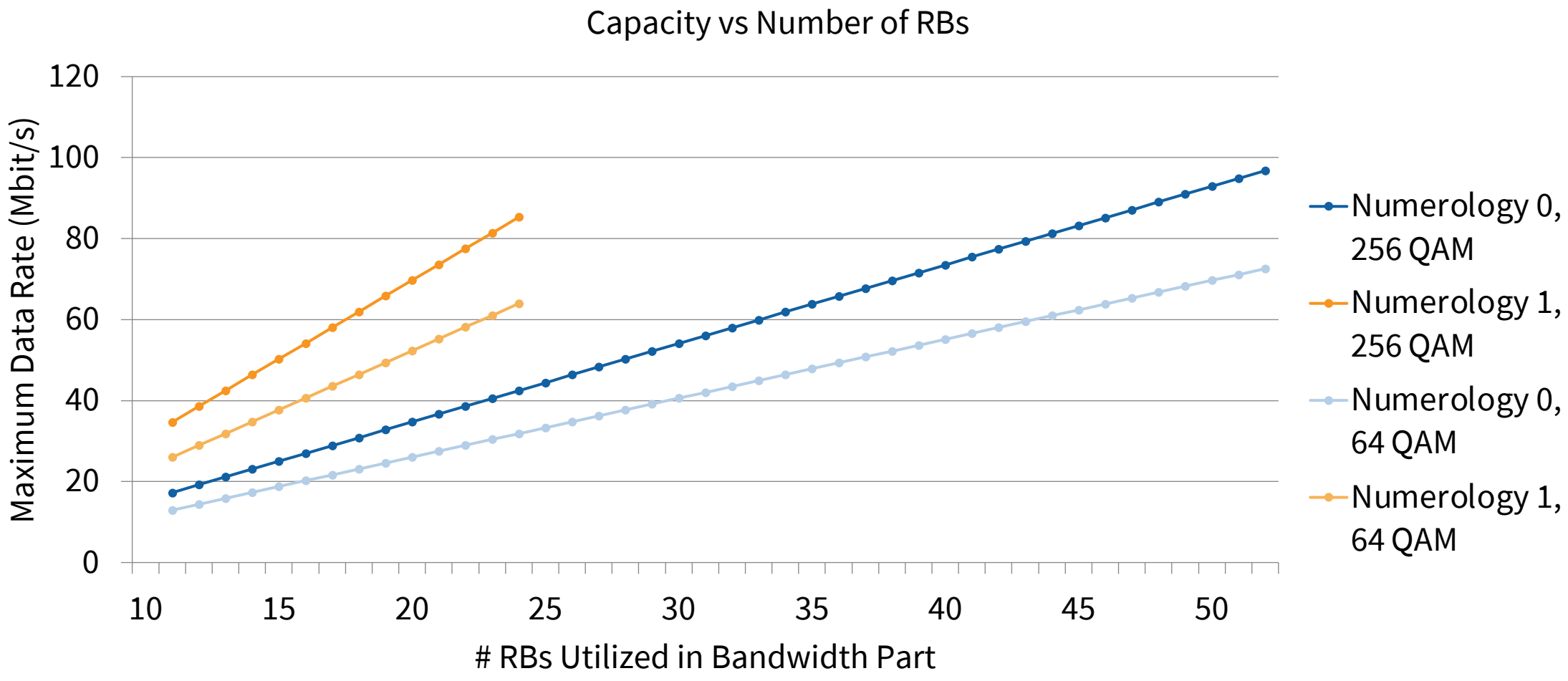
NR CAPACITY RESULTS – NUMEROLOGY AND DEVICE CAPABILITY



NR max configuration: Numerology 0 + Full bandwidth + 256 QAM capability + One blind transmission.

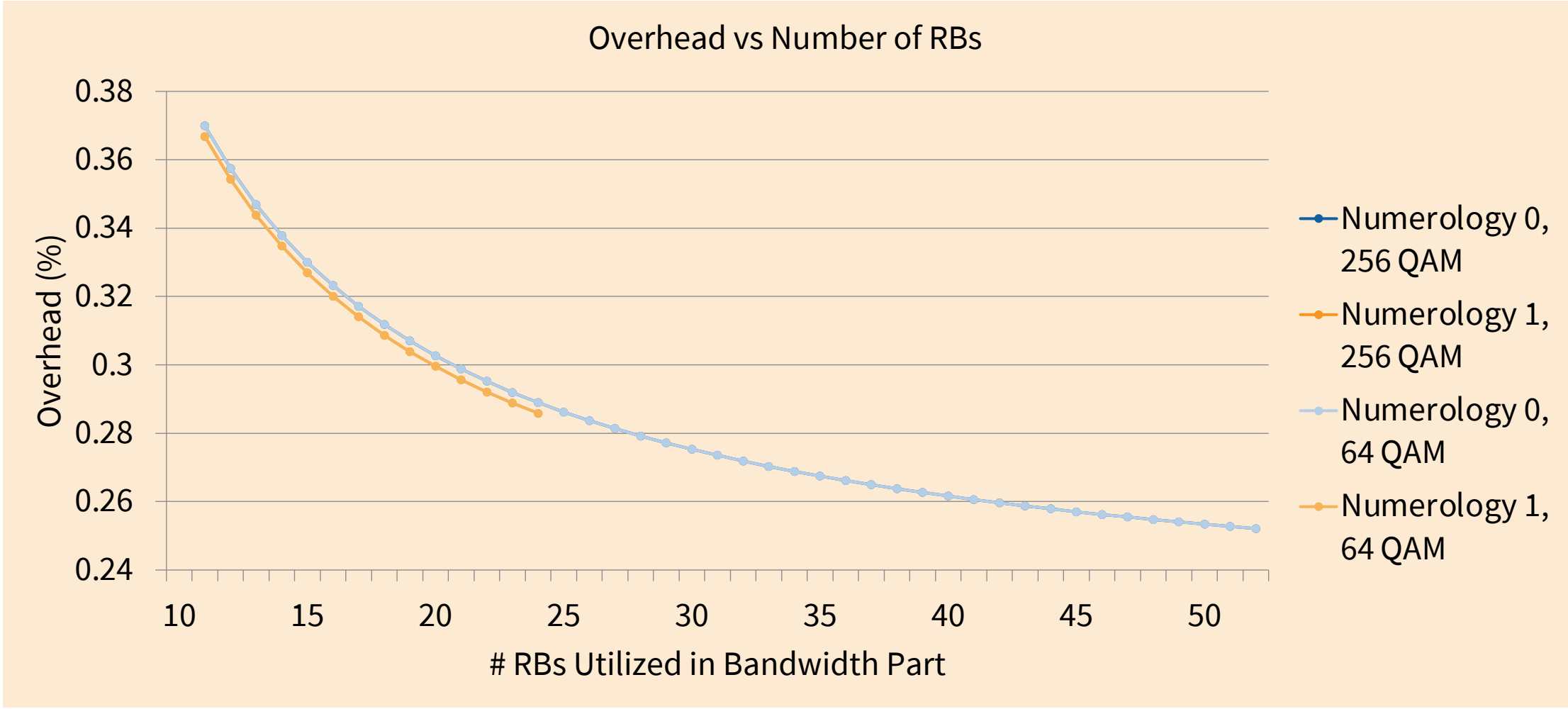
Numerology 0 has higher capacity than numerology 1.
Limitation on device capability leads to a 1/4 reduction in capacity.

NR CAPACITY RESULTS – BANDWIDTH PART



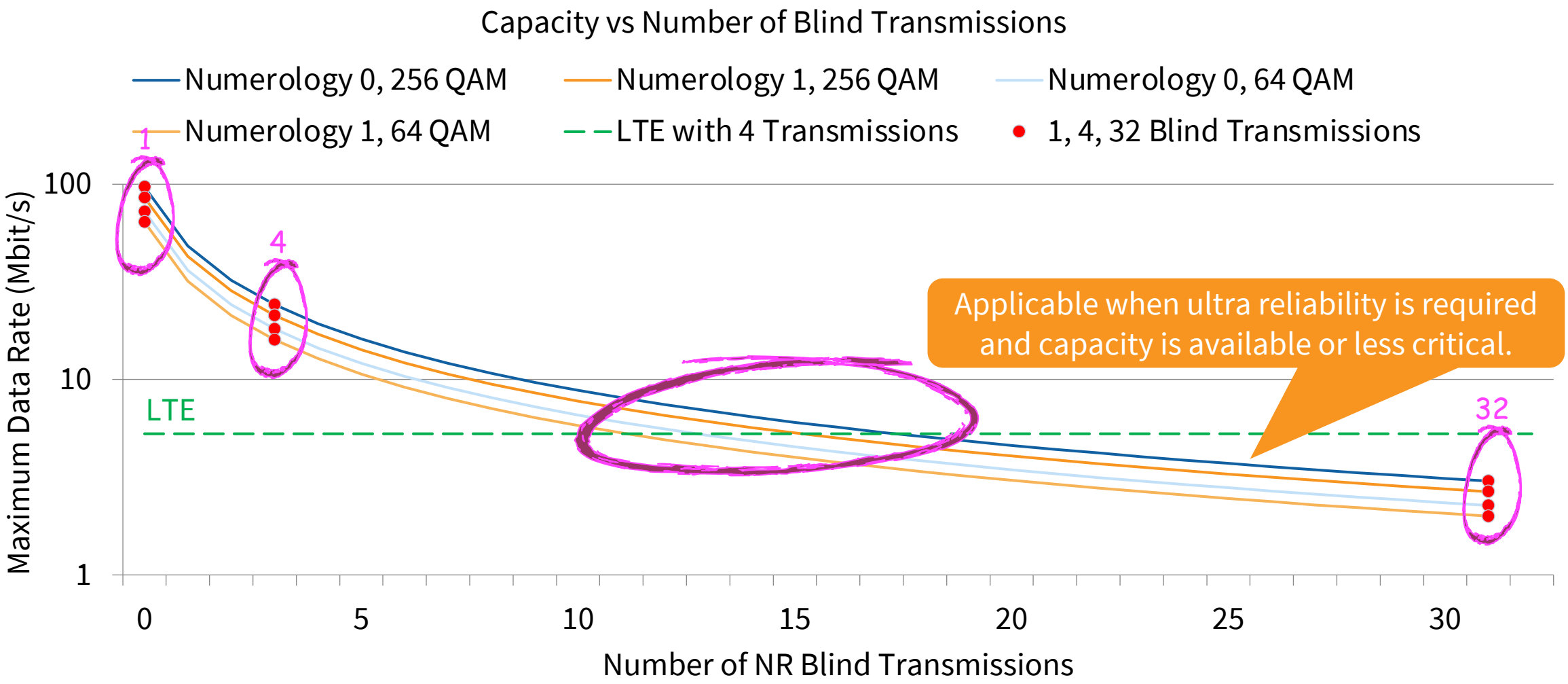
Capacity increases almost linearly with increasing # RBs utilized in bandwidth part.

NR CAPACITY RESULTS – BANDWIDTH PART



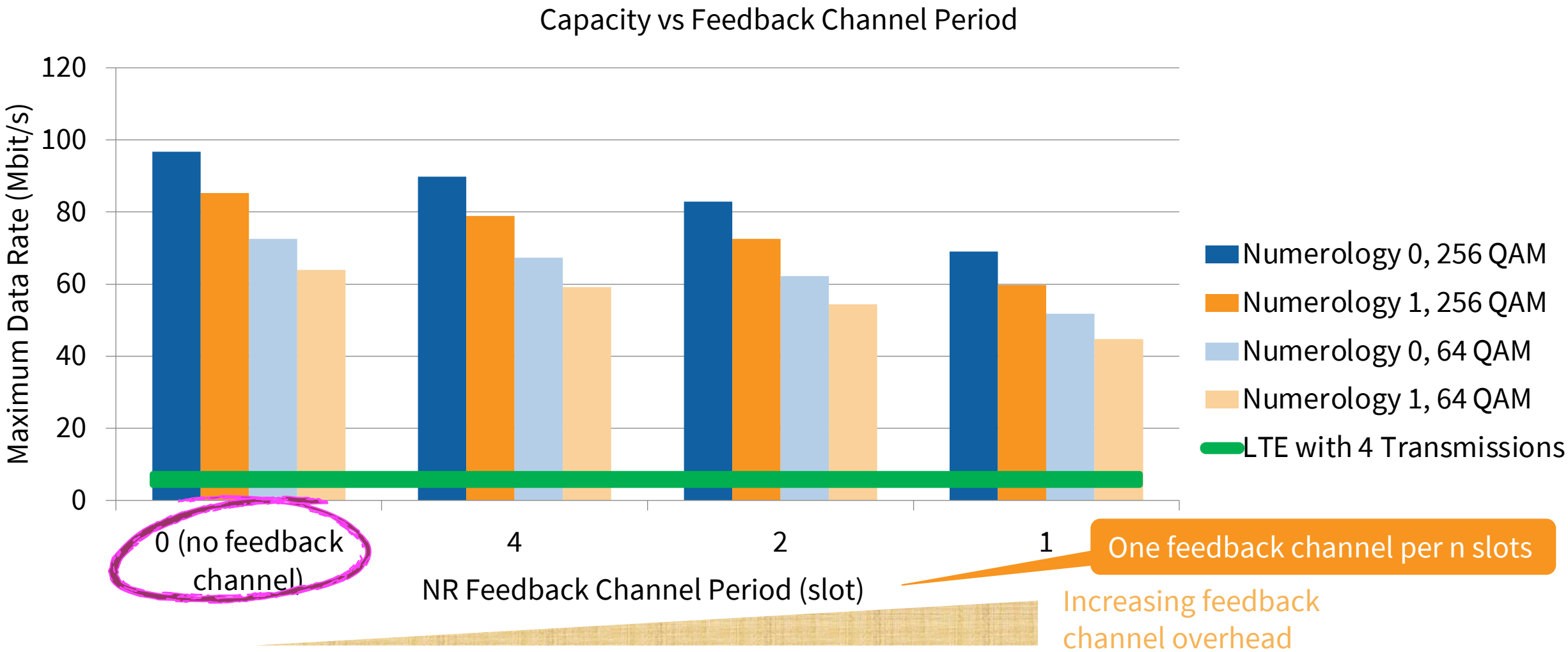
Capacity increases almost linearly with increasing # RBs utilized in bandwidth part.

CAPACITY RESULTS – BLIND TRANSMISSION



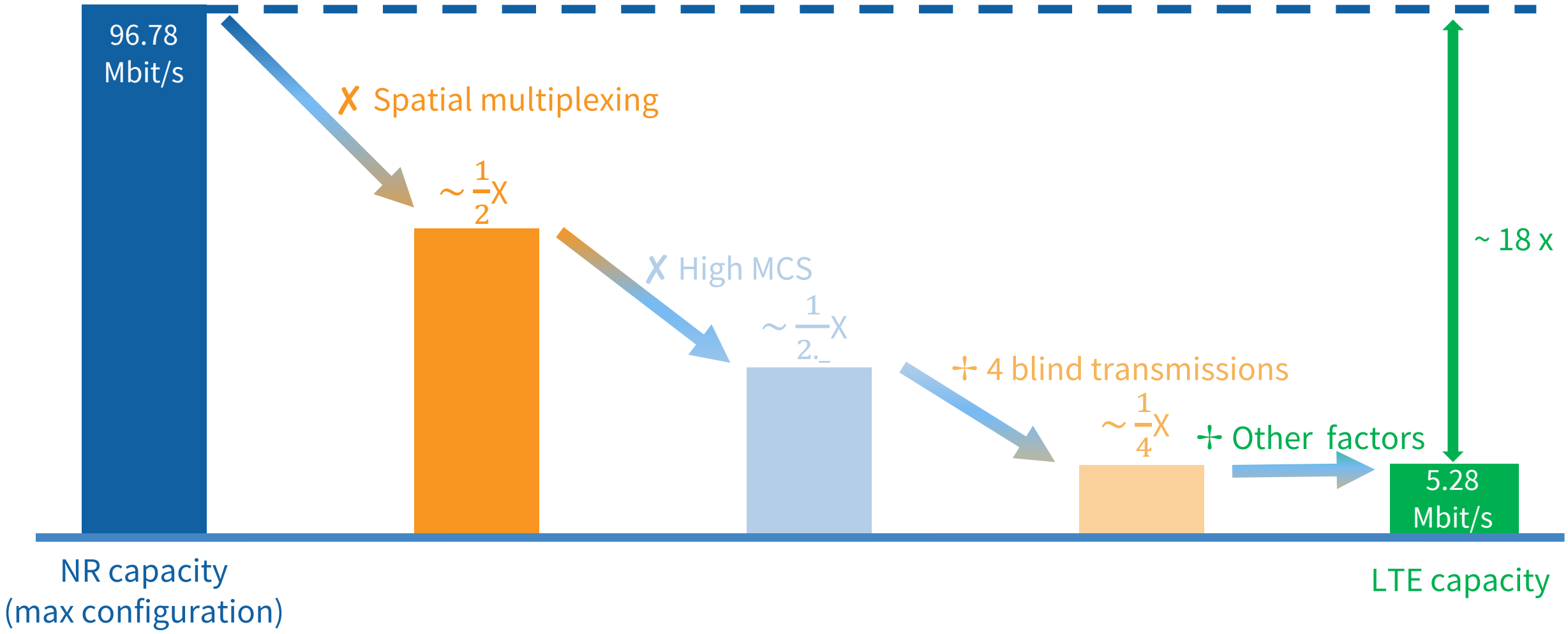
Capacity is approximately inverse proportional to the configured # transmissions.
A high # transmissions enables NR to provide ultra reliability at cost of longer latency and less capacity.

NR CAPACITY RESULTS – FEEDBACK-BASED HARQ



Feedback-based HARQ could reduce unnecessary retransmissions but introduces overheads. Frequent feedbacks lead to higher overheads and a reduced capacity.

FEATURES THAT DIFFERENTIATE



Major features that improves NR capacity are
spatial multiplexing, higher MCS, and configurable HARQ transmissions.

SUMMARY

The sidelink capacity was studied under different operational configurations and device capabilities: numerology, bandwidth part, device capability, and HARQ configuration.

- Using band n14 10 MHz as an example, the sidelink capacity varies significantly under different configurations, and is the highest under numerology 0, full bandwidth, 256 QAM capability, and one blind transmission

NR improves capacity over LTE while allowing flexible configurations to adapt to different deployment scenarios and service requirements, achieving tradeoff between reliability, latency, and capacity.

- Major features that improve NR capacity: configurable HARQ, support of higher modulation and coding, and spatial multiplexing

Next steps:

- Capacity in multicast and broadcast
- Capacity in other metrics such as number of users

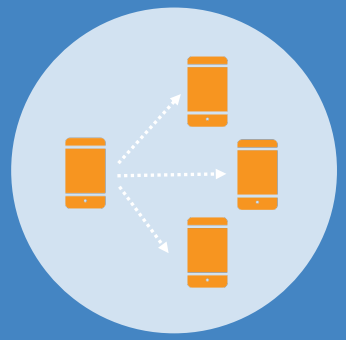
PSCR ONGOING RESEARCH IN NEW RADIO SIDELINK

LTE and NR Coexistence

Allow devices to share radio resources fairly between LTE system and NR system.

Quality of Service (QoS)

Allow devices to prioritize transmission for different users based on QoS requirements.



Resource Management

Allow devices to utilize spectrum resources efficiently, exploiting the resource allocation flexibility that NR supports.

Relay

Allow devices to access the network using the sidelink with another device in proximity.

- For more information on the above topics and the capacity study, please refer to the following report published by our group: https://doi.org/10.6028/NIST.IR.8372

GET CONNECTED

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THANK YOU

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