November, 2015

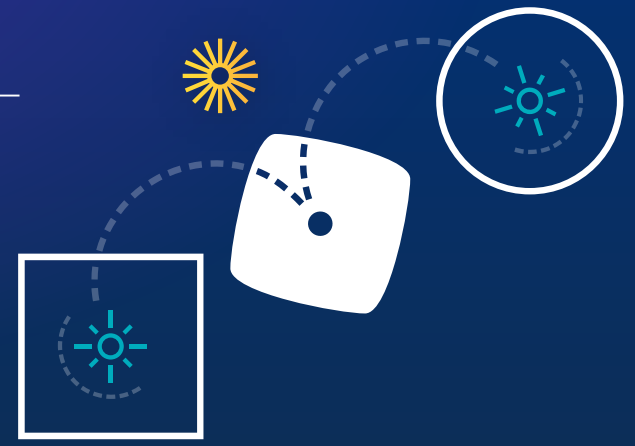
Qualcomm Technologies Inc.

The 5G Unified Air Interface

Scalable to an extreme variation of requirements

QUALCOMM®

Why Wait™



5G to meet significantly expanding connectivity needs

Building on the transformation started in 4G LTE

Connecting

new industries and devices

Enabling

new services

Empowering

new user experiences

Scalable

To an extreme variation of requirements

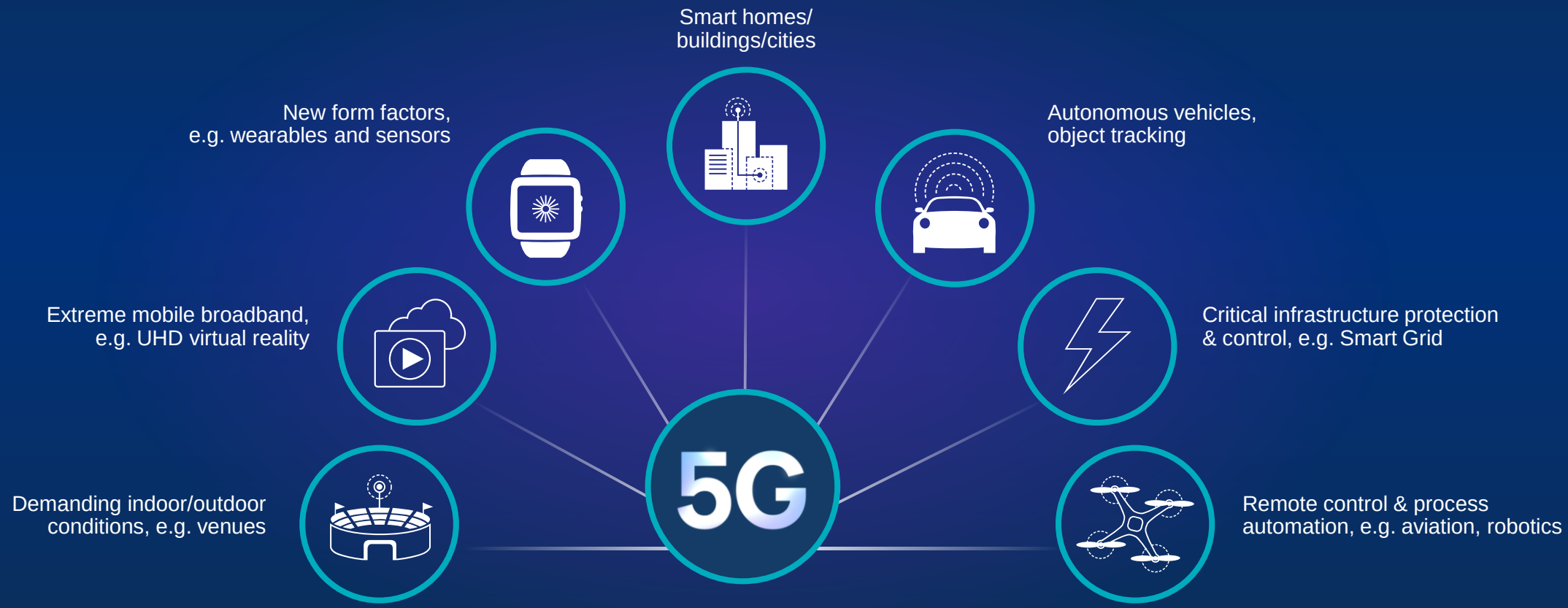
Edgeless

For uniform experiences with new ways of connecting

Unified

Across all spectrum types/bands, services and deployments

5G will enhance existing and expand to new use cases



Enhanced Mobile Broadband

Faster, more uniform user experiences

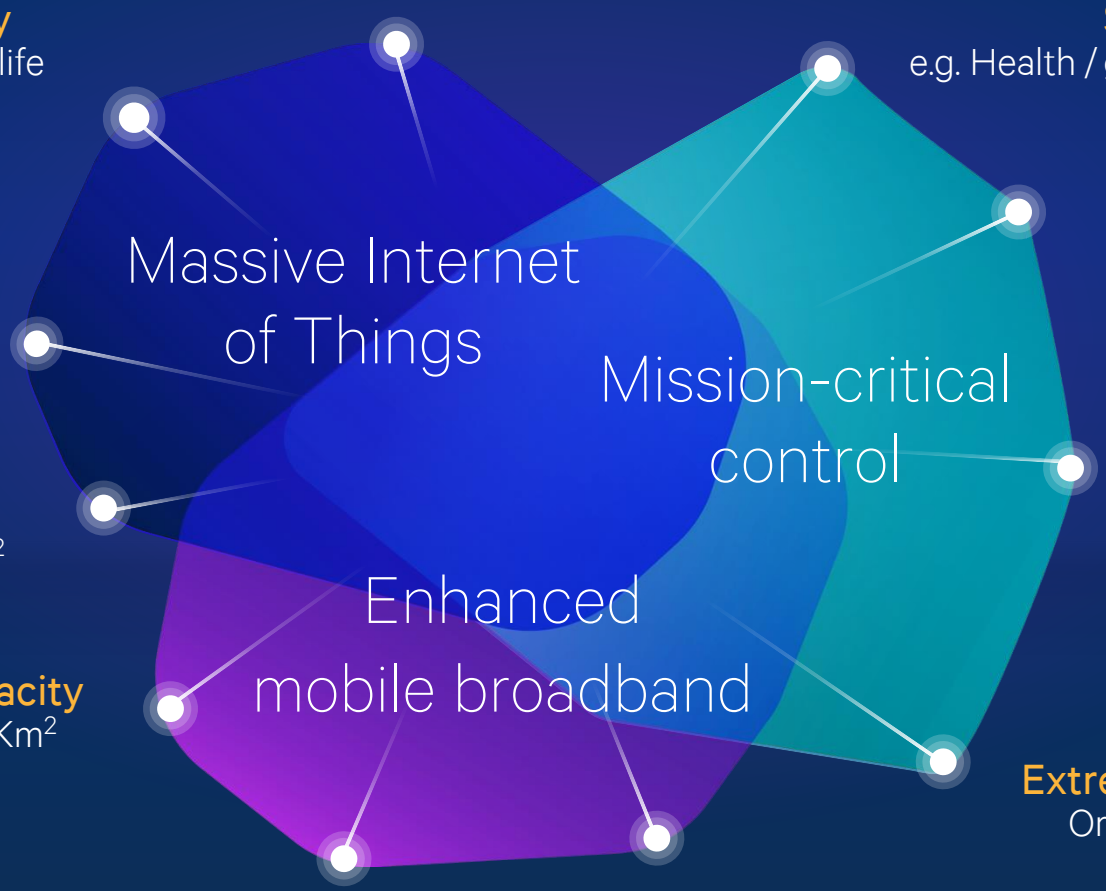
Massive Internet of Things

Efficient, low cost communications with deep coverage

Mission-Critical Control

Ultra-low latency and high reliability

Scalable across an extreme variation of requirements



Deep coverage
To reach challenging locations

Ultra-low energy
10+ years of battery life

Strong security
e.g. Health / government / financial trusted

Ultra-high reliability
<1 out of 100 million packets lost

Ultra-low complexity
10s of bits per second

Ultra-low latency
As low as 1 millisecond

Ultra-high density
1 million nodes per Km^2

Extreme capacity
10 Tbps per Km^2

Extreme user mobility
Or no mobility at all

Extreme data rates
Multi-Gigabits per second

Deep awareness
Discovery and optimization

Based on target requirements for the envisioned 5G use cases

A new 5G unified air interface is the foundation

Diverse spectrum

Licensed, shared licensed, and unlicensed spectrum

Spectrum bands below 1 GHz, 1 GHz to 6 GHz, & above 6 GHz (incl. mmWave)

FDD, TDD, half duplex

Device-to-device, mesh, relay network topologies

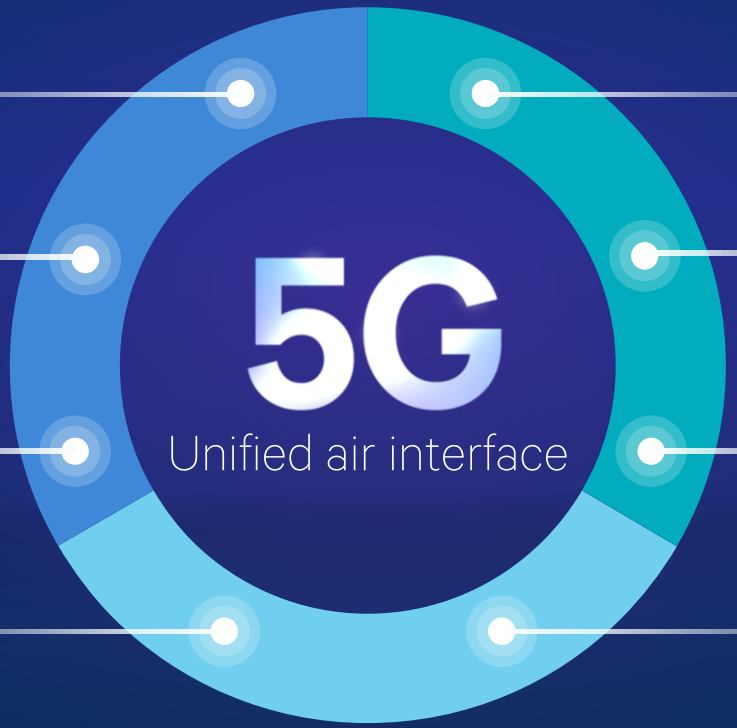
Diverse services and devices

From wideband multi-Gbps to narrowband 10s of bits per second

Efficient multiplexing of mission-critical and nominal traffic

From high user mobility to no mobility at all

From wide area macro to indoor / outdoor hotspots



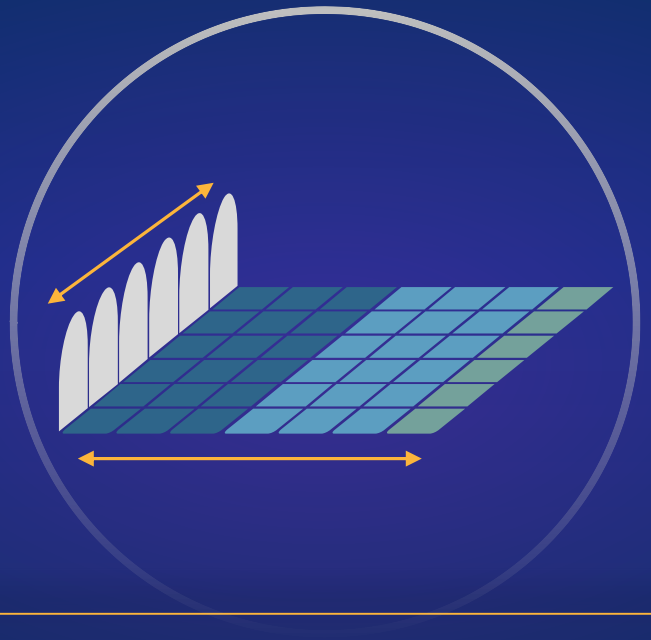
Diverse deployments

Designing the 5G Unified Air Interface

A new PHY & MAC design that is scalable to an extreme variation of requirements

Optimized OFDM-based waveforms

With scalable numerology and TTI, plus optimized multiple access for different use cases



A common, flexible framework

To efficiently multiplex services and features—designed for forward compatibility

Advanced wireless technologies

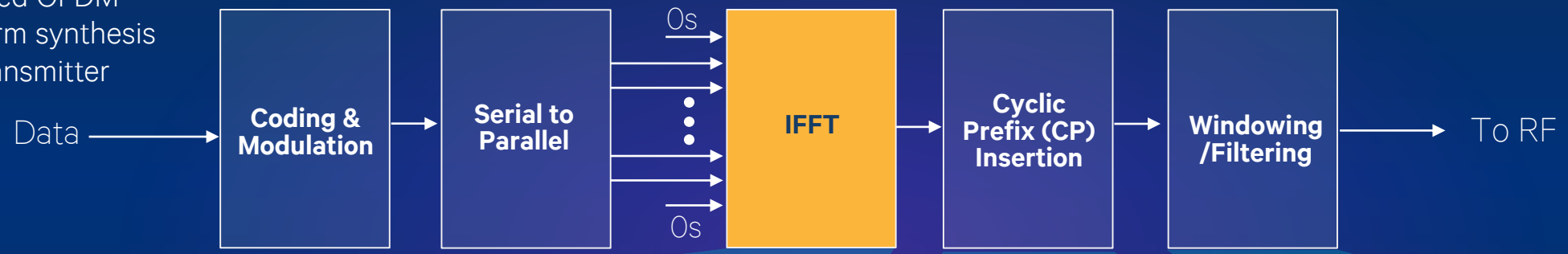
Such as massive MIMO, robust mmWave and a flexible self-contained TDD design

Designing optimized waveforms & multiple access with heavy reliance on OFDM

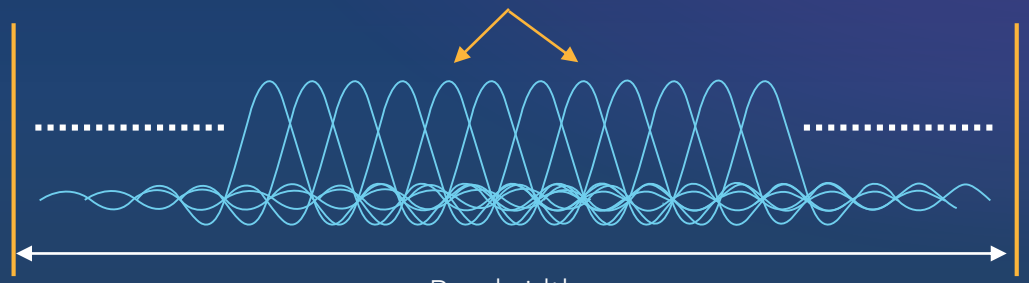
IFFT/FFT is the foundation to OFDM

Quick refresh on Orthogonal Frequency Division Multiplexing

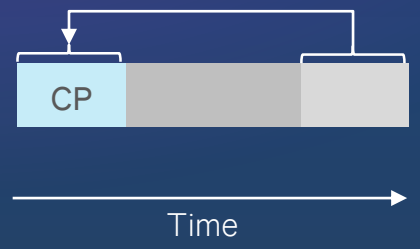
Simplified OFDM waveform synthesis for a transmitter



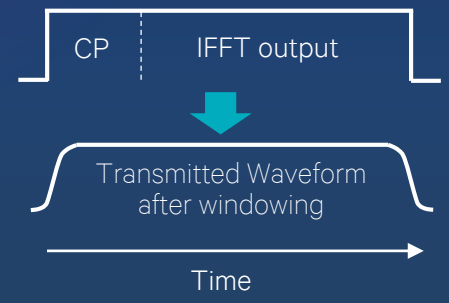
Data transmitted via closely-spaced, narrowband subcarriers – IFFT operation ensures subcarriers do not interfere



Helps maintain orthogonality despite multipath fading



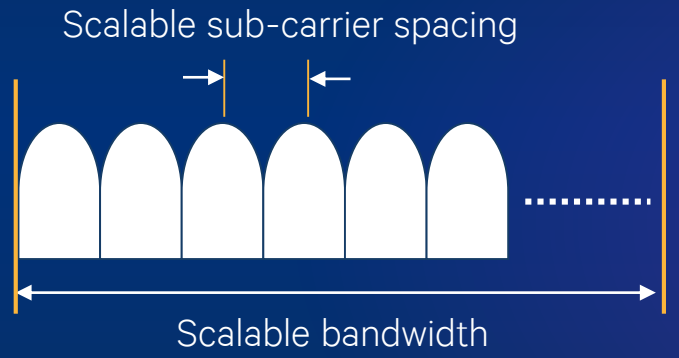
Helps achieve better frequency localization

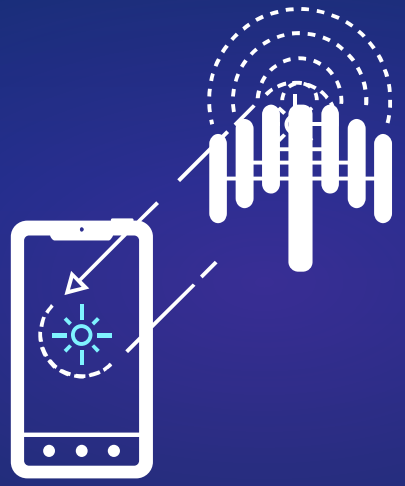


OFDM-based waveforms highly utilized in e.g. LTE and Wi-Fi systems today

OFDM family well suited to meet 5G requirements

Wide bandwidth, high capacity, low latency, low complexity per bit





Scalable

To wide bandwidths with scalable symbol duration and subcarrier spacing

Low Complexity

Does not require complex receivers even when scaling to wide bandwidths

Efficient for MIMO

Elegant framework for MIMO spatial multiplexing that scales to wider bandwidths

The OFDM family allows for enhancements

To address different use cases—a key focus for 5G

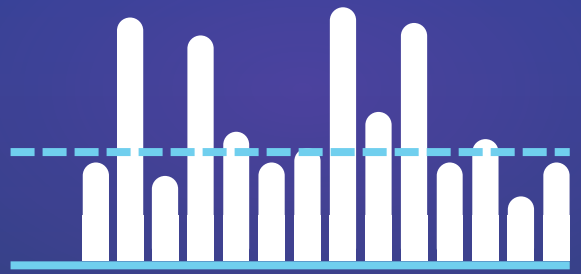
Frequency localization

To reduce in-band and out-of-band emissions

Additional OFDM windowing/filtering reduces both inter-symbol[1] and inter-channel[2] interference

Uplink energy efficiency

Due to power variations on a per OFDM subcarrier basis

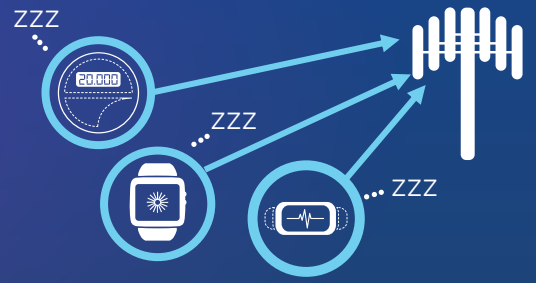


Especially in macro deployments

Add DFT spreading to achieve a single-carrier OFDM signal with smaller power variations

Asynchronous uplink

To support sporadic uplink transmissions of small data bursts



Such as for massive IoT

Support for asynchronous, grant-free multiple access such as Resource Spread Multiple Access

[1] Among users within allocated band; [2] among neighboring operators, e.g. low Adjacent-Channel Leakage Ratio (ACLR)

Numerous OFDM-based waveforms considered for 5G

Multi-carrier OFDM waveforms

OFDM variants with windowing/filtering enhancements for better frequency localization

CP-OFDM with windowing[1]

Time domain windowing to soften edges of symbols—used in 4G LTE downlink today

UFMC[2]

Customized filtering over a block of contiguous OFDM subcarriers[2]

FBMC / GFDM[3]

Customized subcarrier pulse shaping achieved through oversampling[4]

IFFT/FFT

All waveforms based on OFDM Synthesis

Single-carrier OFDM waveforms

Single-carrier OFDM variants that use DFT spreading to reduce power variations in uplink

SC-OFDM with windowing[1]

DFT spreading with cyclic prefix (CP) insertion—used in 4G LTE uplink today

Zero-tail SC-OFDM

DFT spreading with dynamic zero-pad instead of fixed CP for higher spectral efficiency

[1] Time domain windowing heavily used in commercial LTE systems, but not specified in 3GPP standard; [2] Universal Filtered Multi-Carrier; [3] Filter Bank Multi-Carrier and Generalized Frequency Division Multiplexing

CP-OFDM & SC-OFDM with windowing most optimal

Alternative proposals add complexity—radio design, multiplexing—with marginal benefits

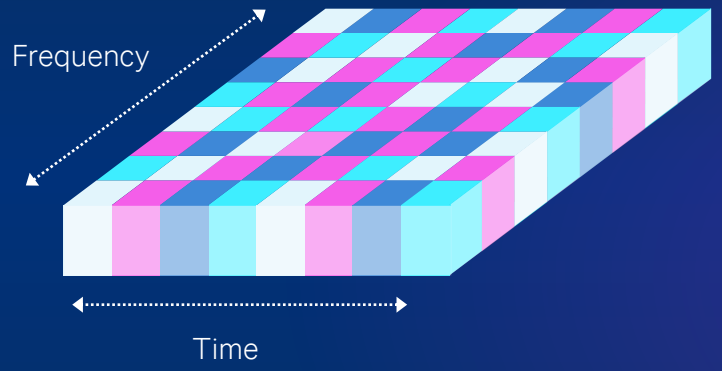
		Pros	Cons
Multi-carrier alternatives	FBMC	• Best frequency localization (marginalized in practical systems[1])	• Requires complex modulation • Integration with MIMO non-trivial
	UFMC	• Better frequency localization than CP-OFDM (equivalent to CP-OFDM with windowing)	• High Tx and Rx (2x FFT size) complexity • No CP – interference from multipath fading
	GFDM	• Better frequency localization than CP-OFDM (equivalent to CP-OFDM with windowing)	• Complicated receiver to handle interference • Requires large guardband to multiplex services
Single-carrier alternatives	Zero-tail SC-OFDM	• Marginal spectral efficiency gains • Better OOB suppression with synchronization	• Requires extra signaling that adds complexity • Non-trivial to multiplex with OFDM

Download Qualcomm Research whitepaper for detailed analysis:
www.qualcomm.com/documents/5g-waveform-multiple-access-techniques

[1] Due to non-linearity in practical receiver implementations; Qualcomm Research is a division of Qualcomm Technologies, Inc.

Different multiple access schemes for different use cases

Orthogonal, Centralized Scheduling



OFDMA & SC-FDMA for mobile broadband and beyond

Utilizes CP-OFDM and SC-OFDM waveforms respectively

OFDMA well suited for spectrally efficient large data transmissions

SC-FDMA well suited for efficient UL transmissions in macro deployments

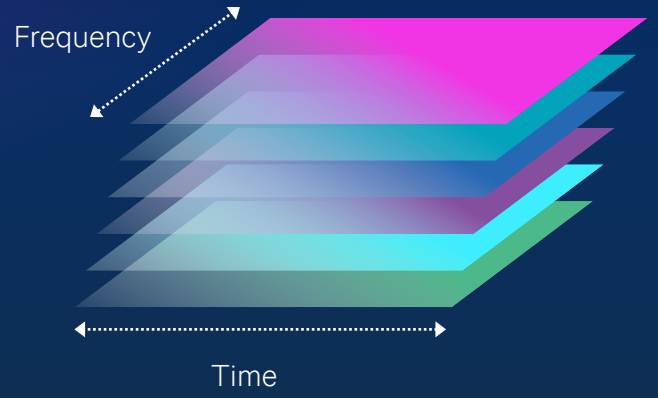
Resource Spread Multiple Access (RSMA) for target use cases

Enables asynchronous, non-orthogonal, contention-based access well suited for e.g. IoT UL

Spreads bits through low rate coding[1] across resource elements in time or frequency

Signals may occupy same resources—separate with different e.g. scrambling codes

Non-orthogonal, Distributed Scheduling



[1] As opposed to legacy Code Division Multiple Access (CDMA) schemes which attempted to orthogonalize users with e.g. Walsh codes

Optimized 5G waveforms and multiple access

With heavy reliance on the OFDM family

5G Downlink

A single waveform for flexible service multiplexing

CP-OFDM[1] + OFDMA

Also recommended for D2D & basestation-to-basestation communications to maximize transmit/receiver design reuse

5G Uplink

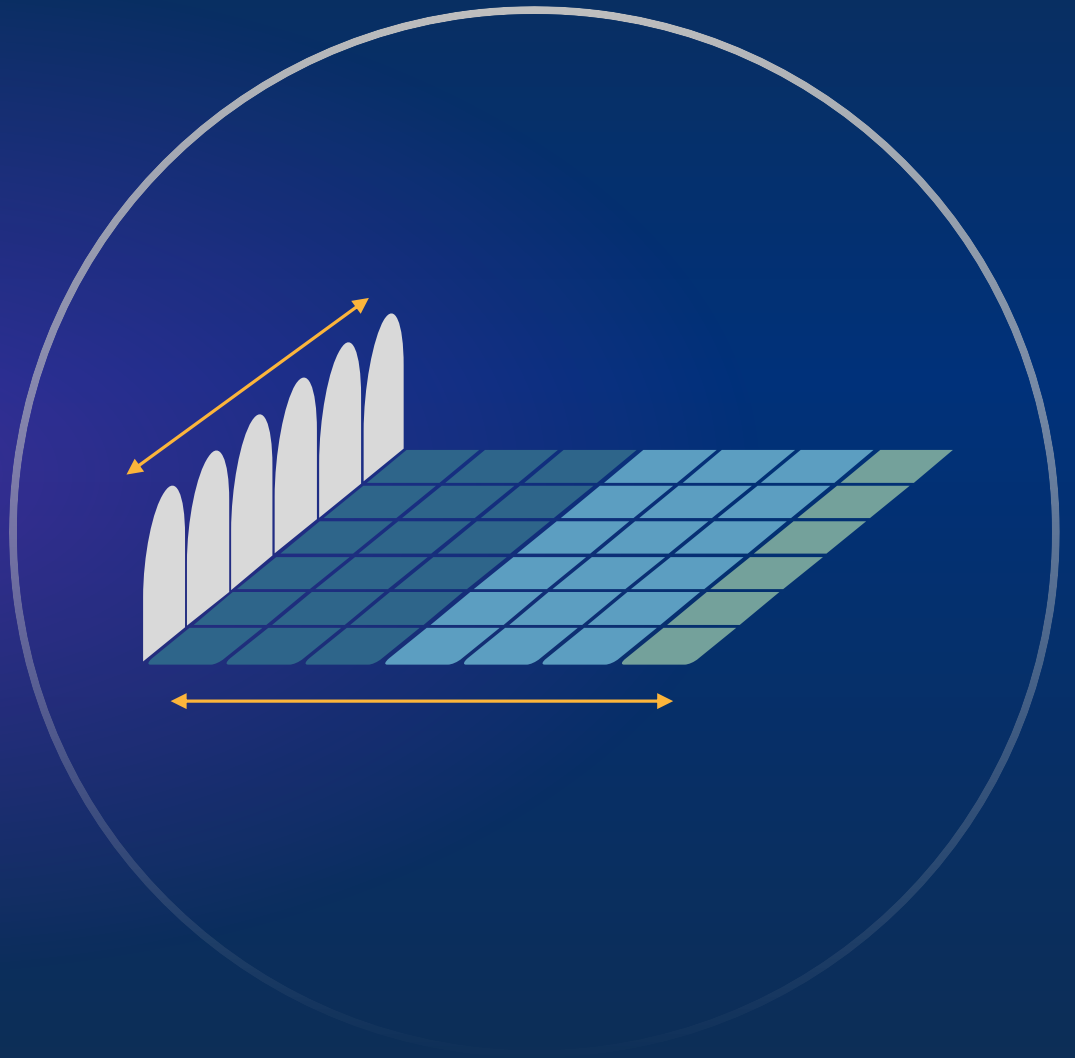
Optimized waveforms for different use cases

Macro coverage	SC-OFDM[1] + SC-FDMA To maximize device energy efficiency
Small cells	CP-OFDM[1] + OFDMA To maximize spectral efficiency
Massive IoT	Low energy single-carrier[2] + RSMA For energy efficient small data bursts
Mission-critical	CP-OFDM/SC-OFDM[1] + RSMA[3] For low latency, grant-less small data bursts

Download Qualcomm Research whitepaper for detailed analysis:
www.qualcomm.com/documents/5g-waveform-multiple-access-techniques

[1] With time domain windowing as common in LTE systems today; [2] Such as SC-FDE and GMSK; [3] May also use OFDMA/SC-FDMA for applications that may be scheduled

Designing a flexible framework to multiplex envisioned & unknown 5G services



Unified 5G design across spectrum types and bands

Licensed Spectrum	Shared Licensed Spectrum	Unlicensed Spectrum
Cleared spectrum	Complementary licensing	Multiple technologies
EXCLUSIVE USE	SHARED EXCLUSIVE USE	SHARED USE

Below 1 GHz: longer range for massive Internet of Things

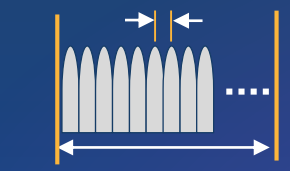
1 GHz to 6 GHz: wider bandwidths for enhanced mobile broadband and mission critical

Above 6 GHz, e.g. mmWave: extreme bandwidths, shorter range for extreme mobile broadband

Scalable numerologies to meet diverse deployments

From narrowband to wideband, licensed & unlicensed, TDD & FDD

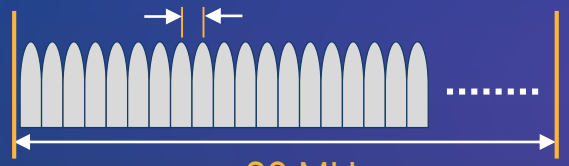
Outdoor and macro coverage
FDD/TDD <3 GHz



Sub-carrier spacing = N
(extended cyclic prefix)

e.g. 1, 5, 10 & 20 MHz

Outdoor and small cell
TDD > 3 GHz



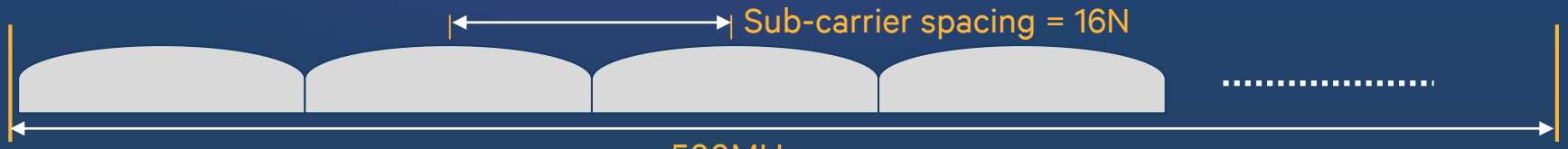
Sub-carrier spacing = 2N
(normal cyclic prefix)

e.g. 80 MHz

Indoor wideband
TDD e.g. 5 GHz
(Unlicensed)

e.g. 160MHz

mmWave
TDD e.g. 28 GHz

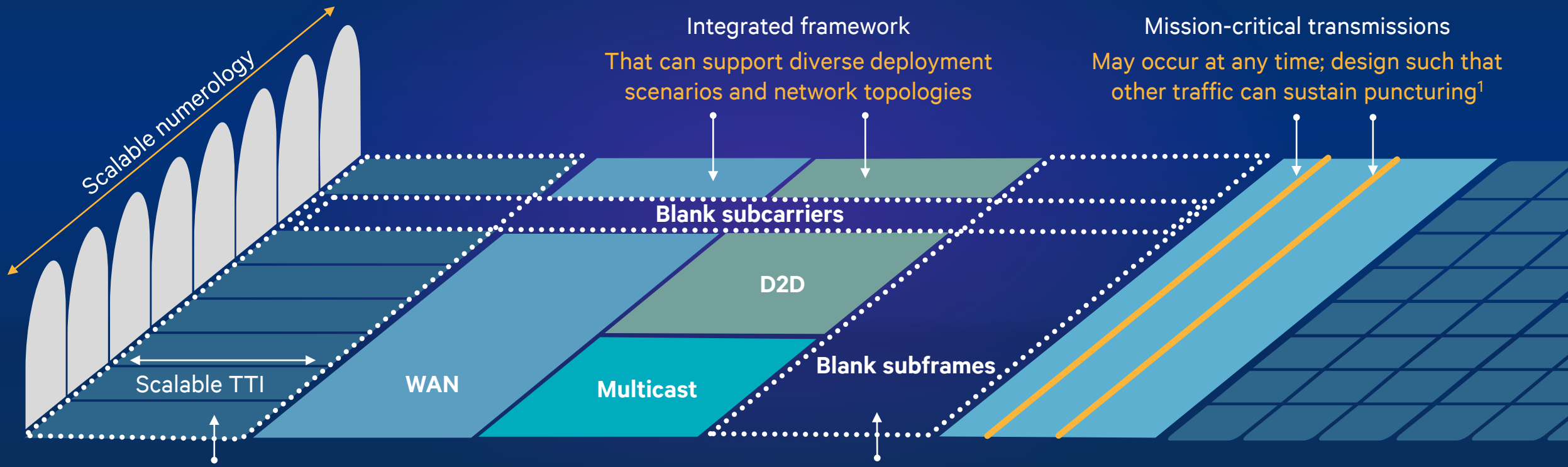


e.g. 500MHz

Example usage models and channel bandwidths

A flexible framework with forward compatibility

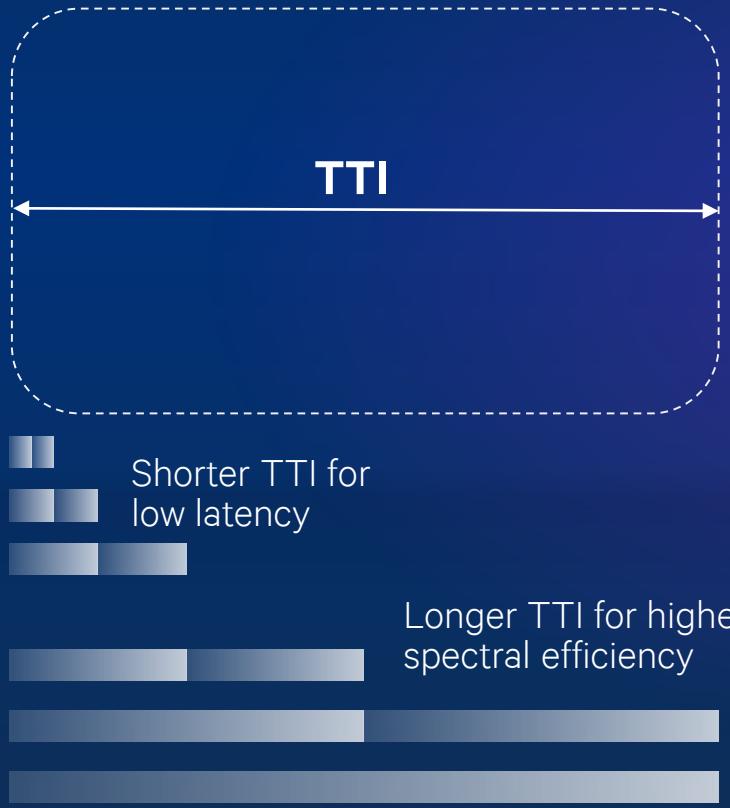
Designed to efficiently multiplex envisioned & unforeseen 5G services on the same frequency



[1] Nominal 5G access to be designed such that it is capable to sustain puncturing from mission-critical transmission or bursty interference

Scalability to much lower latency

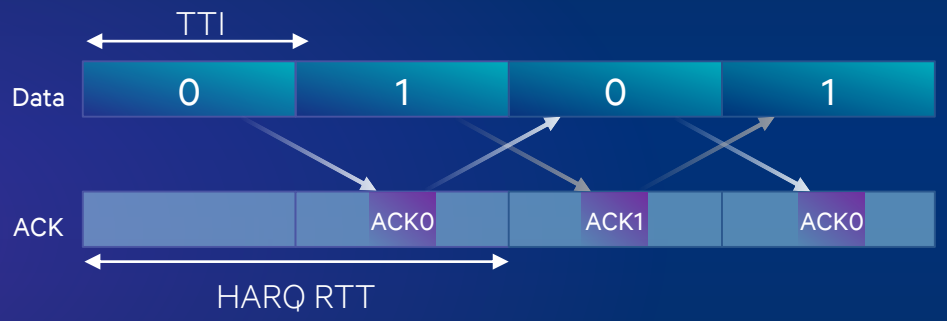
Scalable TTI for diverse latency & QoS requirements



Order of magnitude lower Round-Trip Time (RTT) than LTE today

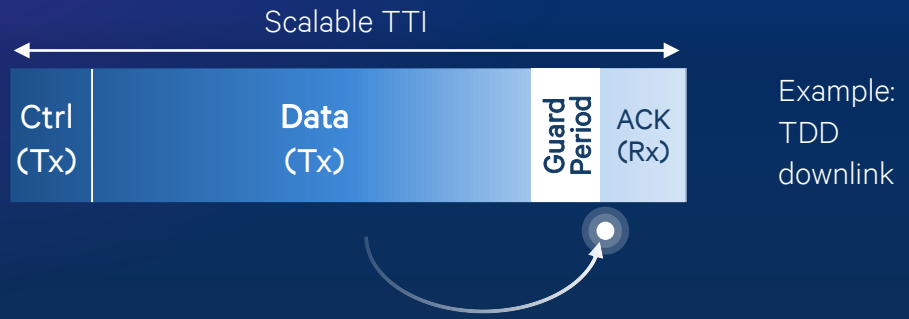
FDD

Fewer (variable) interlaces for HARQ[1]



TDD

Self-contained design reduces RTT



[1] Compared to LTE's 8 HARQ interlaces

Self-contained TDD subframe design

Faster, more flexible TDD switching & turn around, plus support for new deployment scenarios

Unlicensed spectrum

Listen-before-talk headers e.g. clear Channel Assessment (CCA) and hidden node discovery

Massive MIMO

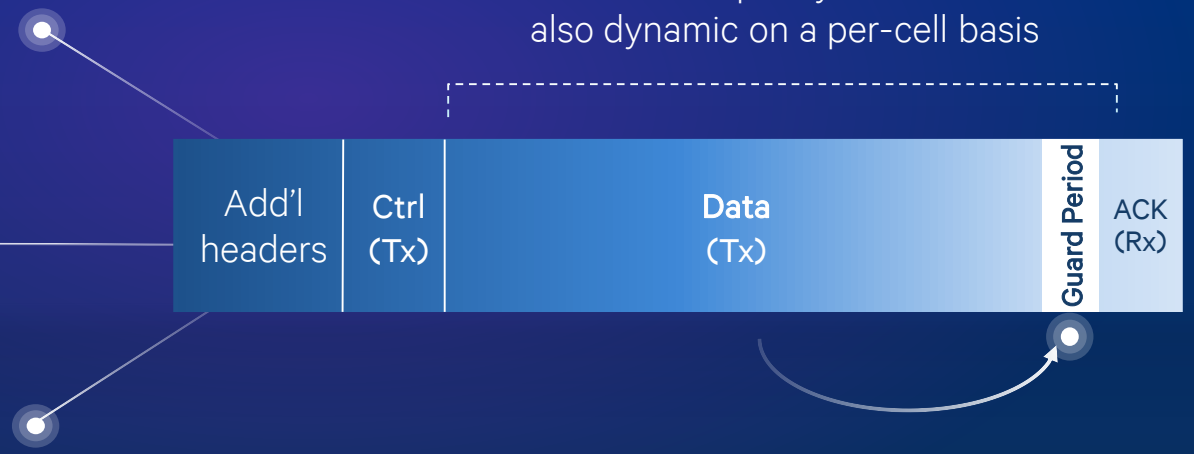
Leveraging channel reciprocity in UL transmission for DL beamforming training

D2D, mesh and relay

Headers for e.g. direction of the link for dynamic distributed scheduling

Adaptive UL/DL configuration

Flexible capacity allocation;
also dynamic on a per-cell basis

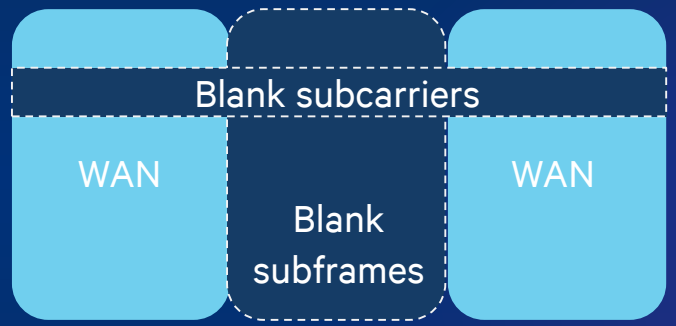


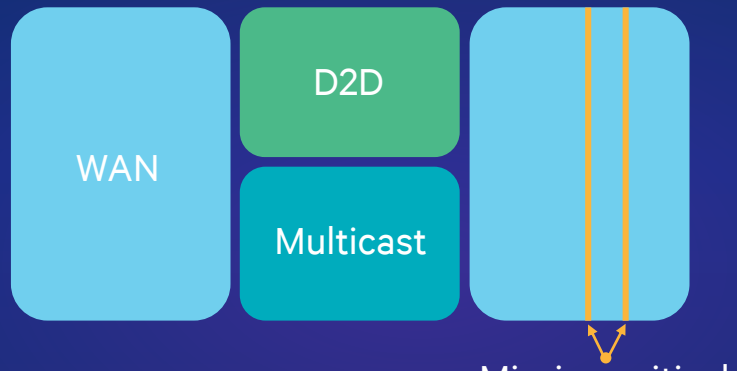
Example: TDD downlink

Self-contained TDD sub-frame: UL/DL scheduling info, data and acknowledgement in the same sub-frame

Designing Forward Compatibility into 5G

Flexibly phase in future features and services





Blank resources[1]

Enable future features/service to be deployed in the same frequency in a synchronous and asynchronous manner

Service multiplexing

E.g. nominal traffic designed to sustain puncturing from mission-critical transmissions or bursty interference

Common frame structure

Enable future features to be deployed on a different frequency in a tightly integrated manner, e.g. 5G sub 6 GHz control for mmWave

[1] 'Blank' resources may still be utilized , but designed in a way to not limit future feature introductions

Natively incorporate advanced wireless technologies across 5G services

Natively incorporate advanced wireless technologies

Key 5G design elements across services

Enhanced Mobile Broadband

Faster, more uniform user experiences

- Scalable to wider bandwidths
- Designed for all spectrum types
- Massive MIMO
- Robust mmWave design
- Improved network/signaling efficiency
- Native HetNets & multicast support
- Opportunistic carrier/link aggregation

Massive Internet of Things

Efficient, low cost communications

- Low complexity, narrow bandwidth
- Low energy waveform
- Optimized link budget
- Decreased overheads
- Managed multi-hop mesh

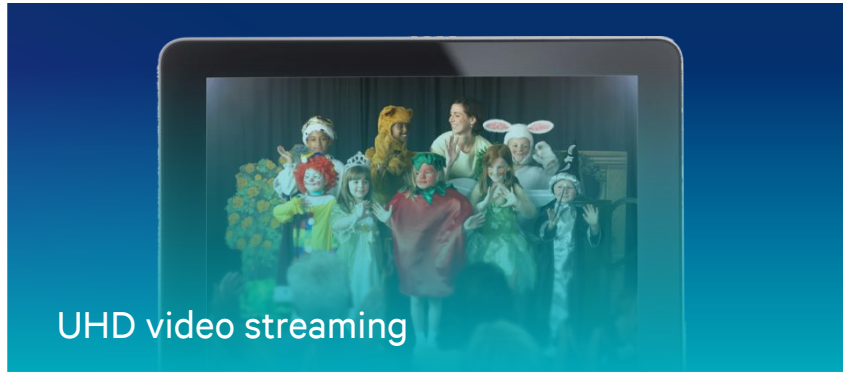
Mission-Critical Control

Ultra-low latency and high reliability links

- Ultra-low latency bounded delay
- Optimized PHY/pilot/HARQ
- Efficient multiplexing with nominal
- Simultaneous, redundant links
- Grant-free transmissions

Enhanced mobile broadband

Ushering in the next era of immersive experiences and hyper-connectivity



Extreme throughput

multi-gigabits per second

Ultra-low latency

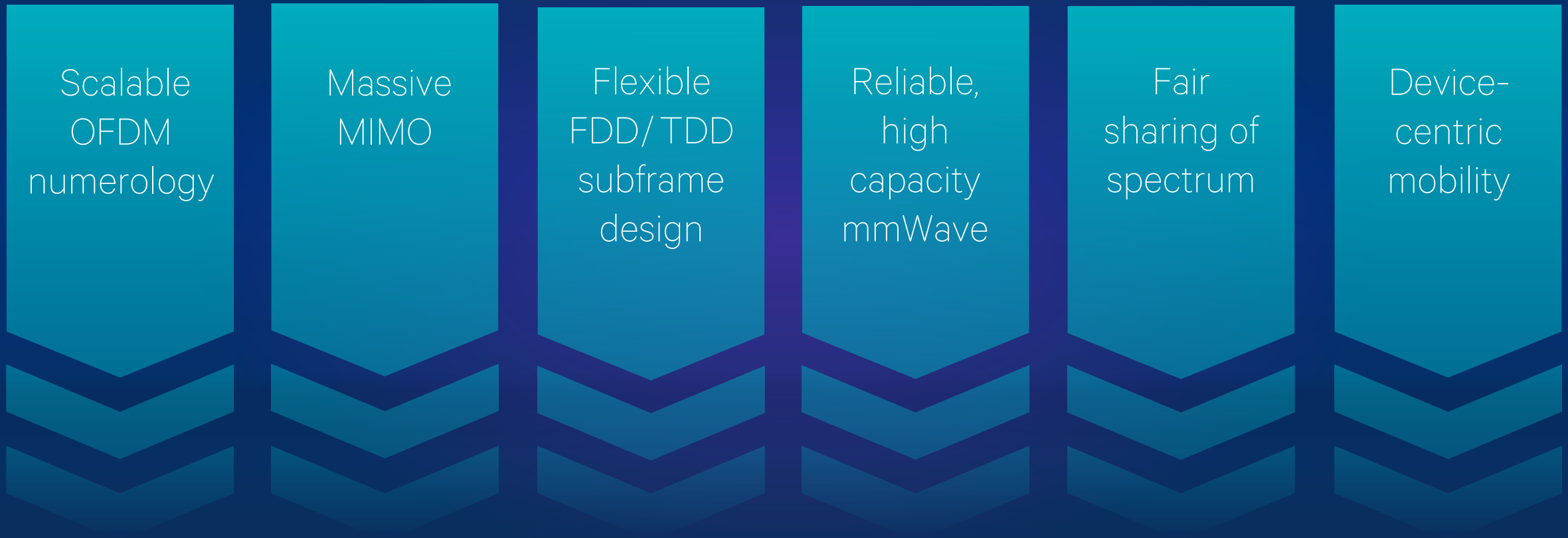
down to 1ms e2e latency

Uniform experience

with much more capacity

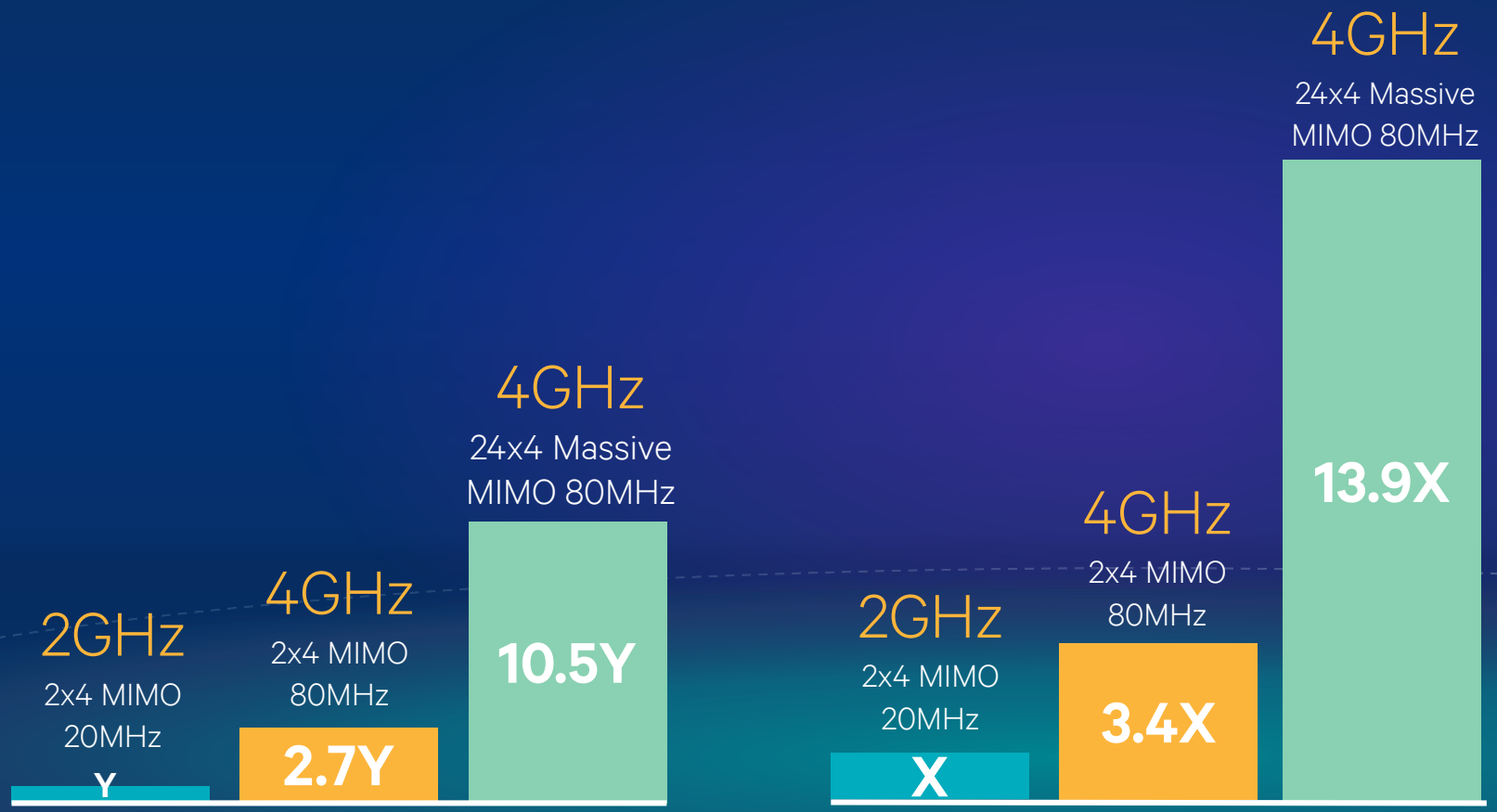
Scaling up to enhance mobile broadband

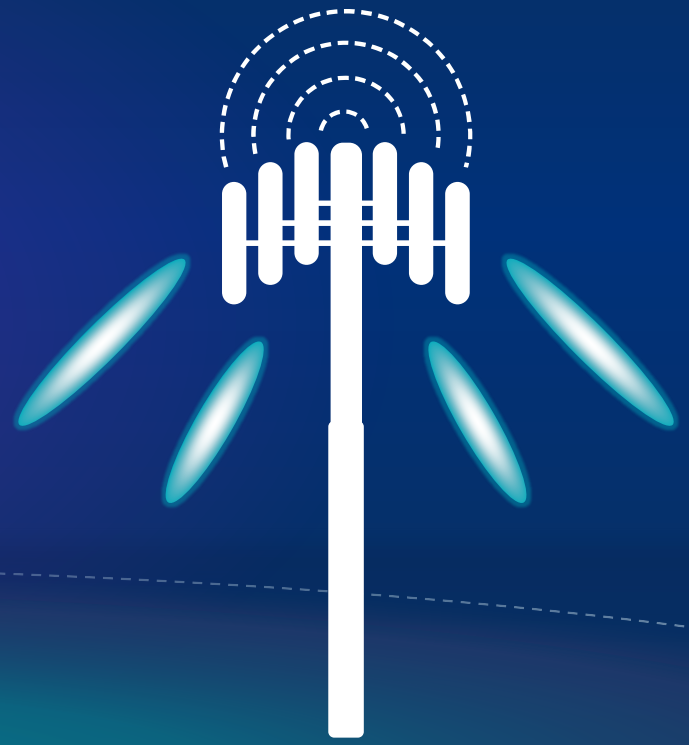
Key 5G Unified Air Interface design elements



Massive MIMO at 4 GHz allows reuse of existing sites

Leverage higher spectrum band using same sites and same transmit power





Macro site

1.7km inter-site distance

Source: Qualcomm simulations; Macro-cell with 1.7km inter-site distance, 10 users per cell, 46 dBm Tx power at base station,, 20MHz@2GHz and 80MHz@4GHz BW TDD, 2.4x Massive MIMO – detailed simulation data available in the appendix

Realizing the mmWave opportunity for mobile broadband

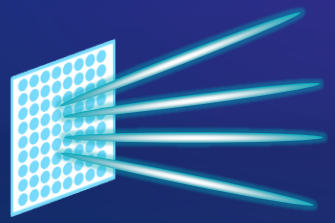
The extreme mobile broadband opportunity

- Large bandwidths, e.g. 100s of MHz
- Multi-Gpbs data rates
- Flex deployments (integrated access/backhaul)
- High capacity with dense spatial reuse

The challenge—'mobilizing' mmWave

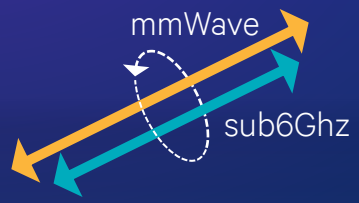
- Robustness due to high path loss and susceptibility to blockage
- Device cost/power and RF challenges at mmWave frequencies

5G Solutions



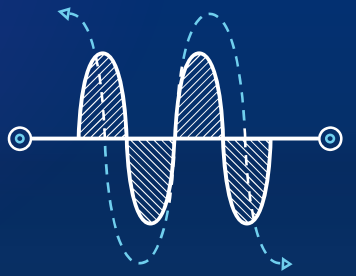
Smart beamforming & beam tracking

Increase coverage & provide seamless connectivity



Tight interworking with sub 6 GHz

Increase robustness and faster system acquisition



Phase noise mitigation in RF components

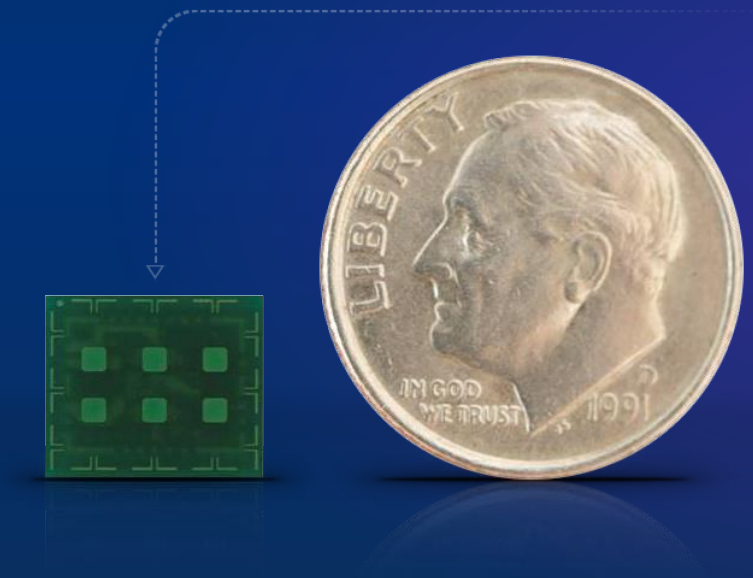
For low cost, low power devices

Making mmWave a reality for mobile

Qualcomm Technologies is setting the path to 5G mmWave

60 GHz chipset commercial today

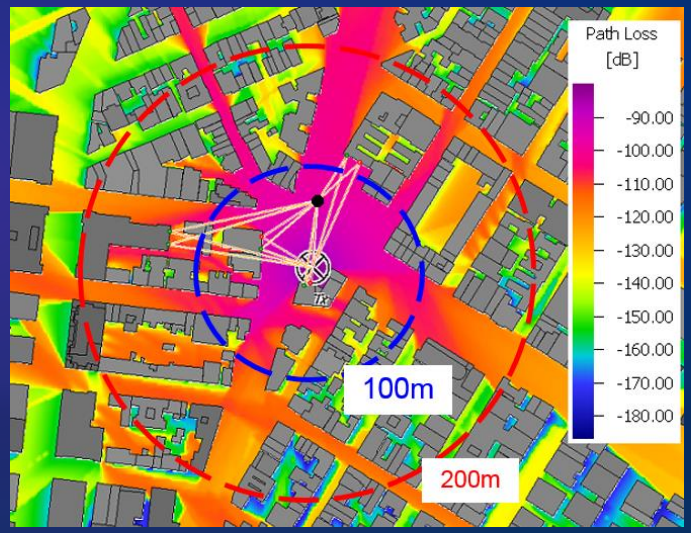
For mobile devices, notebooks and access points



Qualcomm® VIVE™ 802.11ad technology for the Qualcomm® Snapdragon™ 810 processor operates in 60 GHz band with a 32-antenna array element

Developing 5G mmWave

For extreme mobile broadband both outdoor and indoor



Manhattan 3D Map

* Results from ray-tracing[1]

28 GHz outdoor example with ~150m dense urban LOS and NLOS coverage using directional beamforming[1]

Qualcomm VIVE is a product of Qualcomm Atheros, Inc.; Qualcomm Snapdragon is a product of Qualcomm Technologies, Inc.

[1] Based on Qualcomm Simulations

Making the best use of all spectrum types

To efficiently grow data capacity

Introduced in 4G LTE

LTE-U and LAA

Licensed shared access (LSA) and similar

MuLTEfire™

Efficiently designed for all spectrum types from the beginning

Unlicensed spectrum with licensed anchor channel

Shared licensed spectrum solutions

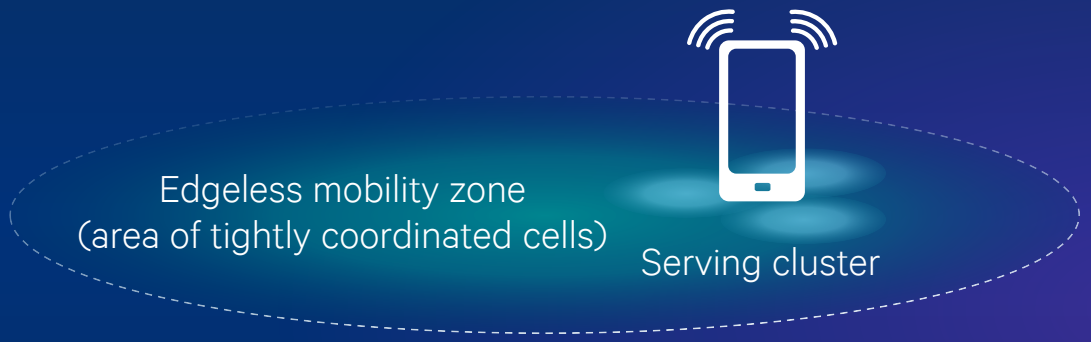
Pure unlicensed spectrum

Fair coexistence across all spectrum types

Aggregation across spectrum types and bands

Device-centric mobility management in 5G

Control plane improvements to improve energy and overhead efficiency

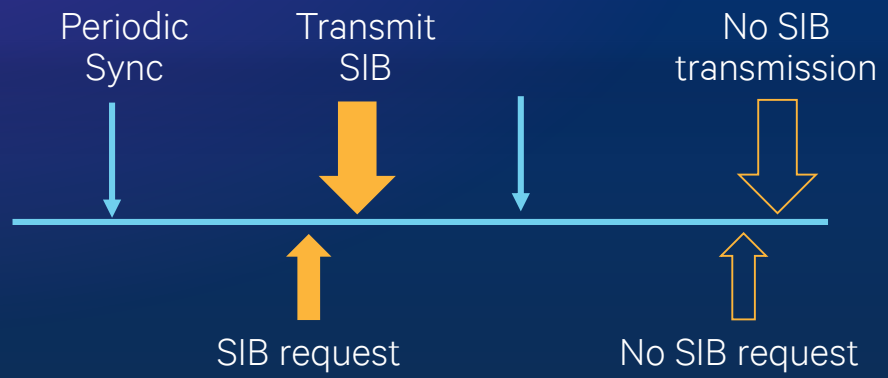


Lightweight mobility for device energy savings

- Apply COMP-like[1] concepts to the control plane
- Intra-zone mobility transparent to the device

Less broadcast for network energy savings

- Low periodic beacon for initial discovery of device(s)
- On-demand system info (SIB) when devices present[2]



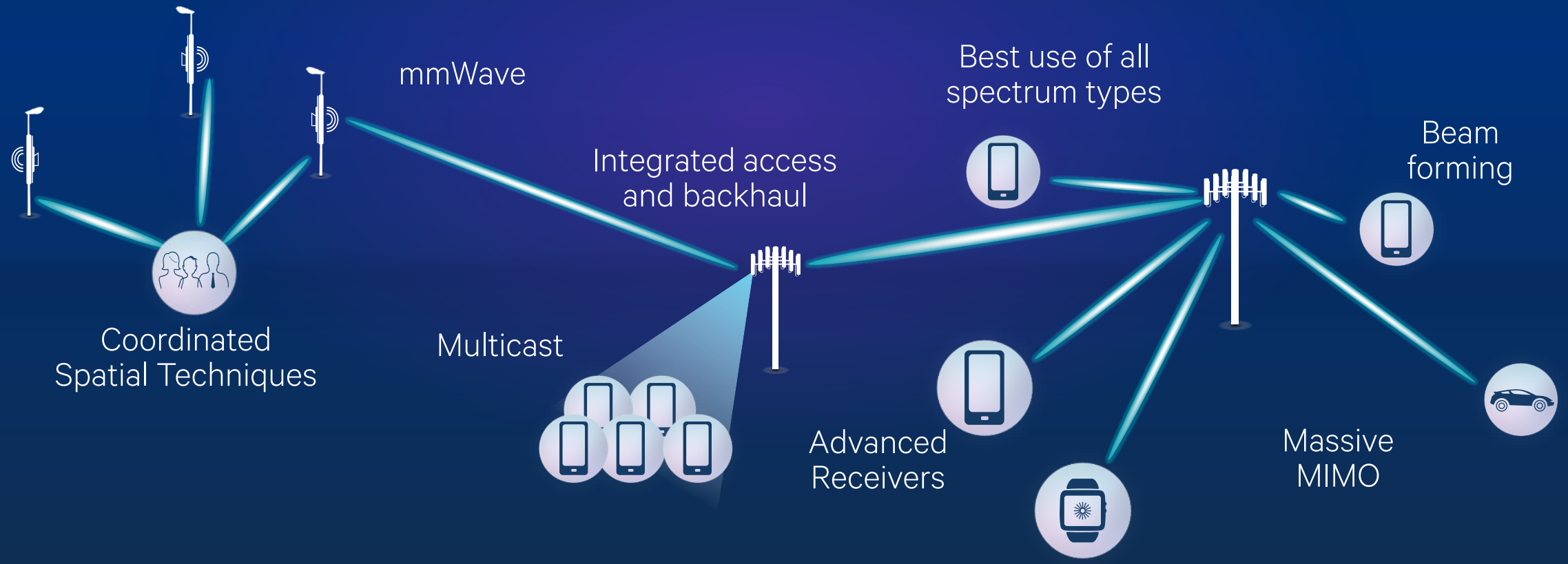
[1] Coordinated MultiPoint is an LTE Advanced feature to send and receive data to and from a UE from several access nodes to ensure the optimum performance is achieved even at cell edges;

[2] May dynamically revert to broadcast system info when needed, e.g. system info changes

Natively incorporate solutions to efficiently grow capacity

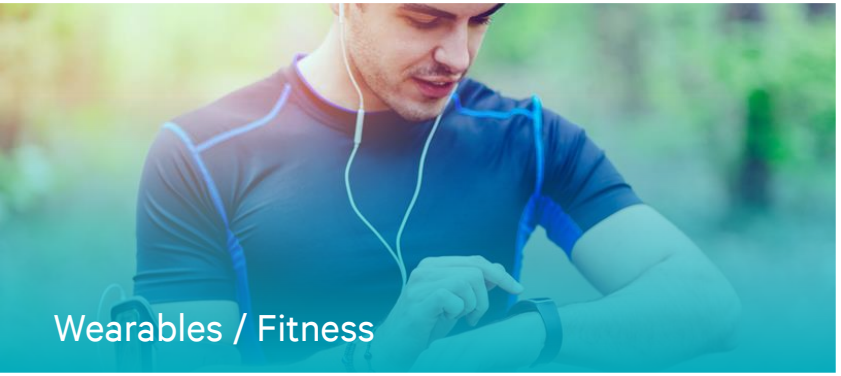
Delivering enhanced, uniform user experiences

Context and service awareness | Full Self-Configuration | Truly unplanned deployments | Hyper dense deployments



Massive Internet of Things

Optimizing to connect anything, anywhere with efficient, low cost communications



Power efficient

Multi-year battery life

Low complexity

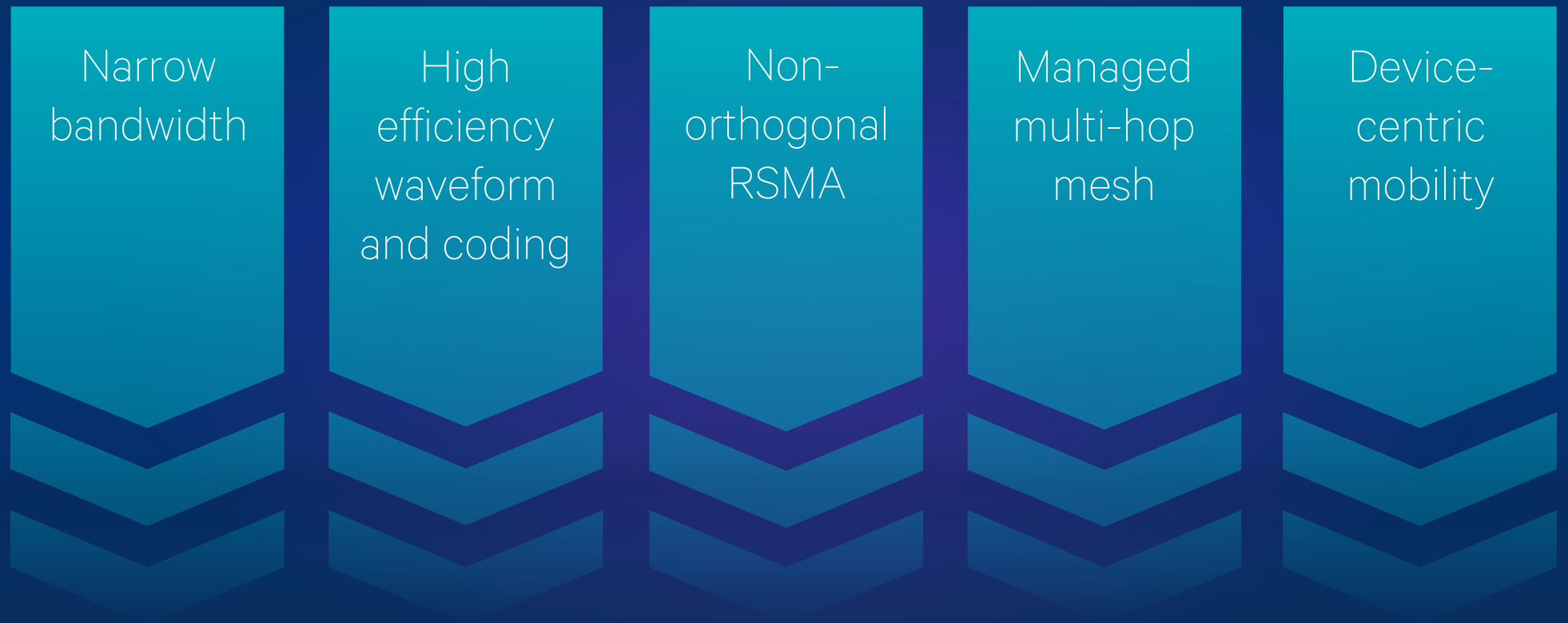
Low device and network cost

Long range

Deep coverage

Connecting the massive Internet of Things

Key 5G Unified Air Interface design elements



Narrow bandwidth to enable low device complexity & long range

Optimized waveform to improve efficiency & reduce complexity

For asynchronous grant-free uplink transmissions

To improve uplink coverage — aided by WAN

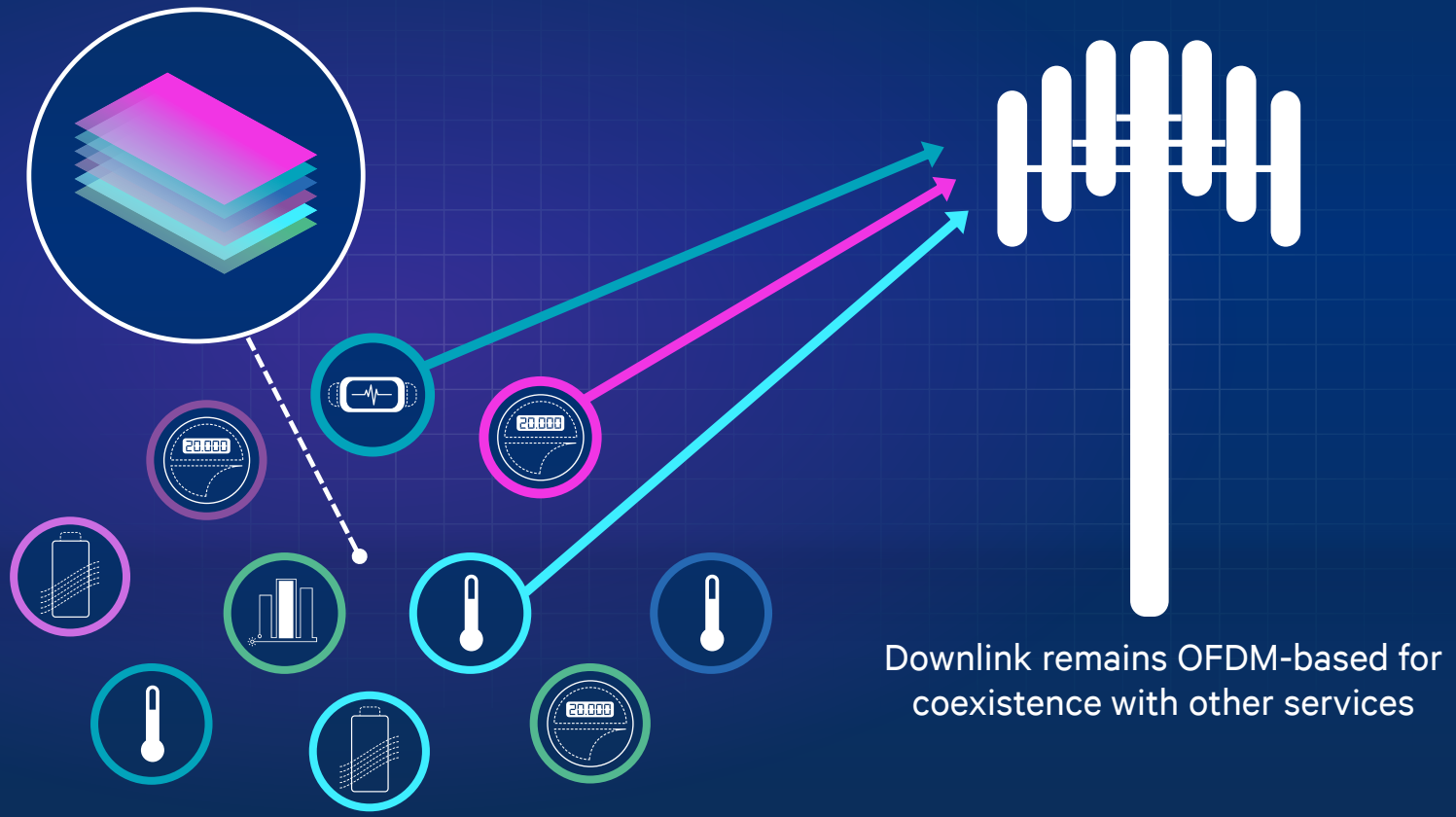
Control plane improvements for better efficiency

Non-orthogonal RSMA for efficient IoT communications

Characterized by small data bursts in the uplink where signaling overhead is a key issue

Grant-free transmission of small data exchanges

- Eliminates signaling overhead for assigning dedicated resources
- Allows devices to transmit data asynchronously
- Capable of supporting full mobility



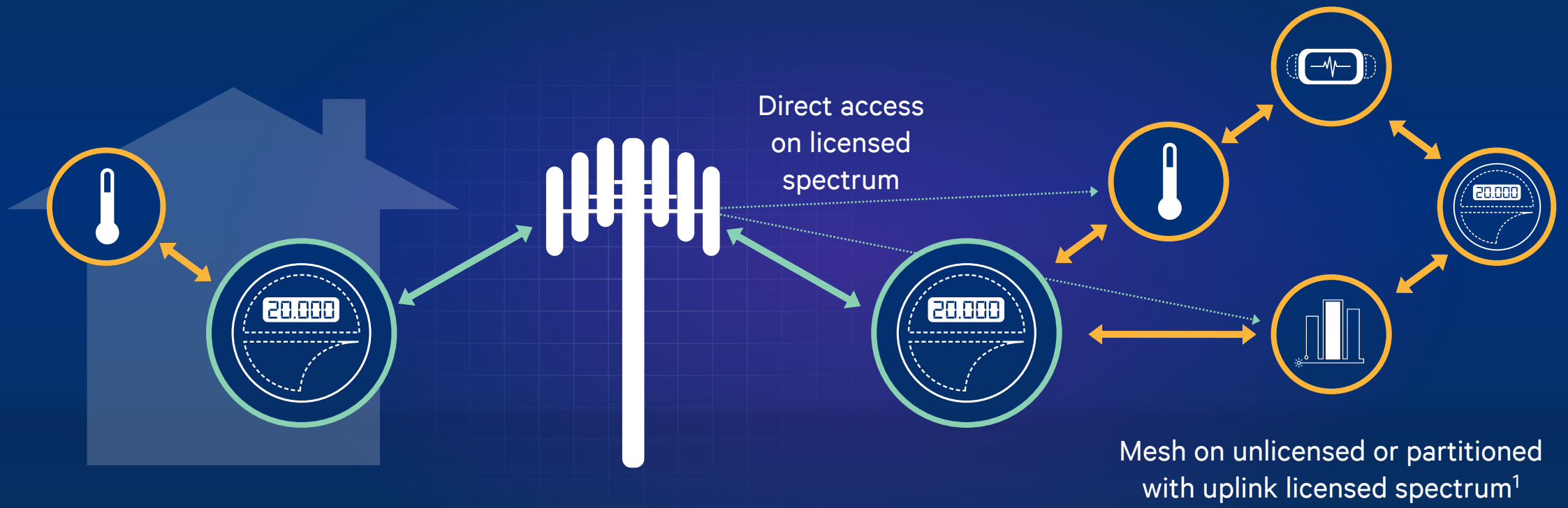
Downlink remains OFDM-based for coexistence with other services

Increased battery life

Scalability to massive # of things

Better link budget

Support for multi-hop mesh with WAN management



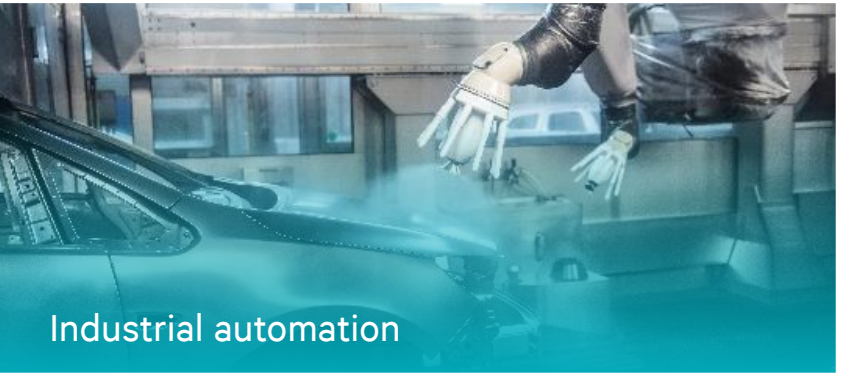
Problem: uplink coverage | Due to low power devices and challenging placements, in e.g. basement

Solution: managed uplink mesh | Uplink data relayed via nearby devices—uplink mesh but direct downlink.

[1] Greater range and efficiency when using licensed spectrum, e.g. protected reference signals . Network time synchronization improves peer-to-peer efficiency

Mission-critical control

Enabling new services with ultra-reliable, ultra-low latency communication links



High reliability

Extremely low loss rate

Ultra-low latency

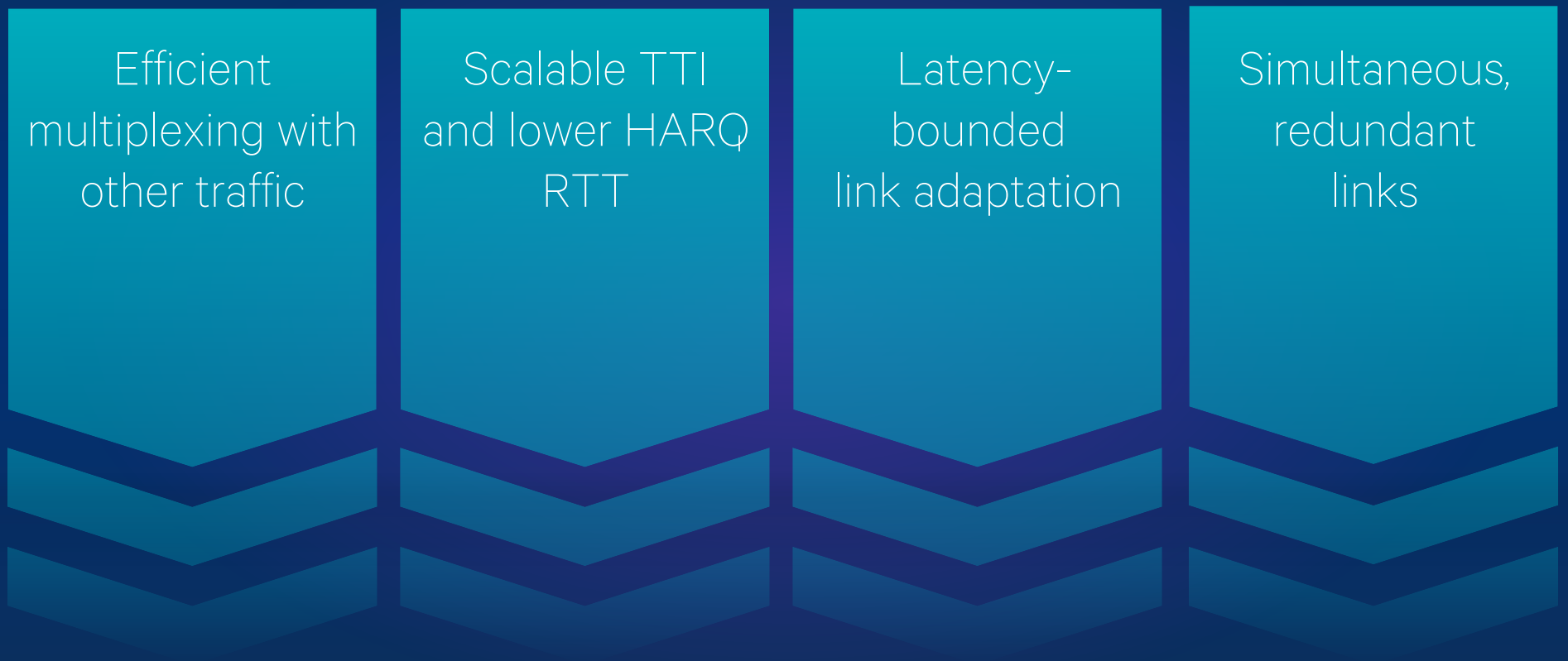
Down to 1ms e2e latency

High resilience

Multiple links for failure tolerance and mobility

Delivering mission-critical control services

Key 5G Unified Air Interface design elements



Time multiplexing through puncturing other service's TTI

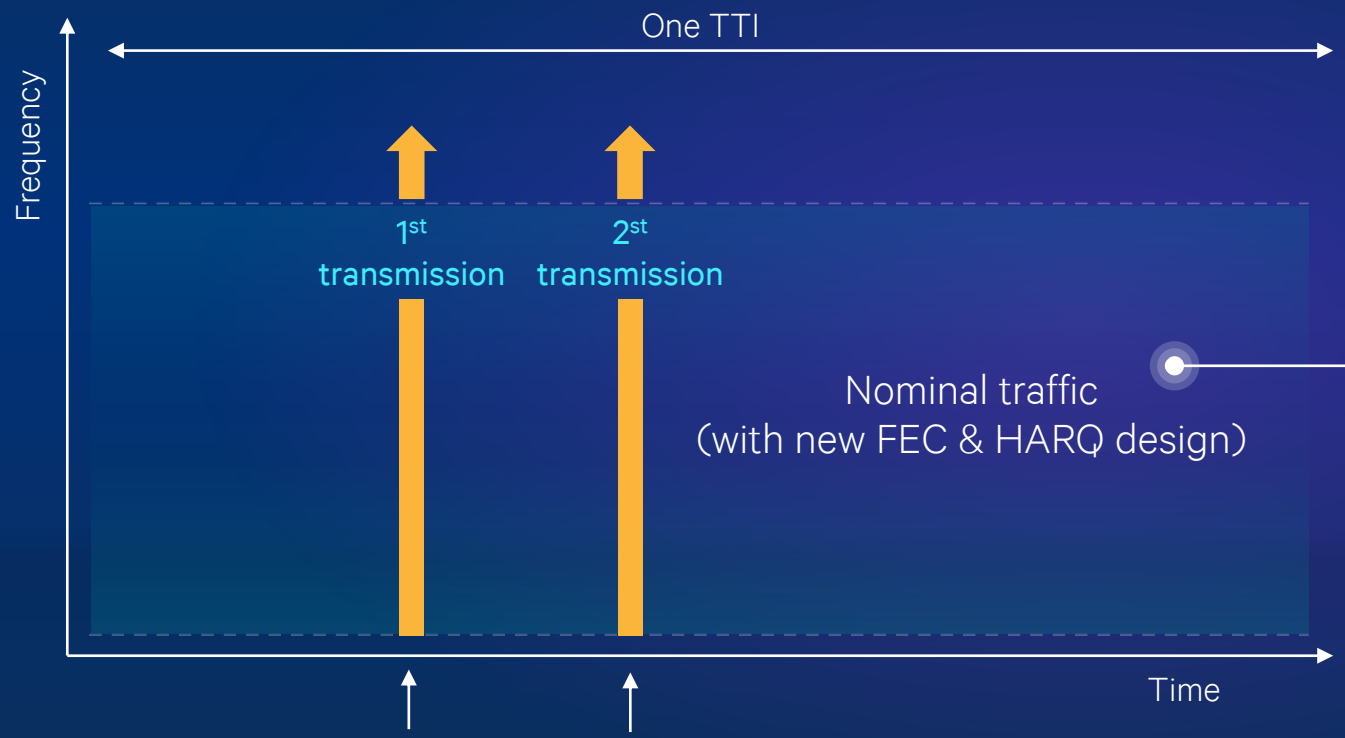
Enables end-to-end latency an order of magnitude lower than LTE

New link adaptation paradigm for lower link error rates

Redundancy if primary link is interrupted

Efficient mission-critical multiplexing with other services

A more flexible design as compared to dedicated mission-critical resources (e.g. FDM)



Design such that other traffic can **sustain puncturing** from mission-critical transmission

Mission-critical transmission

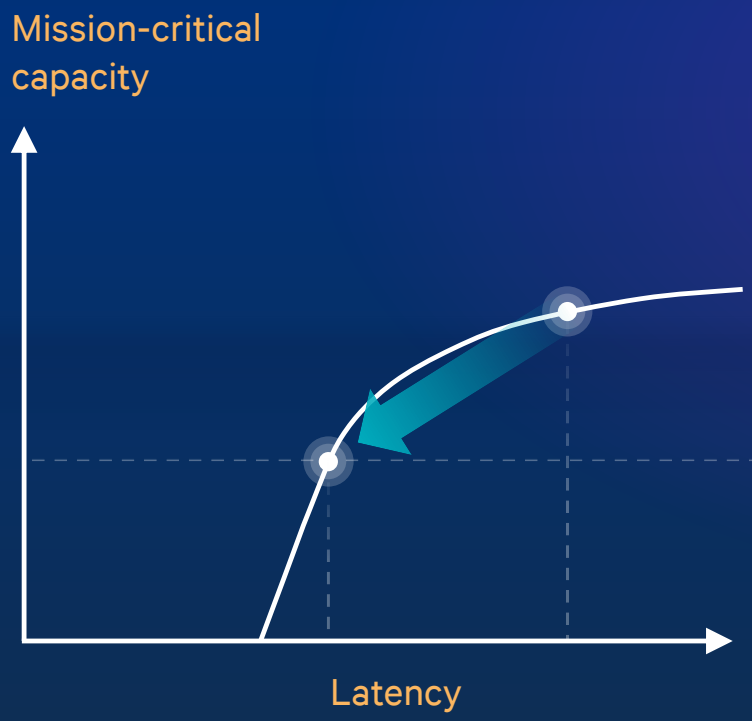
may occur at any time and cannot wait for scheduling

Opportunity for **uplink RSMA** non-orthogonal access using OFDM waveforms

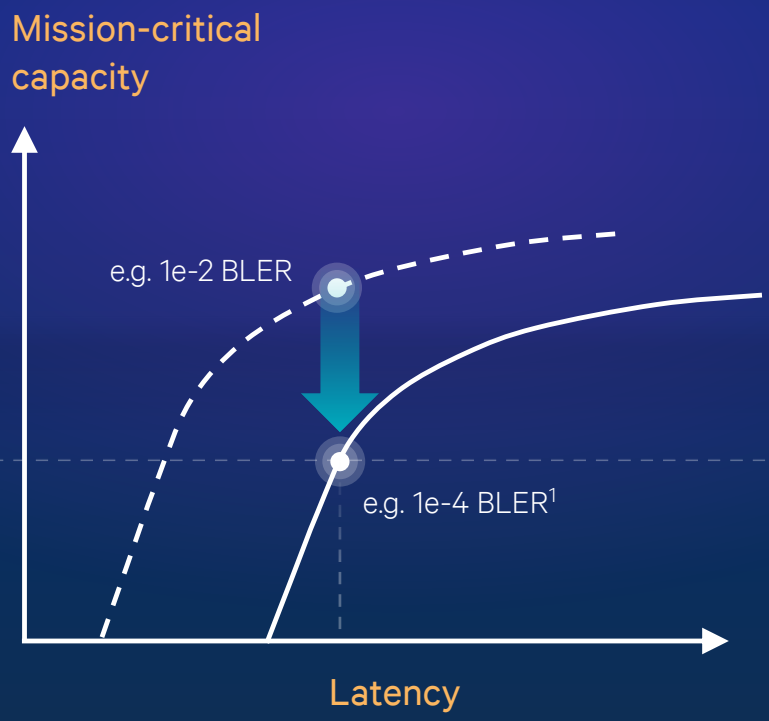
New 5G design allows for optimal trade-offs

E.g. leveraging wider bandwidths to offset mission-critical capacity reductions

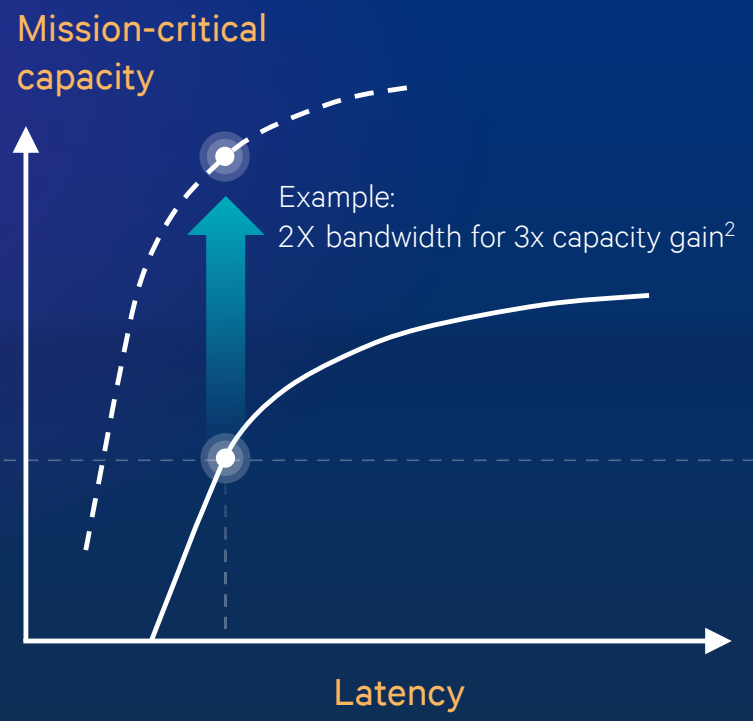
Lower latency reduces capacity…



…increased reliability reduces capacity…

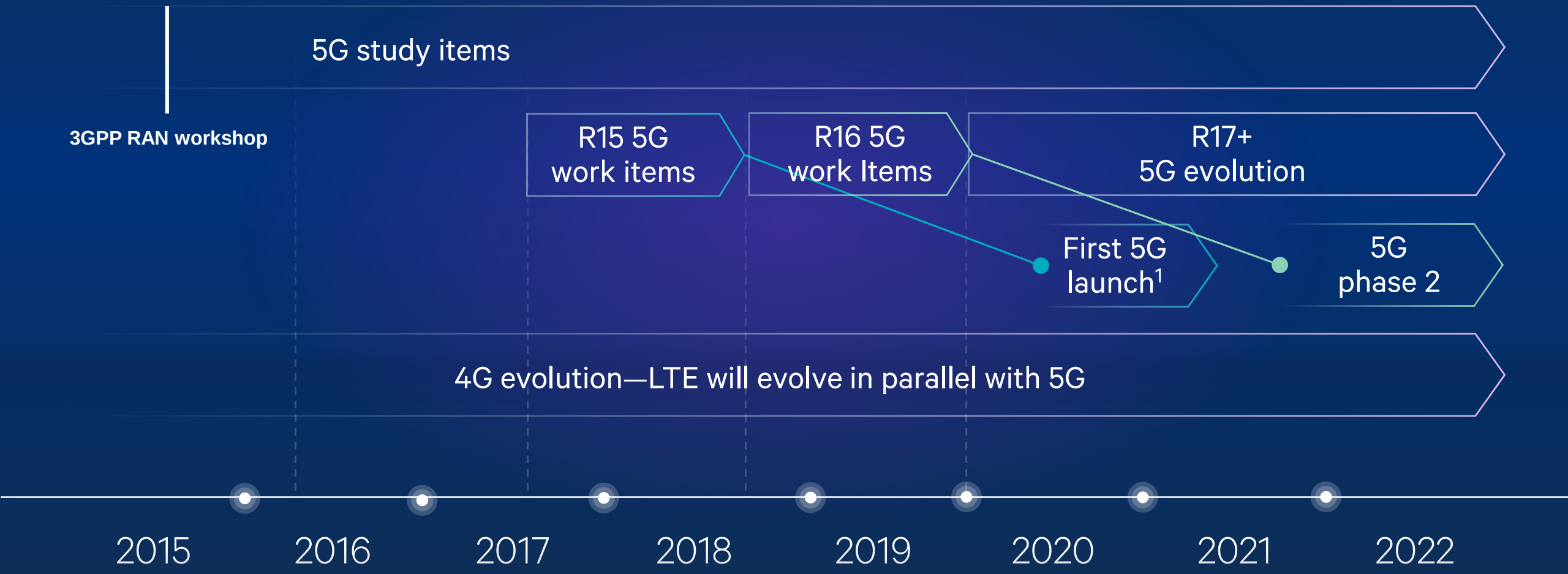


…but, wider bandwidth can offset reductions



[1] Low BLER Block Error Rate, required to achieve high-reliability with a hard delay bound [2] All data based on Qualcomm simulations with approximate graphs and linear scales. 3x gain when increasing from 10Mhz to 20Mhz for 1e-4 BLER.

Proposed 5G standardization for 2020 launch



Note: Estimated commercial dates; [1] Forward compatibility with R16 and beyond

In parallel: driving 4G and 5G to their fullest potential

Expanding and evolving LTE Advanced – setting the path to 5G

Simplifying 5G deployments with multi-connectivity

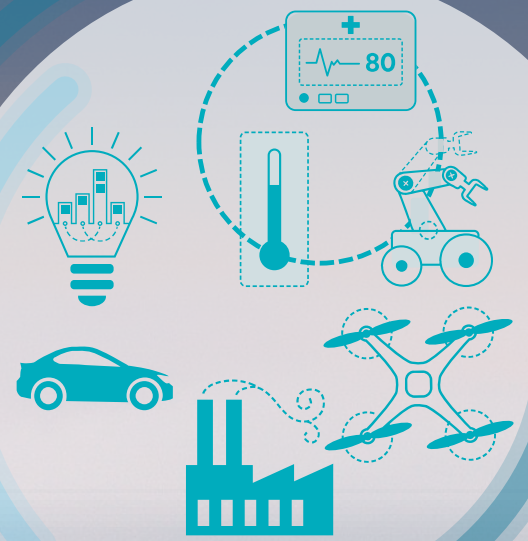
A phased 5G introduction that fully leverages 4G LTE and Wi-Fi investments

Today: 4G LTE below 6 GHz with Dual Connectivity and LTE-Wi-Fi Link Aggregation

Phase 1 (R15): New 5G radio access below 6 GHz using LTE anchor for mobility management

Phase 2 (R16+): New multi-access 5G core network, new 5G radio access above 6 GHz

5G: not just a new generation, but a new kind of network



Connecting
new industries and devices

Enabling
new services

Empowering
new user experiences

For more information: www.qualcomm.com/5G

QUALCOMM® Why Wait™

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Working to solve the 1000x data challenge

Innovative small cells and spectrum solutions

More capacity

- Small cells and self organizing technology
- LTE in unlicensed spectrum, MuLTEfire™
- LTE Advanced carrier aggregation, dual connectivity
- Advanced receivers and interference management
- Spectrum innovations like LSA
- Wi-Fi – 11ac, 11ad, MU-MIMO, OCE, 11ax
- 3G

Creating the connectivity fabric for everything

Intelligently connect everything/everyone, empower new services, drive convergence

A new connectivity paradigm

- LTE-M (Machine-Type Communications), NB-IOT
- LTE Direct device-to-device
- LTE Broadcast
- LTE – Wi-Fi Convergence
- Wi-Fi – 11ah, 11ad, Wi-Fi Aware, Wi-Fi Direct, DSRC
- Bluetooth Smart
- OneWeb
- 5G

Bringing cognitive technologies to life

Devices and things that perceive, reason, and act intuitively

Next level of intelligence

- Machine learning
- Computer vision
- Always-on sensing
- Immersive multimedia
- Cognitive connectivity
- Intuitive security
- Heterogeneous computing

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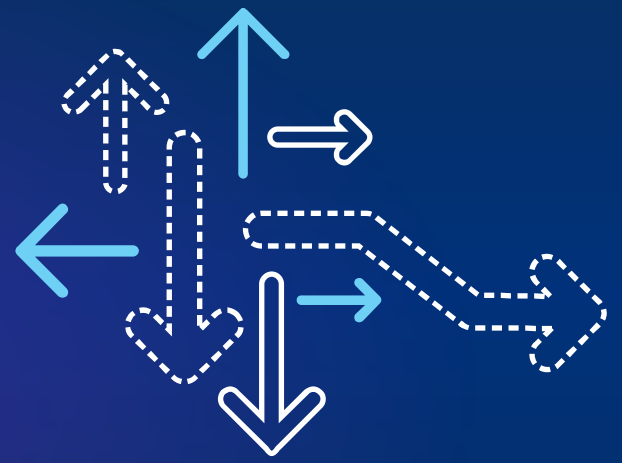

Thank you

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