Air Interface – Part III
5G NR

5G NR

5G's new air interface is based on LTE's OFDMA
but features several improvements

- new RF bands (including mmWaves)
- wider bandwidth (up to 400 MHz) and larger FFT sizes (up to 4k)
- multiple subcarrier spacings (15 kHz ... 480 kHz)
- higher order modulations (up to 256 QAM) and so higher spectral efficiencies
- new error correcting codes
- more flexible frame formats, including self-contained integrated subframe
- massive MIMO (64+ antennas) and beam-forming
- carrier aggregation

Spectrum

5G needs bandwidth, and can use anything it can get

RF bands are divided into :

- low (< 1 GHz) and medium frequencies (<6 GHz)
  for macro cells
- mm waves (> 6GHz) where the range is expected to be < 500 meters
  so will be used for small cells (LoS 300m, urban multipath 150m)

Operating bands being considered:

	low (MHz)	medium (GHz)	high (GHz)
US	600	3.5	28, 37-40, 64-71
EU	700	3.4-3.8	24.25-27.5
China		3.4-3.6	24.25-27.5
Japan		3.6-4.2, 4.4-4.9	27.25-29.5
South Korea			28, 37.5-40

Each band has a standardized name n# (LTE used just #)

when the bands are the same, the numerical value is the same

R15 operating bands

FR1 (< 6GHz)

NR operating band	Uplink (UL) *operating band* BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) *operating band* BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
n2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
n3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
n5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
n8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
n20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
n28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
n38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
n50	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	TDD
n51	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	TDD
n66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD
n70	1695 MHz – 1710 MHz	1995 MHz – 2020 MHz	FDD
n71	663 MHz – 698 MHz	617 MHz – 652 MHz	FDD
n74	1427 MHz – 1470 MHz	1475 MHz – 1518 MHz	FDD
n75	N/A	1432 MHz – 1517 MHz	SDL
n76	N/A	1427 MHz – 1432 MHz	SDL
n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD
n80	1710 MHz – 1785 MHz	N/A	SUL
n81	880 MHz – 915 MHz	N/A	SUL
n82	832 MHz – 862 MHz	N/A	SUL
n83	703 MHz – 748 MHz	N/A	SUL
n84	1920 MHz – 1980 MHz	N/A	SUL

FR2 (>6GHz)

NR Operating Band	Uplink (UL) operating band BS receive UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating band BS transmit UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n257	26500 MHz – 29500 MHz	26500 MHz – 29500 MHz	TDD
n258	24250 MHz – 27500 MHz	24250 MHz – 27500 MHz	TDD
n260	37000 MHz – 40000 MHz	37000 MHz – 40000 MHz	TDD

mmWave challenges (1)

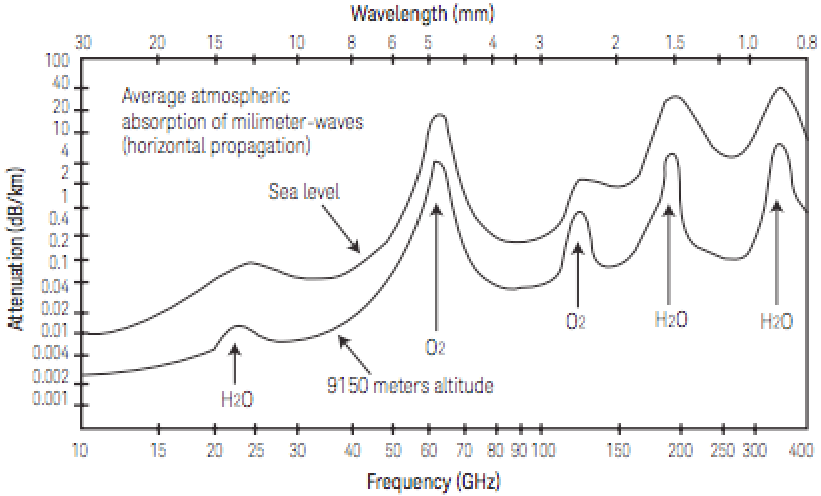
30 GHz corresponds to 1 mm wavelength

so the 24, 27, 28 GHz bands are informally called mm waves

At these high RF frequencies there is plenty of real estate for 5G

but there are multiple challenges to exploiting these frequencies!

1. signal attenuation
   - free space signal attenuation scales like f^2 due to antenna aperture size
     so increasing from 3 GHz to 30 GHz increases loss by 20 dB = factor of 100 !
   - dry oxygen, water vapor, etc. have absorption lines



SOLUTION: much smaller cell sizes – 150-200 m

mmWave challenges (2)

2. concrete and glass strongly absorb mm waves - so need clean line of sight
   but 80% of expected usage is indoors
   SOLUTION: indoor coverage

3. much shorter channel coherence time (time over which can assume channel stationarity)
   for mobile user the coherence time scales like 1/f
   increasing from 3 GHz to 30 GHz decreases the coherence time by a factor of 10!
   SOLUTON: much more frequent channel probing

4. energy efficiency (and carbon footprint)
   scaling BW by 10 usually equates to 10 times more power
   and scaling data rate by 10-100 produces the same scaling in the backhaul
   SOLUTION: more directive antennas, energy-efficient system design, sleep modes

5. implementation issues
   - power amplifiers are very inefficient at mmWaves (< 10% is common)
   - need low loss/low dielectric constant materials for multi-layer PCBs
   - copper traces have high resistance due to skin effect
   - need temperature stable high-Q dielectrics
     - various ceramics and polymers being investigated
   - need new magnetic materials for high-frequency oscillators
     - Yttrbium Iron garnet, Ni-Zn ferrites, Li-based spinels being investigated

mmWave (3) health issues

6. health issues
   - there is no data on the long-term safety of continuous mmwave exposure
   - direct effect will be on external 2 mm of skin or eyes
     - 30-40% of power will be reflected
   - thermal effects known for radiation above 5 mW/cm^2
     so FCC guidelines limit public to 1 mW/cm^2 over 30 minutes fro 1.5-100GHz
   - non-thermal effects reported for mmWaves:
     - long term exposure may be carcinogenic
     - altering structural and functional properties of plasma membranes
       by modifying ion channel activity or modifying the phospholipid bilayer
     - skin nerve ending damage
     - activation of the immune system and peripheral neural system
     - changes to blood and bone marrow composition
     - changes to activity of various enzymes
     - modification of microbes (growth depression and property alteration)
       may lead to various effects including antibiotic resistance,

SOLUTION: none yet

5G Scalable numerology

While LTE had a constant subcarrier spacing SCS of 15 kHz

5G introduces a scalable SCS with $\Delta f = 2^{\mu} * 15$ kHz

(i.e., SCS = 15, 30, 60, 120, 240, 480)

but not all SCS options are available for all operating bands

μ	SCS	RF	CP
0	15	< 6GHz	normal
1	30	< 6GHz	normal
2	60	both	normal/extended
3	120	> 6 GHz	normal
4	240	not in R15	normal
5	480	not in R15	normal

Of course OFDM requires the symbol rate to equal the SCS

so the symbol durations are shorter for higher μ

Channel bandwidth

LTE defined channel bandwidths of 1.4, 3, 5, 10, 15, 20 MHz

5G has more options, and higher bandwidth efficiency (>98%!)

- for RF bands under 6 GHz
  - 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100 MHz
- for RF bands above 6GHz
  - 50, 100, 200, 400 MHz (and maybe higher later)

For example:

SCS (slot)	20 MHz	50 MHz	100 MHz	200 MHz	400 MHz
15 kHz 1 ms	**1320** FFT 2048 OH = 1%	**3300** FFT 4096 OH = 1%			
30 kHz 500 µs	**660** FFT 1024 OH = 1%	**1644** FFT 2048 OH = 1.36%	**3300** FFT 4096 OH = 1%		
60 kHz 250 µs	**324** FFT 512 OH = 2.8%	**816** FFT 1024 OH = 2.08%	**1644** FFT 2048 OH = 1.36%	**3300** FFT 4096 OH = 1%	
120 kHz 125 µs		**408** FFT 512 OH = 2.08%	**816** FFT 1024 OH = 2.08%	**1644** FFT 2048 OH = 1.36%	**3300** FFT 4096 OH = 1%

subcarriers
FFT size
guard overhead

LTE
SCS=15kHz/BW=20MHz used only 1200 subcarriers (OH = 10%)

higher efficiency
higher frequency sync requirements

Scalable SCS, bands, and bandwidths

Only certain combinations of SCS and bandwidth are allowed in given bands

NR band / SCS / UE Channel bandwidth												
NR Band	SCS kHz	5 MHz	10[1,2] MHz	15[2] MHz	20[2] MHz	25[2] MHz	30 MHz	40 MHz	50 MHz	60 MHz	80 MHz	100 MHz
n1	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60		Yes	Yes	Yes							
n2	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60		Yes	Yes	Yes							
n3	15	Yes	Yes	Yes	Yes	Yes	Yes					
	30		Yes	Yes	Yes	Yes	Yes					
	60		Yes	Yes	Yes	Yes	Yes					
n5	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60											
...												
n41	15		Yes	Yes	Yes			Yes	Yes			
	30		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes
	60		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes
n50	15	Yes	Yes	Yes	Yes			Yes	Yes			
	30		Yes	Yes	Yes			Yes	Yes	Yes	Yes[3]	
	60		Yes	Yes	Yes							
n51	15	Yes										
	30											
	60											

...

Scalable symbol durations

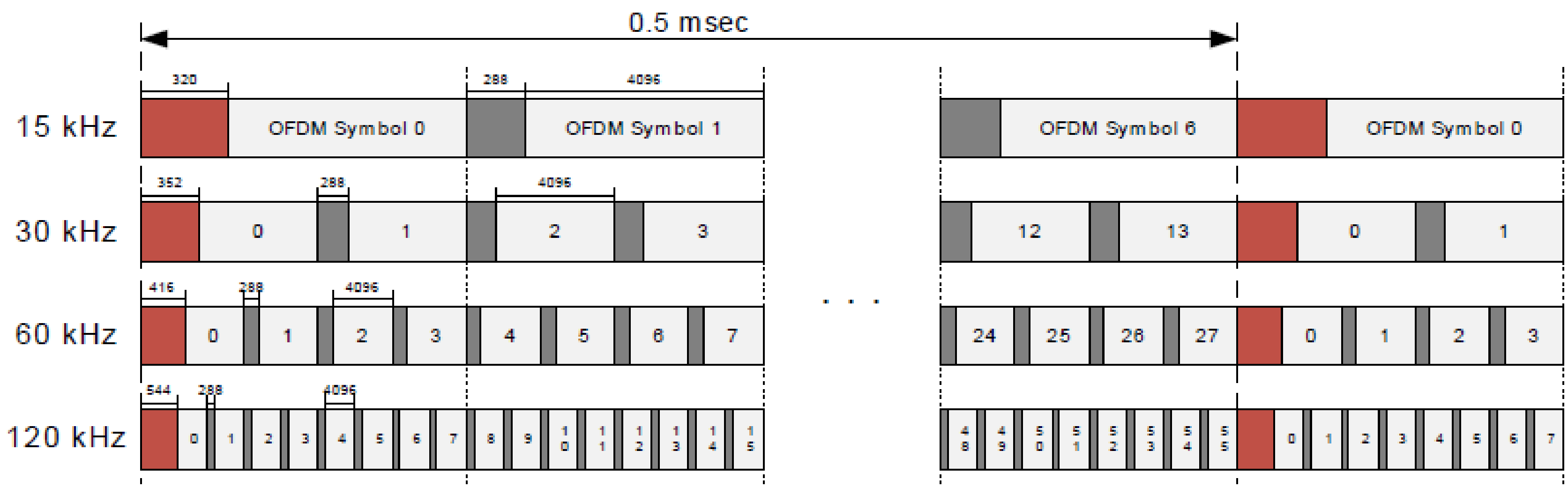
As we said, the symbol duration in OFDM must be 1 / SCS

So, each 15 KHz OFDM symbol duration (including CP) equals

- 2 symbol durations for SCS = 30 KHz
- 4 symbol durations for SCS = 60 KHz
- 2^{μ} symbol durations for SCS = 2^{μ} *15kHz

and this is true even for the first symbol in the subframe

which has a different CP (in order for the subframe to be precisely ½ ms)



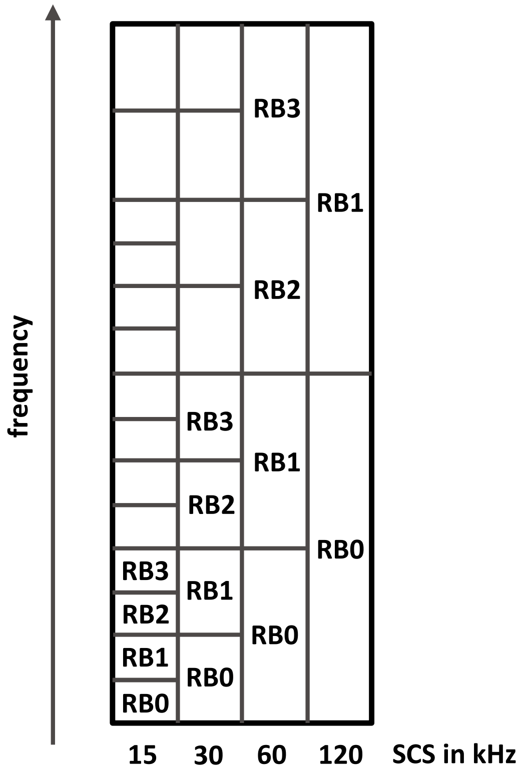
Nested RBs

Each RB is 12 consecutive subcarriers

- for SCS=15 kHz 1 RB = 180 kHz
- for SCS=30 kHz 1 RB = 360 kHz
- for SCS=60 kHz 1 RB = 720 kHz

So, RBs are nested!

The nesting of slots and RBs
enables muxing different numerologies
for the same cell / same UE



Slots

In NR (like LTE) the frame is always 10 ms = 10 subframes of 1 ms

For normal CP there are 14 symbols per subframe (for SCS < 240 kHz)
and this is defined as the basic slot (not 7 symbols = ½ ms like in LTE!)
(also called the **T**ransmission **T**ime **I**nterval)

So, the slot duration = 1 ms / 2^{μ}

- for SCS=15 kHz slot = 1 ms 1 slot per subframe
- for SCS=30 kHz slot = ½ ms 2 slots per subframe
- for SCS=60 kHz slot = ¼ ms 4 slots per subframe etc.

We say that the slots *nest* across numerologies

However, NR is even more flexible, allowing:

- slot aggregation
  transmission occupies 2 or more slots, in order to reduce overhead
- mini-slots (non-slot-based scheduling)
  transmission occupies less than a slot (2, 4, or 7 OFDM symbols)
  in order to reduce latency
- flexible (mixed DL/UL) slots for TDD operation

Flexible slots

A TDD slot can contain

- all DL symbols
- all UL symbols
- both DL and UL symbols, with 1 or 2 switching points per slot

The type is indicated by the Slot Format Indication (configured by PDCCH or RRC)

The *self-contained integrated* subframe (2 switching points)

always starts with a DL control burst and end with a UL control burst

- DL-centric subframe

  DL control, DL data (single user), guard, UL control

- UL-centric subframe

  DL control, guard, UL data (to multiple users), UL control

This enables (e.g., for DL-centric subframes)

- lower latency, since the UL HARQ ACK is in the same subframe (self-contained)

  note: LTE assumes HARQ processing time of 3 ms, NR requires DL < 1 ms and UL < 0.3-0.8 ms
- massive MIMO tracking, since the UL link quality is in the same subframe
- use of shared spectrum, via Listen-Before-Talk indications from network

Some more technical details

NR supports 1008 cell identities (twice as many as LTE!) (N_1=0...335)

PSS, SSS, frame number, PBCH/MIB, PDCCH, and PDSCH are similar to LTE
although details may vary, especially for > 6 GHz

In particular, there are added indications for SCS and the other new features

PDSCH and PUSCH support QPSK, 16-QAM, 64-QAM, and 256-QAM
(PBCH and PDCCH use QPSK, PUCCH uses BPSK or QPSK)

Instead of LTE's *turbo* and *tail-biting convolutional* codes, NR uses:

- *LDPC* codes for PDSCH and PUSCH
- *polar* codes for PDCCH and PBCH (up to 80 bit blocks)
- *polar*, *repetition*, *simplex*, and/or *Reed-Muller* codes
  for PUCCH and for control information in the PUSCH

LDPC was chosen for

- flexibility under block length scaling
- efficiency gain over LTE turbo codes
- parallelization for lower complexity and latency

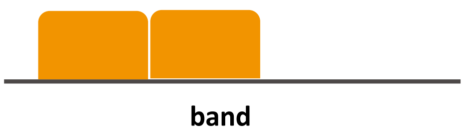
and there are many many more minor technical advances ...

Carrier aggregation

CA was introduced in LTE-A to achieve higher data rates
by assigning multiple subcarriers to the same user

We differentiate between:

- intra-band contiguous aggregation
  (RB aggregation)



- intra-band non-contiguous aggregation
  (integration in MAC)

- inter-band aggregation
  (integration in MAC or L3)

MIMO

While LTE supports 4*2 MIMO (4 BS and 2 UE antennas)
R15 supports 32*4 MIMO (and this will increase significantly!)

MIMO is critical for both < 6 GHz and > 6 GHz operating bands
but for different reasons

- for < 6 GHz
  - cells are large
  - there will be rich multipath
  - many users in cell
  - users will be highly mobile
  - so MIMO will use spatial mux to help achieve spectral efficiency goals
- for > 6 GHz
  - signal attenuation much higher (100 times higher?)
  - cells are small and little multipath
  - few users in cell
  - users are relatively static in the cell
  - so MIMO will use beamforming to overcome the high attenuation

Low frequency MIMO

For low frequencies MIMO exploits multipath
  each receive antenna receives linear combination of channels

With MIMO, the Shannon capacity $C = N \, BW \log_2(SNR + 1)$
  where N is the number of MIMO channels

MIMO works by increasing N
  which is much more effective than increasing SNR!

Standard **S**ingle **U**ser MIMO requires the UE to invert the channel matrix
  in order to recover the N independent data streams
    which leads to substantial battery drain

An alternative is for the base station (which is less power constrained)
  to perform channel precoding (pre-filter with the inverse channel matrix)
    so that each UE antenna receives a clean channel

With **M**ulti **U**ser MIMO the BS always uses channel precoding
  since each UE only handles some of the channels

But this solution hits power constraints (in order to guarantee high SNR for each UE)

Beamforming

The basic idea can be understood by considering (see figure)

  2 transmitting antennas emitting the same sinusoid

    spaced ½ wavelength apart

If there is no phase shift to either antenna

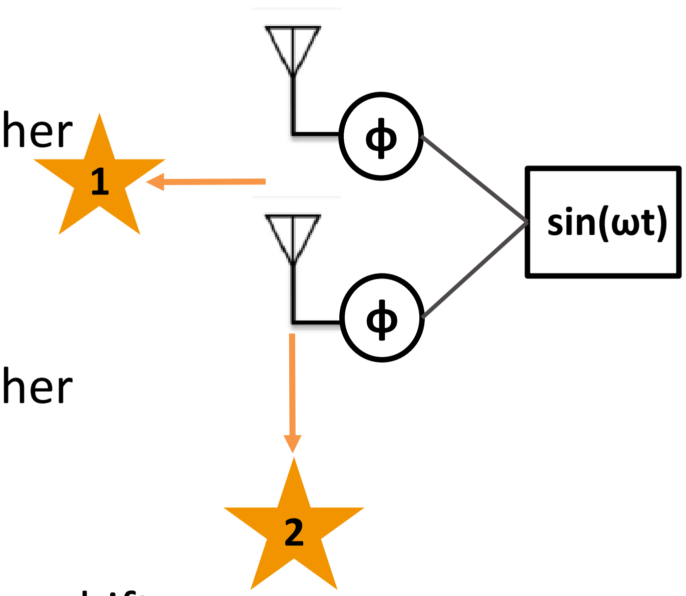
  at point 1 the signals will re-enforce each other

  at point 2 the signals will cancel out

If we apply a phase shift of π to one antenna

  at point 1 the signals will cancel out

  at point 2 the signals will re-enforce each other



More generally, we can achieve a focused beam

  by using a linear array of antennas

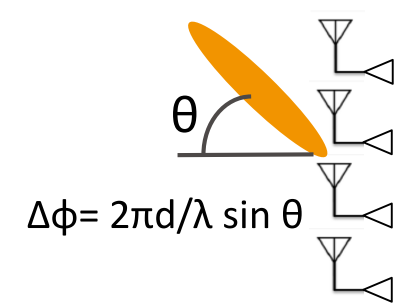
  with amplifiers (to reduce side-lobes) and phase shifters

The structure is analogous to MA filter

  but in the spatial axis rather than frequency

And similarly, an FFT structure (called the *Butler matrix*)

  can be used to efficiently steer the array



MIMO vs. beamforming

We saw that MIMO increases N in the Shannon capacity

Beamforming improves SNR for a given transmitted power!
By having a highly directional beam, the transmitted power is not wasted
and the more antennas we use, the more focused the beam can be

MIMO and beamforming are actually opposites

- MIMO sends energy in many directions to get N *different* channels
- beamforming focuses energy in one direction to improve SNR

Massive MIMO combines beamforming and MU MIMO
by using many more antennas than the number of Ues
we can focus energy on each UE
In practice, digital beamforming is first employed for coarse steering
followed by analog beamforming for fine tuning

Massive MIMO allows each UE to have different power and data rates

NR beamforming

For beamforming to work, various mechanisms are needed

- initial access
- beam quality measurement
- beam quality reporting
- beam assignment
- recovery if quality is low
- mobility tracking

Quality measurement is based on accurate **C**hannel **S**tatus **I**nformation

- for UL the **S**ounding **R**eference **S**ignal is used
- for DL TDD (with channel reciprocity!) the UL signals themselves can be used
- for DL FDD a new 2-stage high resolution spatial precoding is used
  to approximate the channel eigenvector