STANFORD

Supplementary Lecture 5C

Cellular Example

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4G and 5G wireless = Cellular (licensed bands)

- Mobile/cellular connectivity also uses OFDM (and vector OFDM).
- 4G uses up to 4 xmit/rcvr antennas.
- 5G allows use of much larger number of antennas (Massive MIMO),
  - usually best 32 of 128 at cell site (smaller at device, typically 2-4).
- Cellular uses 500 μs time "slots" (20 of them in a "frame" of 10 ms ; 2 of them in a subframe of 1ms).
- Each time slot uses an integer tone-width index *m*=1,2,4,8, 12, and 16 to multiply:

$$\Delta f = 15 \text{ kHz}$$

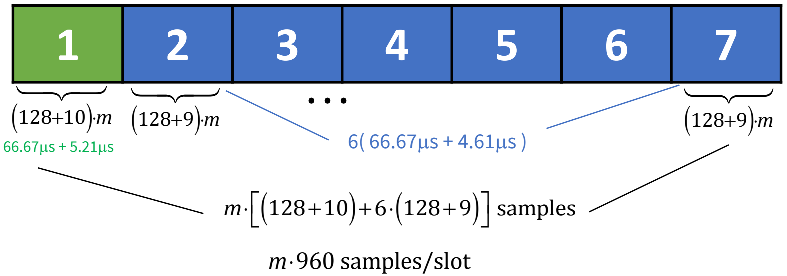
$$\frac{1}{T'} = \left(1.92 \text{ MHz}\right) \cdot m \quad N = 128 \cdot m \quad , \quad m = 1,2,4,8,12,16$$

$$m \cdot 960 \text{ samples/slot} \quad , \quad m = 1,2,4,8,12,16$$

Short and Long Cyclic Prefixes

500 μs – Cellular Slot of 7 OFDM symbols

Short Prefix

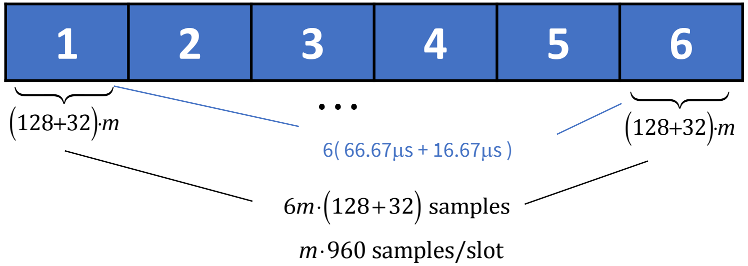


data rates are multiples of 14 kbps

$$\left(\frac{7}{500\mu s}\right)$$

500 μs – Cellular Slot of 6 OFDM symbols

Long Prefix

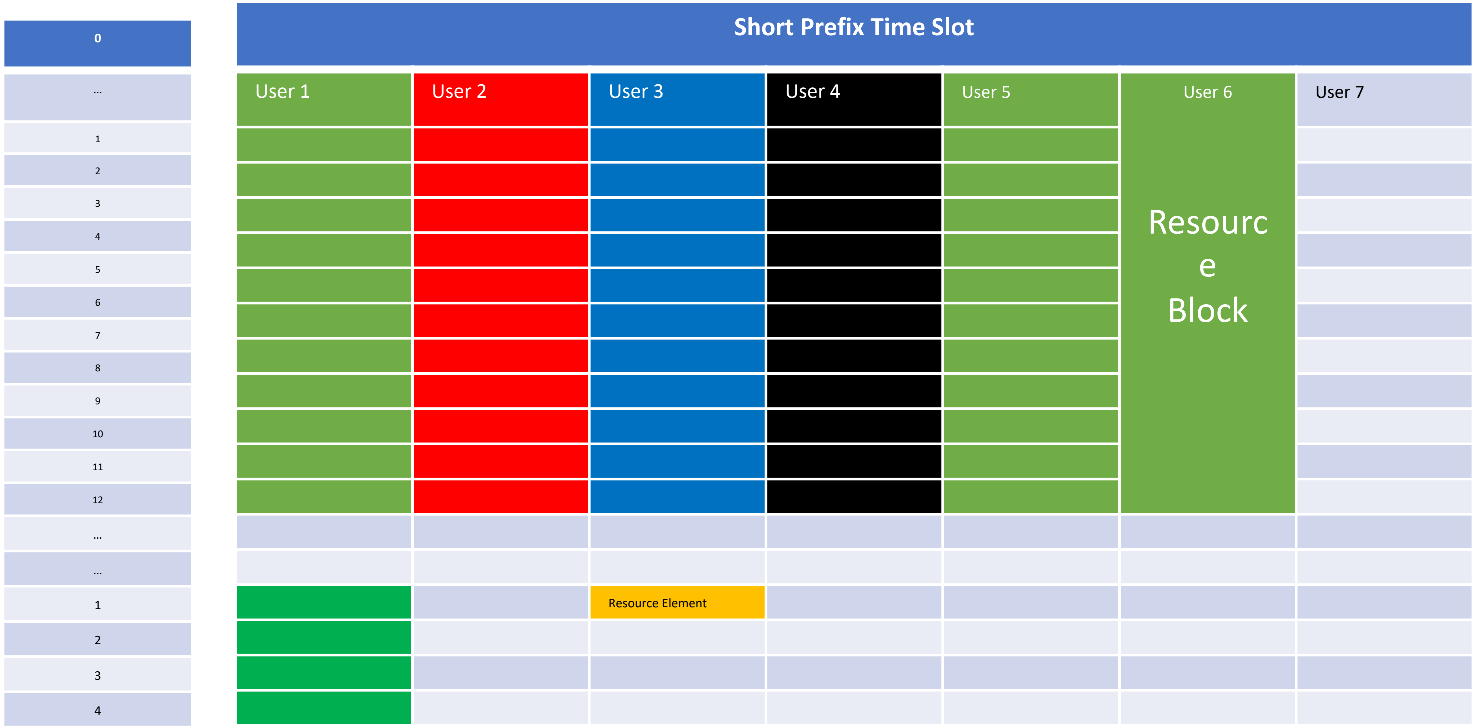


data rates are multiples of 12 kbps

$$\left(\frac{6}{500\mu s}\right)$$

- Each symbol decomposes into "resource elements" and "resource blocks."

CELLULAR's Resource Blocks (RBs) – 12-tone groups



User could be control channel

- RB is Smallest unit that can be assigned to a user, per subfrane
  - loading applies to RBs (but not to individual tones) – 12 tones within a single symbol.
  - Single MCS to any one user though, no matter how many RBs.
  - Lowest data rate would be 28 kbps if only one RB per subframe.
- There can be pilots, synch symbols, and other overhead scattered throughout a slot so total number of tones need not be a multiple of 12.

Low Bandwidth (small devices) Cellular

bwdth MHz	m	$1/T'$ MHz	$N+\nu_s$ $(1/T_s = 14$ kHz$)$ / $N+\nu_l$ (*) $(1/T_l = 12$ kHz$)$	N^* used tones	samples slot	Δf kHz	RBs Resource blocks	b_{min} b_{mid} b_{max}	L 1 1	R_{min} R_{mid} R_{max} Mbps *
1.25	1	1.92	128+6.17 128+32	76	960 960	15	6	2 4 6 6 6	1 1 1 2 4	2.016 4.032 6.048 12.096 24.192
3	2	3.84	256+12.33 256+64	181	1920 1920	15	15	2 4 6 6 6	1 1 1 2 4	5.04 10.08 15.12 30.24 60.48

- Individual users
  - 12 x 12 =144 kbps for RB=1, lcp
  - 12 x 14 = 168 kbps for RB=1, scp

Example (6 RBs x 12 tones/RB x 2 bits/tone x 14 KHz = 2.016 Mbps

Code overhead included

- Cellular attempts to address low-bandwidth uses where power may be very limited.
  - MIMO can reduce power to get same data rate or can also permit more narrow bandwidth use for same rate.

Wider Bands need more (licensed) spectra

- Wider bandwidths are for higher speeds.
  - MIMO helps that also.

- Cellular's
  - 20 MHz option can use a Wi-Fi channel. "5G-U"
  - "Look before talk."

bwdth MHz	m	$1/T'$ MHz	$N+\nu_s$ ($1/T_s = 14$ kHz) $N+\nu_l$ (*) ($1/T_l = 12$ kHz)	N^* used tones	samples slot	Δf kHz	RBs	b_{min} b_{mid} b_{max}	L 1 1	R_{min} R_{mid} R_{max} Mbps *
5	4	7.68	512+24.67 512+128	301	3840 3840	15	25	2	1	8.40
								4	1	16.80
								6	1	25.20
								6	2	50.40
								6	4	100.8
10	8	15.36	1024+49.33 1024+256	601	7680 7680	15	50	2	1	16.80
								4	1	33.60
								6	1	50.4
								6	2	100.8
								6	4	200.16
15	12	23.04	1536 +74 1536+384	901	11520 11520	15	75	2	1	25.20
								4	1	50.40
								6	1	75.6
								6	2	151.2
								6	4	302.4
20	16	30.72	2048 +98.67 2048+384	1201	15360 15360	15	100	2	1	33.6
								4	1	67.20
								6	1	100.8
								6	2	201.60
								6	4	403.20

Wider Yet

- Wider yet
- Max FFT is 4096
  - So 30 kHz used at 100 MHz.

40	32	61.44	4096 +197.33 4096+768	2592	30720 30720	15 15	200	2 4 6 6 6	1 1 1 2 4	67.2 134.4 201.6 403.2 806.24
50	40	30.72	4096 +197.33 4096+768	3240	38400 38400	15 15	270	2 4 6 6 6	1 1 1 2 4	90.72 181.44 272.16 544.32 1008.64
100	80	30.72	4096 +197.33 4096+768	2592	38400 38400	30 30	273	2 4 6 6 6	1 1 1 2 4	183.456 366.912 550.368 1100.736 2201.472

- LDPC Codes used in 5G are irregular (matlab has encoder/decoder functions for them)
- See 379A L11 on LDPC codes (more information on the rates that can be chosen for LDPC)
- There is a **control channel that uses BPSK on 1** or more tones. It uses 379A's Polar Codes with $\bar{b} < 1$ for super reliability. This channel carriers for instance the mapping of RBs to users.

Uplink Cellular

- Aggregates RB’s into a single carrier (with same cyclic prefix).
  - Presumably saves upstream energy (although not clear that is really true – peak/average with filters - See 4.10).

- The receiver is what was originally known as a “Cyclic DFE” (see Chapter 5).
  - This was overlooked and the oxymoron “SC-OFDM” is in common use.(“single carrier– OFDM”)
  - Long after cyclic DFE name was introduced.

- Same data rates, FFT sizes, etc – just computation executed for minimum number of RB’s that are assigned to the user uplink.

5G allows more carrier frequencies

- 5G adds some capabilities:
  - Lower band (FR1): 450 MHz -- 6 GHz (FDD/TDD)
  - Millimeter Wave Band: (FR2): 24.25 GHz – 52.6 GHz (TDD only)
  - Δf now increased to
    - 15 (same), 30 and 60 kHz in FR1,
    - 60 and 120 kHz in FR2,
    - 5G also adds 256 QAM.
  - Channel Bandwidths now extend to as much as 400 MHz (depends on band).
  - Number of antennas is unlimited (Massive MIMO), but …
    - Maximum layers (so significant singular values or used dimensions) remains at 8 for a SINGLE user (4 for Uplink).
    - Maximum number of virtual antenna ports for which ”SVD-like” info can be supplied is 32 (4 for Uplink).
- See Tables to Follow and also Lecture 12 (Section 7.3)

- 6G coming spectra wars
  - 7-15 GHz FR3 band
  - Someone else has to release this spectrum
  - Possibly also THz band (> 100 GHz)
    - Short range

3GPP TS38.101-1 Table 5.2-1: 5G operating bands in FR1/2

Band Name	Uplink			Downlink			Duplex
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	–	894MHz	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
n78	3300 MHz	–	3800 MHz	3300 MHz	–	3800 MHz	TDD
n77	3300 MHz	–	4200 MHz	3300 MHz	–	4200 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

Band Name	Uplink			Downlink			Duplex
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

Downlink Powers

BS class	$P_{rated,c,AC}$
Wide Area BS	(Note)
Medium Range BS	< 38 dBm
Local Area BS	< 24 dBm
NOTE: There is no upper limit for the $P_{rated,c,AC}$ rated output power of the Wide Area Base Station.	

Source: 3GPP TS38.104 Table 6.2.1-1: *BS type 1-C* rated output power limits for BS classes

Uplink Power limit is 23 dBm, except n41, which is 26 dBm.

3GPP TS38.101-1 Table 5.3.5-1: Channel Bandwidths for Each 5G FR1 band

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											
n7	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60		Yes	Yes	Yes							
n8	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60											
n20	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60											
n28	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60											
n38	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60		Yes	Yes	Yes							
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	
	60		Yes	Yes	Yes							
n51	15	Yes										
	30											
	60											
n66	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes			Yes				
	60		Yes	Yes	Yes			Yes				

Continued from previous slide

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
n70	15	Yes	Yes	Yes	Yes	Yes						
	30		Yes	Yes	Yes	Yes						
	60		Yes	Yes	Yes	Yes						
n71	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60											
n74	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60		Yes	Yes	Yes							
n75	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60		Yes	Yes	Yes							
n76	15	Yes										
	30											
	60											
n77	15		Yes		Yes			Yes	Yes			
	30		Yes		Yes			Yes	Yes	Yes	Yes	Yes
	60		Yes		Yes			Yes	Yes	Yes	Yes	Yes
n78	15		Yes		Yes			Yes	Yes			
	30		Yes		Yes			Yes	Yes	Yes	Yes	Yes
	60		Yes		Yes			Yes	Yes	Yes	Yes	Yes
n79	15							Yes	Yes			
	30							Yes	Yes	Yes	Yes	Yes
	60							Yes	Yes	Yes	Yes	Yes
n80	15	Yes	Yes	Yes	Yes	Yes	Yes					
	30		Yes	Yes	Yes	Yes	Yes					
	60		Yes	Yes	Yes	Yes	Yes					
n81	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60											
n82	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60											
n83	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60											
n84	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60		Yes	Yes	Yes							

FR2 band: 3GPP TS38.101-2 Table 5.3.5-1: Channel bandwidths

NR band / SCS / UE Channel bandwidth					
NR Band	**SCS kHz**	**50 MHz**	**100 MHz**	**200 MHz**	**400 MHz**
n257	60	Yes	Yes	Yes	Yes
	120	Yes	Yes	Yes	Yes
n258	60	Yes	Yes	Yes	Yes
	120	Yes	Yes	Yes	Yes
n260	60	Yes	Yes	Yes	Yes
	120	Yes	Yes	Yes	Yes

- At mmW frequencies of FR2, these wider-bandwidth channels are only a small fraction of total bandwidth in this range.

Resource Blocks

SCS (kHz)	5MHz	10MHz	15MHz	20 MHz	25 MHz	30 MHz	40 MHz	50MHz	60 MHz	80 MHz	100 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}
15	25	52	79	106	133	[TBD]	216	270	N/A	N/A	N/A
30	11	24	38	51	65	[TBD]	106	133	162	217	273
60	N/A	11	18	24	31	[TBD]	51	65	79	107	135

SCS (kHz)	50MHz	100MHz	200MHz	400 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}
60	66	132	264	N.A
120	32	66	132	264

$$R = 168 \text{ kHz} \times N_{RB} \times b \times L \times \frac{\Delta f}{15 \text{ kHz}}$$

Example $R = 168 \times 133 \times 4 \times 4 \times 2 = 715.008\text{Mbps}$

- 5G is slightly more efficient in more RB’s allocated at lower frequencies too (than 4G).

End Supplementary Lecture 5

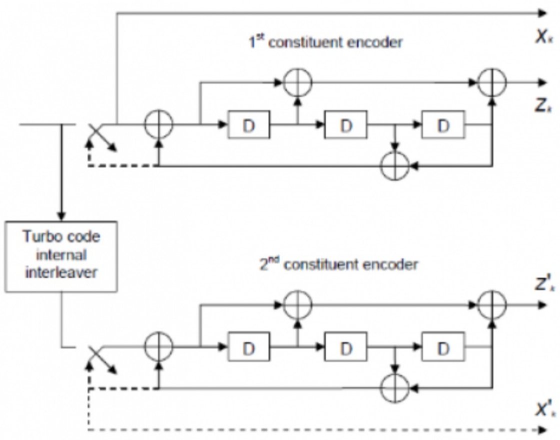
Cellular Coding and Loading

- Listed data rates were encoder-output data rates.
- A rate 1/3 "turbo code" (8 states in each constituent code, see Chapter 8)
  - Can be punctured from 1/3 up to 95%.
- MIMO cellular systems do not return M from SVD on each tone in Vector OFDM (unlike Wi-Fi)
  - Instead, one of 16 pre-defined M's is selected during training/adaptation (called a "codebook"), see L5:29-30.
- Loading will select code-puncturing, power level for RB, and the constellation size.

4G's Turbo Code

- IET Engineering Community

The scheme of the Turbo encoder for LTE is a Parallel Concatenated Convolutional Code (PCCC) with two 8-state constituent encoders and one Turbo code internal interleaver. The theoretical structure of a Turbo encoder is represented in the next figure:



The tail bits are independently appended at the end of each information bit stream to clean up the memory of all registers, for example, by terminating the encoder trellis to a zero state. Generally, the length of the tail bits is equal to the number of registers in one constituent encoder (3 registers are used in one constituent encoder in LTE). The sequence of tail bits is rearranged and 4 tail bits are attached after each information bit stream. Hence, the length of each bit stream becomes 4+*K*.

See 379A