The Evolution of Wi-Fi

Fredrik Brännström

Chalmers University of Technology, Gothenburg, Sweden

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Principal Design Engineer for Wi-Fi 802.11b/a/g/n,
Quantenna Communications, Fremont CA, 2006 – 2010

Quantenna

Quantenna

- Founded in 2006 by Dr. Behrooz Rezvani, Prof. Andrea Goldsmith, and four other leading experts.
- Received over $200 million in funding from leading venture capital firms, lead by Sequoia Capital (around 25%), Menlo Park, CA.
- Sequoia Capital has invested in over 250 companies since 1972 : Apple, Google, Oracle, PayPal, YouTube, Instagram, Yahoo! and WhatsApp.
- Headquarters in the heart of Silicon Valley: San Jose (California)
- R&D design centers: Phoenix (Arizona), St. Petersburg (Russia), Shanghai/Wuxi (China), Taipei (Taiwan), and Sydney (Australia)
- Currently 400+ employees.
- Quantenna's technology is deployed by 50+ major service providers including: AT&T, DirecTV, Orange, Bell Canada, Swisscom, Telefonica, France Telecom, Rostelecom, TeliaSonera, …

802.11 Standards

	802.11	Release	Freq [GHz]	Rate [Mbit/s]	Modulation
	-	Jun 1997	2.4	1 or 2	DSSS
	b	Sep 1999	2.4	5.5 or 11	CCK
	a	Sep 1999	5	6 – 54	OFDM
Oct 3, 2018	g	Jun 2003	2.4	6 – 54 ?	OFDM
Wi-Fi 4	n	Oct 2009	2.4 / 5	6.5 – 600	OFDM
Wi-Fi 5	ac	Nov 2013	5	up to 6933 ?	OFDM
Wi-Fi 6	ax	Sep 2019	2.4 / 5	up to 9608	OFDMA

- Direct Sequence Spread Spectrum (DSSS)
- Complementary Code Keying (CCK)
- Orthogonal Frequency Division Multiplexing (OFDM)
- How to increase the data rate from 54 Mbit/s to 600 Mbit/s?
- How to reach almost 10 Gbit/s (178 times faster than 11a/g)?

802.11a/g: Scrambler

- The scrambler (SCR) scrambles the DATA bits (in a known fashion without changing the order) to reduce the probability of long sequences of zeros or ones.
  - Input (32): 01100000 00000000 00111111 11111111
  - Output (32): 11101001 11100101 01001000 01010111

802.11a/g: Channel Code

DATA → SCR → **BCC** → INT → MAP → DPZ → IDFT → GI → RF

- A 64-state binary convolutional code (BCC) with code rate R=1/2 followed by a puncturer that removes some redundant bits.
- No puncturing: 12 bits in → 24 bits out → R=12/24=1/2
  - Input (12): 111010 011110
  - Output (24): 101001 001001 011100 110010
- 25% puncturing: 12 bits in → 24 – 6=18 bits out → R=12/18=2/3
  - Input (12): 1110 1001 1110 (period 4)
  - Output (18): 101~~0~~ 010~~0~~ 100~~1~~ 011~~1~~ 001~~1~~ 001~~0~~
- 33% puncturing: 12 bits in → 24 – 8=16 bits out → R=12/16=3/4
  - Input (12): 111010 011110 (period 6)
  - Output (16): 101~~00~~1 001~~00~~1 011~~10~~0 110~~01~~0

802.11a/g: Interleaver

DATA → SCR → BCC → **INT** → MAP → DPZ → IDFT → GI → RF

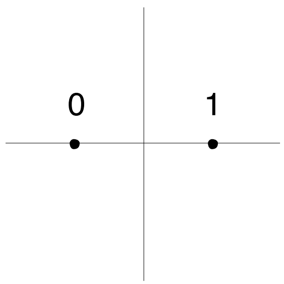
- The bit interleaver (INT) permutes the order of the coded bits to prevent long sequences of adjacent noisy bits (frequency-selective fading) from entering the BCC decoder.
- The size of the interleaver = the size of the OFDM symbol.
- Input (row) 3 x 16 = 48 bits for BPSK:
- Output (column) 3 x 16 = 48 bits for BPSK:

00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47

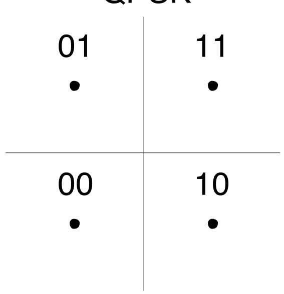
802.11a/g: Mapper

- The mapper (MAP) maps the interleaved bits to constellation points (complex numbers) using Gray labeling.

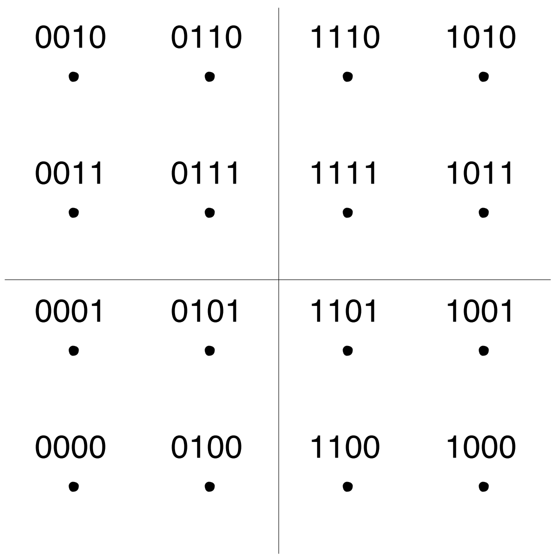
BPSK



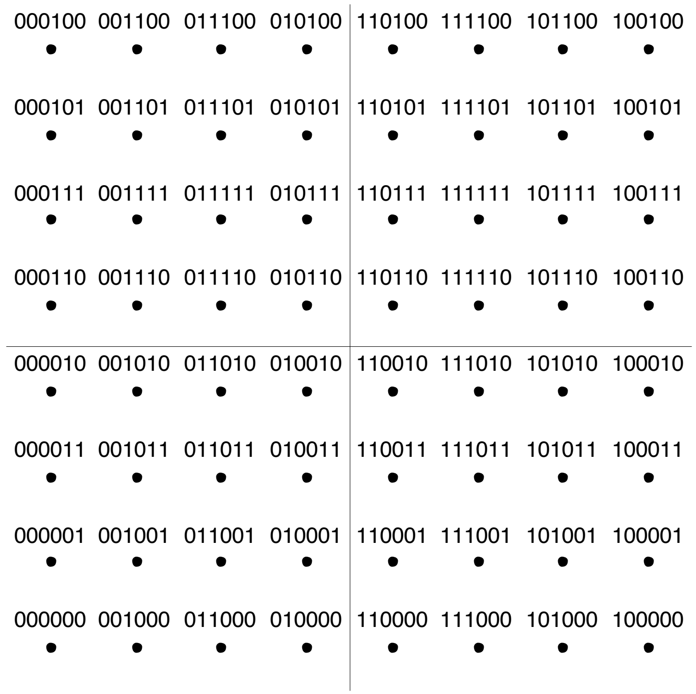
QPSK



16-QAM

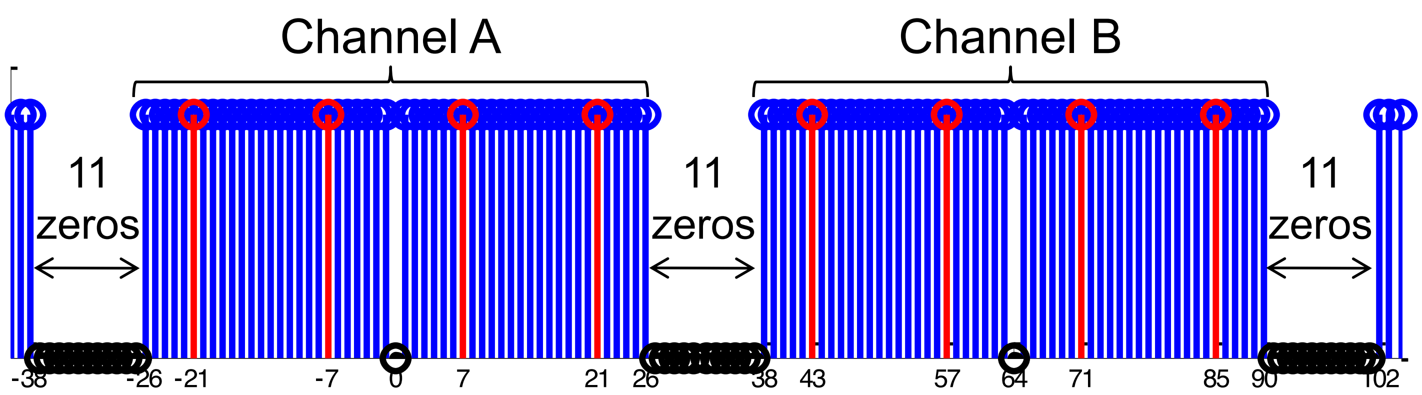


64-QAM



802.11a/g: Data/Pilot/Zero (DPZ) Allocation

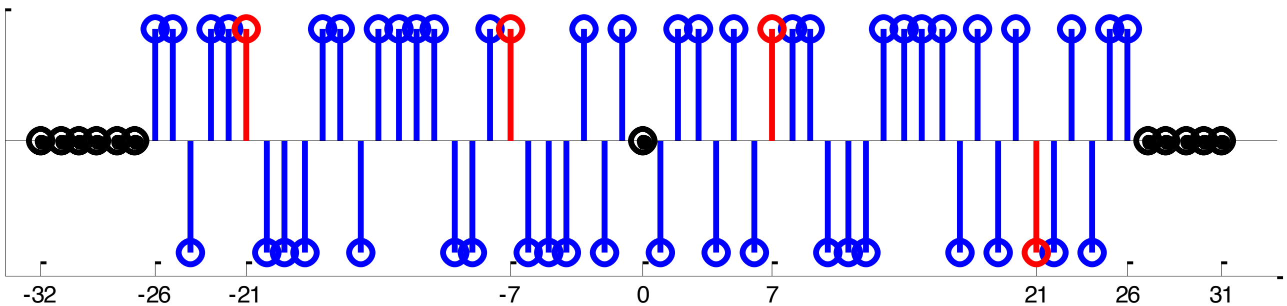
- 64 sub-carriers in 20 MHz give a sub-carrier spacing of 20 MHz / 64 = 312.5 kHz.
- 48 DATA sub-carriers from mapper output.
- 4 PILOT sub-carriers are inserted to track for example carrier frequency offset and changes in the channel.
- 12 ZERO sub-carriers (DC and between channels).



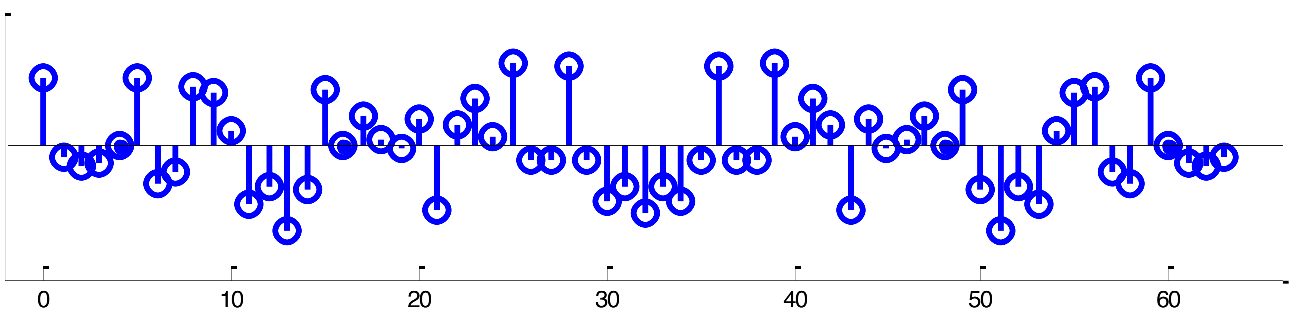
802.11a/g: OFDM

- The Inverse Discrete Fourier Transform (IDFT) converts a block of 64 complex valued constellation points 312.5 kHz apart to a time domain block of 1 / 312.5 kHz = 3.2 μs.

- Frequency
  20 MHz
  BPSK

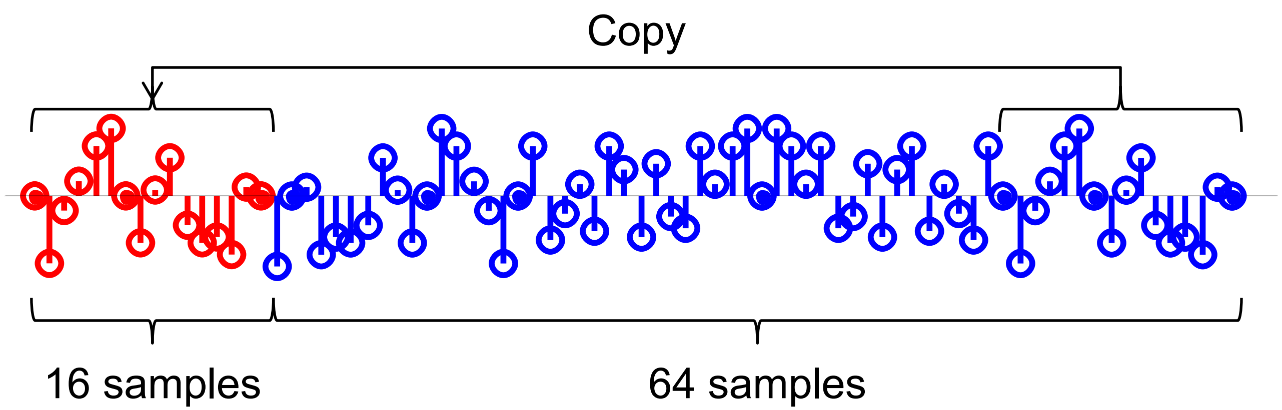


- Time
  3.2 μs
  64 samples



802.11a/g: Guard Interval

- A guard interval (GI) is added by copying the last 25% of the IDFT output and attach it to the beginning (cyclic prefix) to create the OFDM symbol of 3.2 + 0.8 = 4 µs.

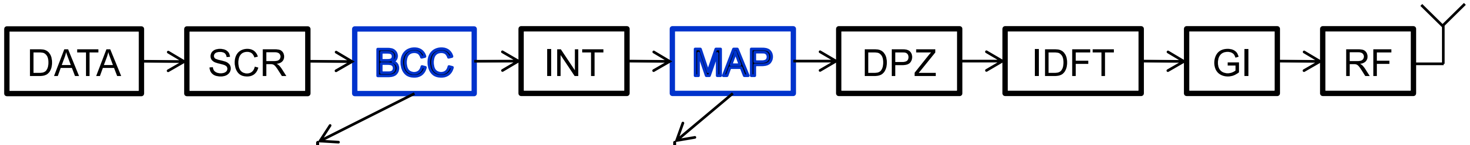


- Using GI reduces the sensitivity to time synchronization problems and eliminates the OFDM intersymbol interference (ISI) if the multipath time-spreading is shorter than the GI.

802.11a/g: Analog

- The analog block up-converts the complex baseband waveform to a radio frequency (RF) signal according to the center frequency of the desired channel (around 2.4 GHz for 802.11g and around 5 GHz for 802.11a).

802.11a/g: Rate Parameters

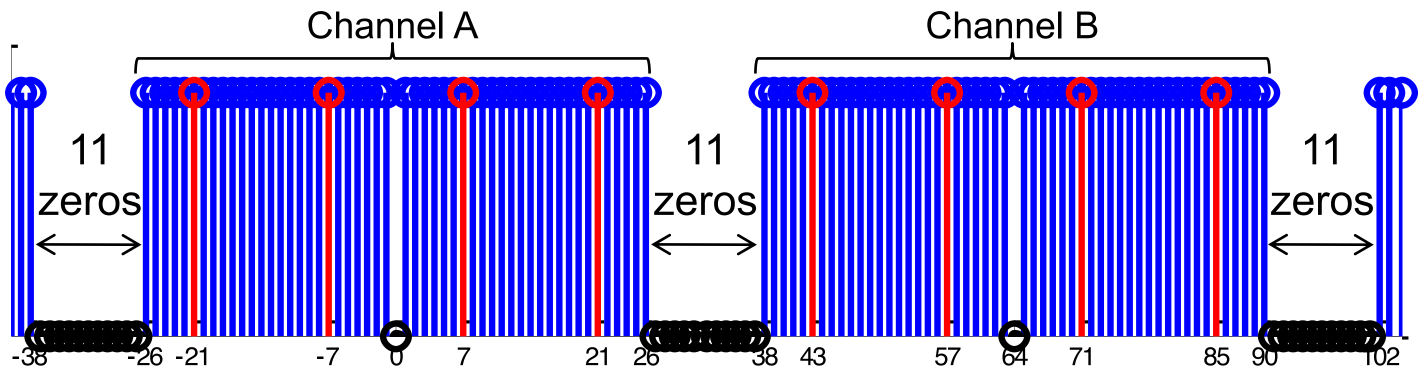


Code rate R	Modulation	Date rate [Mbit/s]
1/2	BPSK	6
3/4	BPSK	9
1/2	QPSK	12
3/4	QPSK	18
1/2	16-QAM	24
3/4	16-QAM	36
2/3	64-QAM	48
3/4	64-QAM	54

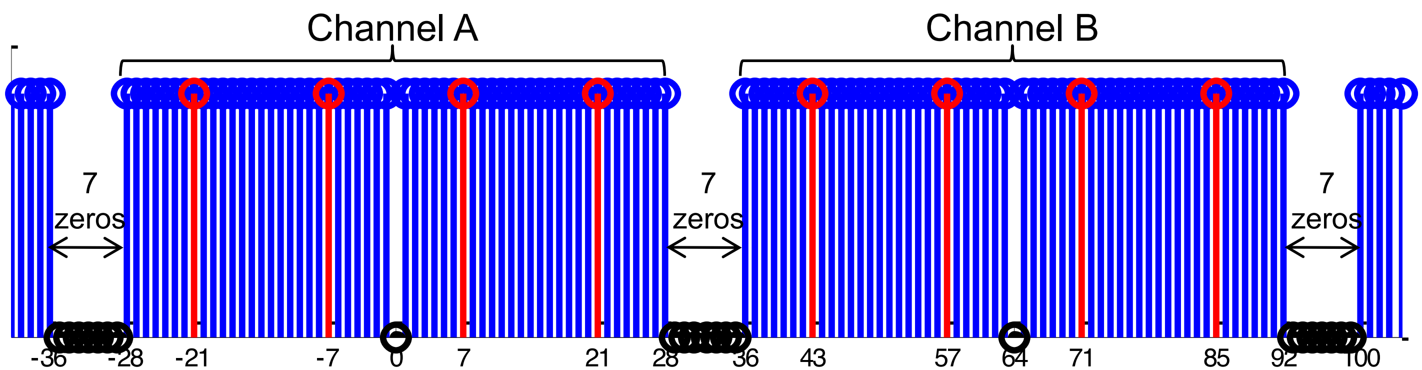
- Four modulations and three code rates, but only 8 valid combinations.
- How can we increase the data rate from 54 to 600 Mbit/s?

802.11n: Data/Pilot/Zero (DPZ) Allocation

- 802.11a/g: 48 DATA, 4 PILOT, and 12 ZERO.
- 54 Mbit/s



- 802.11n: 52 DATA, 4 PILOT, and 8 ZERO.
- 54·52/48 =58.5 Mbit/s



802.11n: Scrambler

DATA → **SCR** → BCC → INT → MAP → DPZ → IDFT → GI → RF

- 802.11a/g: The scrambler (SCR) scrambles the DATA bits (in a known fashion without changing the order) to reduce the probability of long sequences of zeros or ones.
  - Input (32): 01100000 00000000 00111111 11111111
  - Output (32): 11101001 11100101 01001000 01010111
- 802.11n: No update can increase the data rate!

802.11n: Channel Code

DATA → SCR → **BCC** → INT → MAP → DPZ → IDFT → GI → RF

- 802.11a/g: A 64-state binary convolutional code (BCC) with code rate R=1/2 followed by a puncturer that removes some redundant bits.
  - No puncturing: R=1/2
  - 25% puncturing: R=2/3
  - 33% puncturing: R=3/4
- 802.11n: More puncturing gives higher data rate!
- 40% puncturing: 20 bits in → 40 – 16=24 bits out → R=20/24=5/6
  - Input (20): 1110100111 1001011010 (period 10)
  - Output (24): 101~~00~~10~~01~~0 010~~11~~10~~01~~1 010~~11~~10~~01~~1 010~~11~~10~~01~~1
- Maximum data rate: 58.5 Mbit/s → 58.5·(5/6)/(3/4) = 65 Mbit/s

802.11n: Interleaver

DATA → SCR → BCC → **INT** → MAP → DPZ → IDFT → GI → RF

- 802.11a/g: Input (row) 3 x 16 = 48 bits for BPSK:
- 802.11a/g: Output (column) 3 x 16 = 48 bits for BPSK:

00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47

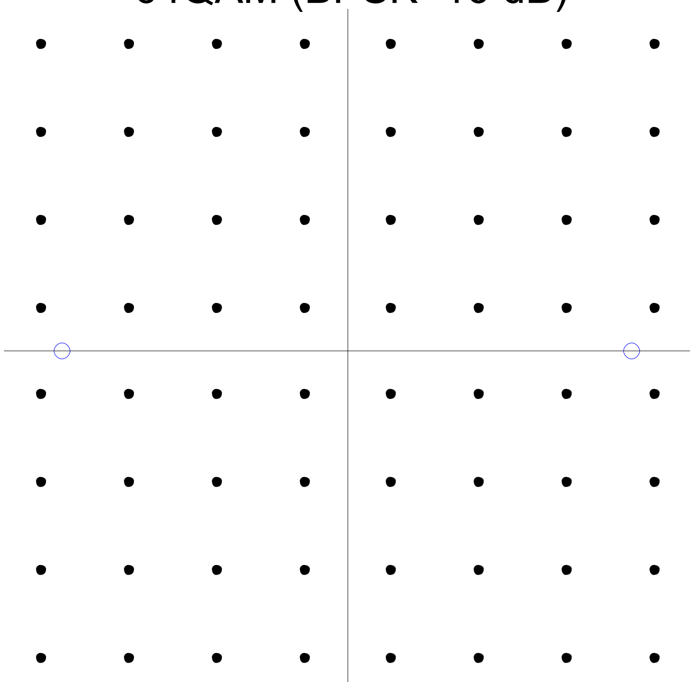
- 802.11n: Input (write row) 4 x 13 = 52 bits for BPSK:
- 802.11n: Output (read column) 4 x 13 = 52 bits for BPSK:

00	01	02	03	04	05	06	07	08	09	10	11	12
13	14	15	16	17	18	19	20	21	22	23	24	25
26	27	28	29	30	31	32	33	34	35	36	37	38
39	40	41	42	43	44	45	46	47	48	49	50	51

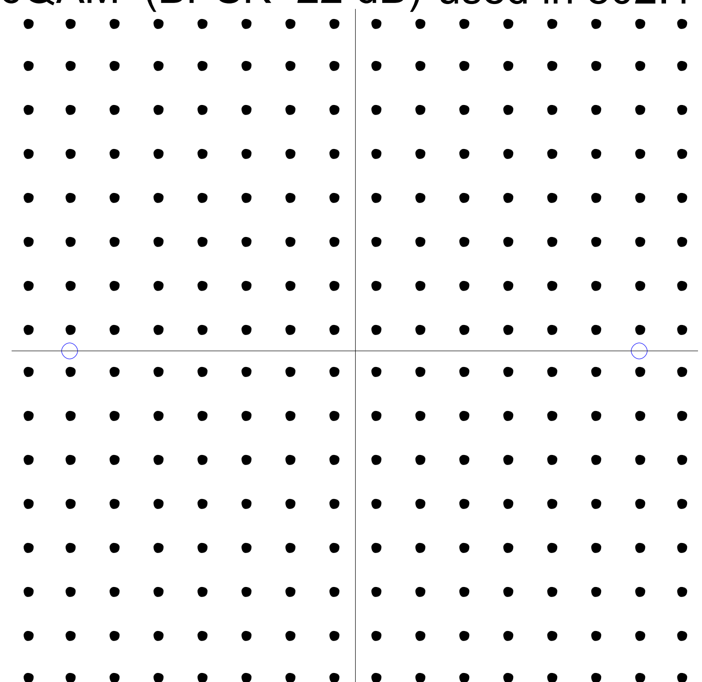
802.11n: Mapper

- 802.11a/g: BPSK, QPSK, 16-QAM, and 64-QAM
- 802.11n: No update! (higher constellations require very high SNR)

64QAM (BPSK+16 dB)

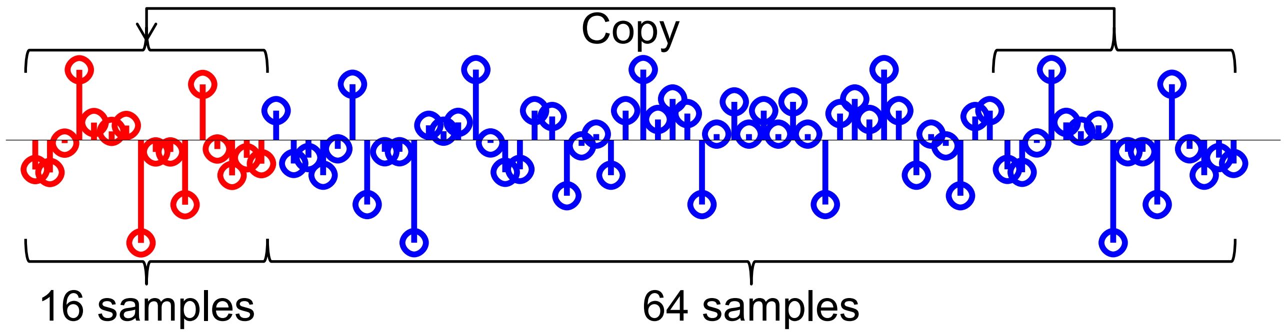


256QAM (BPSK+22 dB) used in 802.11ac



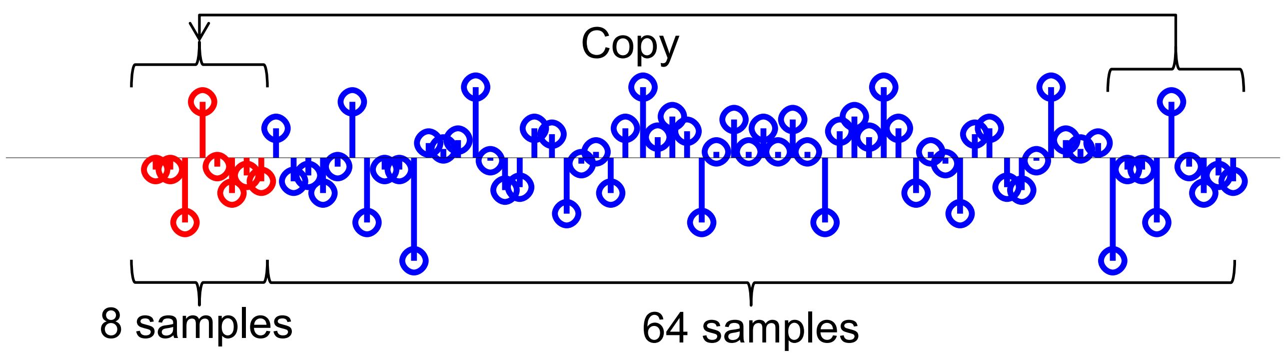
802.11n: Guard Interval (GI)

- 802.11a/g: 25% of the end is copied to the beginning: 3.2 + 0.8 = 4 μs.



- 65 Mbit/s
- Long GI (LGI)

- 802.11n: 12.5% of the end is copied to the beginning: 3.2 + 0.4 = 3.6 μs.



- 65·4.0/3.6 = 72.2 Mbit/s
- Short GI (SGI)

802.11n: Modulation and Coding Scheme (MCS)

DATA → SCR → **BCC** → INT → **MAP** → DPZ → IDFT → **GI** → RF

MCS	Code rate R	Mod	802.11a/g [Mbit/s]	802.11n LGI [Mbit/s]	802.11n SGI [Mbit/s]
0	1/2	BPSK	6	6.5	7.2
-	3/4	BPSK	9	-	-
1	1/2	QPSK	12	13.0	14.4
2	3/4	QPSK	18	19.5	21.7
3	1/2	16-QAM	24	26.0	28.9
4	3/4	16-QAM	36	39.0	43.3
5	2/3	64-QAM	48	52.0	57.8
6	3/4	64-QAM	54	58.5	65.0
7	5/6	64-QAM	-	65.0	72.2

$54 \xrightarrow{\text{DPZ}} 58.5 \xrightarrow{\text{BCC}} 65.0 \xrightarrow{\text{SGI}} 72.2$

- 33% increase of the data rate – how do we increase it further?

802.11n: DPZ Allocation, 40 MHz

802.11a/g 20 MHz

48 D, 4 P, 12 Z

54 Mbit/s

802.11n 20 MHz

52 D, 4 P, 8 Z

72.2 Mbit/s

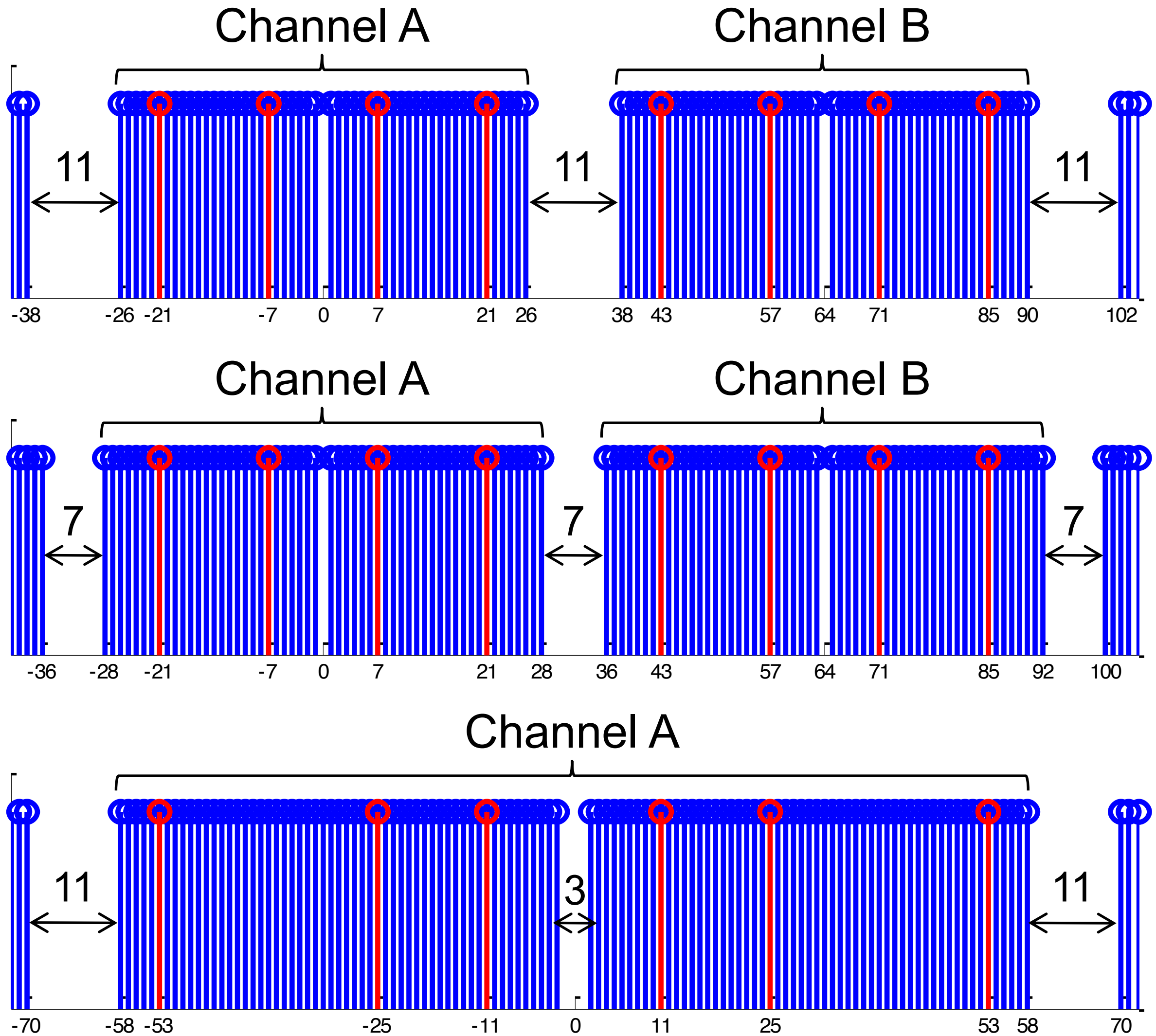
802.11n 40 MHz

108 D, 6 P, 14 Z

72.2·108/52

= 150 Mbit/s

128-point IDFT



802.11n: MCS for 20 MHz and 40 MHz

DATA → SCR → **BCC** → INT → MAP → **DPZ** → **IDFT** → **GI** → RF

MCS	Code rate R	Mod	802.11a/g 20MHz [Mbit/s]	802.11n 20MHz LGI [Mbit/s]	802.11n 20MHz SGI [Mbit/s]	802.11n 40MHz LGI [Mbit/s]	802.11n 40MHz SGI [Mbit/s]
0	1/2	BPSK	6	6.5	7.2	13.5	15.0
-	3/4	BPSK	9	-	-	-	-
1	1/2	QPSK	12	13.0	14.4	27.0	30.0
2	3/4	QPSK	18	19.5	21.7	40.5	45.0
3	1/2	16-QAM	24	26.0	28.9	54.0	60.0
4	3/4	16-QAM	36	39.0	43.3	81.0	90.0
5	2/3	64-QAM	48	52.0	57.8	108.0	120.0
6	3/4	64-QAM	54	58.5	65.0	121.5	135.0
7	5/6	64-QAM	-	65.0	72.2	135.0	150.0

DPZ

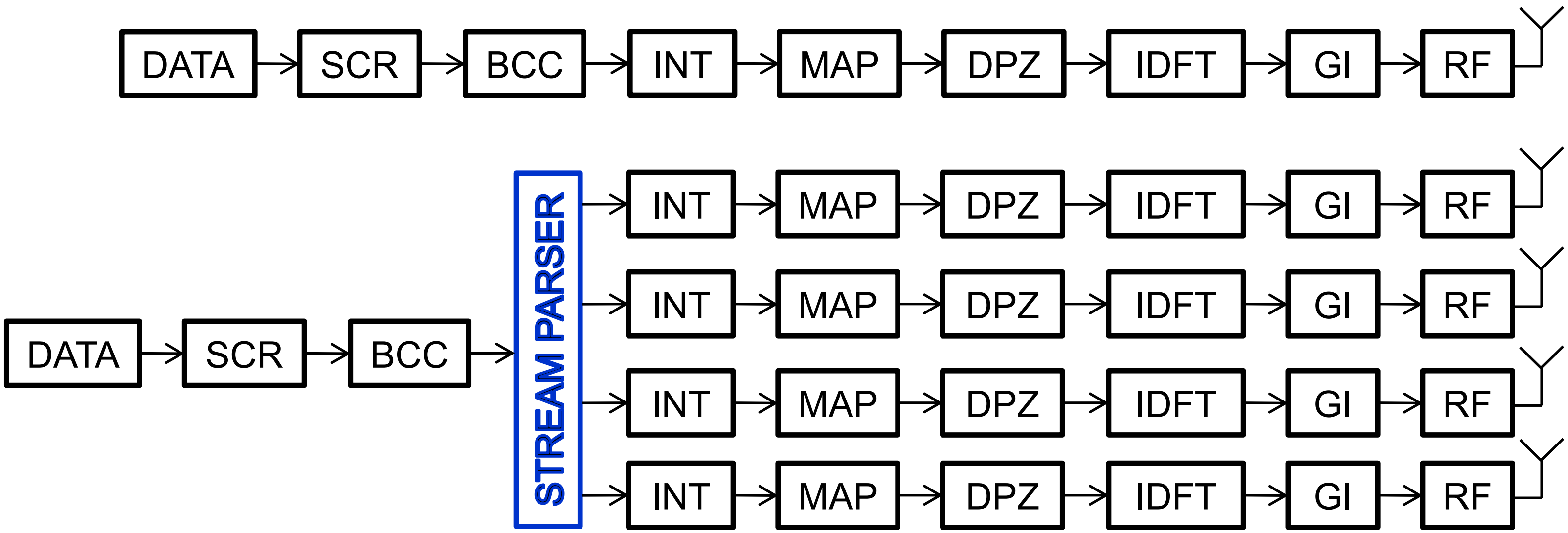
SGI

BCC

40 MHz

- How do we get from 150 to 600 Mbit/s?

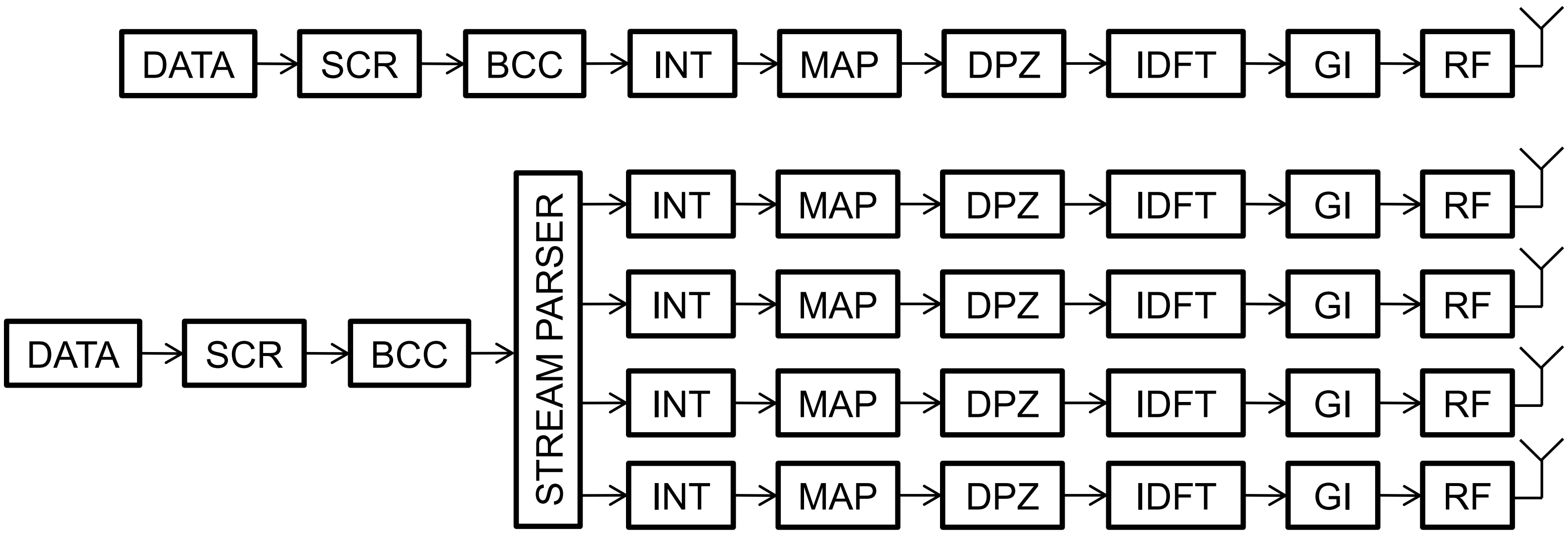
802.11n: Multiple Input Multiple Output (MIMO)



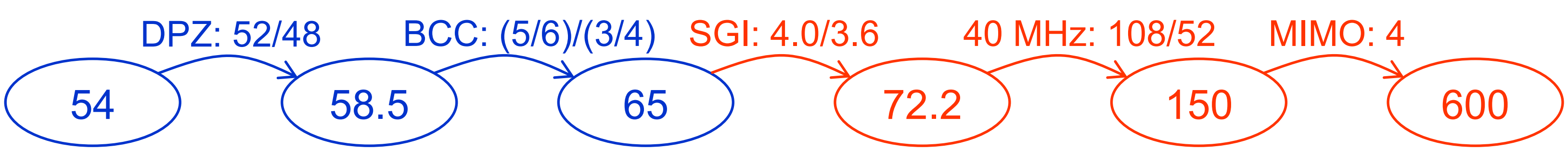
- One to four spatial streams (SSs) of data at the same time in the same channel give a data rate up to 4·150 = 600 Mbit/s.

MCS	R	Mod SS0	Mod SS1	Mod SS2	Mod SS3	20MHz LGI [Mbit/s]	20MHz SGI [Mbit/s]	40MHz LGI [Mbit/s]	40MHz SGI [Mbit/s]
31	5/6	64QAM	64QAM	64QAM	64QAM	260	288.9	540	600

802.11n: Performance?

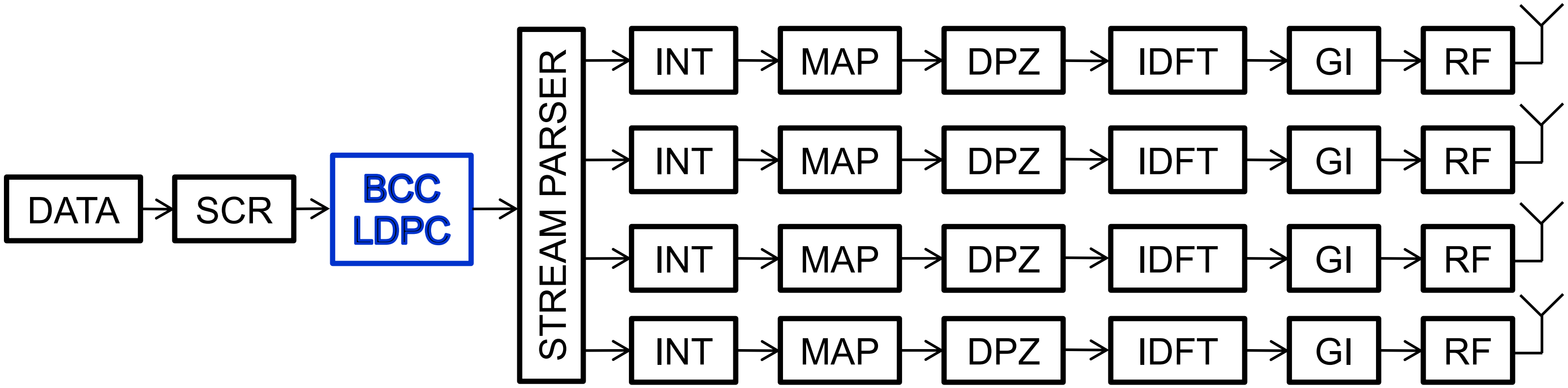


- The data rate is increased from 54 to 600 Mbit/s.
- Mandatory (DPZ and BCC) and optional (SGI, 40 MHz, MIMO) features.



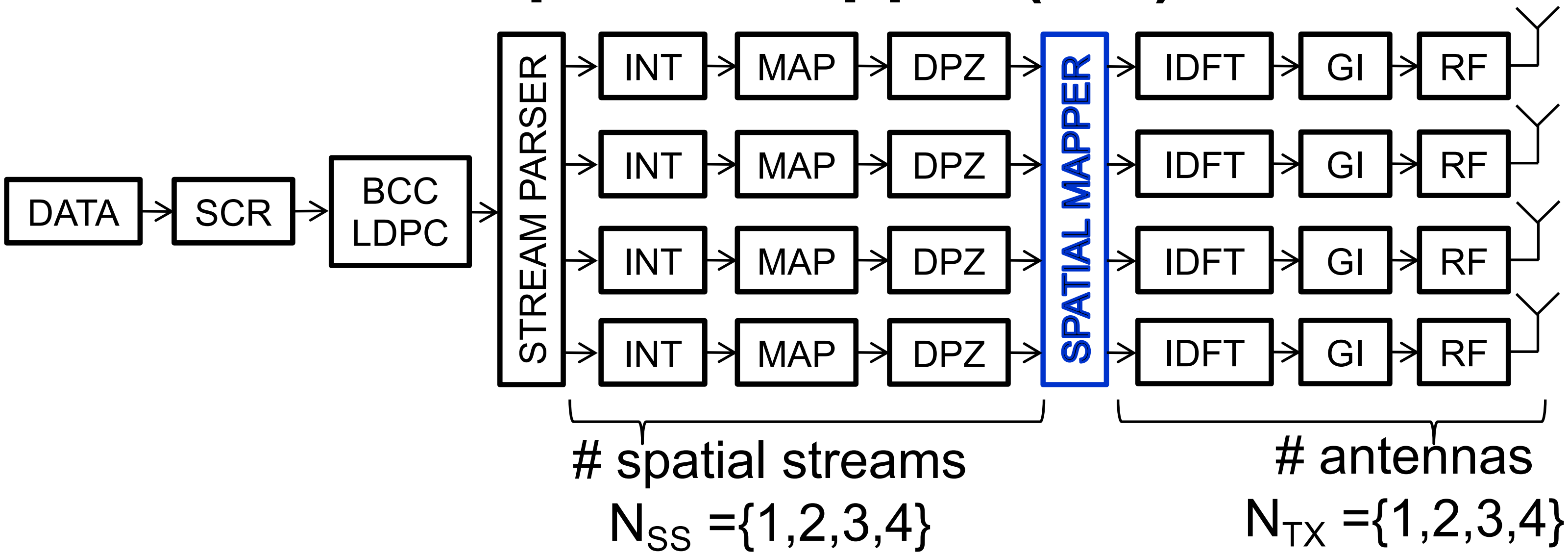
- What about the performance? Can it be improved? Suggestions?

802.11n: LDPC



- Low Density Parity Check (LDPC) code.
- Same four code rates as BCC, R={1/2, 2/3, 3/4, 5/6}.
- Better performance than BCC.
- More complex encoder/decoder than BCC, i.e., harder to implement.
- Block code instead of convolutional code, i.e., usually longer delay.

802.11n: Spatial Mapper (SM) or TxBF



- Increasing number of streams: $1 \le N_{SS} \le N_{TX} \le 4$
- The SM maps the N_{SS} spatial streams to N_{TX} antennas for sub-carrier k using a complex matrix Q_k of size N_{TX} times N_{SS}
- The performance depends on the choice of Q_k.
- Q_k is not standardized.
- It can be static, or dynamically derived, e.g., from the channel estimate.
- It can be generated in the receiver or transmitter.

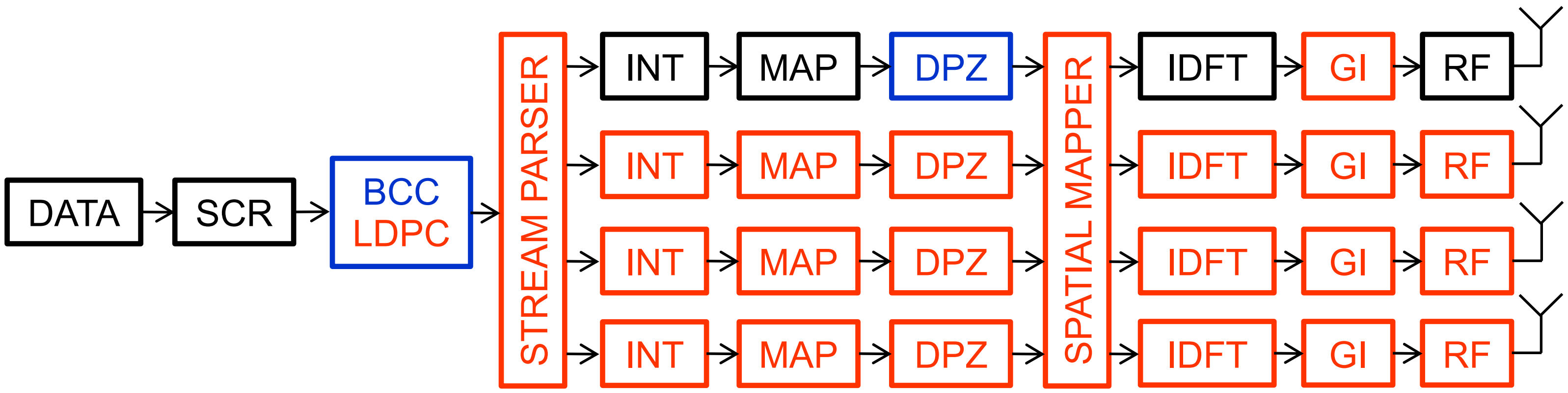
802.11n: Unequal Modulation

- There are 76 different MCS values.
- MCS 0 to 31 have equal modulation of the spatial streams.
- MCS 33 to 76 have unequal modulation of the spatial streams.
- For example:

MCS	R	Mod SS0	Mod SS1	Mod SS2	Mod SS3	20MHz LGI [Mbit/s]	20MHz SGI [Mbit/s]	40MHz LGI [Mbit/s]	40MHz SGI [Mbit/s]
33	1/2	16QAM	QPSK	-	-	39	43.3	81	90
42	1/2	64QAM	16QAM	QPSK	-	78	86.7	162	180
70	3/4	64QAM	16QAM	16QAM	QPSK	156	173.3	324	360

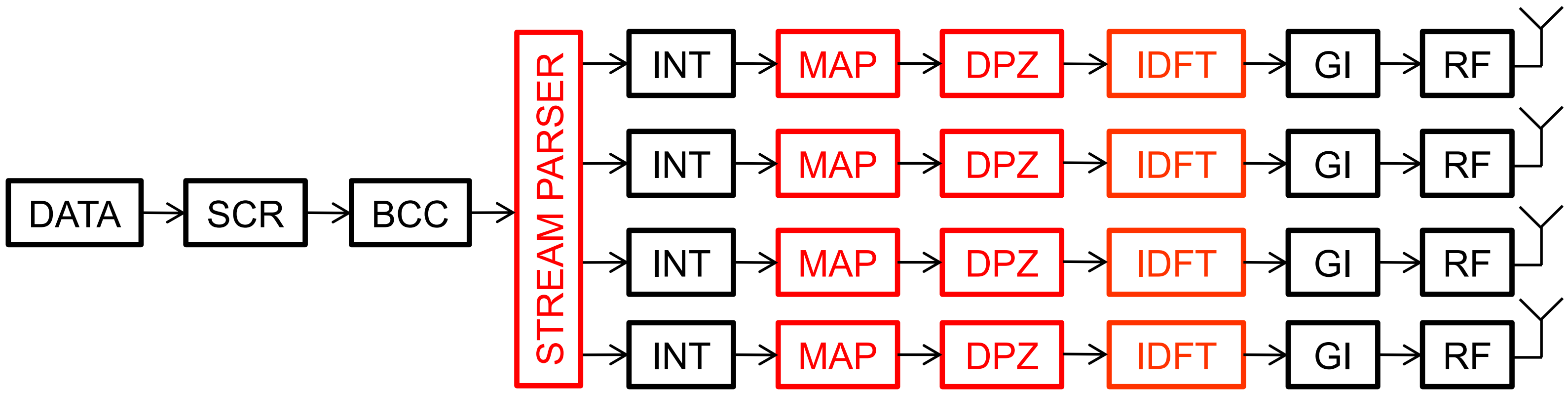
- Unequal modulation can be useful in beamforming, when the channels for different spatial streams are different (rate adaptation).
- There are 8 different rates in 802.11a/g.
- There are $76 \cdot 2 \cdot 2 = 304$ different rates in 802.11n.

802.11n: Summary



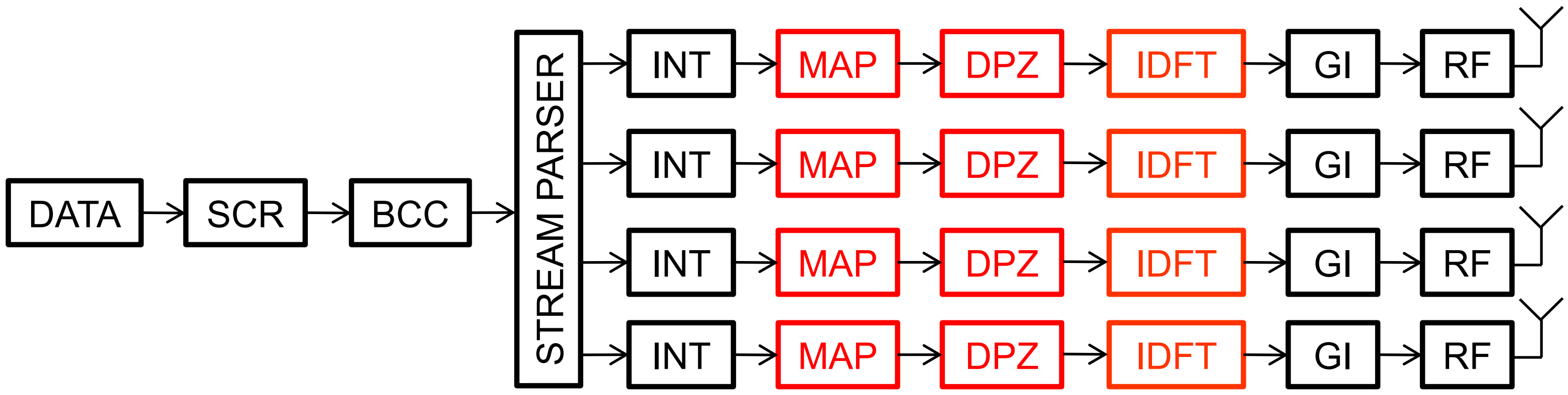
- 802.11a/g: 8 different rates {6, 9, 12, 18, 24, 36, 48, 54} Mbit/s
- Mandatory in 802.11n: 20 MHz MCS 0 – 7, BCC, DPZ, 2.4 GHz
  8 different rates {6.5, 13, 19.5, 26, 39, 52, 58.5, 65} Mbit/s
- Optional in 802.11n: 20 MHz MCS 8 – 76, 40 MHz MCS 0 – 76, 5 GHz, SGI, LDPC, STBC, SM, 296 different rates: 7.2 – 600 Mbit/s
- 802.11a/g: 54 Mbit/s using 48 subcarriers, each 312.5 kHz: 3.6 bit/s/Hz
- 802.11n: 600 Mbit/s using 108 subcarriers, each 312.5 kHz: >17 bit/s/Hz
- Next time you buy a Wi-Fi device, read the specification!

802.11ac



- MAP: 64QAM to 256QAM, 600·8/6 = 800 Mbit/s
- DPZ: 108 DATA carriers in 40 MHz to 468 DATA carriers in 160 MHz, 800·468/108 = 3467 Mbit/s
- IDFT: 128 FFT to 512 FFT
- STREAM PARSER: 4 streams to 8 streams, 3467·8/4 = 6933 Mbit/s
- Multi-user MIMO (MU-MIMO) in downlink
- 6933 Mbit/s using 468 subcarriers, each 312.5 kHz: >47 bit/s/Hz

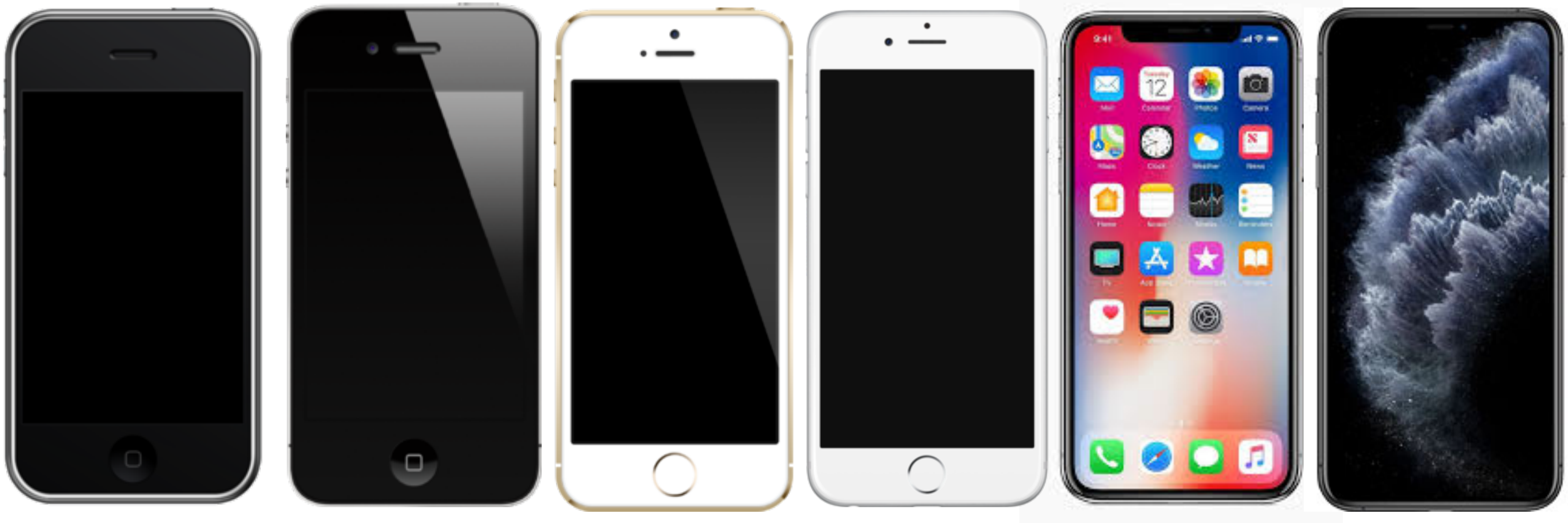
802.11ax



- MAP: 256QAM to 1024QAM, $6933 \cdot 10/8 = 8666$ Mbit/s
- Subcarrier spacing: 312.5 kHz to 78.125 kHz (both 160 MHz)
- DPZ: 468 DATA carriers in 3.2+0.4 μs to 1960 DATA carriers in 12.8+0.8 μs
  $8666 \cdot 3.6/468 \cdot 1960/13.6 = 9608$ Mbit/s
- IDFT: 512 FFT to 2048 FFT
- MU-MIMO also in uplink
- Orthogonal Frequency Division Multiple Access (OFDMA)
- 9608 Mbit/s using 1960 subcarriers, each 78.125 kHz: >62 bit/s/Hz

iPhone

2007-2009 2010-2011 2012-2013 2014 2015-2018 2019



- *iPhone 1/3G/3GS*: 802.11g, 1 stream, 20 MHz, 2.4 GHz, **54 Mbps**
- *iPhone 4/4S*: 802.11n, SGI, STBC, **72.2 Mbps**
- *iPhone 5/5S*: 802.11n, 40 MHz, 5 GHz, LDPC, **150 Mbps**
- *iPhone 6*: 802.11ac, 80 MHz, 256 QAM, TxBF, **433 Mbps**
- *iPhone 6S/7/8/X/Xs*: 802.11ac, 2 streams, **867 Mbps**
- *iPhone 11:* 802.11ax, >**1320 Mbps ?**

Quantenna

- Oct. 2008 – announced the world's first fully integrated 802.11n chipsets with 4x4 MIMO and transmit beamforming (TxBF) 600 Mbps
- Nov. 2011 – released the world's first 802.11ac chipset for retail Wi-Fi routers and consumer electronics
- Jan. 2015 – the world's first full 802.11ac including 8x8 MIMO, Multi-User MIMO (MU-MIMO) and 160 Mhz channel support.
- Sept. 2015 – first and only company to support speeds over 10 Gbps. True 8x8™ MIMO for 5GHz + 4x4 MIMO on 2.4 GHz using 1024QAM. Was the world's fastest Wi-Fi chip!
- Oct. 2016 – industry's first 802.11ax Wi-Fi chipset
- Oct 28, 2016 – Registered as QTNA on NASDAQ to raise around $123 million in an initial public offering (IPO).
- June 19, 2019 - ON Semiconductor Corporation acquires Quantenna for $1.07 billion

Next time you buy a Wi-Fi device, read the specification!

Asus Rapture GT-AX11000, 10.756 Gbps
5290 SEK at Kjell & Company