6NTCM009W Internet of Things

- **Lecture 5 - Objectives**
- ISM bands
- Link design and link budgets
- Link budget for Bluetooth
- The Wi-Fi family and channels
- Link budget for Wi-Fi 802.11n
- OFDM and multiple antennas
- Receiver sensitivity

The ISM bands

- The Industrial, Scientific and Medical (ISM) bands are unlicensed according to ITU.
- ISM radio bands are portions of the radio spectrum reserved internationally for industrial, scientific, and medical purposes
- A congested band especially around 2.4 GHz with many applications.

Frequency band	Center frequency (MHz)	Bandwidth (MHz)
6.765–6.975 MHz	6.78	0.03
13.553–13.567 MHz	13.56	0.014
26.957–27.283 MHz	27.18	0.326
40.66–40.7 MHz	40.68	0.04
433.05–434.79 MHz	433.92	1.74
902–928 MHz	915	26
2400–2500 MHz	2450	100
5725–5875 MHz	5800	150
24–24.250 GHz	24125	250
61–61.5 GHz	61250	500
122–123 GHz	122500	1000
244–246 GHz	245000	2000

Applications for ISM Band

- Near Field Communication (NFC) devices for contactless payment systems allowing mobile payments
- walkie-talkies,
- garage door openers
- keyless entry systems for cars,
- wireless doorbells, wireless microphones, baby monitors,
- radio control channels for UAVs (drones),
- wireless surveillance systems,
- Radio Frequency Identification (RFID) to automatically identify and track tags attached to objects, useful for inventory/stock control

Link design

- Link denotes the transmission path between a transmit and receive antenna.
- Signal strength attenuates due to distance (signal path).
- The main goal is to predict the path loss L_P as accurately as possible to derive the range of the radio link (coverage).
- The maximum range occurs when the received power reaches the receiver sensitivity level which provides just acceptable signal quality.
- The value of free space loss L_P for which this minimum power level is received is usually expressed in dB.

Link budget analysis

- A link budget analysis determines the loss in power a signal will suffer when transmitted to a receiver some distance away.
- The link budget determines the received power of a wireless link, considering the transmit power, antenna gains, propagation losses, and a link margin for channel effects.
- It is important to guarantee a minimum signal power at the receiver to extract data at the receiving side.

Link budget: received power and path loss

A simplified link budget follows the transmission equation:

$$Pr = Pt + Gt + Gr - Lm - Lp \qquad \text{or}$$

$$Lp = Pt - Pr - Lm + Gt + Gr$$

where

- *P*r is the received power in decibels relative to a reference (dBm)
- *P*t is the transmit power in decibels relative to a reference (dBm)
- *G*t is the transmit antenna gain in dBi
- *G*r is the receive antenna gain in dBi
- *L*m is the link margin in dB
- and *L*p is the path loss in dB
- NOTE: 1Watt -> 10log(1) = 0dBW = 30dBm

Link budget: Free Space Path loss

- For free space, the path loss can be computed as follows:

$$Lp(\mathrm{dB}) = 20\log(d_{\mathrm{km}}) + 20\log(f_{\mathrm{GHz}}) + 92.45$$

- where d is the distance between the transmitter and receiver in Km and *f* is the frequency in GHz
- Path loss is proportional to the distance of the communication link and to the frequency value of the radio signal
  - **The higher the distance the greater the loss and the weaker the received signal**
  - **The higher the frequency of operation the greater the loss of the communication link**

Example: Link budget for Bluetooth

- Receiver sensitivity is defined as the minimum signal strength (power) at the receiver.
- The Bluetooth standard specifies a reference receiver sensitivity of –70 dBm. The standards require that at this minimum, the receiver be able to achieve a Bit Error Rate (BER) = 1 error in 1000 bits = 10^{-3}. A class 3 transmitter transmits at 0 dBm and both transmit and receive antennas are omnidirectional with a gain of 2 dBi. The band of operation is the 2.4 GHz ISM band. The link is Line-Of-Sight (LOS). The link margin is chosen as 10 dB.
- Calculate the maximum distance of this link.
- Note that Class 3 transmitter transmits Pt = 0 dBm therefore Pt = $10^{(0/10)}$ = 1mW

Example: Link budget for Bluetooth

Lp = Pt − Pr − Lm + Gt + Gr		
Transmit Power	0	dBm
Minimum Receive Power	-70	dBm
Link Margin	10	dB
Tx Antenna Gain	2	dBi
Rx Antenna Gain	2	dBi
Maximum Allowable Path Loss	64	dB

frequency	2.4	GHz
20log(f in GHz)	7.60	dBGHz

20log(d in Km) = Lp - 20log(f in GHz)-92.45		
20log(d in Km)	- 36.0542	dBkm
d in Km	0.01575	km
d in m	15.75	m

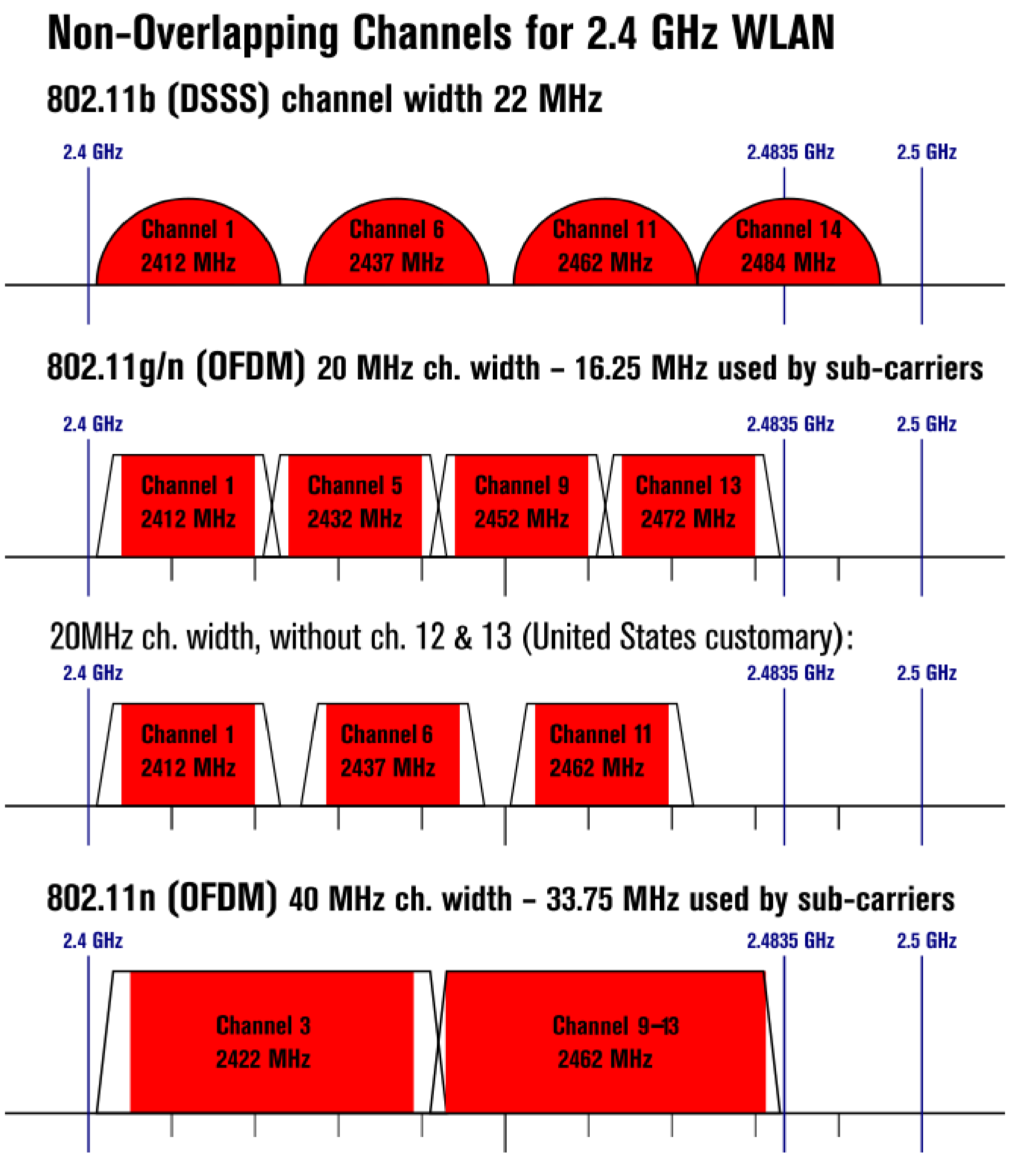
Wi-Fi the 802.11 family

- Wi-Fi connectivity is often an obvious choice for many IoT services
  - ➢wide infrastructure -> deployed in many homes and businesses.
- It is a well-understood technology and can be installed directly with minimal support.
- It is suitable for services that handle large volumes of data and require relatively high data transfer speeds.
- The downside is that it is power consuming.

Wi-Fi generations

- Wireless local area network (WLAN) technology based on the IEEE 802.11 standard series is one of the most successful wireless communication technologies of the last two decades.
- Essentially based on an OFDM access scheme and typically operating on license-exempt bands, such as 2.4 GHz, 5 GHz and 6GHz it carries an essential portion of traffic from various devices in the wireless communications networks of today and tomorrow.
- The sixth generation of Wi-Fi (Wi-Fi 6), based on the IEEE 802.11ax standard, represents communication efficiency and will be also operating in the newly available 6 GHz spectrum (Wi-Fi 6E).
- Moreover, the standardization of the seventh generation (Wi-Fi 7) has already started, with the target to enable extremely high throughput (IEEE 802.11be).

Wi-Fi Channels at 2.4 GHz – ISM band



Why Wi-Fi 802.11n

- Generation 4 of Wi-Fi family of standards
- Mature technology
- Implements MIMO technology
- Raspberry Pi Pico W board is using
  - Infineon CYW43439 chip 2.4GHz 802.11n Wi-Fi 4 and Bluetooth 5.2
  - 1x1 Single-Band 802.11n and Bluetooth

802.11n standard definition: sensitivity levels, modulation coding schemes and data rates

Data Rate

The data rate is the number of bits that are conveyed or processed per unit of time. Since higher data rates require greater transmission power, a wireless device may offer different Tx power specifications for different data rates.

Rx Sensitivity = receiver sensitivity of device

This is the wireless device's receiver sensitivity and is typically measured in dBm. With greater Rx sensitivity, the device is able to receive weaker signals, which means greater transmission distances can be supported. If two devices have different Tx power and Rx sensitivity specifications, the theoretical transmission distance may be different depending on which direction the data is being transmitted. You will need to consider the Tx power and Rx sensitivity in both directions. In most cases, it is simpler to make sure that every wireless device in your network adheres to the same specifications for Tx power and Rx sensitivity.

Receiver Minimum Input Level Sensitivity					
Modulation	Rate (R)	Adjacent Channel Rejection (dB)	Nonadjacent Channel Rejection (dB)	Minimum Sensitivity (20 MHz channel spacing) (dBm)	Minimum Sensitivity (40 MHz channel spacing) (dBm)
BPSK	1/2	16	32	-82	-79
QPSK	1/2	13	29	-79	-76
QPSK	3/4	11	27	-77	-74
16-QAM	1/2	8	24	-74	-71
16-QAM	3/4	4	20	-70	-67
64-QAM	2/3	0	16	-66	-63
64-QAM	3/4	-1	15	-65	-62
64-QAM	5/6	-2	14	-64	-61

Figure 8 - Receive Sensitivity

Modulation Coding Schemes (MCS) and Data Rates

Modulation Coding Schemes, Data Rates & RSSI									
				Data Rate (Mbps)					
				20 MHz Channel Width			40 MHz Channel Width		
MCS Index	Spatial Streams	Modulation Type	Coding Rate	800ns Guard Interval	400ns Guard Interval	Min. RSSI Sensitivity (dBm)	800ns Guard Interval	400ns Guard Interval	Min RSSI Sensitivity (dBm)
0	1	BPSK	1/2	6.50	7.20	-82	13.50	15.00	-79
1	1	QPSK	1/2	13.00	14.40	-79	27.00	30.00	-76
2	1	QPSK	3/4	19.50	21.70	-77	40.50	45.00	-74
3	1	16-QAM	1/2	26.00	28.90	-74	54.00	60.00	-71
4	1	16-QAM	3/4	39.00	43.30	-70	81.00	90.00	-67
5	1	64-QAM	2/3	52.00	57.80	-66	108.00	120.00	-63
6	1	64-QAM	3/4	58.50	65.00	-65	121.50	135.00	-62
7	1	64-QAM	5/6	65.00	72.20	-64	135.00	150.00	-61
8	2	BPSK	1/2	13.00	14.40	-82	27.00	30.00	-79
9	2	QPSK	1/2	26.00	28.90	-79	54.00	60.00	-76
10	2	QPSK	3/4	39.00	43.30	-77	81.00	90.00	-74
11	2	16-QAM	1/2	52.00	57.80	-74	108.00	120.00	-71
12	2	16-QAM	3/4	78.00	86.70	-70	162.00	180.00	-67
13	2	64-QAM	2/3	104.00	115.60	-66	216.00	240.00	-63
14	2	64-QAM	3/4	117.00	130.00	-65	243.00	270.00	-62
15	2	64-QAM	5/6	130.00	144.40	-64	270.00	300.00	-61
2 Streams Shown			3 Stream = 450M max			4 Streams = 600M max			

Figure 5: Data Rates Based on 1 or 2 Spatial Streams

Example 1: Wi-Fi 802.11n

- An IoT device uses 802.11n Wi-Fi to connect to a router which is 300 m away. It uses a single stream 20 MHz channel in the 2.4 GHz band. Its Tx High Power Amplifier (HPA) outputs 100 mW and it is equipped with an omnidirectional antenna of 0 dBi:
  - What is the connectivity data rate and the link margin for a Line of Sight (LOS) situation?
  - What is the connection data rate and the link margin when the signal goes through a concrete wall which introduces 10 dB attenuation?
- Note that the router is equipped with a 0 dBi antenna and the possible 802.11n modulation options are given.

Answer:

		LOS	Wall
Tx HPA	mW	100	100
Tx HPA	dBm	20	20
Tx Antenna Gain	dBi	0	0
Tx EIRP	dBm	20	20
Distance	km	0.3	0.3
Band	GHz	2.4	2.4
Free Path Loss	dB	89.6	89.6
Wall attenuation	dB	0	10
Rx Antenna Gain	dBi	0	0
Rx Power	dBm	-69.6	-79.6
Rx sensitivity required	dBm	-74	-82
Rx Data rate	Mbps	28.9	7.2
Link Margin	dB	4.4	2.4

The path loss: $\boldsymbol{Lp\text{(dB)} = 20\log(d_{km}) + 20\log(f_{GHz}) + 92.45}$

Rx power: $\boldsymbol{Pr = Pt + Gt + Gr - Lp = EIRP + Gr - Lp}$

Using figure 5 from 802.11n standard

Example 2: Wi-Fi 802.11n

- An IoT device uses 802.11n Wi-Fi to connect to a router. It uses a single stream 20 MHz channel in the 2.4 GHz band. Its Tx HPA outputs 100 mW and it is equipped with an omnidirectional antenna of 0 dBi. The required radio link margin is 10dB and the data rate is 43.3 Mbps for a Line of Sight (LOS) situation.
- What is the most suitable modulation and coding for this scenario? What is the required sensitivity level?
- Calculate the maximum operating range in meters (i.e. how far away from the router the IoT device is)

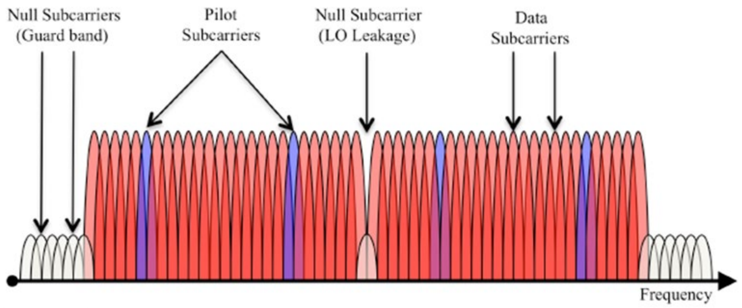
Example 2: Wi-Fi 802.11n - solution

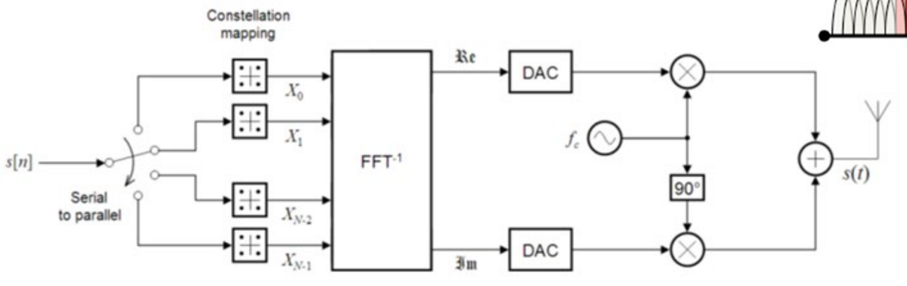
Reading From Figure 5:

- For 43.3 Mbps the modulation is 16-QAM with coding rate ¾
- Rx sensitivity of -70 dBm
- The link budget is recalculated backwards to identify the only unknown being 'Distance' which is calculated as 100 meters

		LOS
Tx HPA	mW	100
Tx HPA	dBm	20
Tx Antenna Gain	dBi	0
Tx EIRP	dBm	20
Distance	km	0.1
Band	GHz	2.4
Free Path Loss	dB	80.0
Wall attenuation	dB	0
Rx Antenna Gain	dBi	0
Rx Power	dBm	-60.0
Rx sensitivity required	dBm	-70
Rx Data rate	Mbps	43.3
Link Margin	dB	10.0

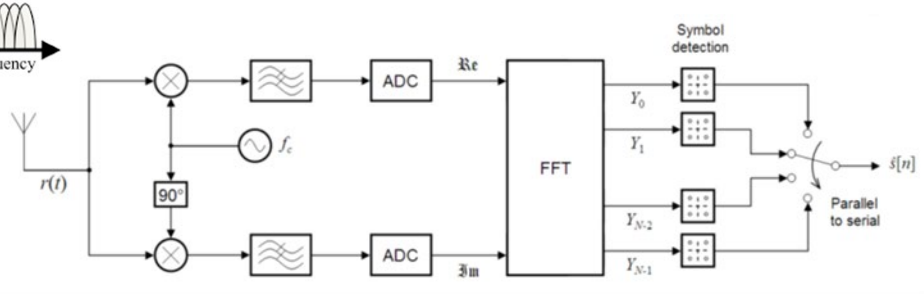
Wi-Fi 802.11n OFDM Transmitter, Receiver and Subcarriers in the Frequency Domain





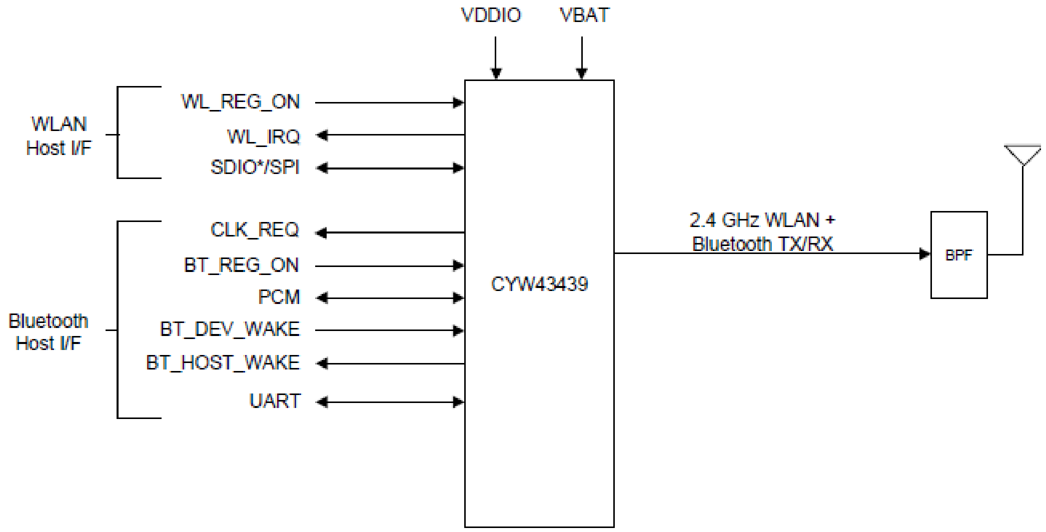
OFDM Transmitter

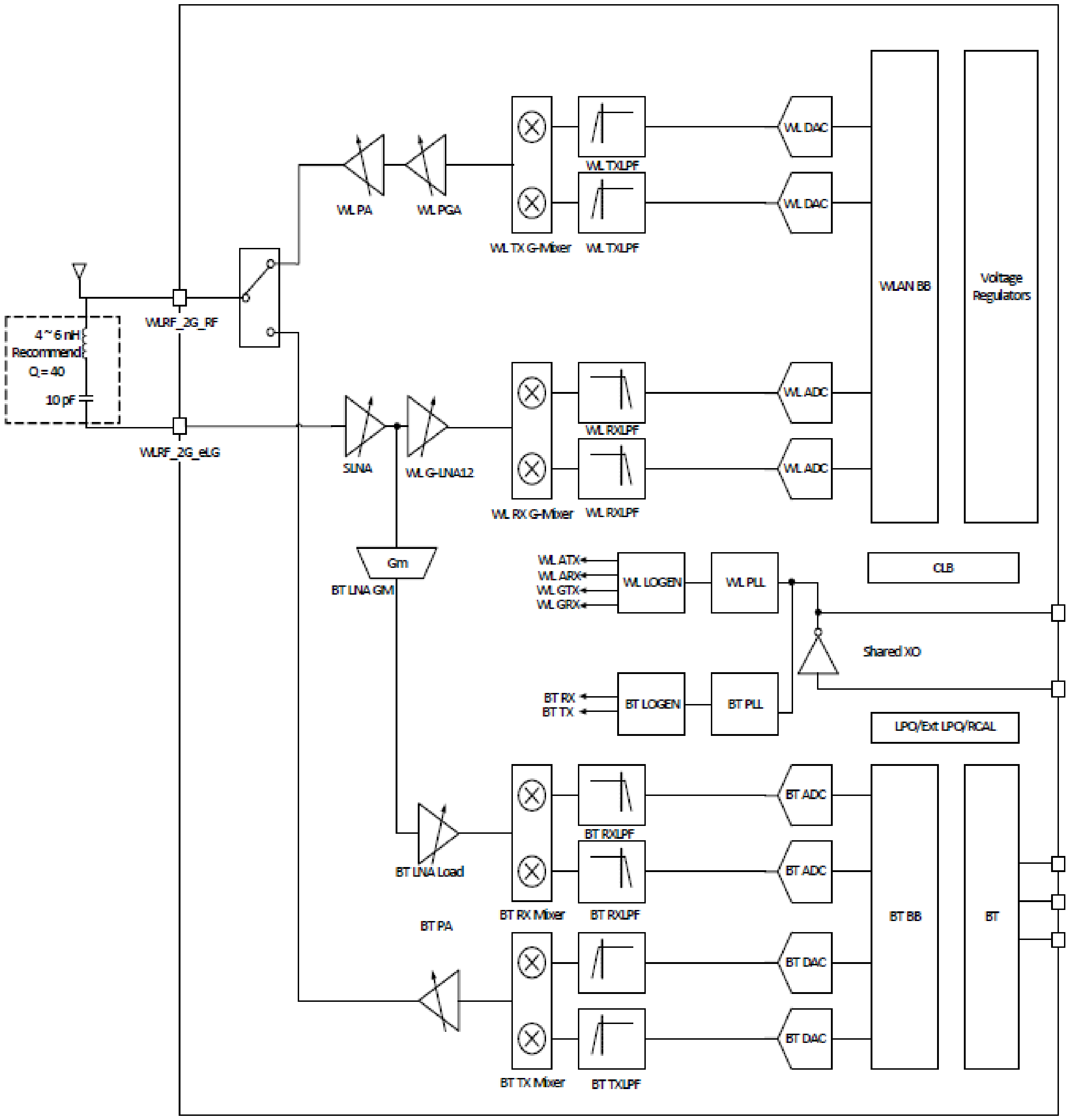
OFDM Spectrum



OFDM Receiver

Wi-Fi and Bluetooth chip Connectivity and Radio





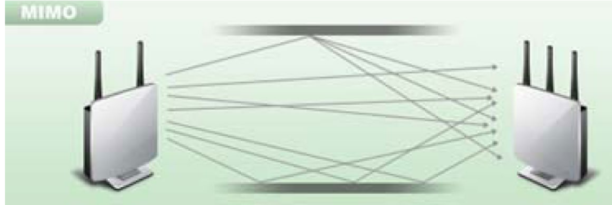
Wi-Fi 802.11n OFDM Data Rate Calculation one Transmit and one Receive Antenna

- Example of 802.11n over 20 MHz at 2.4 GHz:
  - Symbol duration 3.6 μs or 277.7ksps
- FFT size of 64 subcarriers:
  - 52 are Data, 4 are Pilots, 8 zeros for Guard band
- Data rate calculation for 16QAM(=4 b/symbol) modulation and coding rate of R=3/4:
  - $(52*4*3/4)/(3.6*10^{-6})$ = 43.3 Mbps in Single Input Single Output (SISO)
  - Rx sensitivity -70dBm
- Max data rate is achieved using:
  - 64QAM(=6 b/symbol) modulation with coding rate of R=5/6
  - $(52*6*5/6)/(3.6*10^{-6})$ = 72.2 Mbps in SISO
  - Rx sensitivity -64dBm
- **SISO Max Data Rate = $(Data\ Carriers \times Bits\ per\ Symbol \times Coding\ Rate)\ /\ Symbol\ Duration$**

Multiple In Multiple Out (MIMO)

- 802.11n allows to receive and/or transmit simultaneously through multiple antennas. It defines many “M x N” antenna configurations, ranging from “1 x 1” to “4 x 4”. This refers to the number of transmit (M) and receive (N) antennas, examples:
  - An AP with two transmit and three receive antennas is a “2 x 3” MIMO device.
  - An AP with one transmit and one receive antennas is a “1 x 1” Single In Single Out (SISO) device.
- Multiple antennas do not by themselves increase data rate or range. Those improvements come from how the MIMO device actually uses its multiple antennas

Spatial Multiplexing



- Spatial Multiplexing (SM) subdivides an outgoing signal stream into multiple pieces, transmitted through different antennas. Because each transmission propagates along a different path, those pieces – called spatial streams – arrive with different strengths and delays.
- Provided the individual streams arrive at the receiver with sufficiently distinct spatial signatures, an SM enabled receiver can reassemble them back into the original signal stream. Multiplexing two spatial streams onto a single channel (radio frequency) effectively doubles capacity and thus maximizes data rate.
- All 802.11n APs must implement at least two spatial streams, up to a maximum of four 802.11n terminals can implement as few as one spatial stream.
- **Max Data Rate = (**$Spatial\ Streams \times Data\ Carriers \times Bits\ per\ Symbol \times Code\ Rate$**) /** $Symbol\ Duration$

Wi-Fi 802.11n OFDM Data Rate Calculation with four Transmit and four Receive Antenna (4x4)

- Example of 802.11n over 20 MHz at 2.4 GHz with 4x4 MIMO:
  - Up to 4 Spatial Streams
  - Symbol duration 3.6 µs or 277.7ksps
- FFT size of 64 subcarriers:
  - 52 are Data, 4 are Pilots, 8 zeros Guard band
- With 16QAM(=4 b/symbol) and R=3/4:
  - (4*52*4*3/4)/3.6E-6 = 173.2 Mbps with 4x4 MIMO
  - Rx sensitivity -70dBm
- Max data rate is achieved using:
  - 64QAM(=6 b/symbol) with R=5/6
  - (4*52*6*5/6)/3.6E-6 = 288.8 Mbps with 4x4 MIMO
  - Rx sensitivity -64dBm
- Max Data Rate = $(Spatial\ Streams \times Data\ Carriers \times Bits\ per\ Symbol \times Code\ Rate) / Symbol\ Duration$

Wi-Fi 802.11n OFDM Data Rate Calculation at 5 GHz over 40 MHz channels

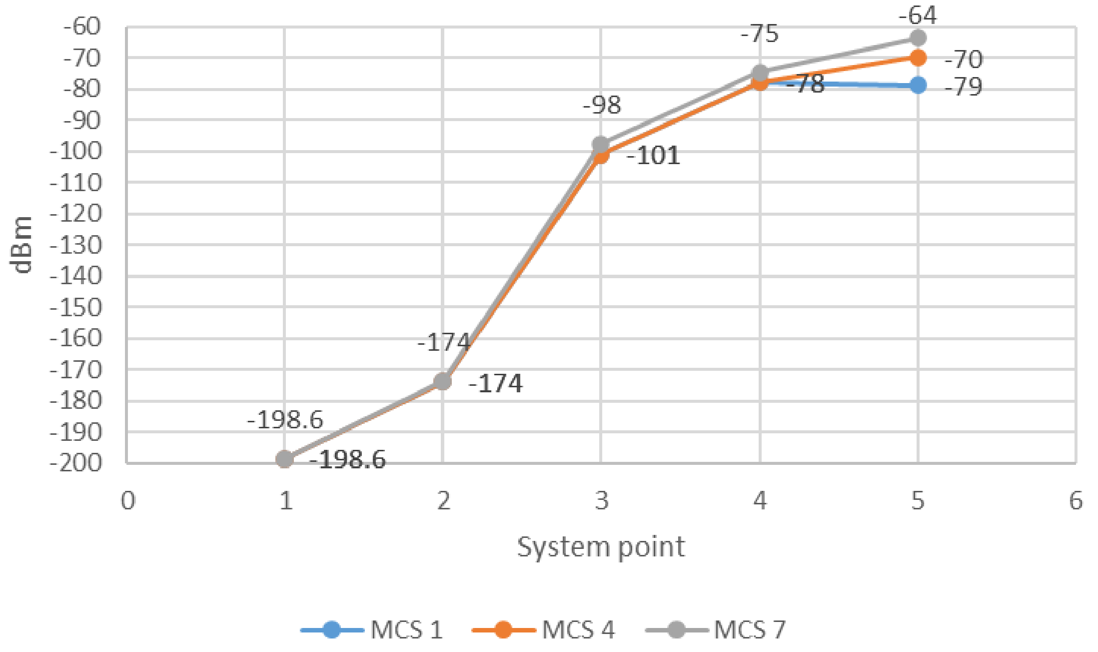
- Example of 802.11n over 40 MHz at 5 GHz with 4x4 MIMO:
  - Up to 4 Spatial Streams
  - Symbol duration 3.6 µs or 277.7ksps
- FFT size of 128 subcarriers:
  - 108 are Data, 8 are Pilots, 12 zeros Guard band
- With 16QAM(=4 b/symbol) and R=3/4:
  - (4*108*4*3/4)/3.6E-6 = 360 Mbps with 4x4 MIMO
  - Rx sensitivity -67 dBm
- Max data rate is achieved using:
  - 64QAM(=6 b/symbol) with R=5/6
  - (4*108*6*5/6)/3.6E-6 = 600 Mbps with 4x4 MIMO
  - Rx sensitivity -61 dBm
- Max Data Rate = $(Spatial\ Streams \times Data\ Carriers \times Bits\ per\ Symbol \times Code\ Rate)\ /\ Symbol\ Duration$

Receiver Sensitivity

- Receiver sensitivity is like hearing of humans.
- Higher receiver sensitivity enables a receiver with higher capability to capture weak signals. If the signal strength is lower than receiver sensitivity, the receiver will not receive correct data.
- Receiver sensitivity refers to the minimum signal received power on an antenna port for receivers to accurately decode a given signal:
  - **S = 10log(kTB) + NF + SNR** denotes the receiver sensitivity S, in dBm.
- A smaller value indicates better performance of the receiver. A larger value indicates lower performance of the receiver.
  - k: Boltzmann constant = $1.38*10^{-23}$, in J/K
  - T: (=273C+20C) temperature, in K. As the temperature increases, receiver sensitivity increases degrading receiver performance. Therefore, decrease the ambient temperature as much as possible.
  - B: signal bandwidth, in Hz. Higher signal bandwidth represents a larger NF, higher receiver sensitivity, and therefore lower receiver performance.
  - kTB: thermal noise power within the bandwidth range, in Watts.
  - NF: Receiver noise figure (=SNRout-SNRin), in dB.
  - SNR: signal-to-noise ratio required for correctly decoding the data, in dB.

Wi-Fi 802.11n Receiver Sensitivity

Operational case				
MCS Index	Index	MCS 1	MCS 4	MCS 7
Channel bandwidth	MHz	20.0	20.0	40.0
Noise calculation				
k	dB(W/K/Hz)	-228.6	-228.6	-228.6
T	C	20.0	20.0	40.0
kT	dB(mW/Hz)	-174.0	-174.0	-174.0
Rx Noise	dBm	-101.0	-101.0	-98.0
Rx NF	dB	23.0	23.0	23.0
Noise before FEC	dBm	-78.0	-78.0	-75.0
Rx sensitivity calculation				
Modulation index	QAM	4	16	64
Efficiency	bit/symbol	2	4	6
FEC coding rate	R	0.5	0.75	0.83
SNR requirement	dB	-1.0	8.0	11.0
Rx Sensitivity	dBm	-79.0	-70.0	-64.0
Data throughtput calculation				
OFDM data subcarriers	N	52	52	108
OFDM symbol duration	ns	3.6	3.6	3.6
Data rate	Mbps	14.4	43.3	150



Plot	Point	dBm	dBm	dBm
Noise density at 0 deg K	1	-198.6	-198.6	-198.6
Noise density at 20 deg C	2	-174	-174	-174
Noise power over Bdw	3	-101	-101	-98
Noise power before FEC	4	-78	-78	-75
Min signal power for no errors	5	-79	-70	-64