IEEE 802.15.4

Low-Rate Wireless Networks

: PHY Layer

2011 version: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6012487
2015 version: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7460875
2020 version: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9144691

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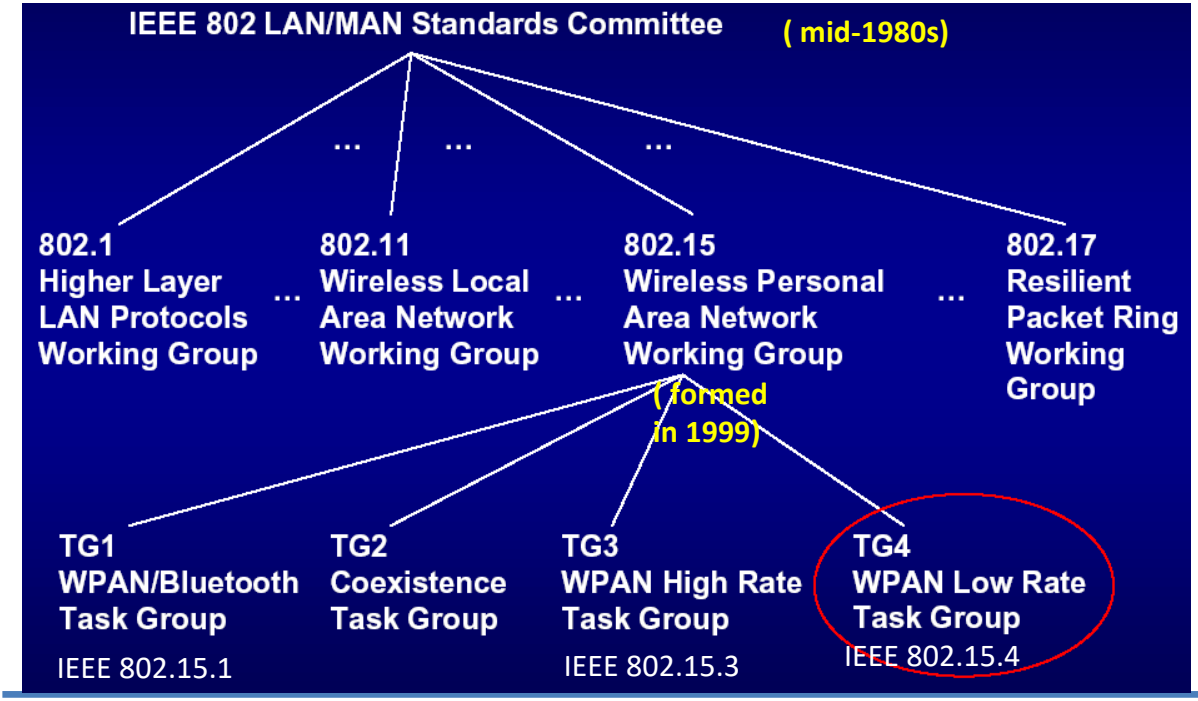
IEEE 802.15 Working Group

- IEEE 802.11 was concerned with features like
  - Ethernet like speed
  - Medium range (~100 m) communication
  - Seamless roaming
  - Less complex message forwarding
  - Data throughput ~ 2-11 Mbps

- IEEE 802.15 are focused to
  - Short range
    - space around a person or a object (~ 10 m)
  - Low cost
  - Low power
  - Very small packet size



IEEE 802.15 working group mainly defines three standards:

1. High data rate WPAN
   - IEEE 802.15.3
   - e.g. for multimedia applications
2. Medium rate WPAN
   - IEEE 802.15.1 / Bluetooth
   - e.g. for device to device communication
3. Low rate WPAN
   - IEEE 802.15.4
   - e.g. relaxed data rate, and battery powered device

IEEE 802.15 - Task Group 4

- Task Group 4 (TG4) was formed to define
  - low-data-rate PHY and MAC layer specifications for wireless personal area networks (WPAN)

- WPAN work group (WG) plans to have the following:
  - span in a small area
    - e.g., a private home, an individual workspace
  - short distance communication
  - low-powered communication
    - e.g. lifetime must be few months or years
  - primarily uses ad-hoc networking
  - Generally wireless; could be wired
  - Intended to serve industrial, residential and medical applications

IEEE 802.15.4 LR-WPAN

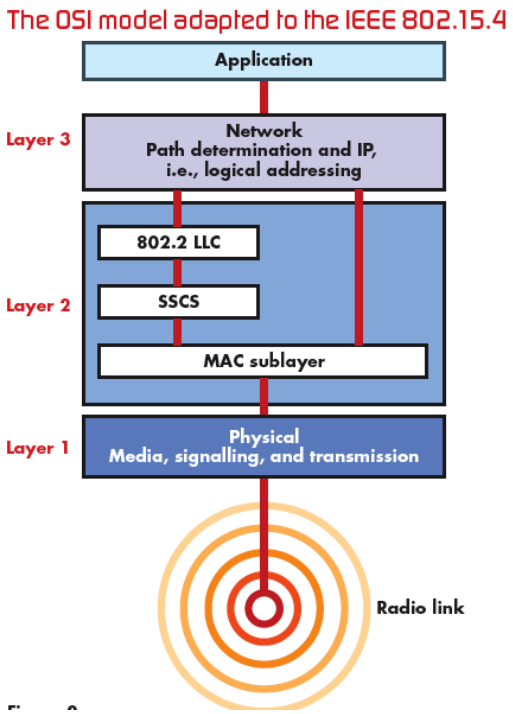
- Low-rate WPAN (LR-WPAN)
- It is a
  - ✓ simple,
  - ✓ low-cost communication network
  - ✓ that allows wireless connectivity in applications
  - ✓ with limited power and
  - ✓ relaxed throughput requirements.

- Standard has evolved over time:
  - ➢ IEEE 802.15.4-2003
  - ➢ IEEE 802.15.4-2006
  - ➢ IEEE 802.15.4-2011
  - ➢ IEEE 802.15.4-2015
  - ➢ IEEE 802.15.4-2020

- Few important features of an LR-WPAN are
  - ✓ ease of installation,
  - ✓ reliable data transfer,
  - ✓ extremely low cost,
  - ✓ a reasonable battery life,
    - ✓ while maintaining a simple and flexible protocol.

Reference: IEEE Std 802.15.4™-2020, "IEEE Standard for **Low-Rate Wireless Networks**",
Developed by the LAN/MAN Standards Committee of the IEEE Computer Society, Approved on 6 May 2020.

IEEE 802.15.4 Stack – PHY & MAC



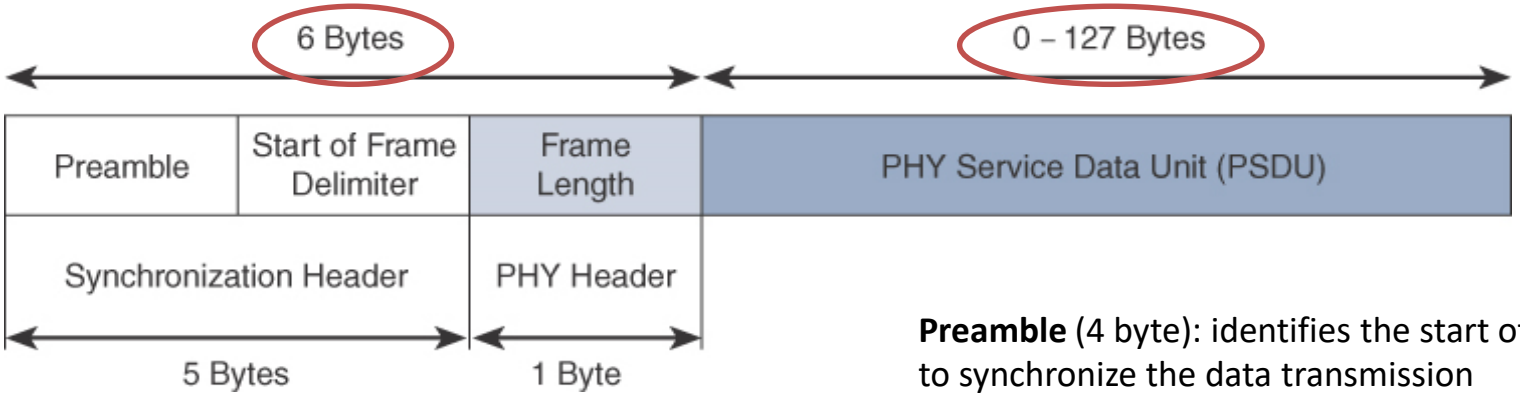
LLC: Logical Link Control – provides protocol multiplexing
SSCS: Service Specific Convergence Sublayer

- IEEE 802.15.4 standard is limited to the **PHY & MAC** Layers
- IEEE 802.15.4 standard PHY provides the PHY data service and PHY management services:
  - The **PHY data service** enables the transmission and reception of PHY protocol data units (PPDU) across the physical radio channel.
  - The **PHY's features** include
    - radio transceiver activation/deactivation,
    - radio channel selection,
    - energy level detection (ED) ,
    - received signal quality (RSI) or link quality indicator (LQI),
    - clear channel assessment (CCA),
    - channel selection
    - transmitting and receiving packets in 2.4-GHz band.

Image Source: https://www.embedded.com/ieee-802-15-4-zigbee-hardware-and-software-open-the-applications-window/

IEEE 802.15.4 PHY

IEEE 802.15.4 PHY Layer



IEEE 802.15.4 PHY Frame Format

Preamble (4 byte): identifies the start of the frame; used to synchronize the data transmission

SFD (1 byte): informs the receiver about the starting point of frame content. It shall be formatted as "1110 0101"

PHY functionalities:

- Activation & deactivation of the radio transceiver
- Energy level detection (ED) within the current channel

- Link quality indication (LQI) or received signal quality (RSI) for received packets
- Clear channel assessment (CCA) for CSMA-CA

- Channel frequency selection
- Data packet transmission and reception at given frequency

Spectrum

- Federal Communications of Commissions (FCC) in USA decides frequency bands
- Applications using ISM band do not require a licence for stations emitting less than 1W.

FCC Band	Max. Transmit Power	Frequencies
Industrial Band	< 1 W	902 MHz – 928 M Hz
Scientific Band	< 1 W	2.4 GHz – 2.48 GHz
Medical Band	< 1 W	5.725 GHz – 5.85 GHz
U-NII (Unlicensed National Information Infrastructure)	< 40 mW	5.15 GHz – 5.25 GHz
	< 200 mW	5.25 GHz – 5.35 GHz
	< 800 mW	5.725 GHz – 5.82 GHz

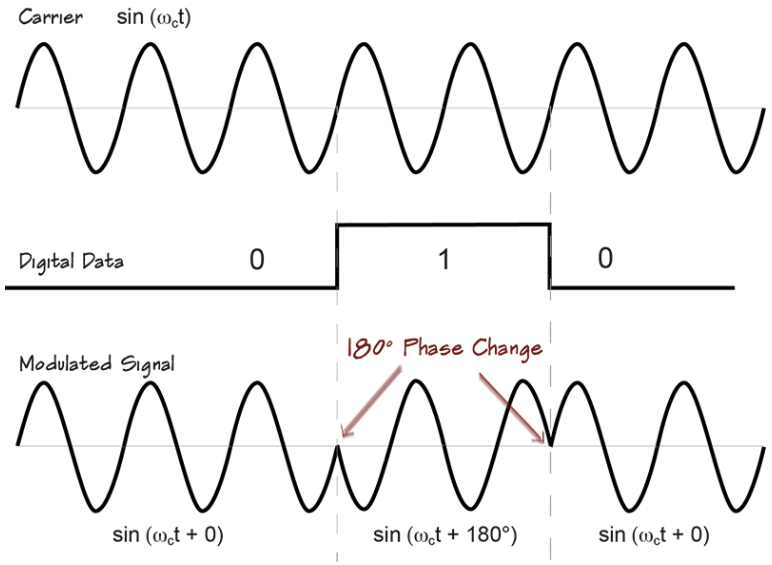
- Physical layer transmission options in IEEE 802.15.4-2015
  - **2.4 GHz**, 16 channels, data rate 250 kbps - (This is primary)
  - **915 MHz**, 10 channels, data rate 250 kbps
  - **868 MHz**, 3 channel, data rate 100 kbps

Modulation

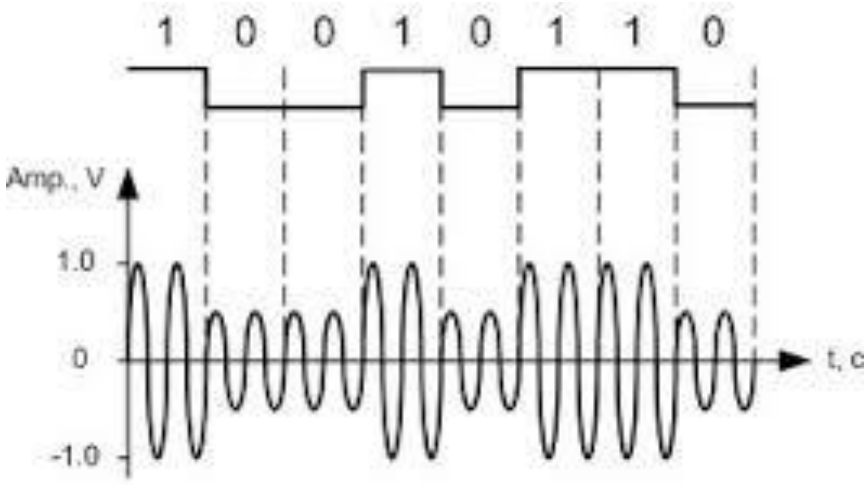
Modulation is the process by which some characteristic of a carrier wave is varied in accordance with an information/ modulating signal.

Modulation schemes

- **OQPSK PHY :** DSSS PHY employing Offset Quadrature Phase-Shift Keying (OQPSK) – This is Primary Scheme
- **BPSK PHY :** DSSS PHY employing binary phase-shift keying (BPSK)
- **ASK PHY :** PSSS PHY employing Amplitude Shift Keying (ASK) and BPSK



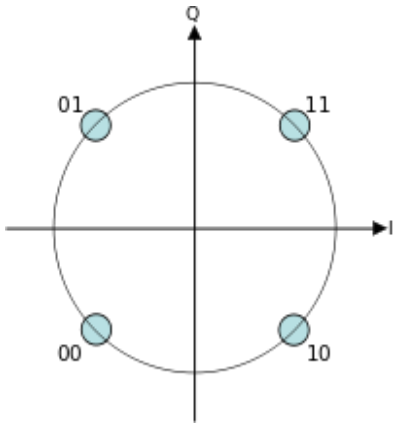
Binary Phase-Shift Keying (BPSK)



Amplitude Shift Keying (ASK)

QPSK

Bit number	1	2	3	4	5	6	7	8	9	10
value	1	−1	1	1	−1	−1	−1	1	1	1
	I	Q	I	Q	I	Q	I	Q	I	Q
Input signal										
In-phase $I(t)$	1		3		5		7		9	
quadrature phase $Q(t)$	2		4		6		8		10	
Phase of output signal	$-\pi/4$		$\pi/4$		$-3\pi/4$		$3\pi/4$		$\pi/4$	



Constellation diagram for QPSK

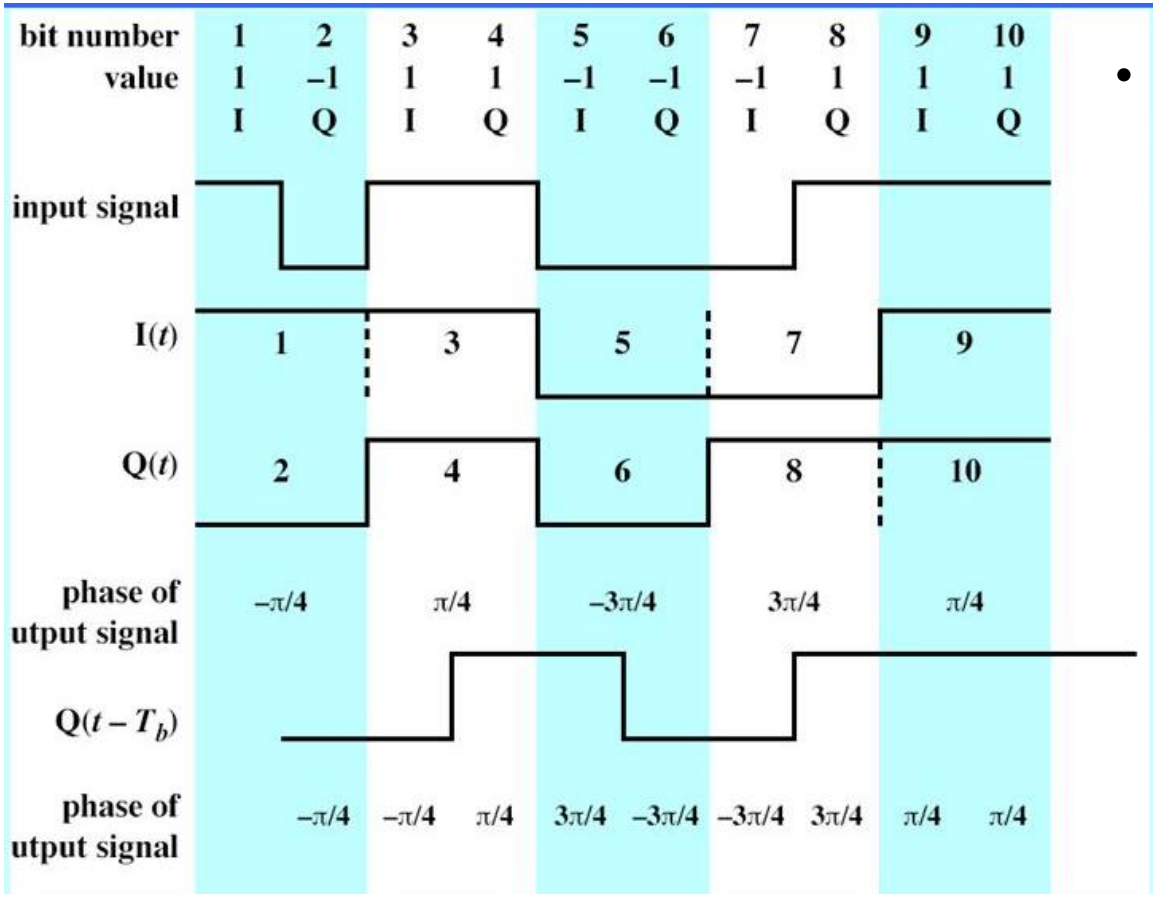
Quadrature Phase-Shift Keying (QPSK)

- More efficient use of bandwidth
  - as each signalling element represents more than one bit.

$$\text{QPSK} \quad s(t) = \begin{cases} A\cos\left(2\pi f_c t + \frac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \frac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \frac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \frac{\pi}{4}\right) & 10 \end{cases}$$

Orthogonal QPSK

- Problem in QPSK: large phase shift at high transition rate is difficult to perform. Phase shift is 180° in QPSK.

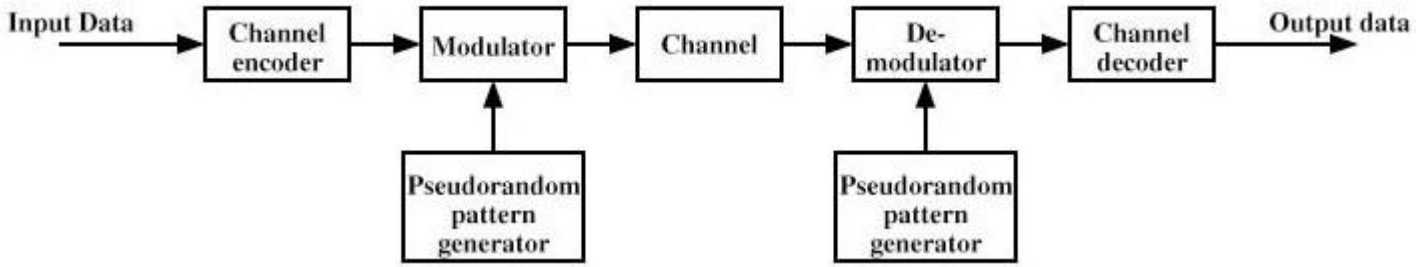


- OQPSK
  - ✓ a variation of QPSK known as offset QPSK or orthogonal QPSK
  - ✓ a delay of one bit time is introduced in the Q stream of QPSK
  - ✓ Its spectral characteristics and bit-error performance are the same as that of QPSK
  - ✓ at any time the phase change in the combined signal never exceeds 90° (π/2)

Spread Spectrum

Spread Spectrum is a method of spreading a transmitted spectrum over a wide bandwidth, so that the energy at any particular frequency is not detectable without special foreknowledge of the spreading technique.

- Spread-spectrum transmission offers many advantages over a fixed-frequency transmission.
  - Spread-spectrum signals are highly resistant to narrow band interference
  - Signals are difficult to intercept, so immune to jamming
- **Types**:
  - direct sequence spread spectrum (**DSSS**)
  - frequency hopping spread spectrum (**FHSS**)



Cont…

- Pseudorandom numbers
  - generated by an algorithm using some initial value called the seed
  - produce sequences of numbers that are not statistically random, but passes reasonable tests of randomness
  - unless you know the algorithm and the seed, it is impractical to predict the sequence

- **Gain from** this **apparent waste of spectrum**
  - The signals gains immunity from various kinds of noise and multipath distortion.
  - Immune to jamming attack
  - It can also be used for hiding and encrypting signals.
  - Several users can independently use the same higher bandwidth with very little interference. (e.g. CDMA)

DSSS

- each bit in the original signal is represented by multiple bits in the transmitted signal, using a spreading code
- spreading code spreads the signal across a wider frequency band in direct proportion to the number of bits used

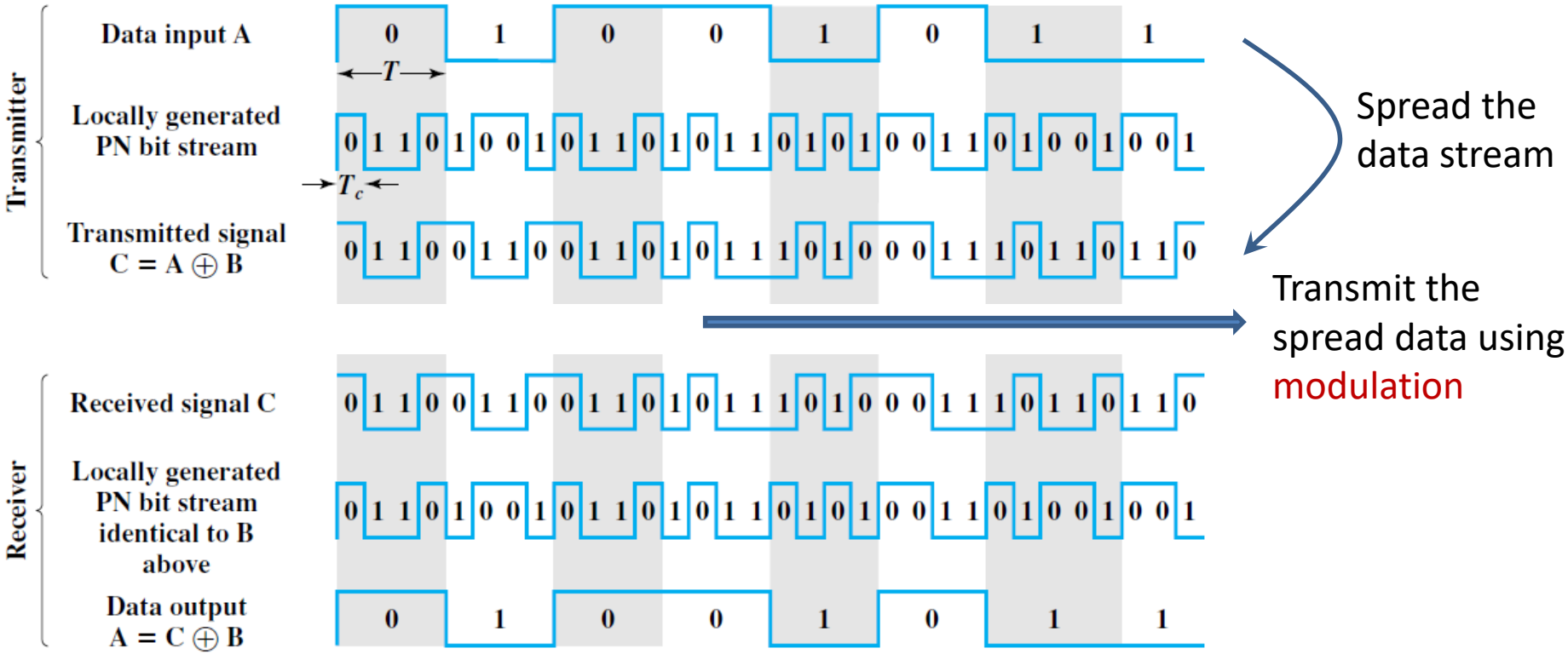
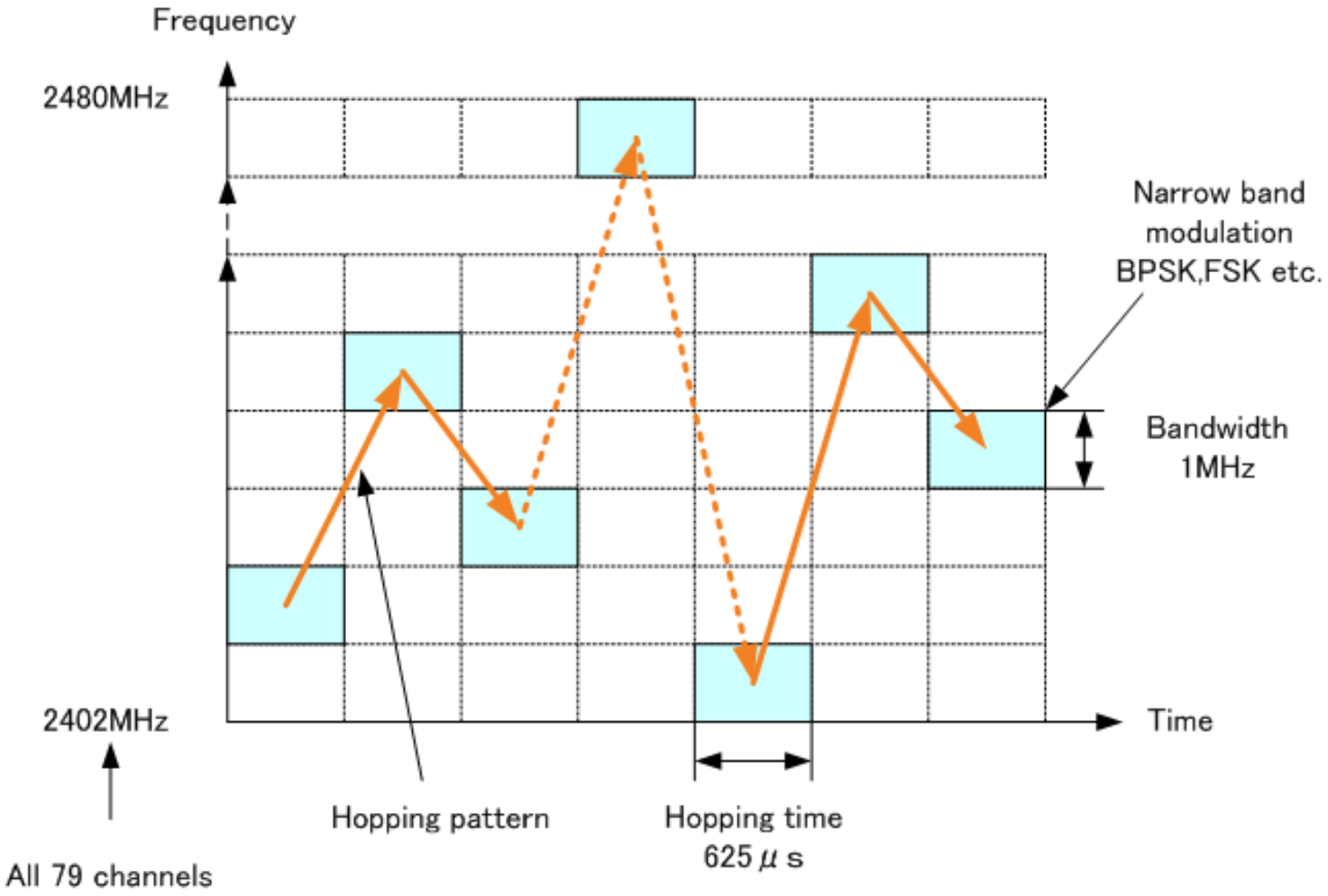
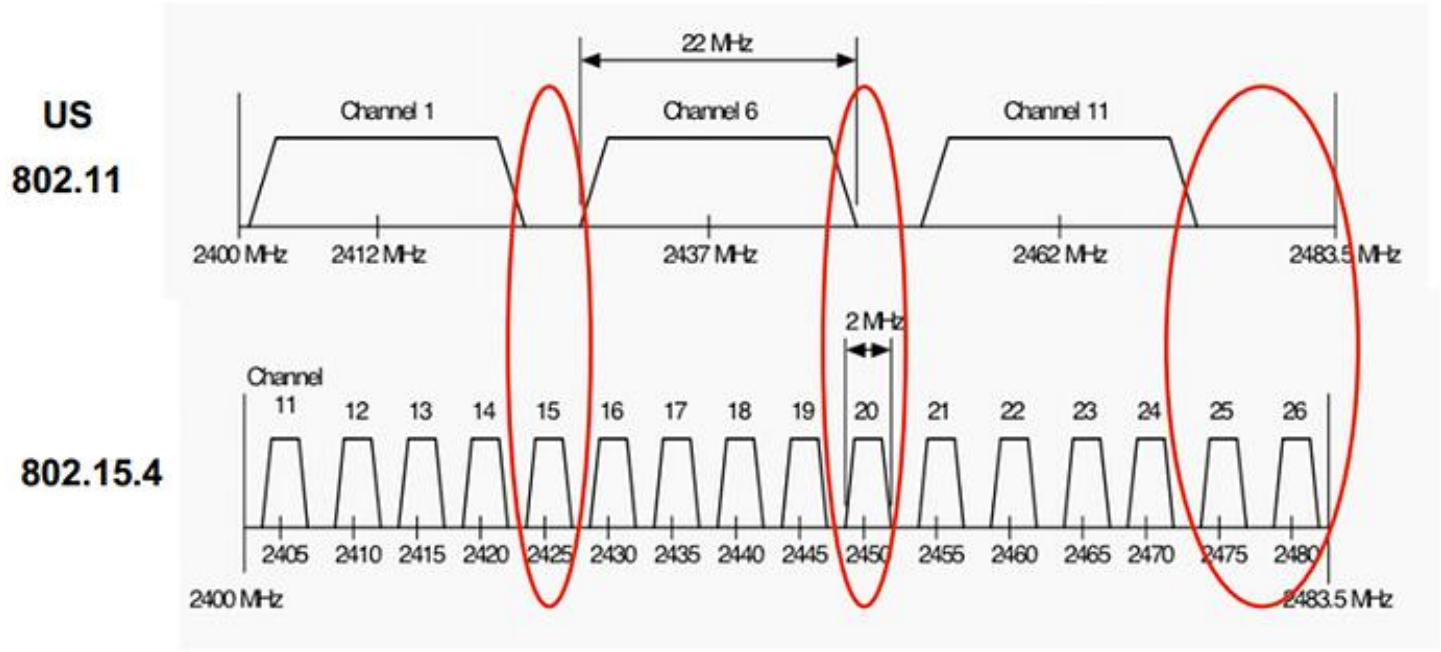


Figure 9.6 Example of Direct Sequence Spread Spectrum

FHSS


Frequency
2480MHz
Narrow band
modulation
BPSK,FSK etc.
Bandwidth
1MHz
2402MHz
Time
Hopping pattern
Hopping time
625 μ s
All 79 channels

Other PHY Attributes



- IEEE 802.15.4 does not prefer to use frequency hopping to minimize energy consumption.
- To minimize interference in 2.4 GHz band, IEEE 802.15.4 prefer channel no. 15, 20, 25, 26

- Transmission power is adjustable from 0.5 mW (min. in 802.1.5.4) to 1 W (max. in ISM band)
- Transmission power 1 mW provides theoretical distances as:
  - Outdoor range 300 m.
  - Indoor range 100 m.

Cont…

- 802.15.4 **PHY** provides energy detection (ED) feature
  - Application can request to asses each channel's energy level
  - It is an estimate of the received signal power within the bandwidth of the channel
  - Coordinator can make optimal selection of channel based on channels energy level

- 802.15.4 **PHY** provides link quality information (LQI) to **NET and APP layers**
  - The LQI measurement is a characterization of the strength and/or quality of a received packet.
  - The measurement may be implemented using
    i. receiver ED
    ii. signal-to-noise ratio (SNR) estimation, or
    iii. combination of the above methods.
  - Transmitter may decide to use high transmission power based on LQI
  - Applications may dynamically change 802.15.4 channels based on LQI

- 802.15.4 uses **CSMA/CA** which ask the PHY layer to do CCA
  - Clear Channel Assessment (CCA) is performed by any one of the below methods:
    - Energy above ED threshold regardless of modulation
    - Carrier sense only (i.e. based on the detection of a signal with modulation and spreading characteristics)
    - Combination of both the above

Lessons Learned

- ✓ What is IEEE 802.15.4
  - Introduction to IEEE 802.15 WG
  - Genesis of LR-WPAN

- ✓ IEEE 802.15.4. PHY
  - Functionalities
  - Modulation: QPSK, OQPSK
  - Spread Spectrum: DSSS, FHSS

Thanks!

Figures and slide materials are taken from the following sources:

1. David Hanes *et al.*, “IoT Fundamentals: Networking Technologies, Protocols, and Use Cases for the Internet of Things”, 1st Edition, 2018, Pearson India.
2. Oliver Hersent et al., “The Internet of Things: Key Applications and Protocols”, 2018, Wiley India Pvt. Ltd.