AI/ML in Networking

Lecture 1: Overview of Wi-Fi

Francesc Wilhelmi (francisco.wilhelmi@upf.edu)

Università degli Studi di Cagliari

Overview

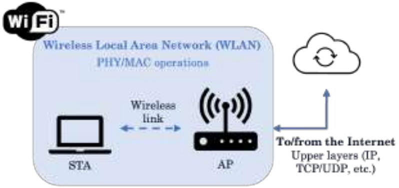
1. What is Wi-Fi?
2. Wi-Fi's PHY
3. Wi-Fi's MAC
4. Machine Learning & Wi-Fi

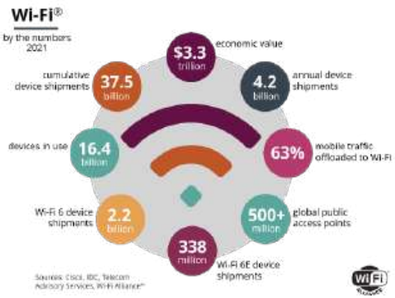
Outline

1. What is Wi-Fi?
2. Wi-Fi's PHY
3. Wi-Fi's MAC
4. Machine Learning & Wi-Fi

What is Wi-Fi?

- Wi-Fi is a wireless technology that offers local (LAN) connectivity to wireless devices (e.g., laptops, smartphones, game consoles, fridges).
- PHY & MAC protocols of Wi-Fi are defined by the IEEE 802.11 standard.
- Thanks to an integration with upper layer protocols (e.g., DHCP, DNS, NAT) and much more (e.g., WPA3), Wi-Fi has become one of the most popular wireless technologies for accessing the Internet.
- Wi-Fi ecosystem:
    - Standards development (IEEE, Wi-Fi Alliance, FCC, ETSI),
    - Device manufacturers (e.g., Nokia, Cisco, Netgear, TP-Link),
    - Chip makers (e.g., Qualcomm, Broadcom, Intel),
    - Antenna manufacturers (e.g., wireless instruments).





What the 802.11 defines?

PHY features

- Frequency bands, modulations, MIMO...

MAC features

- Channel access, fragmentation, resource allocation, QoS...

Management features

- Association/Authentication, roaming, encryption, Beaconing...

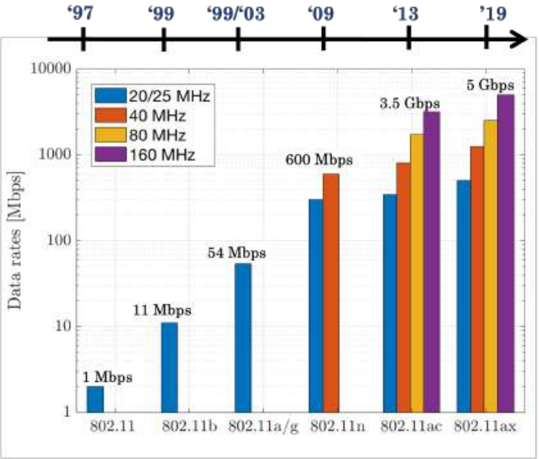
- A Basic Service Set (BSS) is a group of Wi-Fi devices that can communicate with each other.
- The BSSID (Basic Service Set Identifier) identifies a given BSS
- The Service Set Identifier (SSID) is the human name of a Wi-Fi network (e.g., “eduroam”)

A bit of perspective (Wi-Fi history)

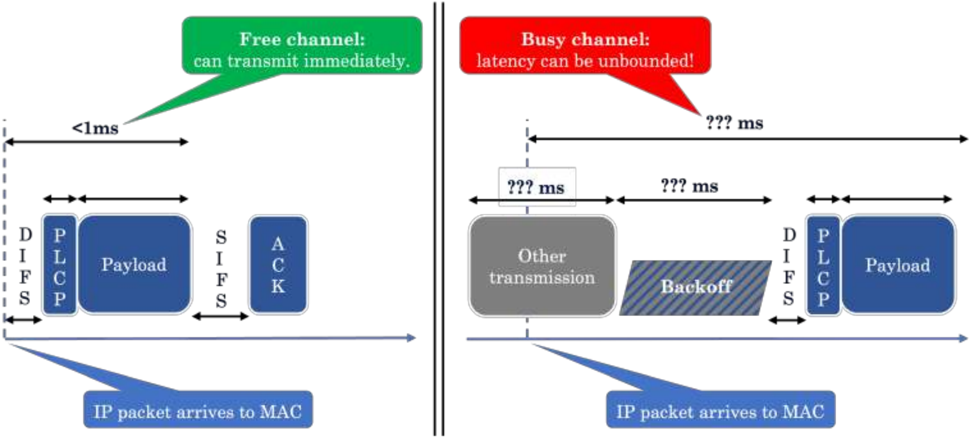
- 1970s: The ALOHA protocol was created at University of Hawaii.
- 1985: The FCC (US) first made spectrum in the ISM bands available for unlicensed usage.
- 1997: The first IEEE 802.11 standard was released.
- 1999: The Wi-Fi Alliance (formerly, WEC) was created.
- 2000s: 802.11a and 802.11g led to a fast adoption of Wi-Fi in laptop devices.
- 2010s: 802.11n (Wi-Fi 4) and 802.11ac (Wi-Fi 5) consolidated Wi-Fi with significantly high speeds.
- 2020s: 802.11ax (Wi-Fi 6) and 802.11be (Wi-Fi 7) made Wi-Fi even faster and also efficient.

What the 802.11 defines?

- 802.11n (Wi-Fi 4) [2.4 & 5 GHz]
  - Single-user MIMO
  - Packet aggregation
- 802.11ac (Wi-Fi 5) [5 GHz]
  - Multi-user MIMO (DL)
  - Channel bonding
- 802.11ax (Wi-Fi 6) [5 & 6 GHz]
  - OFDMA
  - Multi-user MIMO (UL)
- 802.11be (Wi-Fi 7) [2.4, 5 & 6 GHz]
  - Multi-link operation



Wi-Fi contention



Outline

1. What is Wi-Fi?
2. Wi-Fi's PHY
3. Wi-Fi's MAC
4. Machine Learning & Wi-Fi

Capacity of wireless channels

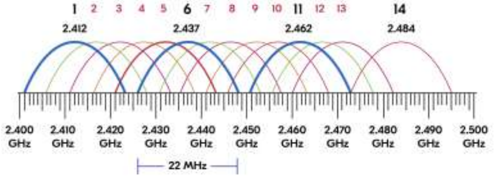
$$Capacity = Streams \times Bandwidth \times \log(1 + SNR)$$

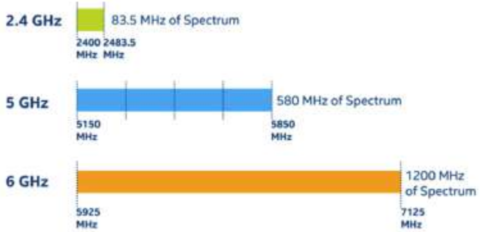
Shannon's capacity:

☐ Number of signals you can transmit simultaneously (MIMO)
☐ Available spectrum (subcarriers) to transmit the data (Channel bonding)
☐ Wireless link quality, allowing for better/worse RX sensitivity (MCS, beamforming, interference management)

Bandwidth (I)

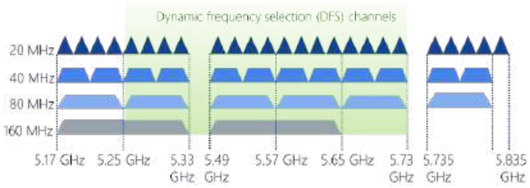
- Wi-Fi uses the unlicensed (licensed-exempt) spectrum (free of use)
- Most popular bands (WLAN usage):
    - 2.4 GHz,
    - 5 GHz,
    - and now 6 GHz
- Other bands:
    - 60 GHz (802.11ad, WiGig): very high transmission rates but very low coverage
    - 860/900 MHz (802.11ah, IoT)

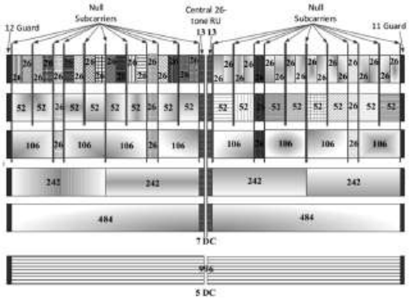




Bandwidth (II)

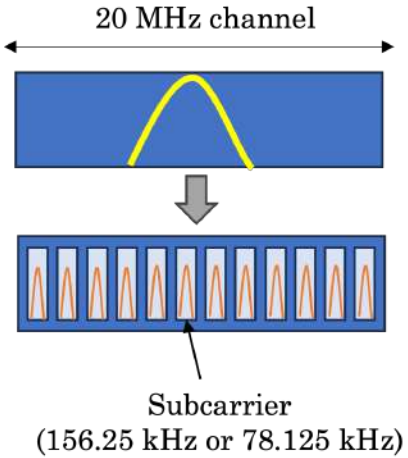
- The IEEE 802.11 standard defines the channels used for transmitting data
  - Each channel has a central frequency and a specific range.
    - e.g., Channel #1 in the 2.4 GHz band goes from 2401 GHz to 2423 GHz (20 MHz in total).
  - Multiple widths are possible: 20 MHz (basic channel), 40 MHz, 80 MHz, 160 MHz, and 320 MHz.
- Each channel contains a given number of subcarriers ("tone plan", next slide).





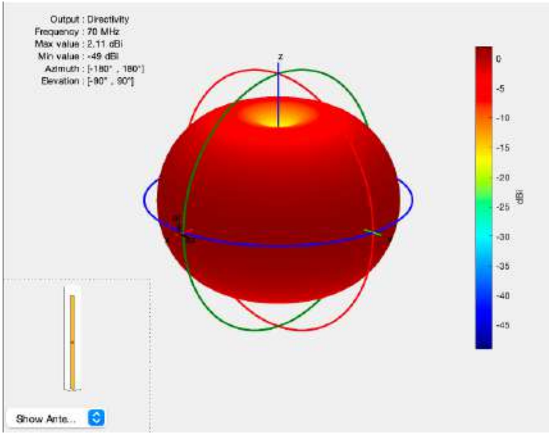
Bandwidth (III)

- OFDM (Orthogonal Frequency Division Multiplexing): The signal modulation technique used in Wi-Fi and other technologies like cellular (LTE/5G).
  - OFDM divides the channels into smaller pieces (subcarriers), which are transmitted all together in parallel.
  - Each subcarrier is used to transmit a symbol (e.g., through QAM).
  - OFDMA is the multi-user version of OFDM (i.e., it allows to assign different subcarriers to different users).



SNR (I)

- Transmission power (Ptx): Power fed to the antenna for radiating electromagnetic waves
  - Measured in W/mW or dBm
    - $P_{tx}[dBm] = 10\log_{10}(P_{tx}[mW])$
    - $P_{tx}[mW] = 10^{(P_{tx}[dBm])/10}$
    - Wi-Fi typically uses 100 mW to 1 W
- Power received (P_{rx}): Power received at the receiver antenna
  - Converted into an AC signal by an oscillator

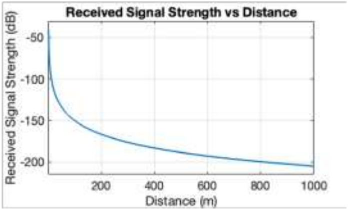


SNR (II)

- Path loss: A wireless signal loses strength as it travels to a receiver.

$$P_{rx}[dBm] = P_{tx}[dBm] - PL[dB]$$

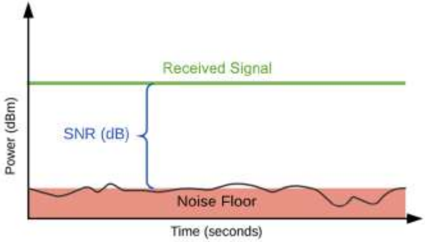
- Factors affecting the transmitted signal:
  - **Distance:** The farther the signal travels, the weaker it gets (free space path loss).
  - **Obstacles:** Objects (walls, trees, cars, people) can block or scatter the signal, making it weaker when it reaches the receiver.
  - **Environment:** Rain, fog, air pollution, etc. also absorb or scatter the signal.
- Well-known models are used to characterize the path loss in particular environments (e.g., log-distance path loss, Hata model, 3GPP Urban Macro (UMa) model for LTE/5G).




```
% Path loss versus distance
PL_d = 20*log10(distance) + 20*log10(f) -
147.55 + 10*n*log10(distance/d0);
% Power received
P_received = P_transmitted - PL_d;
```

SNR (III)

- SNR (Signal-to-Noise Ratio): Difference between the signal of interest and the ground noise.
  - Noise can be in the order of -90 dBm.
  - A high SNR allows detecting more granular symbols (with more data).
  - A low SNR leads to a high Bit Error Rate (BER) because the receiver cannot properly differentiate the symbols received.
  - SINR (Signal-to-Interference plus Noise Ratio) also includes interference from other devices.
  - Modulation and Coding Scheme (MCS): Depending on the SNR at the receiver, one MCS or another is used to keep the transmission error low.
  - Higher MCSs allow for transmitting more bits per symbol.
  - Short ranges favor the use of a high MCS
  - Lower MCSs provide less capacity but are more robust in the presence of noise.
  - Large ranges require the use of a low MCS.

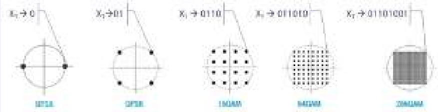


Signal to Noise Ratio	Excellent		Good		Poor	Very Poor
	24dB	18dB	12dB	6dB	0dB	-6dB
Speech Discrimination Score						
Normal Hearing	100%	100%	100%	90%	60%	10%
Impaired Hearing	90%	70%	50%	30%	5%	0%

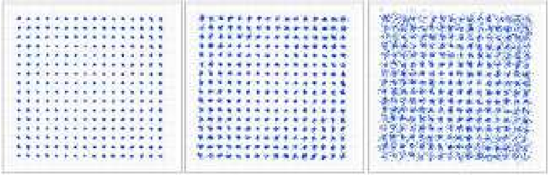
SNR (IV)

- Modulation and Coding Scheme (MCS):
  - Depending on the SNR at the receiver, one MCS or another is used to keep the transmission error low.
  - Higher MCSs allow for transmitting more bits per symbol (short ranges favor the use of a high MCS)
  - Lower MCSs provide less capacity but are more robust in the presence of noise (large ranges require the use of a low MCS).

MCS	Modulation	Rate	Minimum Sensitivity [dBm]			
			20 MHz	40 MHz	80 MHz	160 MHz
0	BPSK	1/2	-82	-79	-76	-73
1	QPSK	1/2	-79	-76	-73	-70
2	QPSK	3/4	-77	-74	-71	-68
3	16-QAM	1/2	-74	-71	-68	-65
4	16-QAM	3/4	-70	-67	-64	-61
5	64-QAM	2/3	-66	-63	-60	-57
6	64-QAM	3/4	-65	-62	-59	-56
7	64-QAM	5/6	-64	-61	-58	-55
8	256-QAM	3/4	-59	-56	-53	-50
9	256-QAM	5/6	-57	-54	-51	-48



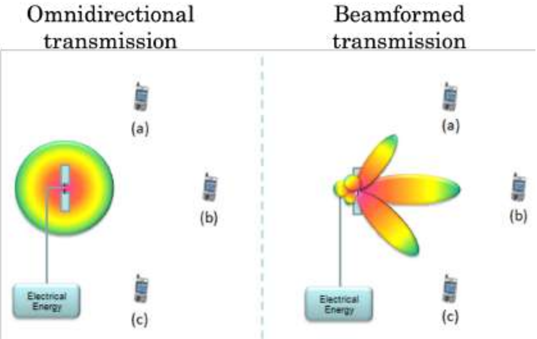
- BPSK uses two phases (e.g., 0° and 180°) to transmit 1 bit (0 or 1)
- QPSK uses four phases (e.g., 0°, 90°, 180° and 270°) to transmit 2 bits (00, 01, 10, 11)
- 16-QAM uses four phases and four amplitudes to transmit 4 bits (0000, . . . , 1111)
- . . .



SNR = 37 dB   SNR = 32 dB   SNR = 27 dB

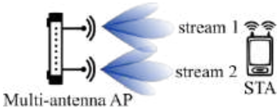
SNR (V)

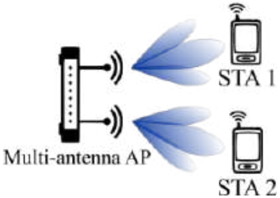
- **Beamforming:** a multi-antenna technology (antenna arrays) that allows focusing the radiated energy towards a particular direction.
- Using beamforming allows achieving a higher SNR gain using the same power.
- In addition, less interference is placed to other devices, thus allowing for more simultaneous transmissions.



Streams

- SU-MIMO: transmit multiple spatial streams of information to a single user.
    - Achieved thanks to spatial filtering.
- MU-MIMO: transmit multiple spatial streams of information to multiple users.
    - 802.11ac (Wi-Fi 5 – 2013): 8 spatial streams to 4 devices (DL only)
    - 802.11ax (Wi-Fi 6 – 2019): 8 spatial streams to 8 devices (UL & DL)
    - 802.11be (Wi-Fi 7 – 2024): up to 16 spatial streams





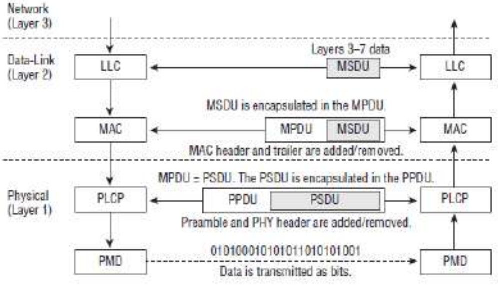
Outline

1. What is Wi-Fi?
2. Wi-Fi's PHY
3. Wi-Fi's MAC
4. Machine Learning & Wi-Fi

MAC layer operations

Main responsibilities:

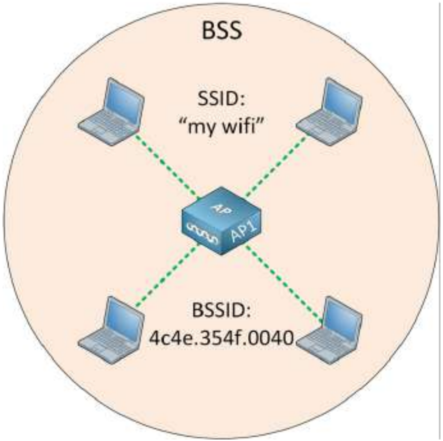
- *Network management:* network discovery, onboard users, measurement & reporting...
- *Medium Access Control:* channel access, framing, retransmissions, error detection...
- *Other:* power management, mobility, security, QoS...



Wi-Fi's MAC layer focuses on the reliable and efficient operation of wireless networks.

Wi-Fi architecture and management

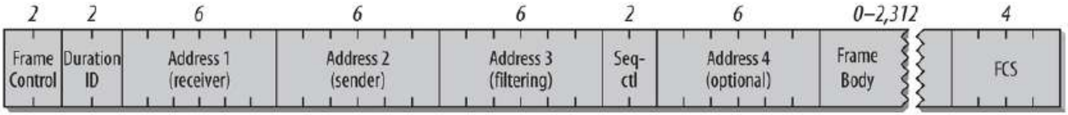
- An AP creates a local network (i.e., a Basic Service Set (BSS)) and manages it:
  - Network discovery: announce network and capabilities using Beacons.
  - User authentication: ensure that the users are legitimate (e.g., WPA2/WPA3 to authenticate users and encrypt data).
  - User association: onboards users, so that communication can be started.
  - The AP decides the network configuration (which frequency band and channels, transmission power, modes of operation, etc.).
- Stations (STAs) connect to the AP and exchange data with it.



IEEE 802.11 frames

Frame types in the 802.11:

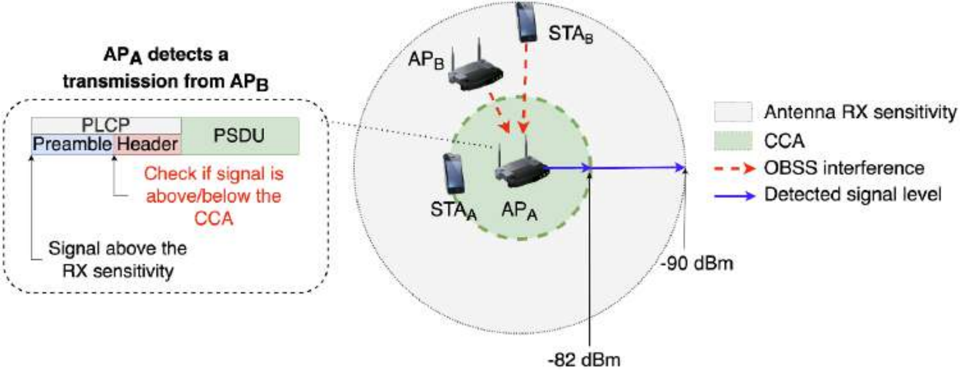
- Management frames: Used to establish the network and handle users. [cite: 45, 46]
- Examples of management frames: Beacon, Probe Request/Response, Authentication Request/Response, Association Request/Response.
- Control frames: Used to assist the transmission of data and control features (e.g., MAC reliability).
- Examples of control frames: ACK, CTS, RTS.
- Data frames: Used to carry the data.



Channel access (I)

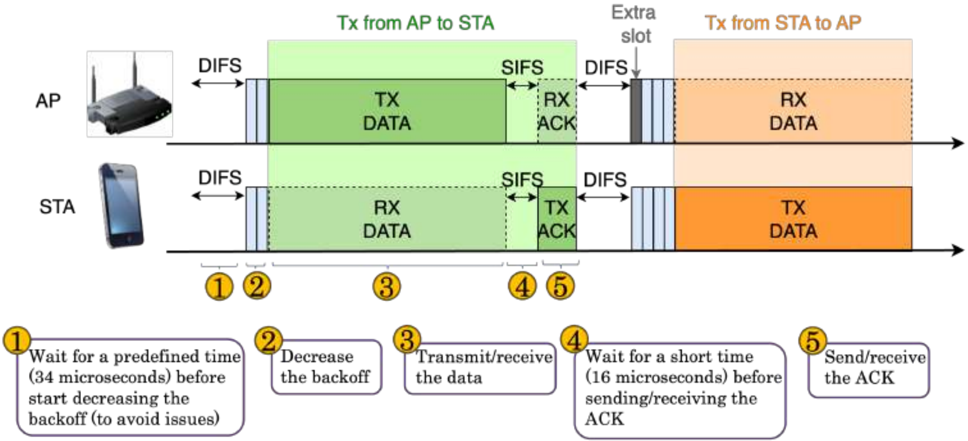
- Wi-Fi devices compete for the channel (unlicensed spectrum) in a decentralized manner.
- Synchronization is achieved "on the go".
- Simultaneous transmissions can lead to losing data due to interference (collisions).
- The channel access arbitration is done using the Distributed Coordination Function (DCF), which consists of:
  - CSMA/CA protocol for orchestrating the access to the channel.
    - Listen Before Talk!
  - Binary Exponential Backoff (BEB) to address collisions.
  - Automatic Repeat Request (ARQ) (e.g., "Stop & Wait") for packet retransmissions.

Channel access (II)



Based on CSMA principles, every time a transmission is detected, one must wait until the channel is free (idle) again

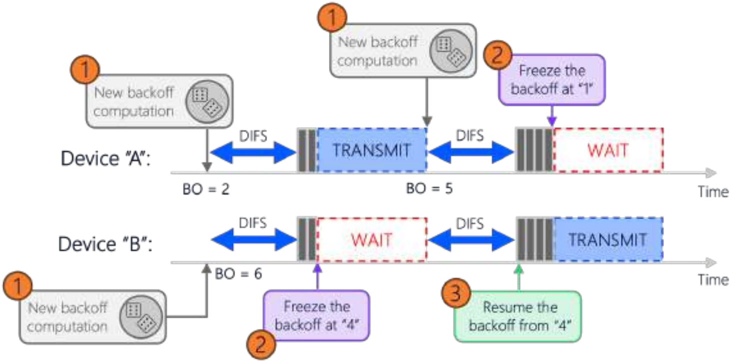
Channel access (III)



- Wi-Fi uses the unlicensed spectrum (free of use, uncontrolled), so the channel access is randomized
- The Distributed Coordination Function (DCF), which is based on CSMA, is the main protocol used
- Wi-Fi uses Automatic Repeat Request (ARQ), Cyclic Redundancy Check (CRC), and Forward Error Correction (FEC) for error control

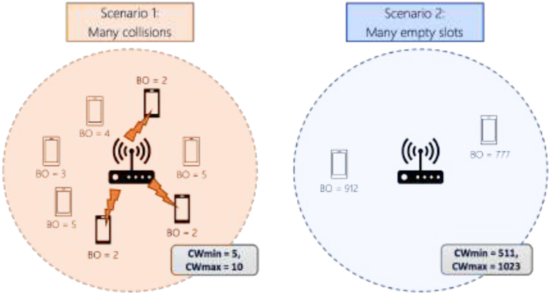
Random Backoff

- Every time a device needs to transmit data (and access the channel), it computes a random backoff.
- The backoff is computed from a Contention Window (CW) parameters.
  - BO $\in$ [0, CW]
- When the channel is found busy, the backoff is paused/frozen, and it is resumed when the channel becomes free again.



Binary Exponential Backoff

- The randomization of the channel access reduces the number of simultaneous transmissions (thus collisions)...
- ...but does not solve the problem.
- Collisions can occur if CW is not well dimensioned.
- BEB doubles the CW every time there is a collision.
  - This is done until a maximum CW stage (e.g., 5).
- When a transmission is successful, the CW is reset to the initial value (e.g., 15).



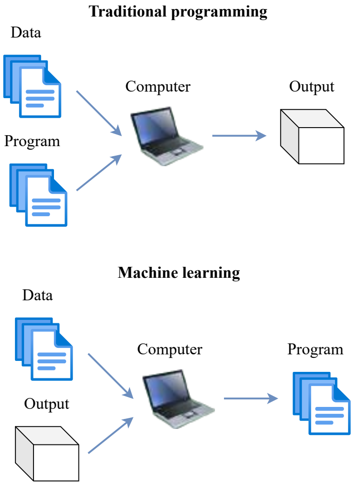
Example: for N = 50 devices and CW = 15, the probability that two or more devices transmit simultaneously is 0.99921908338.

Outline

What is machine learning?

- Machine learning (ML) is an area in computer science that automates the extraction of knowledge for its application (e.g., representation, prediction)
- Data-centric approach:
  - Learn from data
  - Infer from data
  - Repeat (improve over time)

ML algorithms are sets of instructions that allow learning from data (fit model to data).



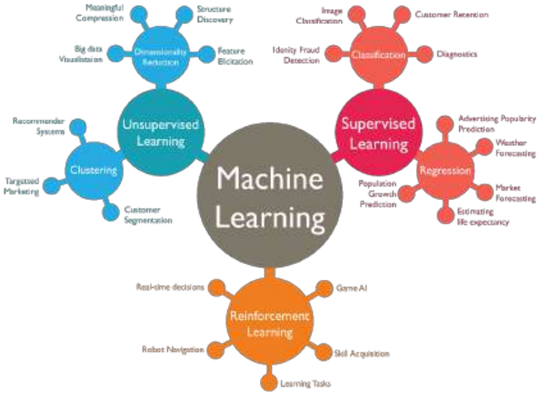
When to use machine learning?

We use ML when:

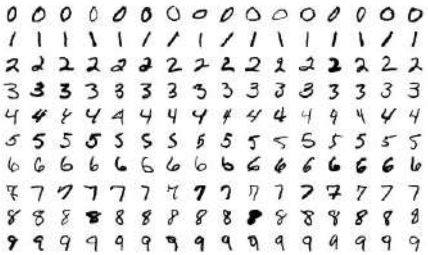
- Knowledge does not exist
- Knowledge cannot be explained
- Knowledge can be improved
- Knowledge is varying

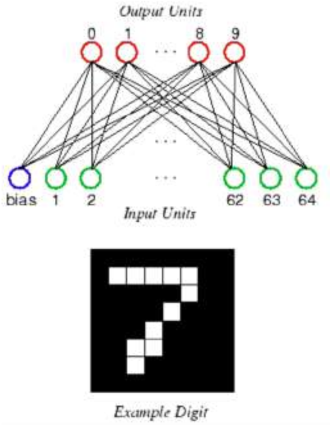
ML is good for:

- Recognizing patterns
- Generating patterns
- Identifying anomalies
- Predicting from complex data
- ...



Machine learning success stories (I)

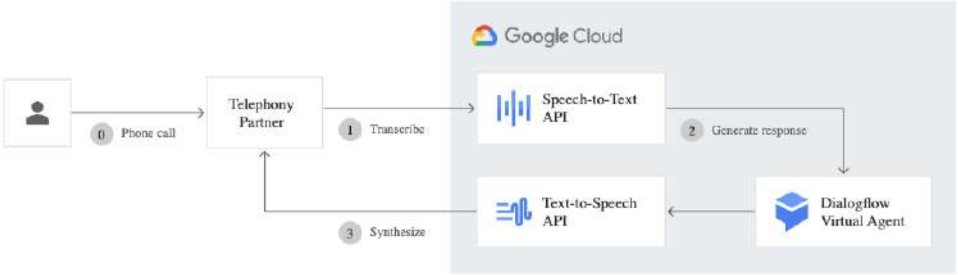




https://paperswithcode.com/dataset/mnist

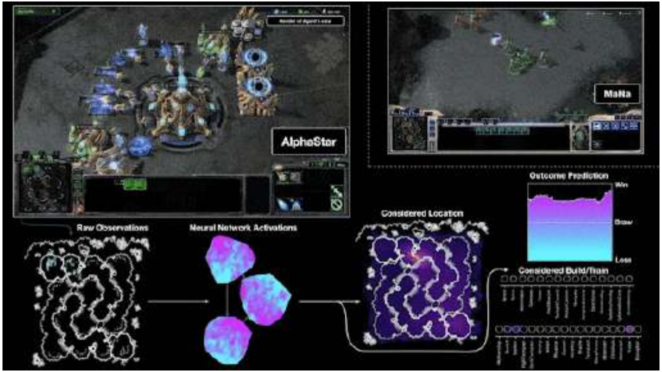
https://nn.cs.utexas.edu/demos/digit-recognition/

Machine learning success stories (II)



https://cloud.google.com/text-to-speech#voicebots-in-contact-centers

Machine learning success stories (III)



Link

https://paperswithcode.com/method/alphastar

A bit of perspective (ML history)

- 1950s: Arthur Samuel created a program that could learn how to play checkers from experience. The term "Machine Learning" was coined.
- 1957: The perceptron algorithm was implemented by Frank Rosenblatt.
- 1970s-1980s: A first 'AI winter' (due to limitations in computing power) stopped the early enthusiasm on AI and ML.
- 1980s: Geoffrey Hinton et al. led the foundations of artificial neural networks.
- 1990s:
  - Second 'AI winter'
  - Development of important concepts: convolutional networks, Markov models, reinforcement learning, support vector machines...
- 2000s: Applied ML (natural language, vision...)
- 2010s: Neural networks and deep learning (AlphaGo, text-to-speech, object recognition...)
- 2020s: Generative AI, Large Language Models (LLMs)

Why do we want to apply ML to Wi-Fi (and networks)?

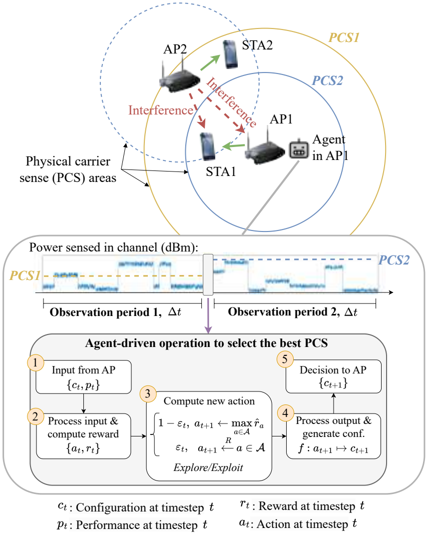
ML method	Algorithms	Potential applications	Examples of input data
Supervised Learning	Linear classifiers, Regression methods (e.g., ARIMA), Neural Networks, Hidden Markov Models, Random Forest, Support Vector Machines, k-Nearest Neighbors	Traffic forecasting, mobility pattern prediction, flow classification, routing, anomaly detection, spectrum management, failure detection, QoE prediction	IP traffic matrices, temporal user location, availability of routing paths, application data, channel measurements, performance metrics
Unsupervised Learning	Clustering, Mixture models, Generative models, Non-Negative Matrix Factorization, Evolutionary algorithms, Principal Component Analysis	Traffic classification, virtual topology design, path computation, intruder detection, signal separation	IP traffic matrices, historical end-to-end bit-rate, received symbols
Reinforcement Learning	Monte Carlo, Q-learning, SARSA, Deep Q Network, Actor-critic, Multi-Armed Bandits, Learning automaton	Power control, rate adaptation, routing, channel selection, spatial reuse, smart caching, traffic offloading, cognitive channel access, energy harvesting	Channel measurements, link status, performance metrics (e.g., throughput, delay)

Table: Overview of Machine Learning Methods in Networking

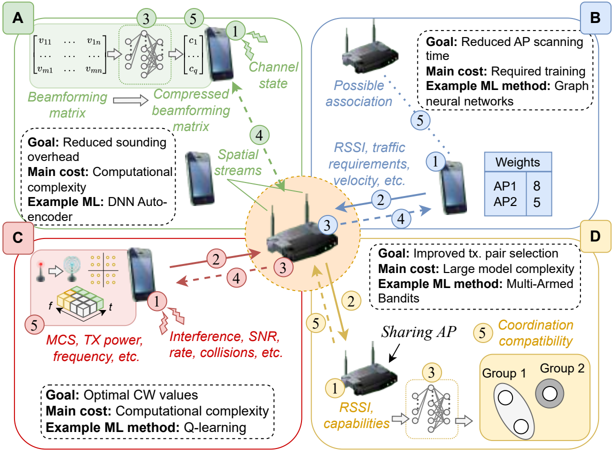
Should we expect that the use of ML techniques will improve raw 'performance' (e.g., throughput, delay and reliability), improve QoE (e.g., better AP selection), manage and operate networks better (network planning, configuration), enable new functionalities (e.g., sensing, data analytics), contribute to reduce 'overheads' by reducing the amount of exchanged data...

Why do we want to apply ML to Wi-Fi (and networks)?

- Adaptation to different environments
  - Find satisfactory configurations of IEEE 802.11 MAC/PHY parameters
  - Recognize conditions: LOS/NLOS, interferers, coexisting technologies...
- Smart decisions
  - AP selection, wait/transmit (e.g. in MLO), CW/MCS selection...
- Improve parameter estimation
- Beamforming coefficients, overhead reduction...



Why do we want to apply ML to Wi-Fi (and networks)?



ML operation steps/actions:

1. Collect measurements (e.g., KPIs)
2. Exchange measurements/data for ML models
3. Perform ML model inference
4. Exchange models, outputs, decisions, commands
5. Apply output to drive operation/optimization

Recommended reading: Wilhelmi, Francesc, et al. "Machine Learning and Wi-Fi: Unveiling the Path Toward AI/ML-Native IEEE 802.11 Networks." IEEE Communications Magazine (2024). [arXiv version: https://arxiv.org/pdf/2405.11504]