Introduction to Wireless and Mobile Networking

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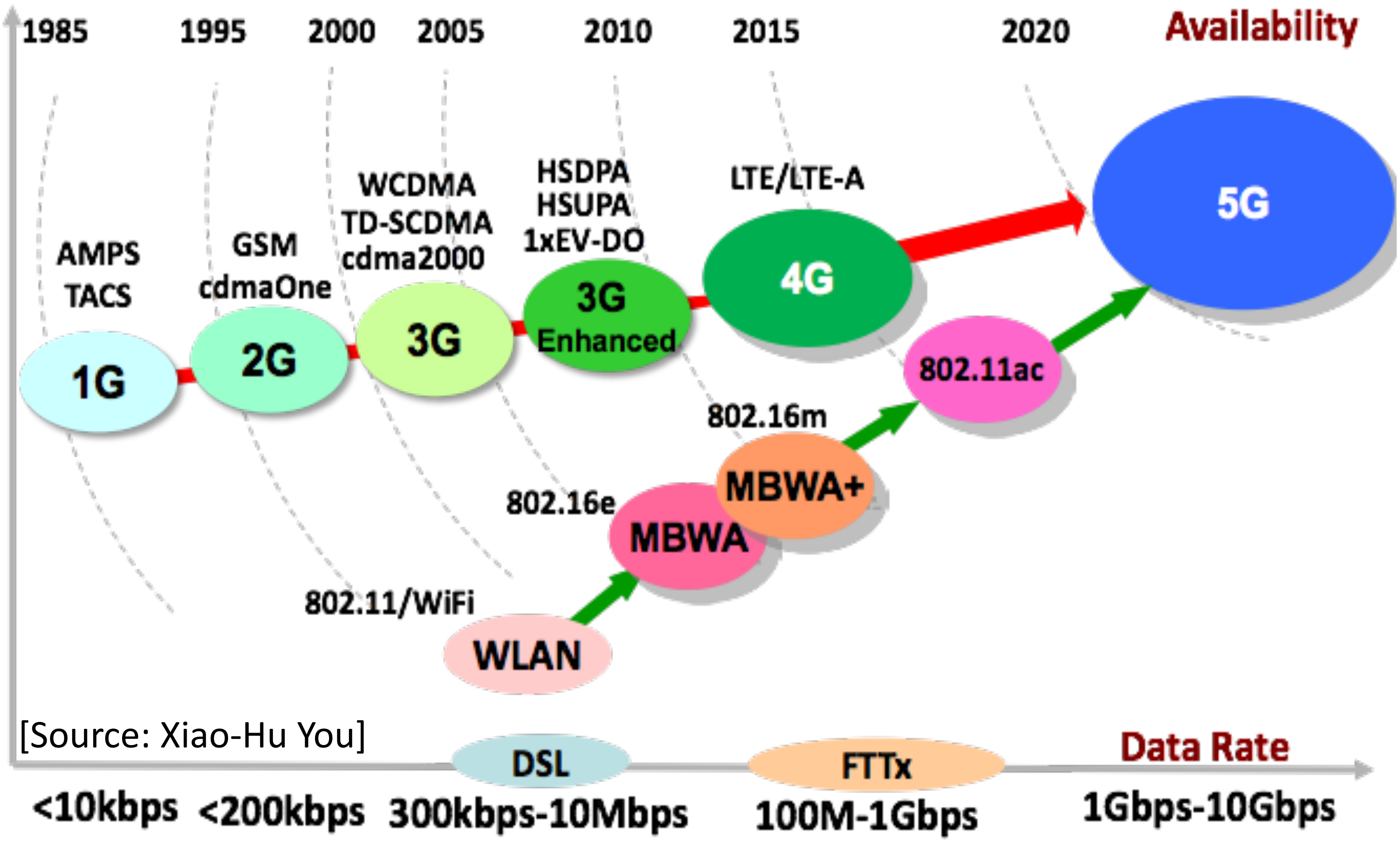
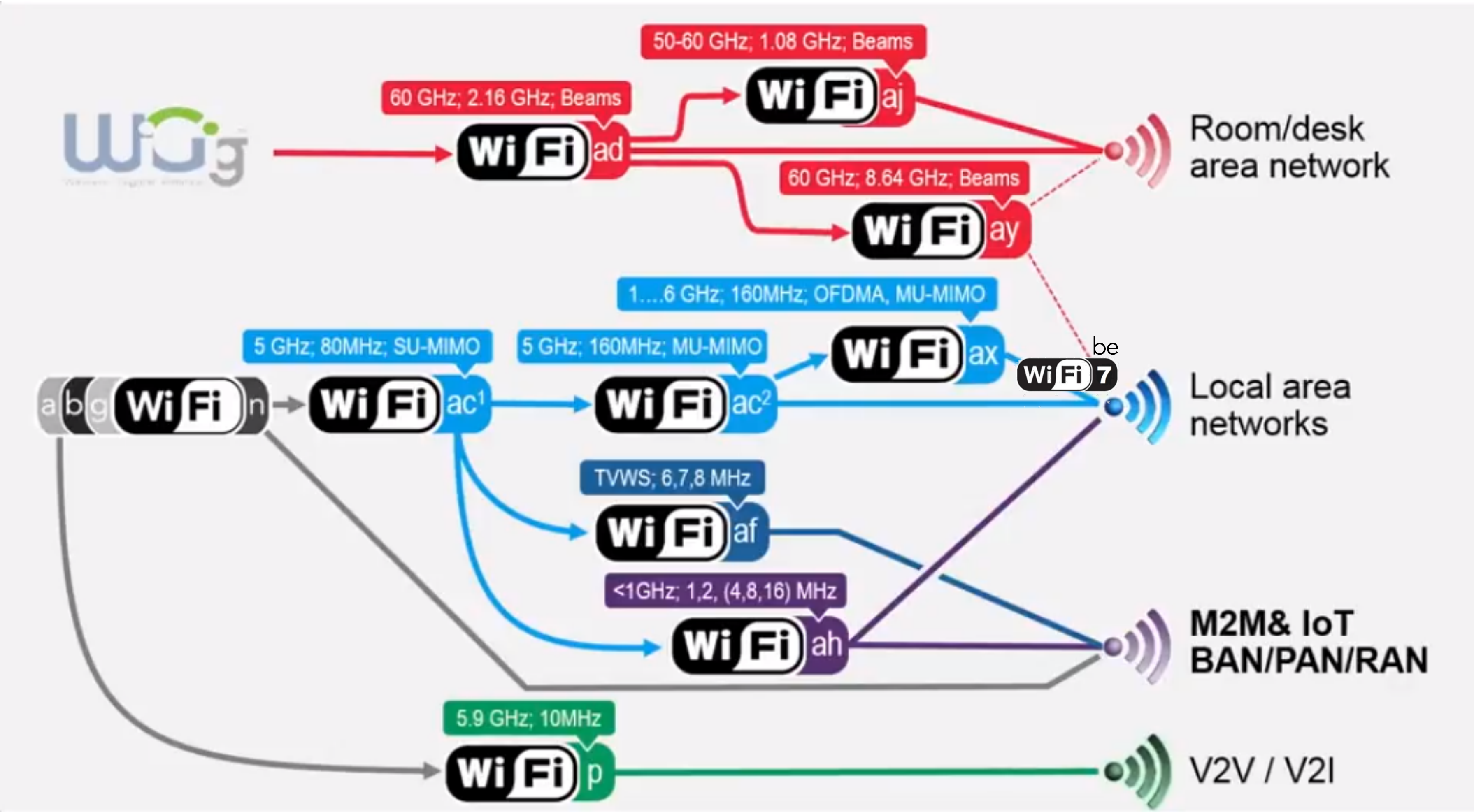
Wireless Networks Roadmap



[Source: Xiao-Hu You]

IEEE 802.11 Family



Source: ROHDE&SCHWARZ

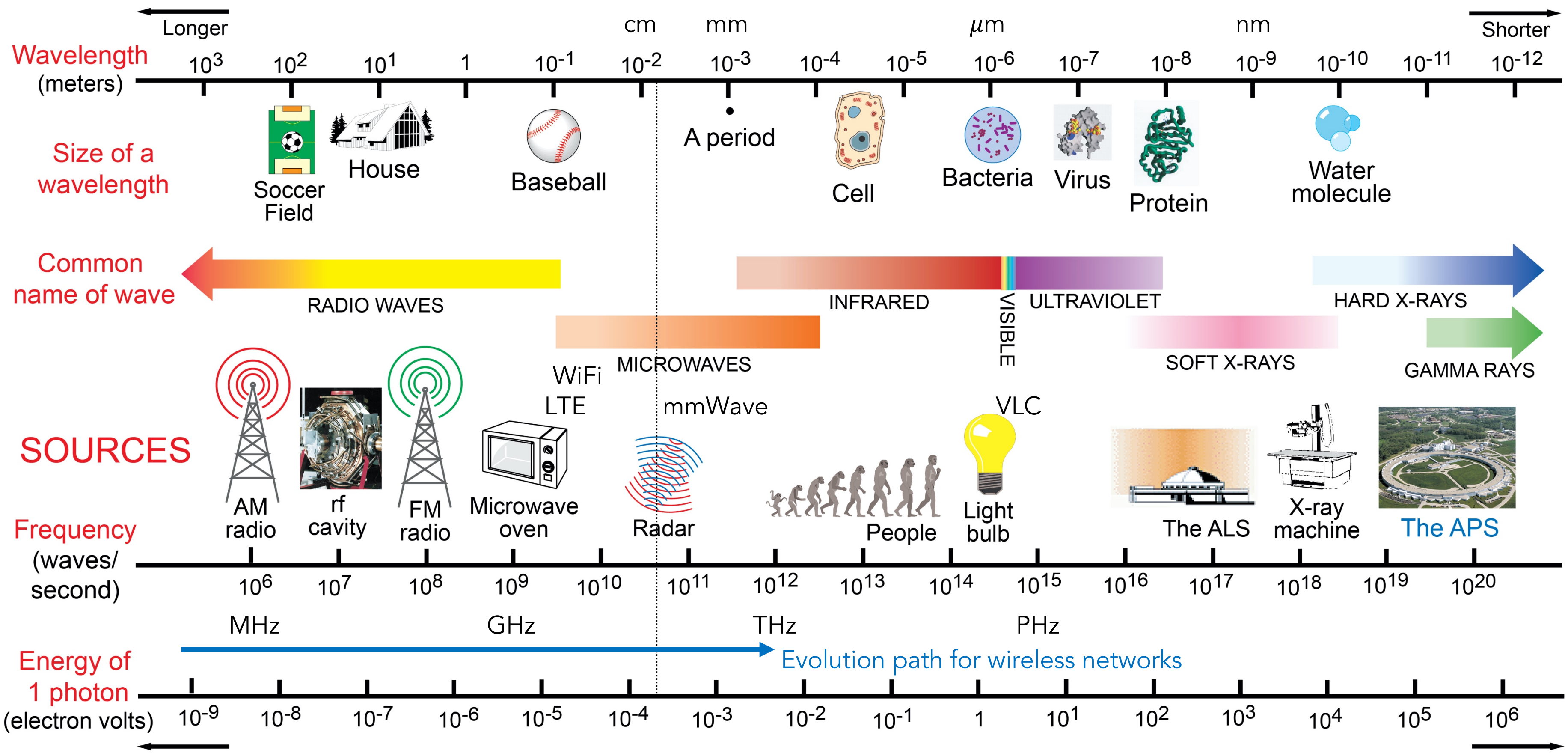
Why are they so Many?

- Diverse deployments
  - Licensed frequency bands or not
  - Infrastructure based, no infrastructure
- Technologies have different …
  - Signal penetration
  - Frequency use
  - Cost
- Different applications have different requirements
  - Energy consumption
  - Range
  - Bandwidth
  - Mobility
  - Cost

review

Electromagnetic Spectrum

	Frequency Bands	Frequency Range		
VLF	very low frequency	3 kHz	-	30 kHz
LF	low frequency	30 kHz	-	300 kHz
MF	medium frequency	300 kHz	-	3 MHz
HF	high frequency	3 MHz	-	30 MHz
VHF	very high frequency	30 MHz	-	300 MHz
UHF	ultra high frequency	300 MHz	-	3 GHz
SHF	super high frequency	3 GHz	-	30 GHz
EHF	extremely high frequency	30 GHz	-	300 GHz



Source: Argonne National Laboratory

Signal Propagation

- Decibel (dB) vs. dBm (dB from 1mW, 30dBm=1W)
  - X_1/X_0 [dB] = 10 $\log_{10}$ (X_1/X_0)
  - Attenuation [dB] = 10 $\log_{10}$ (transmitted power / received power)

- Theory: Path loss model
  - Receiving power is proportional to $(1/d)^{\alpha}$: $\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d}\right)^{a}$
  - α =2,3,…8 called path loss exponent, depends on environment
  - λ : wavelength, depends on frequency ($\lambda = \frac{v}{f} = \frac{c}{f}$)
  - Attenuation: $Loss := \frac{P_t}{P_r} = \left(\frac{4\pi d}{\lambda}\right)^{a}$
  - Attenuation in dB for $\alpha = 2$
    - $Loss_{dB} := 10\log_{10}\left(\frac{P_t}{P_r}\right) = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right)$

Signal Propagation

- How much is the signal attenuated between 10m and 100m (α=2)?

$$10\log\left(\frac{P_{10m}}{P_{100m}}\right) = 10\log\left(\frac{P_0/10^2}{P_0/100^2}\right) = 20\ dB$$

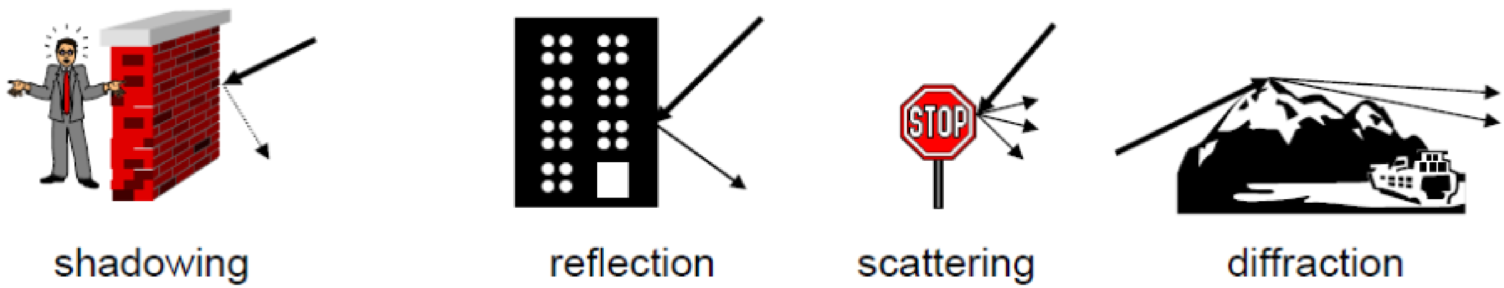
- Path loss exponents

α	**Environment**
2.0	Free space
1.6 to 1.8	Inside a building, line of sight
1.8	Grocery store
1.8	Paper/cereal factory building
2.09	A typical 15 m × 7.6 m conference room with table and chairs
2.2	Retail store
2 to 3	Inside a factory, no line of sight
2.8	Indoor residential
2.7 to 4.3	Inside a typical office building, no line of sight

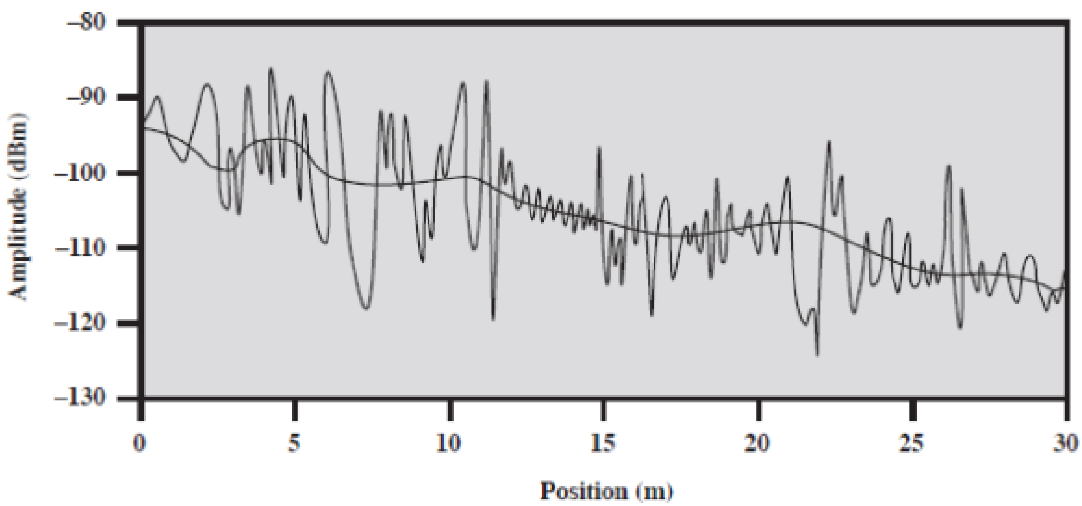
Source:
Lawrence Berkeley
National Lab.

Signal Propagation

- In Reality



- More issues (Fading and Mobility)

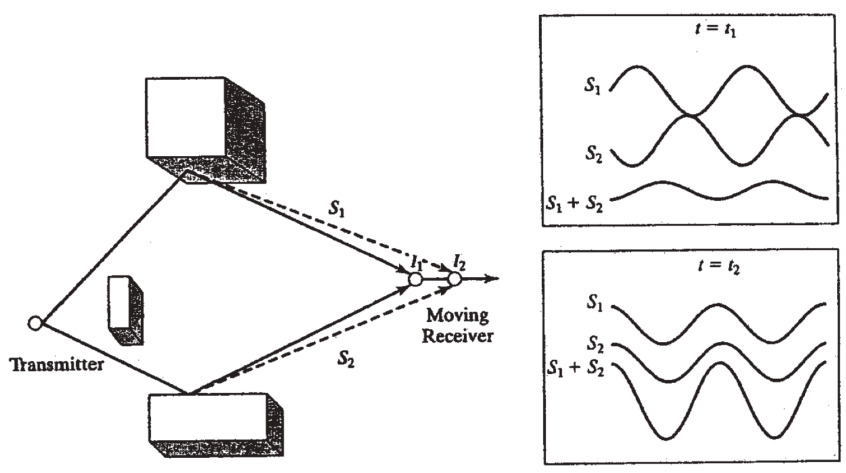


Slow and Fast Fading

Fast Fading vs. Slow Fading

- The phenomenon of *fast fading* is represented by the rapid fluctuations of the signal over small areas.
- When the signals arrive from all directions in the plane, fast fading will be observed for all directions of motion.
- In response to the variation in the nearby buildings, there will be a change in the average about which the rapid fluctuations take place. This middle scale over which the signal varies, which is on the order of the buildings dimensions is known as *shadow fading*, *slow fading* or *log-normal fading*.

Fast fading (e.g., Rayleigh, Rician, Nakagami)
The received signal is the sum of a number of signals reflected from local surfaces, and these signals sum in a constructive or destructive manner ⇒ relative phase shift. Phase relationships depend on the speed of motion, frequency of transmission and relative path lengths.

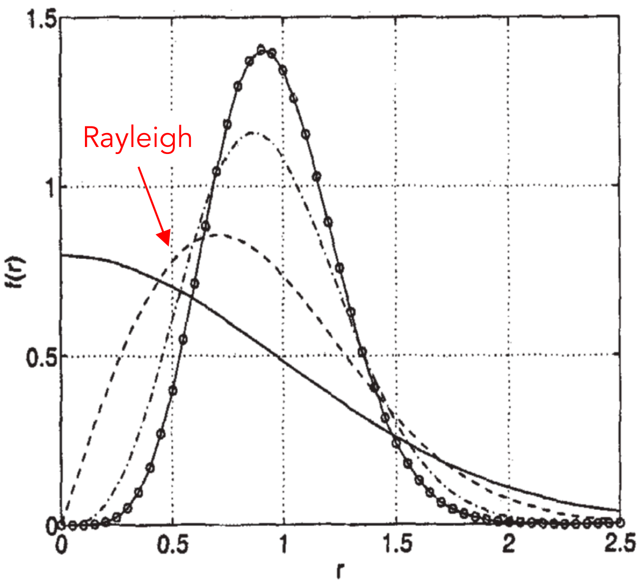


Fast Fading: Distribution Models

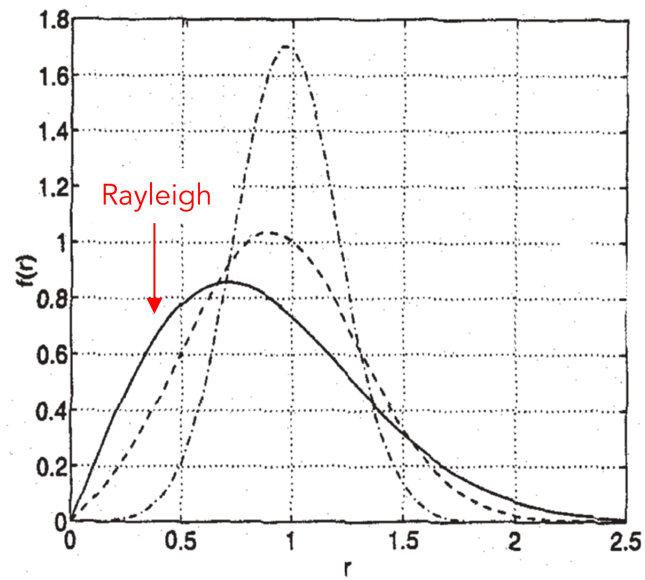
Rayleigh distribution: $f(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}$ (NLOS (uniform rand phase), Nakagami with k=1, Ricean with $K = -\infty$ dB)

Nakagami distribution: $f(r) = \frac{2}{\Gamma(k)} \left(\frac{k}{2\sigma^2}\right) r^{2k-1} e^{-\frac{kr^2}{2\sigma^2}}$

Rician distribution: $f(r) = \frac{r}{\sigma^2} e^{-\frac{r^2+\nu^2}{2\sigma^2}} I_0(\frac{rv}{\sigma^2})$, Rice factor (LOS/NLOS): $K = \frac{\nu^2}{2\sigma^2}$



Nakagami probability density function, (—) $\kappa = \frac{1}{2}$, (– –) $\kappa = 1$ (Rayleigh), (- · -) $\kappa = 2$, (∘) $\kappa = 3$



Ricean probability density function, (—) $K = -\infty$, (– –) $K = 3$ dB, (- · -) $K = 9$ dB.

Slow Fading: Log-normal Shadowing

- Slow fading is often captured by *Log-normal shadowing* model which generalizes *path loss* model to account for effects like shadowing, scattering, etc.

- Attenuation at distance d (in dB):

$$Loss_{dB} = 10\alpha \log\left(\frac{4\pi d}{\lambda}\right) + X\ (dB)$$

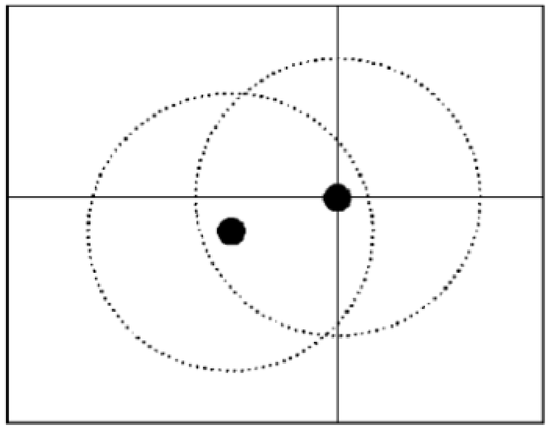
  - X[dB] is a Gaussian random variable with zero mean and standard deviation σ
  - Value for σ depends on the environment
  - Might be able to receive stronger signal at longer distances (due to randomness of X)

Decoding of Wireless Signal

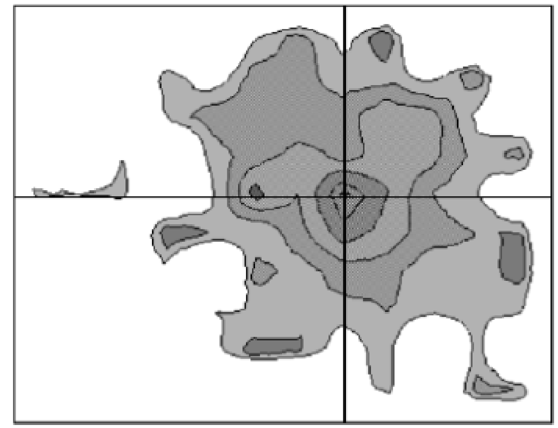
- Signal to Interference plus Noise Ratio (SINR)
  - SINR = S / (N + I)
  - N: Background noise
  - I: Interference from other stations
  - Often measured in dB: SINR(dB) = 10*log(S/(N+I))

- A certain level of SINR is required for decoding
  - SINR of 10dB ➔ BER (bit error rate) of 10^{-6} in 802.11b
  - BER ➔ PER (packet error rate)
  - BER can be overcome by error correction code (coding)
  - PER can be overcome by coding or retransmission

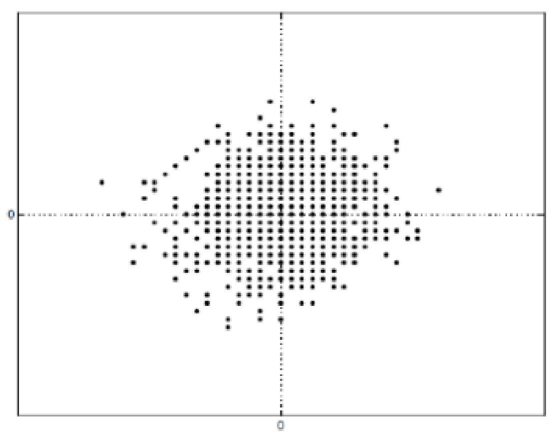
Decoding of Wireless Signal



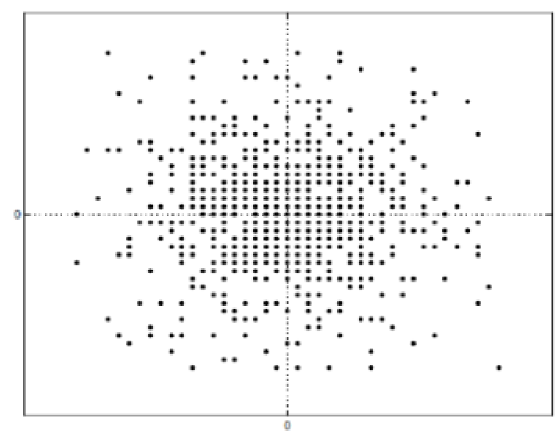
(a) Path Loss Model



(b) Empiric



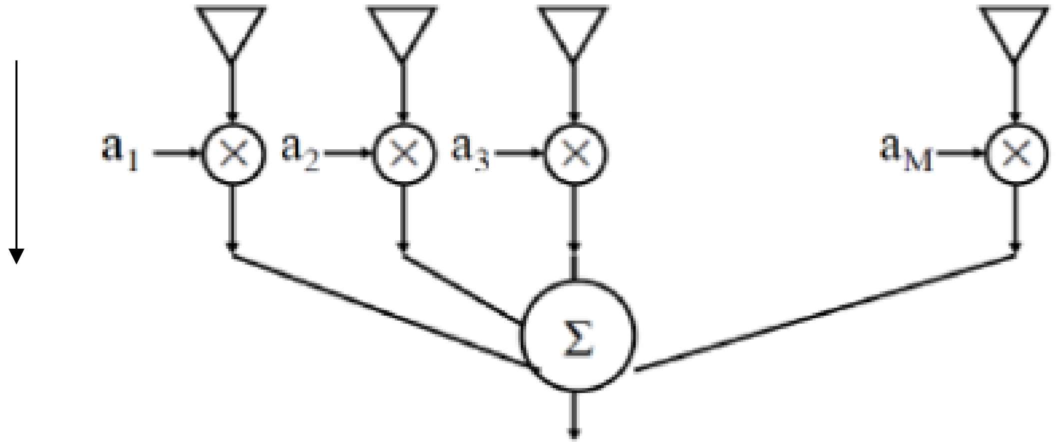
(c) Shadowing with σ=2



(d) Shadowing with σ=4

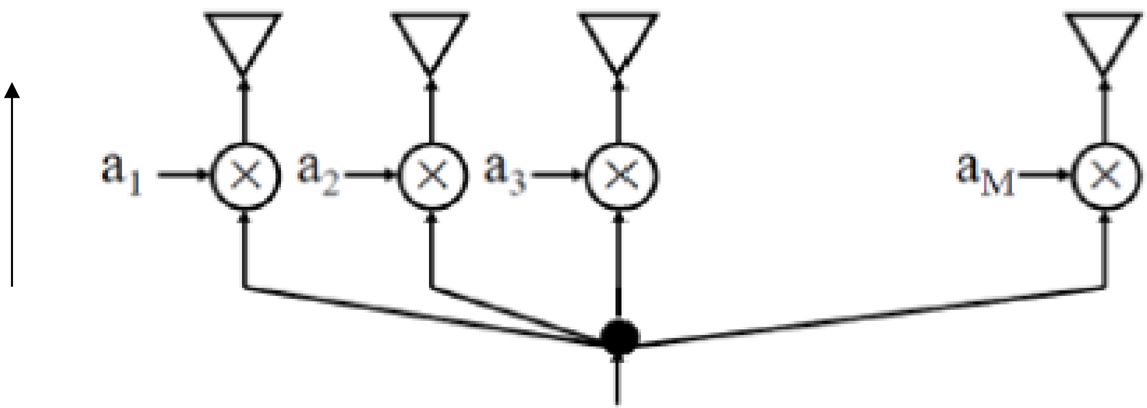
Receiver Diversity

- Multiple receiver antennas per device is possible
- Variations:
  - **Equal-gain combining:** sum all the received signals coherently.
  - **Selection combining:** select antenna with the best signal.
  - **Switched combining:** switches to another signal when the currently selected signal drops below a predefined threshold.
  - **Maximal ratio combining:** adjust phase so that all signals have the same phase, then weighted sum is used as the final signal.



Transmitter Diversity

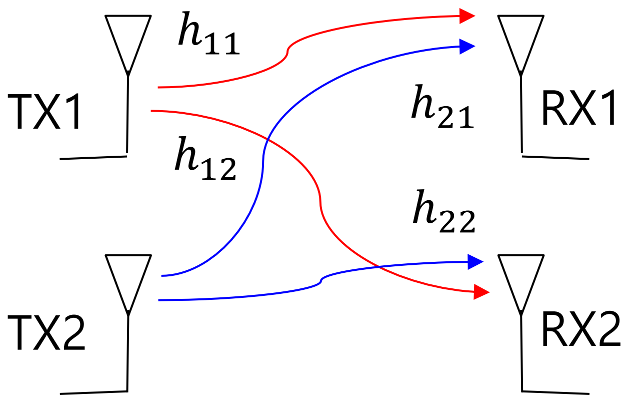
- Multiple antennas to transmit the signal
  - Consider just a single receiver antenna
- Problem:
  - Different transmitter signals might cancel each other out at receiver
- Solution:
  - Phase each signal to make sure the signals arrive "in phase" at the receiver (Phase shift is calculated by receiver and fed back to the transmitter)



MIMO (Multiple Input Multiple Output)

- Sending two symbols x_1 and x_2
  - Send each symbol with a separate antenna (doubles data rate)
  - Symbols are received by the two receiving antennas as

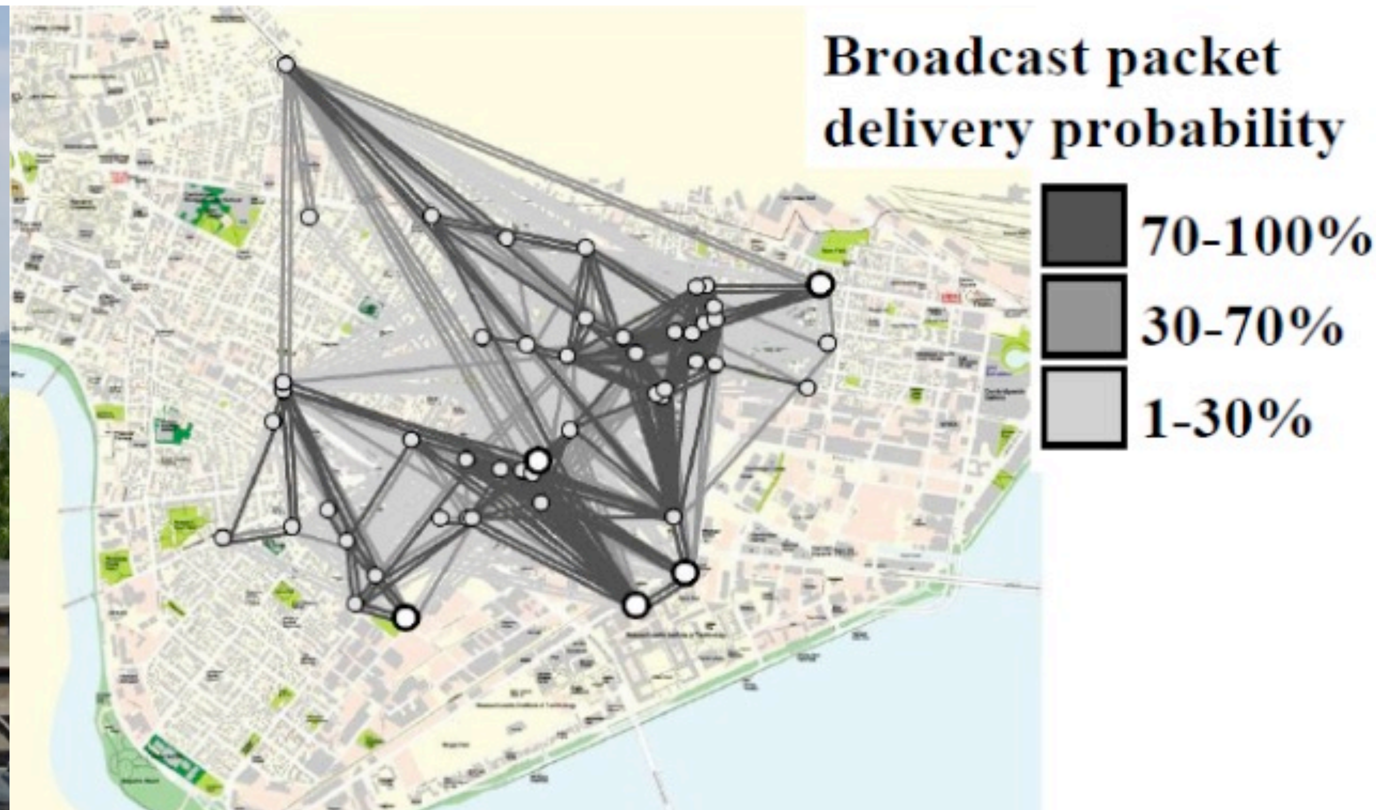
$$y_1 = h_{11} \cdot x_1 + h_{21} \cdot x_2 + n_1$$
$$y_2 = h_{12} \cdot x_1 + h_{22} \cdot x_2 + n_2$$



  - h_{ij} represents how symbols are attenuated and rotated from i to j
  - n_1 and n_2 are the background noise

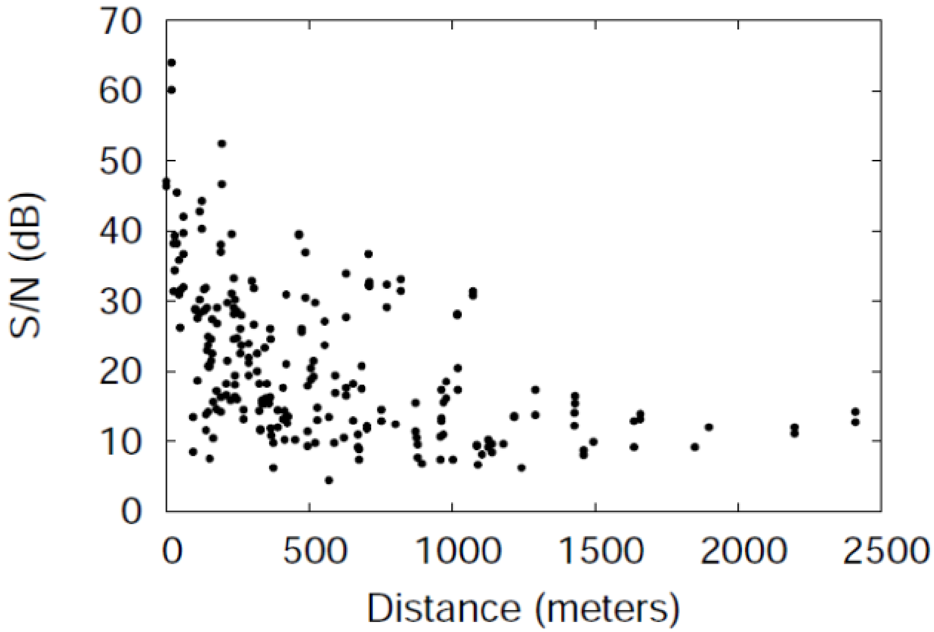
Roofnet Experiment

- Wireless LAN Testbed at MIT
  - Link-level measurement from an 802.11b mesh network, SIGCOMM 2004

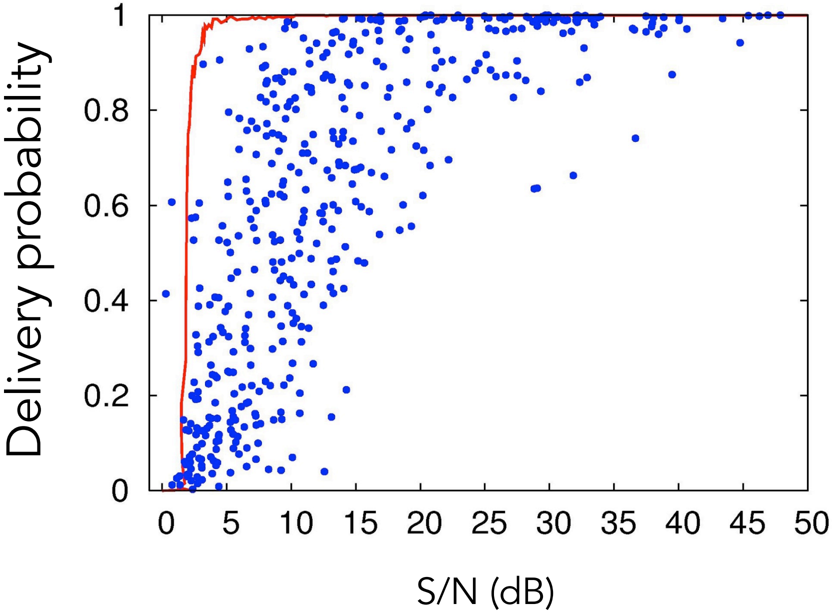


Roofnet Experiment

- SNR vs. Distance



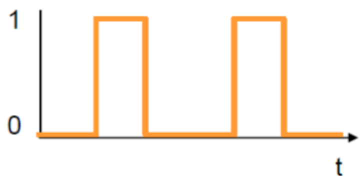
Delivery vs. SNR



- Wireless channel modeling is not simple (and easy)
- Predicting wireless performance is very difficult

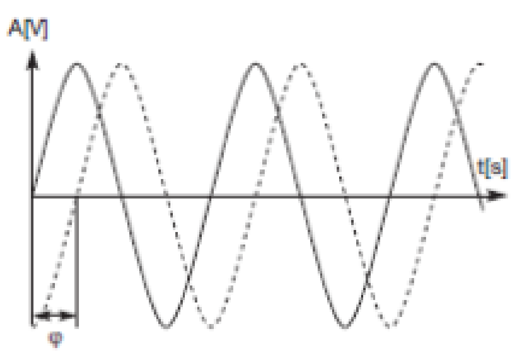
Transmitting Digital Data over Air

- In wireless networks, digital transmission is impossible



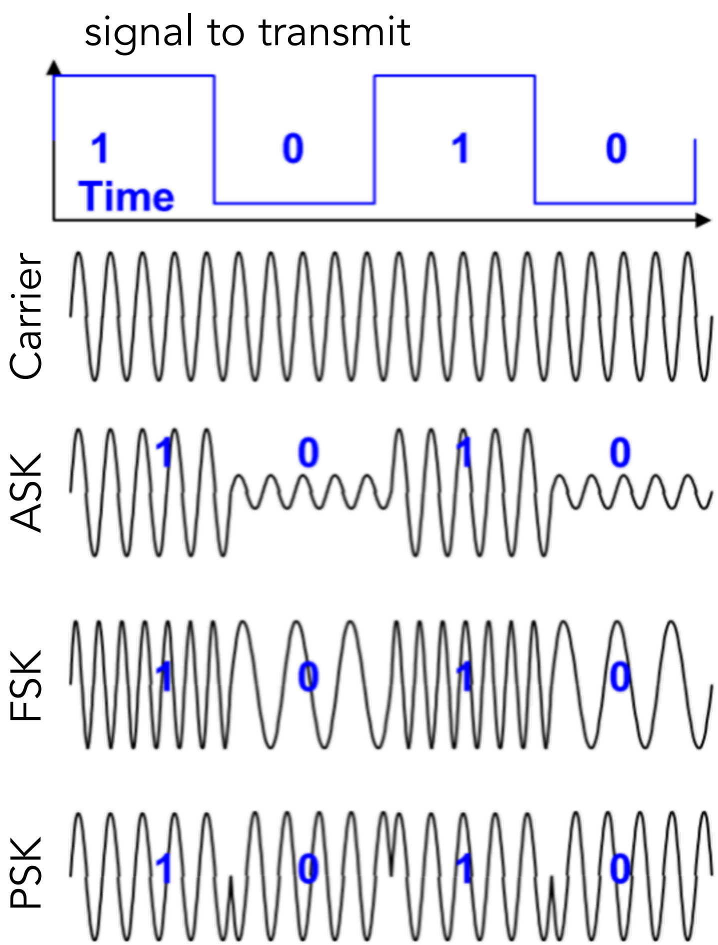
- Utilizing electromagnetic waves require transformation of digital signal to analog signal
  - Converting digital to analog signal ➔ Digital modulation
  - Shifting analog signal into the frequency band used for actual communication ➔ Analog modulation

- $g(t) = A\sin(2\pi f t + \phi)$
  - Amplitude(A), Frequency(f), Phase(ϕ) ➔ Info



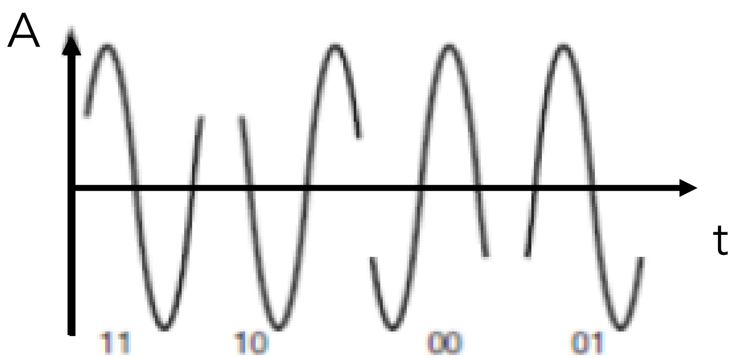
Modulation

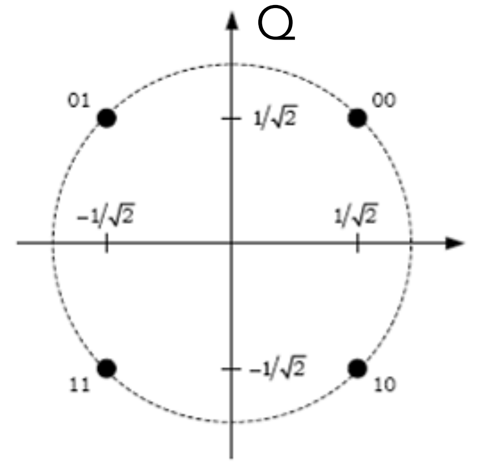
- Amplitude shift keying (ASK)
  - Low bandwidth requirement
  - Very susceptible to interference
- Frequency shift keying (FSK)
  - Example: Binary FSK
  - Needs larger bandwidth
  - Less susceptible to errors
- Phase shift keying (PSK)
  - More complex
  - Robust against interference



Modulation: Quadrature PSK (QPSK)

- IDEA: use a phase shift of $\pi/2$ to create four distinguished signals (each encoding 2 bits)
  - Representation of modulation is in the phase domain
    - [In-phase (I) and quadrature (Q) components]



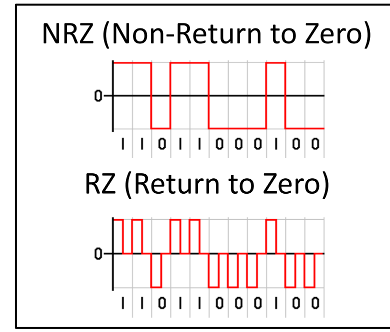


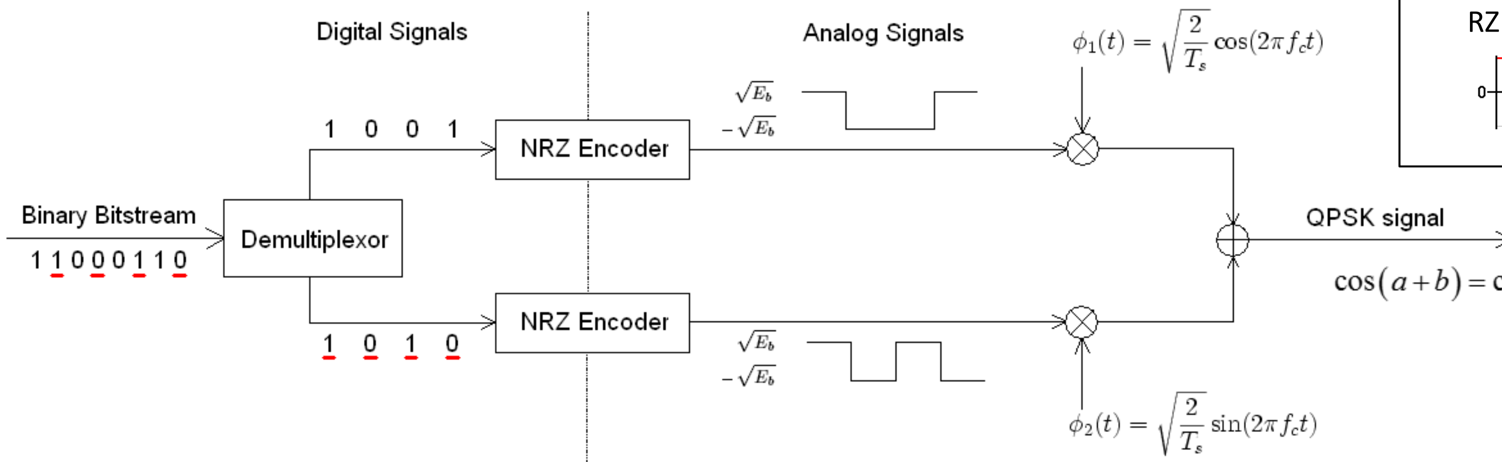
$$s_n(t) = \sqrt{\frac{2E_s}{T_s}} \cos\left(2\pi f_c t + (2n-1)\frac{\pi}{4}\right), \quad n = 1, 2, 3, 4.$$

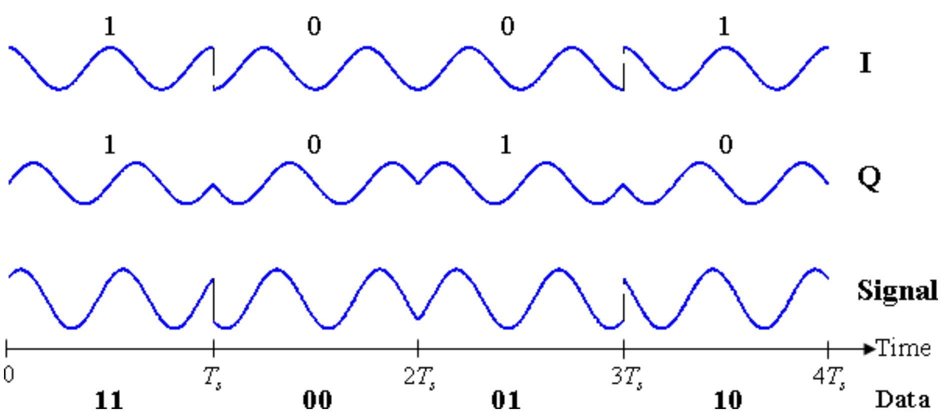
- Problem: Symbol rotation (reference of phase?)
  - Solution: DQPSK (Differential QPSK) – Phase is determined only based on the previous two bits (no reference)

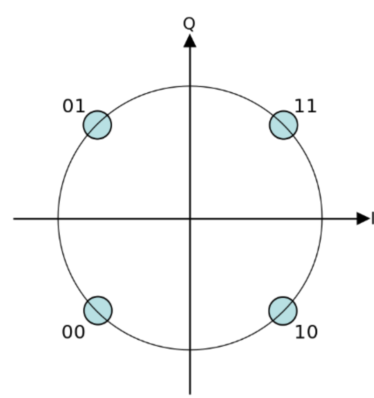
Modulation: Quadrature PSK (QPSK)

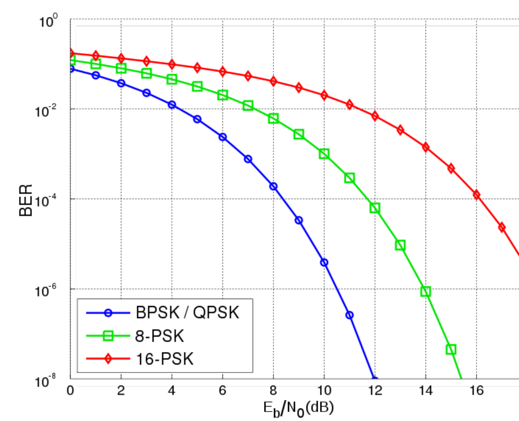
$$s_n(t) = \sqrt{\frac{2E_s}{T_s}} \cos\left(2\pi f_c t + (2n-1)\frac{\pi}{4}\right), \quad n = 1, 2, 3, 4.$$



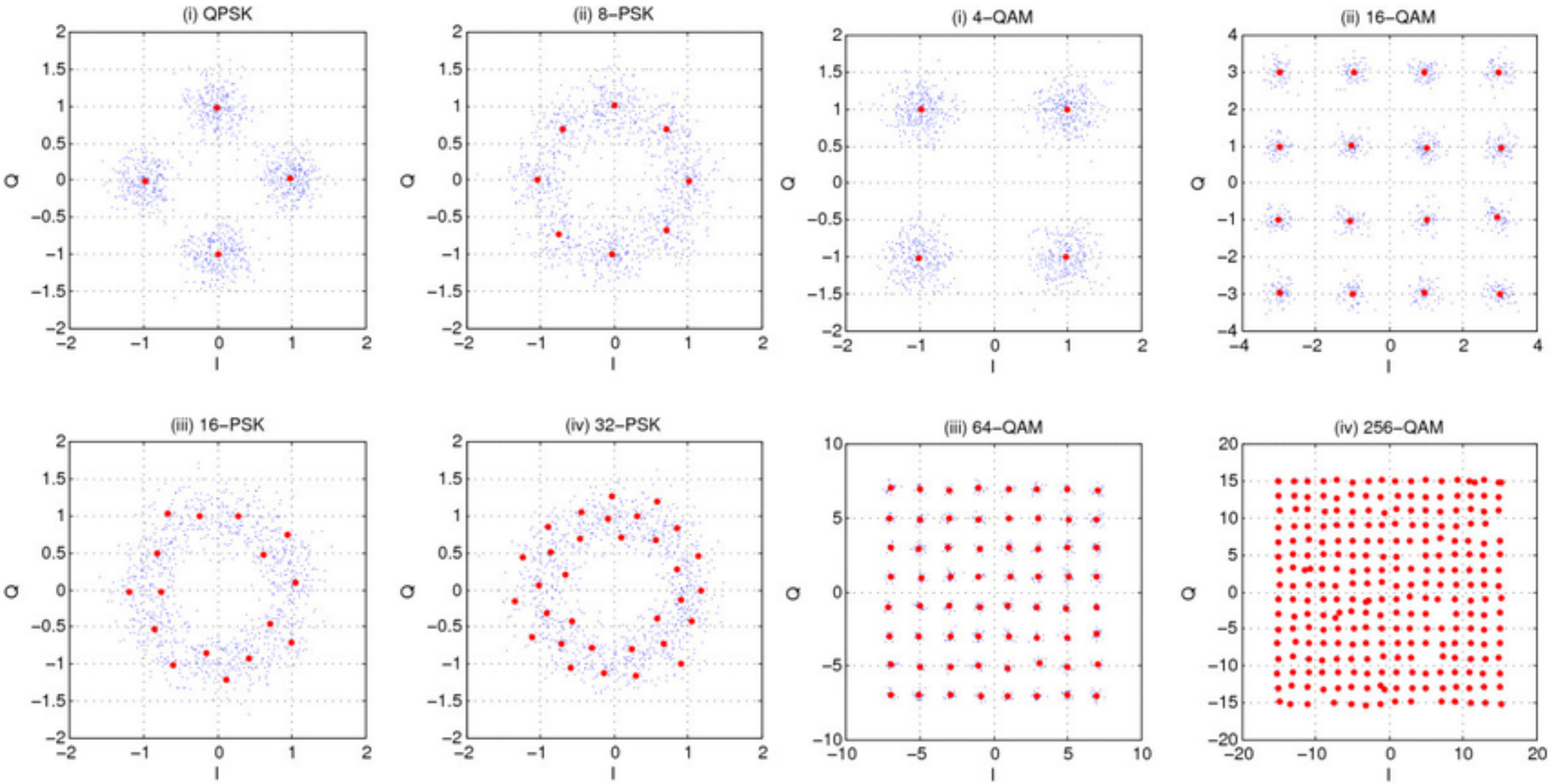








PSK and QAM (Quadrature Amplitude Modulation)



MCS (Modulation and Coding Scheme) in 802.11

802.11ac - VHT MCS, SNR and RSSI

VHT MCS	Modulation	Coding	20MHz				40MHz				80MHz				160MHz			
			Data Rate		Min. SNR	RSSI	Data Rate		Min. SNR	RSSI	Data Rate		Min. SNR	RSSI	Data Rate		Min. SNR	RSSI
			800ns	400ns			800ns	400ns			800ns	400ns			800ns	400ns		
1 Spatial Stream																		
0	BPSK	1/2	6.5	7.2	2	-82	13.5	15	5	-79	29.3	32.5	8	-76	58.5	65	11	-73
1	QPSK	1/2	13	14.4	5	-79	27	30	8	-76	58.5	65	11	-73	117	130	14	-70
2	QPSK	3/4	19.5	21.7	9	-77	40.5	45	12	-74	87.8	97.5	15	-71	175.5	195	18	-68
3	16-QAM	1/2	26	28.9	11	-74	54	60	14	-71	117	130	17	-68	234	260	20	-65
4	16-QAM	3/4	39	43.3	15	-70	81	90	18	-67	175.5	195	21	-64	351	390	24	-61
5	64-QAM	2/3	52	57.8	18	-66	108	120	21	-63	234	260	24	-60	468	520	27	-57
6	64-QAM	3/4	58.5	65	20	-65	121.5	135	23	-62	263.3	292.5	26	-59	526.5	585	29	-56
7	64-QAM	5/6	65	72.2	25	-64	135	150	28	-61	292.5	325	31	-58	585	650	34	-55
8	256-QAM	3/4	78	86.7	29	-59	162	180	32	-56	351	390	35	-53	702	780	38	-50
9	256-QAM	5/6			31	-57	180	200	34	-54	390	433.3	37	-51	780	866.7	40	-48
2 Spatial Streams																		
0	BPSK	1/2	13	14.4	2	-82	27	30	5	-79	58.5	65	8	-76	117	130	11	-73
1	QPSK	1/2	26	28.9	5	-79	54	60	8	-76	117	130	11	-73	234	260	14	-70
2	QPSK	3/4	39	43.3	9	-77	81	90	12	-74	175.5	195	15	-71	351	390	18	-68
3	16-QAM	1/2	52	57.8	11	-74	108	120	14	-71	234	260	17	-68	468	520	20	-65
4	16-QAM	3/4	78	86.7	15	-70	162	180	18	-67	351	390	21	-64	702	780	24	-61
5	64-QAM	2/3	104	115.6	18	-66	216	240	21	-63	468	520	24	-60	936	1040	27	-57
6	64-QAM	3/4	117	130.3	20	-65	243	270	23	-62	526.5	585	26	-59	1053	1170	29	-56
7	64-QAM	5/6	130	144.4	25	-64	270	300	28	-61	585	650	31	-58	1170	1300	34	-55
8	256-QAM	3/4	156	173.3	29	-59	324	360	32	-56	702	780	35	-53	1404	1560	38	-50
9	256-QAM	5/6			31	-57	360	400	34	-54	780	866.7	37	-51	1560	1733.3	40	-48
3 Spatial Streams																		
0	BPSK	1/2	19.5	21.7	2	-82	40.5	45	5	-79	87.8	97.5	8	-76	175.5	195	11	-73
1	QPSK	1/2	39	43.3	5	-79	81	90	8	-76	175.5	195	11	-73	351	390	14	-70
2	QPSK	3/4	58.5	65	9	-77	121.5	135	12	-74	263.3	292.5	15	-71	526.5	585	18	-68
3	16-QAM	1/2	78	86.7	11	-74	162	180	14	-71	351	390	17	-68	702	780	20	-65
4	16-QAM	3/4	117	130	15	-70	243	270	18	-67	526.5	585	21	-64	1053	1170	24	-61
5	64-QAM	2/3	156	173.3	18	-66	324	360	21	-63	702	780	24	-60	1404	1560	27	-57
6	64-QAM	3/4	175.5	195	20	-65	364.5	405	23	-62			26	-59	1579.5	1755	29	-56
7	64-QAM	5/6	195	216.7	25	-64	405	450	28	-61	877.5	975	31	-58	1755	1950	34	-55
8	256-QAM	3/4	234	260	29	-59	486	540	32	-56	1053	1170	35	-53	2106	2340	38	-50
9	256-QAM	5/6	260	288.9	31	-57	540	600	34	-54	1170	1300	37	-51			40	-48

Source: WirelessLAN professionals