CS263: Wireless Communications and Sensor Networks

Matt Welsh

Lecture 3: Antennas, Propagation, and Spread Spectrum
September 27, 2005

Today's Lecture

Antennas and gain

Propagation, fading and loss models

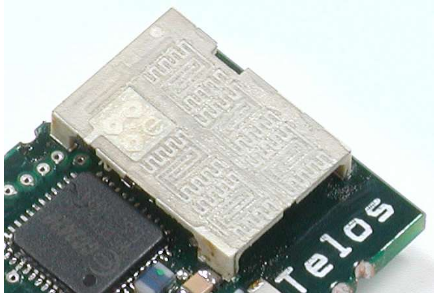
Spread Spectrum techniques

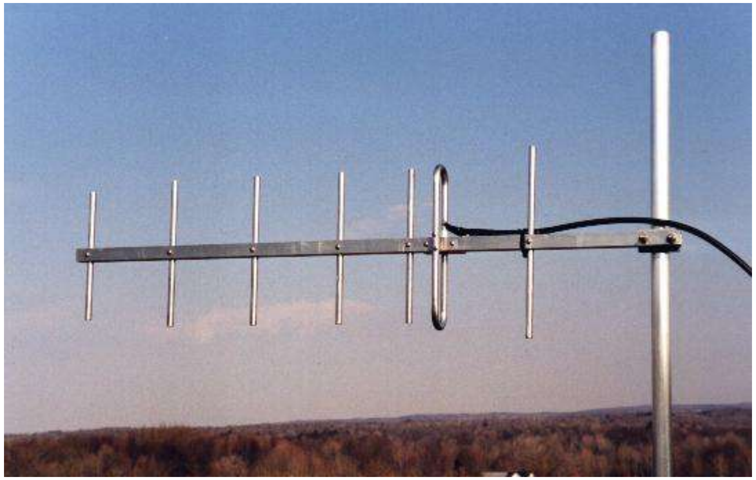
- Frequency Hopping
- Direct Sequence Spread Spectrum (DSSS)
- Use in 802.11 and 802.11b

Antennas

Antennas are conductors that radiate and collect EM energy

- Lots of types...
- Antennas generally designed for a certain range of frequencies





Radiation Patterns

Most antennas do not operate equally well in all directions.

- An antenna's *radiation pattern* represents the energy it transmits/collects in each direction in space

Simplest antenna is a *free-space isotropic radiator*

- An idealized point in space that radiates energy in all directions equally.

Antenna gains are measured in dBi

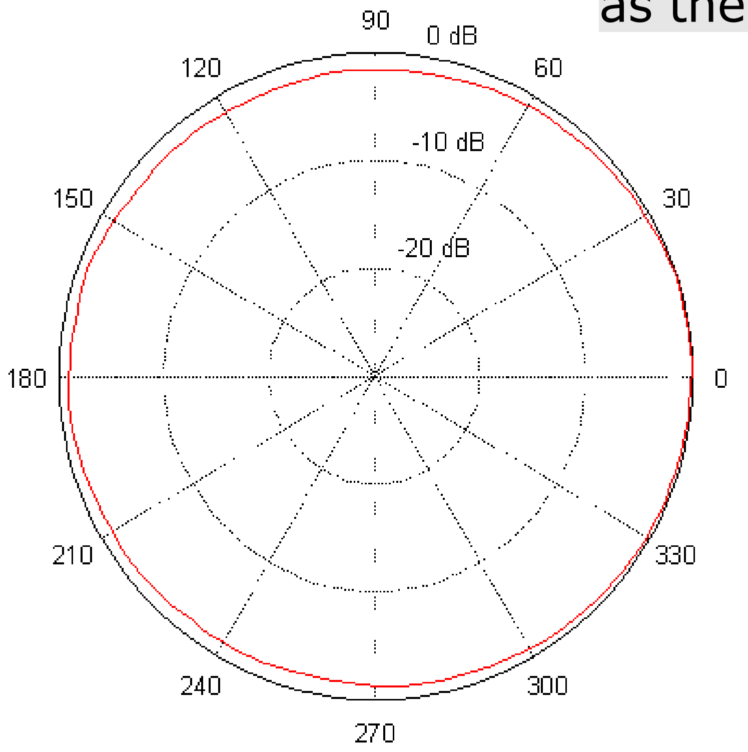
- Power output in a direction compared to that produced by a perfect isotropic antenna
- Example: an 8 dBi Yagi antenna improves on an isotropic antenna by 8 dB in its "preferred" direction
  - *8 dB = 10 log R, so R = 6.3*
- But ... the *total power* radiated by the antenna is the same!!

Radiation Patterns

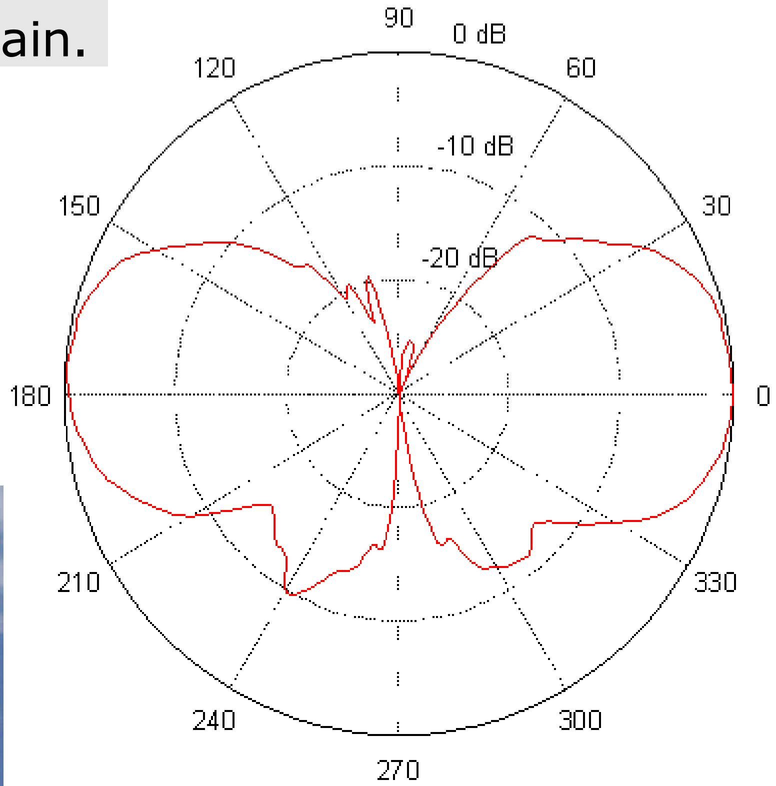
Most antennas do not operate equally well in all directions.

- An antenna's *radiation pattern* represents the energy it transmits/collects in each direction in space

Scale shown in dB, normalized to 0 dB as the maximum gain.



Horizontal

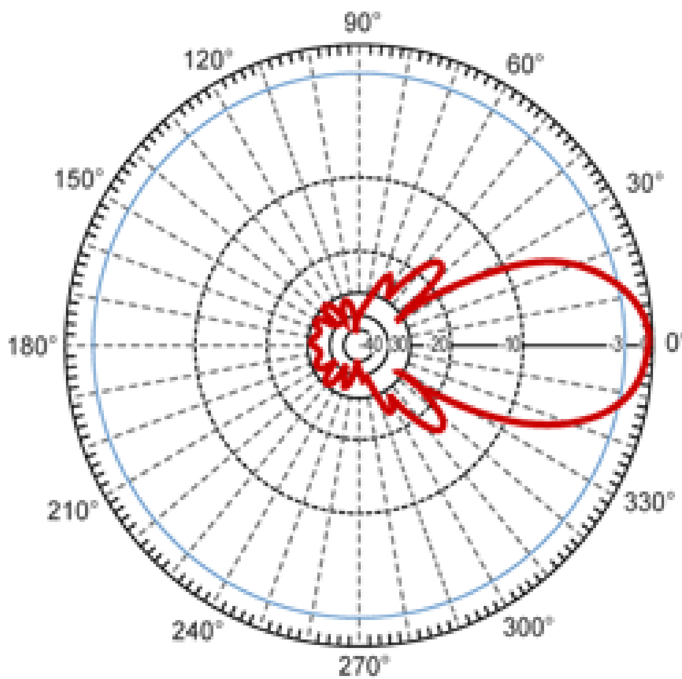


Vertical

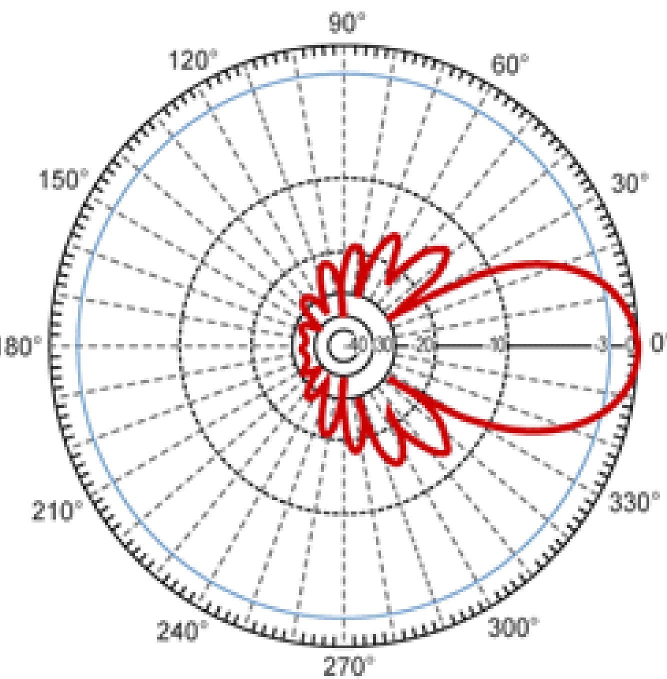
Radiation Patterns

Most antennas do not operate equally well in all directions.

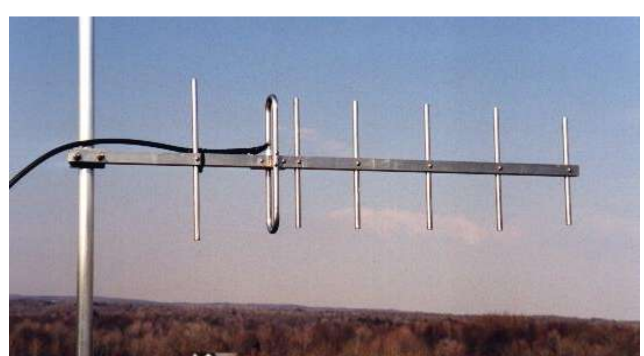
- An antenna's *radiation pattern* represents the energy it transmits/collects in each direction in space



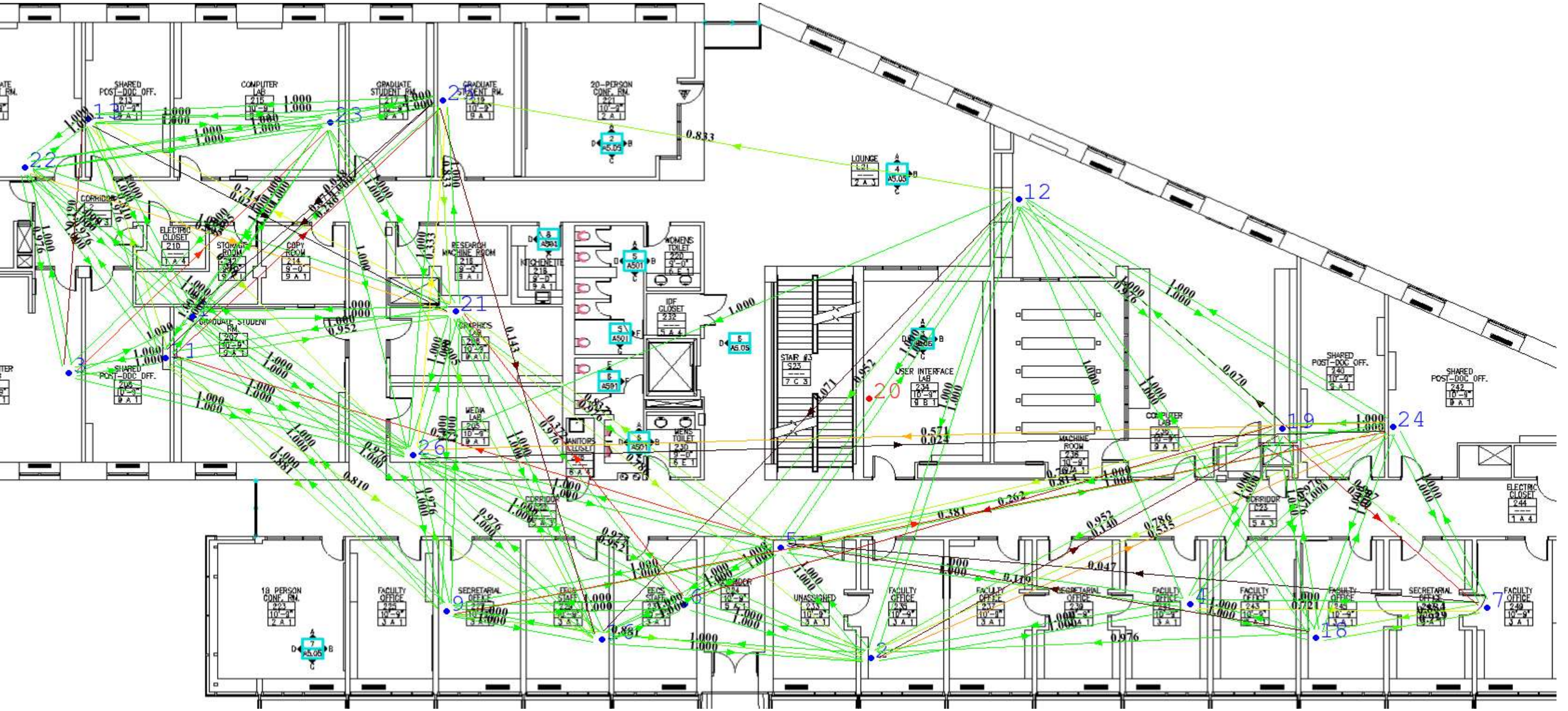
Vertical



Horizontal



Propagation in Maxwell Dworkin



- Propagation in real environments is very complex!
- **What are some possible causes?**

What causes fading?

Free Space Loss

- Radio signal spreading out over space

Interference with other transmitters

- Or other RF sources, e.g., microwave ovens

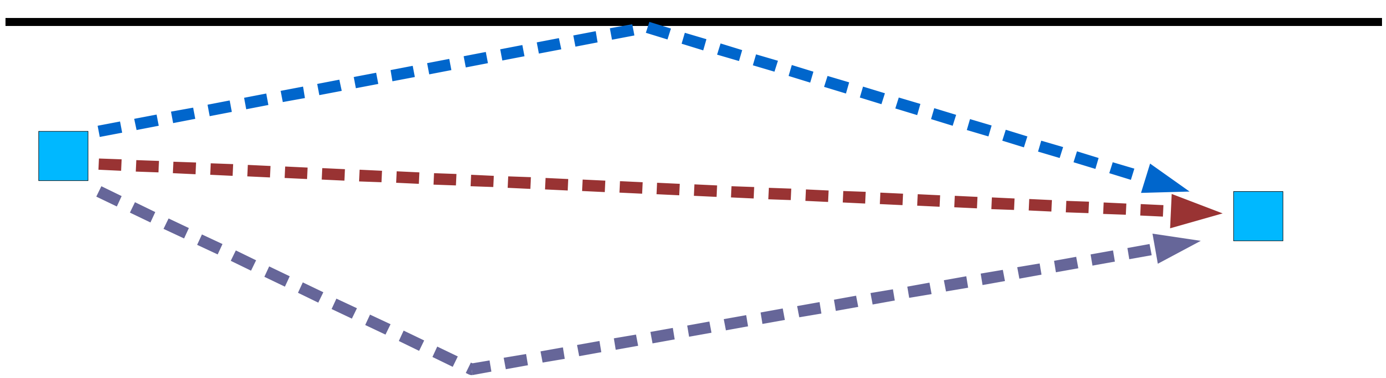
Fast fading

- As receiver moves over distances of ½ the wavelength, very large variations in received signal strength occur!

RF absorption by obstacles, the atmosphere, etc.

- We have noticed that radio connectivity in MD *improves* slightly at night

Multipath effects: RF signal interfering with itself!



Free Space Loss

RF signals disperse with distance

- Receiving antenna will pick up less powerful signal the further it is from the transmitter

Free Space Loss is:

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{G_r G_t \lambda^2}$$

P_t Signal power at transmitter
P_r Signal power at receiver
G_t Gain of transmitting antenna
G_r Gain of receiving antenna
λ Carrier wavelength
d Distance from transmitter to receiver

Example

- Frequency of 2.4 Ghz (λ = 3e8 / 2.4e9 = 0.125 m)
- Receiver is 30 m away
- Each have 2 dBi omni antennas
- Pt / Pr = $(4 * 3.14 * 30)^2$ / $(2 * 2 * 0.125^2)$ = 142122.30 / 0.0625 = 2273956
- Loss is then -10 * log (1 / 2273956) = -10 log 4.39e-7 = -63 dB

Fading models

Apart from FSL, there are lots of other sources of attenuation

- Many models have been proposed to capture these effects in a simple form.

Rayleigh fading

- Captures effects of multipath reception
- Assumes all received signals have same strength

Rician fading

- Captures one direct LOS path plus several weaker multipath signals

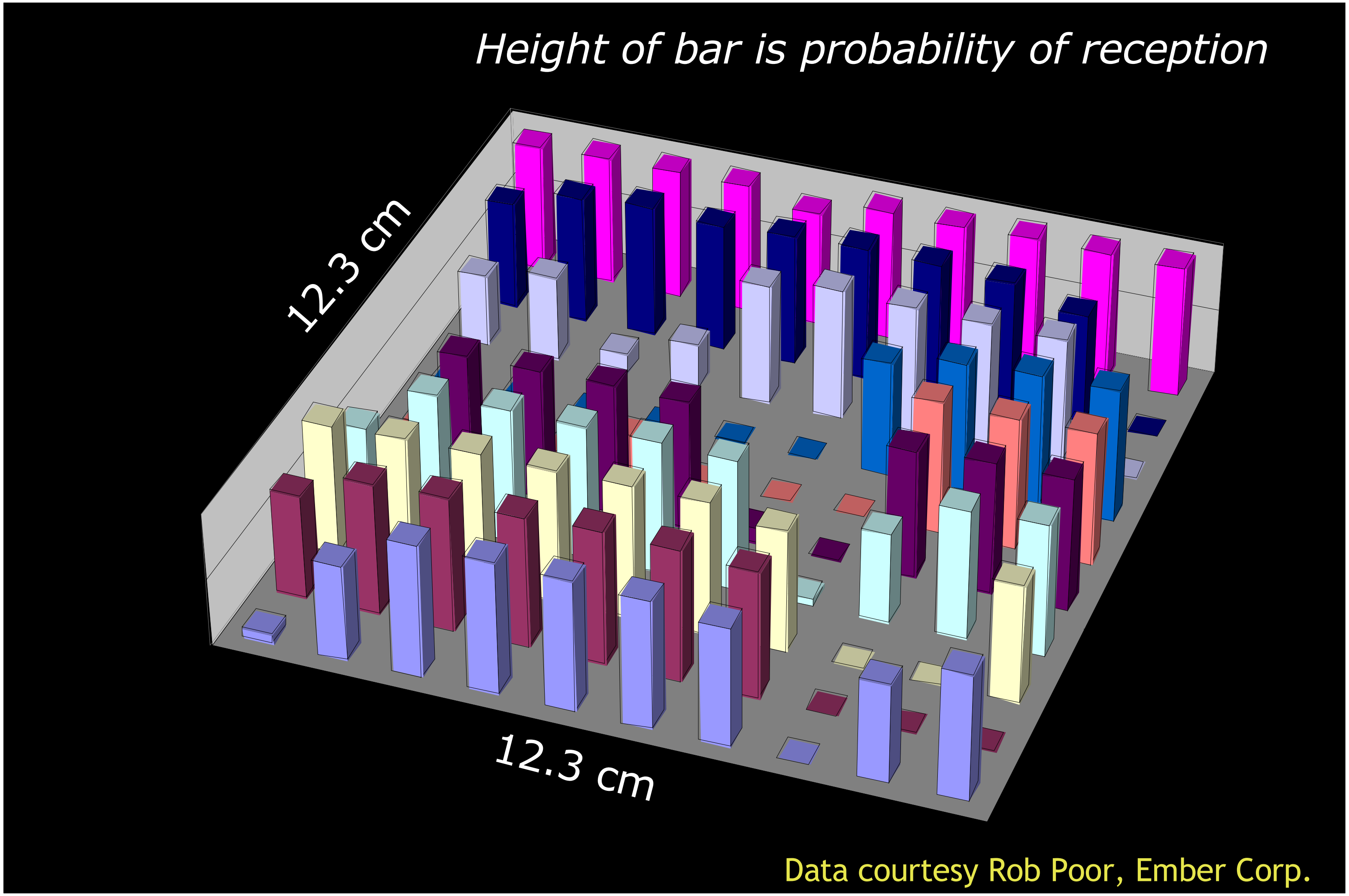
Wall Attenuation Factor model

- Accounts for attenuation according to how many floors and walls a signal passes through (indoor environment)

Small-Scale Fading

Very large changes in signal strength can occur over small changes in transmitter-receiver distance!

- Due to multipath interference: multiple waves colliding at receiver with different phase
- This occurs over a single wavelength!



Spread Spectrum

Idea: Spread transmission over a wider bandwidth

- Initially developed for military applications
- Makes jamming and interception of signals more difficult

Simplest approach: Frequency Hopping (FHSS)

- Use a range of base frequencies f_1, f_2, ... f_n
- Transmitter periodically “hops” to a new frequency in a pseudorandom pattern
  - *What does this require the receiver to do ... ???*

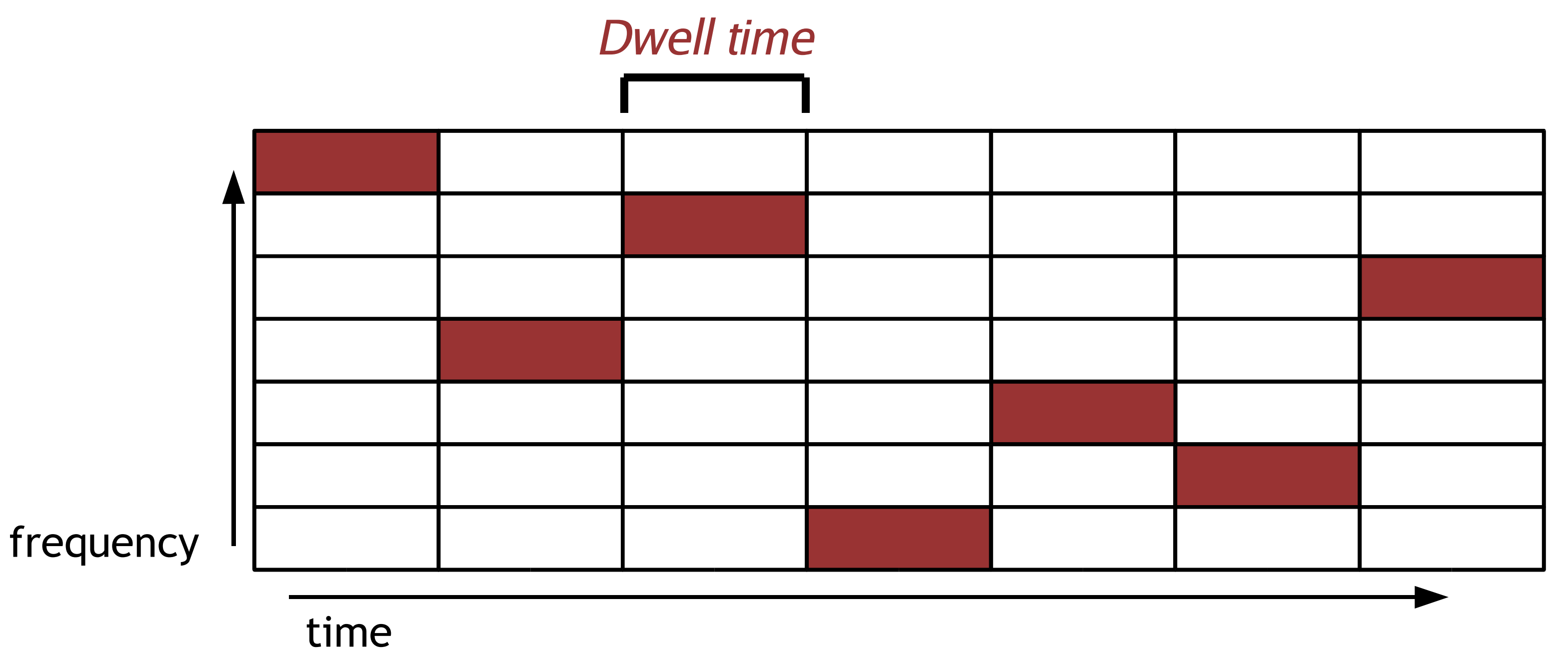
Spread spectrum is used in essentially every wireless network.

- Mitigates the effects of noise and multipath effects
- Allows multiple transmitters in same frequency range
  - *FCC **requires** use of spread spectrum for signals in ISM band above a certain transmission power.*

Frequency Hopping

Spread the signal over a wider bandwidth by transmitting over a range of frequencies.

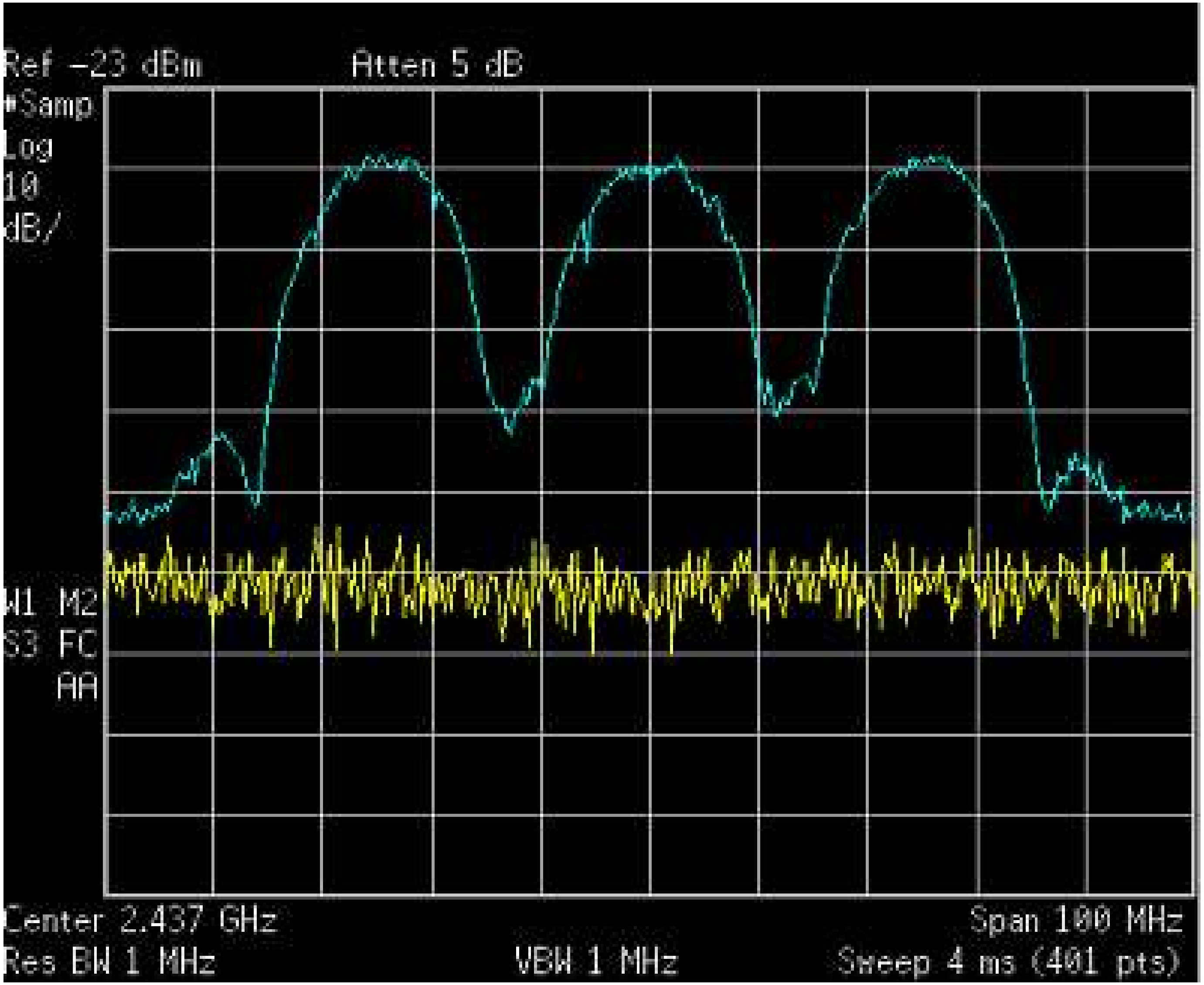
- Transmitter and receiver periodically “hop” to a new *channel*
- A *spreading code* is used to determine the hopping sequence
  - *Must be shared by transmitter and receiver*



Example: Original 802.11 spec used 96 1-MHz channels

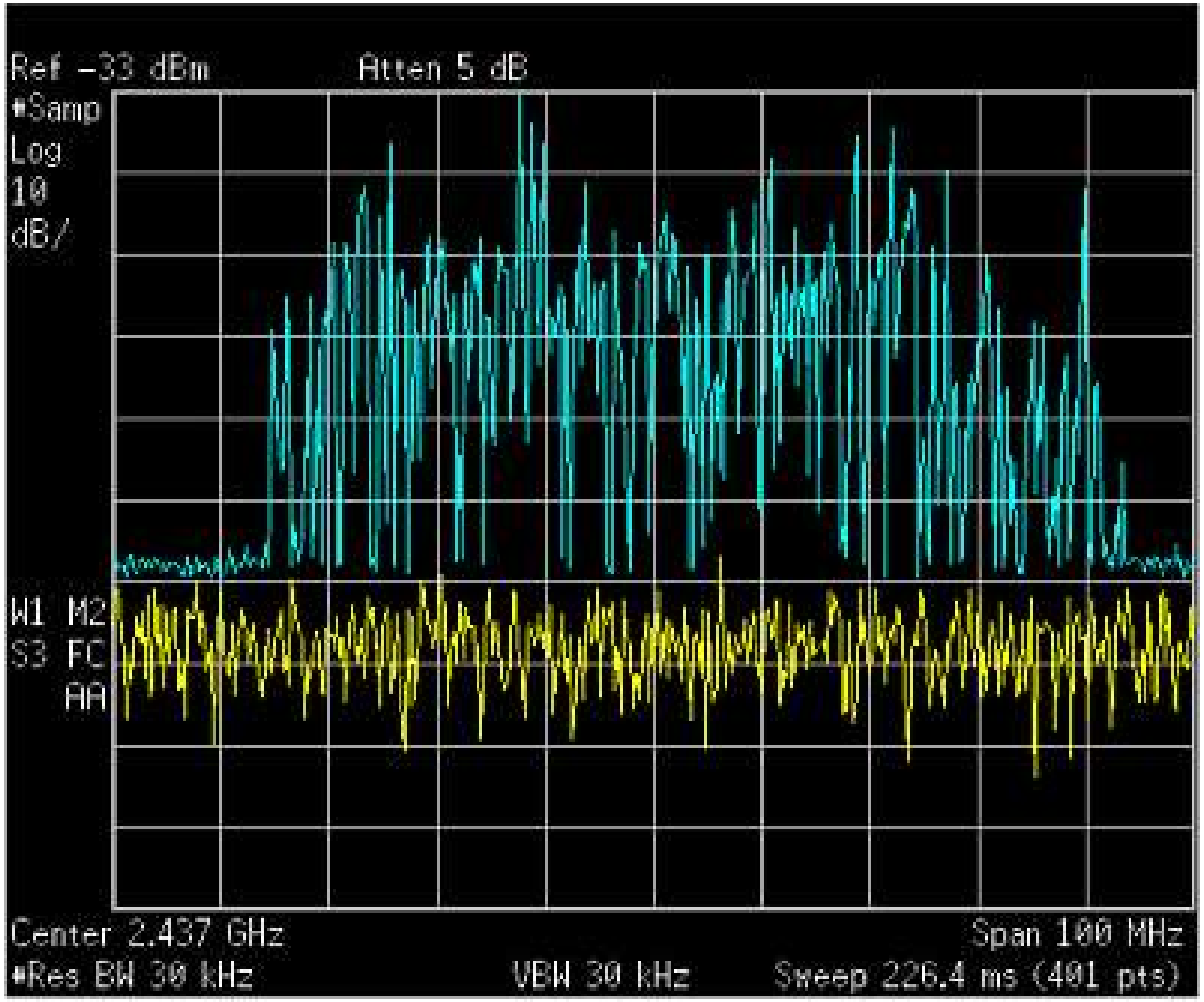
- Only channels 2—79 (2.402—2.479 MHz) permitted for use in U.S.
- *Dwell time* of about 390ms between each hop

802.11 Spectrogram



- Three distinct channels (1, 6, and 11)

Frequency Hopping Spectrogram



Spreading code

How do the transmitter and receiver agree on the spreading code?

One approach: Standardize the hop sequence.

- Original 802.11 had 26 orthogonal (non-overlapping) hop sequences
  - *e.g., sequence 1 is channels <3, 26, 65, 11, 46 ... >*
- Receiving node listens on a fixed frequency until it receives a beacon frame
- Beacon frame indicates which hop sequence is in use, and the current index into the sequence
- Receiver must also synchronize to the transmitter's clock

What is the effect of interference?

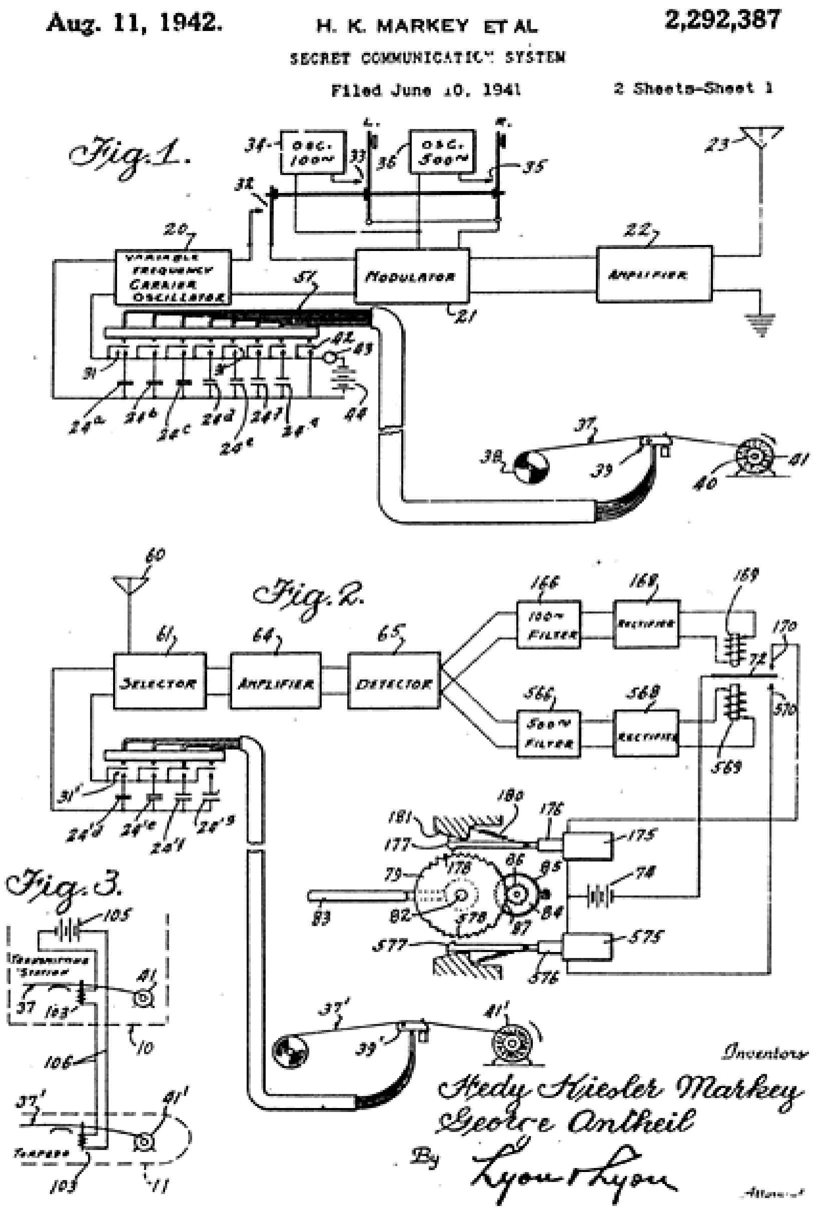
- Say a single channel is knocked out by (long term) interference.
- We have 80 channels of 1 MHz each (in the US)
- So, we are left with (79/80) channels, or 98.75% of the bandwidth

History of Spread Spectrum

Invented by Hollywood actress Hedy Lamarr in the 1940's

Hedy Lamarr and George Antheil

- First devised to guide torpedoes
- George Antheil (avant garde composer) helped develop the idea
- Patented by Lamarr and Antheil on August 11, 1942



Direct Sequence Spread Spectrum

Idea: Encode each bit as *multiple bits* in transmitted signal

- Each transmitted bit is called a *chip*
- *Chipping code* often based on pseudorandom bit sequence

Time →

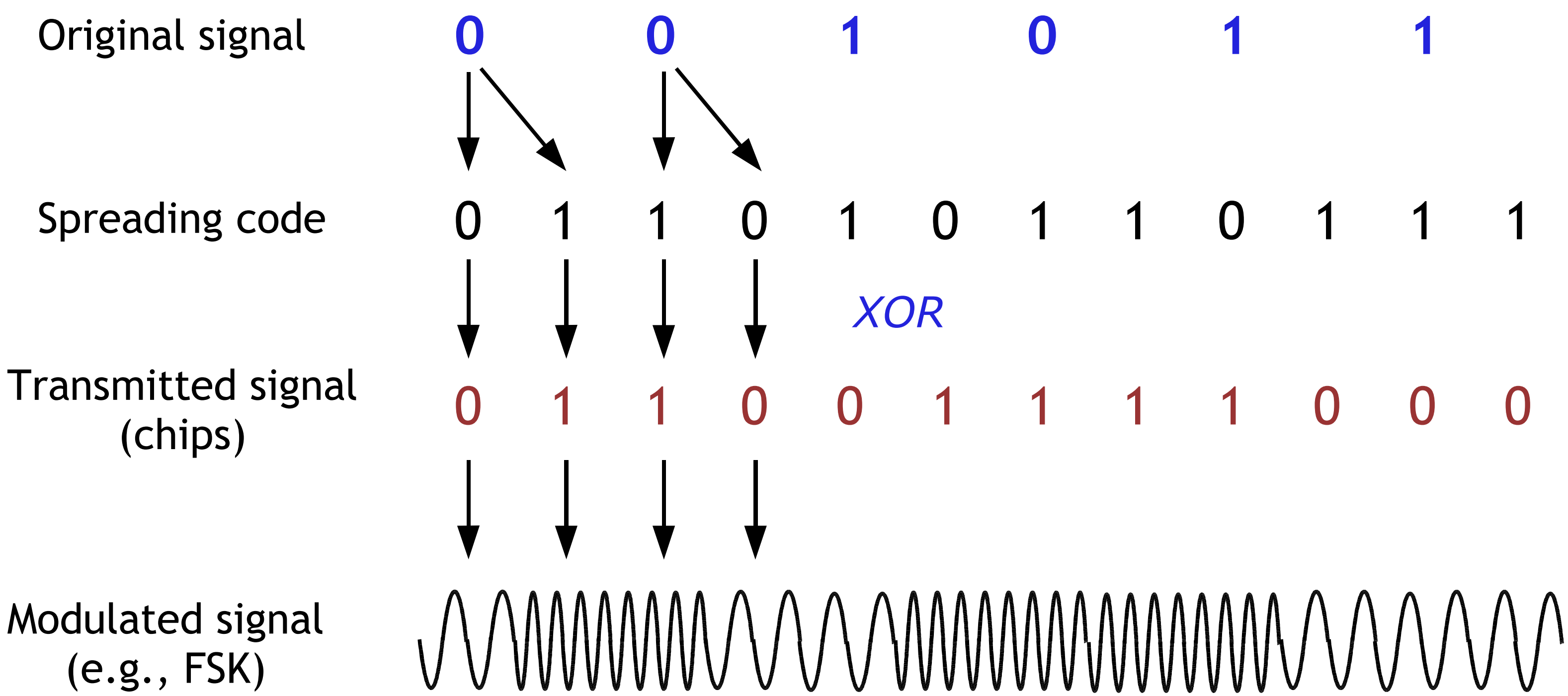
Original signal	**0**		**0**		**1**		**0**		**1**		**1**	
Spreading code (random bits)	0	1	1	0	1	0	1	1	0	1	1	1
Transmitted signal (chips)	0	1	1	0	0	1	1	1	1	0	0	0

Combine original with spreading code using XOR

Transmitted signal uses higher bandwidth than original signal

- Spreading ratio: Number of chips used to transmit a single bit

Putting it all together



Direct Sequence, cont'd

Why does DSSS work?

- Need a wider bandwidth to transmit the chip sequence (to maintain the same underlying data rate)
- So, DSSS effectively *spreads the signal over a wider bandwidth*

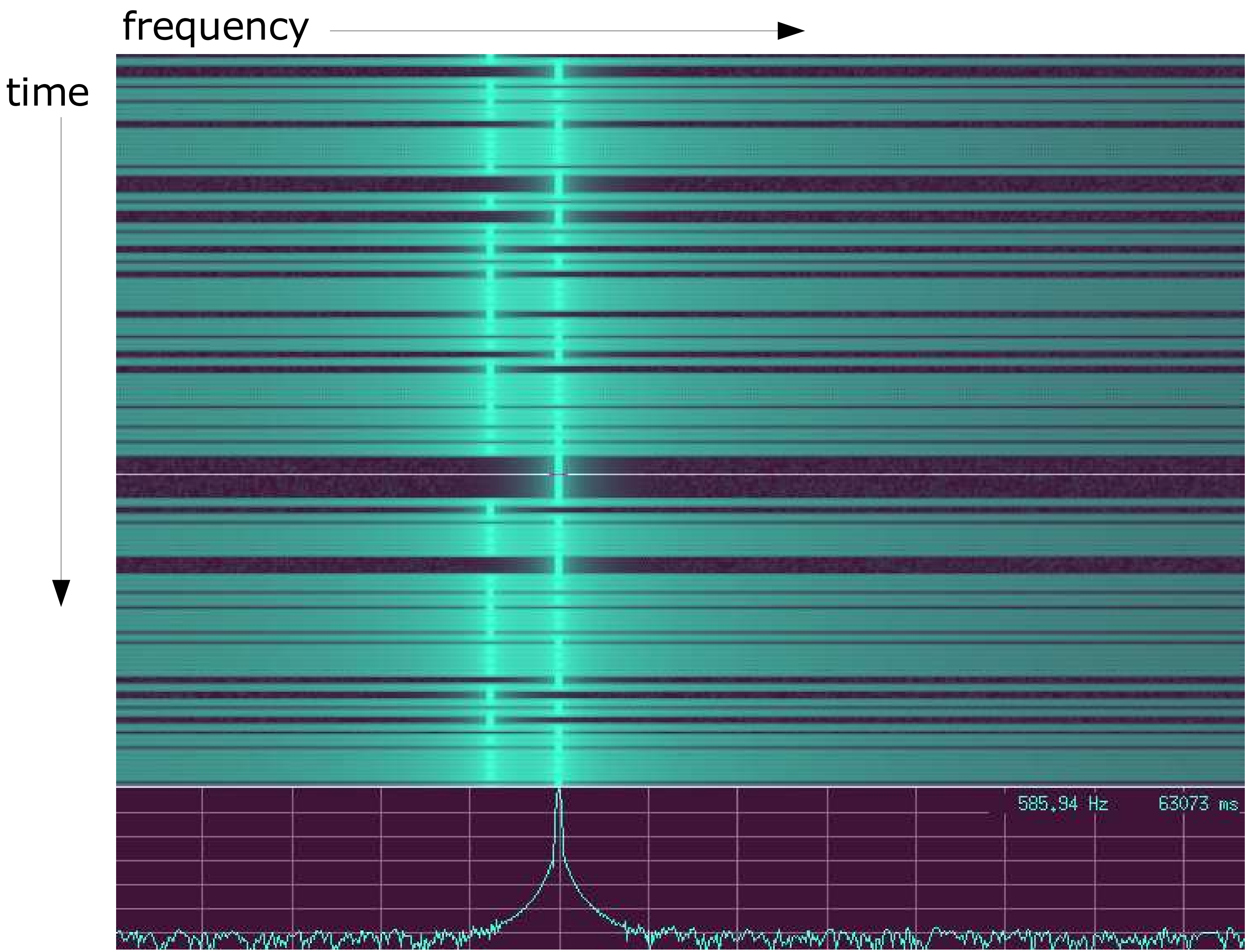
Recall Shannon Capacity Theorem:

- Channel capacity = 2B log M (where B is bandwidth, M is # of voltage levels)
- A 10-to-1 spreading code increases the required channel capacity by 10x
- Therefore, increases the required bandwidth by 10x as well!!

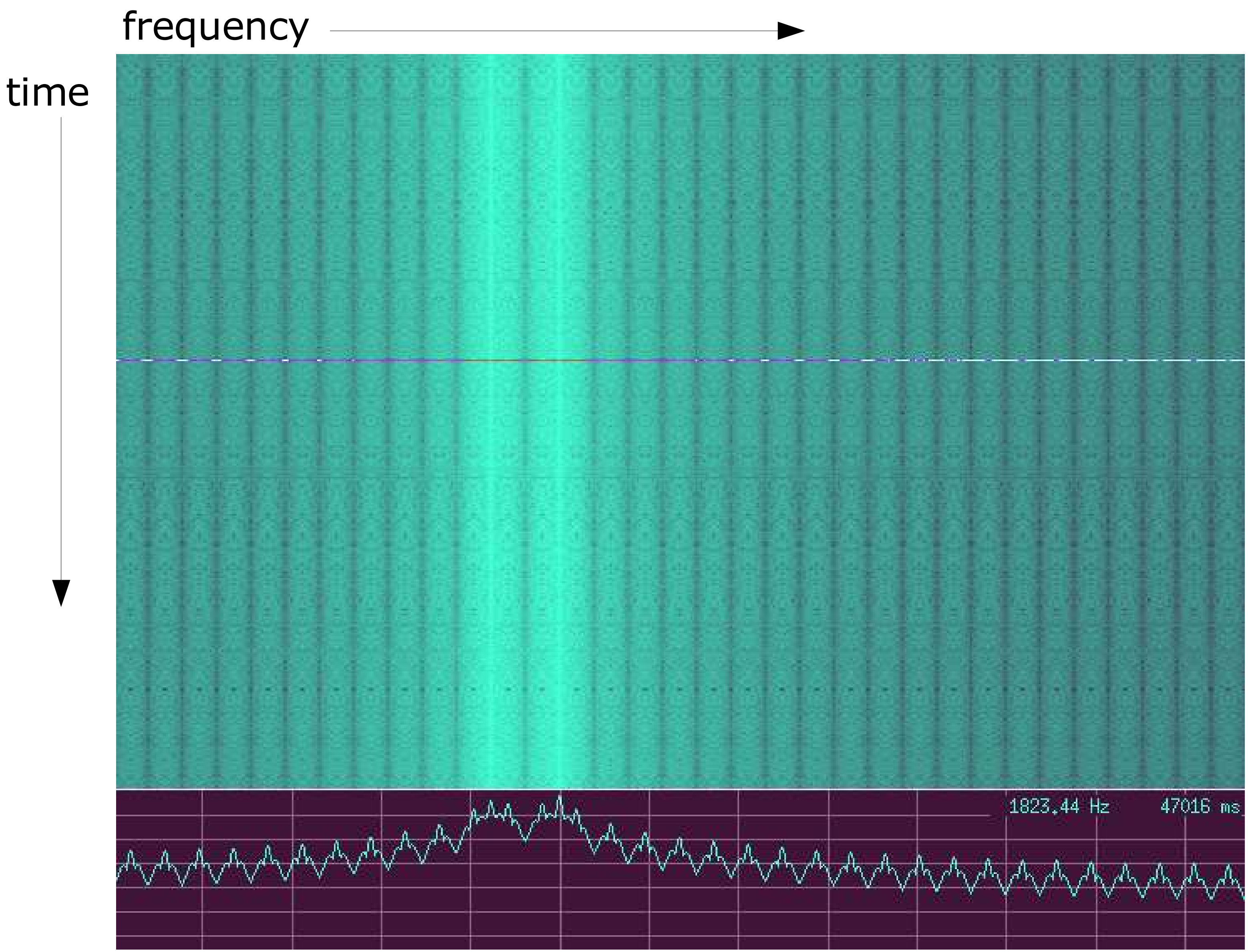
Example (*assume M = 2*):

- Original data stream at 1000 bits/sec
  - *Required bandwidth = C / 2 = (1000 / 2) = 500 Hz*
- Use of a 10-to-1 spreading code increases data rate to 10,000 bits/sec
  - *Required bandwidth = C / 2 = (10000 / 2) = 5,000 Hz*

Original FSK signal



DSSS-encoded FSK signal



Direct Sequence, cont'd

DSSS signal looks like *noise* to any narrowband receiver

- Avoids interference with older narrowband systems

DSSS signal is very resilient to interference

- Can lose several chips in a word before the data bit is corrupted

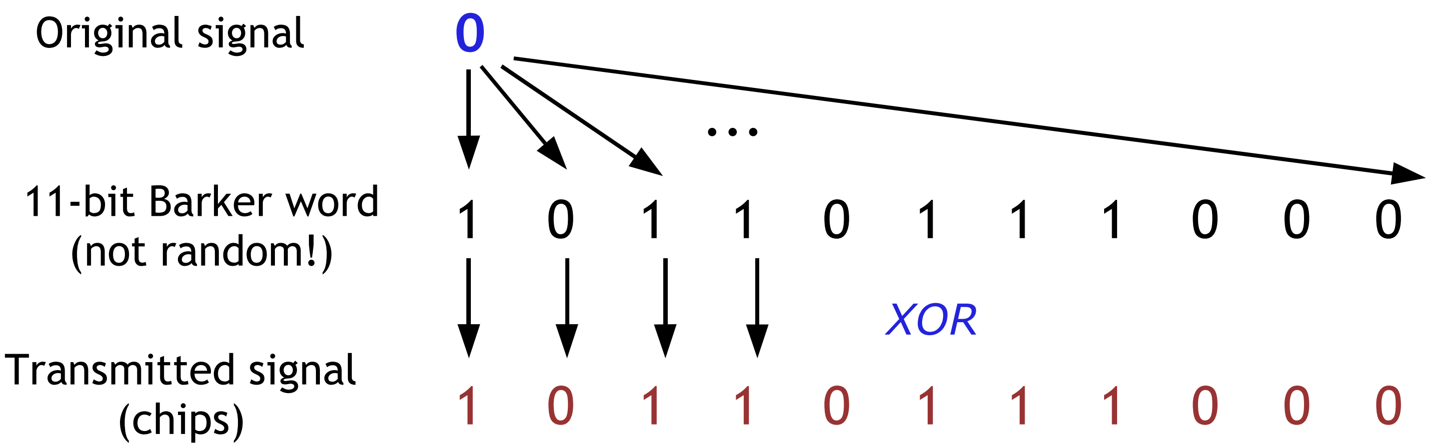
Multiple users can share bandwidth easily

- Simply by using different chipping sequences!
- No need to allocate different frequency ranges to each transmitter/receiver pair

Barker sequence

Original 802.11 DS PHY used the Barker chipping sequence

- 11-to-1 spreading ratio



- Barker sequence has low autocorrelation properties
  - *Multiple overlapping signals do not interfere: resists multipath effects*
- Receiver decodes by counting number of "1" bits during each received word.
- An 11-bit word with 6 "1" bits must correspond to a transmitted 0

802.11b: HR/DSSS

Original 802.11 had max rate of 1 Mbps

- 11 chips per transmitted bit, B-PSK modulation
- (Extension to allow 2 Mbps data rate using Q-PSK modulation)

Limitation: Q-PSK requires receiver to detect ¼ phase shift

- Very difficult to detect smaller phase shifts than this

802.11b extended data rate to 11 Mbps

- New modulation scheme: Complementary Code Keying (CCK)
- Turns each word into one of 64 8-bit symbols
  - *Nice mathematical properties that make it easy to recover symbol in presence of significant noise*
- Results in 1.375 M symbols/sec, 8 bits/symbol = 11 Mbps
- Output of CCK modulated using Q-PSK onto carrier

Next Lecture

Medium Access Control (MAC) Schemes

Reading: Stallings Ch. 9, Ch. 10

- Focus mainly on MAC schemes ... can skim over details of satellite transmission