Introduction to Electrical and Computer Engineering

Wireless Communication

© 2015-22 Tilman Wolf

Module Outline

- Telephony system
- Cellular telephony
- Wireless transmissions
- Synchronization of distributed systems
- Errors, error detection, error correction
- Multipath transmissions

© 2015-22 Tilman Wolf

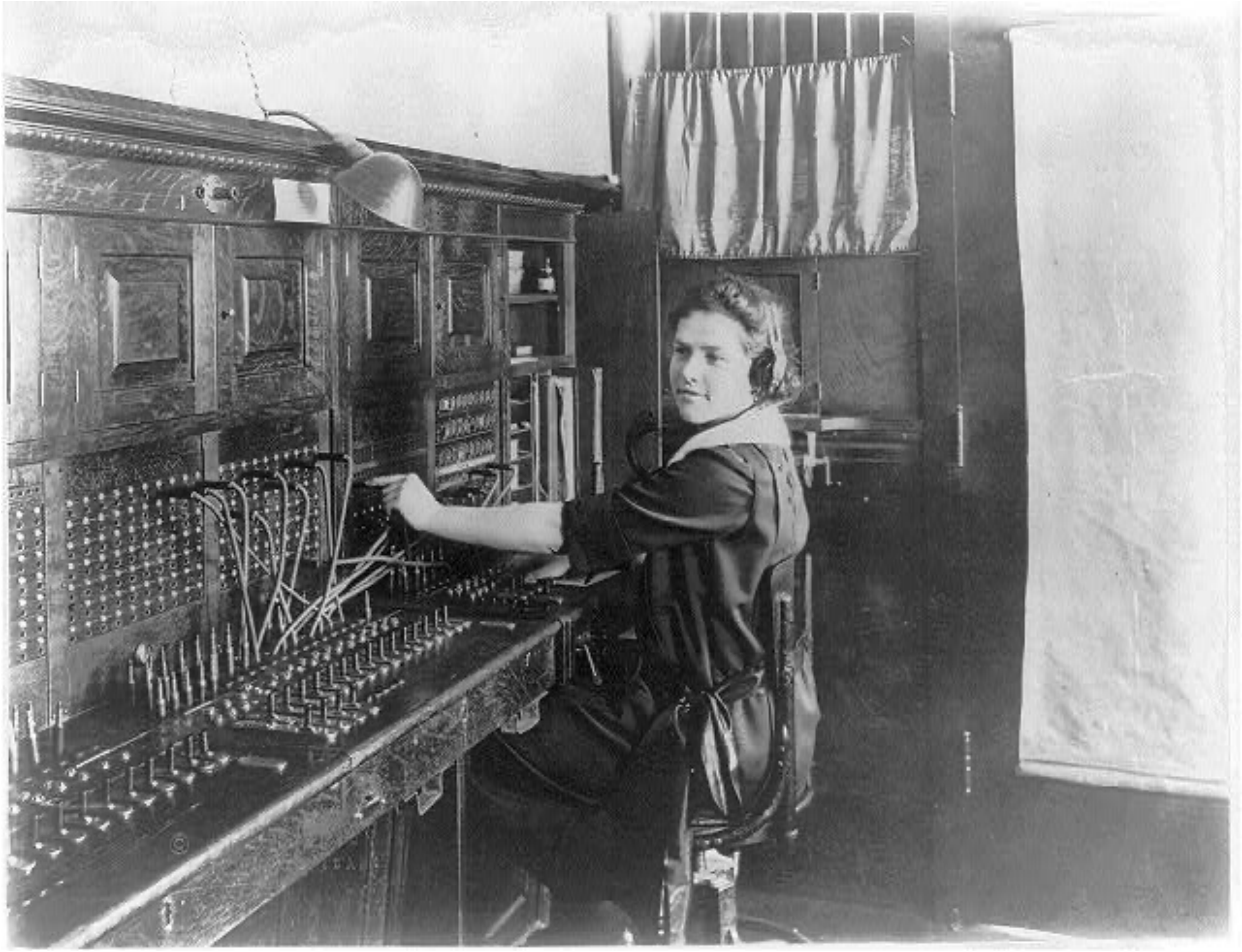
Phone Call

- What happens when calling a phone?

© 2015-22 Tilman Wolf

Telephone Network 1/4

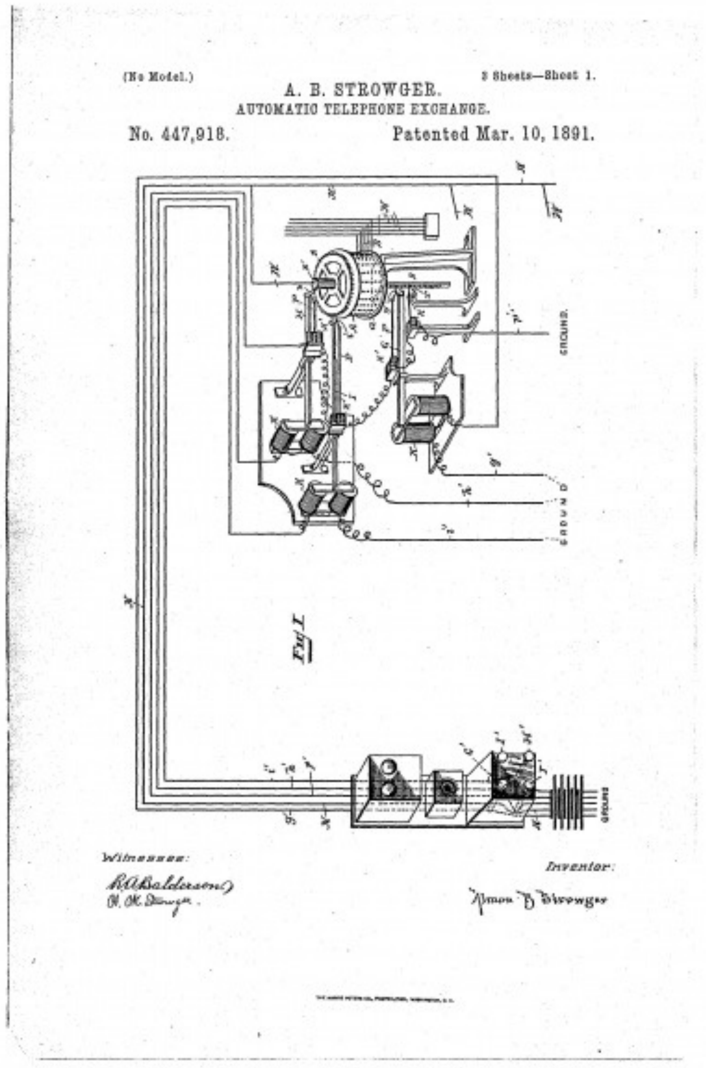
- Two phone need to be "connected" to each other
- First generation technology: human

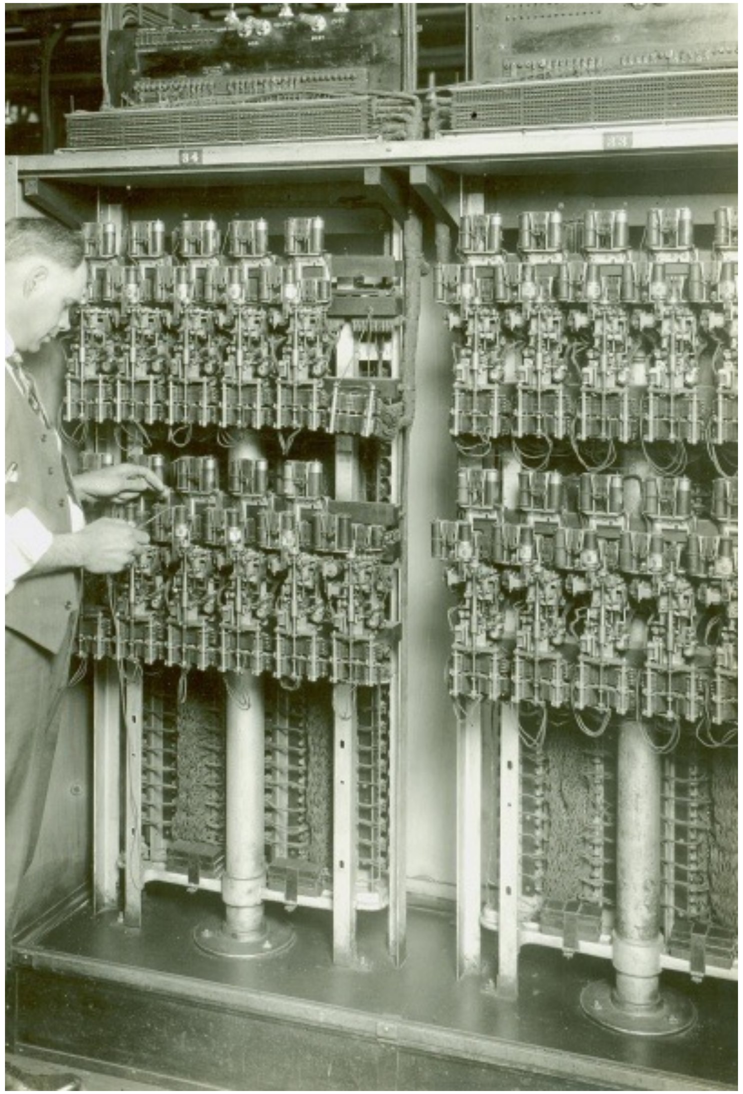


© 2015-22 Tilman Wolf

Telephone Network 2/4

- Second generation technology: electromechanical



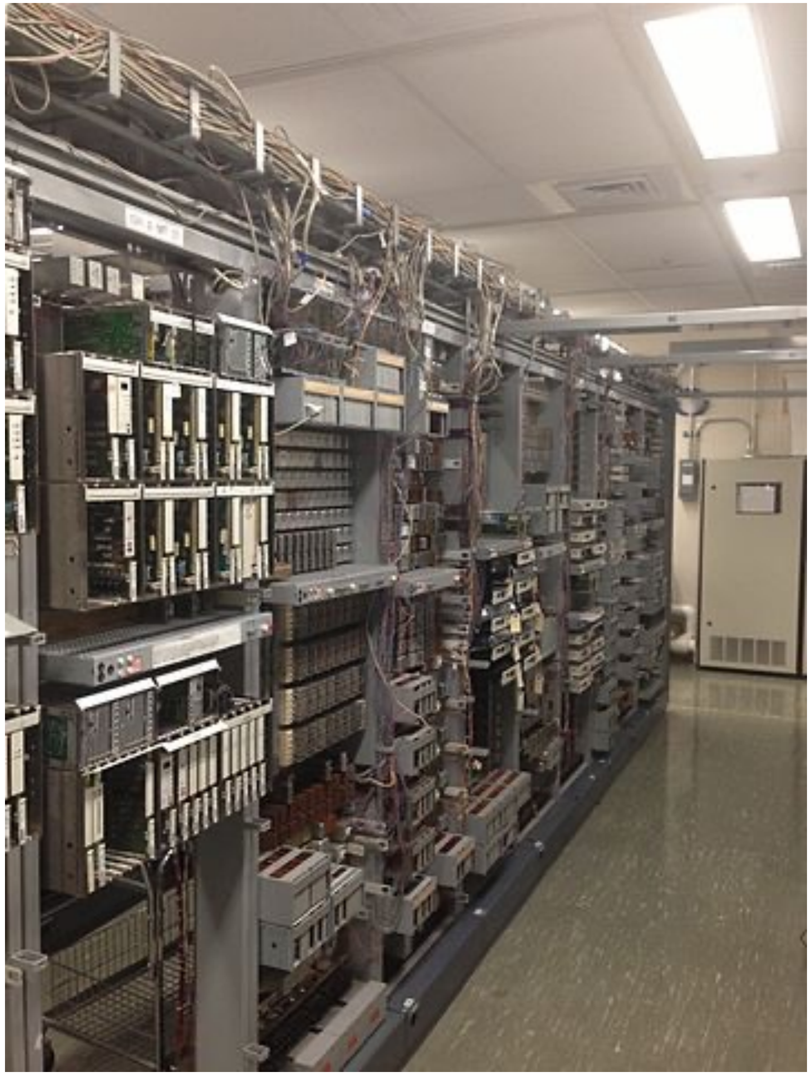


From: http://ethw.org/Electromechanical_Telephone-Switching

© 2015-22 Tilman Wolf

Telephone Network 3/4

- Third generation: fully electronic

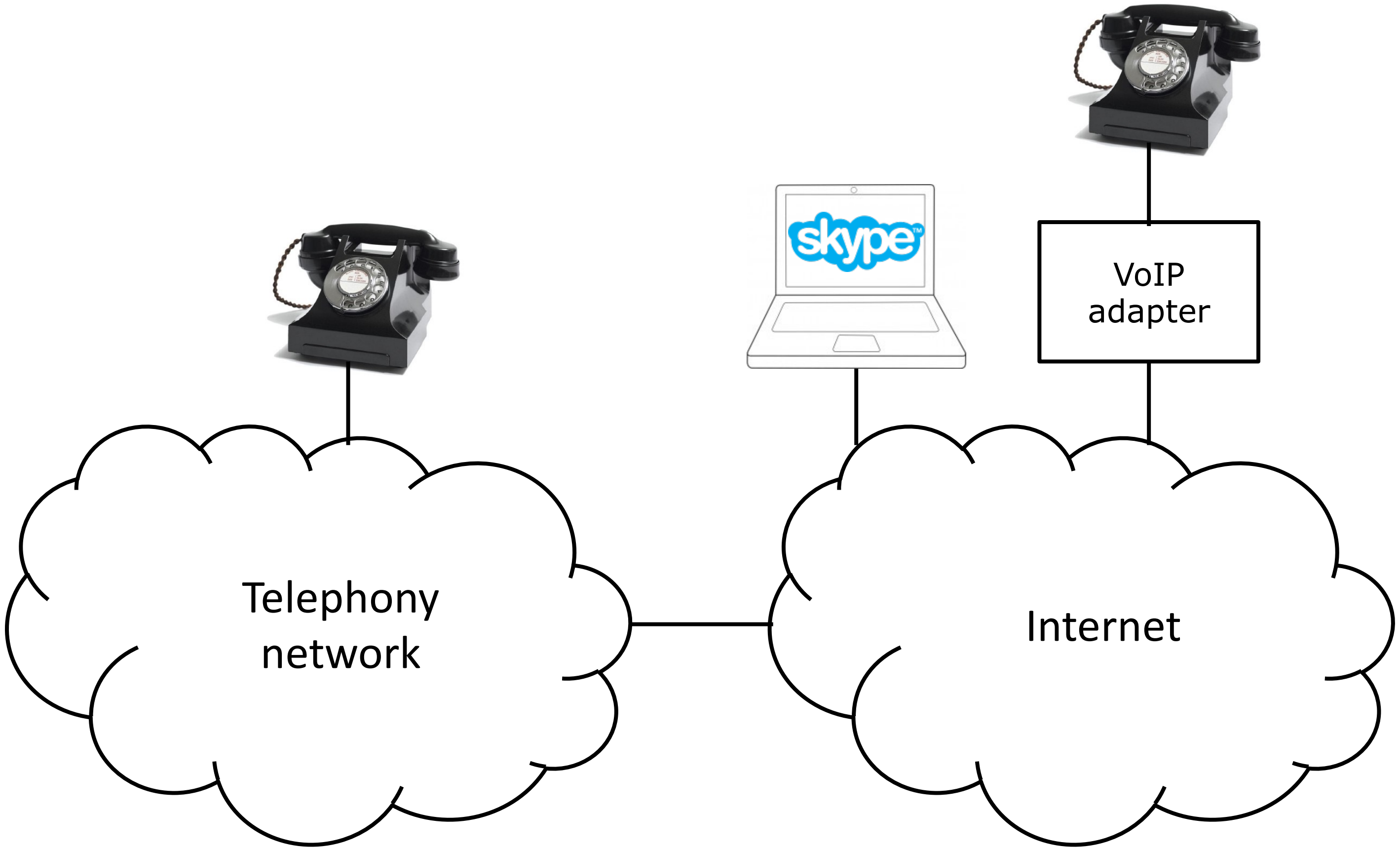


https://en.wikipedia.org/wiki/Number_One_Electronic_Switching_System

© 2015-22 Tilman Wolf

Telephone Network 4/4

- Fourth generation: virtualized



Large Engineered System 1/2

- Telephone network is one of the largest engineered systems
  - How many phones?
  - Who are the "players" in the telephony ecosystem?
  - What kind of structure does telephone system have?

© 2015-22 Tilman Wolf

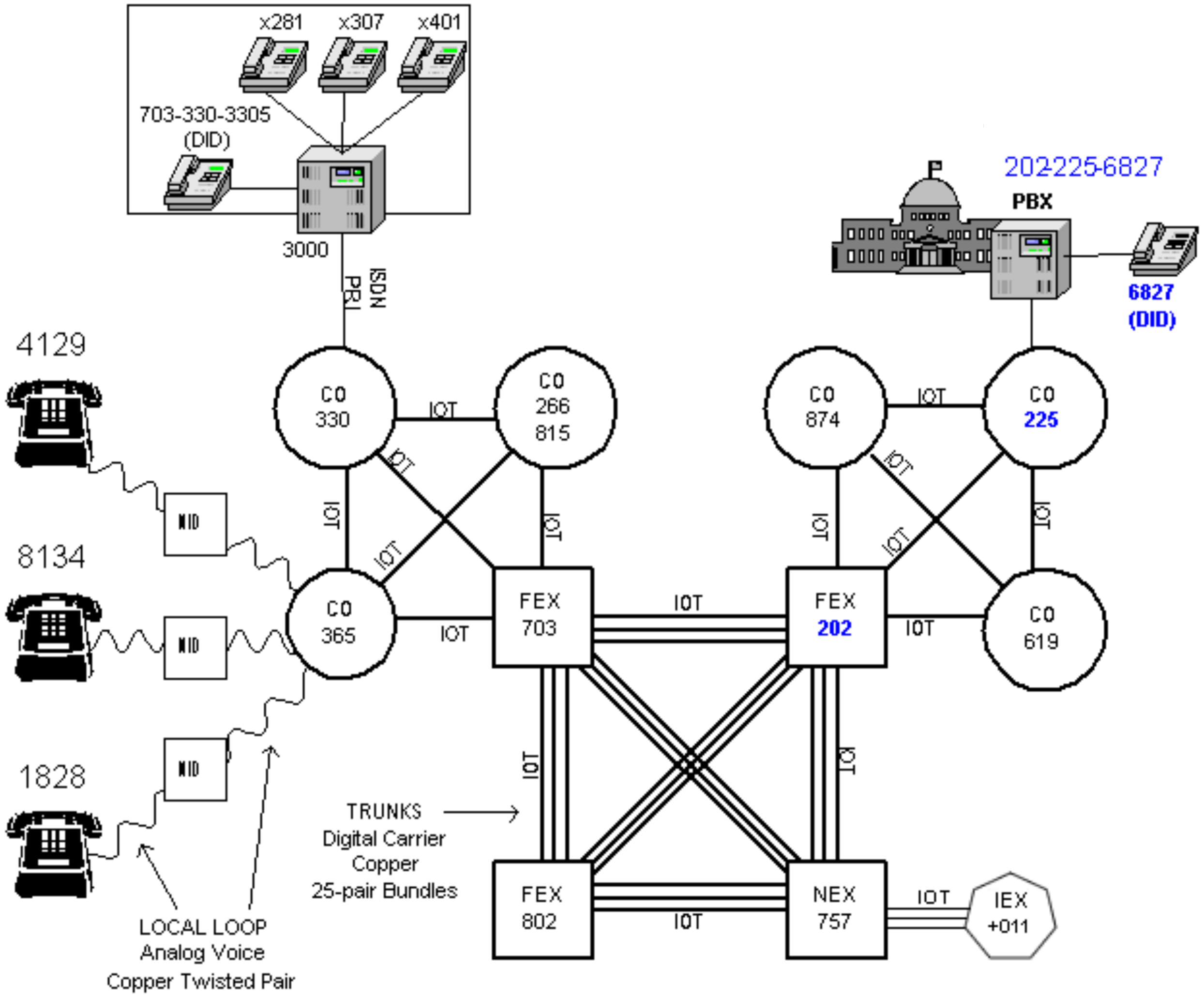
Large Engineered System 2/2

- Telephone network is one of the largest engineered systems
  - How many phones?
    - Billions
  - Who are the “players” in the telephony ecosystem?
    - End-users / customers / humans
    - Telephone companies (local, long distance, international)
    - Computers (e.g., automated system)
  - What kind of structure does telephone system have?
    - Hierarchy: local numbers, area codes, country codes
    - Landlines align with number structure
    - Mobile phones do not follow number structure

© 2015-22 Tilman Wolf

Telephony Network

- Plain Old Telephone Service (POTS)
- Central office types
  - Local exchange connects local subscriber
  - Foreign exchange connects beyond local calling area
  - National exchange connects long-distance providers
  - International exchange connects to other countries
- Communication
  - Local loop is analog
  - Core of phone network digital



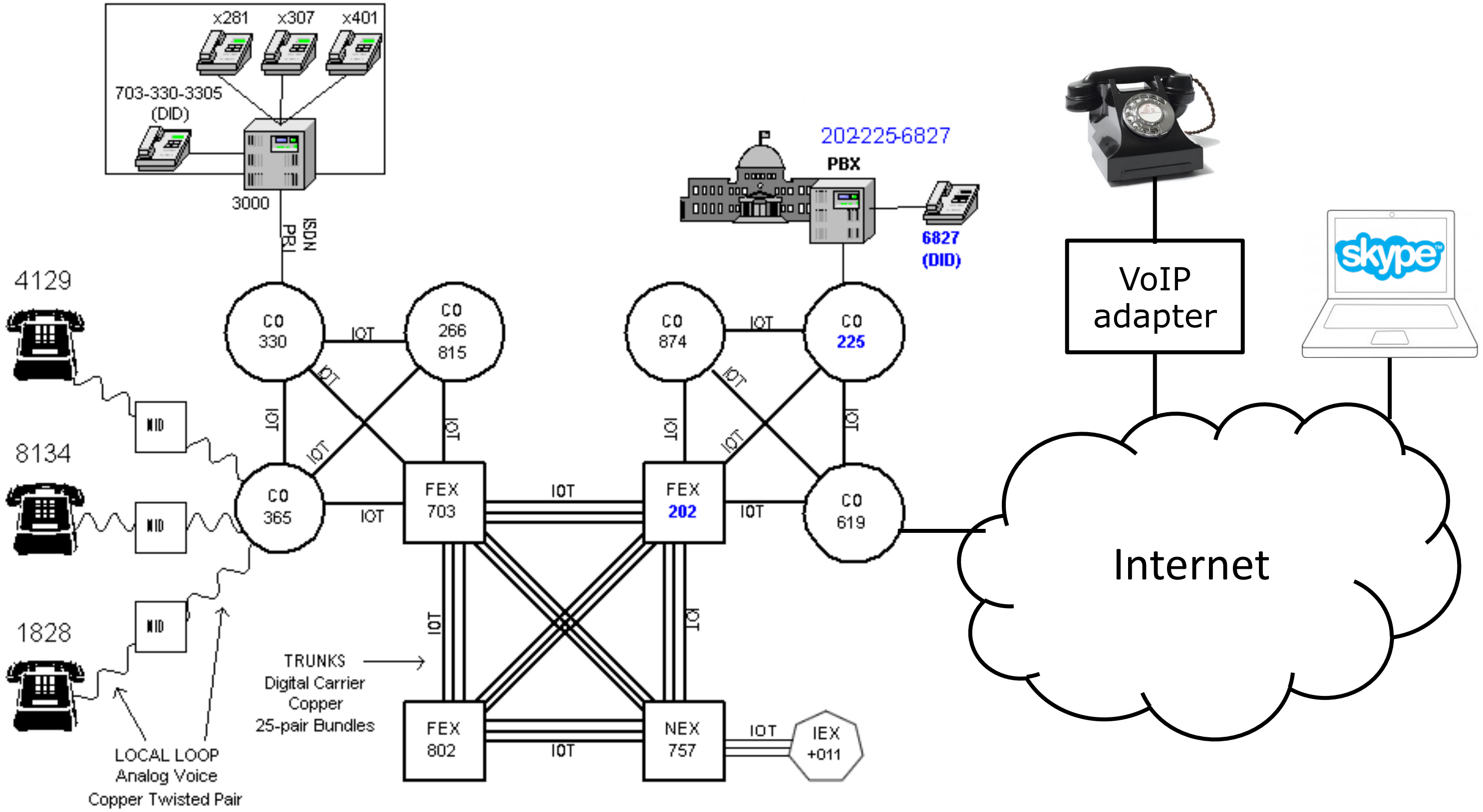
Internet Telephony 1/2

- Voice over Internet Protocol (VoIP)
  - VoIP adapter connects phone to Internet
- VoIP adapter is an embedded computing system
  - Digital encoding of voice
    - Sampling and quantization as discussed in Module 2
  - Encapsulates voice data in network protocols
  - Registers with phone number with
- All-software VoIP using computer
  - E.g., skype call to landline
- VoIP has no geographic constraint for phone number
  - Good: can have any phone number anywhere in the world
  - Bad: response to 9-1-1 calls are more difficult

© 2015-22 Tilman Wolf

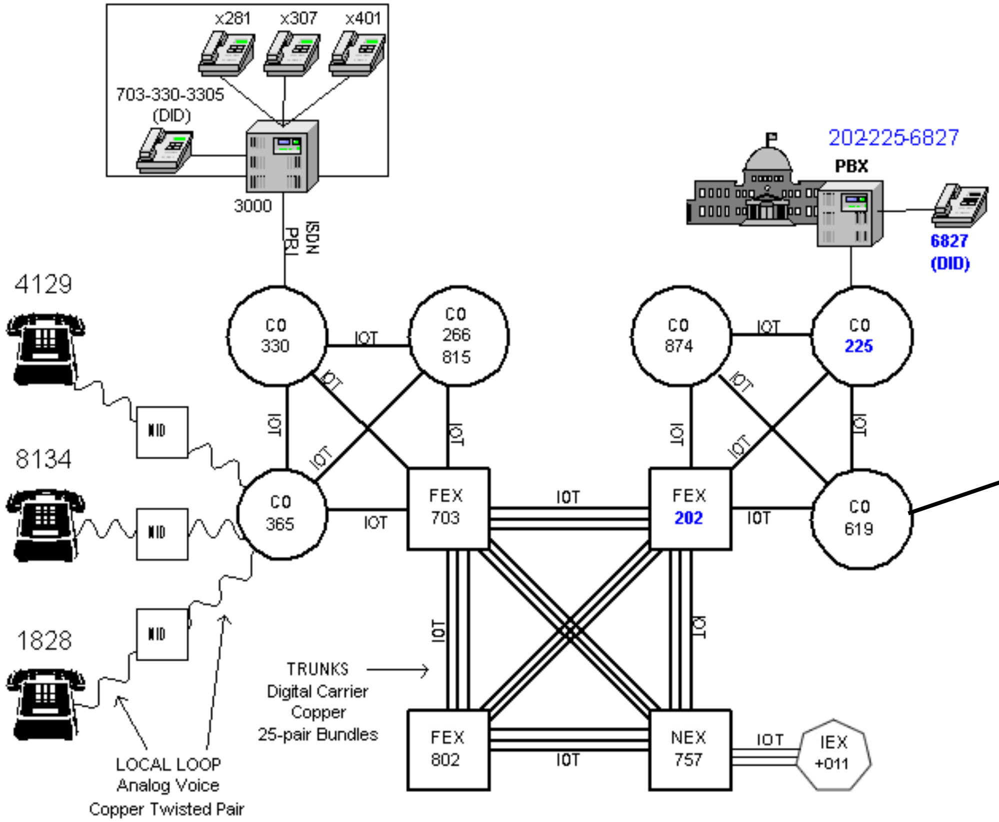
Internet Telephony 2/2

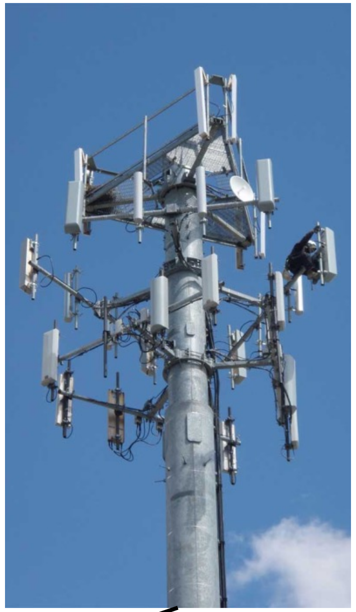
- Internet and telephony network connect together
  - Computer-to-computer calls not via telephone network (e.g., skype-to-skype, Facetime, etc.)



Cellular Telephony Network

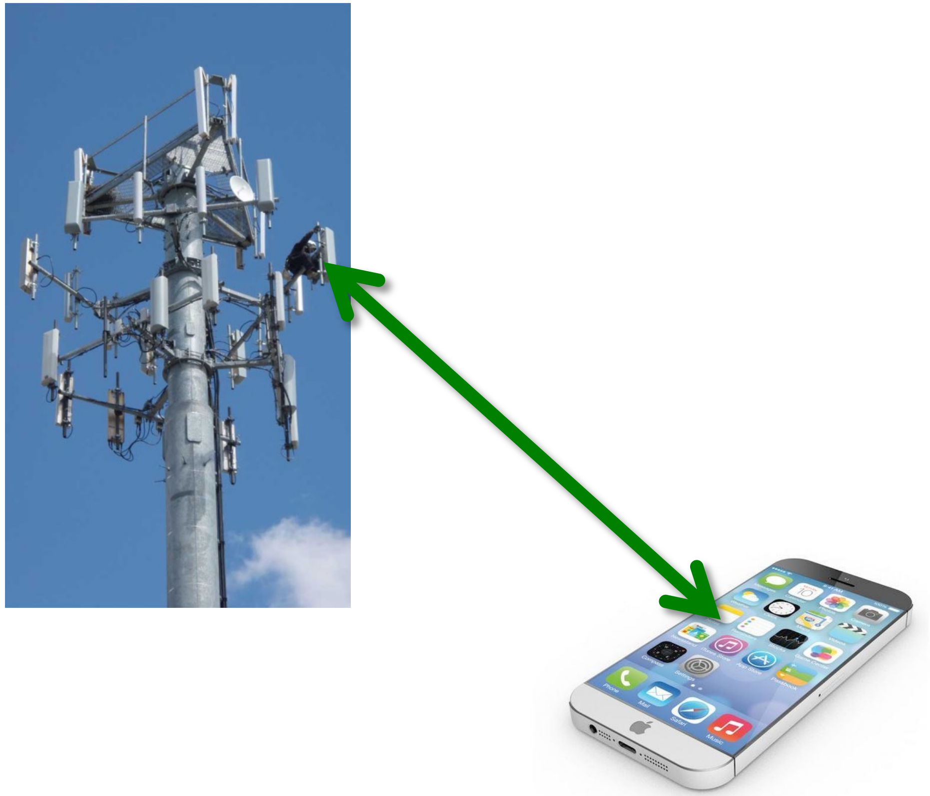
- Cellular network structure
  - Handset connects wirelessly to cell tower
  - Cell tower connects to wired infrastructure

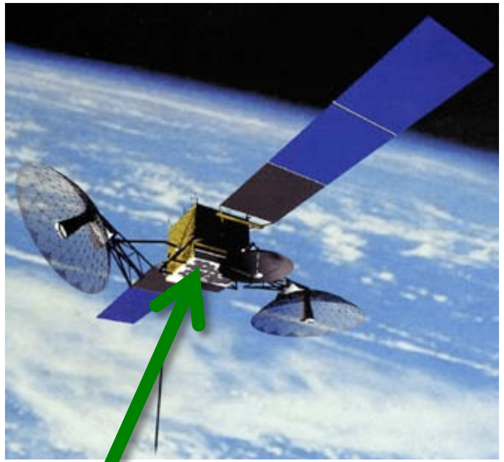




Satellite Phones

- Cell phone system does not involve satellites!
  - Satellite phones exist, but are not common

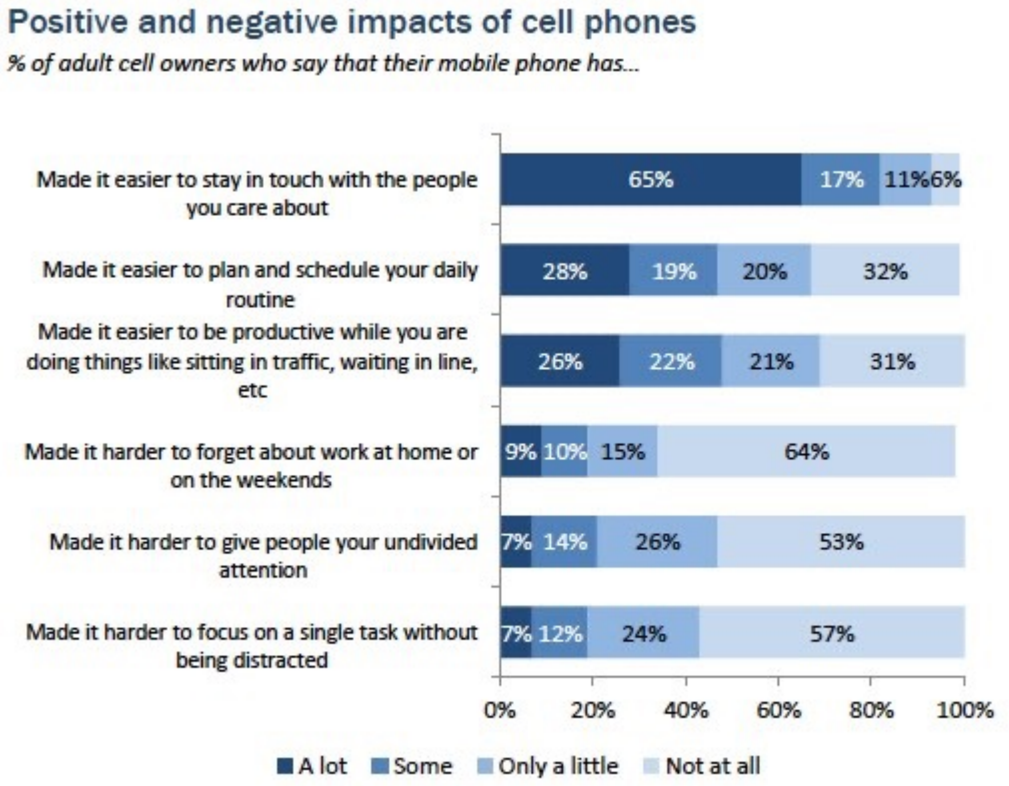




© 2015-22 Tilman Wolf

Societal Impact of Cell Phones

- Cell phone are extremely widely used
  - 6.8 billion subscribers worldwide
- One of the largest engineered systems
  - ECE is at core of cell phone technology
- Amazing social impact
  - Lots of positive impact
  - Some negative impact

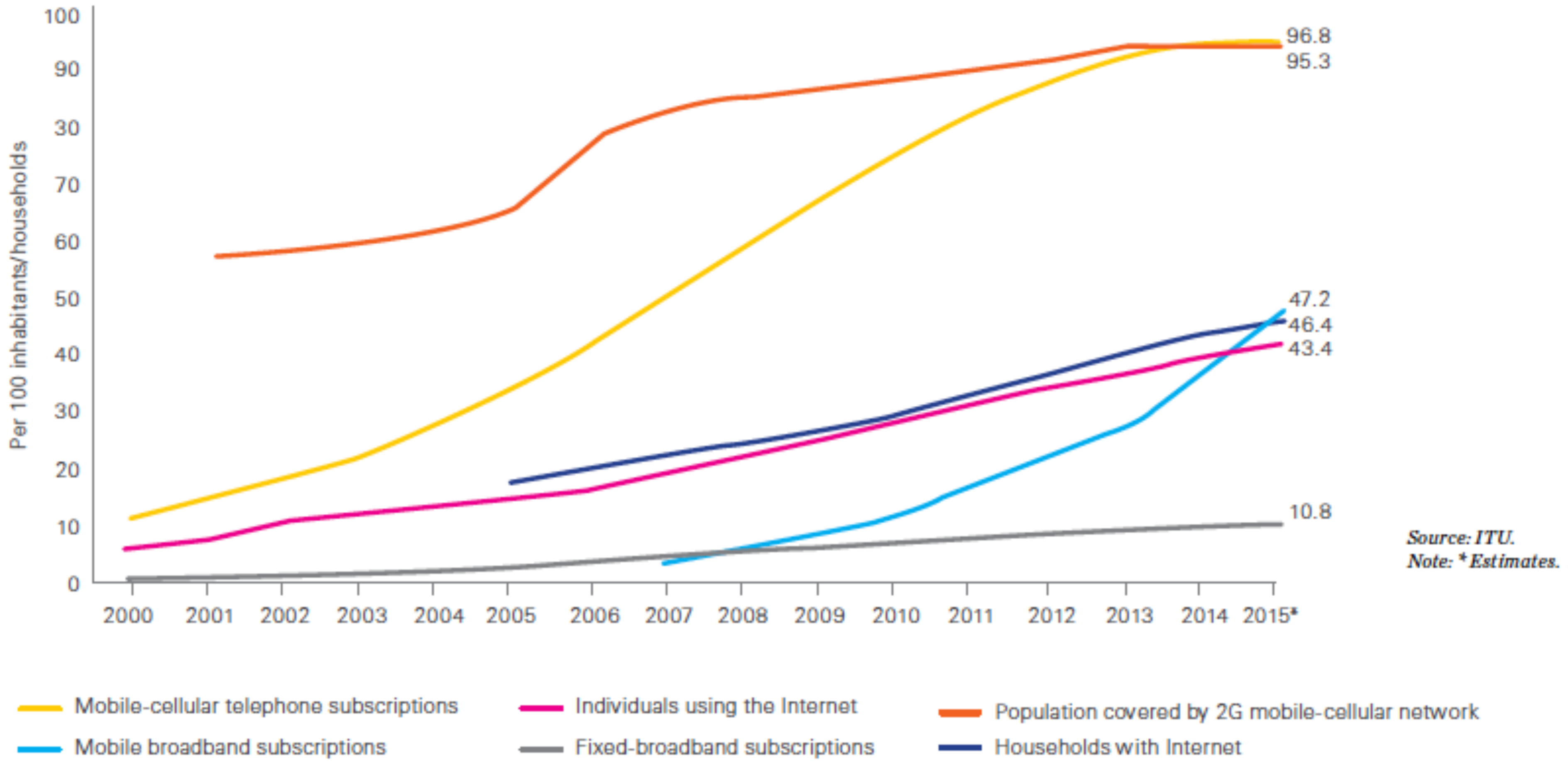


Source: Pew Research Center's Internet & American Life Project, March 15-April 3, 2012 Tracking survey. N=2,254 adults ages 18 and older, including 903 interviews conducted on respondent's cell phone. Margin of error is +/-2.6 percentage points based on cell phone owners (n=1954).

© 2015-22 Tilman Wolf

Phone and Internet Statistics

- What can you observe?

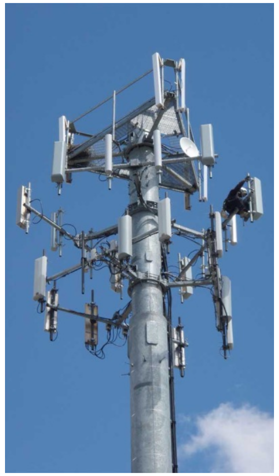


From: ITU ICT Facts & Figures 2015

© 2015-22 Tilman Wolf

Cell Phones Everywhere

- Cell phones are replacing fixed phones
- Infrastructure more easily deployed
  - Cell tower connected to wired telephone network
  - Useful for developing world



© 2015-22 Tilman Wolf

Digital Representation of Voice 1/2

- Voice signal is represented digitally
  - Telephone network links (except local loop)
  - Wireless link between handset and cell tower
  - Internet links when using VoIP
- Typical sampling and quantization configurations:
  - Sampling: 8 kHz (what's the maximum frequency?)
  - Quantization: 8 bits (μ-law or A-law)
    - 12 or 13 bits linear sampled mapped into 8 bits
  - Data rate: 8,000 samples/s $\times$ 8 bits/sample = 64 kbps
    - ITU-T standard G.711

© 2015-22 Tilman Wolf

Digital Representation of Voice 2/2

- Speech compression can reduce data rate
  - Example: Mixed Excitation Linear Predictive (MELP)
  - Artifact may be audible (examples from http://www.signalogic.com/index.pl?page=codec_samples)

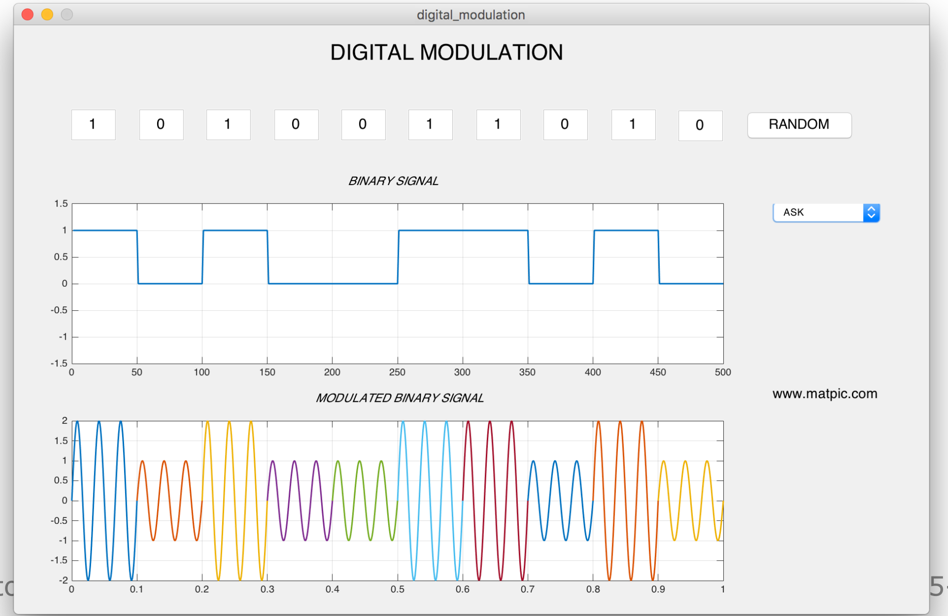
original G.729 8kbps MELPe-Plus 2.7kbps MELPe-Plus 1.2kbps MELPe-Plus 1.2kbps w/ noise

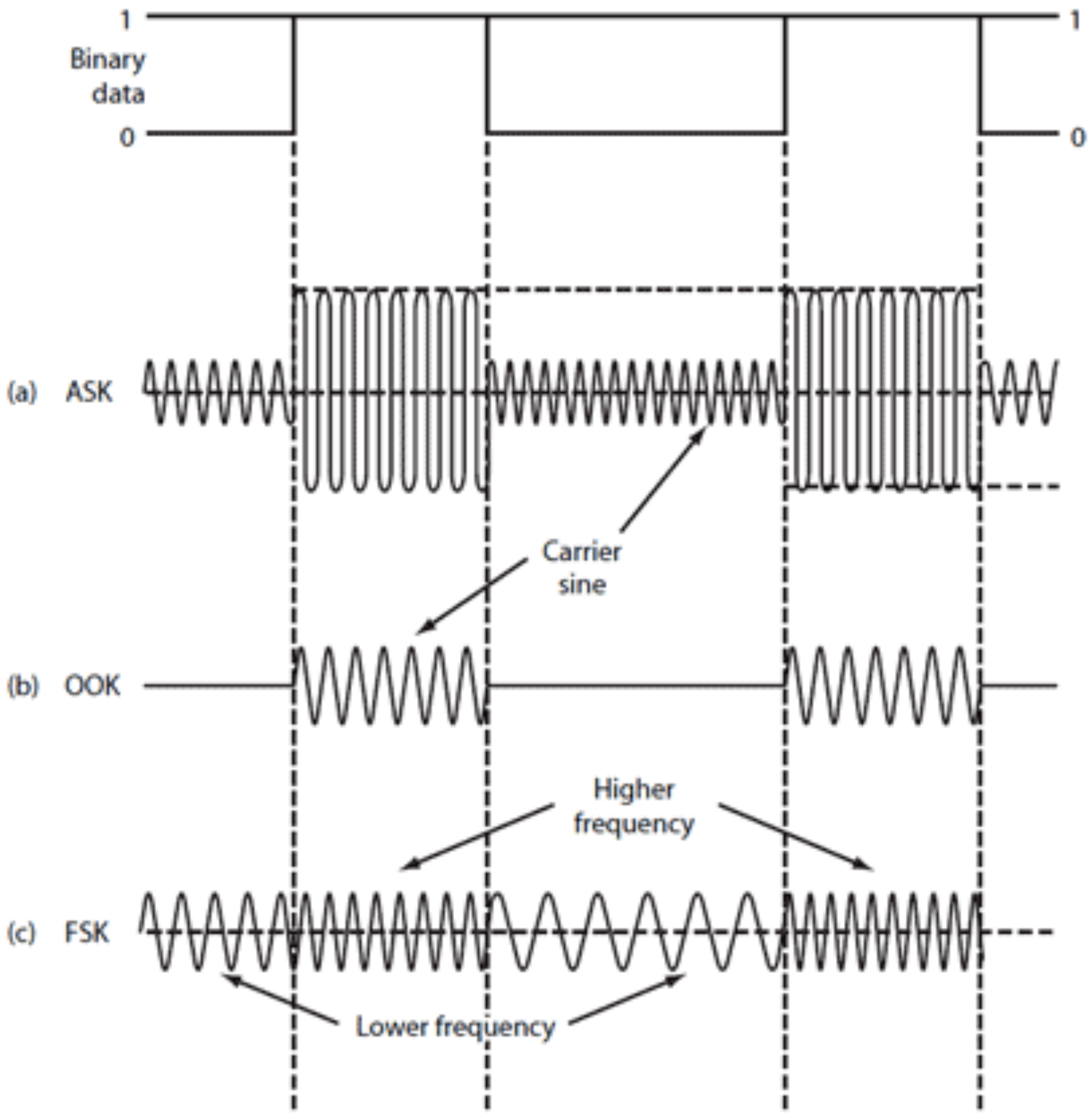
- Telephony has become transmission of binary data

© 2015-22 Tilman Wolf

Digital Modulation

- How are bits represented as signal on carrier wave?
  - Amplitude Shift Keying (ASK)
  - On-Off Keying (OOK)
  - Frequency Shift Keying (FSK)
- Nice demo for Matlab:



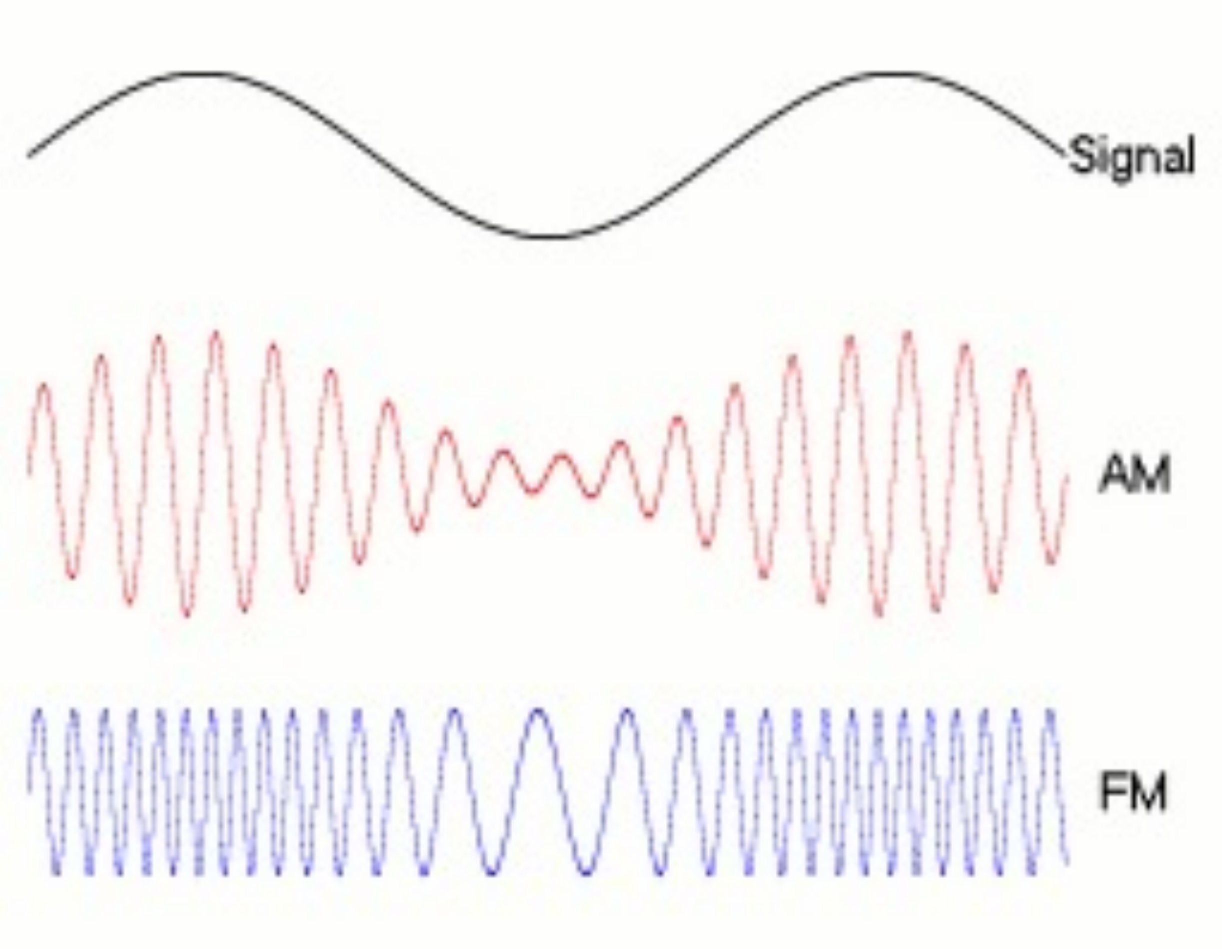


From http://electronicdesign.com/communications/understanding-modern-digital-modulation-techniques

http://www.mathworks.com/matlabcentral/fileexchange/14328-digital-modulation

AM Modulation

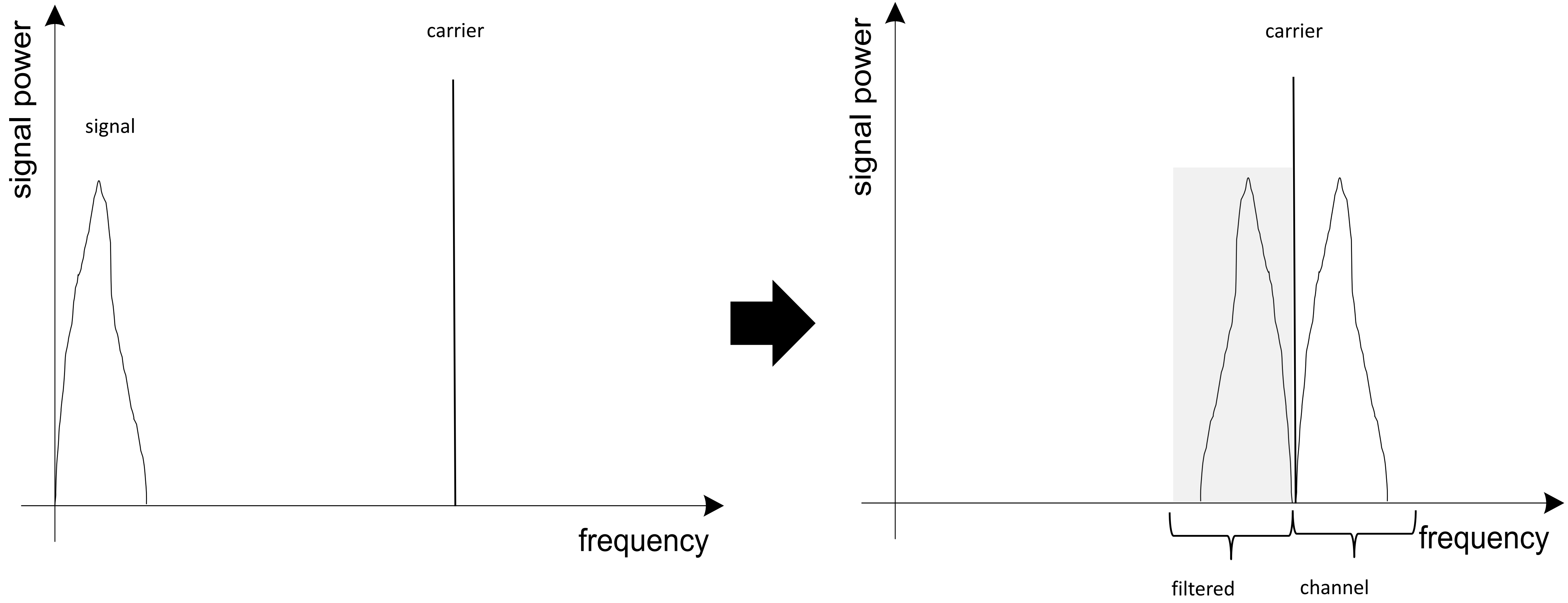
- AM modulation shifts signal in spectrum
  - Suitable filtering necessary to select single shifted signal
- Transmission of bits can be assigned to specific frequency range
  - “Channel”



© 2015-22 Tilman Wolf

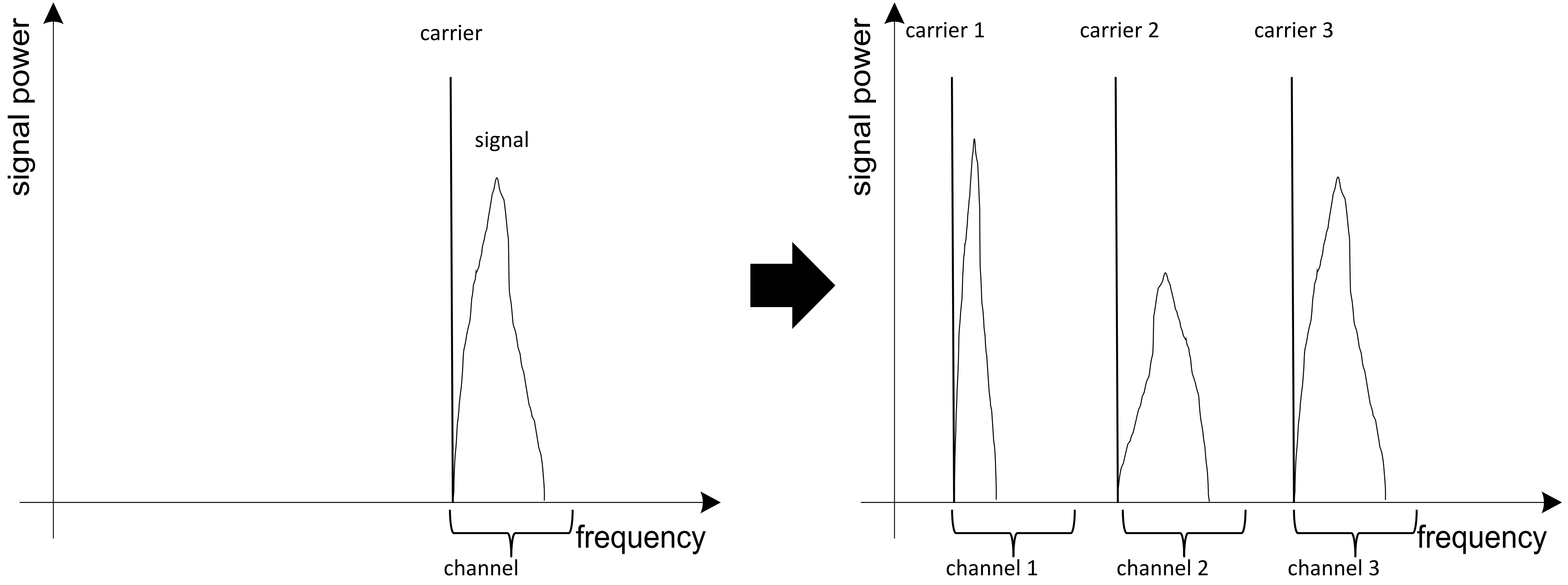
FM Modulation

- FM shifts signal spectrum similarly



Channels

- Multiple channels can coexist
  - Different carrier frequencies
- Spacing needs to be large enough to avoid overlap



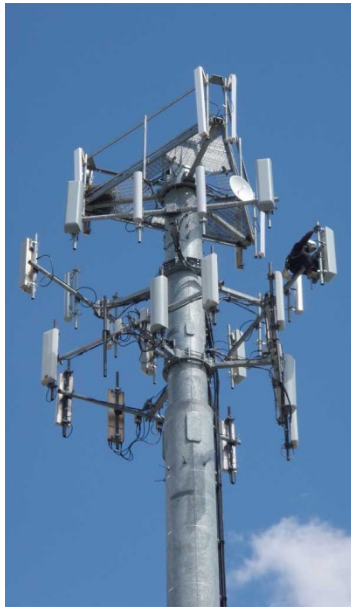
Cells in Telephony Network 1/4

- Single cell tower has limited range
  - Signal attenuates and may be obstructed
  - One tower cannot cover entire country
- What are the challenges with multiple cell towers?

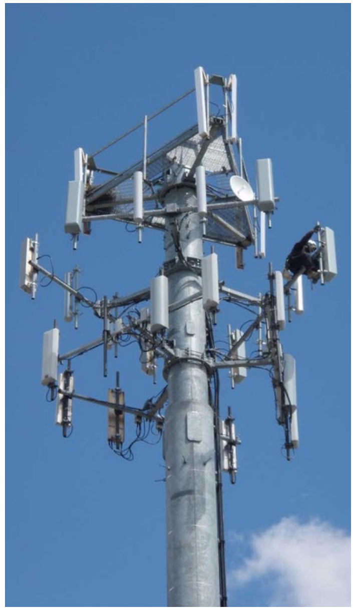
© 2015-22 Tilman Wolf

Signal Attenuation 1/2

- Which cell phone should connect to which tower?







Signal Attenuation 2/2

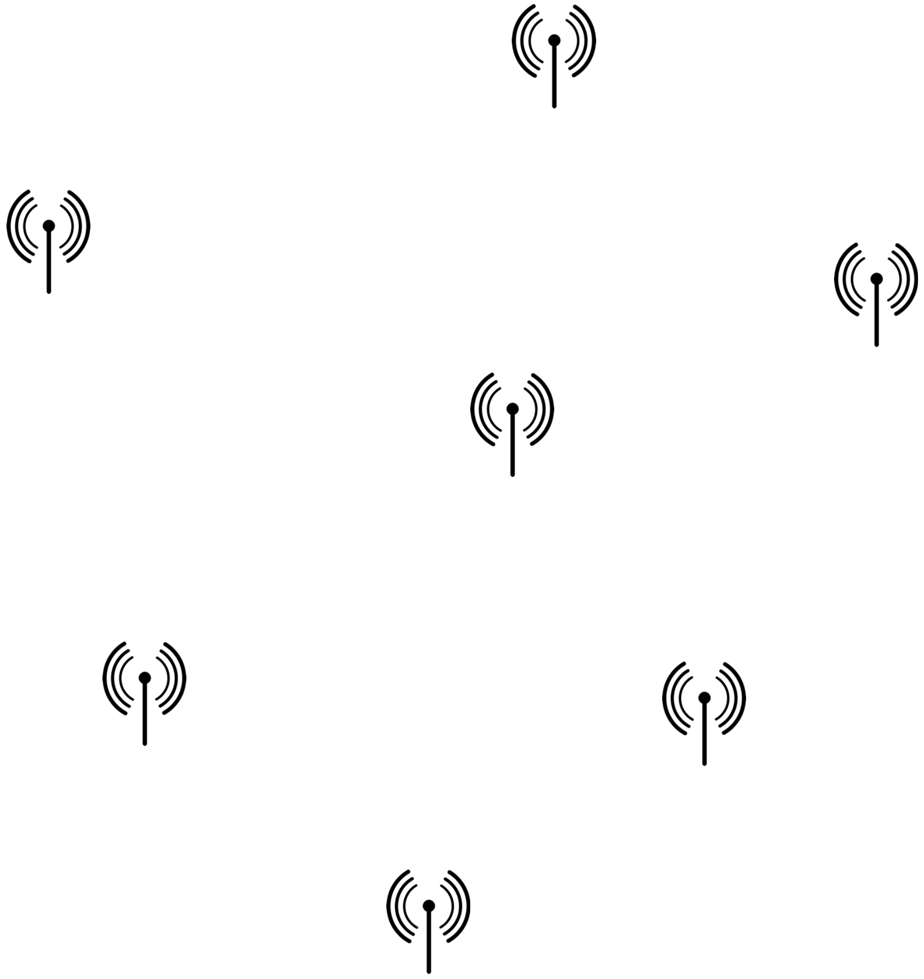
- Which cell phone should connect to which tower?

- Cell phone chooses tower with higher signal strength
  - Crossover point delineates coverage area of tower

© 2015-22 Tilman Wolf

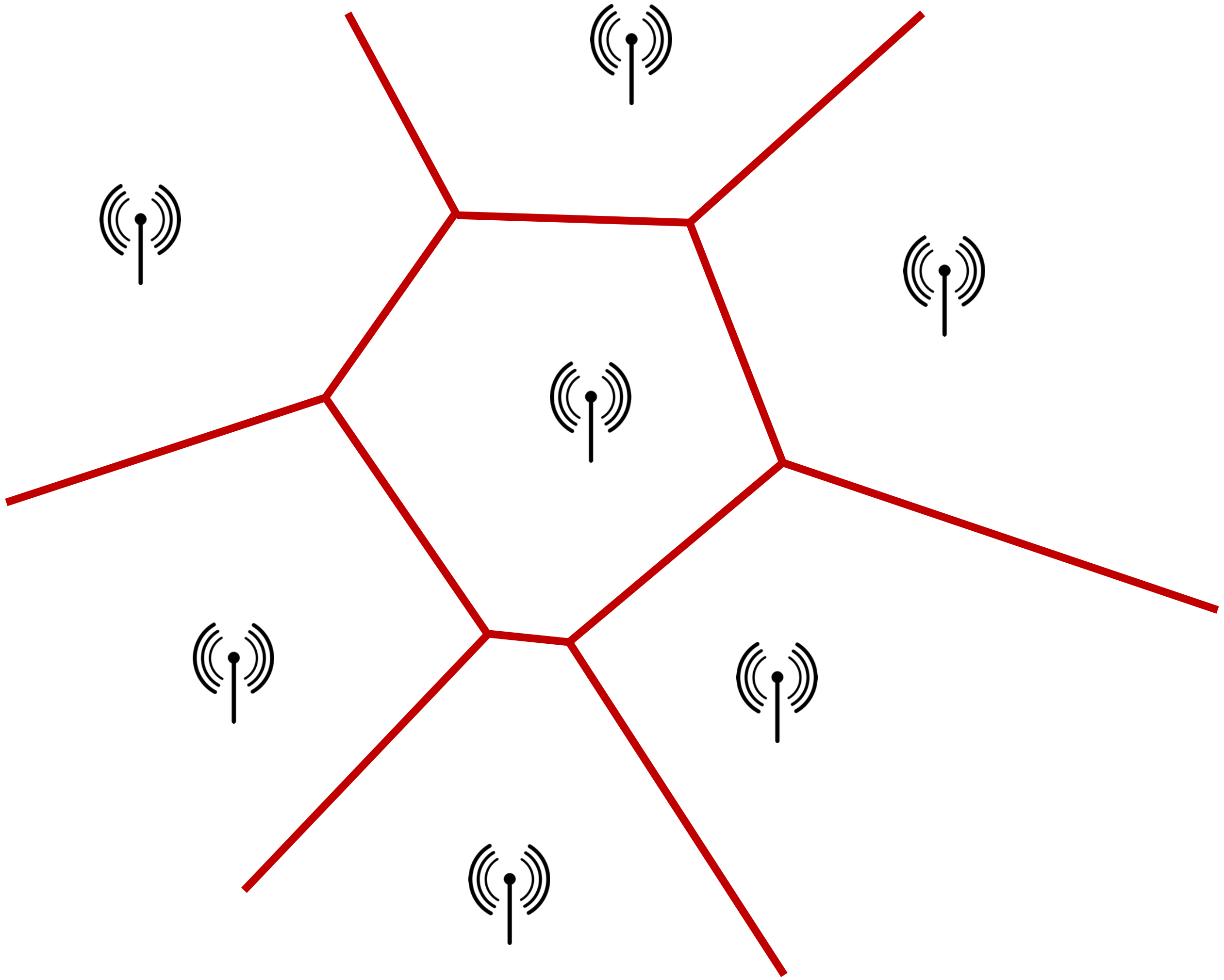
Cells in Telephony Network 2/4

- What are the boundaries between different towers?



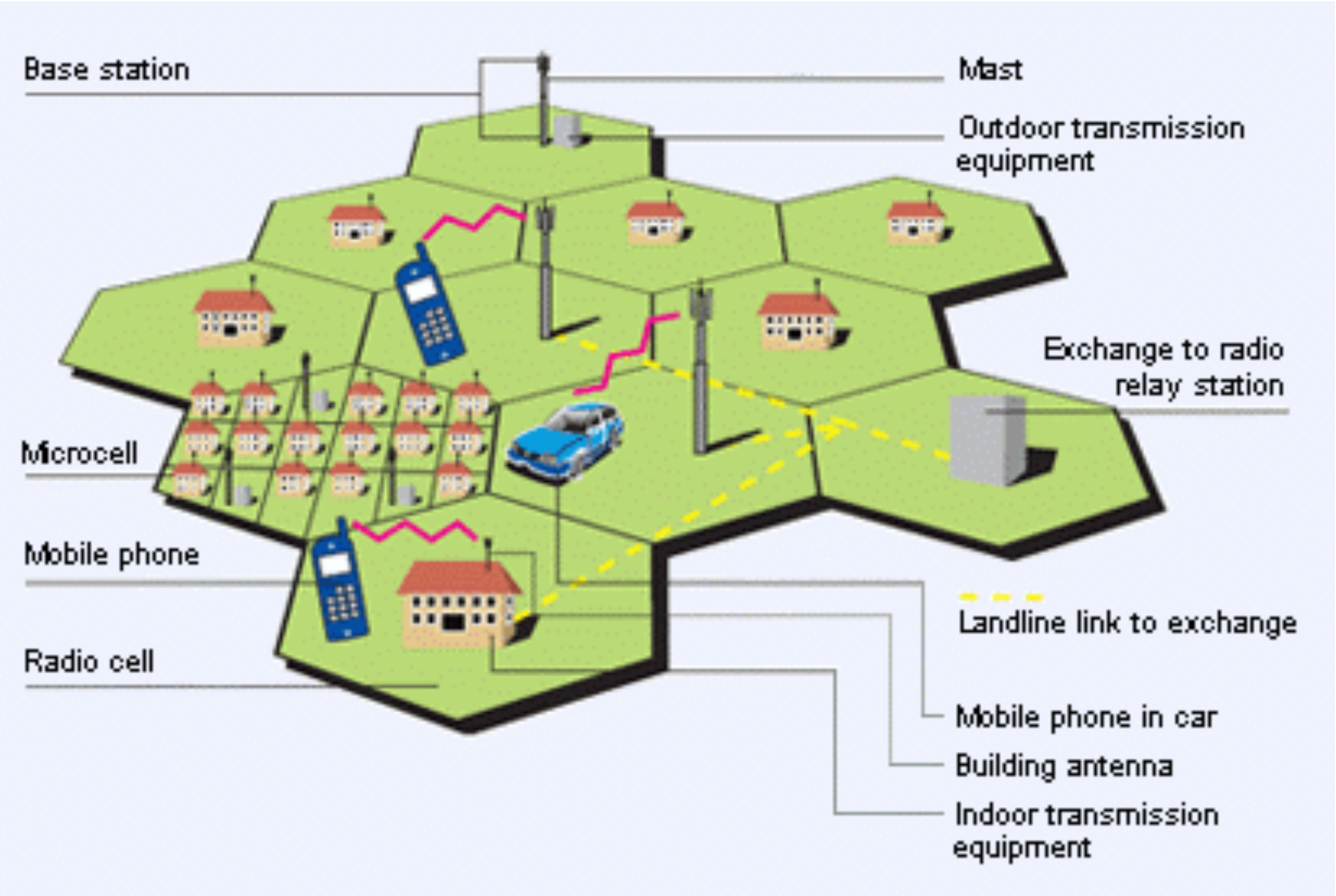
Cells in Telephony Network 3/4

- What are the boundaries between different towers?



Cells in Telephony Network 4/4

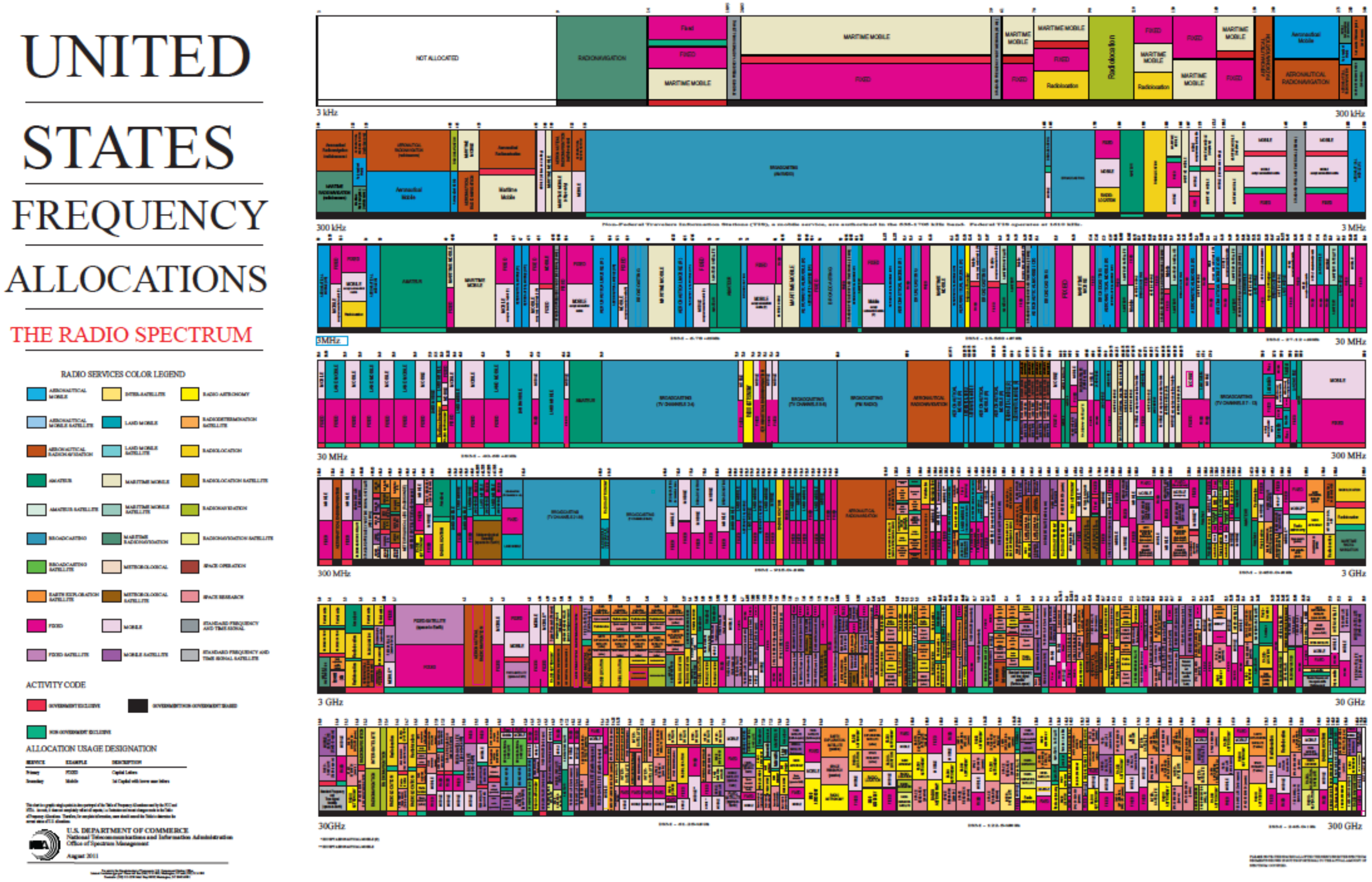
- Frequency spectrum divided into cells
  - Different cells use different frequencies to avoid interference
  - Need coordination to determine frequencies



© 2015-22 Tilman Wolf

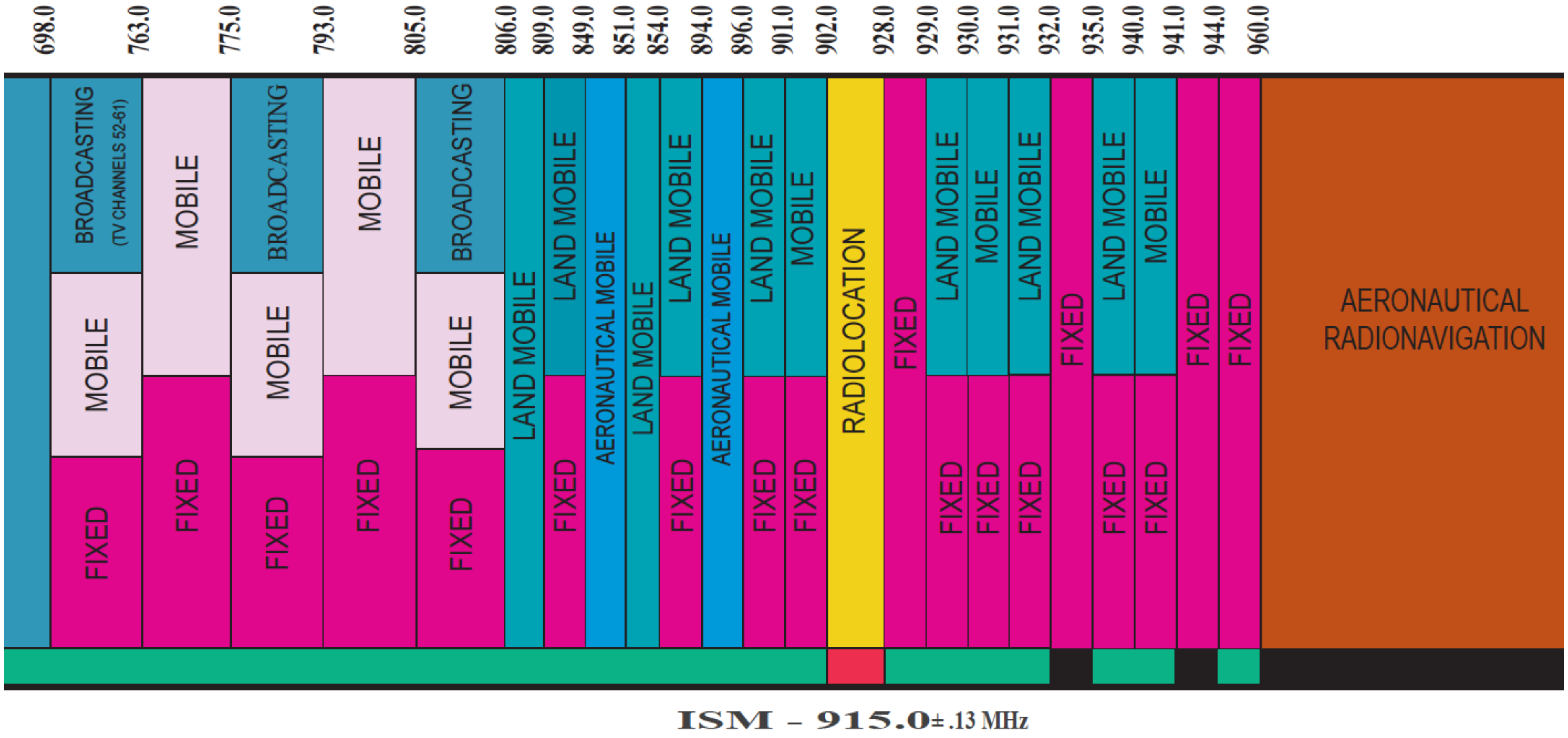
Frequency Spectrum

- Federal Communication Commission (FCC) regulates what frequencies can be used for what purpose



Frequency Spectrum Detail

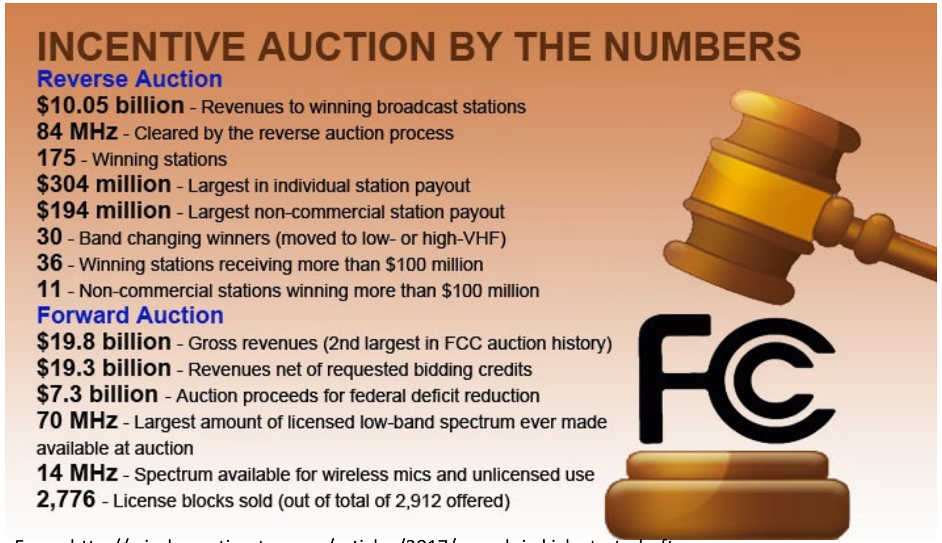
- Example portion used for cellular telephony:



© 2015-22 Tilman Wolf

Spectrum Auctions

- Licenses for spectrum can be big investment
- Auction of TV spectrum in April 2017
  - Total of $19.8B



From: http://wirelessestimator.com/articles/2017/repack-is-kick-started-after-fccs-auction-results-are-unveiled/

call_sign	dma	bidder_as_o	pre_auction_	winning_bid_	compensation
WWTO-TV	Chicago, IL	Trinity Christ	High-VHF	Go off-air	$ 304,250,040
WNBC	New York, NY	NBC Telemu	UHF	Go off-air	$ 214,023,017
WRNN-TV	New York, NY	WRNN Licens	UHF	Go off-air	$ 211,680,472
WXTV-DT	New York, NY	WXTV Licens	UHF	Go off-air	$ 198,965,211
WNJN	New York, NY	New Jersey P	UHF	Go off-air	$ 193,892,273
WZME	New York, NY	NRJ TV NY Li	UHF	Go off-air	$ 191,813,165
WTBY-TV	New York, NY	Trinity Broad	UHF	Go off-air	$ 162,402,181
WLVI	Boston, MA	WHDH-TV	UHF	Go off-air	$ 162,108,481
WGBH-TV	Boston, MA	WGBH Educa	UHF	Move to Low	$ 161,723,929
WPWR-TV	Chicago, IL	Fox Televisio	UHF	Go off-air	$ 160,748,259
KVCR-DT	Los Angeles, CA	San Bernardi	UHF	Move to Low	$ 157,113,171
KBEH	Los Angeles, CA	Hero License	UHF	Go off-air	$ 146,627,980
KRCA	Los Angeles, CA	KRCA License	UHF	Go off-air	$ 142,337,137
WSNS-TV	Chicago, IL	NBC Telemu	UHF	Go off-air	$ 141,658,837
WFMZ-TV	Philadelphia, PA	Maranatha B	UHF	Go off-air	$ 140,482,163
WNJT	Philadelphia, PA	New Jersey P	UHF	Go off-air	$ 138,059,363
KOCE-TV	Los Angeles, CA	KOCE-TV FOU	UHF	Go off-air	$ 138,003,711
KJLA	Los Angeles, CA	KJLA, LLC	UHF	Go off-air	$ 135,542,845
WYDN	Boston, MA	Educational I	UHF	Go off-air	$ 134,987,151
WYBE	Philadelphia, PA	Independenc	UHF	Go off-air	$ 131,578,104
KLCS	Los Angeles, CA	Los Angeles U	UHF	Go off-air	$ 130,510,880
WXFT-DT	Chicago, IL	UniMas Chica	UHF	Go off-air	$ 126,107,725
WLWC	Providence, RI-Ne	OTA Broadca	UHF	Go off-air	$ 125,932,367
WWSI	Philadelphia, PA	NBC Telemu	UHF	Go off-air	$ 125,903,049
WUVN	Hartford-New Hav	Entravision H	UHF	Go off-air	$ 125,568,545
WNVC	Washington, DC	Commonwea	UHF	Go off-air	$ 124,801,961

License Example 1/4

- First of two cellular licenses covering our area:

Common Name: Verizon Wireless / Call Sign: KNKA331

Frequency Band (MHz): 824-835, 869-880, 845-846.5, 890-891.5

Expiration Date	01/22/2018
Licensee FRN	0003290673
Licensee Details	Cellco Partnership 1120 Sanctuary Pkwy, #150 GASA5REG Alpharetta, GA 300097630 Attn: Regulatory Phone: (770) 797-1070 Fax: (770) 797-1036 Email: LicensingCompliance@VerizonWireless.com
Market	CMA063 - Springfield-Chicopee-Holyoke,
Frequency Band (MHz)	824-835, 869-880 845-846.5, 890-891.5
Radio Service	CL -Cellular
Contact Details	Verizon Wireless LicensingCompliance@VerizonWireless.com Alpharetta, GA 300097630 Attn: Regulatory Phone: (770) 797-1070 Fax: (770) 797-1036 Email: LicensingCompliance@VerizonWireless.com

Market Details

* Population is based on 2010 Census figures (Note: US territories are based on 2000 Census figures)

1. Spectrum (MHz): **824-835, 869-880**
845-846.5, 890-891.5

State/County

Massachusetts 2 of 14 Counties

County	Population *	Geographic Coverage (%)
1. Hampden County	463,490	100
2. Hampshire County	157,590	97.03

License Example 2/4

- Second of two licenses of our area:

Common Name: AT&T / Call Sign: KNKA252

Frequency Band (MHz): 835-845, 880-890, 846.5-849, 891.5-894

Expiration Date 10/01/2016

Licensee FRN 0003291192

Licensee Details
NEW CINGULAR WIRELESS PCS, LLC
3300 E. Renner Road, B3132
Richardson, TX 75082
Attn: Reginald Youngblood
Phone: (855) 699-7073
Fax: (972) 907-1131
Email: FCCMW@att.com

Market CMA063 - Springfield-Chicopee-Holyoke,

Frequency Band (MHz) 835-845, 880-890
846.5-849, 891.5-894

Radio Service CL -Cellular

Contact Details
AT&T MOBILITY LLC
1120 20th Street, NW - Suite 1000
Washington, DC 20036
Attn: Michael P. Goggin
Phone: (202) 457-2055
Fax: (202) 457-3073
Email: michael.p.goggin@att.com

Market Details

* Population is based on 2010 Census figures (Note: US territories are based on 2000 Census figures)

1. Spectrum (MHz): **835-845, 880-890**
846.5-849, 891.5-894

State/County

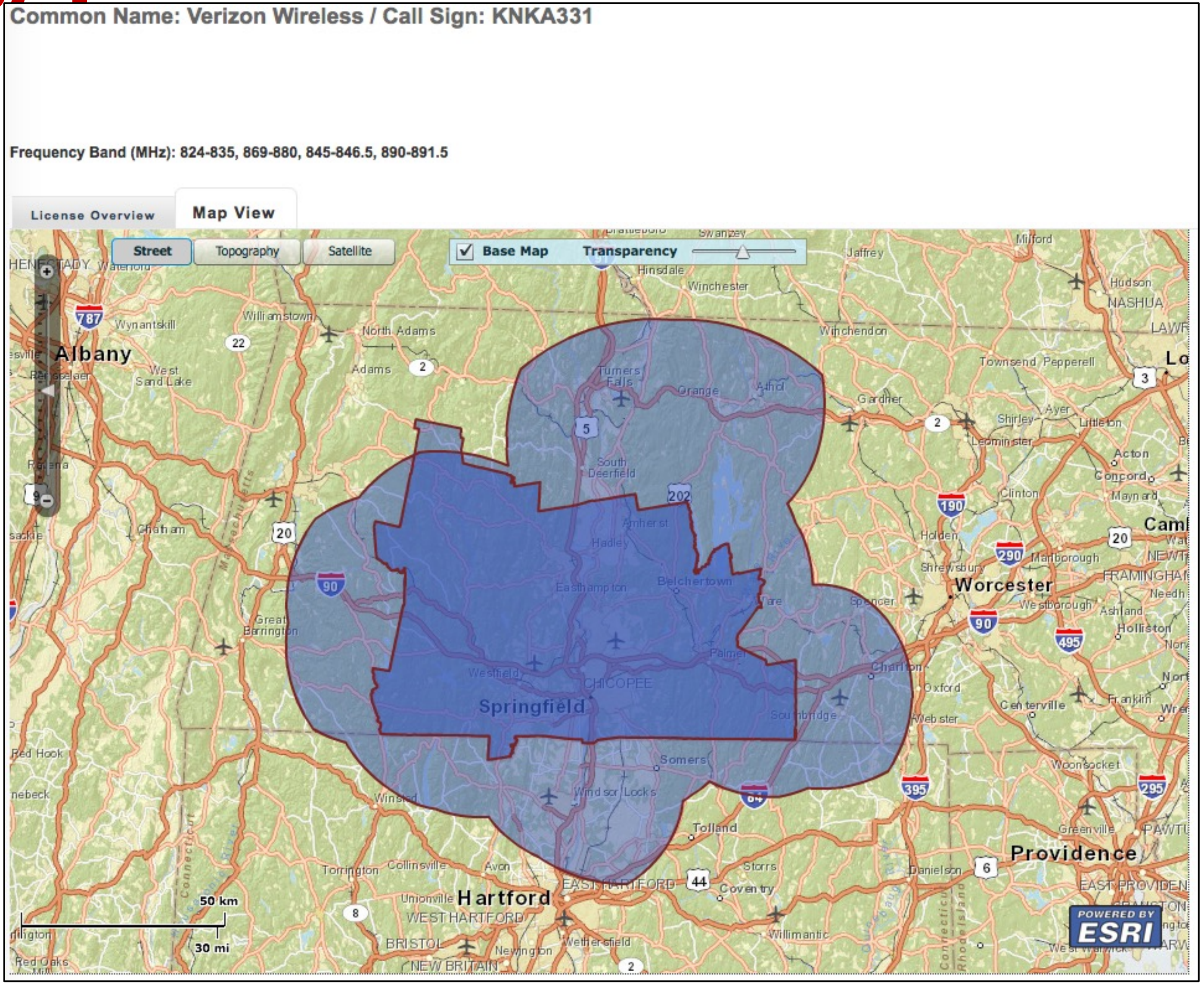
Massachusetts 2 of 14 Counties

County	Population *	Geographic Coverage (%)
1. Hampden County	463,490	100
2. Hampshire County	158,080	100

© 2015-22 Tilman Wolf

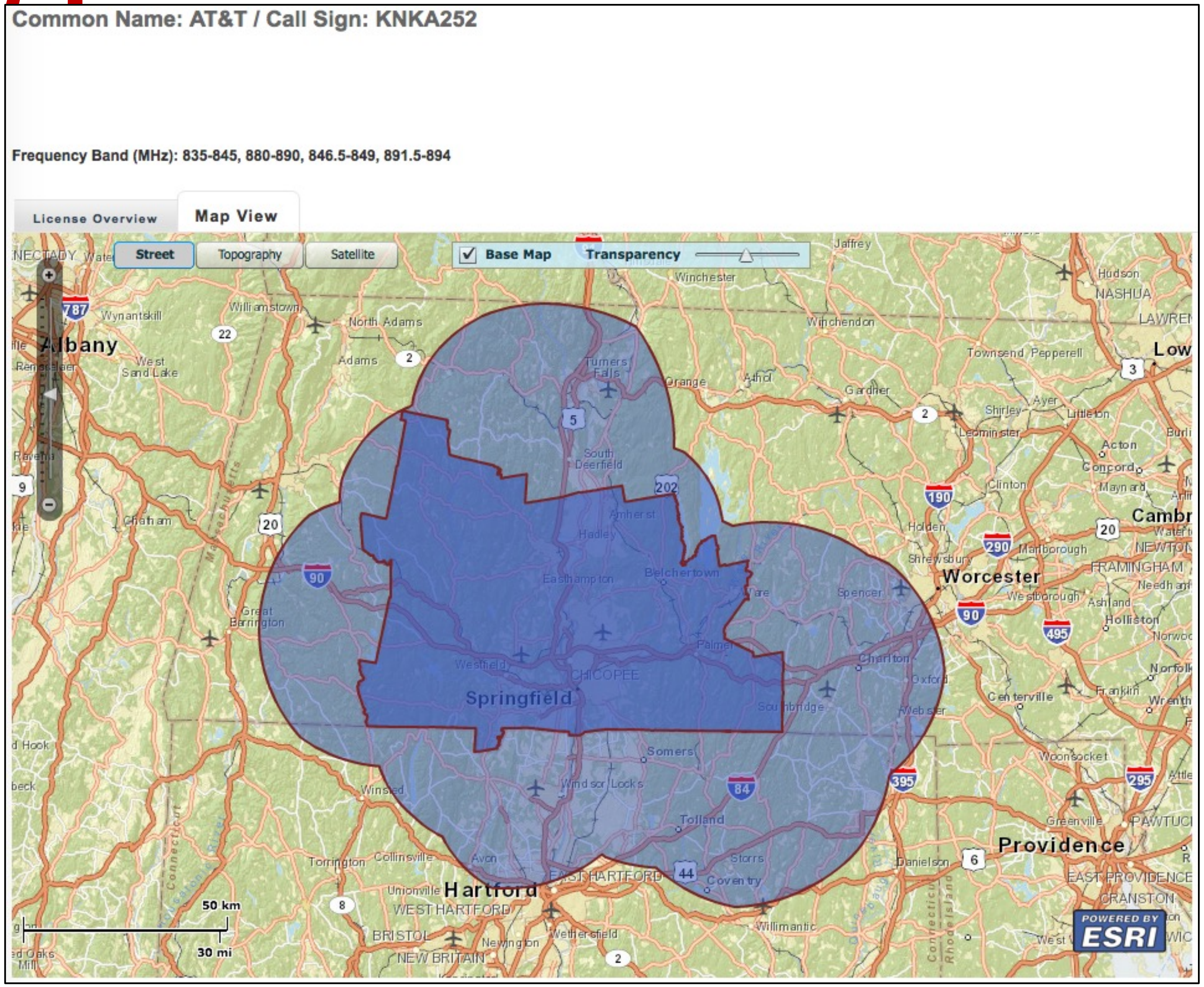
License Example 3/4

- Area covered by first license:



License Example 4/4

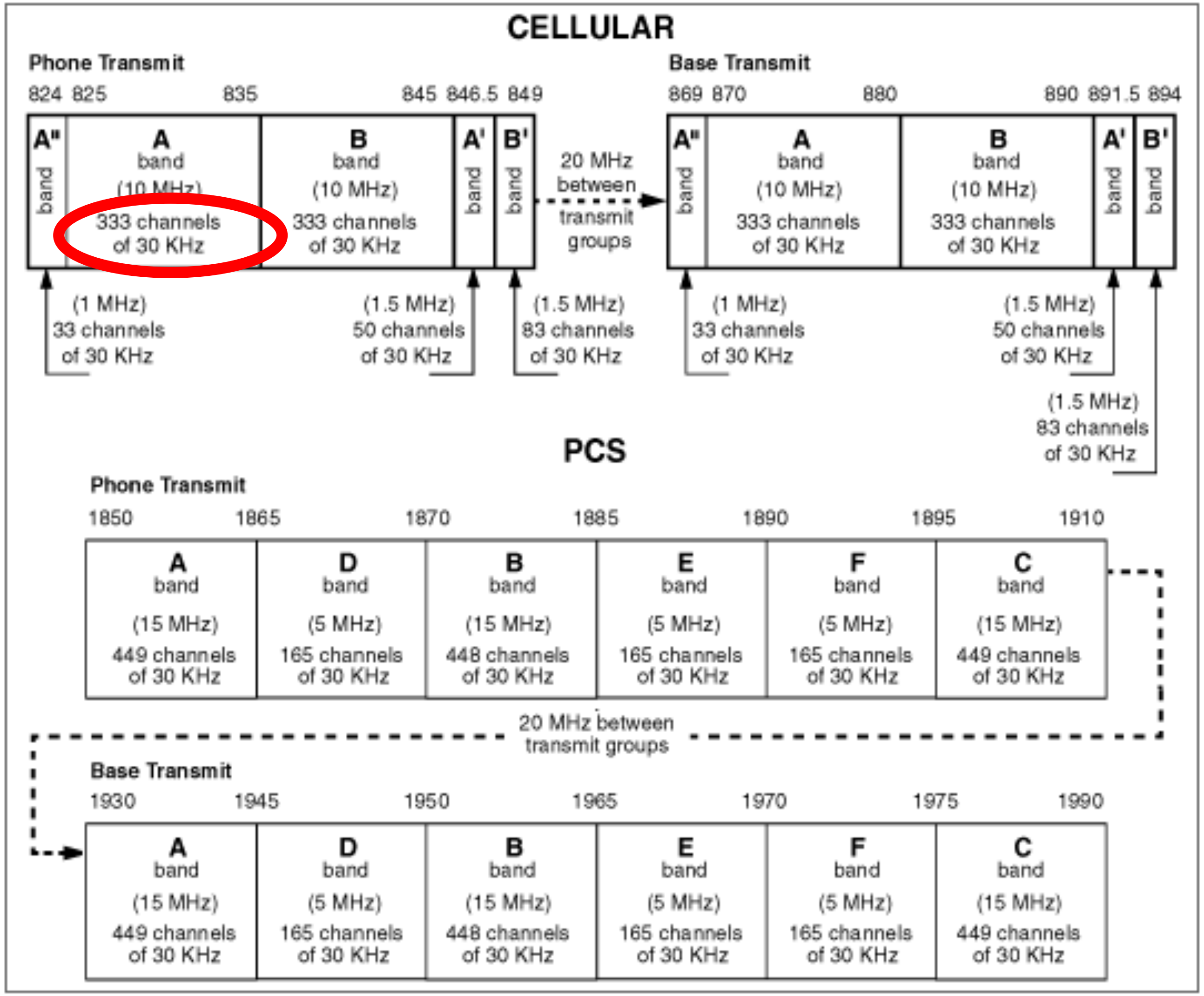
- Area covered by second license:



© 2015-22 Tilman Wolf

Channels in Spectrum

- Phone calls are assigned to one specific channel



From: http://www.jax184.com/projects/StarTAC/wireless/channels/

Frequencies

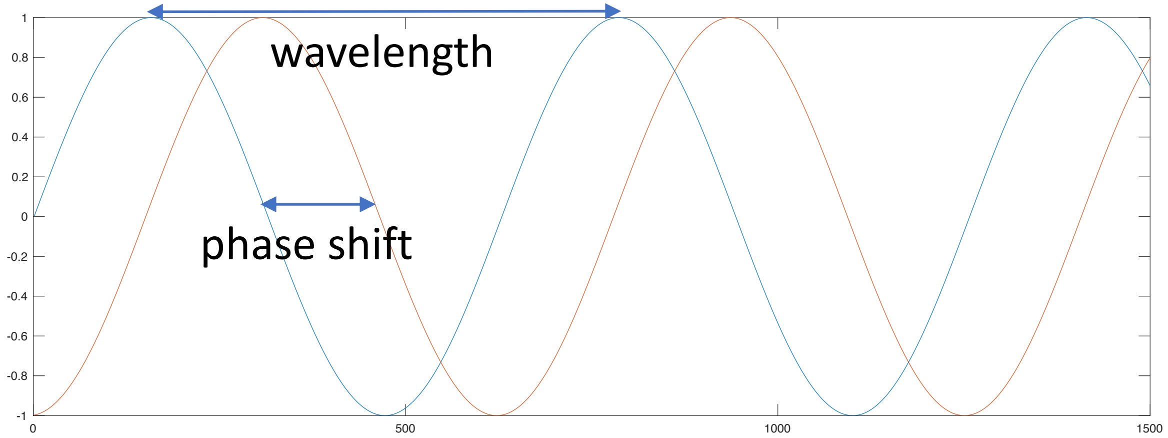
- Cell phones use specific carrier frequencies
  - Standard specifies frequency range (e.g., 2G, 3G, 4G, etc.)
  - Carrier license determines exact bands
  - Cell tower assigns specific channel(s) to a cell phone
- Cell phone must be able to generate accurate carrier
  - If carrier is inaccurate, tower may not receive signal
  - If carrier is inaccurate, cell phone may cause interference
- How to generate oscillation with specific frequency?

Carrier	2G Frequency in MHz Band name			3G Frequency in MHz Band name			4G LTE Frequency in MHz Band number												
	800	850	1900	850	1700 2100	1900	600	L700	L700	U700	800	850	1700 2100	1900	2300	2500	3500	5200	5700
	SMR	CLR	PCS	CLR	AWS	PCS	71	12,17	29[1]	13	26	5	4,66	2,25	30	41	48	252	255
AT&T	No	No	No	UMTS	No	UMTS	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No			
T-Mobile	No	No	GSM	No	UMTS	UMTS	Yes	Yes	No	No	No	Yes[2]	Yes	Yes	No	No		Yes[3]	Yes
Sprint	CdmaOne[4]	No	CdmaOne	No	No	CDMA2000	No	No	No	No	Yes	No	No	Yes	No	Yes			
Verizon	No	CdmaOne	CdmaOne	CDMA2000	No	CDMA2000	No	No	No	Yes	No	Yes	Yes	Yes	No	No			
U.S. Cellular	No	CdmaOne	CdmaOne	CDMA2000	No	CDMA2000	No	Yes	No	No	No	Yes	Yes	Yes	No	No			

From wikipedia.com

Signal Terminology

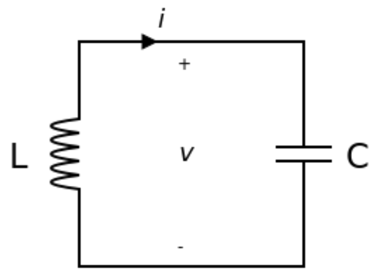
- Wavelength λ: distance over which wave repeats
  - Relationship between wavelength and frequency: $\lambda = \frac{v}{f}$
  - Propagation speed v is speed of light for electromagnetic waves
- Phase shift: distance between two waves

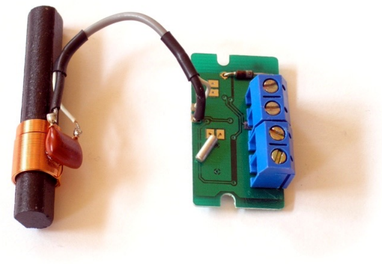


  - Phase shift typically 0..360 degrees (or 0..2π)
  - Phase shift of 180 degrees (or π) on waves:
    - Peaks signals are exactly opposite

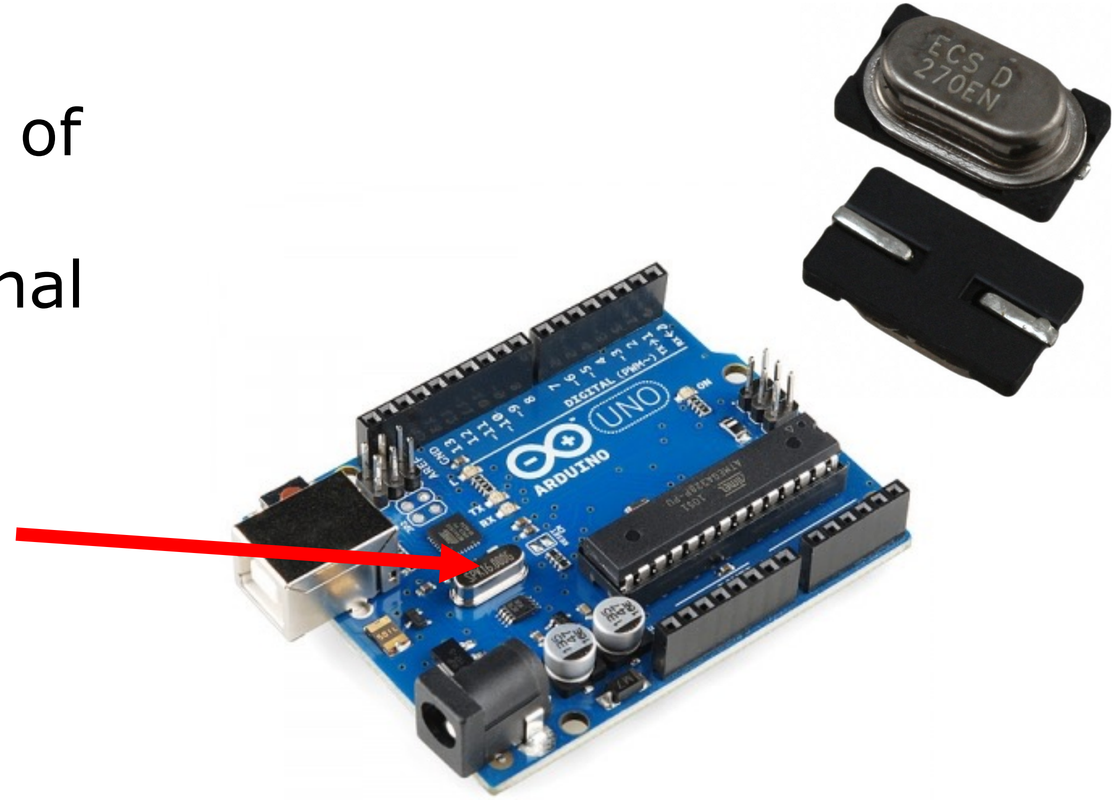
Oscillators

- Resonant circuit
  - Energy oscillates between inductor and capacitor
- Crystal oscillator
  - Mechanical resonance of quartz crystal
  - Generates electric signal with stable frequency
- Arduino uses 16 MHz crystal oscillator as clock



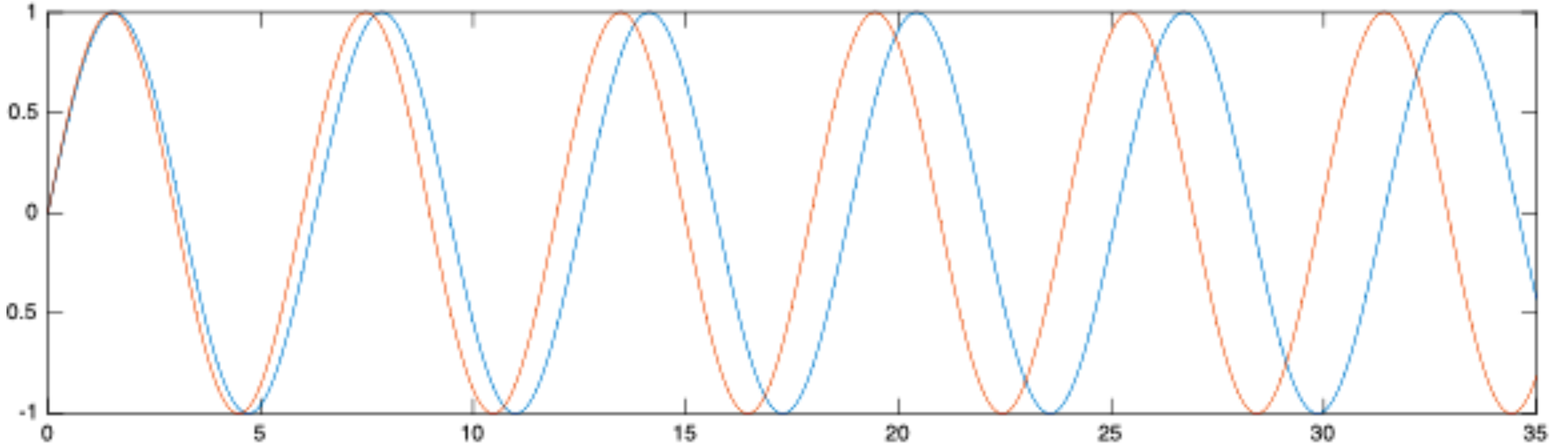


From wikipedia.com



Oscillator Errors

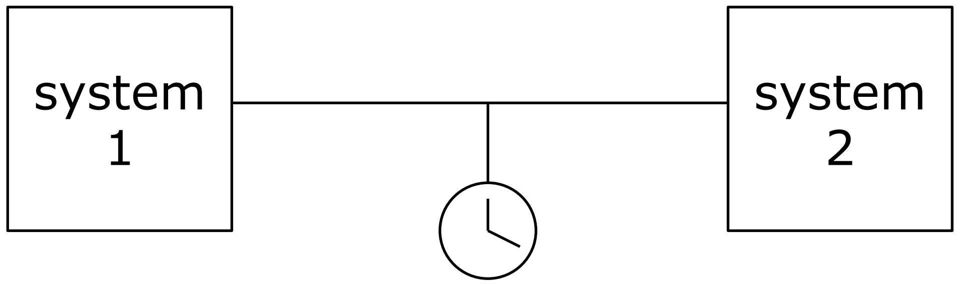
- Sources of inaccuracies
  - Permanent: differences in materials or manufacturing, …
  - Temporary: temperature changes properties of oscillator, …
- Variation in frequencies lead to slow phase shift



- Frequency stability and tolerance of crystals:
  - Typical: ±10 – ±50 ppm (parts per million)
  - Example: 10 ppm of 16 MHz is 160 Hz
    - Range of oscillator: 15999840 Hz – 16000160 Hz

Synchronization

- General systems problem: synchronization
- Systems are synchronized if clocks are identical



- Synchronization with separate clocks is difficult
  - Difference in frequency
  - Difference in phase

- Lack of synchronization can lead to problems
  - E.g., sender sends signal at different frequency or time

© 2015-22 Tilman Wolf

Activity

- Part 1: Common clock
  - Count number of seconds in interval
  - Same number of counts, means same frequency

- Part 2: Everyone uses “internal” clock
  - Clock provides initial synchronization

© 2015-22 Tilman Wolf

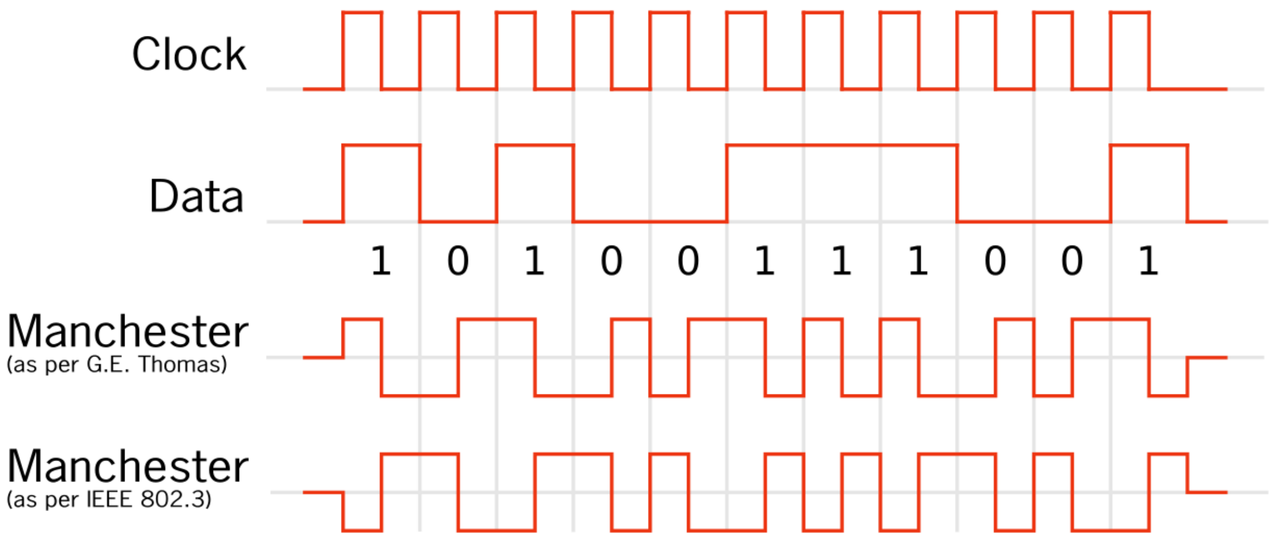
Demo

- Drift of clocks in computer systems
  - Not only humans have varying clocks
- Arduinos are programmed to blink every 500ms
  - Two identical Arduino systems drift, too

© 2015-22 Tilman Wolf

Synchronization in Communications

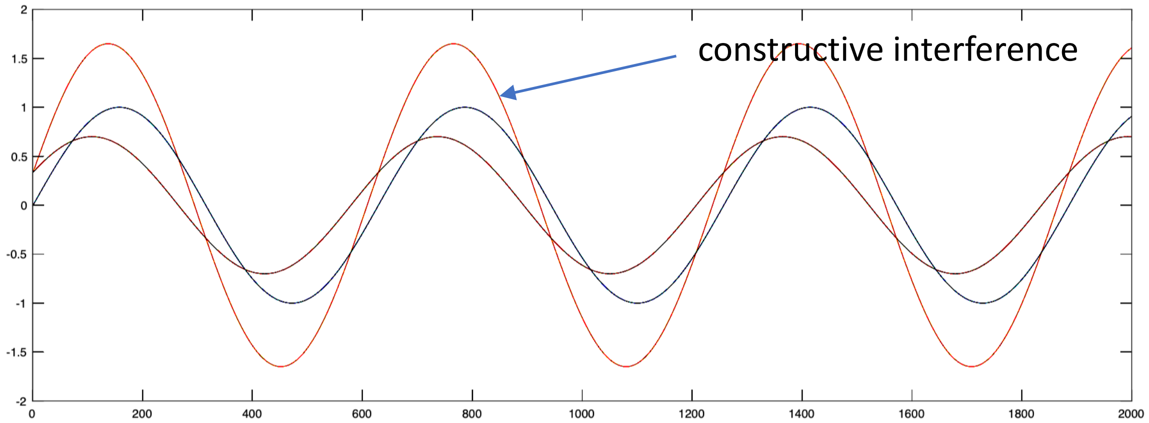
- Communicating systems synchronize using signal
  - Clock information from sender carried in transmission
  - Receiver can adjust to clock of sender
- Frequency acquisition
  - Known pattern sent at beginning of transmission
  - Receiver adjusts phase and frequency
  - Synchronization maintained for short data transmission
- Self-clocking encoding of bits
  - Each bit encoded with phase transition
  - Example: Manchester code
- Many other types of codes

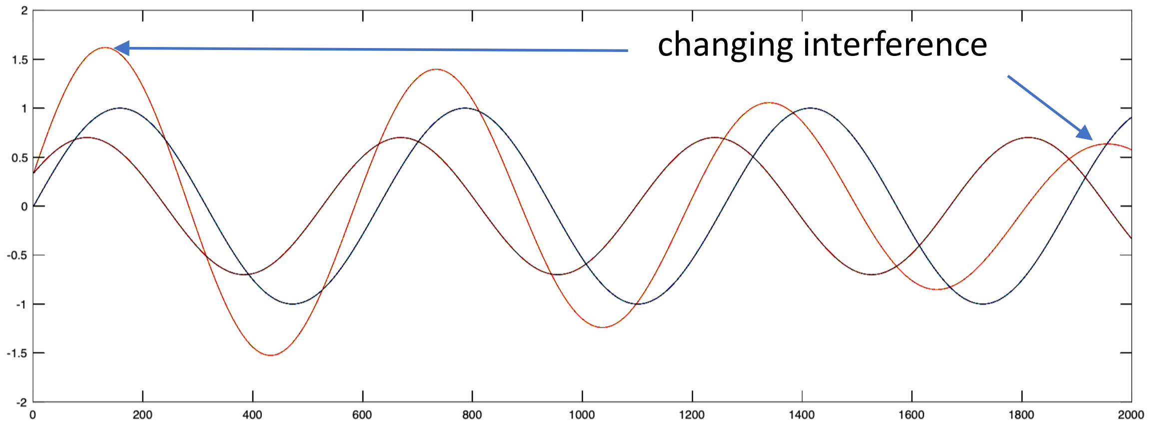


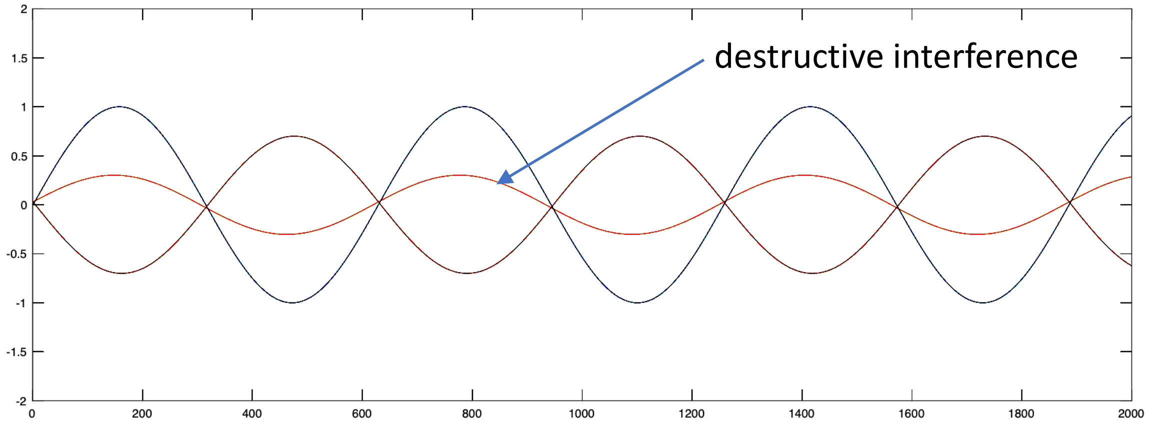
© 2015-22 Tilman Wolf

Interference

- Examples: blue and red signals combine to yellow signal
  - Phase shift determines type of interference
  - Interference can shift due to frequency differences







© 2015-22 Tilman Wolf

Transmission Errors

- Errors can happen during transmission
  - Misinterpretation on receiver (e.g., due to timing)
  - Attenuation of signal
  - Interference from other transmissions
  - Interference from own transmission
  - Etc.
- We consider "bit errors" in the digital domain
  - Error occurs when transmitted 0 is interpreted as 1
  - Error occurs when transmitted 1 is interpreted as 0
- We assume bit errors are independent
  - Error happens with certain probability
  - Does not depend on previous bit having had an error or not
  - Not entirely realistic (but sufficient for us for now)
    - Some errors may occur in bursts

© 2015-22 Tilman Wolf

Experiment I 1/2

- Transmission of 4 bits of data
- We use die to create random, independent events
  - If you roll 1, 2, 3, 4, or 5: correct transmission of bit
  - If you roll 6: incorrect transmission of bit – bit error!
- Transmission is “successful” if no bit errors occur
  - Roll you die four times and count the number of it errors

Bit 1:	Bit 2:	Bit 3:	Bit 4:

- Transmission success? yes/no

Experiment I 2/2

- What is the probability that transmission is correct?
  - First analyze one bit transmission, then 4-bit sequence
- Single bit transmission:
  - Probability of bit error:
    P[bit error] = p = 1/6 = 0.1667
  - Probability of correct bit transmission:
    P[bit correct] = (1-p) = 5/6 = 0.8333
- 4-bit transmission:
  - Transmission correct if all four bits are correct:
    P[successful transmission] =
    P[bit 1 correct] * P[bit 2 correct] * P[bit 3 correct] * P[bit 4 correct] =
    $(1-p) * (1-p) * (1-p) * (1-p) = (1-p)^4 =$
    $(0.8333)^4 = 0.4822 = 48.22\%$
- Transmission succeeds less then half the time!

© 2015-22 Tilman Wolf

Improving Transmission

- Half the time, we get the wrong bit sequence!
- What can we do to improve our system?

© 2015-22 Tilman Wolf

Error Detection

- Error can be detected by adding a “parity bit”
  - If sum of 1’s in data is even, add 0 as parity bit
  - If sum of 1’s in data is odd, add 1 as parity bit
- Error detection
  - Correct transmission has even number of 1’s
  - Transmissions with one bit error have odd number of 1’s
- What if error occurs on parity bit?
- What if two bit errors occur?
- What if more bit errors occur?
- What do we do if error is detected?

© 2015-22 Tilman Wolf

Error Correction 1/2

- How can we can detect and correct bit error?

© 2015-22 Tilman Wolf

Error Correction 2/2

- How can we can detect and correct bit error?
  - Add sufficient redundancy to transmission for recovery
- Simple error-correcting code
  - Send each bit three times (why not twice?)
- Error correction
  - Use majority vote over three bits

© 2015-22 Tilman Wolf

Experiment II 1/2

- Transmission of 4 bits of data
  - If you roll 1, 2, 3, 4, or 5: correct transmission of bit
  - If you roll 6: incorrect transmission of bit – bit error!
- Tx "successful" if no two bit error occur in any triple

Bit 1 triple:			Bit 2 triple:			Bit 3 triple:			Bit 4 triple:		

Bit 1 correct?	Bit 2 correct?	Bit 3 correct?	Bit 4 correct?

- Transmission success? yes/no
  - What else did you observe?

Experiment II 2/2

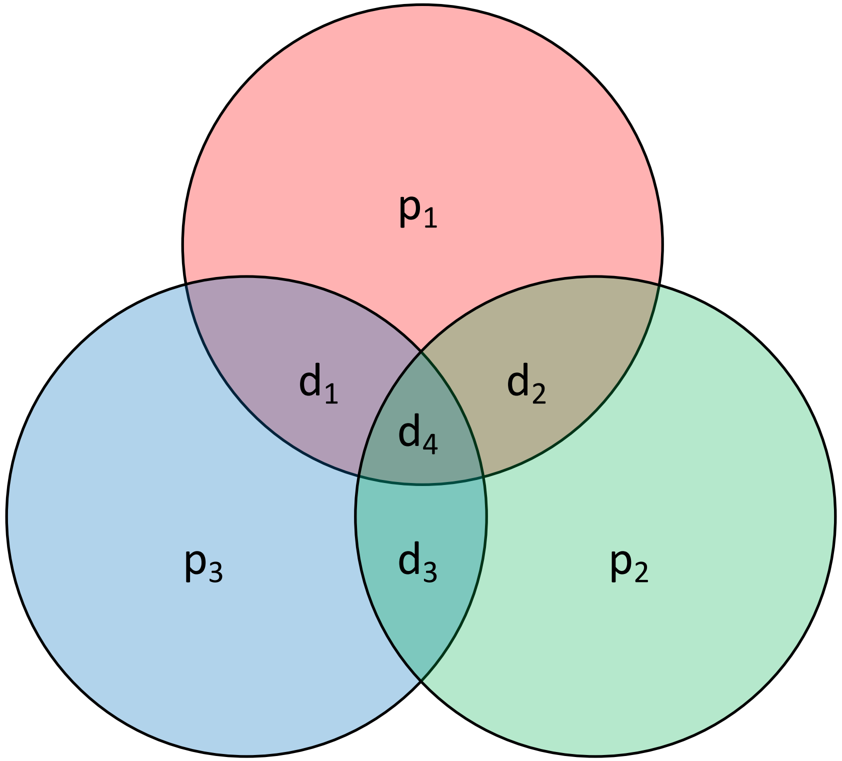
- What is the probability that transmission is correct?
  - First analyze one triple transmission, then 4-bit sequence
- Triple transmission of single data bit:
  - Probability of error in transmitted bit: P[bit error] = p = 1/6
  - Probability of correct/correctable triple transmission:
    - P[no bit error in triple] = $(1-p)^3 = (5/6)^3 = 0.5786$
    - P[one bit error in triple] = $p(1-p)^2 = (1/6)(5/6)^2 = 0.1157$
    - P[no or one bit error] = $(1-p)^3 + 3*p(1-p)^2 = 0.9259$
- 4-bit transmission:
  - Transmission correct if all four triples are correct(able):
    P[successful transmission] = $((1-p)^3 + 3*p(1-p)^2)^4 =$
    $= 0.9259^4 = 0.7350 = 73.50\%$
- Transmission correct in about three quarter of cases
  - Cost of 3x in terms of data transmission

Hamming Code

- Error correction using triple transmission is tedious
  - 8 extra bits for 4 data bits
- More elegant codes can achieve error correction
  - Less additional bits
  - One example: 3 extra bits for 4 data bits
- Hamming(7,4) code uses 7 bits to encode 4 data bits
  - Richard W. Hamming invented this (and many other) code
  - "Coding Theory" is active area of research on codes
- Idea: any two code words need to differ by 3 bits
  - "Hamming distance" defines number of bit differences
  - If Hamming distance is 3 between any two code words, then a single bit flip can be corrected by identifying the code word that is closest

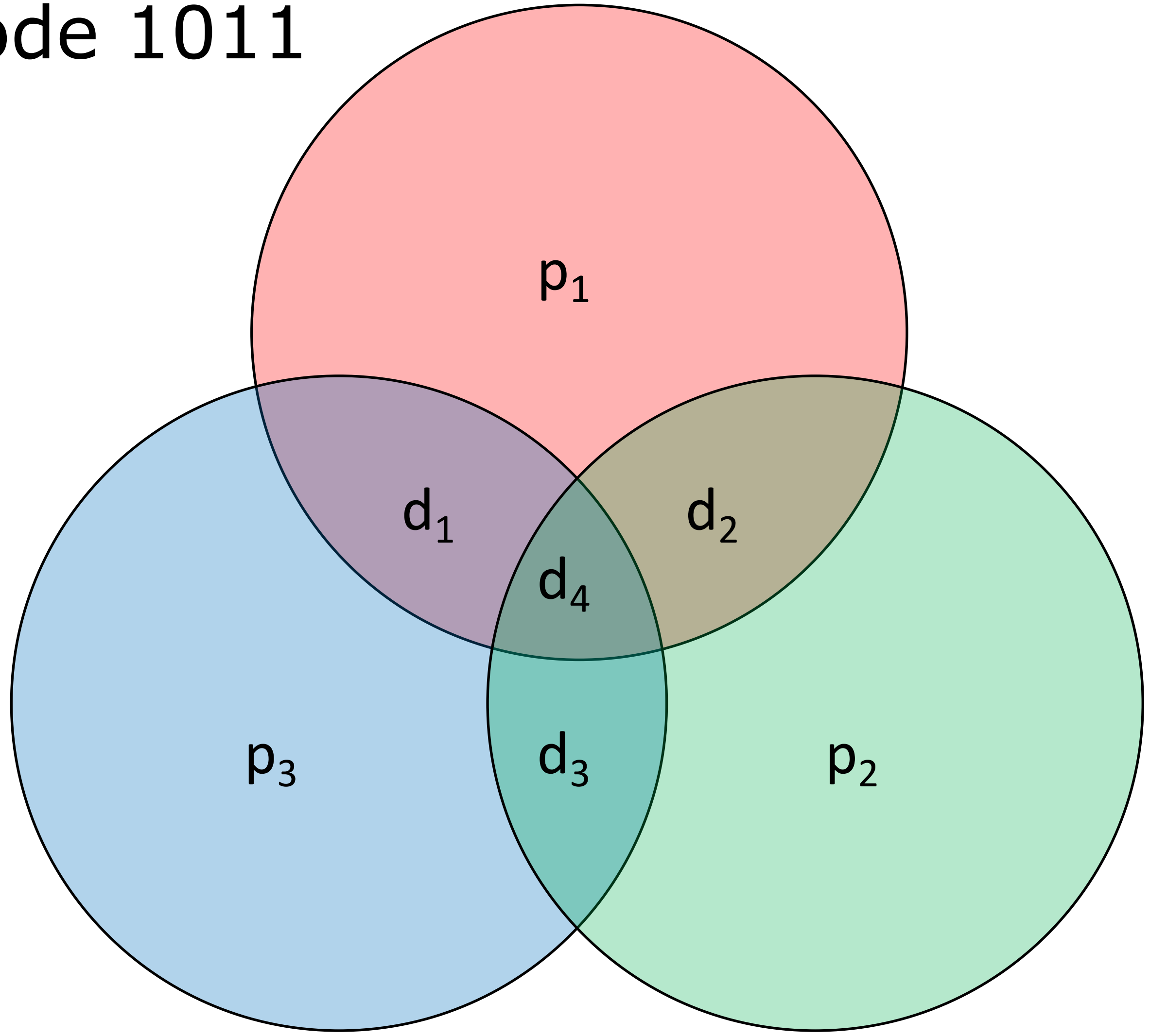
Hamming(7,4) Code

- Illustration for code generation:
  - Four data bits: d_1, d_2, d_3, d_4
  - Three parity bits: p_1, p_2, p_3
- Parity bits cover region of circle
  - Ensure even number of 1's in circle
- Decoding
  - Identify which circles have correct and incorrect parity
  - If one circle has error:
    - Flip parity bit for that circle
  - If two circles have errors:
    - Flip shared data bit (not d_4)
  - If three circles have errors:
    - Flip shared data bit d_4
- Any single error can be corrected



Hamming(7,4) Code Example 1/9

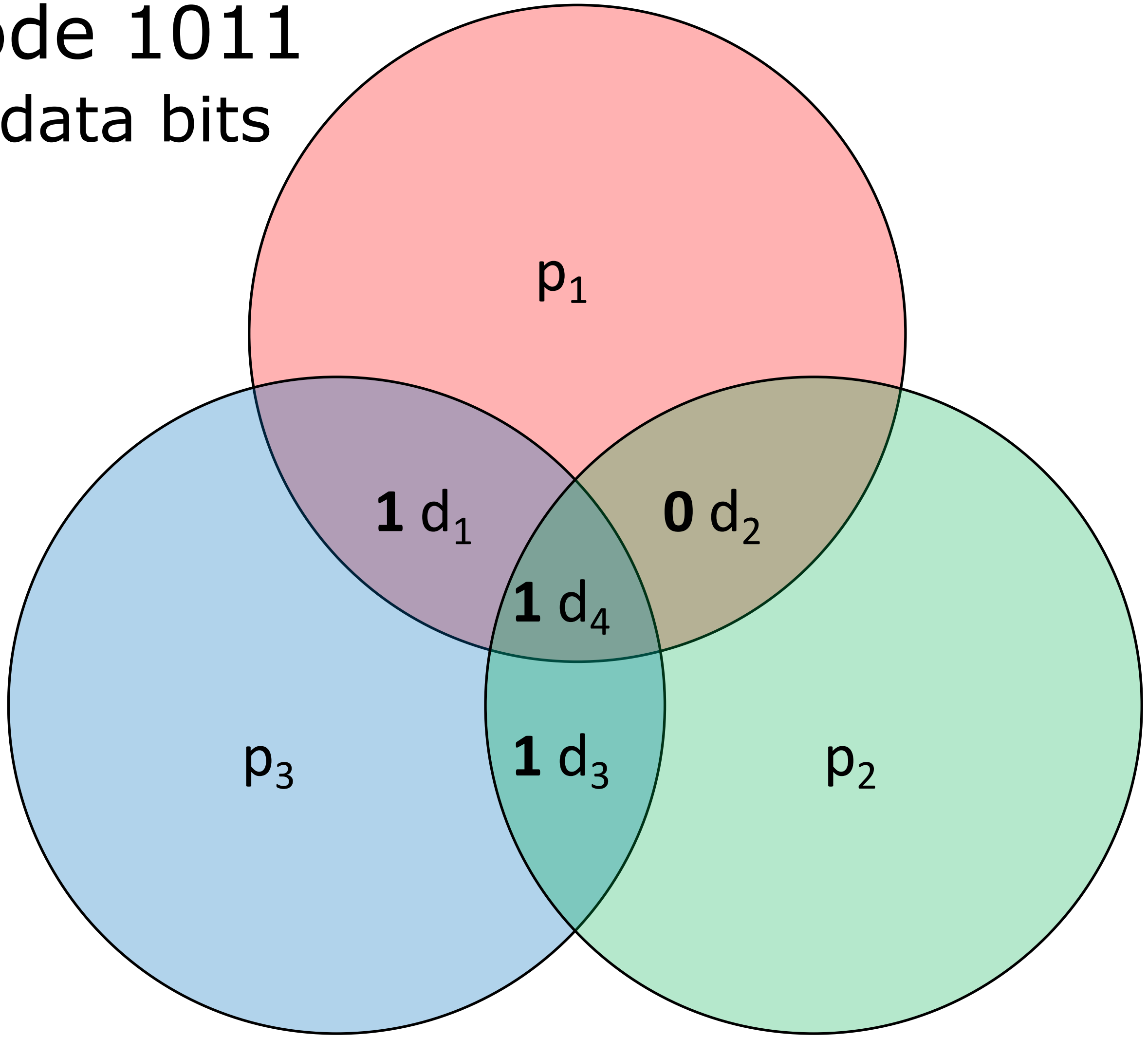
- Example: Encode 1011



© 2015-22 Tilman Wolf

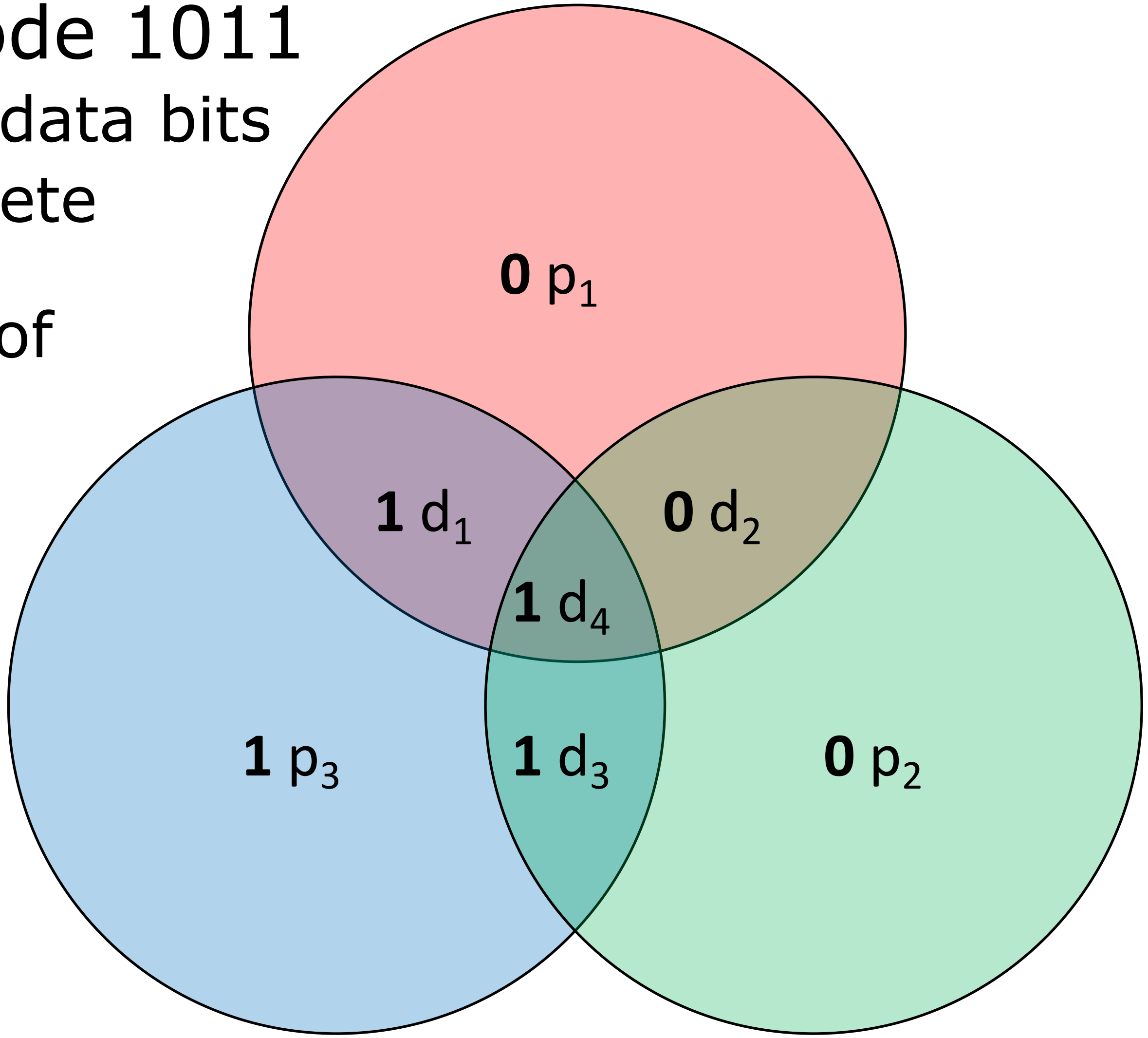
Hamming(7,4) Code Example 2/9

- Example: Encode 1011
  - Step 1: enter data bits



Hamming(7,4) Code Example 3/9

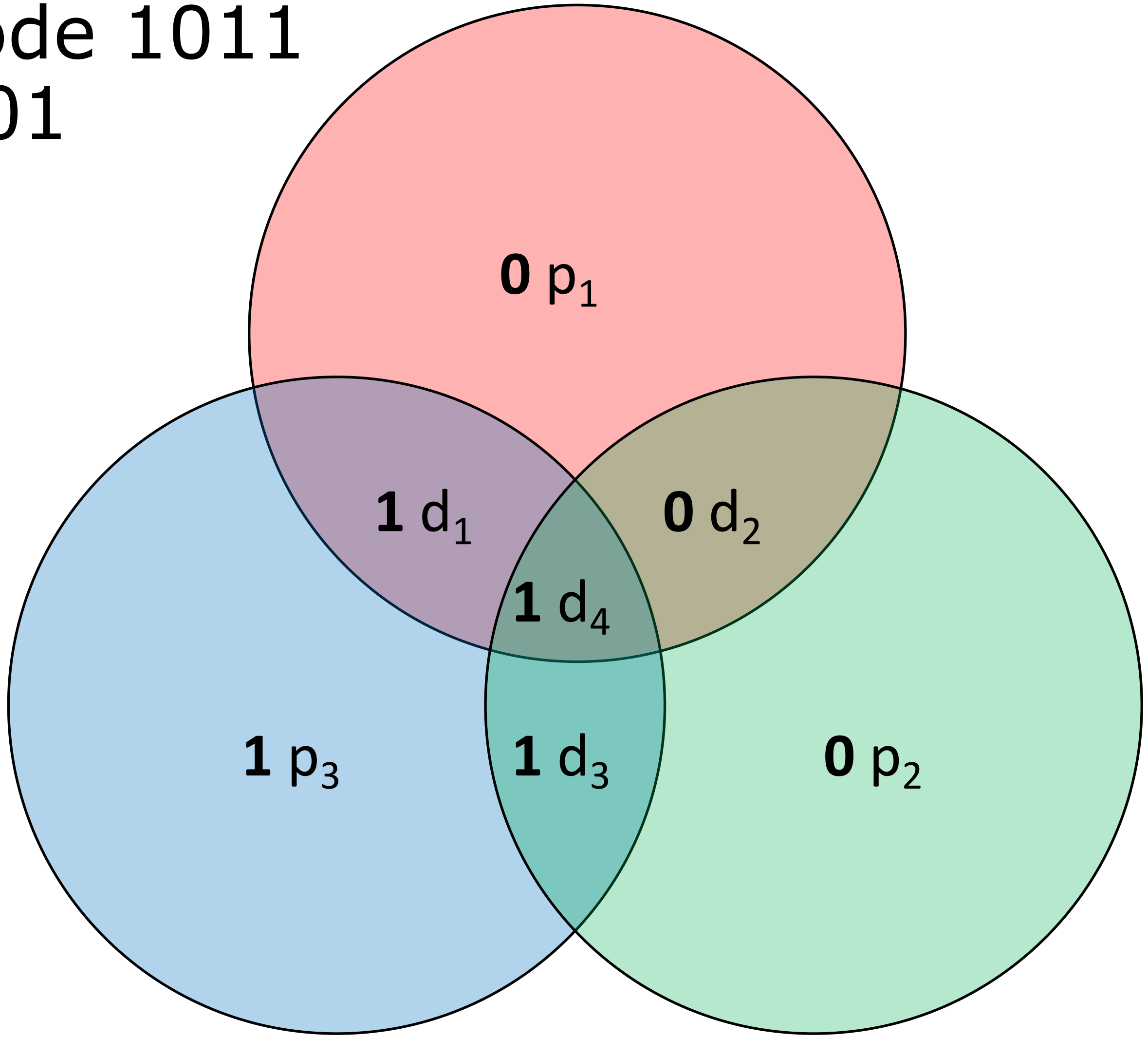
- Example: Encode 1011
  - Step 1: enter data bits
  - Step 2: complete parity bits for even number of 1's in each circle



© 2015-22 Tilman Wolf

Hamming(7,4) Code Example 4/9

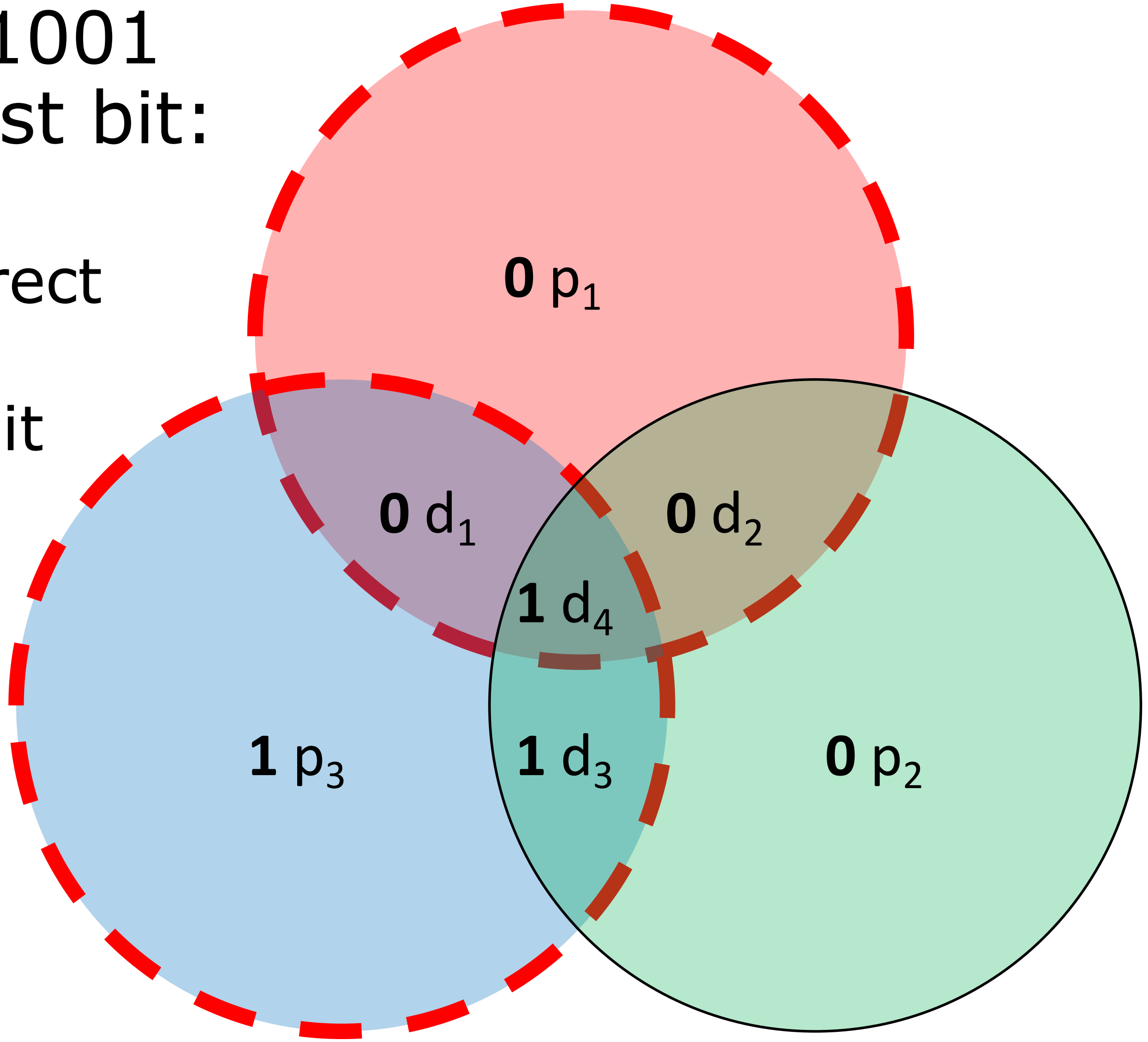
- Example: Encode 1011
  Result: 1011001



© 2015-22 Tilman Wolf

Hamming(7,4) Code Example 5/9

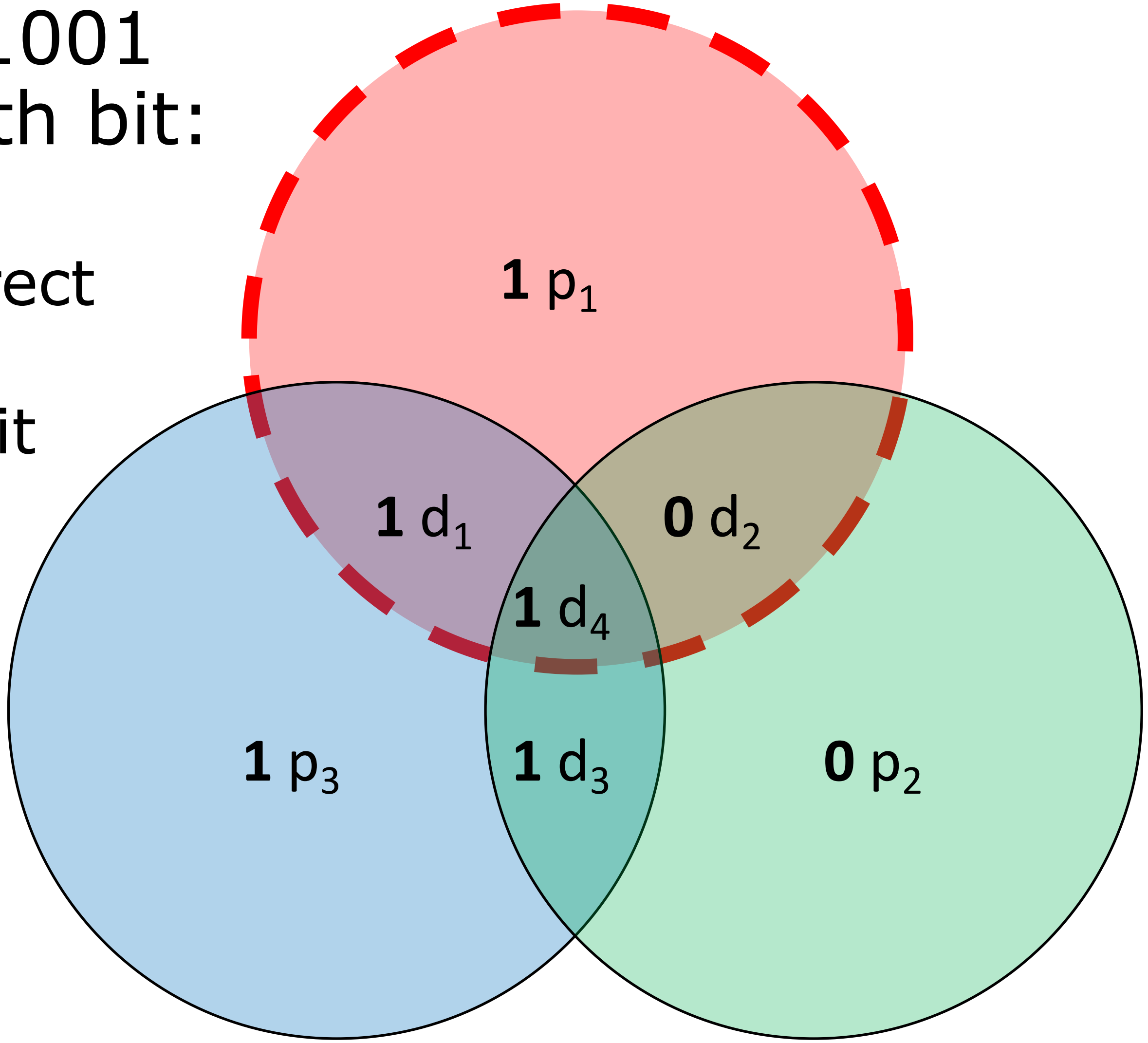
- Example: 1011001 has error in first bit: **0**011001
  - Identify incorrect circles
  - Overlapping bit has error



© 2015-22 Tilman Wolf

Hamming(7,4) Code Example 6/9

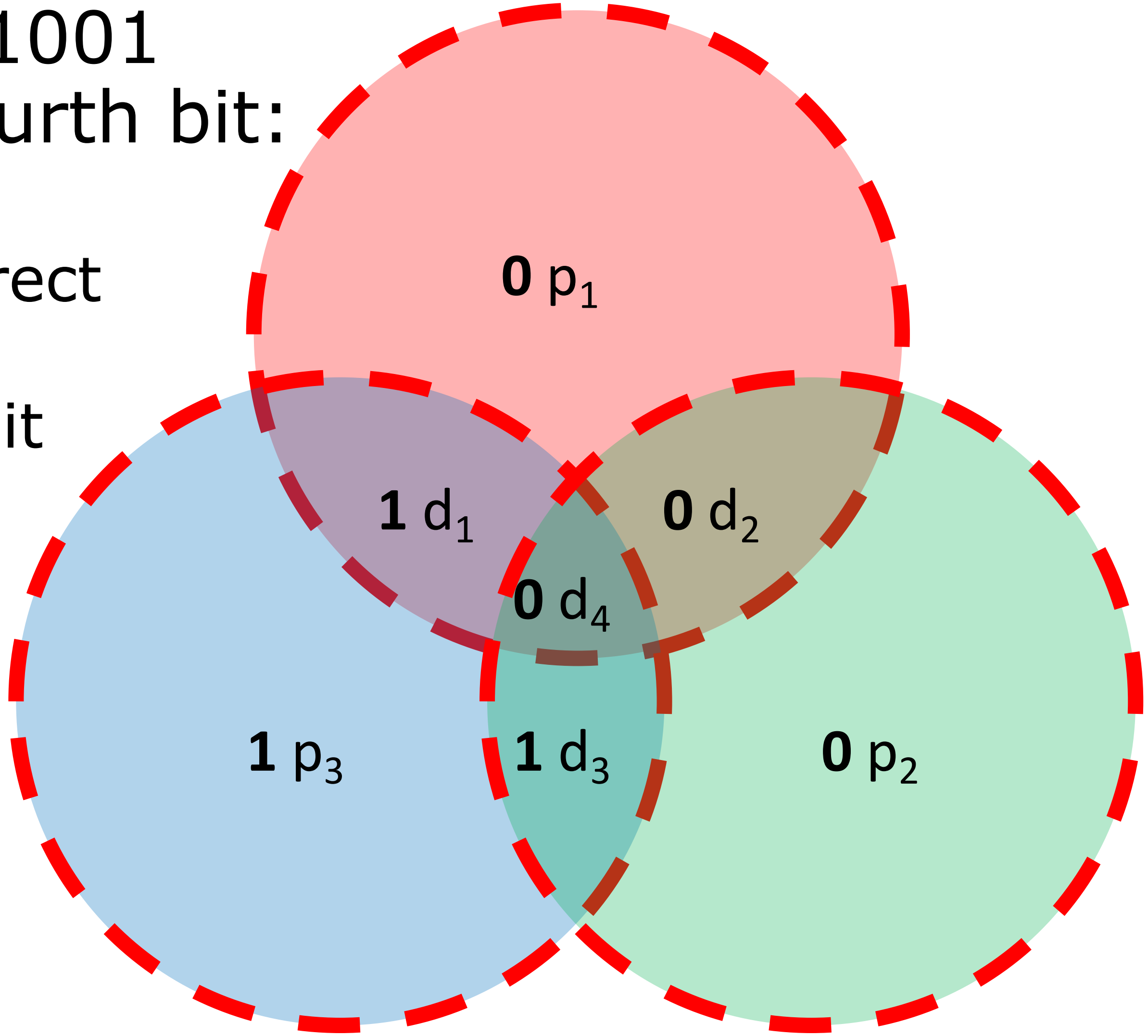
- Example: 1011001 has error in fifth bit: 101**1**101
  - Identify incorrect circles
  - Overlapping bit has error



© 2015-22 Tilman Wolf

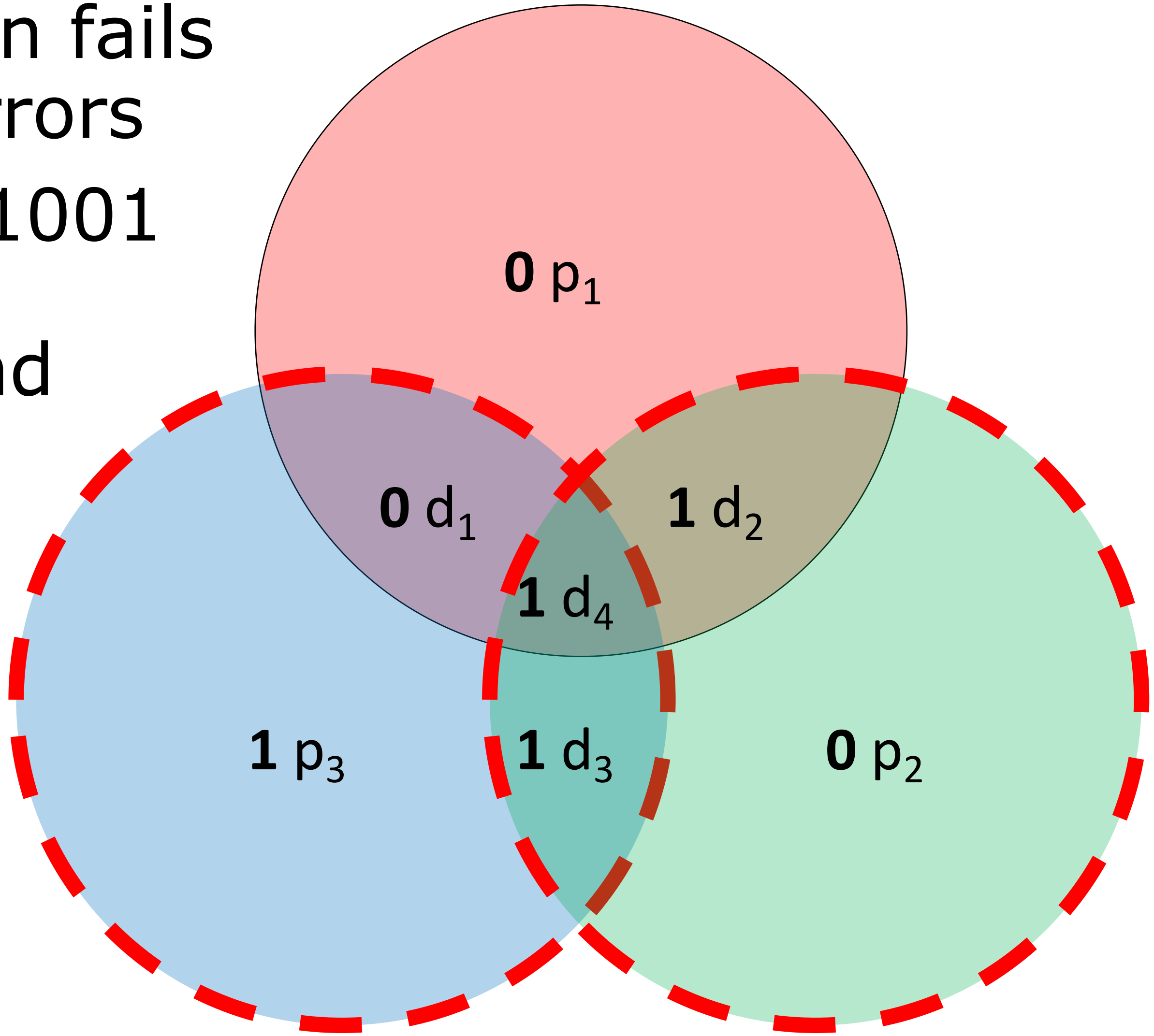
Hamming(7,4) Code Example 7/9

- Example: 1011001 has error in fourth bit: 001**0**001
  - Identify incorrect circles
  - Overlapping bit has error



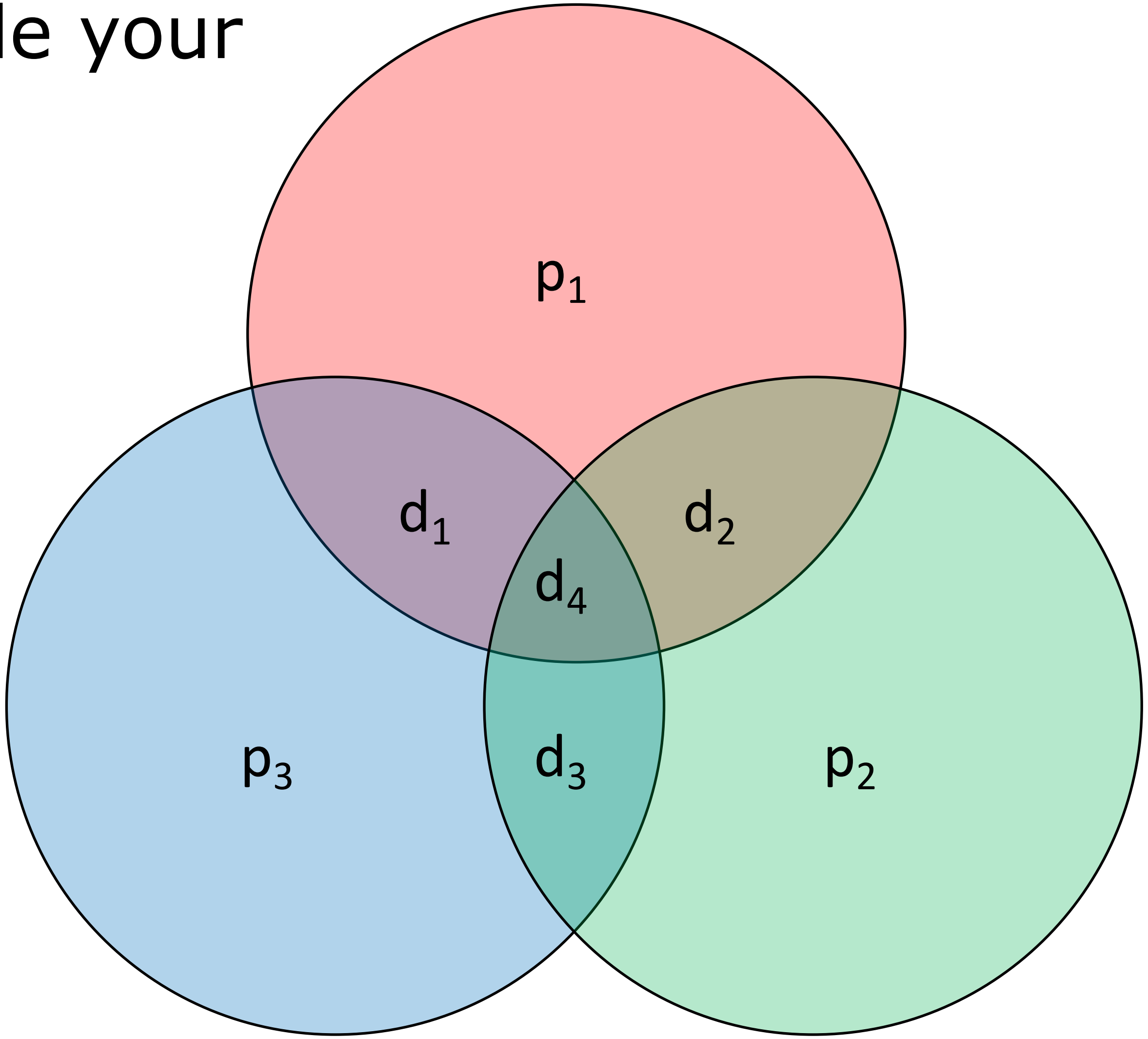
Hamming(7,4) Code Example 8/9

- Error correction fails with two bit errors
- Example: 1011001 has error in first and second bit: **01**11001
  - Correction would flip third bit 01**0**1001



Hamming(7,4) Code Example 9/9

- Activity: Encode your own four bits



© 2015-22 Tilman Wolf

Experiment III 1/2

- Transmission of 4 bits of data
  - If you roll 1, 2, 3, 4, or 5: correct transmission of bit
  - If you roll 6: incorrect transmission of bit – bit error!
- Tx "successful" if no two bit error occur in 7-bit code

Hamming(7,4) code						

- Transmission success? yes/no

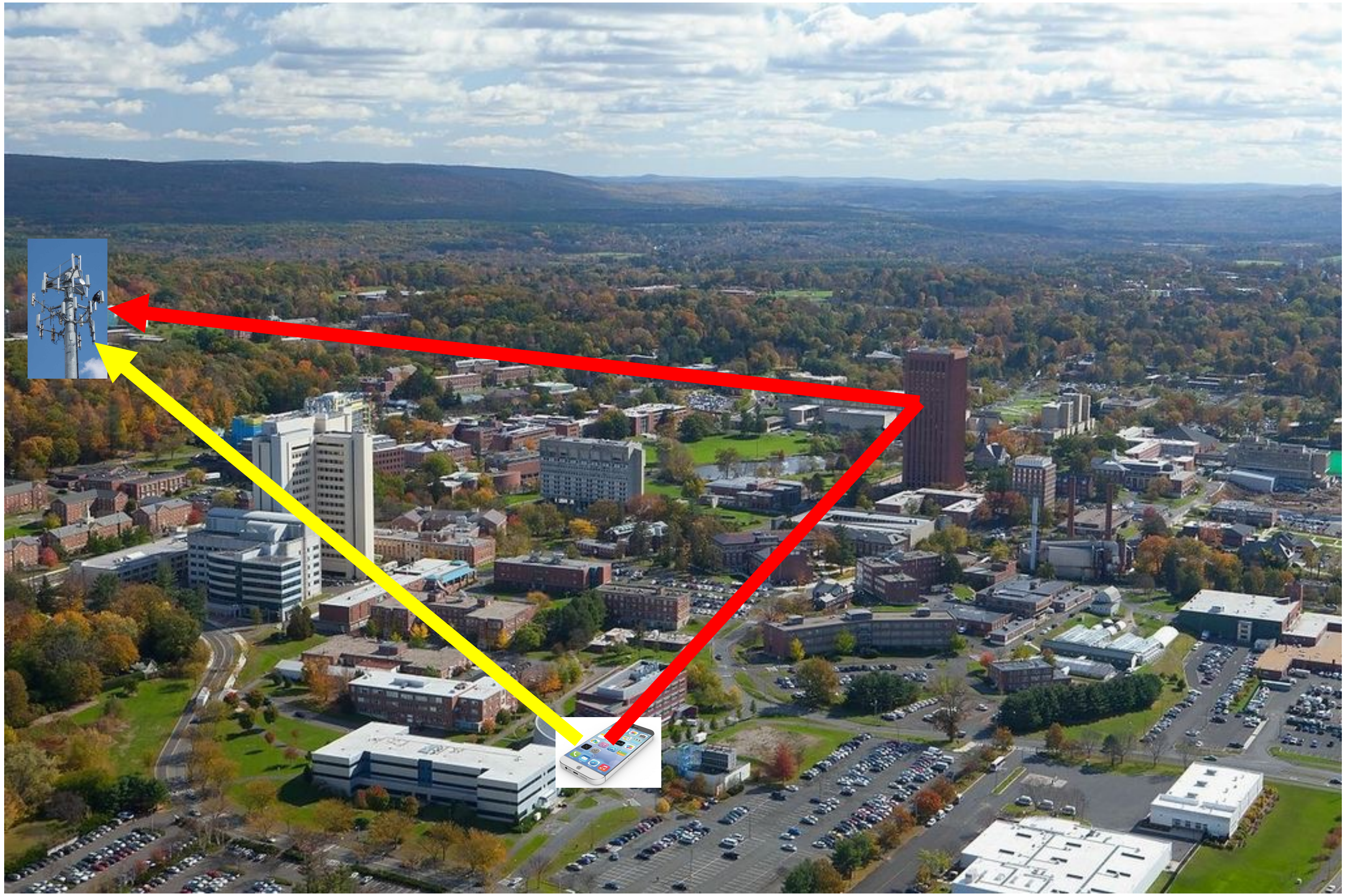
© 2015-22 Tilman Wolf

Experiment III 2/2

- What is the probability that transmission is correct?
  - Zero or one error in 7-bit code sequence
- 7-bit transmission:
  - No error: P[no error in code] = $(1\text{-}p)^7 = (5/6)^7 = 0.2791$
  - One error: P[one error in code] = $p(1\text{-}p)^6 = 1/6(5/6)^6 =$
    $= 0.056$
  - P[successful transmission] = $(1\text{-}p)^7 + 7 * p(1\text{-}p)^6 = 0.6698$
- Transmission correct in about 67% of cases
  - Less success probability than using triples
  - Cost of less than 2x in terms of data transmission

© 2015-22 Tilman Wolf

Multipath Transmission 1/6

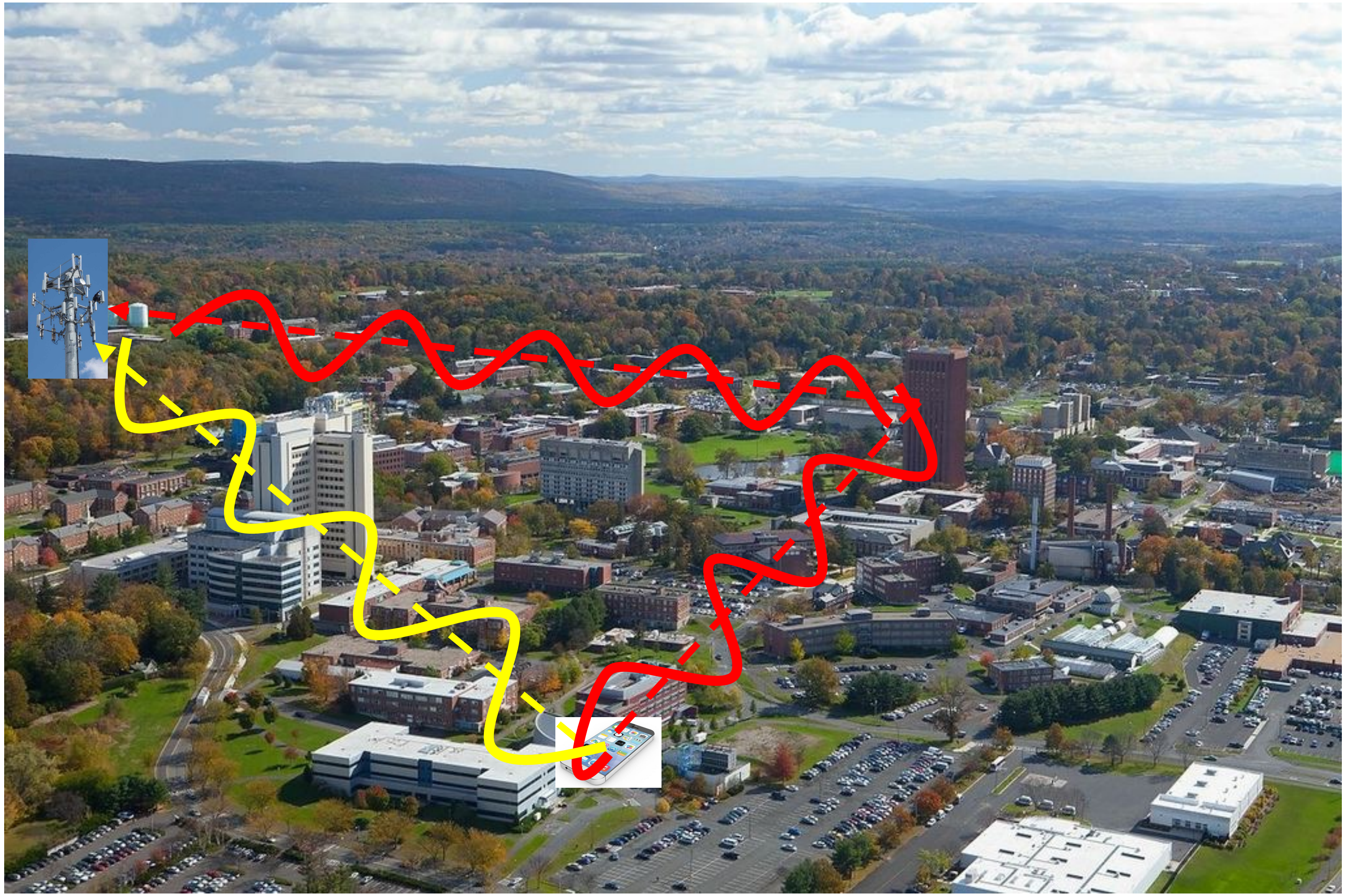


Multipath Transmission 2/6

- Electromagnetic waves may along different paths
  - Direct line-of-sight
  - Bounce off ground
  - Bounce of buildings
  - Etc.
- Copies of signal take different amount of time
  - Propagation with speed of light, but still noticeable
  - Think of number of wavelengths that fit along path
- What happens when copies of a signal arrive at receiver?
  - Difference in phase
  - Difference in amplitude

© 2015-22 Tilman Wolf

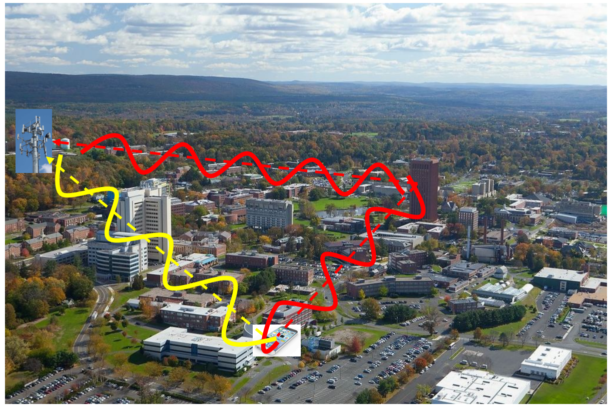
Multipath Transmission 3/6



© 2015-22 Tilman Wolf

Multipath Transmission 4/6

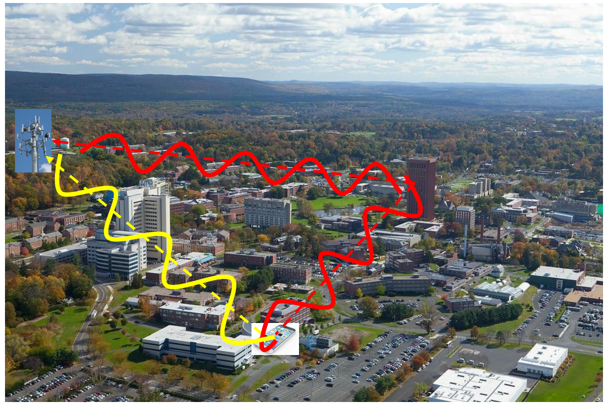
- What is the wavelength of 851MHz cell signal?
  - Relationship between wavelength and frequency: $\lambda = \frac{v}{f}$



- How many wavelengths fit on path?
  - Yellow path (1000m):
  - Red path (1250m):
- What is the phase difference between yellow and red signal?

Multipath Transmission 5/6

- What is the wavelength of 851MHz cell signal?
  - Relationship between wavelength and frequency: $\lambda = \frac{v}{f}$
  - Assume v = 300,000 km/s
  - λ = 300,000 km/s / 851 MHz = 0.3525m



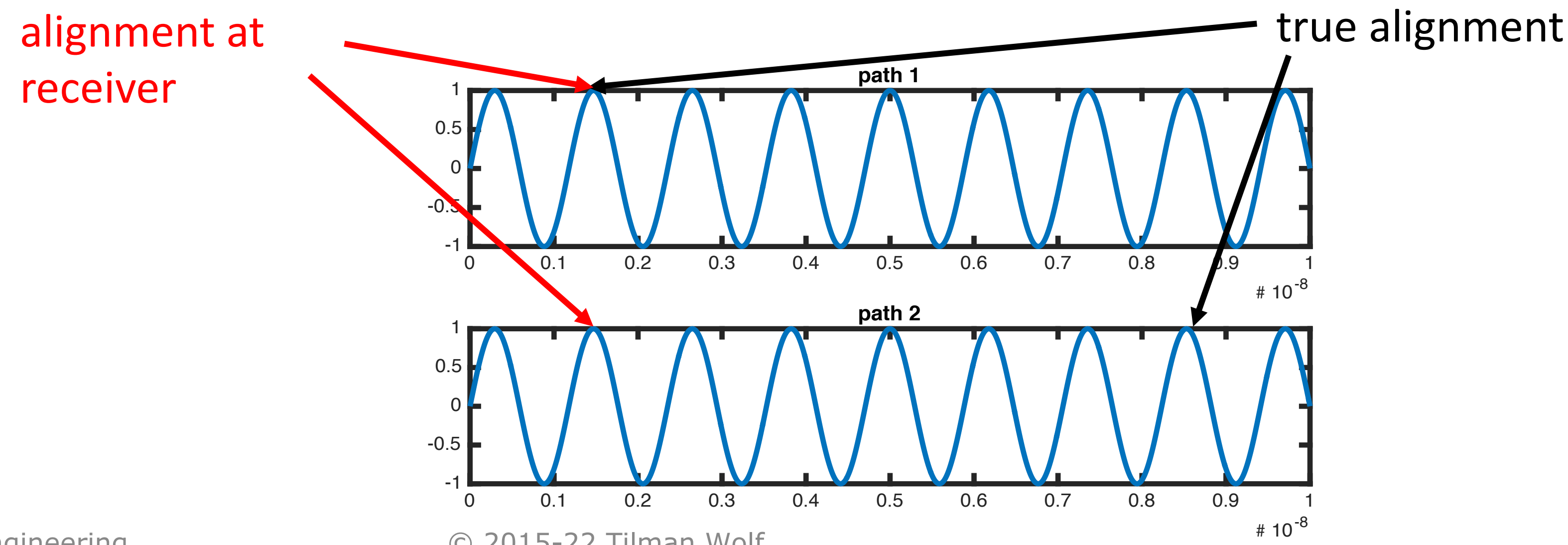
- How many wavelengths fit on path?
  - Yellow path (1000m):
    - 1000m/0.3525m=2836.67 wavelengths
  - Red path (1250m):
    - 1250m/0.3525m=3545.83 wavelengths

- What is the phase difference between yellow and red signal?
  - 3545.83 – 2836.67 = 709.167 wavelengths

© 2015-22 Tilman Wolf

Multipath Transmission 6/6

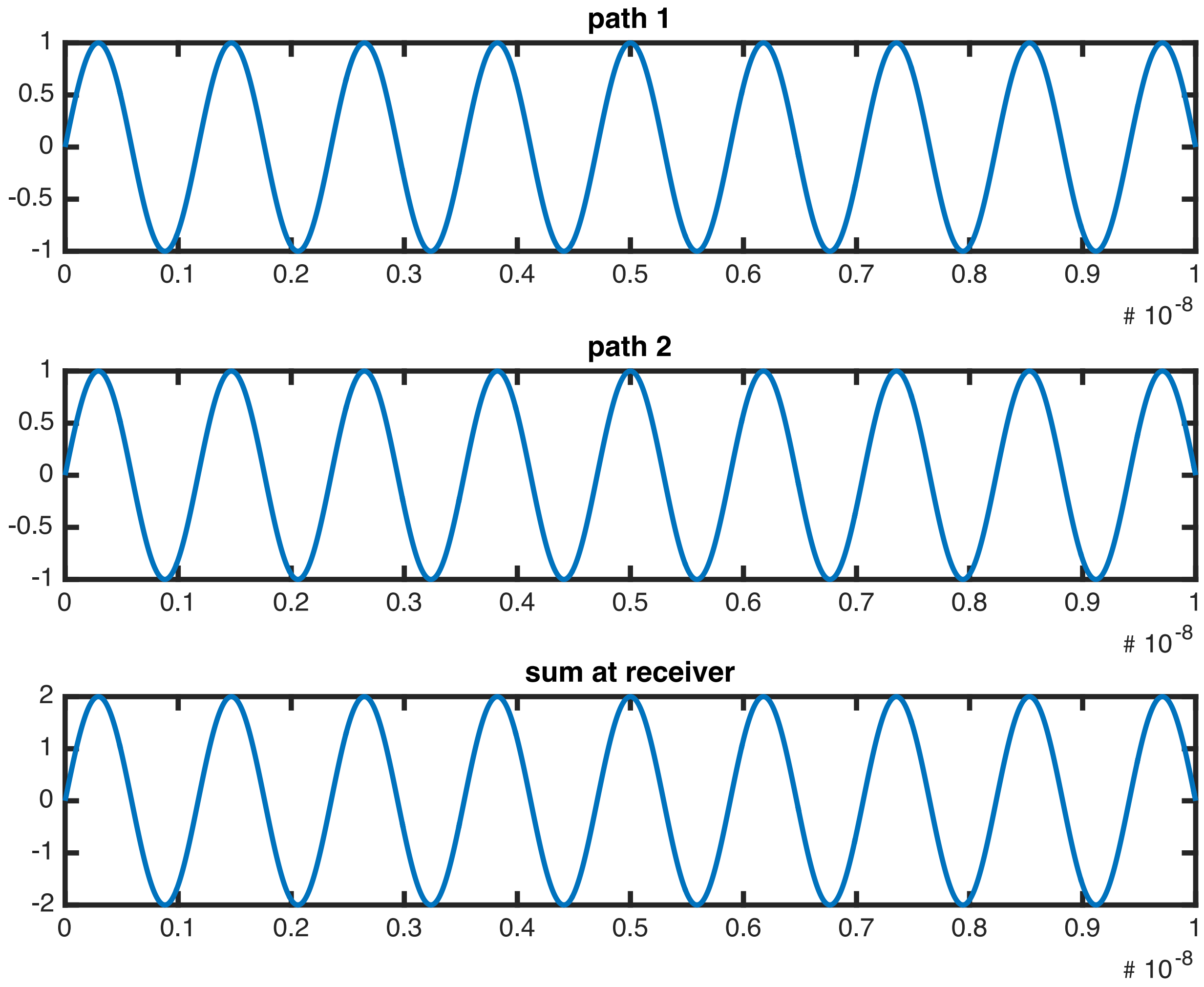
- Example shows large phase difference
  - 709.167 wavelengths
- However: signal has lower frequency than carrier
  - Different carrier signal peaks can align at receiver
  - Only phase difference within one wavelength matters
- Effective phase differences 0.167 wavelengths
  - 60 degrees



© 2015-22 Tilman Wolf

Interference 1/3

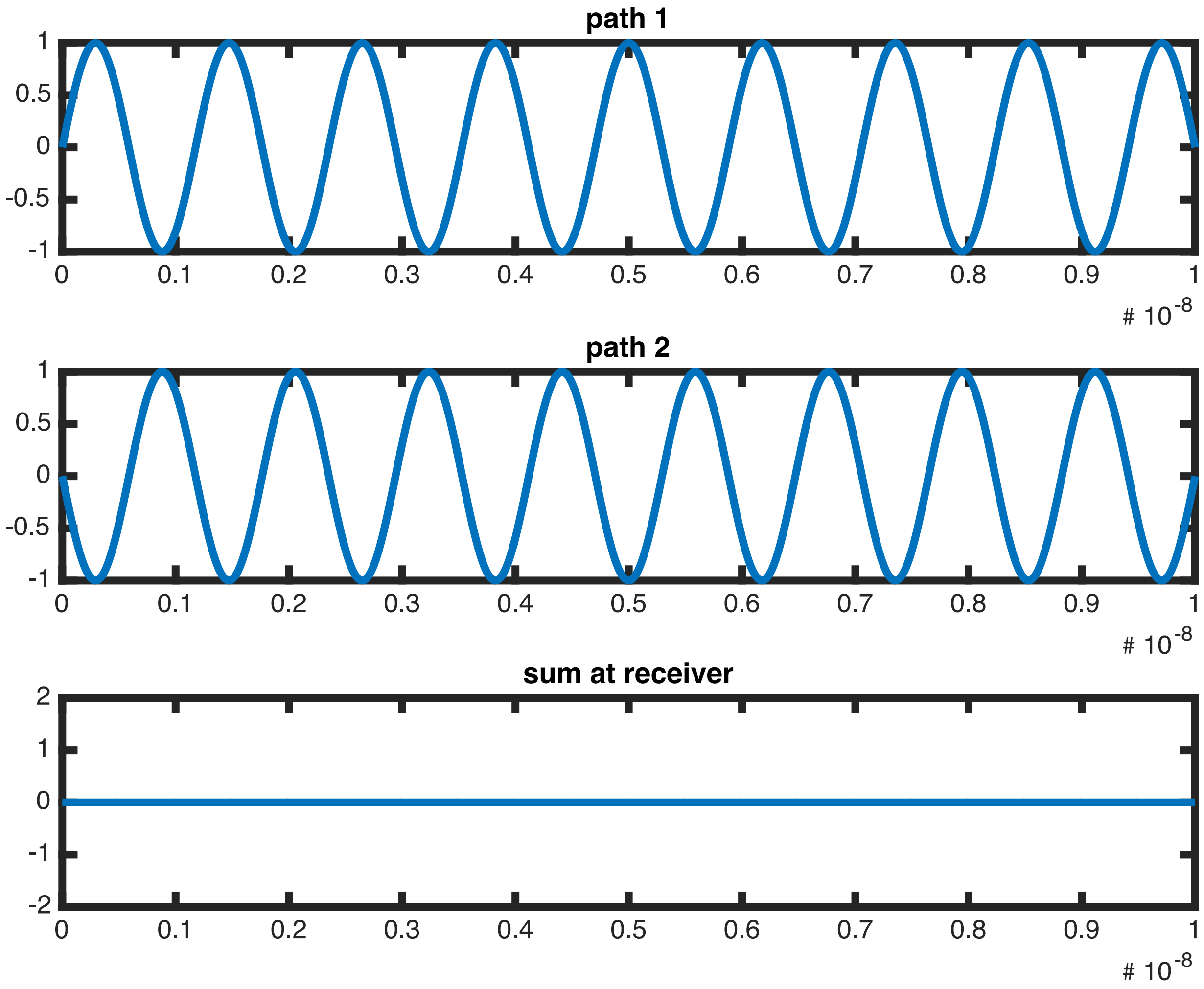
- Constructive interference
  - Both paths arrive in phase
  - Peaks and valleys align and amplify



© 2015-22 Tilman Wolf

Interference 2/3

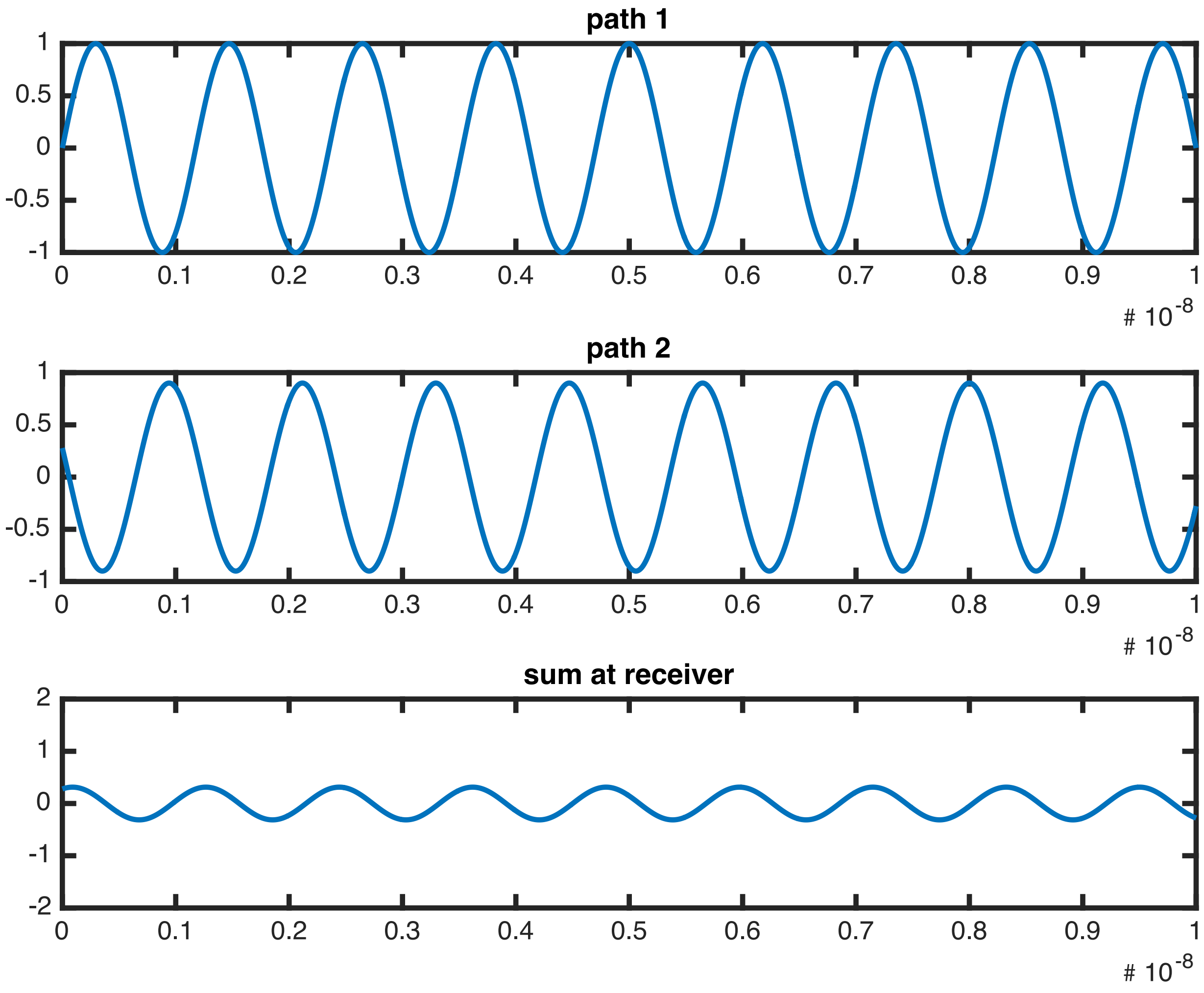
- Destructive interference
  - Paths arrive 180 degrees out of phase
  - Peaks align with valleys and cancel out



© 2015-22 Tilman Wolf

Interference 3/3

- Partial interference
  - Paths arrive a bit out of phase with different attenuation
  - Peaks do not exactly align with valleys



© 2015-22 Tilman Wolf

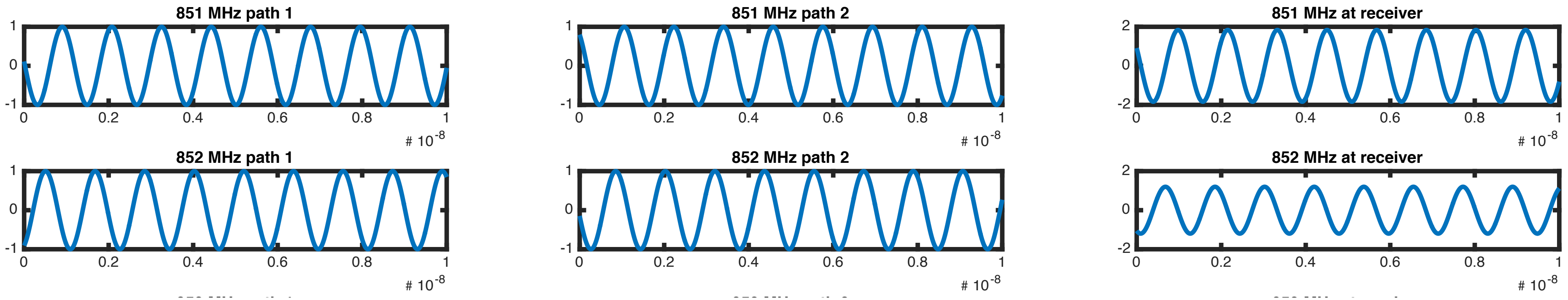
Leveraging Diversity 1/2

- Destructive interferences is a problem
  - Certain areas are bad for given frequency / set of paths
- Phase shift for paths depends on frequency
  - Interference depends on frequency
- Example:
  - Frequencies: f_1=851MHz, f_2=852MHz
    Path distances: d_1=1000m, d_2=1250m
  - Wavelengths: λ_1=0.3522m, λ_2=0.3518m (c=299,703km/s)
  - For f_1: d_1 in wavelengths = 2839.5 (phase 174 degrees)
    d_2 in wavelengths = 3549.4 (phase 127 degrees)
  - For f_2: d_1 in wavelengths = 2842.8 (phase 295 degrees)
    d_2 in wavelengths = 3553.5 (phase 188 degrees)
  - Interference for f_1: 46 degrees
  - Interference for f_2: 107 degrees

© 2015-22 Tilman Wolf

Leveraging Diversity 2/2

- Example (continued):

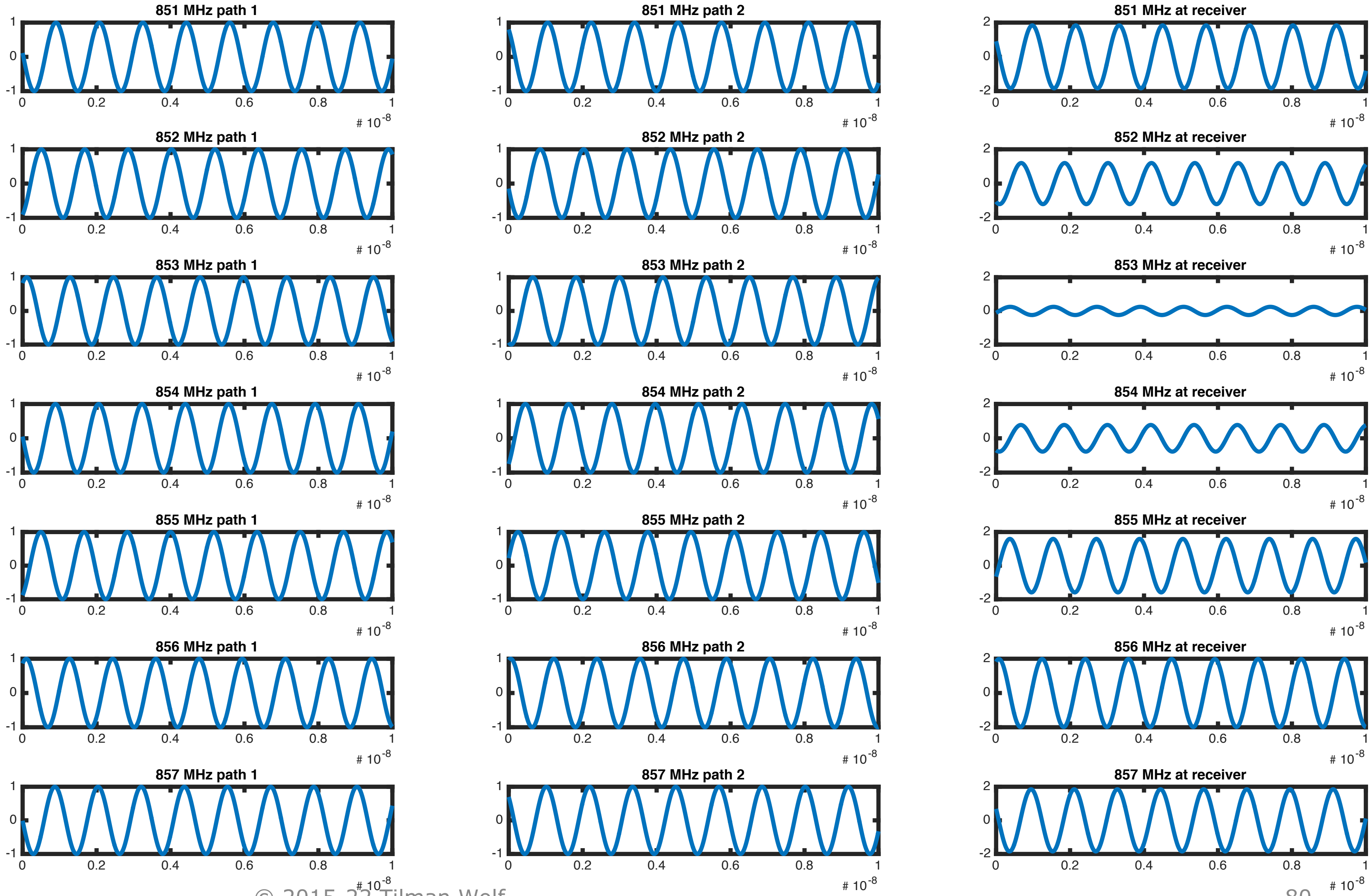


  - 852 MHz experiences a bit more interference than 851MHz
- Diversity of frequencies can avoid “dead spots”
  - Some frequencies may experience destructive interference
  - Other frequencies may experience constructive interference
- Orthogonal Frequency-Division Multiplexing (OFDM)
  - Uses many frequencies at the same time
  - Low data rate on each frequency

 © 2015-22 Tilman Wolf

OFDM Example 1/2

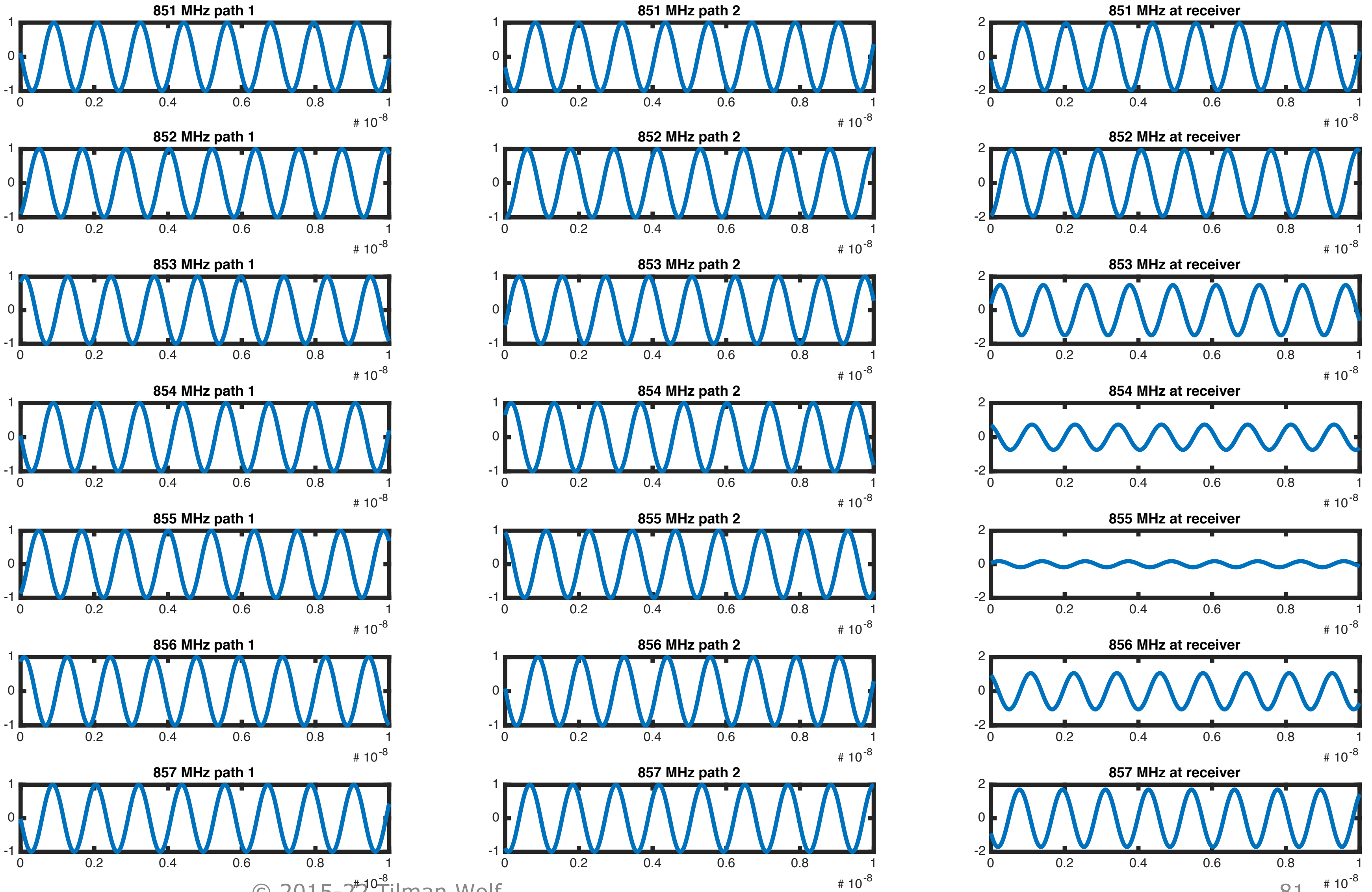
- 7 frequencies (851MHz – 857MHz)



© 2015-22 Tilman Wolf

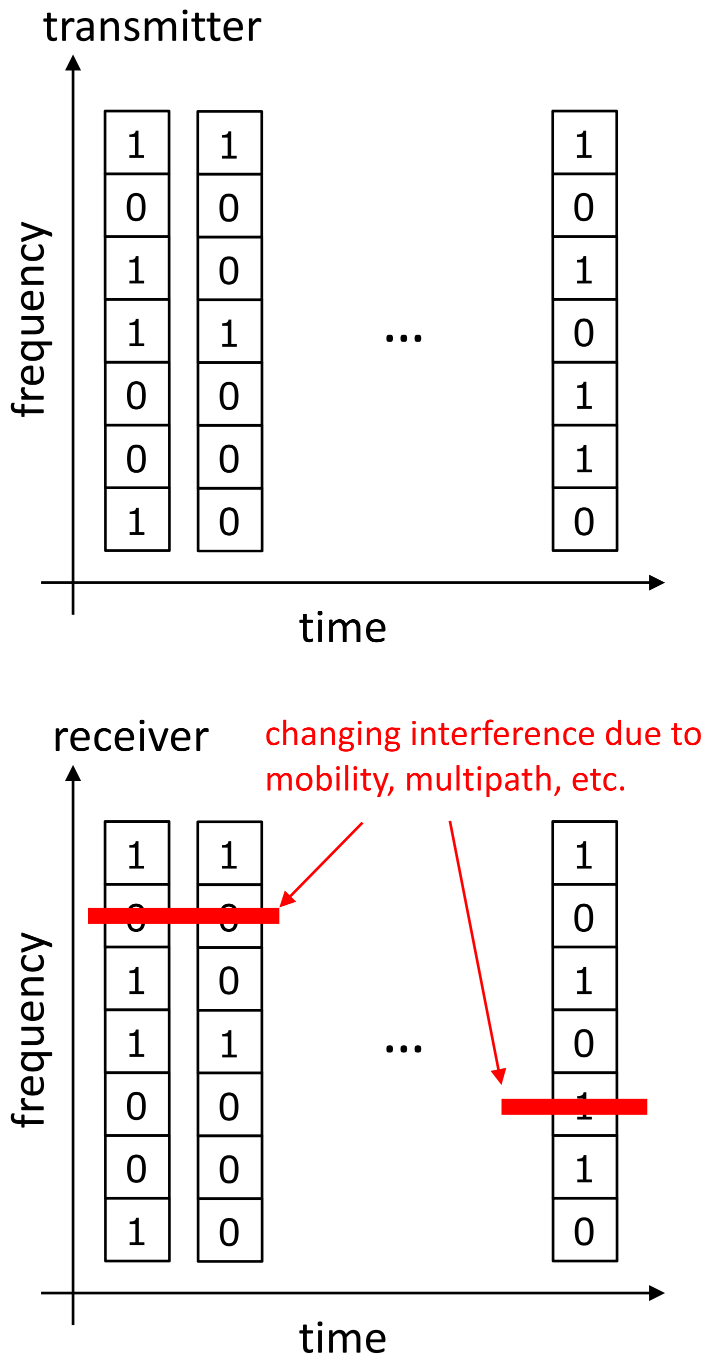
OFDM Example 2/2

- Same example, but path 2 is 5m longer



OFDM Transmission

- How to pick which frequency to use?
  - Difficult to determine a priori – use error correction code!
- OFDM codes across frequencies
  - Error correction to recover bits transmitted in channels with interference
- “Vertical” Hamming code
  - Interference in one channel can be recovered



© 2015-22 Tilman Wolf

Signal Propagation Intuition

- Wavelengths (v = 300,000 km/s)
  - f = 1 MHz: λ = 300 m
  - f = 100 MHz: λ = 3 m
  - f = 1 GHz: λ = 0.3 m
  - f = 3 GHz: λ = 0.1 m
- Intuition:
  - High frequencies are hard to visualize
    - Example: 3 GHz processor clock
  - Fast propagation is hard to visualize
    - Example: speed of light at 300,000 km/s
  - Sometimes magnitudes cancel out to yield imaginable result
    - 3 GHz clock signal travels 10 cm between beats
    - Large clock trees cause different areas of chip be out of sync
- Don’t be intimidated by magnitudes

© 2015-22 Tilman Wolf

Summary

- Cell phones connect to cell tower wirelessly
  - Audio is transmitted as digital data
  - Different modulation techniques to carry digital data
- Frequency spectrum is carefully managed
  - Operators need to obtain licenses
  - Cell tower assigns channel to cell phone
  - Different oscillators and synchronization techniques
- Errors can happen during transmission
  - Error detection, error correction codes
  - Multipath transmission
  - Use of multiple frequencies at the same time
- Of course: everything a bit more complex in practice

© 2015-22 Tilman Wolf