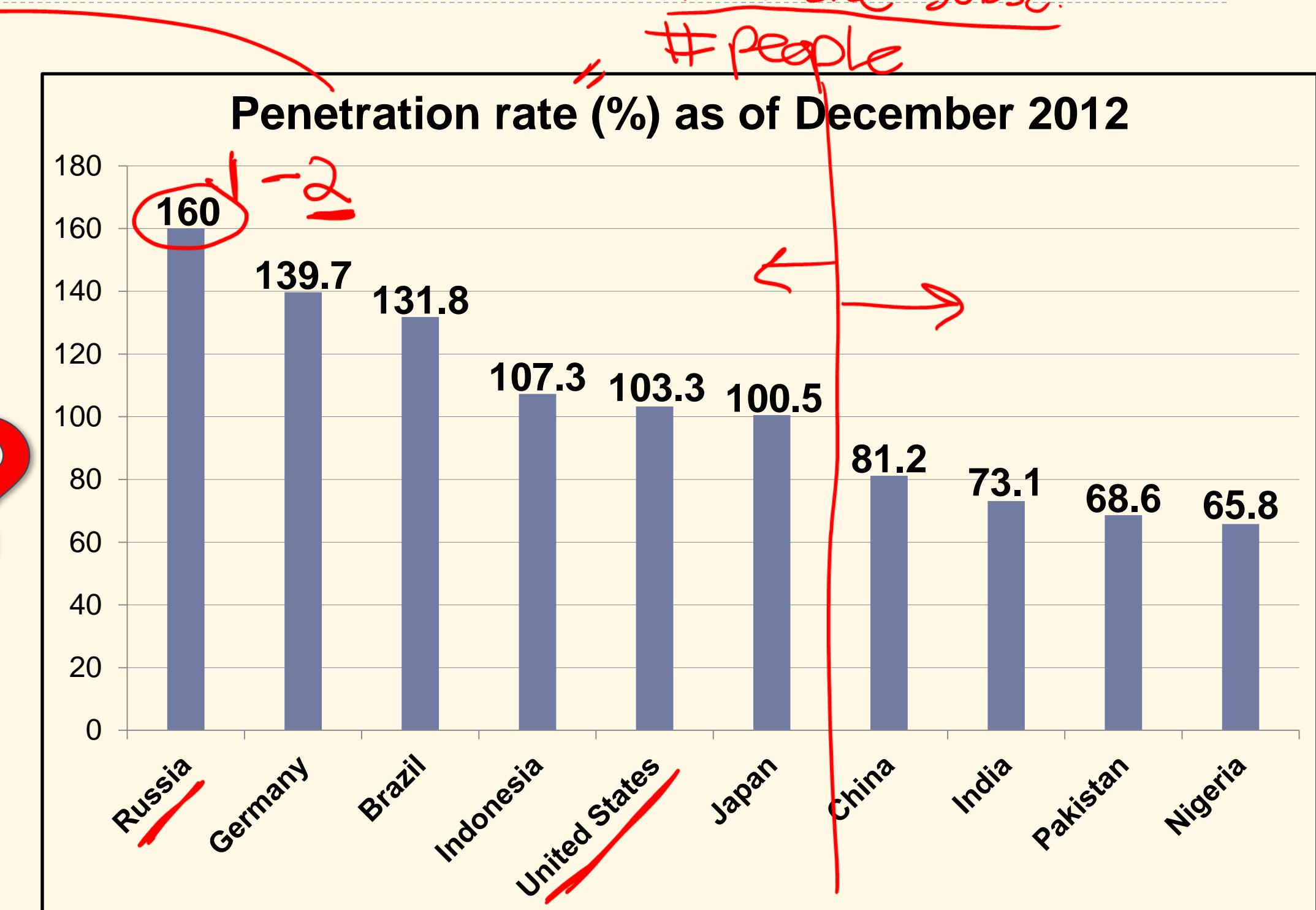
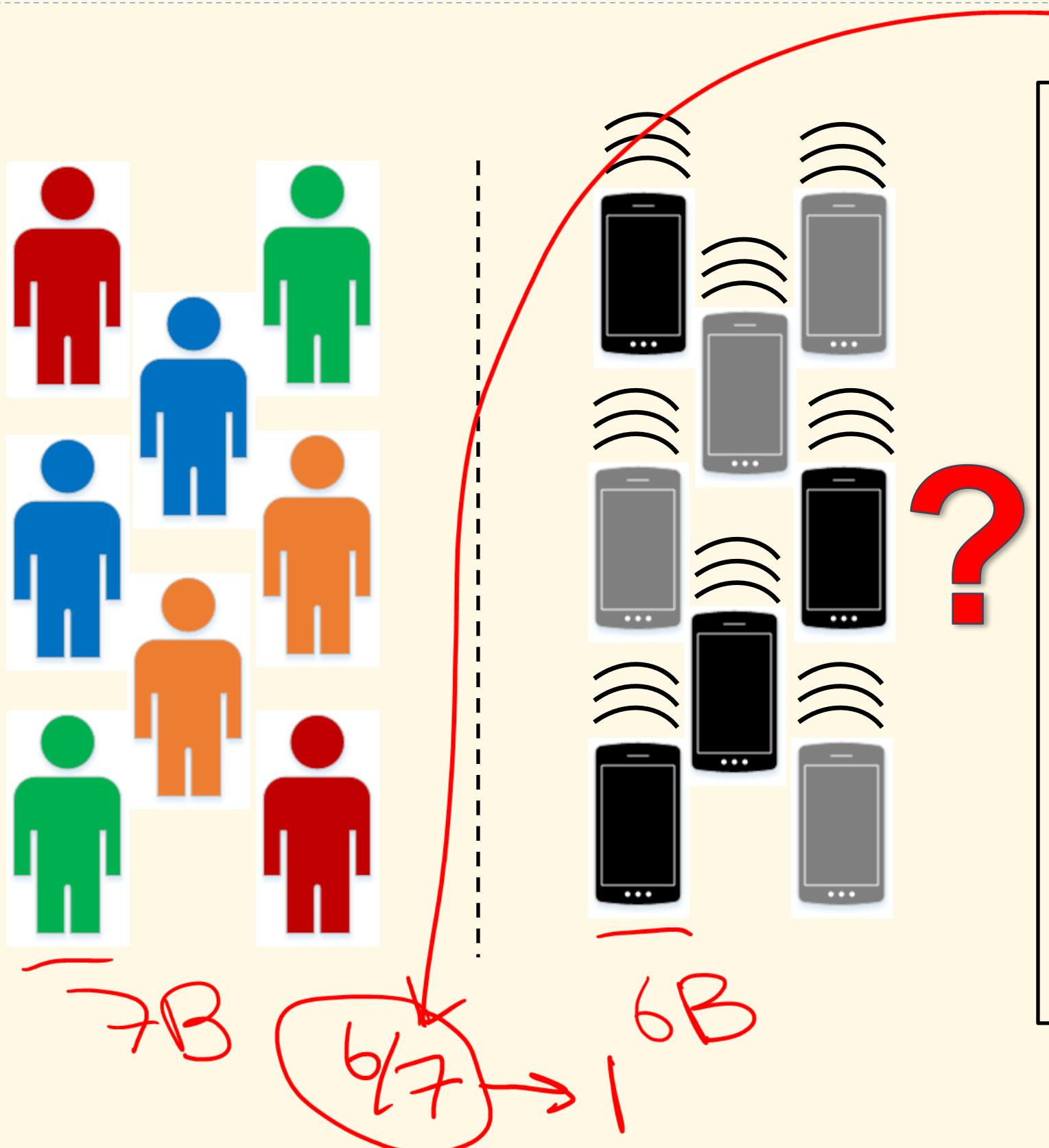


# Sharing Is Hard

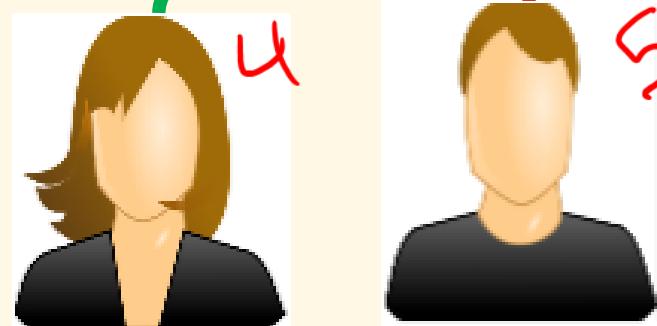
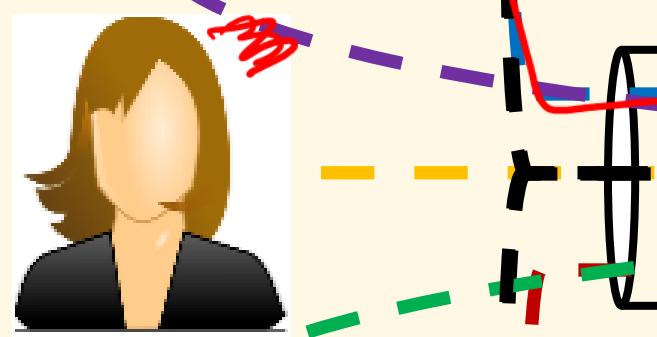
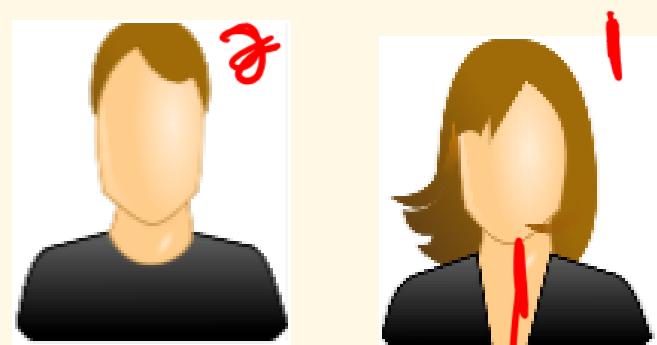


How does your cell phone decide what power to transmit?

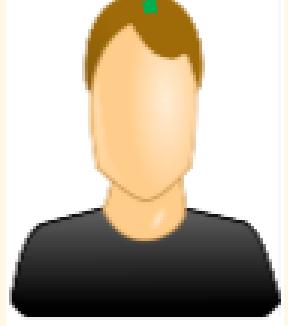
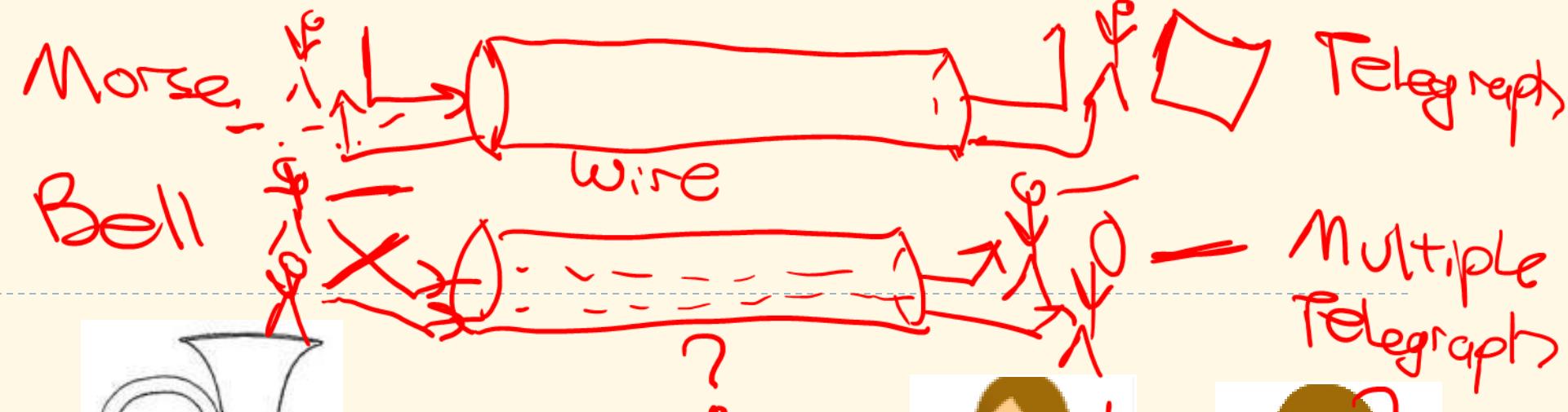
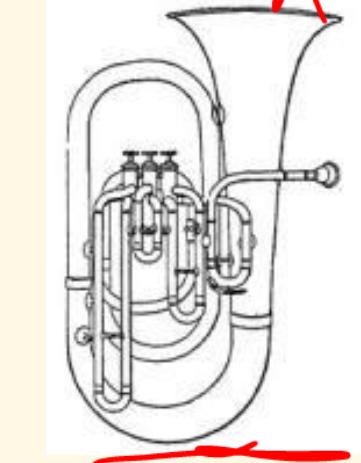
# How many cell phones are there?



# Multiple access



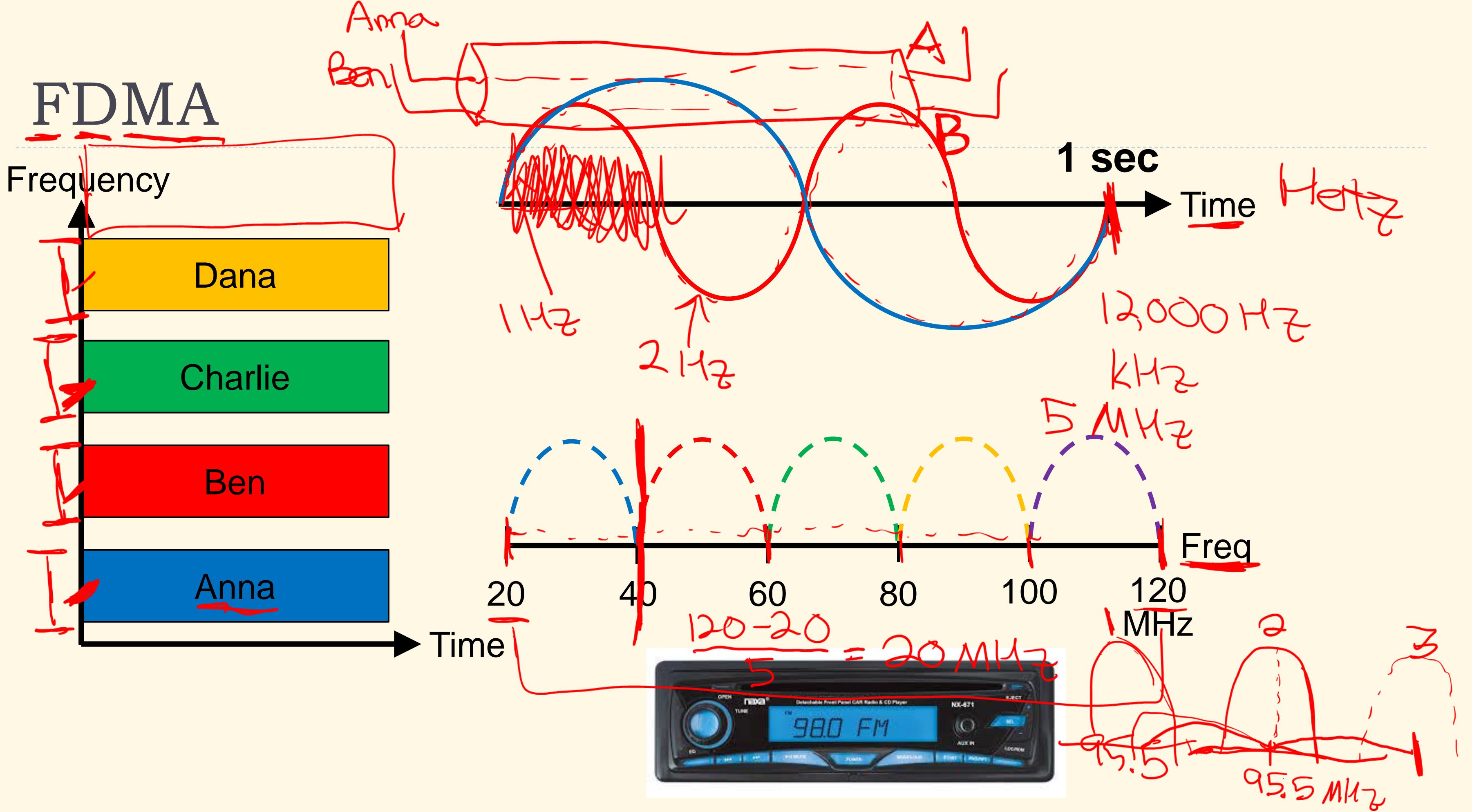
- Time
- Pitch
- Language



감사합니다 Natick  
Grazie Danke Ευχαριστίες Dalu  
Thank You Köszönöm  
Спасибо Dank Tack  
谢谢 Merci Gracias  
Seeé ありがとう



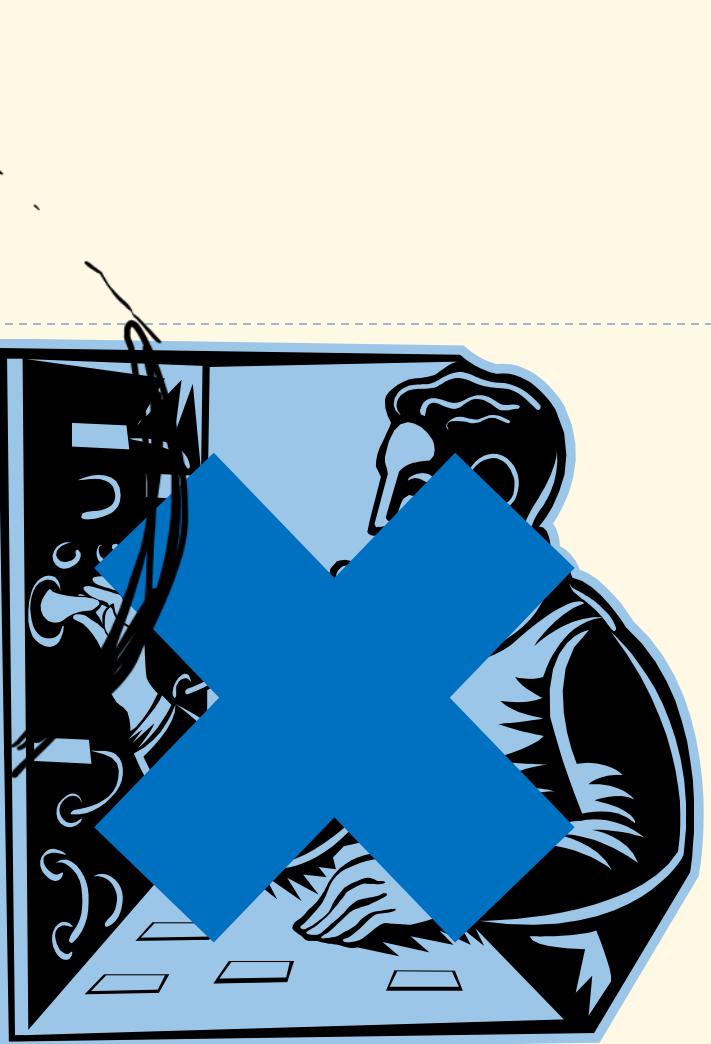
Link



OG

FDMA  
MTS (1946)

IMTS (1964)



1973

DynaTAC

1973

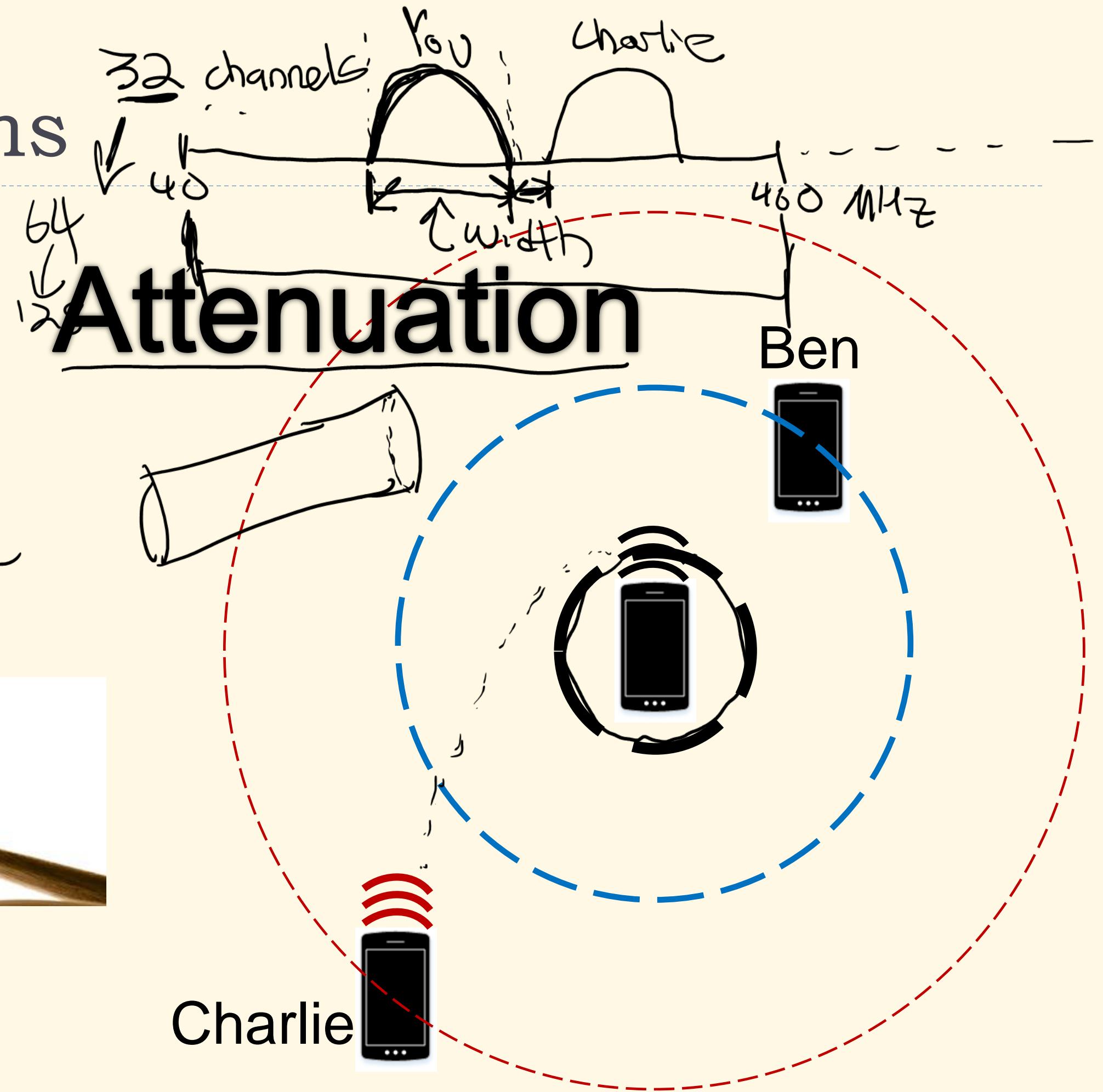
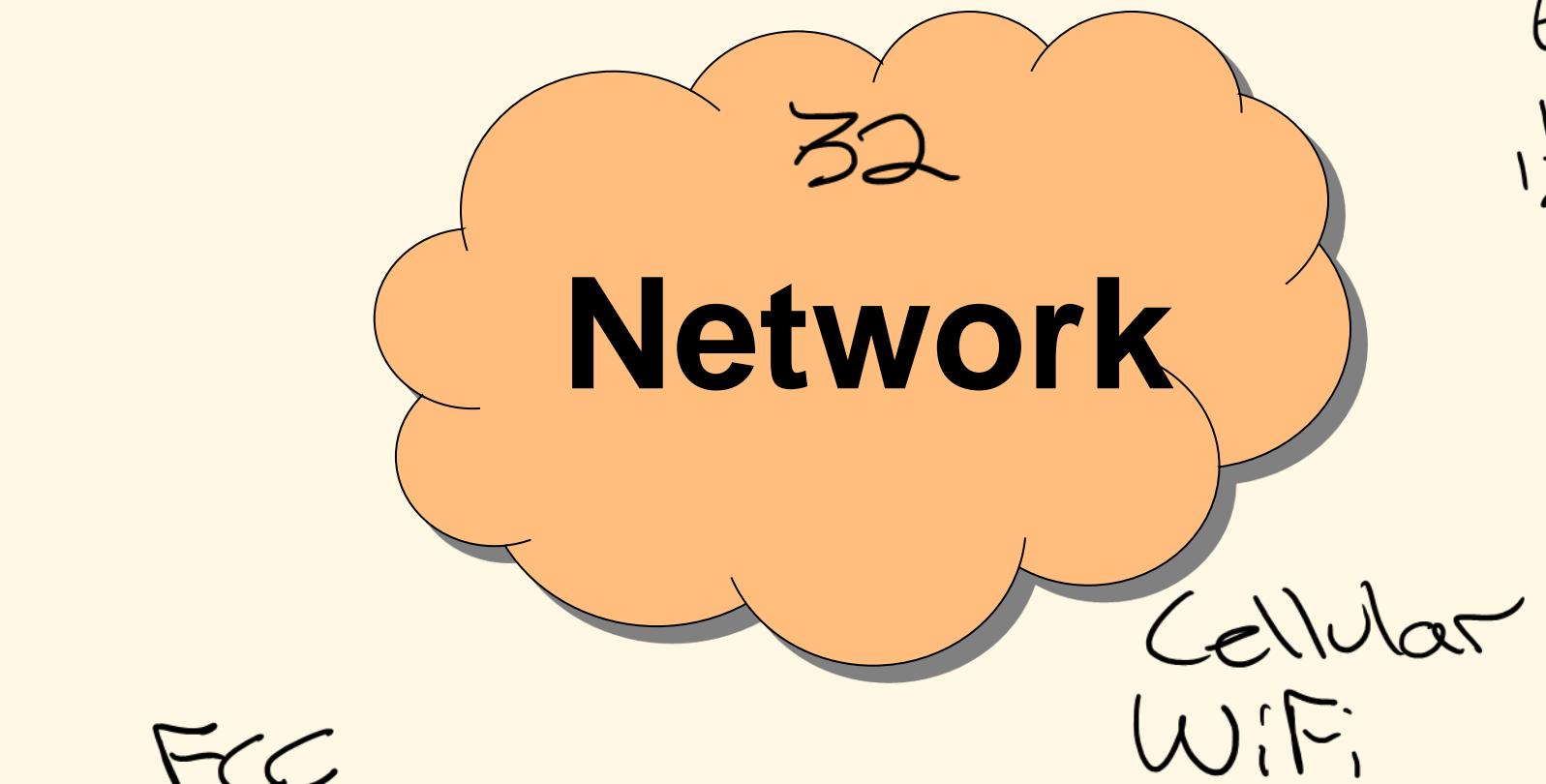
2012



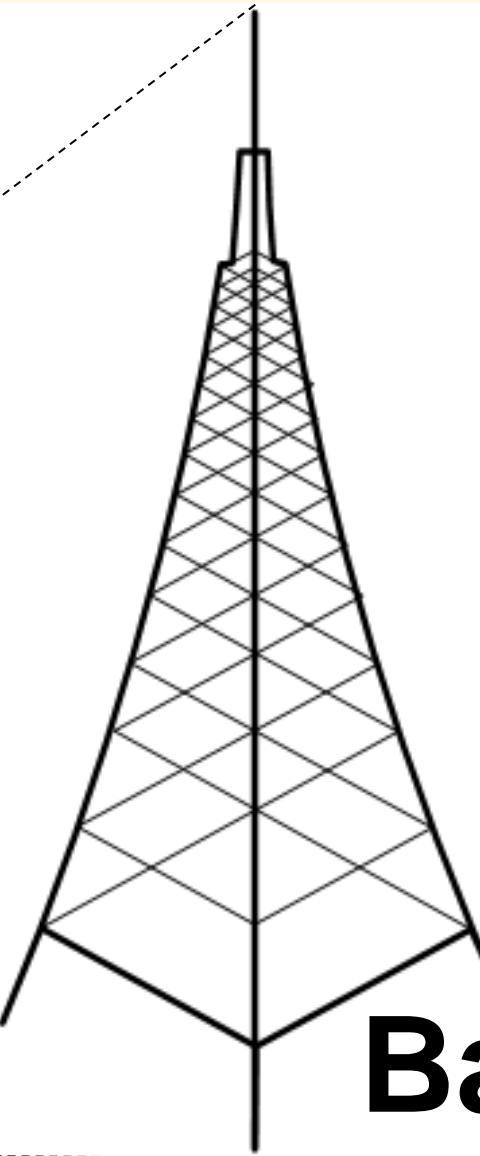
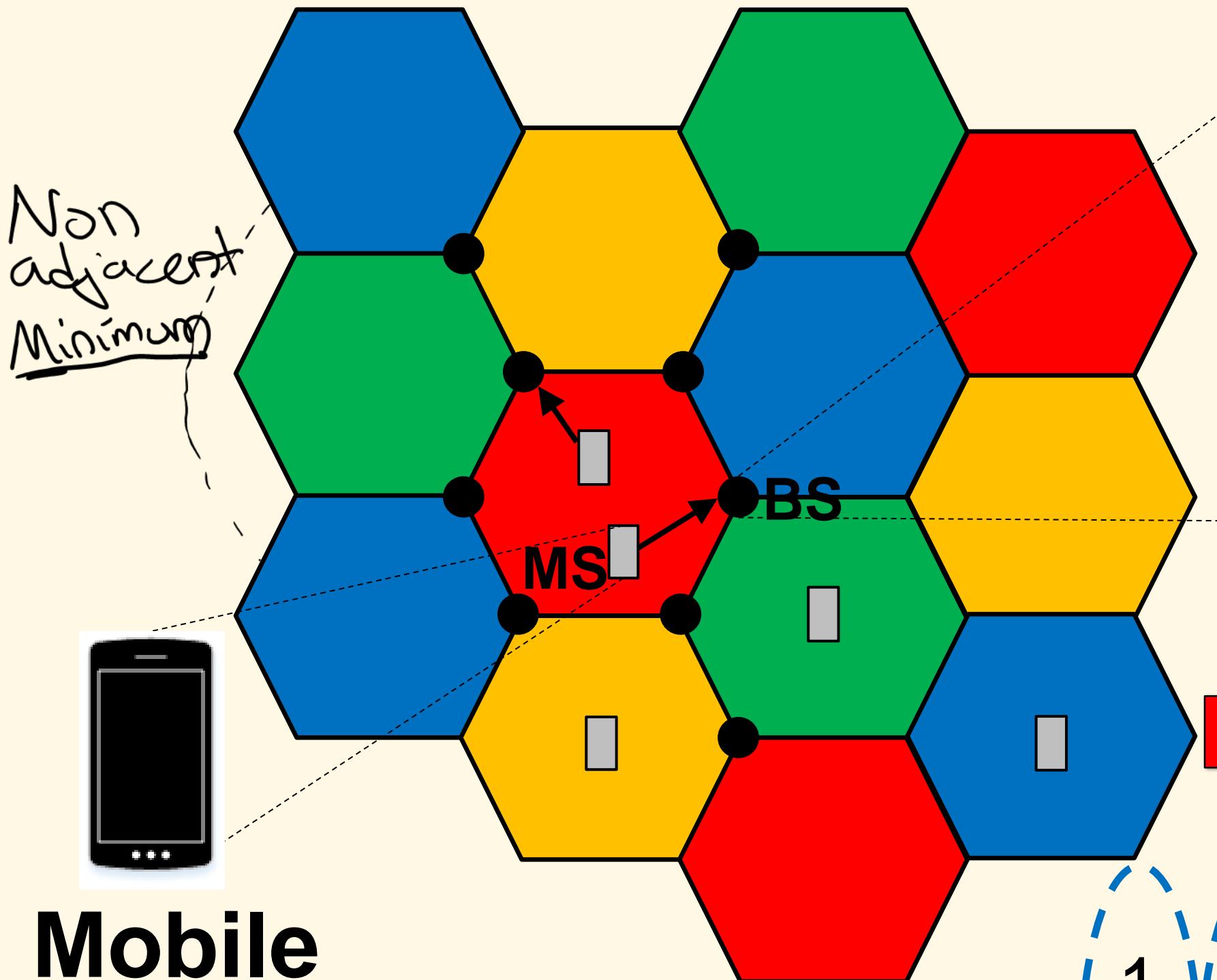
< 1/3 lb  
< \$150  
hrs

2 lb  
~~\$3000~~  
30 min

# Bursting at the seams



# The (non-biological) cell



Base  
Station

800 MHz 1 G

AMPS (1978)

Chicago  
10 cells  
90 people  
mid-1990s  
↳ 25,000,000

(+ 0.5 bands)

Frequency Reuse Factor

1

2

3

4

5

6

7

8

9

10

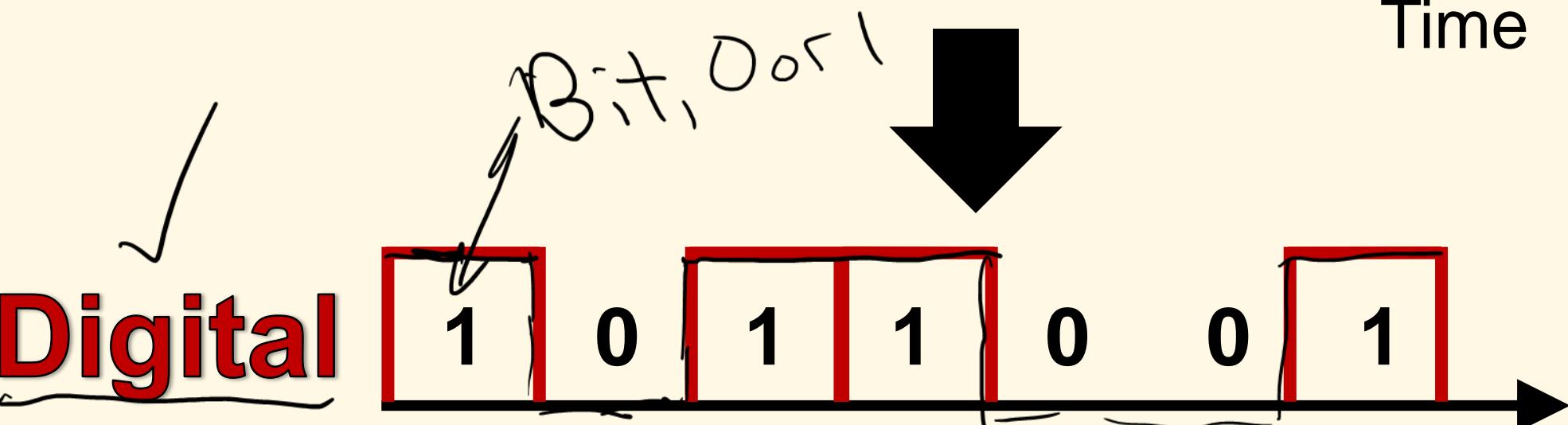
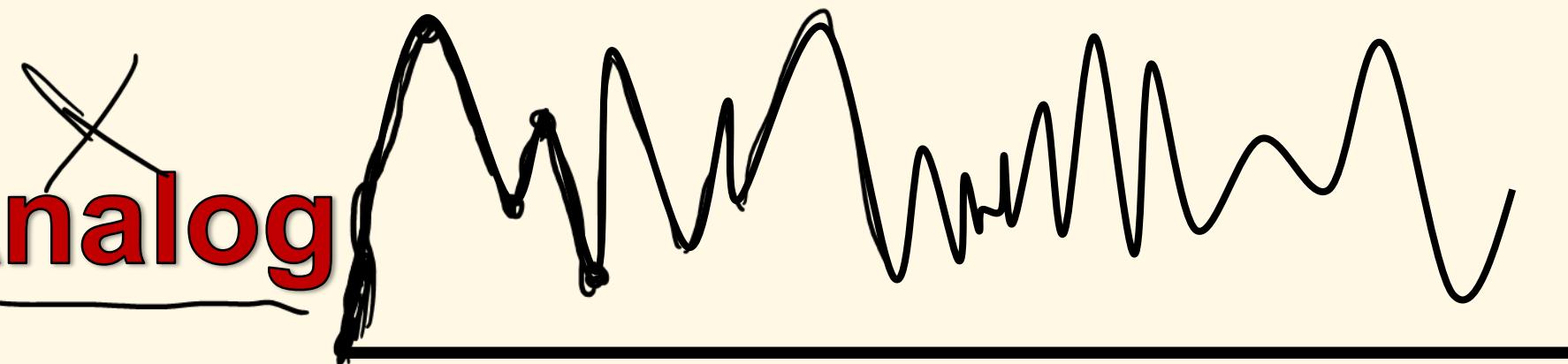
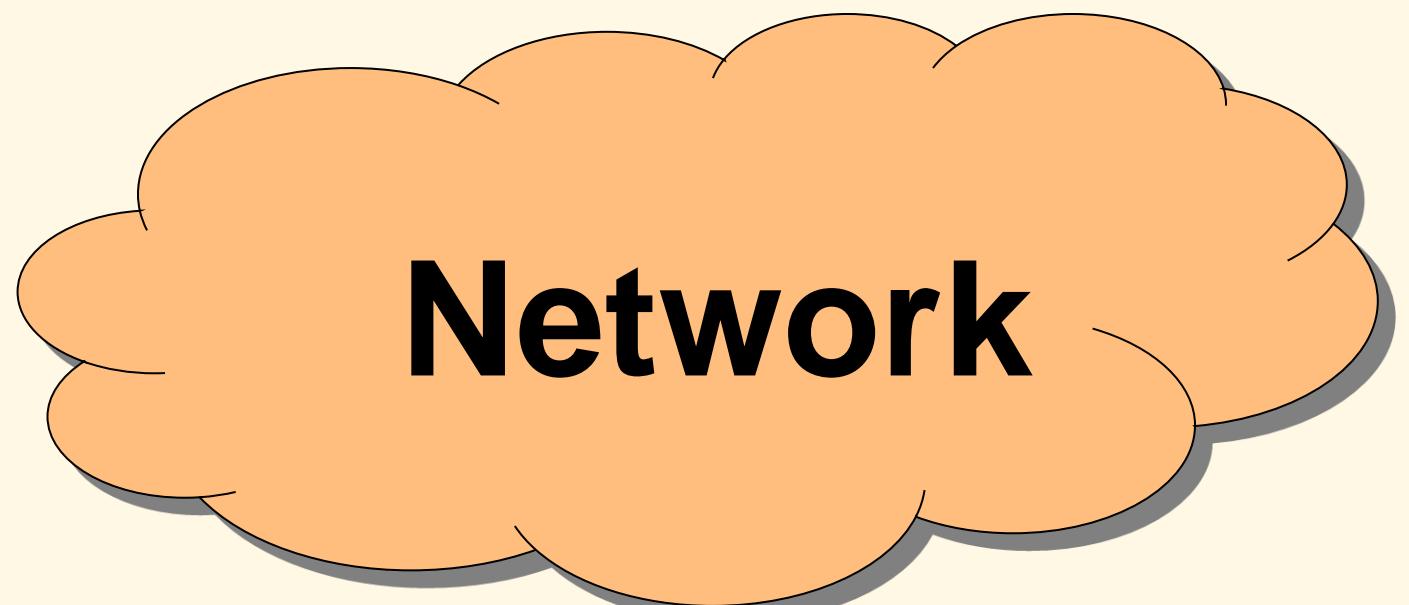
11

12

Frequency

2G

Analog  $\rightarrow$  Digital  
 $1G \rightarrow 2G$

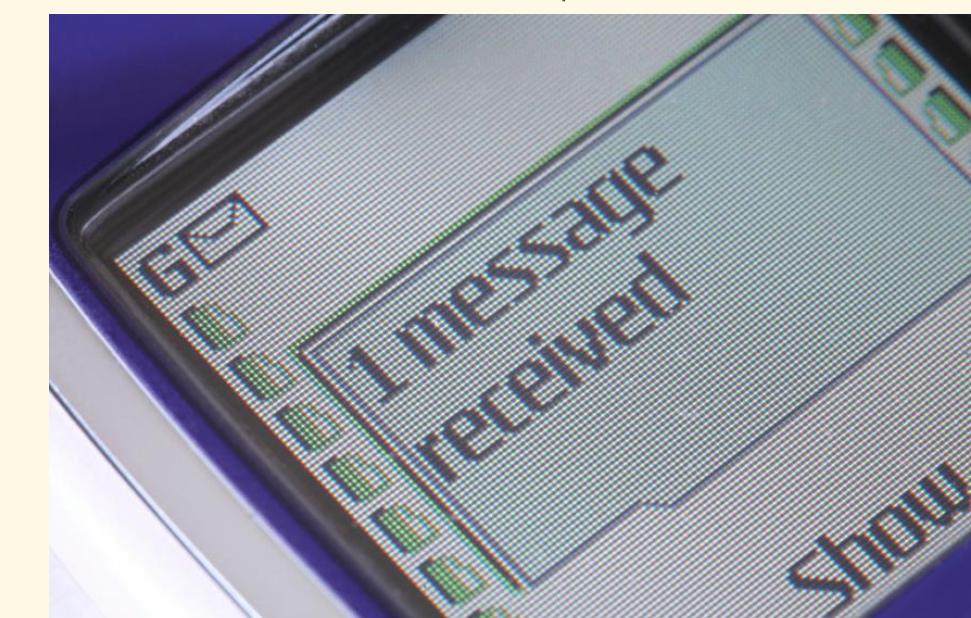


1990

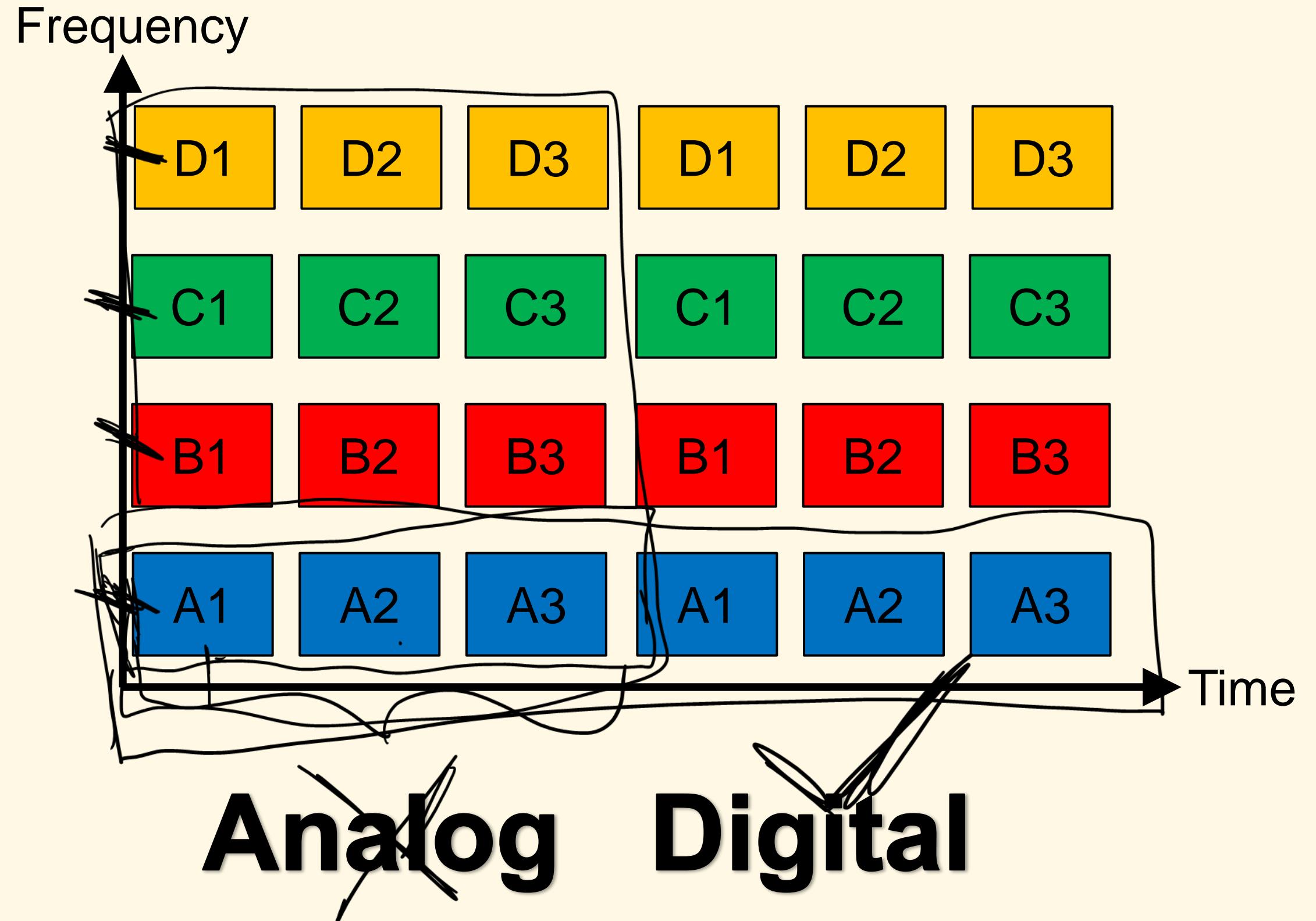
Text



2000



# TDMA



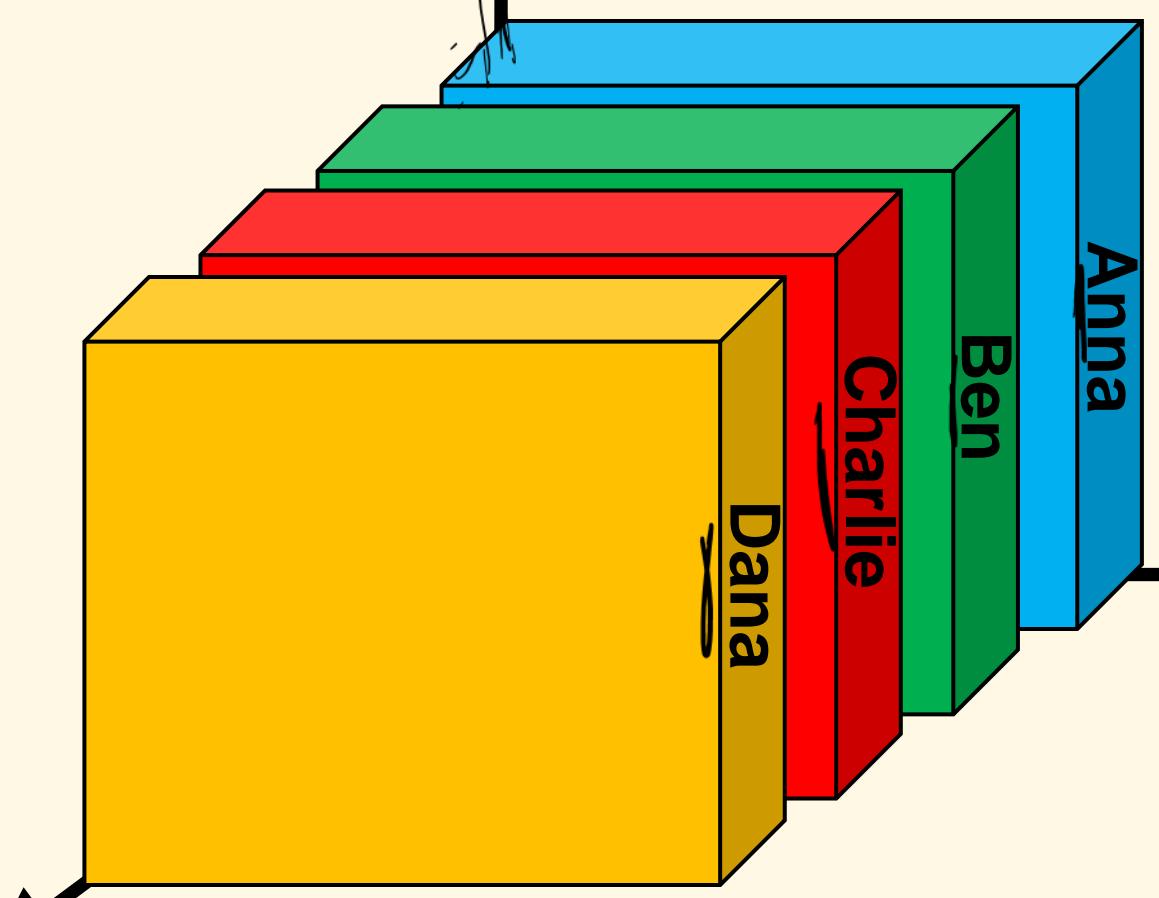
# CDMA



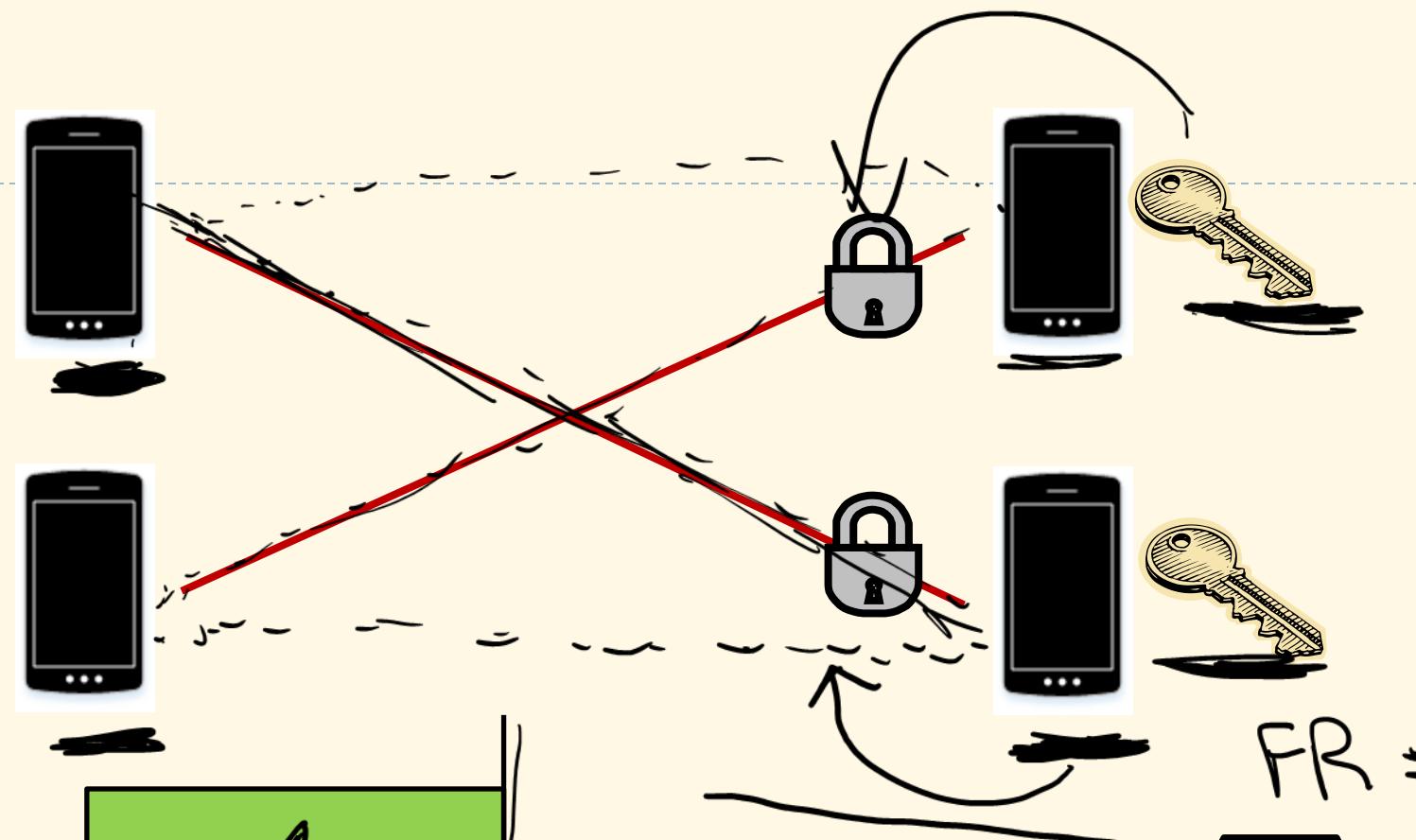
10x

Qualcomm

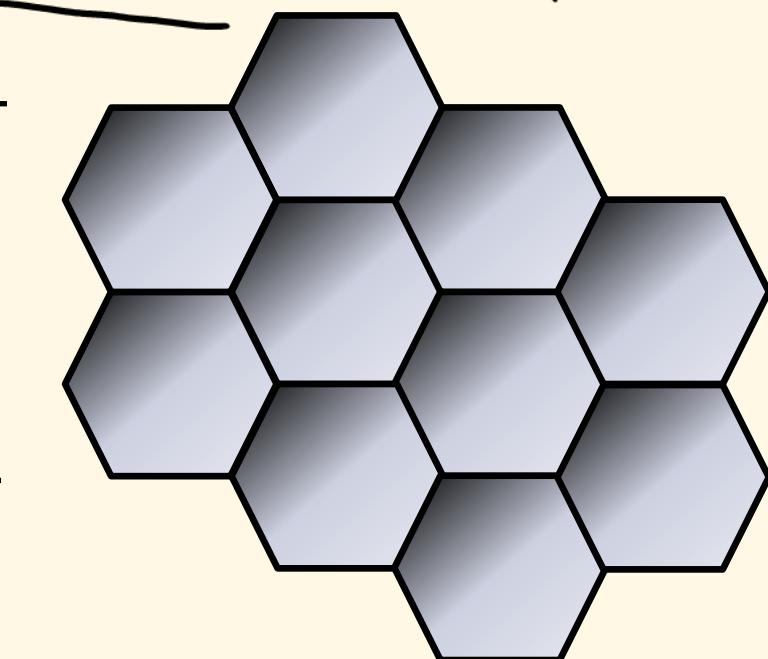
Frequency



1989: TDMA

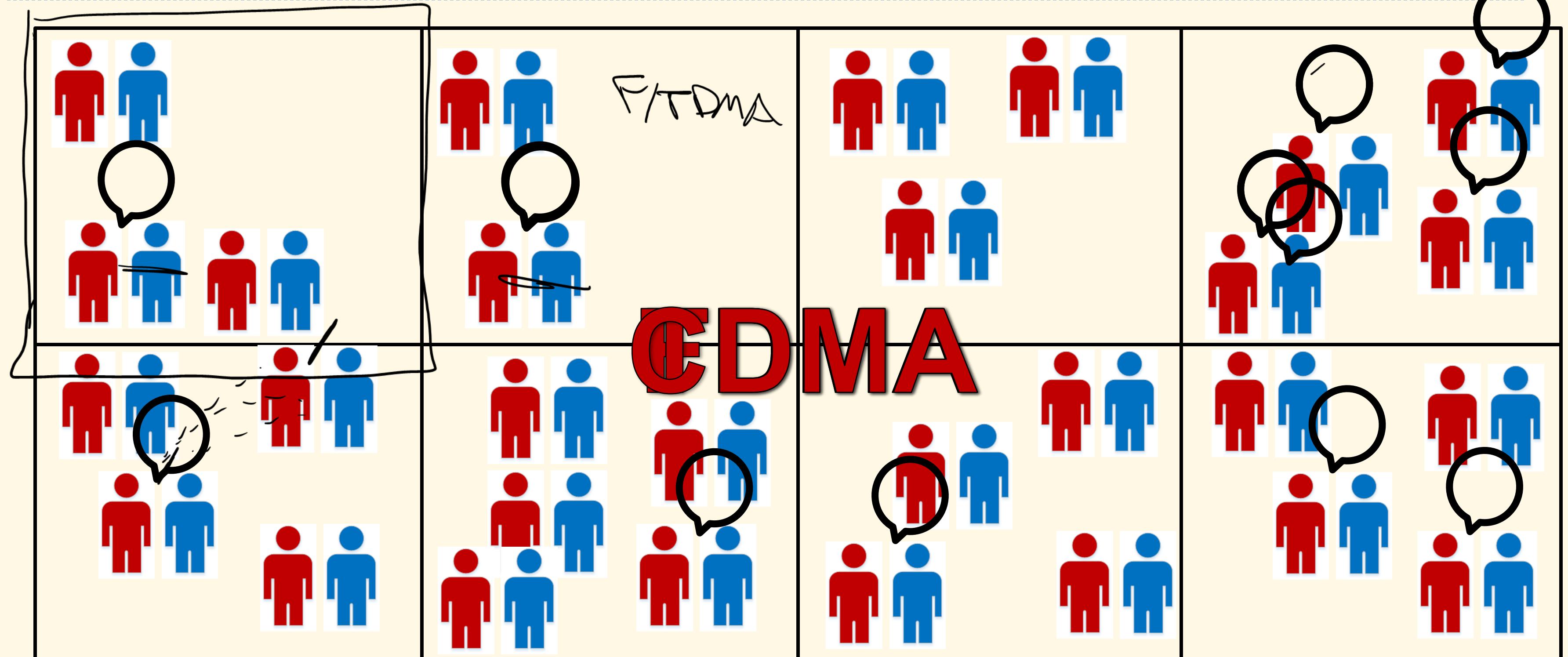
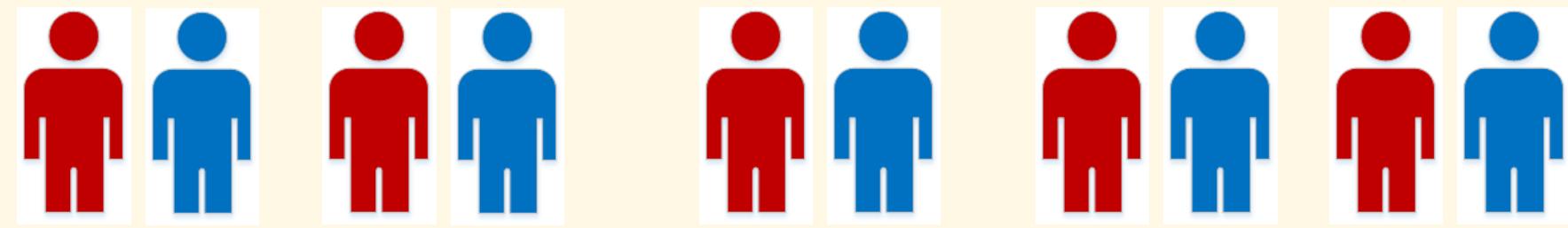


$$FR = 1$$



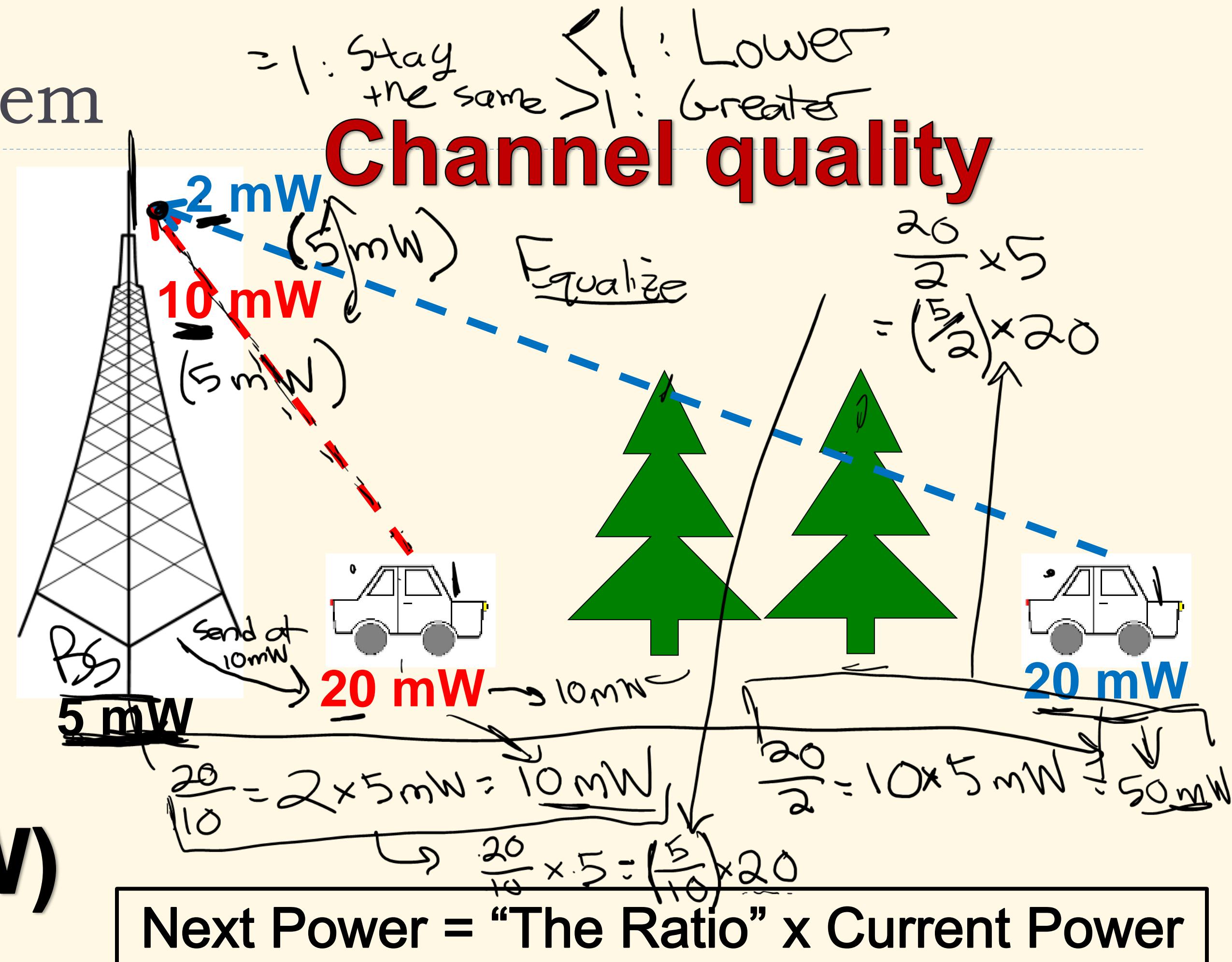
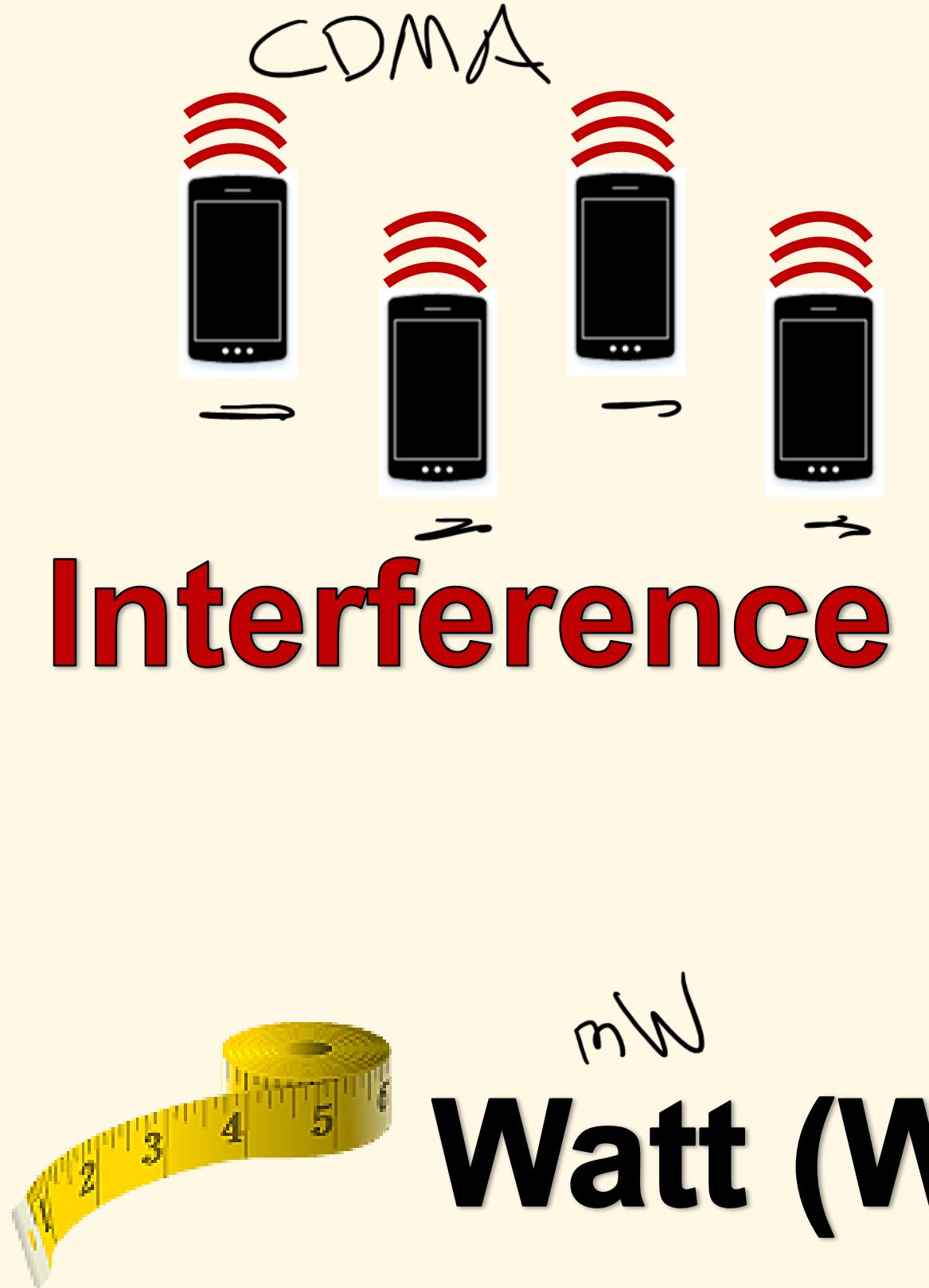
40x!

# Cocktail party



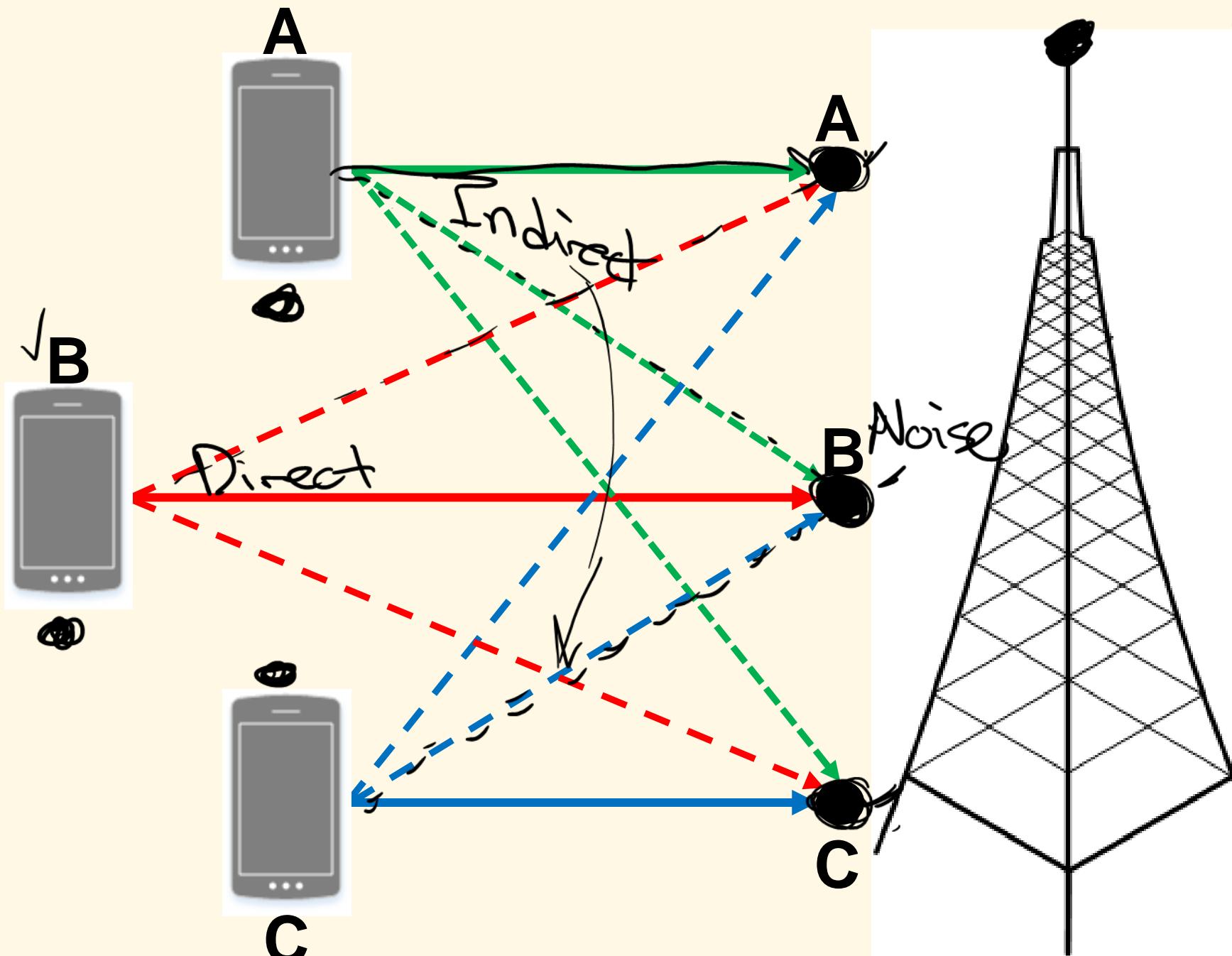
How “loud”?

# Near-far problem



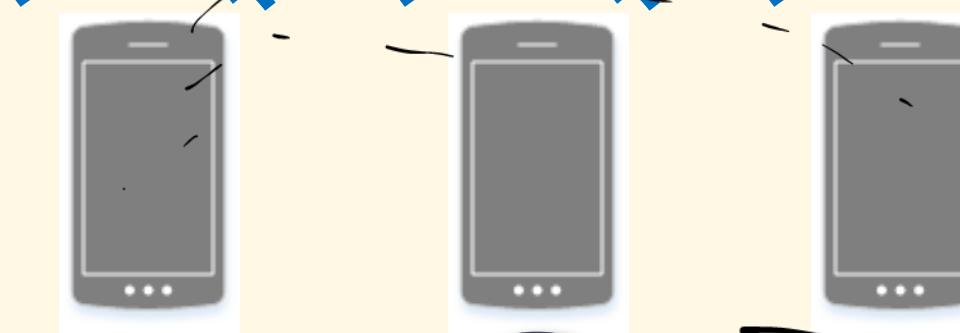
Signal quality

TPC  $\rightarrow$  Signal power



## Signal to Interference Ratio (SIR)

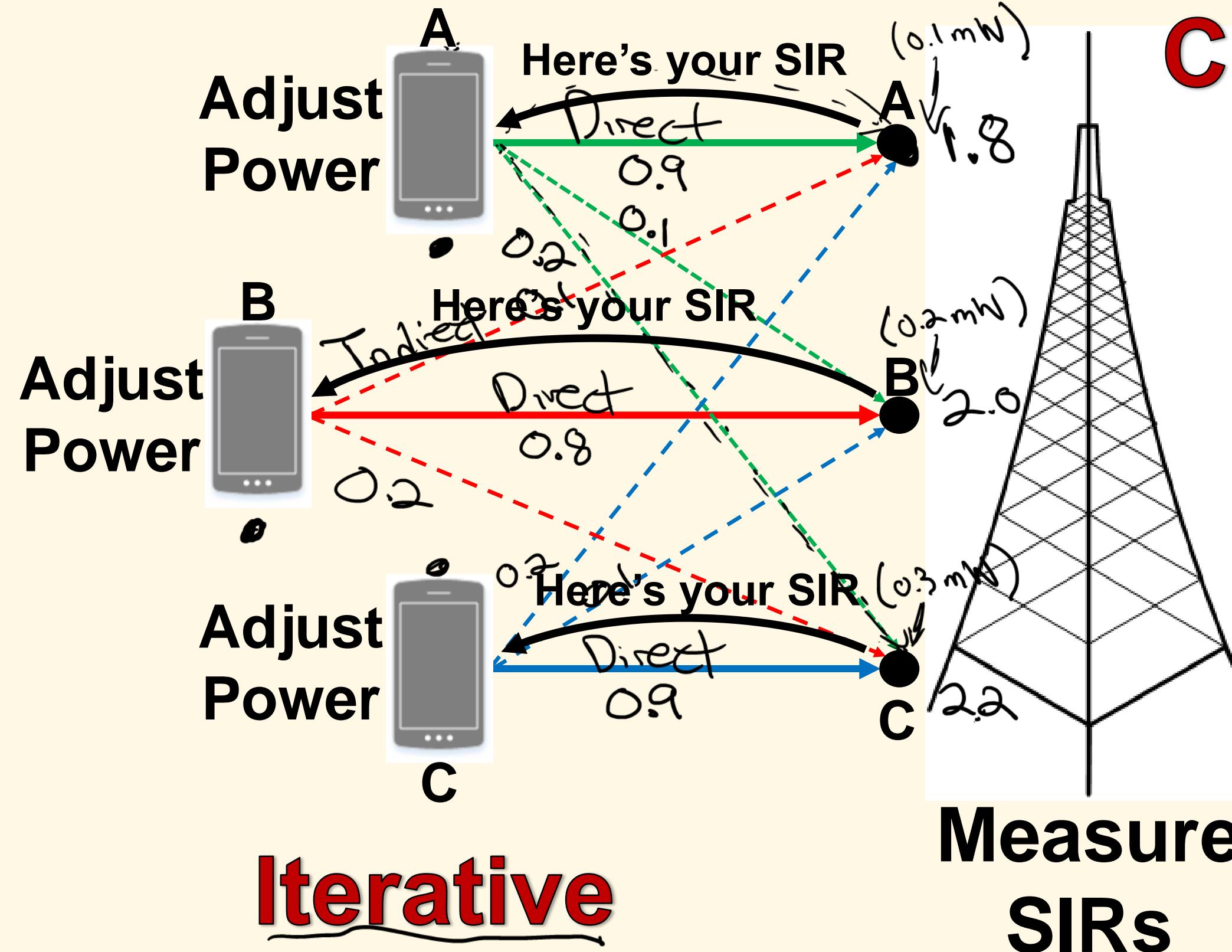
"Good" =  $\frac{\text{Direct Signal}}{\text{Interference} + \text{Noise}}$



Yes!

Feasible

# Distributed Power Control (DPC)



~~SIRs - "Compatible"~~

**Converge ✓ Optimal ✓**

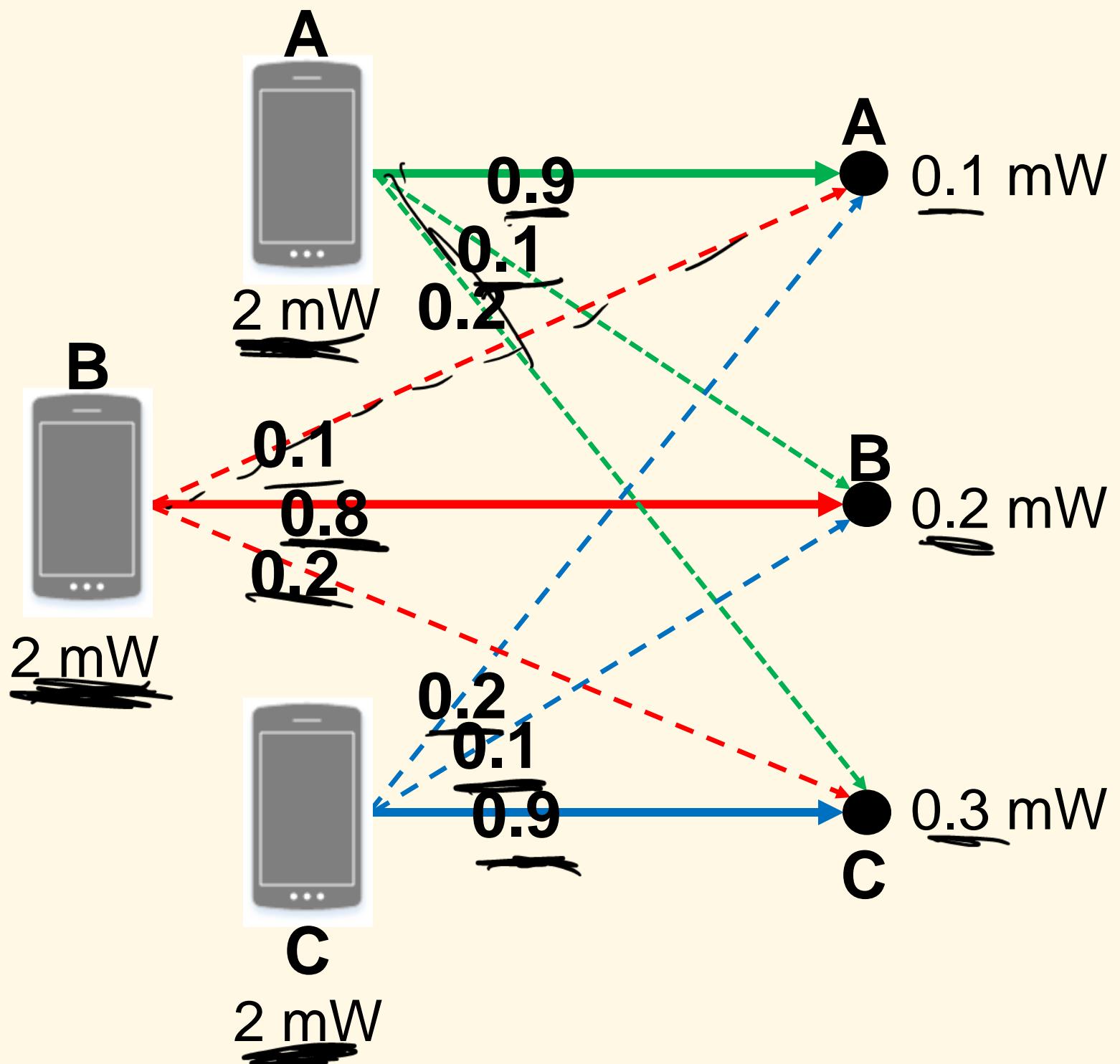
Transmitter		Receiver		
	A	B	C	
A	0.9	0.1	0.2	
B	0.1	0.8	0.2	
C	0.2	0.1	0.9	

*(Gain Direct)*

Link	Target SIR	Noise (mW)
A	1.8	0.1
B	2.0	0.2
C	2.2	0.3

*(Symmetric)*

# DPC: Initial – SIRs



$$\frac{\text{Signal}}{\text{Interference+Noise}} = \frac{0.1 \times 2 \text{ mW}}{0.1 \times 2 \text{ mW} + 0.2 \times 2 \text{ mW} + 0.1 \text{ mW}} = 2.57$$

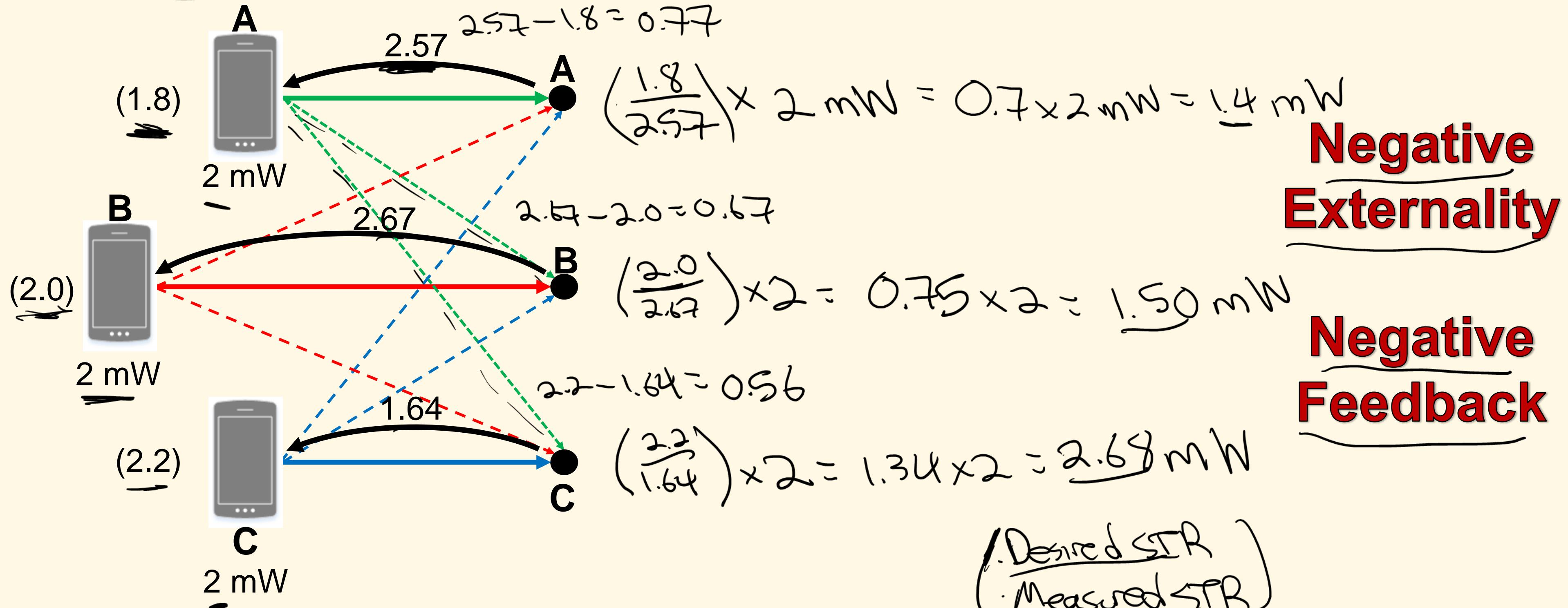
$$\frac{0.2 \times 2 \text{ mW}}{0.1 \times 2 \text{ mW} + 0.1 \times 2 \text{ mW} + 0.2 \text{ mW}} = 2.67$$

$$\frac{0.3 \times 2 \text{ mW}}{0.2 \times 2 \text{ mW} + 0.2 \times 2 \text{ mW} + 0.3 \text{ mW}} = 1.64$$

**Measured SIR =**  $\frac{\text{Signal}}{\text{Interference + Noise}}$

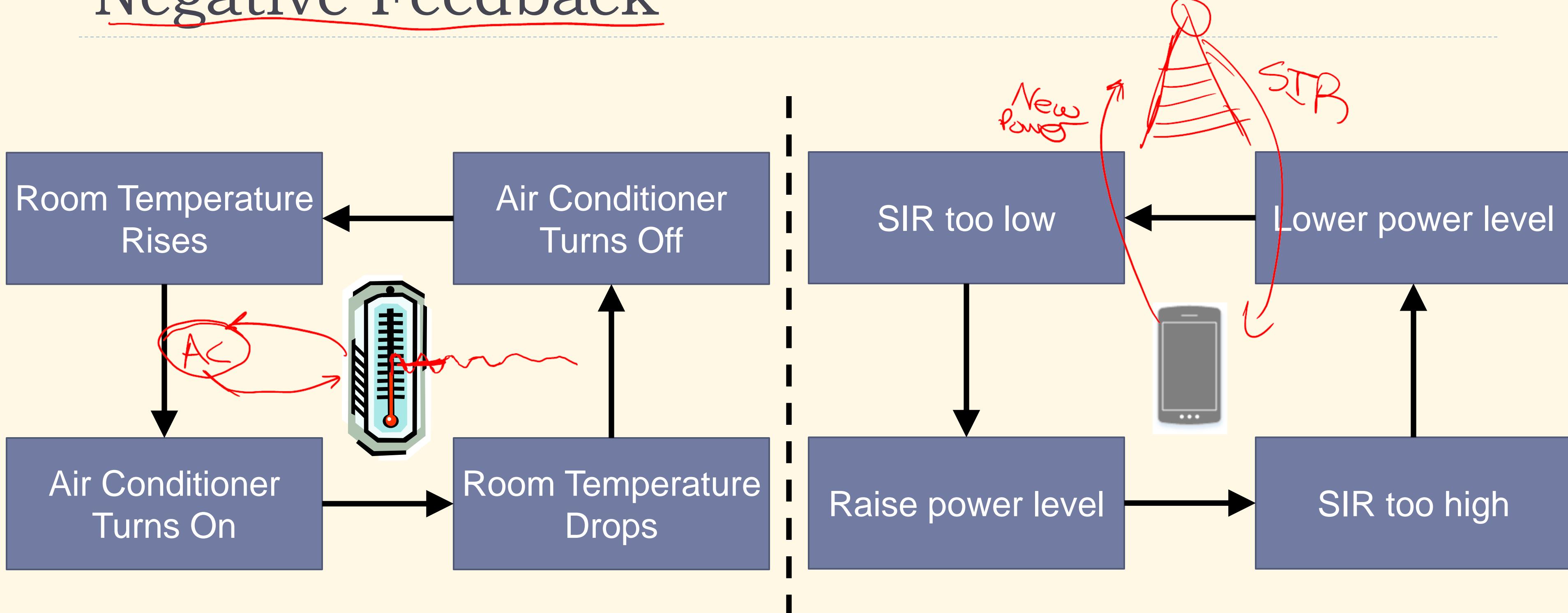
TPC

# DPC: Iteration 1 – Power update

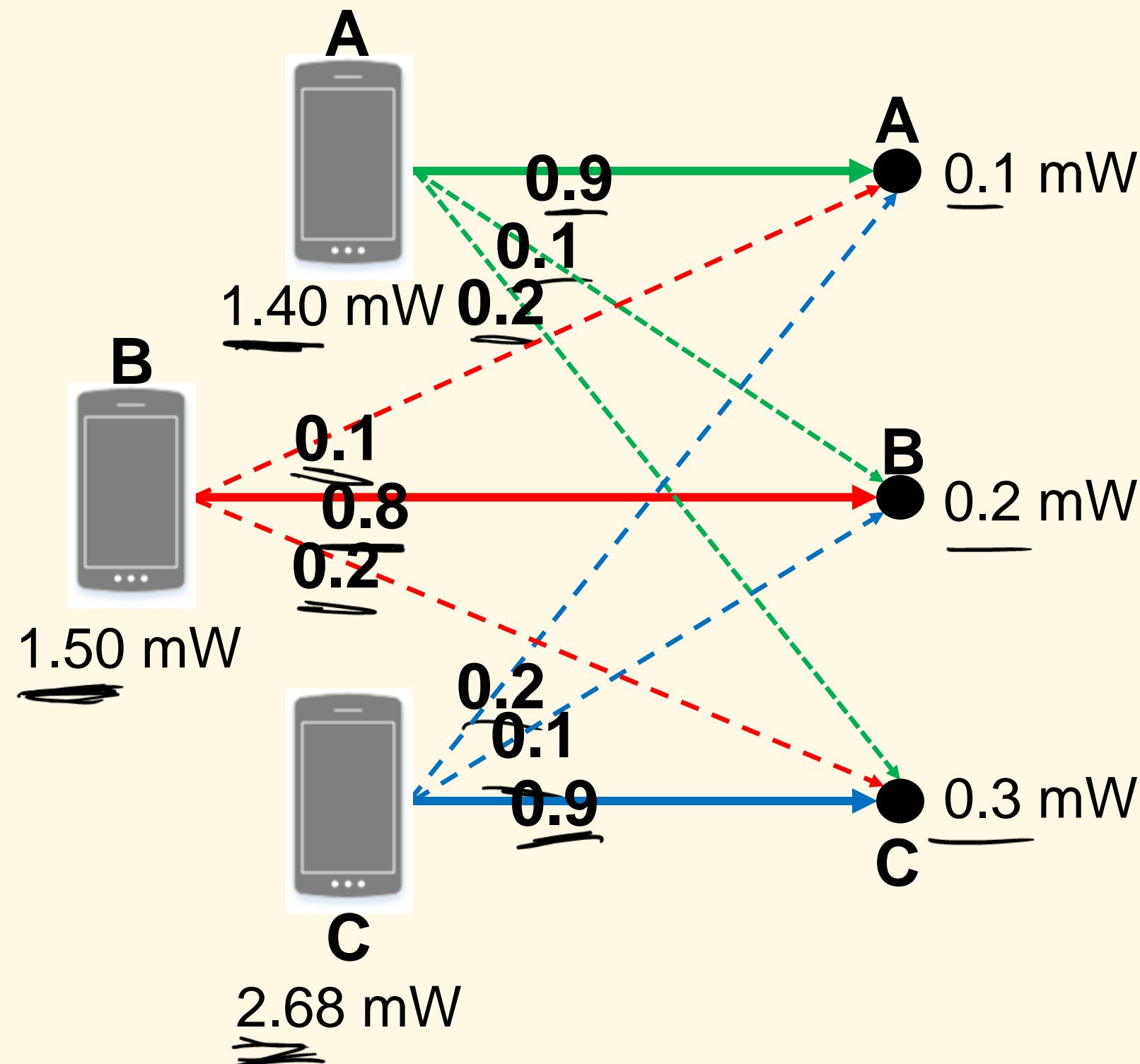


Next Power = “The Ratio”  $\times$  Current Power

# Negative Feedback



# DPC: Iteration 1 – SIRs



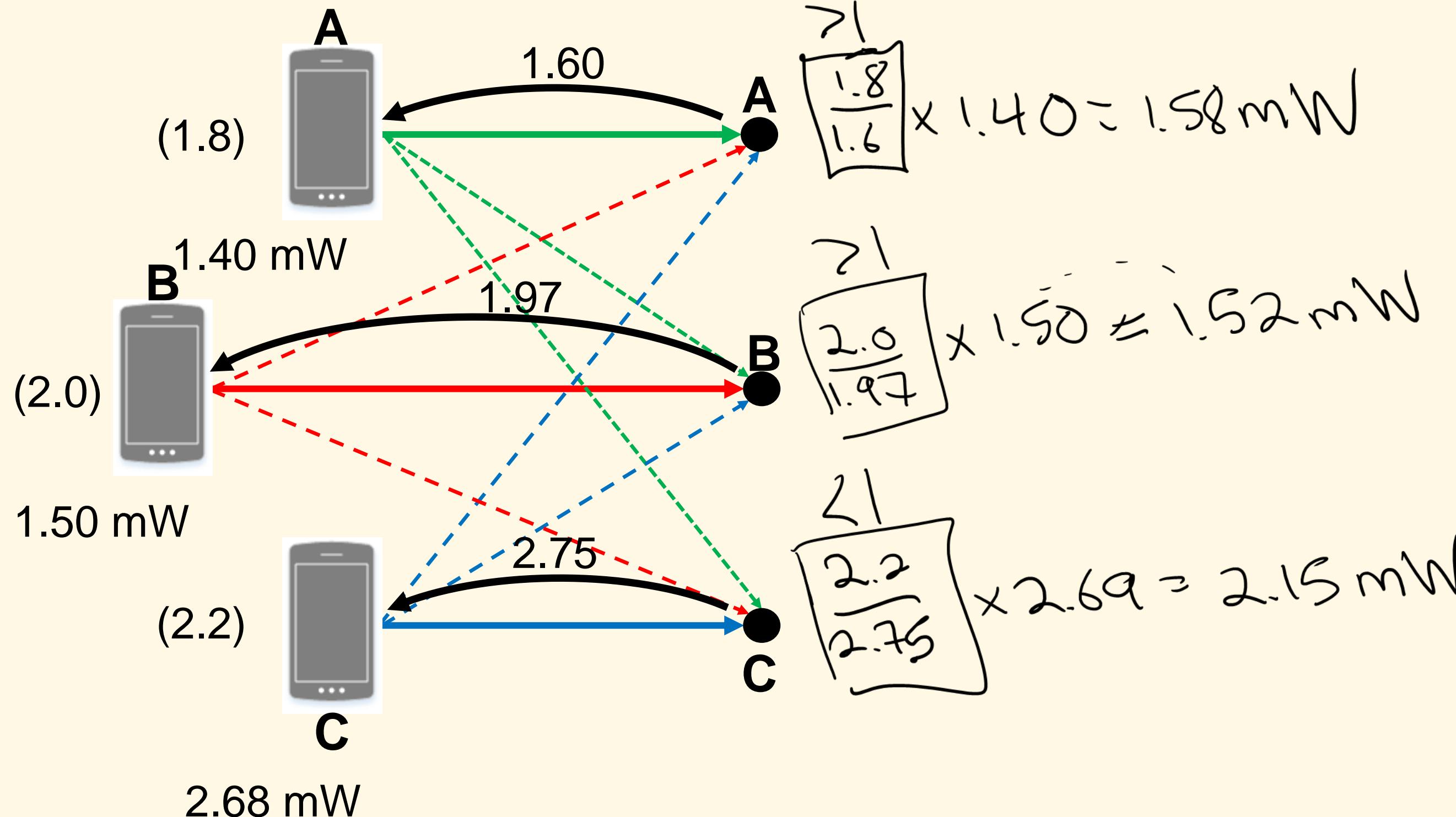
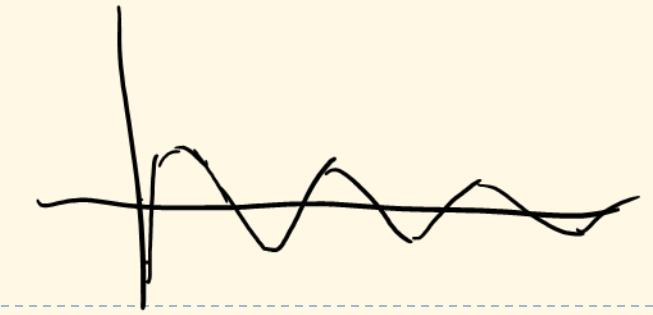
$$\frac{0.9 \times 1.4}{0.1 \times 1.50 + 0.2 \times 2.68 + 0.1} \approx \frac{1.26}{0.786} = 1.60$$

$$\frac{0.8 \times 1.5}{0.1 \times 1.4 + 0.1 \times 2.68 + 0.2} = \frac{1.20}{0.608} = 1.97$$

$$\frac{0.9 \times 2.68}{0.2 \times 1.40 + 0.2 \times 1.50 + 0.3} = \frac{2.412}{0.880} = 2.75$$

**Measured SIR =**  $\frac{\text{Signal}}{\text{Interference} + \text{Noise}}$

# DPC: Iteration 2 – Power update

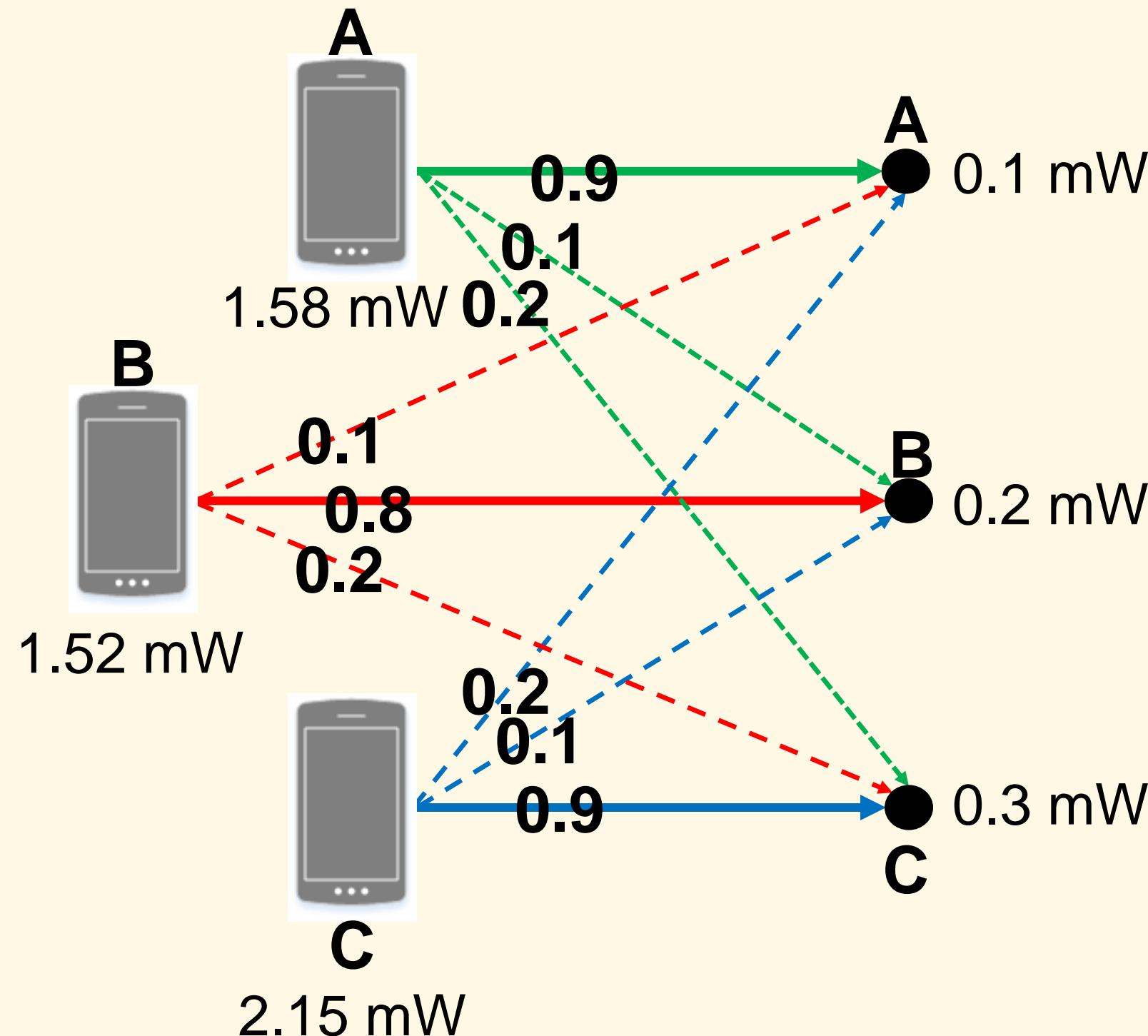


Overshoot

Undershoot

Next Power = “The Ratio” x Current Power

# DPC: Iteration 2 – SIRs



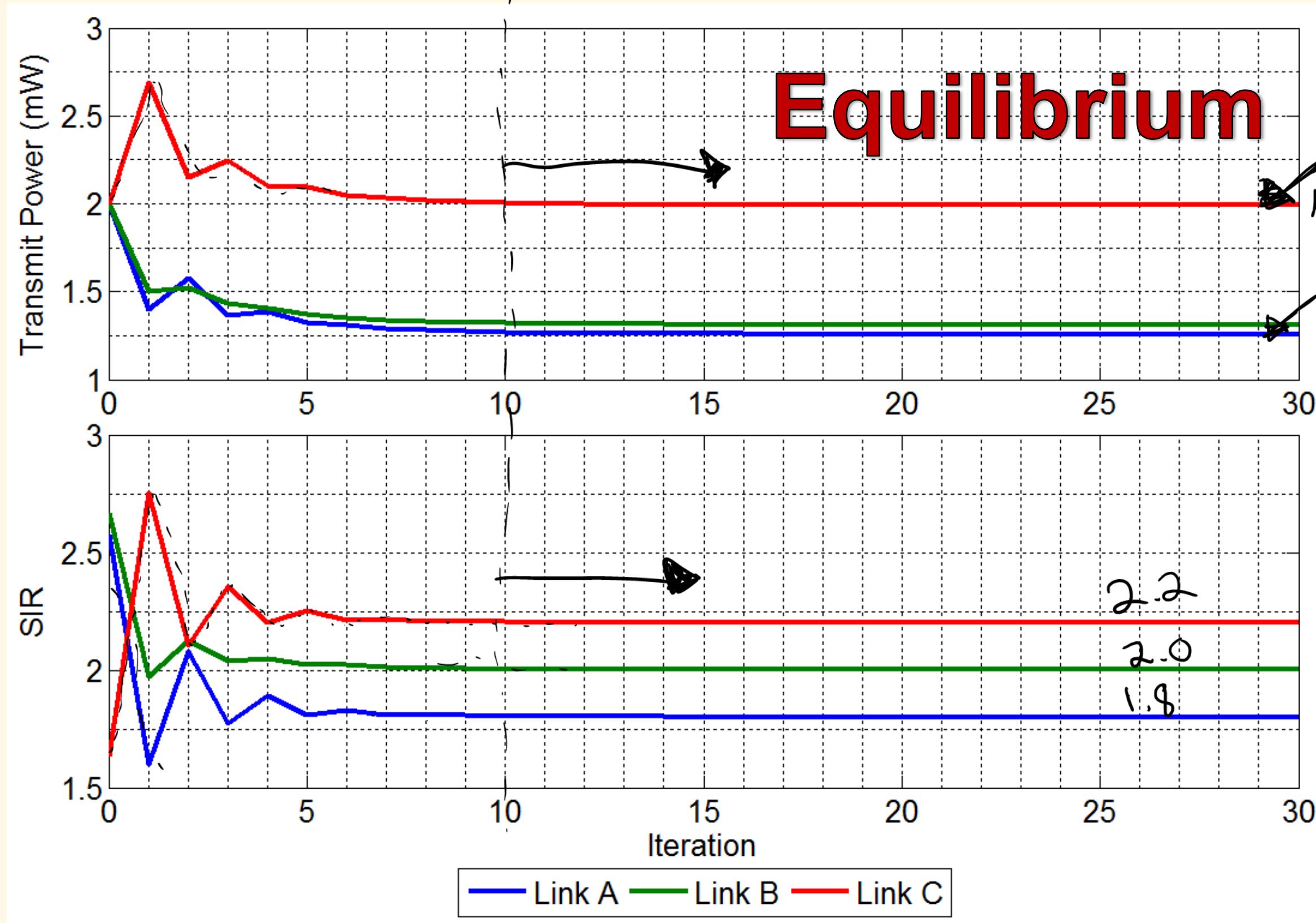
$$\frac{0.9 \times 1.58}{0.1 \times 1.52 + 0.2 \times 2.15 + 0.1} = \frac{1.422}{0.682} = 2.08$$

$$\frac{0.8 \times 1.52}{0.8 \times 1.52 + 0.1 \times 2.15 + 0.2} = \frac{1.216}{0.573} = 2.13$$

$$\frac{0.9 \times 2.15}{0.2 \times 1.58 + 0.2 \times 1.52 + 0.3} = \frac{1.935}{0.920} = 2.10$$

**Measured SIR =** **Signal**  
**Interference + Noise**

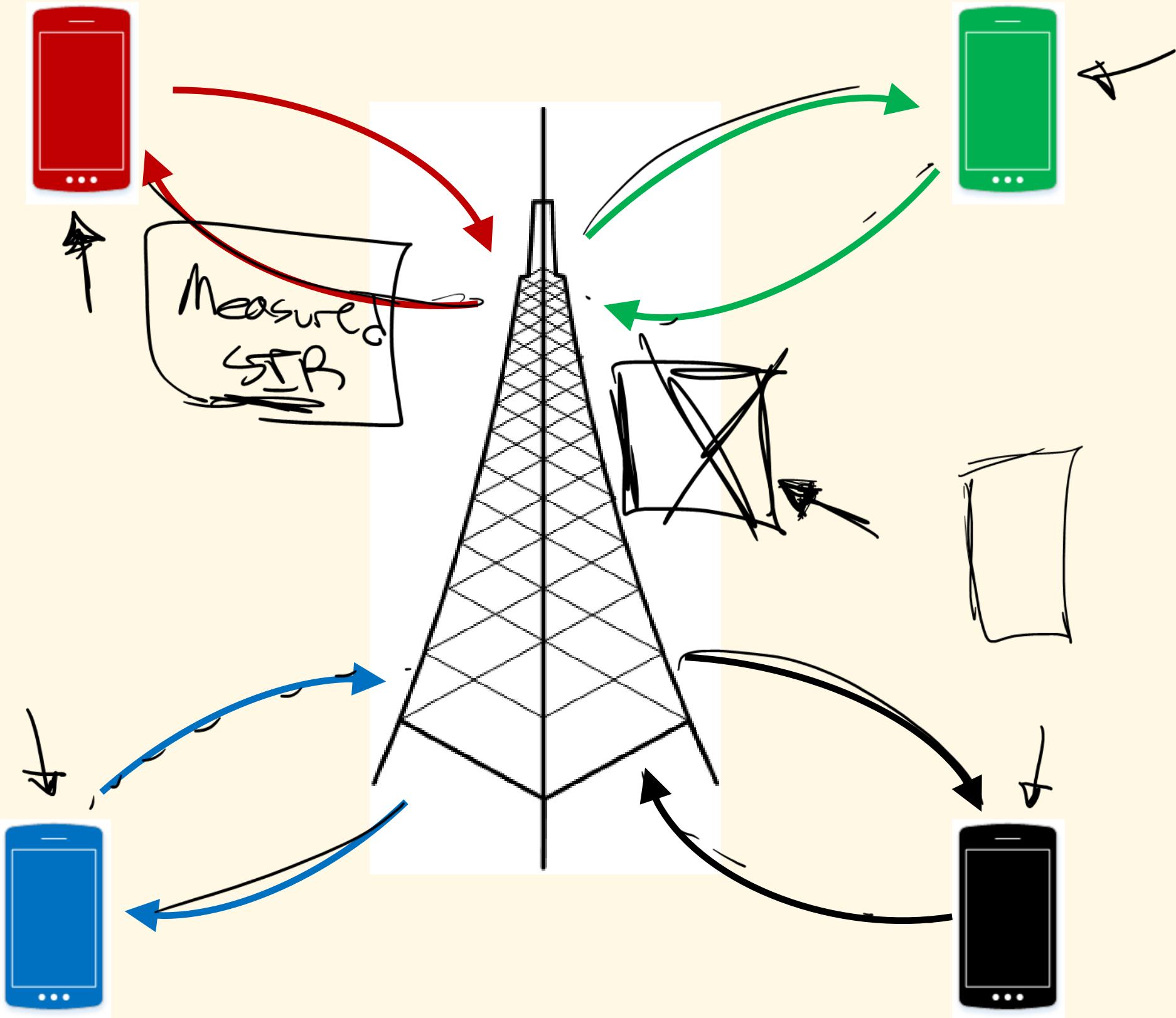
# Future iterations



- Noise component highest ( $0.3 \text{ mW}$ )
- Interfering gains highest ( $0.2$ )
- Highest target ( $2.2$ )

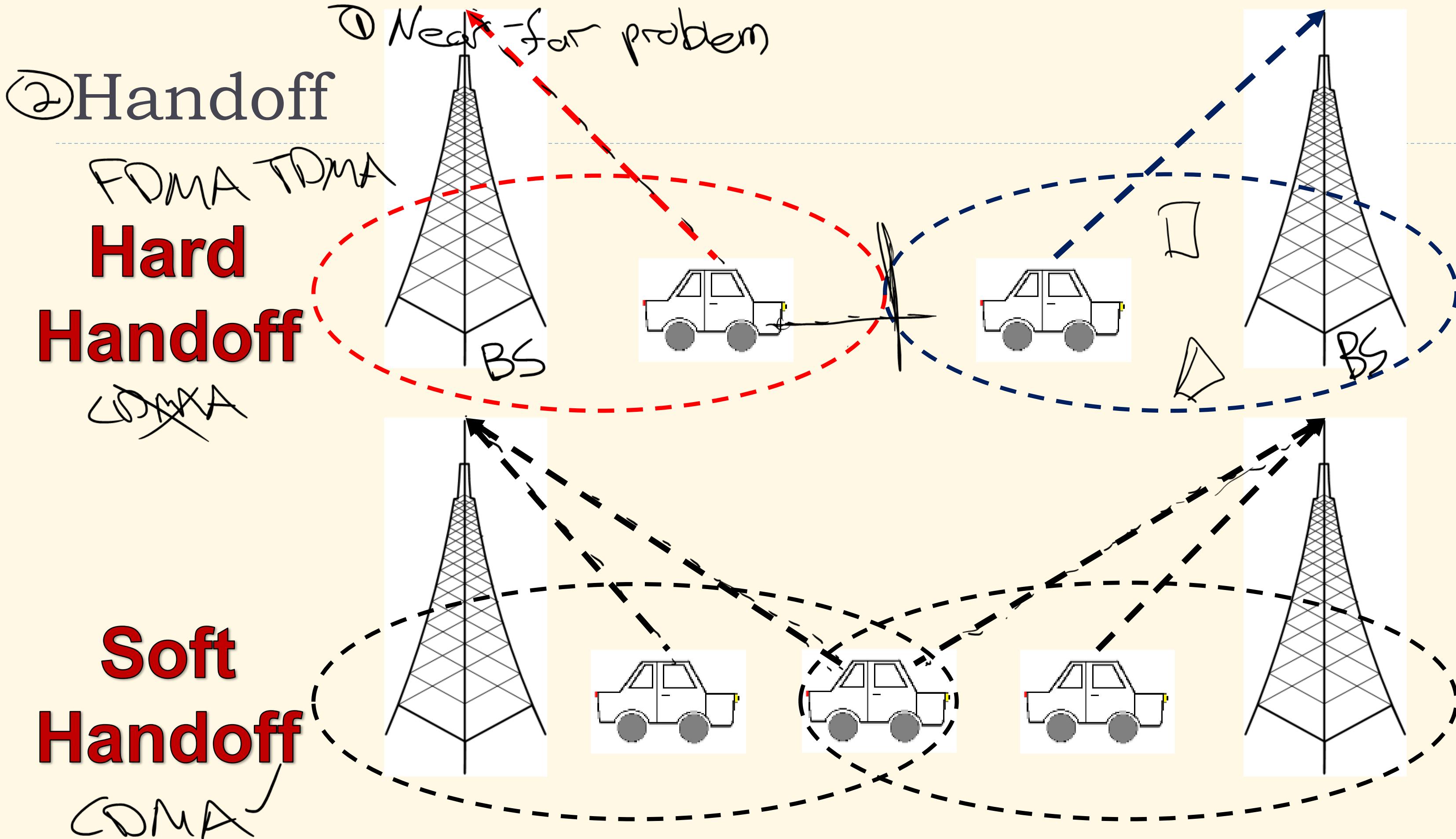
"The Ratio"  $\rightarrow 1$   
xPower

# DRC Distributed computation



**Scalable**  
**Inexpensive**

**1500x per second**



# CDMA approved as 2G standard

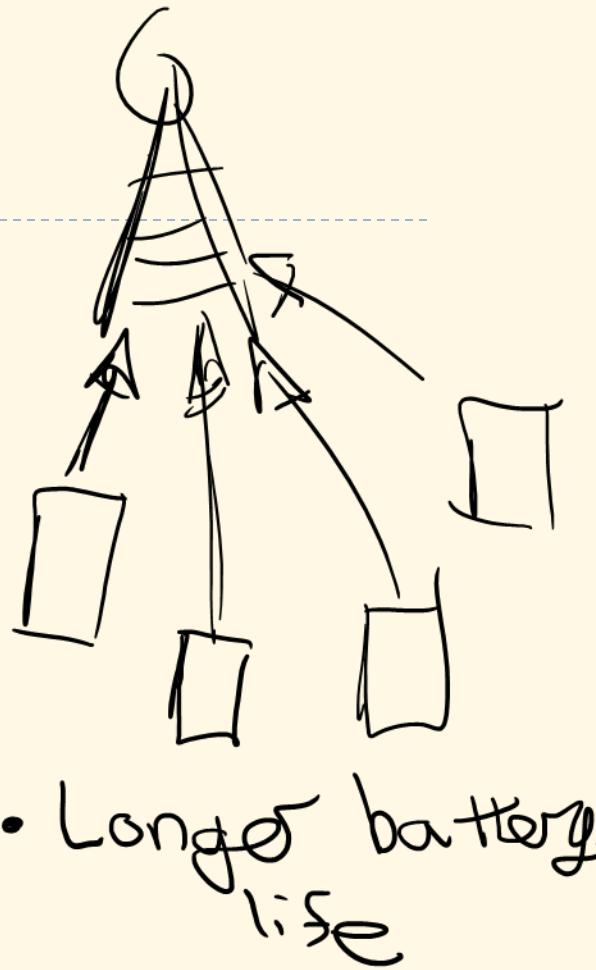
**DPC** ✓

- 10x 3x

**Soft handoff** ✓

- Security

- Better voice quality



- Longer battery life

1993



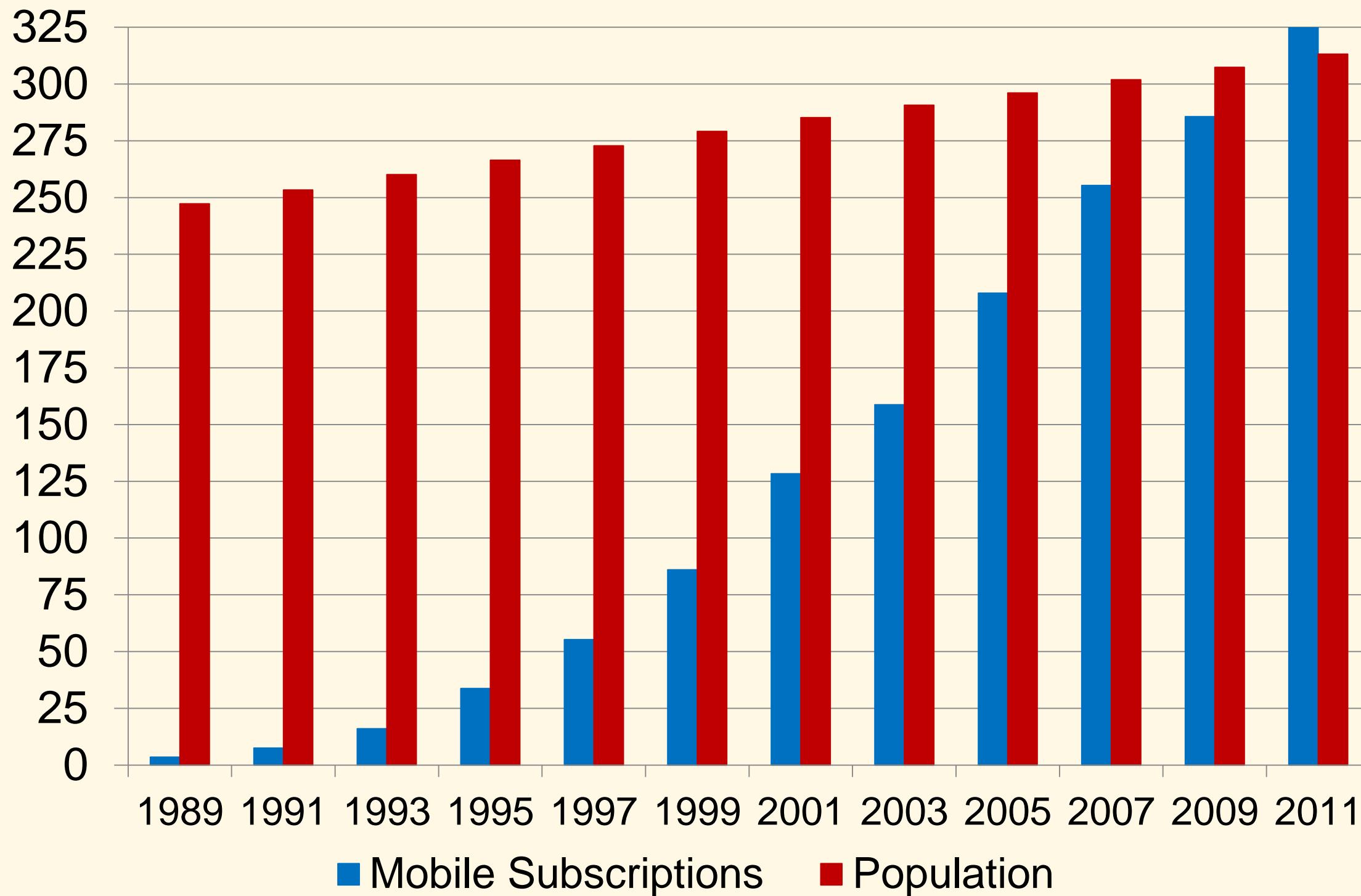
cdmaOne **IS-95**



# Where we are today

2012: 116 million

2016: 200 million



## 2000s

3G → UMTS  
3G → CDMA2000

↑ Call  
Text Internet  
Mobile TV

# Smartphone



# Summary

---

- ▶ Multiple access
  - ▶ FDMA (0G-1G)
  - ▶ TDMA (2G)
  - ▶ CDMA (2G-3G)
  - ▶ OFDMA (4G)
- ▶ Interference management
  - ▶ TPC
  - ▶ DPC
- ▶ Themes
  - ▶ Negative feedback
  - ▶ Negative externality
  - ▶ Distributed computation