

Wireless!

The forces and strategies that shaped a revolution



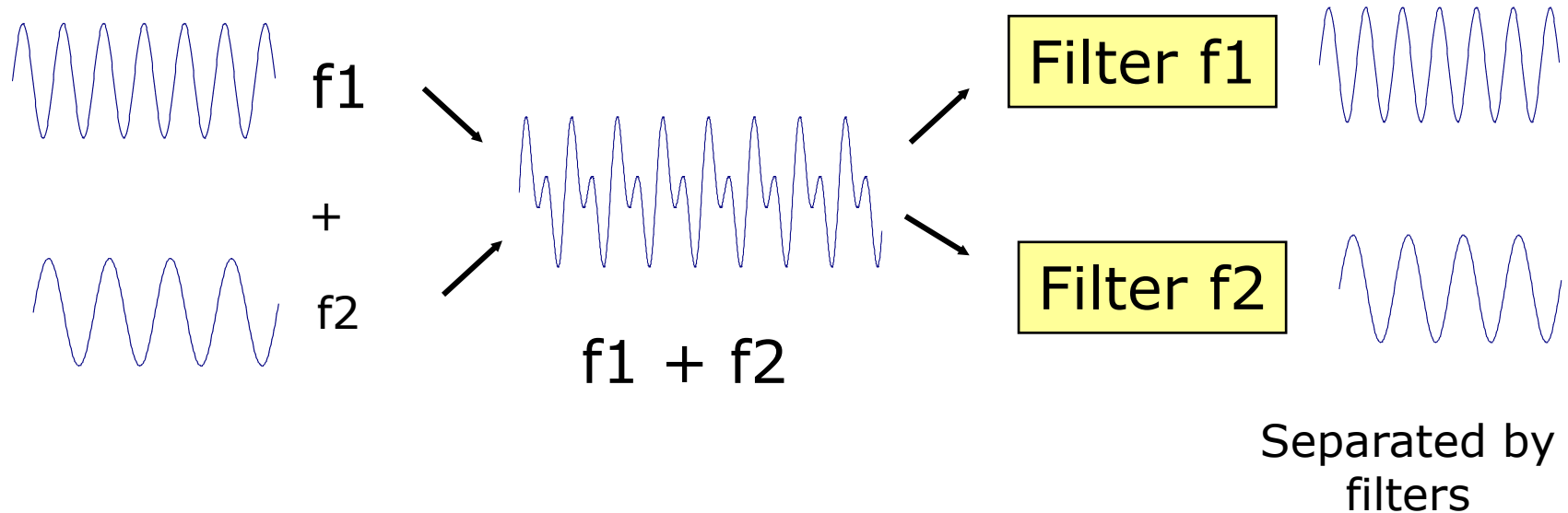
Lecture 14

**Spectrum, Bandwidth
Capacity and Cost**

Lecture 14- Classwork

1. Please summarize in 3-4 sentences the Pre-Lecture reading for Lecture 14 including some important takeaways from your reading.
2. How much more bandwidth does a video signal require than a voice signal?
3. What is the effect of buying additional spectrum on the economics of cellular? What does the profitability depend on?
4. What are the different viewpoints from which one can assess the value of spectrum?

We are immersed in a sea of radio signals that we separate with filters



Viewing just two signals on different frequencies

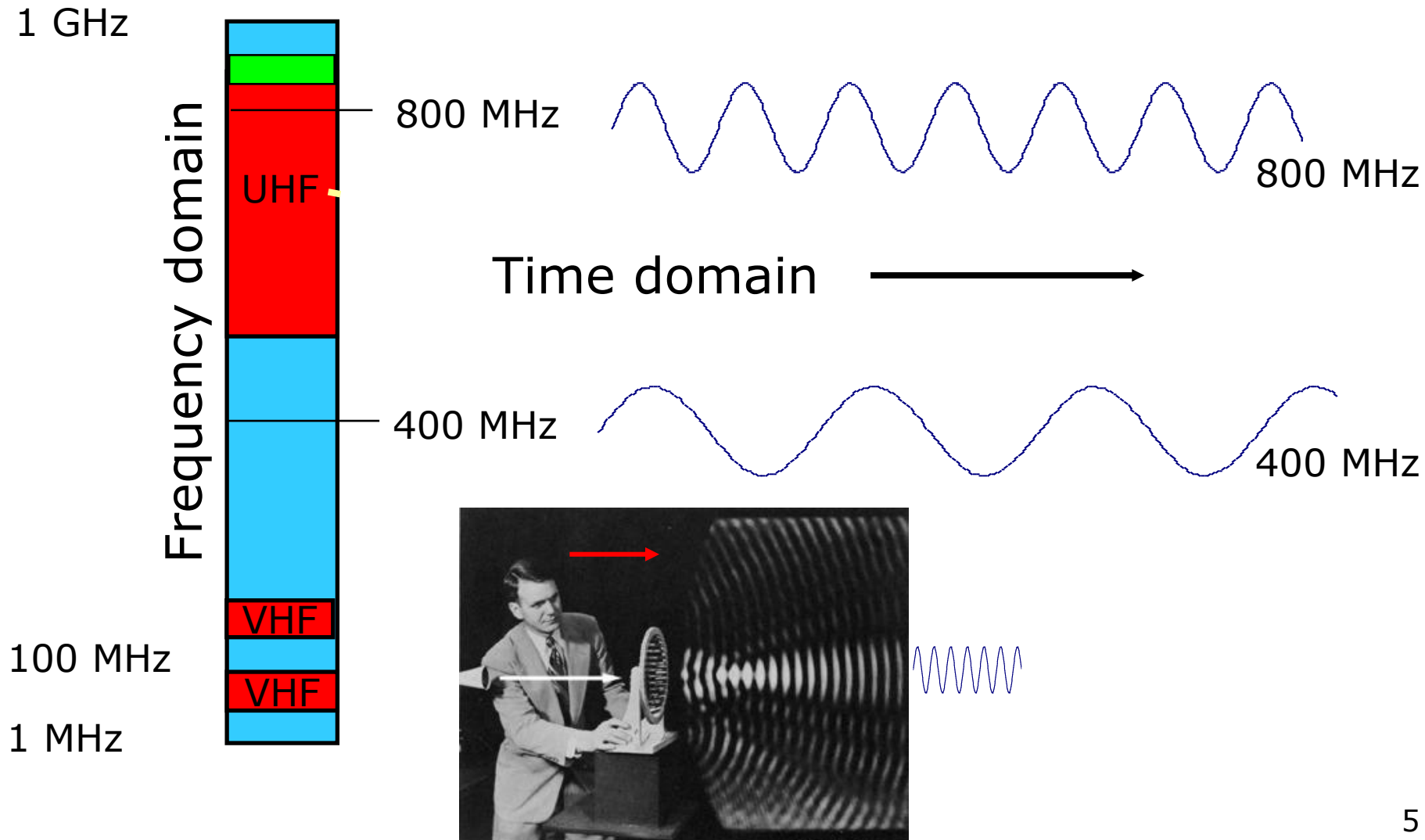
But there are a lot of “frequencies”

▣ 900,000,000 Hz; 900,000,001 Hz, etc....

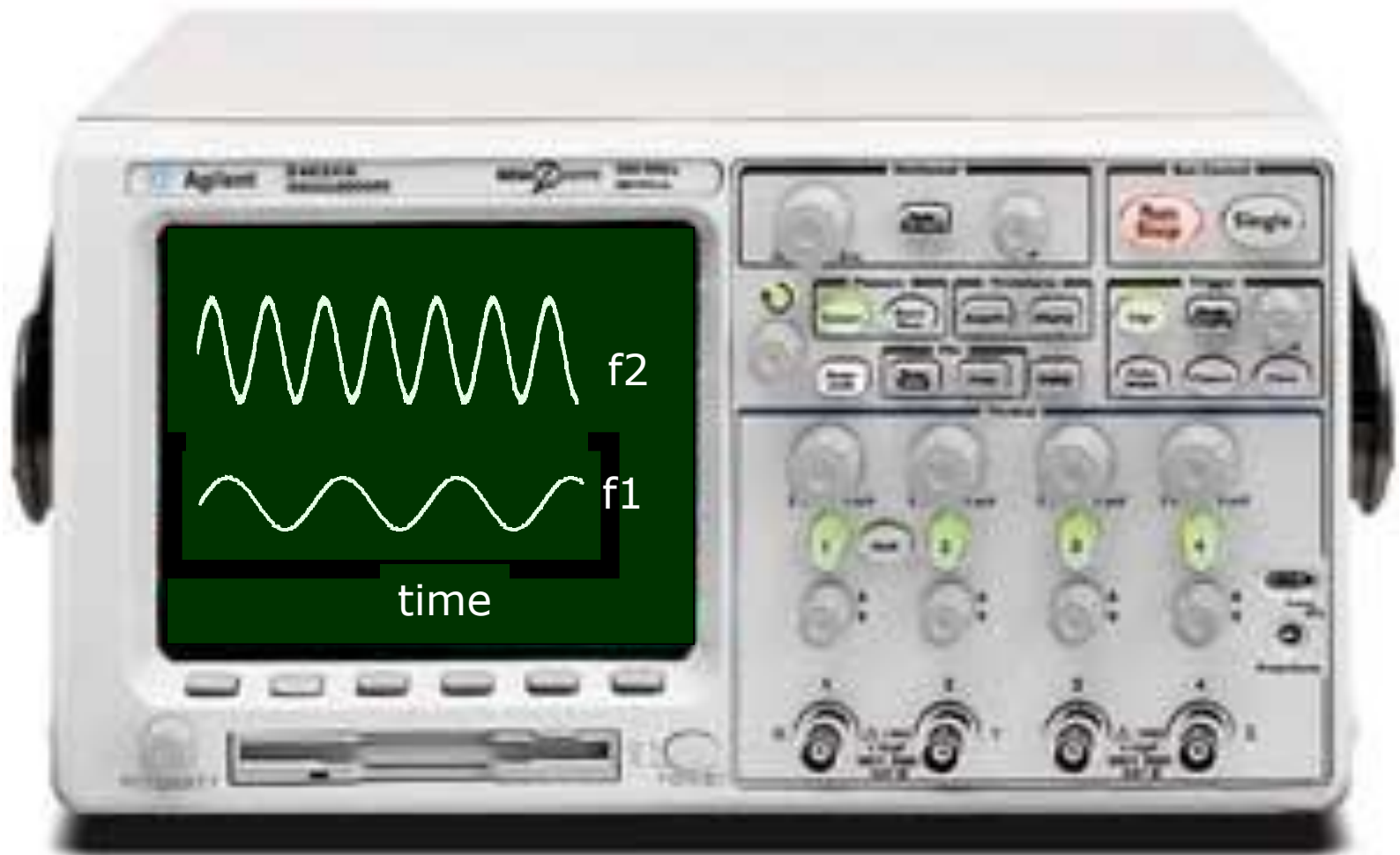
- And why not 900,000,000.25 Hertz?
- An infinite number of frequencies?
- So why was there a shortage of “channels”?

Two ways to show the same frequencies

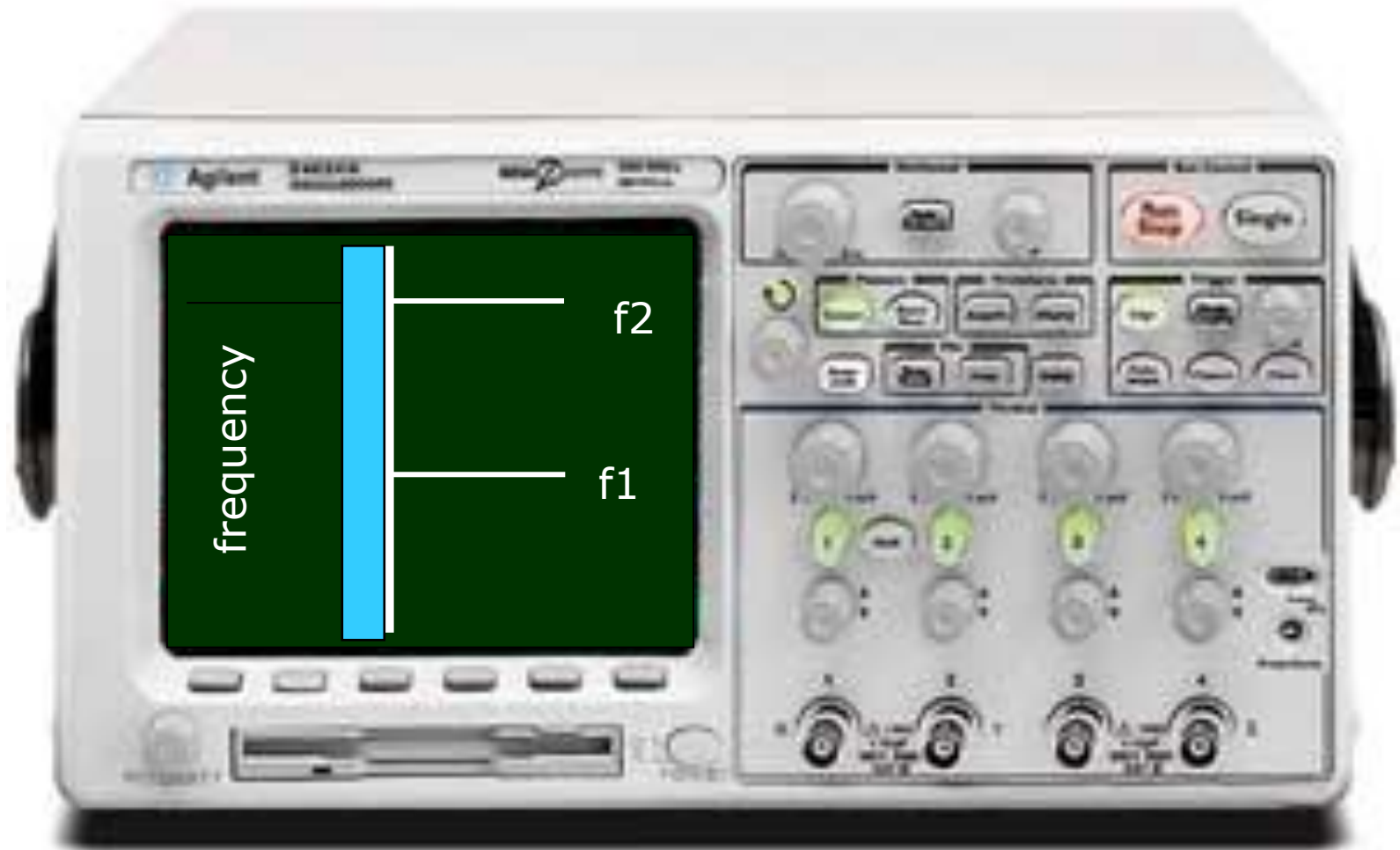
Frequency/Spectrum domain and Time domain



A time-domain display of the two frequencies on an oscilloscope

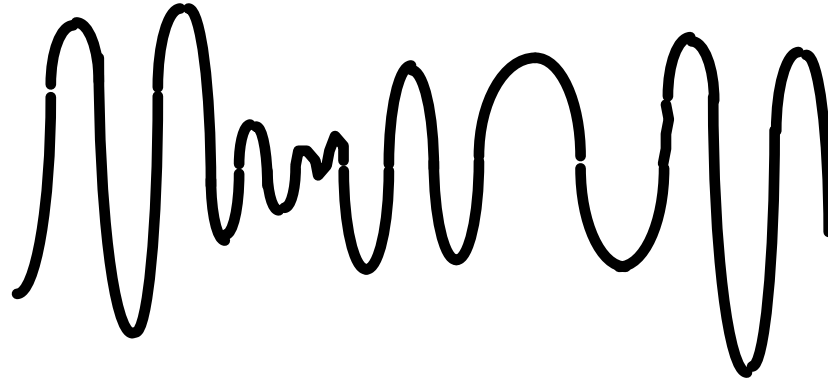


A frequency-domain display of the same signals



Putting voice on a “Channel”

A complicated pressure wave



Air
pressure

A time-domain display of a voice signal



Amplitude Modulation of Voice on a Radio Wave: Wave: What it would actually look like



The radio frequency is MUCH higher than the voice frequency
so you wouldn't see the individual cycles

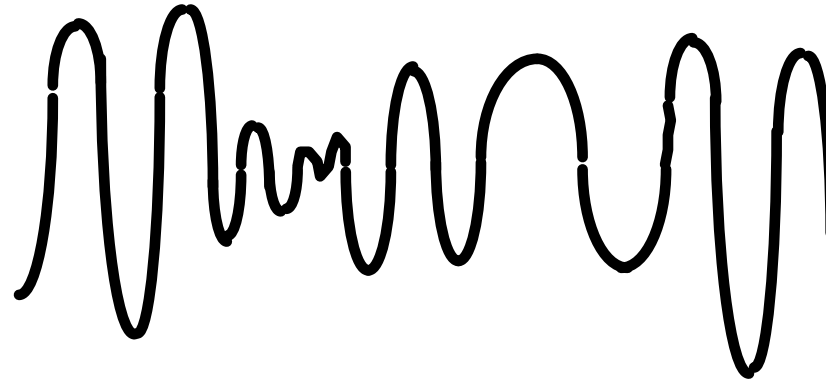
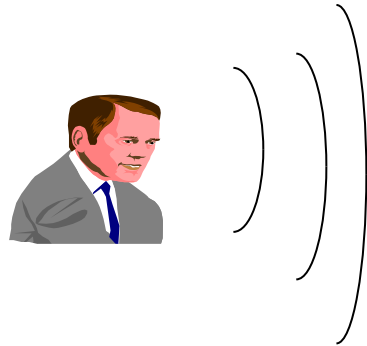
A frequency-domain display of the same voice “Information” is spread over a range of frequencies (a “channel”) and must be preserved to recover the voice



(“telephone quality voice” range is $\sim 300\text{-}3000$ Hz for “good enough” quality)

Putting voice on a “Channel”

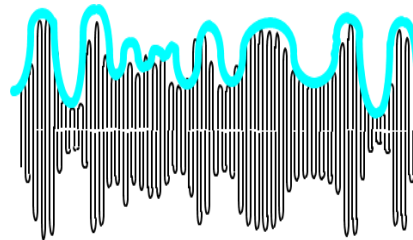
A complicated pressure wave



Air
pressure



Information
Signal in Time
Domain



Modulated
Radio Signal in
Time Domain



Information
Signal in
Frequency
Domain

“Channel”

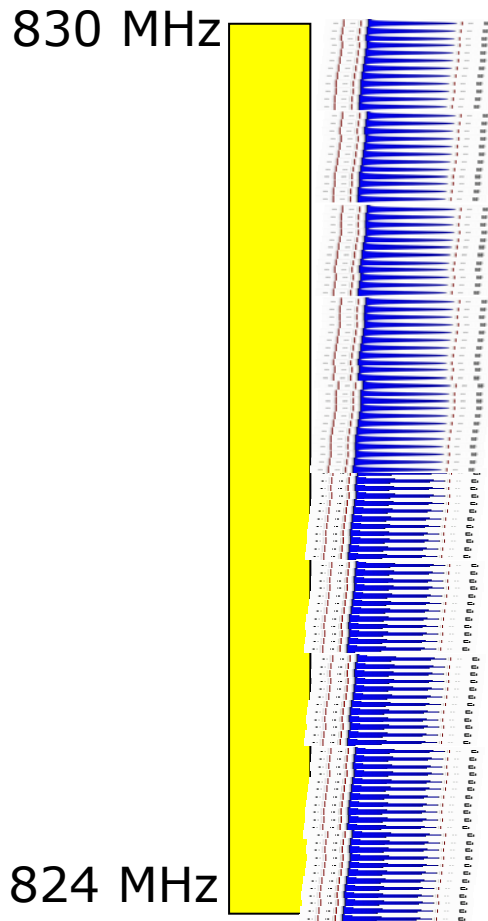


Broadcast of an opera singer with “good quality”
Would need a wider range of frequencies
and thus be spread over a wider channel

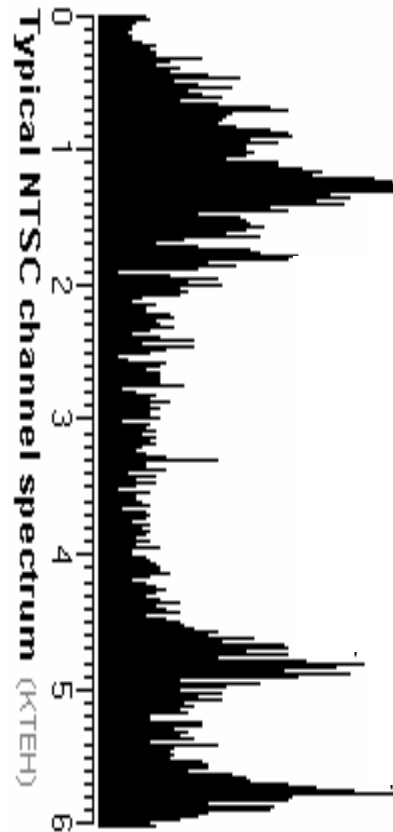


Q2

A TV channel with video and audio information requires a much wider channel



200 cellular "uplink" or
"downlink" channels



1 TV channel

The video + audio of the TV channel carries 200 times more information than a cellular voice channel:

- 1 TV channel uses up 6 MHz, the same amount of spectrum as 200 "one-way" ("uplink" or "downlink") cellular channels. This also requires more power to transmit the same distance.

How much bandwidth does “digital stuff” need?

- Audio (cellular voice)
 - ~10-15 Kbps
- Audio (MP3)
 - ~300 Kbps
- You Tube Video (480p)
 - ~1.5 Mbps
- DVD quality Video
 - 5 Mbps
- iPhone Video
 - 15 Mbps
- 4K quality Video
 - 25-40 Mbps

Q4, Q5

Comparing the power of cellular and TV

Wider channels contain proportionately more noise and need proportionately more power to travel the same distance. A 6 MHz TV channel has 200x the bandwidth of a 30 KHz cellular channel and therefore needs 200x the power.

We have also learned that “free space” path loss is “square law” but with real-world “clutter” it becomes closer to “fourth power” law, so 4x distance = 256x power.

As shown below, if a 30KHz cellular channel needs 1W to travel 5 miles, a 6MHz TV channel will require 50 KW to travel 20 miles

Cellular Channel = 30KHz Range ~ 5 miles Power ~ 1 W	TV Channel 6 MHz (200 x cellular) Range ~20 miles (4x cellular) Power ~ 1W x 200 x 4 ⁴ = 50 KW
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Spectrum value as an alternative to cells

Cellular system with 1M users and 12.5 MHz or 25 MHz 20M POPs; Spectrum at \$1/MHz/POP

Balance Sheet (1M users)			P&L		
	25 MHz	12.5 MHz		25 MHz	12.5 MHz
Channels	400	200	Monthly Rev/sub	\$60	\$60
Users/cell	1000	500	Oper Revenue	\$720M	720M
Number of cells	1000	2000	Expenses	\$475M	562M
Tot Assets	\$1.5B	\$2.3B	SG&A	350M	350M
cells	\$1.0B	\$2.0B	Depreciation	100M	200M
spectrum	\$0.5B	\$0.25B	Amortization	25M	12.5M
Shareholder's equity	\$1.5B	\$2.3B	BT Earnings	\$ 245M	158M
			Tax	\$ 82M	53M
			Profit	\$ 163M	\$106M
			Return on equity	10.9%	4.6%

No question we would buy 25 MHz of spectrum at \$1/MHz/POP

So should we buy even more spectrum (say 50 MHz)
at \$1/MHz/POP?

Balance Sheet			P&L		
	50 MHz	25 MHz		50 MHz	25 MHz
Channels	800	400	Monthly Rev/sub	\$60	\$60
users/cell	2000	1000	Oper Revenue	\$720M	720M
Number of cells	500	1000	Expenses	\$450M	475M
Assets	\$1.5B	\$1.5B	SG&A	350M	350M
cells	\$0.5B	\$1.0B	Depreciation	50M	100M
spectrum	\$1.0B	\$0.5B	Amortization	50M	25M
Shareholder equity	\$1.5B	\$1.5B	BT Earnings	\$270M	245M
			Tax	\$90M	82M
			Profit	\$180M	\$163M
			Return on equity	12%	10.9%

Doubling the spectrum costs twice as much as before; half the cells saves half as much. There is still an advantage, but it is reduced. Each additional MHz we buy has less benefit! Competitors with less spectrum are incented to pay more.

Same questions at \$4/MHz/POP

12.5 MHz vs 25 MHz

Balance Sheet (1M users)			P&L		
	25 MHz	12.5 MHz		25 MHz	12.5 MHz
Channels	400	200	Monthly Rev/sub	\$60	\$60
Users/cell	1000	500	Oper Revenue	\$720M	720M
Number of cells	1000	2000	Expenses	\$550M	600M
Tot Assets	\$3.0B	\$3.0B	SG&A	350M	350M
cells	\$1.0B	\$2.0B	Depreciation	100M	200M
spectrum	\$2.0B	\$1.0B	Amortization	100M	50M
Shareholder's equity	\$3.0B	\$3.0B	BT Earnings	\$ 170M	120M
			Tax	\$ 57M	40M
			Profit	\$ 113M	\$80M
			Return on equity	3.8%	2.7%

As the price for spectrum goes up, there is less advantage to buying additional spectrum, and less profit in general.

Same questions at \$4/MHz/POP

50 MHz vs 25 MHz

Balance Sheet			P&L		
	50 MHz	25 MHz		50 MHz	25 MHz
Channels	800	400	Monthly Rev/sub	\$60	\$60
users/cell	2000	1000	Oper Revenue	\$720M	720M
Number of cells	500	1000	Expenses	\$600M	550M
Assets	\$4.5B	\$3.0B	SG&A	350M	350M
cells	\$0.5B	\$1.0B	Depreciation	50M	100M
spectrum	\$4.0B	\$2.0B	Amortization	200M	100M
Shareholder equity	\$4.5B	\$3.0B	BT Earnings	\$120M	170M
			Tax	\$40M	57M
			Profit	\$80M	113M
			Return on equity	1.7%	3.8%

For 1M users and \$4/MHz/POP, 50 MHz is less profitable than 25 MHz
 (so at 1M users and \$4/MHz/POP, 25 MHz is better than either 12.5 MHz or 50 MHz)

But should we buy even more spectrum (say 50 MHz)
at \$4/MHz/POP with **4M** users?

Balance Sheet		50 MHz	25 MHz
Channels		800	400
users/cell		2000	1000
Number of cells		2000	4000
Assets		\$6.0B	\$6.0B
cells		\$2.0B	\$4.0B
spectrum		\$4.0B	\$2.0B
Shareholder equity	\$6B		\$6B

P&L			
Monthly Rev/sub	\$60		\$60
Oper Revenue	\$2880M		\$2880M
Expenses	\$1100M		\$1200M
SG&A	700M		700M
Depreciation	200M		400M
Amortization	200M		100M
BT Earnings	\$1780M		\$1680M
Tax	\$593M		\$560M
Profit	\$1186M		\$1120M
Return on equity	19.8%		18.7%

Same cost of spectrum as previous example, but we are saving more cells at 4M users than we were at 1M users, so when we reach 4M users, even at \$4/MHz/POP, 50 MHz is more profitable than 25 MHz
How fast are we growing? When will more spectrum become available?

But should we buy 50 MHz at **\$10**/MHz/POP with **4M** users? (Verizon in NY in 2000)

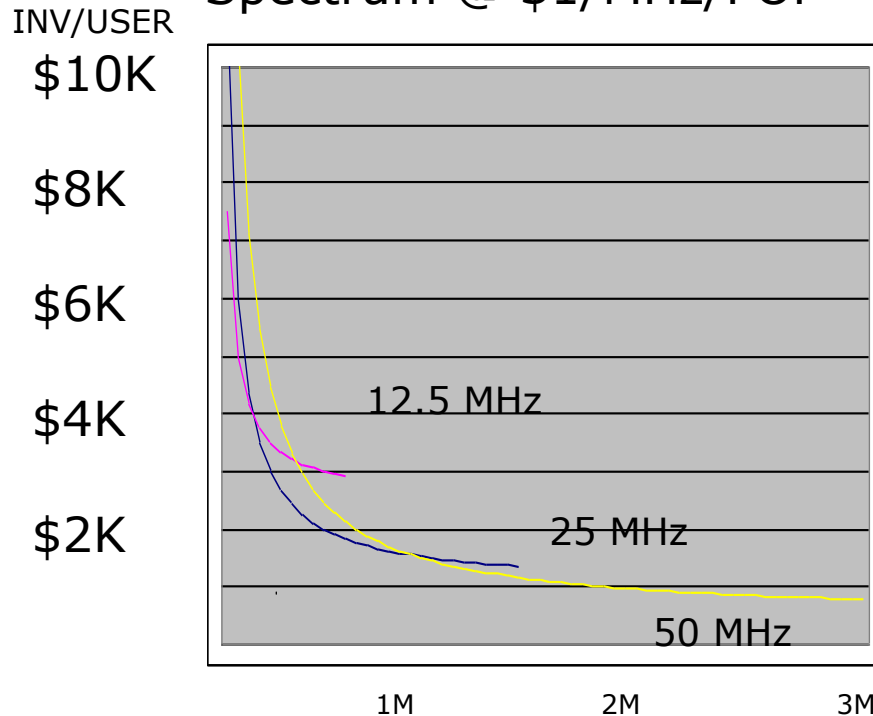
Balance Sheet			P&L		
	50 MHz	25 MHz			
Channels	800	400	Monthly Rev/sub	\$60	\$60
users/cell	2000	1000			
Number of cells	2000	4000	Oper Revenue	\$2880M	\$2880M
Assets	\$12.0B	\$9.0B	Expenses	\$1400M	\$1350M
cells	\$2.0B	\$4.0B	SG&A	700M	700M
spectrum	\$10.0B	\$5.0B	Depreciation	200M	400M
			Amortization	500M	250M
Shareholder equity	\$12B	\$9B	BT Earnings	\$1480M	\$1530M
			Tax	\$493M	\$510M
			Profit	\$987M	\$1020M
			Return on equity	8.2%	11.3%

Not a good deal, but not crazy as we thought (and were they hitting a limit in cell-size)?

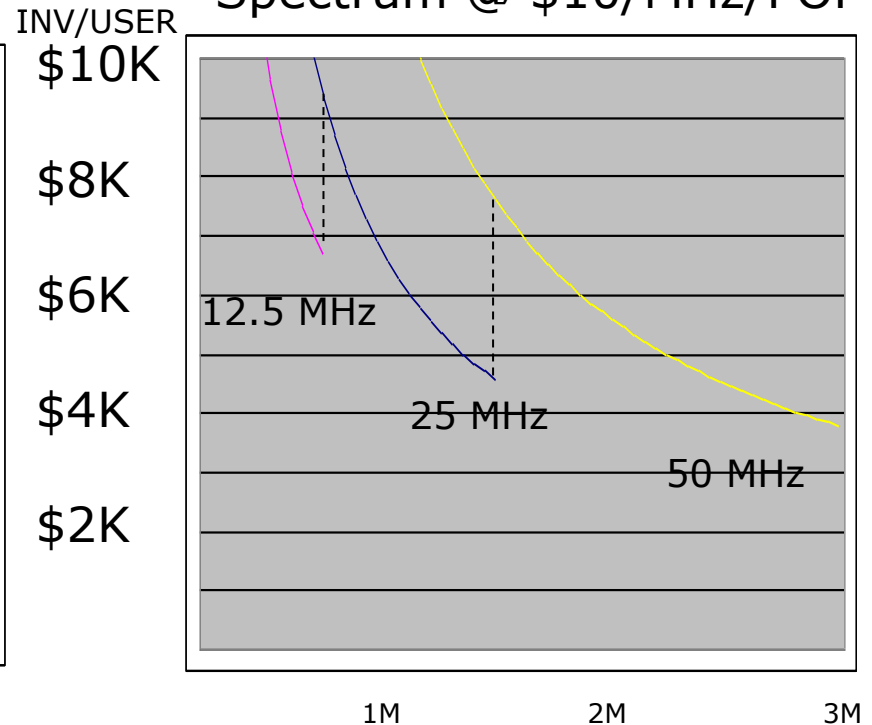
It becomes more complicated when we consider a limit in cell-splitting at (say) 1500 cells

These curves show Investment PER USER with a limit on number of cells
1500 cells yields 600K users for 12.5MHz; 1.5M users for 25 MHz; 3M users for 50 MHz

INV/USER Spectrum @ \$1/MHz/POP



INV/USER Spectrum @ \$10/MHz/POP



Do we buy a lot of spectrum up front or hope it's there when we need it? (and how will we make a profit at \$10/MHz/POP)?

The value of spectrum from different viewpoints

- ❑ It's worth a lot if we have reached the limits of cell splitting
- ❑ It's an amount we can calculate, as an alternative to more cells
 - But the more spectrum we have, the less the next purchase is worth
 - But it's worth more as we grow
 - ❑ How fast are we growing?
 - ❑ Will they auction more in the future?
- ❑ It's worth an uncertain amount, if we are considering new services
 - And what if those new services need a lot of spectrum, but people will still only pay \$50-60/month

And starting a new system has additional problems

- ❑ New entrants to the market must buy spectrum
 - But in 1994 (buying 2 GHz spectrum) they were competing with systems that got free spectrum and already had millions of customers, and they would need more cells at startup because of the higher frequency
 - They would need to charge less to grow against the competition, but they would have higher costs because of the spectrum
 - Two decades later, Verizon and AT&T were dominating the market, while T-Mobile (now merged with Sprint) is catching up and possibly exceeding them
- ❑ Investors who are excited about an important new technology often don't understand these strategic issues