University of Illinois at Urbana-Champaign
Dept. of Electrical and Computer Engineering

ECE 101: Computing Technologies and the Internet of Things

Cellular Networks

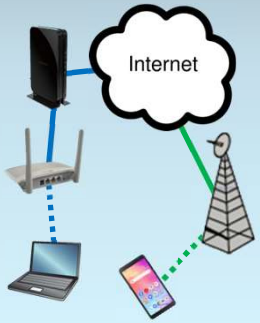
1

First Technologies: Wifi and Cellular

We're done with Wifi…

Now we're going to move on to cellular.

Next week, we'll dive into the workings of the Internet.



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Why No Wifi When Driving?

I have a tablet in my car.

Why can't I stay connected
- **to my home Wifi**
- **when I drive around town,**
- **or to Chicago, or to Atlanta?**

Signals attenuate and won't be strong enough compared with noise and interference.

3

How Far Can Wifi Reach?

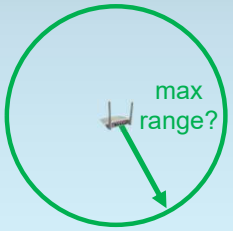
Can we use SINR to estimate the range of Wifi?

Think back to our discussion from Monday.

Signal power **attenuates as 1 / distance^2**.

Need SINR of 100× to 1000× for a good Wifi signal.

Let's **ignore interference**:
- assume that Wifi protocols
- prevent transmitters from
- sending at the same time.



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Use Needed SINR to Formulate a Limit on Distance

As before,
- antenna **noise N: 1 pW (10^{-12} Watts) = 10^{-6} µW**
- received **power at 1 m: 1 µW**
- (so **$S = (1 / R^2)$ µW**, where **R** is distance in meters)
- Assume **I = 0**.

Plugging in,

$$\text{SINR} = \frac{S}{I+N} = \frac{S}{N} = 10^6 / R^2 > 1000$$

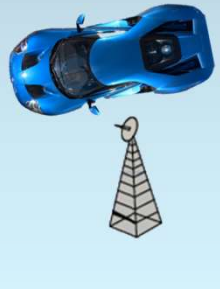
Wifi Limit Around 20-30 Meters, But Now Adjusts Speed

$$10^6 / R^2 > 1000$$
$$10^3 / R^2 > 1$$
$$10^3 > R^2$$
$$31.6 \text{ m} > R$$

Modern **Wifi adjusts protocol based on SINR**: continues to operate further away, but at reduced throughput (bits per second).

But I Want My Wifi!

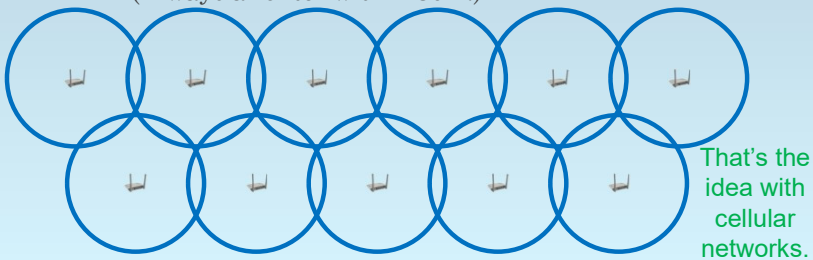
Desire for mobile connectivity
- motivated development of cellular networks
- in which we change our access point as we move.



Want Access from Anywhere—Create Cells!

Why not blanket a city with Wifi routers?

(Always a router within 30m.)



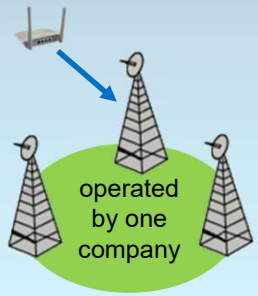
That's the idea with cellular networks.

Cellular Differs in Technology and Administration

What's the difference?

Cellular uses a **different technology**:
- instead of routers, build cell towers
  - **tall towers** easier to see,
  - signal **less likely to hit obstacles**,
  - and less likely **to bounce off ground**.

Also uses a **different model of administration** (a **single owner** instead of independent routers).



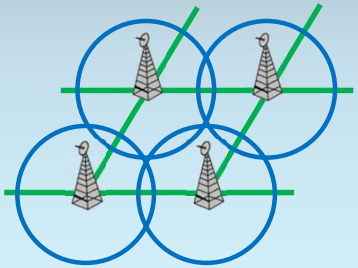
Cell Towers Use More Power and Connect by Wires

Cell tower **transmission power**
- much higher than Wifi
- **around 10-50W** (**100-500×**)*

The term **"cell" comes from**
- **hexagonal basis** for coverage.
- Buildings/trees may necessitate different geometry.

Towers linked by wires.

*For safety, phones use much less (~1W), thus asymmetric.



Who Cares How Cell Towers are Managed?

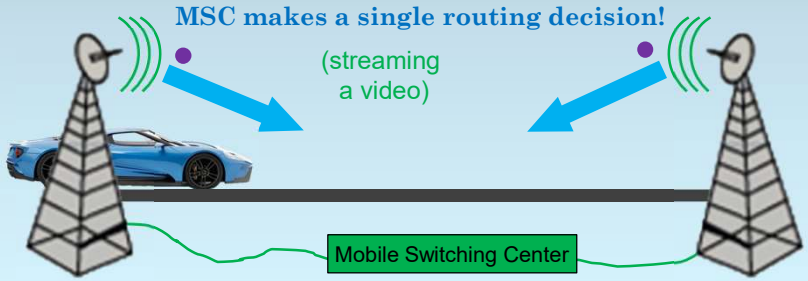
Why does centralized administration matter?

Three key reasons:
1. easier to manage handoff between towers,
2. simplify billing and accounting, and
3. easier to avoid interference (through scheduling).

Handoff: MSC Decides (No Arbitrating Requests)

When should my phone switch towers?

MSC makes a single routing decision!



Consensus Takes Time, Leading to Service Breaks

If routers were independent, how could we make the decision?

Need to negotiate and communicate with other routers in the Internet.

- Can be done, but **much slower**.
- Such delays show up as **breaks in your Internet service**.

Think about switching Wifi networks—to be fair, Wifi is not designed to support handoff.

Centralized Control Makes Handoff Faster and Easier

With **centralized tower administration**,

- MSC compares
  - current signal strength and
  - signal strength changes
  - from towers in range, then
- **hands off instantly.**
- Further packets routed to new tower.

Centralized control also simplifies billing and accounting.

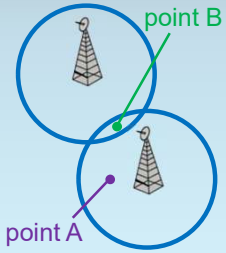
Centralized Control Simplifies Transmission Scheduling

The **final benefit** of a single company owning a set of cell towers is the ability to **reduce interference through scheduling**.

Tower ranges overlap to support handoff.

Where would you rather use your phone, point A or point B?

Why?

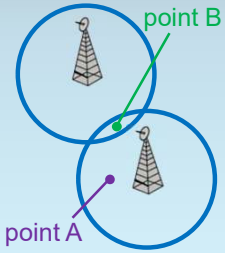


Better Signal and Less Interference at Point A

A has better signal.

And B may have interference from the other tower.

Every cellular company wants to provide uniform service to all customers (without customers having to move around)!

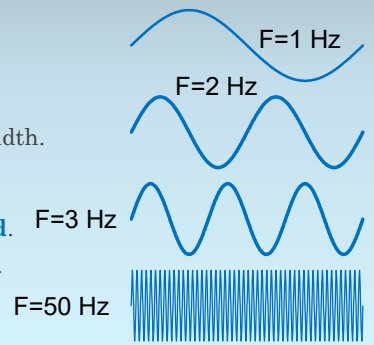


Frequency: Number of Up/Down Periods per Second

To understand how centralized administration of cell towers
- helps with avoiding interference,
- we need to develop some ideas
- of frequency, spectrum, and bandwidth.

A signal's **frequency** is
- **how many times the signal**
- **goes up and down in one second**.

Frequency is measured in Hertz (Hz).



Different Signals Use Different Bands

A **range of frequencies**, such as **900 to 1000 Hz**, is **called a band**.

Different signals, such as Wifi, Cellular (3G, 4G, 5G), TV, and radio, **use different bands**.

The width of the band (called **bandwidth**) **determines how much data can be sent per second** with those signals.

For example, the **band from 900 to 1000 Hz has** a **bandwidth of (1000 – 900) = 100 Hz**.

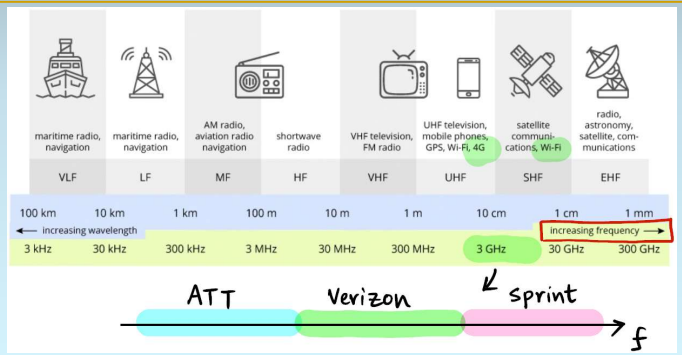
Signals in Different Bands Do Not Interfere

What do you think happens when a signal in another band collides with a signal to which you're listening?

Hint: do you see radio waves? Or microwaves (in a microwave oven)? These bands do not overlap with human vision bands.

The answer? **Nothing.** Out of band signals are (mostly) irrelevant.

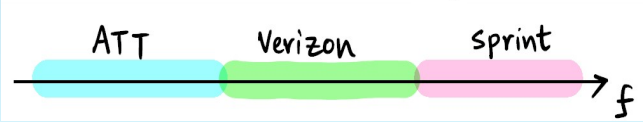
Both Wifi and Cellular Use Bands in the GHz Range



Unlike Wifi, Cell Bands Licensed for Private Use

Wifi bands
- around **2.4 GHz** and **5 GHz**,
- with more bands in some countries,
- are **available for use by everyone**.

In contrast, **governments license bands to cellular companies for private use**.



Dying Technologies Make Room for New Ones

Providers need spectrum/bandwidth
- to meet tremendous demand for data throughput,
- but the spectrum is really crowded!
- Not much of the spectrum is free.

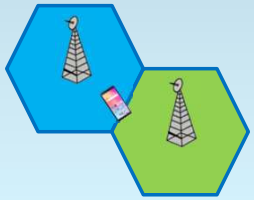
Recently, as **TV companies** started to vanish,
- their licensed **bands were auctioned off**
- and many are now licensed **to cellular providers**.

Each Provider Divides their Band into Channels

Each **provider** further **divides** their licensed **bands into several channels** (smaller bands).

A **phone** then **communicates over one channel** with the nearest tower.

If your phone
- is communicating over the blue channel,
- and a nearby tower transmits
- over the green channel,
- there's no interference!



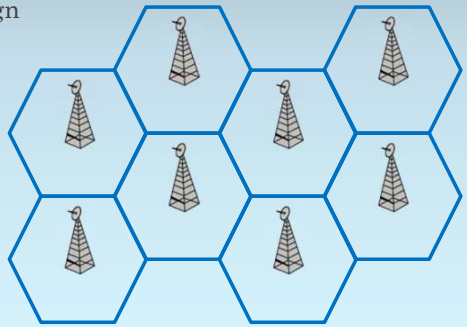
How Can Channels be Assigned to Reduce Interference?

A central operator can assign channels to each cell tower.

Imagine three channels: blue, green, and yellow.

Can you color the cells to minimize interference?

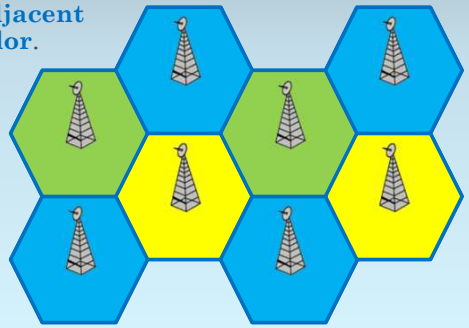
Hint: can you say anything about the colors of two adjacent cells?



Example of Channel Assignment with Three Channels

In this example, **no two adjacent cells share a common color**.

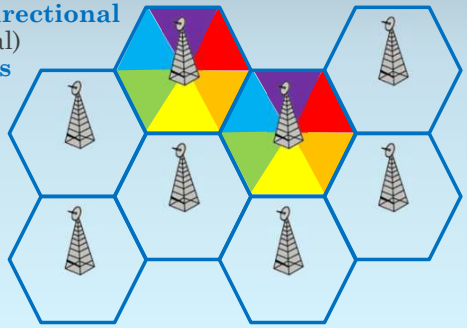
The closest cell with the same color is always two cells away.



Directional Antennae Further Reduce Interference

Modern systems also use **directional** (rather than omnidirectional) **antennae**, which **improves signal strength** and **further reduces interference**.

For example, with six channels, we might divide each cell as shown here…

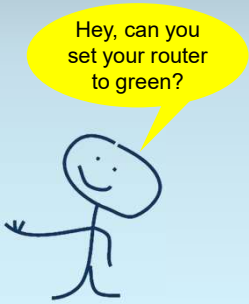


Channel Scheduling Requires Organization and Control

Channel scheduling is **only possible**
- **when a single company**
- **places and operates** all **towers**.

In contrast, Wifi routers are
- placed more or less randomly and
- controlled autonomously, often with a different operator for each router.

"No way—you do it! I like blue! You're trying to trick me!"



Each Company Offers a Different Optimization Strategy

How do companies differentiate themselves?

Each cellular provider **explores how to make the best use of their** portion of the **spectrum**.

Each may **optimize for different things**:
- geographic coverage,
- low interference,
- high throughput,
- fast handoff,
- and so forth.

Evolution of Cellular Technologies in Last 50 Years

Features	1G Analog	2G Dig.	3G	4G MIMO	5G
Start/Devlopment	1970/1984	1980/1999	1990/2002	2000/2010	2010/2015
Technology	AMPS, NMT, TACS	GSM	WCDMA	LTE, WiMax	MIMO, mm Waves
Frequency	30 KHz	1.8 Ghz	1.6 - 2 GHz	2 - 8 GHz	3 - 30 Ghz
Bandwidth	2 kbps	14.4 - 64 kbps	2 Mbps	2000 Mbps to 1 Gbps	1 Gbps and higher
AccessSystem	FDMA	TDMA/CDMA	CDMA	CDMA	OFDM/BDMA

→ smaller range

→ More bandwidth

phone call → Data

Higher frequencies, shorter range, so more towers and less time between handoffs.

The Internet of Things is on the Horizon

In the coming decade, humans will start to connect everything, forming an "Internet of Things" (IoT).

For example,

- robots that walk store aisles and interact with products,
- every medicine bottle, and
- every animal (insect!?) in a herd.

All connect to 5G.

Cellular Use Has Hazards to Humans

Cellular technologies poses health hazards, both directly and indirectly.

Cell phone transmission power has dropped significantly to reduce the **risk to human health**, but more may be needed.

Indirectly, texting and other **cell phone use** often **distracts drivers**, leading to accidents and deaths.

Cellular Use Also Brings Benefits to Society

Cellular technology also brings benefits.

In some countries, cellular network **talk time has become a de facto currency**, enabling commerce.

Currently, throughput is insufficient **to deliver education** (Zoom, for example) **to global audiences**, but **future cell networks** may remove that limitation.

Terminology You Should Know from These Slides

- cellular network
- cell tower
- cell
- frequency (in Hertz or Hz)
- band / channel
- bandwidth
- channel scheduling
- Internet of Things (IoT)

Concepts You Should Know from These Slides

- how to calculate maximum range of a signal using SINR
- differences between Wifi and cellular
- reasons for central administration of cell networks
- different bands do not interfere
- cellular bands are licensed—only the owner can transmit (or allow others to transmit)
- hazards and benefits of cellular technology

Slide circle 11 .. Wifi in society

There has also been some discussion

- of whether companies might do a better job of managing the Wifi bands,
- in other words, restricting access to specific companies, but
- lack of commercial incentive to provide access to everyone.

