Physical Layer

Introduction

This is a strange chapter. There is a lot to read and I am not sure you need to read it all. It is basically a catalog of the physical media with a little bit on the theory behind the physics and mathematics of bits “on the wire,” even when it isn’t literally a wire. It is interesting to know how the common media work and it's good to know a little bit about how all this works on the wire. There are some fundamentals here you should know well and much of the rest is a matter of interest and importance. I will try to point out the important points as we go along. You should familiarize yourself with the major aspects of the media. It is important to have an idea of what sort of errors it is susceptible to, maximum range it can run, etc. What we are really interested in here is how do we get these bits on the wire and to the other machine.

Let’s start at the very beginning.

Let There Be Light!

(and all the other wavelengths)

$$\nabla \bullet E = \rho/\varepsilon$$

$$\nabla \bullet B = 0$$

$$\nabla \times E = -\partial B/\partial t$$

$$\nabla \times B = -\mu J + \mu\varepsilon\partial E/\partial t$$

We're not going to do anything with these. The math is way beyond a CS curriculum. But this is one of the great accomplishments of modern physics. These are Maxwell's Equations worked out by James Clerk Maxwell in 1876. Everything there is to know about classical electricity and magnetism is in these four simple equations. Everything from the angle of incidence equals the angle of reflection to that a dipole radiates, ie., that radio and tv are possible. They are vector differential equations that use two special operators called *divergence* (a form of dot product) and *curl* (a cross-product). They don't look like this in Maxwell's 1876 Treatise on Electricity and Magnetism. Heaviside translated them into vector differential equations and recast them in this form. This is the form that is taught to every electrical engineer. It is all in there, you just have to know how to get it out.

Maxwell died young, so he is not as well known outside of physics and electrical engineering. But he really founded modern physics. From what little I have read (and I need to read more), it is clear that physics really became physics after Maxwell.

I can't say enough about what an elegant and powerful accomplishment this is. I was lucky enough to have advanced E&M from the head of the antenna lab at Illinois. About two thirds of the way through the course, it comes to deriving that are dipole radiates. In other words, radio.

The derivation took two class periods. It isn't simple. About halfway through the derivation, Maxwell posited a magnetic dual to Coulomb's Law, just as a mathematical tool to simplify the calculation. After explaining this, the professor pointed out that 100 years later Feynman proved that magnetic potential existed. Sometimes the math leads the science.

Since everything we do runs on electricity, and you have an interest in the history of science (and you should, being computer *scientists*), look for a chance to read more about Maxwell and how they figured out electricity. (I know many of you have the view: "just tell me what I need to know to get a job." That is quite myopic. I can't begin to list all of the insights I have had by understanding how something came about. Sometimes what I explored was not specifically about computing, but I was trying to unravel a problem that was totally new.) It took 3 outsiders to figure out electricity and magnetism. The scientific establishment tried to make it Newtonian, but it wasn't. It took researchers who listened to what the problem told them rather than what they wanted it to be.

Guided Transmission Media

Persistent Storage

Read

Read Tanenbaum Chapter 2, Section 2.1.1, pp. 90–91.

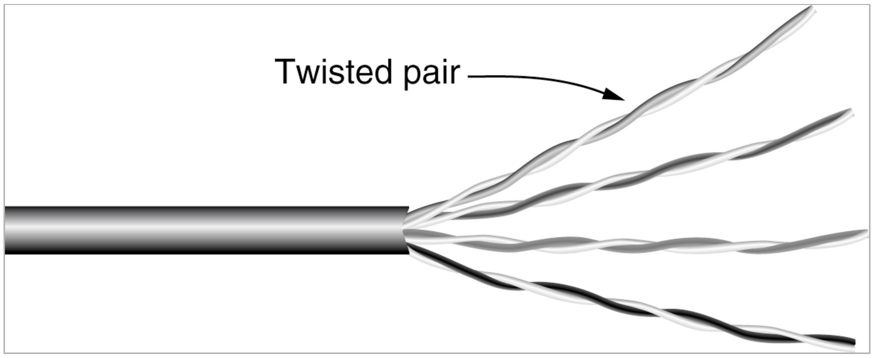
A fun calculation everyone has to do sometime: what's the data rate of a station wagon full of mag tapes (or memory sticks) going down the highway at 70 miles per hour.

Twisted Pair

Read

Read Tanenbaum Chapter 2, Section 2.1.2, pp. 91–93.

Twisted Pairs



A category 5e twisted pair consists of two insulated wires gently twisted together. Four such pairs are typically grouped in a plastic sheath to protect the wires and keep them together.

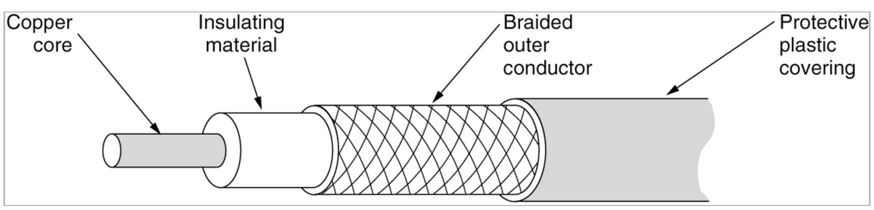
A changing electric current in a wire will generate a changing magnetic field around it, which will induce a changing current in a wire next to it. This “cross-talk” can interfere with a signal in the other wire and vice versa. Sometimes the solution is very simple. Simply twisting the wires around each other will cause the fields to cancel each other out.

Coaxial Cable

Read

Read Tanenbaum Chapter 2 Section 2.1.3 p. 93.

Coaxial Cable



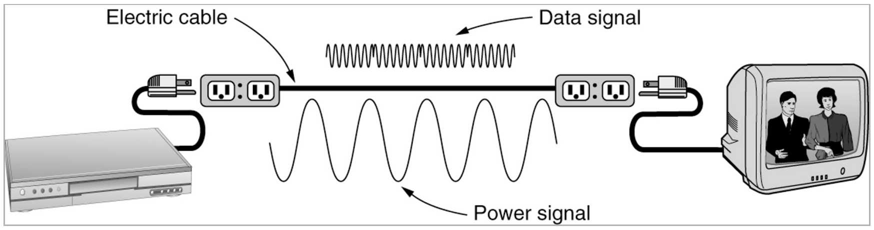
A coaxial cable consists of a stiff copper wire as the core, surrounded by an insulating material. The insulator is encased by a cylindrical conductor, often as a closely woven braided mesh. The outer conductor is covered in a protective plastic sheath.

Power Lines

Read

Read Tanenbaum Chapter 2, Section 2.1.4, p. 94.

Power Lines



Using power lines for networking is simple. In this case, a TV and a receiver are plugged into the wall, which must be done anyway because they need power. Then they can send and receive movies over the electrical wiring.

The problem with using this for any distance is that it won't work through a transformer. The data signal must be routed around the transformer and introduced on the power line.

Fiber Optics

Read

Read Tanenbaum Chapter 2, Section 2.1.5, pp. 95–100.

Wireless Transmission

Read

Read Tanenbaum Chapter 2, Section 2.2.1, pp. 100–102.

The big problem for wireless is if two transmitters transmit at the same time, it obliterates both signals. They collide. The signals add and are unintelligible. A lot of the technologies here are trying to avoid collisions. One approach is frequency hopping. The transmitters change frequency within a range very fast, and the receivers switch to the next frequency just as fast as the transmitters do. Different transmitters use different “hopping sequences.” By jumping around you're reducing the chance of a collision.

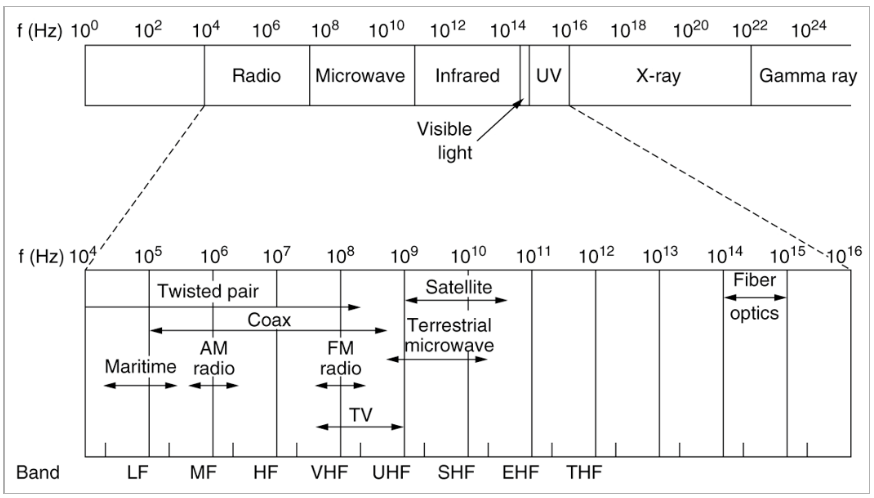
The Electromagnetic Spectrum

Read

Read Tanenbaum Chapter 2, Section 2.2.1, pp. 101–102.

Traditional AM radio is about six 630 Khz to about one and a half MHz. LORAN was very low frequency maritime band that was in use, probably by the turn of the 20th century. The frequencies were very low and had some good distance properties.

The Electromagnetic Spectrum



The electromagnetic spectrum and its uses for communication.

If you look at the AM radio band, the high-power stations are the low end of the band, because those frequencies have much better distance properties. Toward the high end of the band, the distance properties tend to get shorter. This is why local radio stations are in the high end of the band. When this was being explored in the early 20thC, people thought that propagation distance would continue to get shorter and shorter and shorter. It was ham (amateur) radio operators who started exploring the 160meter and 80m ham band where distances started increasing. As they moved higher, they kept finding bands where propagation distances were even greater. So by 20 meters, you could get to any place in the world. In the low frequencies, the waves stayed low are called the *ground waves*. Those waves stay close to the ground. But as the frequency goes up, they get shorter. What was unknown was that at the higher frequencies, there is a band of charged particles around Earth, called the *ionosphere*. They were bouncing radio waves off the ionosphere. So they could get much greater distances.

For an amateur radio, a license was required, for which there were two criteria: the ability to send a certain number of words per second in Morse code and being able to pass an exam on the electronics. Today the Morse code requirement has been dropped, but there is still an exam for radio electronics. As the technology developed over time, and more and more became possible, there was a push for an unlicensed radio band. The first of these was taken from the 11-meter ham band, which was pretty useless during high spot cycles anyway. They dedicated it to what was known as CB radio, Citizens Band radio. Transmitter power, which was limited to 5 watts to limit its range. This was used for local dispatching truck traffic and things like that.

Frequency Hopping, Direct Sequence Spread Spectrum

Read

Read Tanenbaum Chapter 2, Section 2.2.2, 3, pp. 103–104.

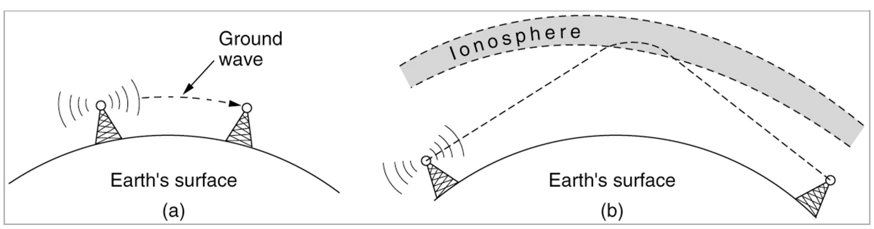
Using the Spectrum for Transmission

Radio Spectrum

Read

Read Tanenbaum Chapter 2, Section 2.3.1, pp. 104–109.

Radio Transmission



In the VLF, LF, and MF bands, radio waves follow the curvature of Earth. In the HF band, they bounce off the ionosphere.

From Waveforms to Bits

The Theoretical Basis for Data Communications

Read

Read Tanenbaum Chapter 2, Section 2.4.1, pp. 110–113.

We model the behavior of variation of voltage or current with mathematical functions. A major result from mathematics is that any periodic waveform can be created by a Fourier series that follows the following equation:

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

Function reconstructed with:

$$a_n = \frac{2}{T}\int_0^T g(t)\sin(2\pi nft)dt$$
$$b_n = \frac{2}{T}\int_0^T g(t)\cos(2\pi nft)dt$$
$$c_n = \frac{2}{T}\int_0^T g(t)dt$$

While we don't have to solve these equations, we do have to use the results. This includes a square wave.

Maximum Data Rate of a Channel

Read

Read Tanenbaum Chapter 2, Section 2.4.2, pp. 114–115.

If you sample the signal at twice the bandwidth, this is as close to the original signal as it can be reconstructed. Sampling any faster will not improve it. So if voice is zero to 20,000 cycles, sampling at 40,000 cycles per second or 40,000 hertz and will reconstitute any waveform.

Making Bits

To make bits the number of samples per second, this is the terminology unique to the physical layer. The number of samples per second is the baud rate.

There is one symbol sent for each baud.

> Therefore, if there is a 2400-baud line that uses zero volts for *zero* and one volt for a *one*, then there is one bit per symbol or 2400 bits per second.
>
> If it does four voltage levels, then that's two bits per symbol or 4800 bits per second.
>
> Modulation uses combinations of amplitude, frequency, and phase to encode bits.

More levels can be used to increase the number of bits per symbol and hence the bit rate now, but remember what we saw with distortion. Different wavelengths that make up the signal will distort differently. If four different voltage levels are used to distinguish different symbols, that makes it harder to distinguish what those levels are versus if you just had one level. But there is a higher data rate.

Digital Modulation

Read

Read Tanenbaum Chapter 2, Section 2.4.3, pp. 115–123.

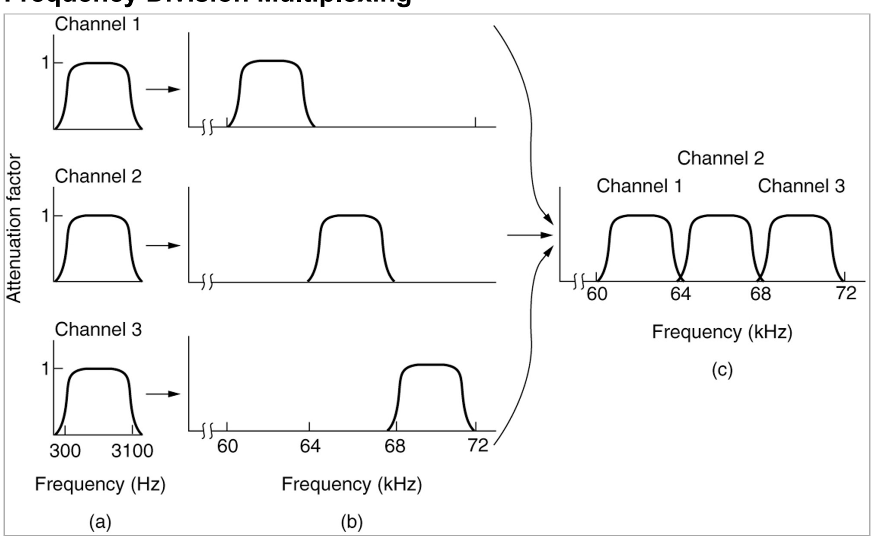
Multiplexing

Frequency Division Multiplexing

Read

Read Tanenbaum Chapter 2, Section 2.4.4, pp. 123–131.

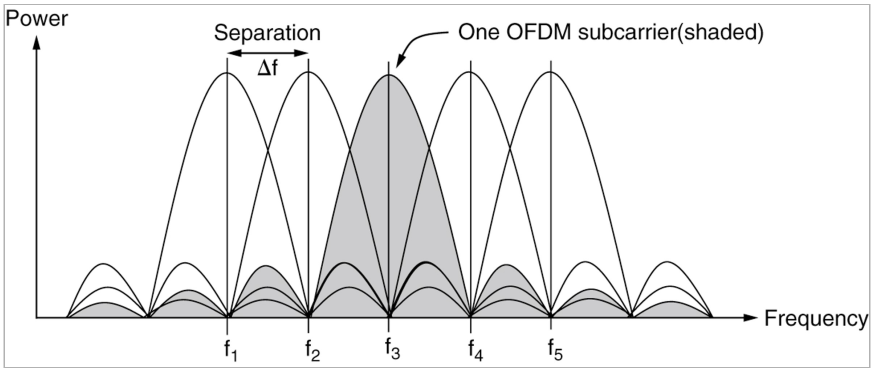
Frequency Division Multiplexing



(a) The original bandwidths. (b) The bandwidths raised in frequency. (c) The multiplexed channel.

The channels are shifted to specific ranges within the band. Each voice call is 3100 Hz, the spacing 4000Hz. The 900Hz difference is the “guard band.”

Frequency Division Multiplexing



Orthogonal frequency division multiplexing (OFDM).

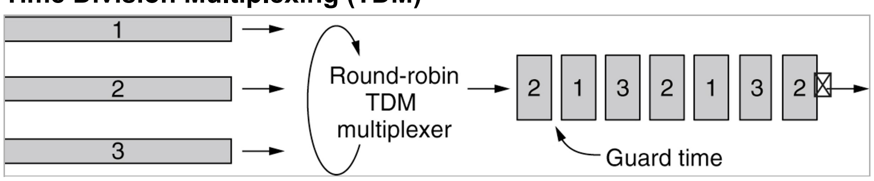
When sending digital data, it is possible to pack the subcarriers tightly, but ensure good separation, so the sidebands are zero by the time one reaches the center of the adjacent channel. Sampling is at the center of each channel without interference. This provides greater efficiency. There is a “guard time” but it is less overhead than the “guard bands” of FDM.

Time Division Multiplexing

Read

Read Tanenbaum Chapter 2, Section 2.4.4, p. 125.

Time Division Multiplexing (TDM)



Code Division Multiplexing (CDMA)

Read

Read Tanenbaum Chapter 2, Section 2.4.4, pp. 126–129.

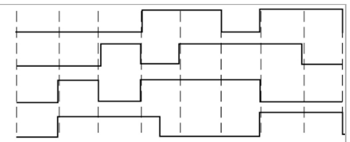
This is a very interesting technique for avoiding collisions by creating orthogonal codewords.

CDMA relies on the properties of the dot product.

Code Division Multiplexing

A = (–1 –1 –1 +1 +1 –1 +1 +1)
B = (–1 –1 +1 –1 +1 +1 +1 –1)
C = (–1 +1 –1 +1 +1 +1 –1 –1)
D = (–1 +1 –1 –1 –1 –1 +1 –1)

(a)



(b)

$S_1 = C$ = (–1 +1 –1 +1 +1 +1 –1 –1)
$S_2 = B+C$ = (–2 0 0 0 +2 +2 0 –2)
$S_3 = A+\overline{B}$ = (0 0 –2 +2 0 –2 0 +2)
$S_4 = A+\overline{B}+C$ = (–1 +1 –3 +3 +1 –1 –1 +1)
$S_5 = A+B+C+D$ = (–4 0 –2 0 +2 0 +2 –2)
$S_6 = A+B+\overline{C}+D$ = (–2 –2 0 –2 0 –2 +4 0)

(c)

$S_1 \bullet C$ = [1+1+1+1+1+1+1+1]/8 = 1
$S_2 \bullet C$ = [2+0+0+0+2+2+0+2]/8 = 1
$S_3 \bullet C$ = [0+0+2+2+0–2+0–2]/8 = 0
$S_4 \bullet C$ = [1+1+3+3+1–1+1–1]/8 = 1
$S_5 \bullet C$ = [4+0+2+0+2+0–2+2]/8 = 1
$S_6 \bullet C$ = [2–2+0–2+0–2–4+0]/8 = –1

(d)

(a) Chip sequences for four stations. (b) Signals the sequences represent. (c) Six examples of transmissions. (d) Recovery of station C's signal.

What Is a Dot Product?

The dot product is an operation on two vectors to produce a scalar. To form the dot product, take two vectors A and B, where $(a_1, a_2, \ldots a_n)$ and $(b_1, b_2, \ldots b_n)$

$$A \bullet B = \Sigma a_i b_i = |A||B| \cos\theta$$

Therefore, when the vectors are parallel, $\cos\theta = 1$ and $A \bullet B = |A||B|$
Or, if the vectors are perpendicular, $\cos\theta = 0$ and $A \bullet B = 0$.
With waves, this can be very useful.

The dot product of two vectors is equal to the length of a times the length of b to the cosine of the angle between them. That means that two vectors are parallel, then the cosine is going to be one. The dot product is just going to be the product of the lengths of the two vectors.

Now apply this to CDMA. If we've chosen the vectors of each channel to be orthogonal and their complement is also orthogonal, then let an orthogonal vector be a 1 and its complement a 0. The transmitter uses those vectors, and the receiver uses the same vectors and takes the dot product to get the bits. If the transmission collides with other transmitters, it doesn't matter because the receiver can take the dot product and get the data intended for it.

Wavelength Division Multiplexing

Read

Read Tanenbaum Chapter 2, Section 2.4.4, pp. 129–130.

Public Switched Telephone Network

Structure of the Telephone Systems

Read

Read Tanenbaum Chapter 2, Section 2.5.1, pp. 131–134.

The Local Loop: Telephone Modems

Read

Read Tanenbaum Chapter 2, Section 2.5.2, pp. 134–137.

Digital Subscriber Line (DSL)

Read

Read Tanenbaum Chapter 2, Section 2.5.2, pp. 137–341.

The trouble is that DSL has a major limitation in that the termination has to be within two and a half miles of a central office, which is two and a half miles as the cable runs not as the crow flies. In Europe, where buildings are a lot denser, DSL has actually been used a fair amount. It is also used there because the PTTs are very strong, and this uses their existing twisted pair. In the United States, distances are much larger, and DSL hasn't been all that effective. Also, when people started installing it, there were a lot of problems of crosstalk between the lines. It was a real mess.

Fiber to the X

Read

Read Tanenbaum Chapter 2, Section 2.5.2, pp. 141–143.

Trunks and Multiplexing

Digitizing Voice Signals

Read

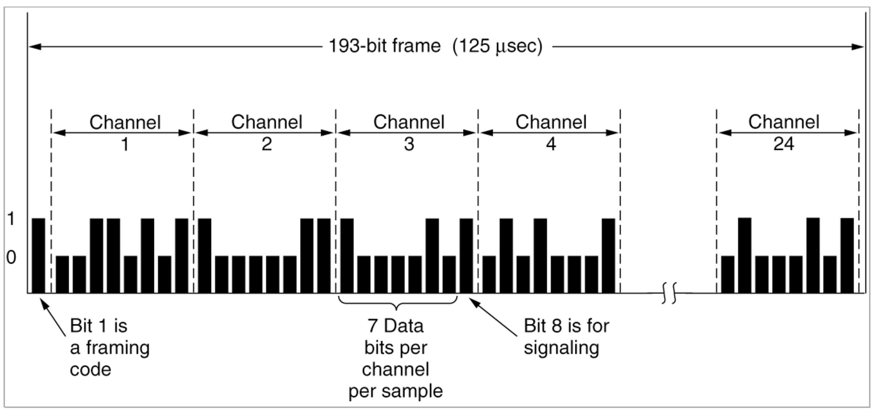
Read Tanenbaum Chapter 2, Section 2.5.3, pp. 143–144.

T-Carrier: Multiplexing Data on the Phone Network

Read

Read Tanenbaum Chapter 2, Section 2.5.3, pp. 144–146.

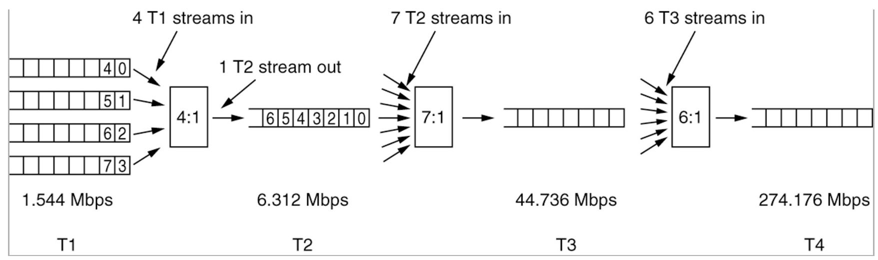
The T1 carrier (1.544 Mbps)



A T1 consists of 24 channels. Each channel is called a *DS0*. In ITU, they did this a little differently. They used the whole frame in other cases that show, so in ITU T1 that is called E1. Therefore, it has 32 eight-bit channels and signaling is out of band, so you get 193 bits every 125 microseconds for voice. The eighth bit was robbed in some channels for signaling. It is not possible to do this for data where only seven bits are used, so it's 56 K in the United States. The Europeans didn't do the framing, so they get a full 64 Kbps.

This was the way WECo built multiplexers and channel banks. First, circa 1960, they started with T1. The distance between loading coils on long copper loops is 6,000 feet, so they used that as the inter-repeater spacing and decided that the 1.5 Mbps range was about what they could do. They digitized voice at 64000 bps based on 3.4 kHz as the upper end of the filter and Nyquist, and they used 8-bit samples. The mux put 24 voice channels onto a T1 line, and they only allocated one bit per frame for framing and control, hence 24*8+1=193 bits/frame * 8000 frame/sec as the DS1 rate.

Multiplexing T1 Streams into Higher Carriers



They built very little T2, but the DS2 level was the next shelf on the mux, which had room for four DS1s plus overhead to accommodate the independent clocking of each (plesiochronous). The M13 mux took seven DS2s, again each independently clocked, so more overhead, and they made one DS3. They could run T3 on coax, at 44.736 Mbps. I suspect the 4 and 7 were originally based on what fit onto a shelf in their original design, but I don't know the inside story.

In ITU, it was much more rational: 64 kb per channel, multiplexed to 32, 128, 512, 2048, and 8192 channels, Or 2.048, 8.848, 34.304, 139.264, and 565.148 Mbps.

SONET/SDH-Multplexing for Optical Networks

Read

Read Tanenbaum Chapter 2, Section 2.5.3, pp. 146–149.

Switching

Circuit Switching

Read

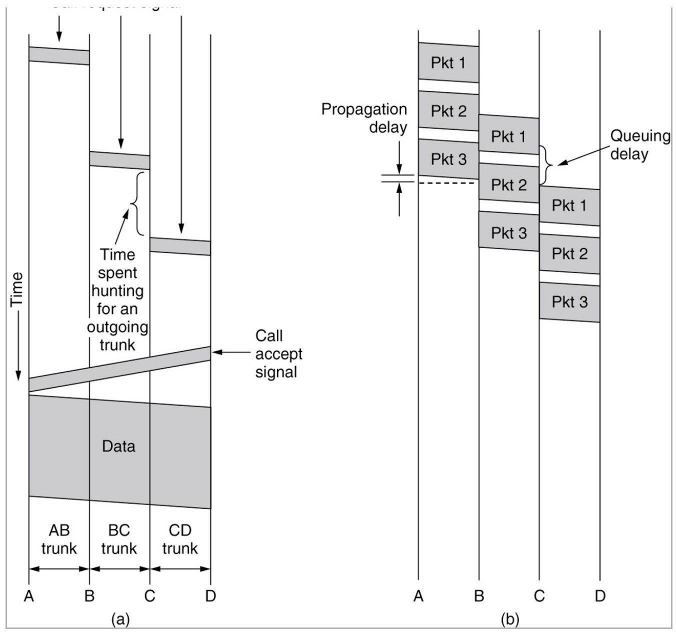
Read Tanenbaum Chapter 2, Section 2.5.4, pp. 149–151.

Packet Switching

Read

Read Tanenbaum Chapter 2, Section 2.5.4, pp. 151–154.

Circuit Switching



Circuit switching has a built-in delay in creating a connection that packet switching avoids, which is all the more reason that circuit switching should be used between intermediate points in the network where a connection has a very long lifetime. There are two forms of packet switching: virtual circuit, which works like circuit-switching in software, and datagrams, where each packet is routed independently.

Packet Switching

Item	Circuit Switched	Packet Switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
A switch crash is fatal	Yes	No
Bandwidth available	Fixed	Dynamic
Time of possible congestion	At setup time	On every packet
Potentially wasted bandwidth	Yes	No
Store-and-forward transmission	No	Yes
Charging	Per minute	Per byte

Tanenbaum points out the difference here in the table. In circuit switching, there is going to be a call setup followed by the data transfer and then [a?] tear down, while in packet switching that doesn't happen. Care must be exercised here, because to some extent we are comparing apples and oranges. Circuit switching occurs in layer 1, and packet switching occurs in higher layers.

This also illustrates how one can get into group think and not see the way out of the “beads-on-string” box. Tanenbaum (and the industry) assumes that the circuit has to go from one edge of the network to another for both, but this is not the case. Later, we will learn that circuit-like switching is best used when traffic density is high. That won’t be at the edge of the network. If they were smart, they would use packet switching at the edge of the network to the metro area. Traffic going to the same region will be routed in the same direction. As I often say, there may not be constant traffic between Lexington, Massachusetts, and Lake Forest, Illinois, but there is constant traffic between the Boston and Chicago switching centers, where traffic density is high and all going to the same place. That implies doing circuit switching between the Boston and Chicago hubs and use packet switching in the layer above, which is better used distributing traffic to the suburbs of the two cities. Since the traffic between the hubs is constant, there is no overhead for setup and teardown, because the connections exist for weeks, if not months.

Cellular Networks

Common Concepts; Cells, Handoffs, Paging

Read

Read Tanenbaum Chapter 2, Sections 2.6, 2.6.1, pp. 154–156.

As you know, as the phone moves, it is handed off from cell to cell. The cell base stations are connected to a wired network that carries the voice traffic to the regular phone system.

It turns out that laying out where the cells can be is a very interesting problem. There are all sorts of strange problems that can arise: buildings, reflections off buildings, mountains getting in the way, etc. To indicate how unexpected it can be consider what happened when Motorola was installing cellular in Houston, TX. They had an area in Northwest Houston where the signal coverage was terrible. They put in transmitters with boosters in various places to no avail. They had trucks driving around with power monitors trying to figure out was happening. It drove them crazy for a long time. Then finally somebody noticed that the Big Piney Forest came down into that part of Houston, and the pine needles were exactly a half wavelength! Those pine trees were just humongous absorbers of radio waves. They had to shift the area into a different part of the band where it wouldn't be a perfect half-wavelength!

First Generation Cellular: Analog

Read

Read Tanenbaum Chapter 2, Section 2.6.2, pp. 156–158.

The story of how cellular came about is very interesting. In the 1950s and 60s, Motorola was the IBM of radio. In the late 50s, AT&T went to Motorola and proposed that Motorola build something like cellular for AT&T. Motorola told AT&T that they would look at the proposal and get back to them. They went off and thought about it for a while, then came back and did a very gutsy thing. They gave AT&T their money back and said they didn't want to do the project. Then Motorola turned around and did it for themselves. In fact, as AT&T was just about to finish building it for themselves, Motorola was demonstrating it for the FCC, just hours apart! The story of all of this is very interesting. A good read if it interests you.

Call Management

Read

Read Tanenbaum Chapter 2, Section 2.6.2, pp. 156–158.

Second Generation: Digital

Read

Read Tanenbaum Chapter 2, Section 2.6.3, p. 158.

Cellular took off in Europe a lot faster than it did in the United States. This is primarily because the wired phone system in Europe was a lot worse than the wired phone system in the United States. Europeans found cellular to be an improvement over wireline phones. So cell phones use grew very, very quickly, and thus density went up very fast. Analog cellular required two frequencies for each call, which was a severe constraint on how many calls could be handled by one cell, whereas one can put 10 or more phone conversations on a digital wireless channel. There was considerable pressure in Europe to move to digital cellular. The opposite occurred in the United States. Early cellular phones were far worse than wireline phones. To make matters worse, the inventor of cellular at Motorola was adamant that good voice quality could only be done with analog. An incredible point of view! Not only was digital much more efficient and could support far more customers, digital signal processing can do a lot to clean up a signal and improve the quality of the voice.

GSM: The Global Systems for Mobile Communications

Read

Read Tanenbaum Chapter 2, Section 2.6.4, pp. 159–162.

Third Generation: Digital Voice and Data

Read

Read Tanenbaum Chapter 2, Section 2.6.5, pp. 162–166.

Fourth Generation: Packet Switching

Read

Read Tanenbaum Chapter 2, Section 2.6.6, pp. 166–168.

Fifth Generation

Read

Read Tanenbaum Chapter 2, Section 2.6.7, pp. 168–169.

Of course, 5G is all the rage these days. The physical layer is a major advance over previous generations. The rest of it is much less so and far too complex. It can probably be made much simpler: from our code comparisons, probably two to three orders of magnitude simpler.

5G was created when the equipment makers were close to have fully deployed 4G and customers were satisfied with that level of service, but that left the equipment makers with nothing to sell, so they came up with 5G.

It has also been proposed that carriers still want to get into the higher margin cloud/datacenter business. One of the big pushes in 5G has been so-called “edge computing” or very low latency applications. What the carriers are trying to do is make latency an issue that is so tight that the datacenters needed to host the applications are at or near their base stations. (The carriers are trying to move in on the cloud computing market, still dreaming of what they failed to do in the 1970s. There is a lot of wishful thinking involved in this. For example, support for autonomous vehicles, when it is clear to the autonomous vehicle developers that all short latency requirements must be handled in the vehicle to ensure resiliency. It is also unclear that the carriers have considered the density and energy requirements to support that degree of latency. They are a bit vague on what these applications would be.

Cable Networks

History of Cable Networks

Read

Read Tanenbaum Chapter 2, Section 2.7.1, p. 170.

The cable network may still look like this for distribution, but for the most part the cable companies now have their own networks. Of course, in the beginning, cable was all one way. One of the big things that the cable companies had to get used to was the idea of two-way communication. The other big change for cable companies was that they had built their networks into residential areas but not office parks and industrial areas. As the use of cable as a general-purpose network grew, they had to build out into those areas as well.

Broadband Internet Access Over Cable

Read

Read Tanenbaum Chapter 2, Section 2.7.2, pp. 170–173.

Cable providers have been moving to a hybrid fiber coax network. Verizon had been doing fiber to the home, while some companies had been doing fiber to the curb or fiber to the neighborhood and cable from there. Verizon realized that they could make more money in cellular. For a while, they froze their fiber rollout. In fact, at one point, they said they were going to finish the ones they said they would do, but then not do any more. They have been pressured into going a bit beyond that, but they really don't want to be in this business. They want to concentrate on the cellular business where the profits are better.

DOCSIS

Read

Read Tanenbaum Chapter 2, Section 2.7.3, pp. 173–174.

Resource Sharing in DOCSIS Networks

Read

Read Tanenbaum Chapter 2, Section 2.7.4, pp. 174–176.

Communication Satellites

GeoStationary Satellites

Read

Read Tanenbaum Chapter 2, Section 2.8.1, pp. 176–181.

For the most part, the satellite is getting away from merely being a reflector or simply amplifying the signal and sending it back. Today, the satellite is actually taking an active part in the network and routing satellite to satellite.

Medium Earth Orbit

Read

Read Tanenbaum Chapter 2, Section 2.8.2, p. 181.

Low Earth Orbit

Read

Read Tanenbaum Chapter 2, Section 2.8.3, pp. 181–184.

Iridium was done in the late 80s. I was actually in the Motorola Strategic Planning office when this proposal came in, and I thought it had too many moving parts.

This is a very interesting market exercise. This was a wonderful engineering idea, with lots of neat problems to solve. The idea was to have a constellation of satellites orbiting and doing handoff from satellite to satellite. Because it required a constellation of 88 satellites to provide worldwide coverage, it was named Iridium, because 88 is the atomic number of Iridium. It is also the element found in the paleontological record that indicates the asteroid that killed the dinosaurs. Iridium almost killed Motorola.

At any one time, there would be three satellites over the horizon. As one satellite went below the horizon, another would be coming above the horizon, and the call would be handed off from satellite to satellite. The call was being handed off on both ends from a caller on a satellite phone to another phone either through a ground station or another satellite phone. (Both ends of the call did not have to be within the range of the same 3 satellites.)

The trouble was, what market was this for? What Motorola hadn't really thought about was that it would always be a relatively small niche market. Where are you going to use this service? Ships at sea would be one scenario. That’s good, but there is never going to be much in the way of customer density on the ocean. Another scenario would be remote places in the desert or jungles, or in remote mountainous regions. Again, places where customer density is low. Insufficient to warrant cellular service in the region. The trouble is that for the land-based markets, providing satellite service early, for example for a mining operation or some other initial activity, ends up creating a greater density of users. Once there is a higher density of users, it has created a market for land-based cellular. Satellite remains a niche market.

Motorola almost bought the farm with this project. In the late 80s, putting up satellites was incredibly expensive. It was pretty much a voice network. It could do data, but the data was only 9.6 Kbps, which, of course, in the late 80s was nothing. It was so unprofitable, they were going to shut it down, but, at the last minute, the U.S. government bought it. The DoD has kept it operational and has been upgrading its satellites.

This is very much like what Elon Musk is doing now, but Starlink has a much larger number of satellites, in the thousands, and the cost of putting up satellites has dropped considerably. Musk is able to put up 10 or 20 satellites at a time.

Musk is now in the process of deploying Starlink with the idea of them being in very low orbit satellites. The delay is not nearly as great, but it is going to require a much larger constellation of satellites. So much so that astronomers are complaining because there is so much stuff orbiting that it is interfering with ground-based telescopes. A report recently said that the sky now has light pollution.

GPS is continually upgraded. Europe's talking about putting up their own GPS, as are Russia and China. It's getting crowded up there.

Not to mention, there is a large amount of space junk floating around. Over 500,000 pieces of space junk are floating around, waiting to have a horrible day; some of it is tiny and some of it is the size of a truck.

Comparison of Different Access Networks

Terrestrial, Cable, Fiber, ADSL

Read

Read Tanenbaum Chapter 2, Section 2.9.1, pp. 184–186.

Satellite vs. Terrestrial Networks

Read

Read Tanenbaum Chapter 2, Section 2.9.2, pp. 186–187.

Policy at the Physical Layer—Spectrum Allocation, Cellular and Telephone

Read

Read Tanenbaum Chapter 2, Section 2.10, pp. 187–194.

This is an odd section. It recounts the political issues surrounding spectrum allocation for the various wireless services, but especially cellular. To really treat this in some depth and in a meaningful way would require a whole course. Similarly, the discussion of deregulating the phone system in the United States is not representative of the rest of the world and got mixed up with the Internet boom. To some degree, the idea of competitive phone systems sharing the "last mile" and there being a long-term, stable competitive environment was a fantasy, just as it is with electric power. It is amazing what supposedly brilliant captains of industry can convince themselves of.

When the push for deregulation started in the in the '80s, AT&T wanted to get into the computer business for the coming networking environment. The settlement of the previous anti-trust case against AT&T and the telecom act prevented AT&T from being in the computer business. That was before the integration of computing and communications was on the horizon.

In the 80s, a new anti-trust action was taken against AT&T where they agreed to be broken up and create seven "Baby Bells." At the time, AT&T was organized into state telephone regionals: New England Bell, Illinois Bell, Ohio Bell, etc. These were grouped into seven Baby Bells. AT&T kept Long Lines, the backbone that connected everything together, and were allowed to buy a computer company. They immediately bought National Cash Register (NCR), and proceeded to screw up everything. Running a computer company is not like running a telephone system. They jumped into the cable market as well and paid too much, then they took a lot of heat from Wall Street about the fact that they weren't as profitable as WorldCom.

This whole move toward deregulation started when MCI bought bulk leased lines from AT&T at a discounted price and then offered lower long-distance rates to consumers. It was a nice little business exploiting the differences in tariffs in the regulated market. WorldCom, which was led by a former high school football coach, bought MCI and some other companies. It was going like gangbusters, reporting all these incredible profits. All of this was coming down during the Internet boom, and Wall Street was putting pressure on AT&T with regards to why they couldn't do what WorldCom was doing. Come to find out, WorldCom was cooking the books. They were lying. The president of WorldCom went to jail over this.

But what happened, of course, was that the Baby Bells existed for a few years and then slowly but surely, they started buying each other out until now we're down to two or three. It really was a lesson that "he who owns the wires controls everything."

The United States is big enough that we can allocate our own spectrum the moment we cooperate with Canada, but the thing is that with cellular, the range is short enough that you really don't have to worry about national boundaries so much.

Countries have been auctioning off bandwidth and selling it to the two carriers to operate their cellular networks in. As you can imagine, this has gotten to be quite a political football.

Boston University Metropolitan College