2.5 Digital Modulation and Multiplexing

**Digital modulation** = transferring a digital bit stream over an analog, bandwidth-limited communication channel, for example over

- A voice channel on the public switched telephone network (frequency range 300-3400 Hz)
- A limited radio frequency band (e.g. the 902-929 MHz ISM band)
- A limited optical wavelength (e.g. 0.95-1.05 μm)

**Modulation** (electronics/radio term) = varying one or more properties of a periodic waveform, called the carrier signal, with a modulating signal that typically contains information to be transmitted.
Do not confuse digital modulation with electronics modulation!

**Multiplexing** is sharing a communications channel among multiple users (transmissions).
2.5.1 Baseband Transmission

-bits are converted directly into signals-

Line codes send **symbols** that represent one or more bits

- NRZ is the simplest, literal line code (+1V="1", -1V="0")
- Other codes tradeoff bandwidth and signal transitions
FYI: RZ (Return to Zero)

Fundamental problem: Compared to the corresponding NRZ signal, RZ doubles the data rate, hence the frequency!

Nyquist Theorem for \( V = 2 \) \( \rightarrow \) \( \text{Max\_data\_rate} = 2B \)

\[ \text{data\_rate} \leq 2B \quad \text{B} \geq \text{data\_rate}/2 \]

If, instead of NRZ, RZ coding is used, the data rate doubles!
Practical problem: Clock Recovery

To decode the symbols, signals need sufficient transitions
• Otherwise long runs of 0s (or 1s) are confusing, e.g.:

```
1 0 0 0 0 0 0 0 0 0 0 0 um, 0? er, 0?
```

NRZ may have long series of 0s or 1s, resulting in clock recovery difficulties.

An improvement is **NRZI**, but long series of 0s are still problematic:

USB uses it!
Further techniques to improve Clock Recovery

- Manchester coding, mixes clock signal in every symbol
- 4B/5B maps 4 data bits to 5 coded bits with 1s and 0s:

<table>
<thead>
<tr>
<th>Data</th>
<th>Code</th>
<th>Data</th>
<th>Code</th>
<th>Data</th>
<th>Code</th>
<th>Data</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>11110</td>
<td>0100</td>
<td>01010</td>
<td>1000</td>
<td>10010</td>
<td>1100</td>
<td>11010</td>
</tr>
<tr>
<td>0001</td>
<td>01001</td>
<td>0101</td>
<td>01011</td>
<td>1001</td>
<td>10011</td>
<td>1101</td>
<td>11011</td>
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<tr>
<td>0010</td>
<td>10100</td>
<td>0110</td>
<td>01110</td>
<td>1010</td>
<td>10110</td>
<td>1110</td>
<td>11100</td>
</tr>
<tr>
<td>0011</td>
<td>10101</td>
<td>0111</td>
<td>01111</td>
<td>1011</td>
<td>10111</td>
<td>1111</td>
<td>11101</td>
</tr>
</tbody>
</table>

- A *scrambler* XORs Tx/Rx data with pseudorandom bits
• The ASCII character ‘a’ (0x61) is coded with 4B/5B. Show the codeword transmitted on the line.

• The following codeword has been received on a 4B/5B line: 11100 11000. What ASCII character was transmitted?
Balanced signals

Some channels strongly attenuate the DC component of the signal → transmitting a DC component is wasted power
• Ensure that the signal has a mix of + and – values which average to zero
• The frequent transitions are also good for CLK recovery!

Solution: **Bipolar encoding** uses alternating +V/-V to represent 1:

In old telephony lingo, 1 is Mark and 0 is Space.
Balanced signals

Optical fiber transponders need to have the lasers finely tuned at 50% average power to ensure thermal stability → DC component must be 0.5

- Ensure that the signal has an equal mix of 0s and 1s
- The frequent transitions are also good for CLK recovery!

Strategy: **8B/10B** maps 8 data bits to 10 coded bits with 1s and 0s:

- Disparity at most 2 at any time
- Max. 5 consecutive 1s or 0s
<table>
<thead>
<tr>
<th>Name</th>
<th>Byte</th>
<th>ascii</th>
<th>fghj</th>
<th>output</th>
<th>Current rd.</th>
<th>Current rd*</th>
<th>Name</th>
<th>Byte</th>
<th>ascii</th>
<th>fghj</th>
<th>output</th>
<th>Current rd.</th>
<th>Current rd*</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0.0</td>
<td>0x00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>D0.1</td>
<td>00</td>
<td>D2.0</td>
<td>0x00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>D2.1</td>
<td>00</td>
</tr>
<tr>
<td>D1.0</td>
<td>0x10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>D1.1</td>
<td>10</td>
<td>D2.1</td>
<td>0x10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>D2.2</td>
<td>10</td>
</tr>
<tr>
<td>D2.0</td>
<td>0x20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>D2.1</td>
<td>20</td>
<td>D4.0</td>
<td>0x40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>D4.1</td>
<td>40</td>
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<tr>
<td>D3.0</td>
<td>0x60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>D3.1</td>
<td>60</td>
<td>D6.0</td>
<td>0x80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>D6.1</td>
<td>80</td>
</tr>
<tr>
<td>D4.0</td>
<td>0x00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>D4.1</td>
<td>00</td>
<td>D6.1</td>
<td>0x00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>D6.2</td>
<td>00</td>
</tr>
<tr>
<td>D5.0</td>
<td>0x10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>D5.1</td>
<td>10</td>
<td>D7.0</td>
<td>0x20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>D7.1</td>
<td>20</td>
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<tr>
<td>D6.0</td>
<td>0x60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>D6.1</td>
<td>60</td>
<td>D7.1</td>
<td>0x60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>D7.2</td>
<td>60</td>
</tr>
<tr>
<td>D7.0</td>
<td>0x00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>D7.1</td>
<td>00</td>
<td>D8.0</td>
<td>0x00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>D8.1</td>
<td>00</td>
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<tr>
<td>D8.0</td>
<td>0x00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>D8.1</td>
<td>00</td>
<td>D9.0</td>
<td>0x00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>D9.1</td>
<td>00</td>
</tr>
</tbody>
</table>

**Rd = running disparity**

Image source: http://www.ceng.metu.edu.tr/~e1250620/corg.htm
Remember the 3 problems with any transmission line

Attenuation [db/km] – **function of freq.** → freq. spectrum modified at destination

Distortion [radians/km] – **function of freq.** → relative phase of individual sines/cosines modified at destination

Noise:
- Thermal (White noise, due to thermal vibration of atoms)
- Crosstalk (Interference from other local loops in the same cable)
- Impulse (Interference from other electric devices)

Conclusion: undesirable to have a wide range of freq. in signal → **baseband** not good!
Three ways to modulate a carrier

(a) A binary/baseband signal
(b) Amplitude modulation
(c) Frequency modulation
(d) Phase modulation (PSK)
2.5.2 Voice modems: Modulation and the Nyquist theorem in action!

Frequency band on a voice-level telephone line is 300-3100 Hz → bandwidth $B \approx 3000$ Hz

$3000 \times 2 = 6000$ samples/s maximum

- Wait a second – is it levels, samples, or symbols?! Answer: All of them: Nyquist’s Th. refers to the number of possible values for any parameter of the transmitted signal!

Max data rate = $2B \cdot \log_2 V$ [bps]

$2B$ is the signaling rate, a.k.a. baud, a.k.a. symbols or samples per second

$log_2 V$ is the number of bits carried by each level/sample/symbol
2.5.2 Voice modems: Modulation and the Nyquist theorem in action!

300-3100 Hz → bandwidth $B \approx 3000$ Hz
$3000 \times 2 = 6000$ samples/s maximum

In practice, most modems send only 2400 samples/s, a.k.a. baud rate is 2400 (although 9600 was also used in voice modems)
The challenge is to increase the informational content of each sample, a.k.a. bits-per-symbol, $\log_2 V$
Modern modems use not only multiple levels, but also multiple phases of a signal
BPSK = Binary PSK

Rule: If the digital signal changes (either way), shift phase by 180 deg. If it doesn’t change, do not shift (shift by 0 deg.).
BPSK QUIZ

If the digital signal changes (either way), shift phase by 180. If it doesn’t change, shift by 0.

Code the baseband signal below using the carrier shown, that has one cycle/bit.

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
</table>

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Voice modems: increasing the bits per symbol

Baud = symbol/sec (usually 2400)
Modulation technique determines # bits/symbol
(a) QPSK → 2 bits/symbol = 4800 bps
(b) QAM-16 → 4 bits/symbol = 9600 bps
(c) QAM-64 → 6 bits/symbol = 14,400 bps
Voice modems: how to assign bits to symbols?

Idea: A small burst of noise should not "mess up" too many bits!
Solution: Use Gray coding!

Figure 2-24. Gray-coded QAM-16.
2.6.3 Modems: guarding against noise with Trellis codes

(b) V.32 → 9600 bps (4 data + 1 parity bit / symbol)
(c) V.32 bis → 14,400 bps (6 data + 1 parity)
V.34 → 28,800 bps (12 data bits)
V.34 bis → 33,600 bps (∼10 data bits, baud rate 3429)
22/189: A modem constellation diagram similar to Fig.2-25 has data points at the following coordinates: (1, 1), (1, -1), (-1, 1), (-1, -1). How many bps can the modem achieve at 1200 baud?
Quiz

23/189: What is the max bit rate achievable in V.32 if the baud rate is 1200 and no error detection is used?

There are 32 points in the constellation!
24/179: How many frequencies does a full-duplex QAM-64 modem use?

Hint: Full duplex means that bit are sent simultaneously in both directions on the line.
Quiz

24/179: How many frequencies does a full-duplex QAM-64 modem use?

Hint: Full duplex means that bit are sent simultaneously in both directions on the line.

A: Two, one for upstream and one for downstream. The modulation scheme uses only the amplitude and phase. The frequency is not modulated.
Remember that V.34 bis → 33,600 bps
Was the fastest modem discussed so far. Is it possible to further increase the # of symbols in the constellation?

Only if the noise allows it!
QUIZ: Telephone local loop

- Frequency band on a voice-level telephone line is 300-3100 Hz
- SNR ≈ 37 dB

Calculate the max data rate with Shannon’s Th.

Hint: First convert the SNR from dB to a ratio!
QUIZ: Telephone local loop

- Frequency band on a voice-level telephone line is 300-3100 Hz
- SNR ≈ 37 dB

Calculate the max data rate with Shannon’s Th.

\[ 37 = 10 \cdot \log_{10}(S/N) \rightarrow S/N = 5011.87 \]
\[ B = 3100 - 300 = 2800 \text{ Hz} \]

Shannon: max rate = \[ B \cdot \log_2(1+S/N) = 34,416 = 34.4 \text{ kbps} \]

V.34 bis modem standard → 33.6 kbps
Modems: beating the Shannon limit

Shannon limit for local loop = 35 kbps
Improvement: 70 kbps by going all-digital on the ISP side

Diagram:
- Computer
- Modem
- Local loop (analog, twisted pair)
- Codec
- Toll office
- Medium-bandwidth trunk (digital, fiber)
- End office
- High-bandwidth trunk (digital, fiber)
- Toll office
- ISP 1
- ISP 2
- Digital line
- Up to 10,000 local loops
- Modem bank
Modems: beating the Shannon limit

Shannon limit for local loop = **35 kbps** for both sides!
Can double to 70 kbps by going all-digital on the ISP side!

V.90:
- Downstream: 56 kbps = 56,000 = 4000 x 2 x 7 (8 in Europe!)
- Upstream: 33.6 kbps

V.92:
- Upstream increased to 48 kbps
- Faster line diagnostic
- With call waiting, incoming tel. call can interrupt the Internet session
2.5.3 Frequency Division MUXing

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

A spike here will be “heard” in the next channel.
Advanced FDM → OFDM

O is for Orthogonal: The Fourier coefficients of any sub-carrier are zero around the center of neighboring carriers!

It’s used in WiFi (802.11), power-line networking, and, under the name DMT, in ADSL.
2.5.4 Time Division MUXing (TDM)

Time division multiplexing shares a channel over time:

- Users take turns on a fixed schedule; this is not packet switching or STDM (Statistical TDM)
- Widely used in telephone / cellular systems

We’ll use TDM in Section 2.6.4 – Trunks and Multiplexing
2.5.5 Code Division Multiplexing (CDMA)

It is neither FDM nor TDM! Instead, each station (cell-phone) transmits over the entire frequency band all the time.

Idea: use a special code to spread the energy of your signal over the entire band in such a way that only the same code can recover it at the other end → “spread-spectrum” technique

Implementation:
• Divide each bit time into $m$ (e.g. 64, 128) chips.
• Each station has its own, unique chip sequence.
• Chip sequences are orthogonal, which makes it possible to extract the bit sent by each station, provided we know its chip sequence!

A: $0 0 0 1 1 0 1 1$  
B: $0 0 1 0 1 1 1 0$  
C: $0 1 0 1 1 1 0 0$  
D: $0 1 0 0 0 0 1 0$

(a)

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: $(-1 +1 -1 -1 -1 +1 -1 -1)$

(b)
A CDMA example will be covered in detail in the next lab.
Why is PSTN used in Computer Networking?
A: B/c running cables on the MAN/WAN scale can be impractical and/or illegal. (… and wireless MANs and WANs are still in their infancy!)

What is the main problem with the PSTN from the viewpoint of Computer Networking?
A: Low speed:
– Initially 300 bps modems
– Now 56 kbps (“voice” modem) or 1-20 Mbps (DSL), but still far from 100 Mbps (Fast Ethernet) or GE (Gigabit Ethernet) or 10GE
Structure of the Telephone System

(a) Initial use of telephones (1876-78): Fully-interconnected network. (pic!)
(b) First switching office: New Haven, CT, 1878: Centralized switch.
   First automatic telephone exchange: invented by Almon Strowger in 1888, patented in 1891, first commercial implementation 1892.
(c) Inter-city connections: Two-level hierarchy.
(d) Five-level hierarchy (source: The End of Federalism in Telecommunication Regulations? by Sickler available on our website)
The n-squared problem in the early days of the telephone 😊
A typical circuit route for a medium-distance call.

End office = Class 5, Toll office = class 4
Toll offices are also called *tandem* o. (they work in tandem w/end o.)
The upper 3 “class” levels (primary, sectional, and regional) have largely lost their hierarchy, being called just switching o.
Major components of the PSTN

a) Local loops
   - Analog twisted pairs (Cat3 UTP, more recently Cat5(e)) going to houses and businesses

b) Trunks
   - Digital fiber optics (in the past coax and microwave) connecting the switching offices

c) Switching offices
   - Where calls are moved from one trunk to another
The local loop

For many more details, pics and history of telecoms, see
Privateline.com: Outside Plant
1984 – the *divestiture* (by court order):

a) Anti-monopoly suit won by US government → AT&T broken up into **AT&T Long Lines, 23 BOCs and 7 RBOCs**:

b) Lower long distance prices.

c) Higher local service prices due to termination of subsidies from long distance.

d) Competition (e.g. MCI = Microwave Communications, Inc.)

e) LATA = Local Access and Transport Area = one area code

f) LEC = Local Exchange Carrier → traditional tel. service within a LATA (BOCs and independent)

   Incumbent LEC = **ILEC**

   Competitive LEC = **CLEC**


g) IXC (Inter eXchange Carrier) → handles inter-LATA traffic

   (initially only AT&T Long Lines, but later Sprint and MCI)
READ: The LATAs, LECs, and IXCs

Circles = LEC switching offices.
Hexagons = IXC Point of Presence (remember Internet POPs!) →
    belongs to the IXC whose number is on it.
Although this illustration shows one LEC within one LATA, state regulations may allow multiple LECs within the same LATA.

Note that IXC 2 does not have POPs in LATAs 1 and 2 and must have a reselling agreement with IXC 1 in order to gain access to those areas.

Source: http://www.pcmag.com/encyclopedia_term/0,2542,t=tandem+office&i=52542,00.asp
IXCs and LECs were forbidden to enter each other’s business. Problem: wireless telephone and cable not covered.

1996 (Law passed by Congress) – Cable TV companies, LECs, IXCs and mobile operators allowed to enter each other’s business:

a) A company can offer single integrated package
b) LEC must implement local portability of phone numbers → increased competition
“Regulated industry” = one where the government has power of decision, e.g. FDA regulates drugs, foods, dietary supplements, medical devices etc.

“DEREGULATION”= “allowing competition”

a) Phone equipment fully deregulated in 1984
b) Long distance partially deregulated in 1984
c) Local service partially deregulated in 1996.

View on the web:
AT&T Breakup 25th Anniversary event
QUIZ for home

a) What does PSTN (a.k.a. POTS) stand for?
b) Define the local loop of the PSTN. (p.140)
c) Explain this statement: “AT&T in 1990 was the world’s largest copper mine.” (p.140)
d) Define LATA, a.k.a. “local area” (p.142)
e) Explain the difference between toll office and tandem office. (p.141)
f) Explain the difference between divestiture and deregulation
2.6.3 The Local Loop: Modem, ADSL, Wireless

The use of both analog and digital transmissions for a computer to computer call. Conversion is done by the modems and codecs.
Digital Subscriber Lines (DSL)

Fact: The 3100 Hz bandwidth is artificial.
- In the end office, a Band-Pass filter removes $f<300$ and $f>3400$
- 300 and 3400 are actually the ”3 dB points” … What does it mean?
- The bandwidth is usually quoted as 4000 Hz.

So, what is the real bandwidth?
Well, it depends … On what?

Fact: The average real bandwidth is about 1.1 MHz!
Digital Subscriber Lines (DSL)

Motto: everything over 56 kbps is broadband!

Bandwidth versus distance over category 3 UTP for DSL.
In the ANSI T1.413 standard the channels are 4312.5 Hz each (they include “guard bands”), so there are only 255 channels, not 256.

https://en.wikipedia.org/wiki/ANSI_T1.413_Issue_2

How are all these channels used? Remember FDM from Sec. 2.5.
ADSL: Discrete MultiTone (DMT)

256 4-kHz Channels

Power

0 25 1100 kHz
Voice Upstream Downstream

0 4 kHz 25.875 kHz 138 kHz 1104 kHz
PSTN Upstream Downstream
ADSL: Discrete MultiTone (DMT)

Channel 0: reserved for POTS
Channels 1-5 not used (guard band)

248 channels are available for data

“Asymmetric”:
- 26 – 138 kHz is the upstream band = 26 channels
- 138 – 1100 kHz is the downstream band = 223 channels

1 ch. upstream and 1 ch. downstream are reserved for CTRL
Each data channel uses QAM with 4000 baud (symbols per second).

The # of bits per symbol is adjusted dynamically based on the current SNR. A larger SNR allows for a larger “constellation”, up to 15 bits/baud.
An ADSL system is operating at the maximum 15 bit/baud, with 224 channels for downstream. What is the downstream data rate?
An ADSL system is operating at the maximum 15 bit/baud, with 224 channels for downstream. What is the downstream data rate?

\[ 4000 \text{ baud} \times 15 \text{ bit/baud} \times 224 = 13.44 \text{ Mbps} \]
Someone says:

Even allowing for the “extended” bandwidth of 4000 Hz (instead of 3100 Hz) of a telephone line, Nyquist’s Theorem still limits the data rate to \(2H = 8000\) bps! Therefore, the telephone companies’ claims that they offer 1 Mbps or even 3 Mbps DSL service are at best marketing hype and at worst false advertising.

What two problems do you see in the statement above?
Problem for scaling DSL

Local loop wires are deployed in bundles of 50, 100 or 150

a) When many of them carry DSL service, crosstalk causes a lot of interference → noise power increases

b) SNR for each individual connection decreases → Shannon limit decreases

c) The Bw available to each individual customer decreases

Solution: Fiber-To-The-Curb or Fiber-to-the-Home or Fiber-to-the-Basement, in a word FttX 😊
FTTH broadband relies on deployment of fiber optic cables to provide high data rates to customers:
- One wavelength can be shared among many houses
- Fiber is passive (no amplifiers, etc.)

The high SNR (low interference) makes it possible to achieve ~ 1Gbps rates over distances up to 20km!
A: The expanding movie-over-the-Internet market. Estimated 4% of US homes (in urban areas only!) have FttH access at Fast Ethernet speeds (∼100 Mbps). Individual homes share a total bandwidth of 2.4 Gbps on the fiber connecting to the end office.
2.6.4 Trunks and TDM

Advantage over FDM: can be implemented digitally (for digital signals) – no analog needed.

Codec (coder-decoder)

a) Do you see the difference between a modem and a codec?
Codecs

The embarassment of digital-to-analog-to-digital. 😊

Sampling:
- Nyquist rate: 4000 Hz x 2 = 8000 samples/second = 1 sample every 125 µs
- Samples are created at discrete time intervals, but their amplitude is still analog!

Quantization → digital samples (7 or 8 bit/sample).

The whole process (sampling + quantization) is called **PCM** – Pulse Code Modulation
Calculate the data rates generated by a PCM-coded voice channel with:

a) 7 bit/sample
b) 8 bit/sample

Sampling:
- Nyquist rate: 4000 Hz x 2 = 8000 samples/second = 1 sample every 125 μs
- Samples are created at discrete time intervals, but their amplitude is still analog!

Quantization → digital samples (7 or 8 bit/sample).
Solution

Sampling:
- Nyquist rate: 4000 Hz x 2 = 8000 samples/second = 1 sample every 125 μs
- Samples are created at discrete time intervals, but their amplitude is still analog!
  Quantization → digital samples (7 or 8 bit/sample).

Calculate the data rates generated by a PCM-coded voice channel with:

a) 7 bit/sample → 8,000 x 7 = 56,000 = **56 kbps** (Sounds familiar?)

a) 8 bit/sample → 8,000 x 8 = 64,000 = **64 kbps**
TDM – T1 carrier

193-bit frame (125 μs)

Channel 1  Channel 2  Channel 3  Channel 4  Channel 24

Bit 1 is a framing code

7 Data bits per channel per sample

Bit 8 is for signaling

7x8000 = 56 kbps

101010... (Why?)
Problem 27/189:
What is the overhead of a T1 carrier? (%)

193-bit frame (125 μsec)

Channel 1
Channel 2
Channel 3
Channel 4
Channel 24

Bit 1 is a framing code
7 Data bits per channel per sample
Bit 8 is for signaling
Problem 29/189:
How many frames need to be examined on average for resynchronization, in order to make the probability of being wrong < 0.001?
What is the total (raw) data rate of a T1 carrier?
Solution

\[(8 \cdot 24 + 1) \cdot 2 \cdot 4000 = 1.544 \text{ Mbps}\]
T1 QUIZ

T1 carrier: \((8 \cdot 24 + 1) \cdot 2 \cdot 4000 = 1.544\text{ Mbps}\)

Problem 5/187: What SNR is needed to put a T1 on a 50-kHz line?
Solution

Shannon Theorem:

\[
1.544 \times 10^6 = 50 \times 10^3 \cdot \log_2 \left( 1 + \frac{S}{N} \right)
\]

\[
\frac{1.544 \times 10^6}{50 \times 10^3} = \log_2 \left( 1 + \frac{S}{N} \right)
\]

\[
30.88 = \log_2 \left( 1 + \frac{S}{N} \right)
\]

\[
2^{30.88} - 1 = \frac{S}{N}
\]

\[
\frac{S}{N} = 1.975,087,932.8
\]

Yes, let's use decibels!
On the origin of the name: AT&T was giving letters to the various long-distance technologies, a.k.a. “carriers”, that it was exploring. For instance, the L-carrier system had a long history, starting in the 1930s and being used until the 1980s. Apparently, ‘T’ was simply the next letter available when the T-carrier project began.

“Terrestrial” is also proposed as a source, b/c at the time the satellite communications were also being developed.
The logical format is called **DS1** = Digital Signal level 1. Technically, DS1 is the logical bit pattern used over a physical T1 line; however, the terms "DS1" and "T1" are often used interchangeably.
The individual channels (56 or 64 kbps) are called **DS0**

a) They were originally designed (by Bell Labs) to carry one digitized phone call each

Today, customers can buy:

a) an individual **DS0**

b) an entire **T1**

c) a **DS0** bundle, a.k.a. **fractional T1**, of up to 23 (!) channels

Outside (US+Japan) they use **E1**: 2.048 Mbps (32 channels instead of 24).
T1 hardware: the D4 channel bank

There have been 5 main generations of T1 terminal equipment used by Telcos in their end offices: the D1, D2, D3, and D4 channel banks, followed by the Digital Carrier Trunk (DCT). Each has slightly different framing and signaling.

For a nitty-gritty account of the evolution of T1, see

All You Wanted to Know About T1 But Were Afraid to Ask

For some electrical details on T1, see

Inet Daemon article on T1

Charles Industries D448. Each “digroup” [dye-group] of 2 shelves implements a complete T1
The “Tn” hierarchy

Multiplexing T1 streams into higher carriers – a mess!

Synchronous = same freq., no phase difference
Mesochronous = same freq., varying phase difference
Plesiochronous = small diff. in freq. (plesios = near to)
The Tn hierarchy is *plesiochronous*, i.e. by design it is accepted that sender and receiver freq. can be different … and mechanisms for addressing this are provided → huge complications.

**Wikipedia entry:**

“In telecommunication, **wander** means long-term random variations of the significant instants of a digital signal from their ideal positions. Phase variations with a frequency content above 10 Hz are considered jitter, while those with a frequency below 10 Hz are referred to as wander. Wander variations are those that occur over a period greater than 1 s. Jitter, swim, wander, and drift have increasing periods of variation in that order.”

Another problem: hard to extract individual streams once they are MUX-ed, or to add new streams into an already MUX-ed one.
TDM - SONET

SONET = Synchronous Optical Net

Design goals:

a) Make sender and receiver totally synchronous
b) Ease of MUX-ing/deMUX-ing
c) Interworking of different carriers (remember 1984!)
d) Combining US, Europe, Japan
e) Continue the Tn hierarchy at higher speeds (T3 ≈ 45 Mbps was the highest used in practice)
f) “Native” OAM (Operations, Admin., Maintenance) support

US standard = SONET, ITU (global) standard = STH (Synch.Digi.Hier.)
Two back-to-back SONET frames.

STS-1 ~ OC-1 = 90x9 = 810 bytes every 125 µs → 51.84 Mbps (gross)
SPE = Synchronous Payload Envelope

Two back-to-back SONET frames.

Synchronization similar to T1: The first two bytes of each frame (in the Section Overhead) have a fixed pattern: 0xF628.
STS-1 ~ OC-1 = 90x9 = 810 bytes every 125 µs → 51 Mbps (gross)
Synchronization similar to T1: 1st 2 bytes of each frame have fixed pattern.

Problem 31/189: SONET clocks have a drift rate of about 1 part in 10⁹. How long does it take for the drift to equal the width of 1 bit? Practical implications?
STS-1 ~ OC-1 = 90x9 = 810 bytes every 125 µs → 51 Mbps (gross)  
Synchronization similar to T1: 1st 2 bytes of each frame have fixed pattern.

Problem 31/189: SONET clocks have a drift rate of about 1 part in 10⁹. How long does it take for the drift to equal the width of 1 bit? Practical implications?

At 51 Mbps, 1 bit lasts for \[ \frac{1}{51 \times 10^6} = \frac{1000}{51} \times 10^{-9} = 19.6 \text{ ns} \]

19.6 ns \times 10^9 = 19.6 \text{ s}

How many frames are transmitted?
19.6 \times 8000 = 156,862.7 \text{ frames}

Clocks need to be resynchronized at smaller intervals!
SONET overheads in the field

REG (huts in the field) → Every 50 mi the signal is amplified, re-shaped etc.
ADM (network nodes, in a lab/office) → Data flows from users are “MUXed in/out”
PTE (customer’s premises) → The source/destination of a particular data flow
### SONET/SDH rates

<table>
<thead>
<tr>
<th>SONET</th>
<th>SDH</th>
<th>Data rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>Optical</td>
<td>Gross</td>
</tr>
<tr>
<td>STS-1</td>
<td>OC-1</td>
<td>51.84</td>
</tr>
<tr>
<td>STS-3</td>
<td>OC-3</td>
<td>155.52</td>
</tr>
<tr>
<td>STS-9</td>
<td>OC-9</td>
<td>466.56</td>
</tr>
<tr>
<td>STS-12</td>
<td>OC-12</td>
<td>622.08</td>
</tr>
<tr>
<td>STS-18</td>
<td>OC-18</td>
<td>933.12</td>
</tr>
<tr>
<td>STS-24</td>
<td>OC-24</td>
<td>1244.16</td>
</tr>
<tr>
<td>STS-36</td>
<td>OC-36</td>
<td>1866.24</td>
</tr>
<tr>
<td>STS-48</td>
<td>OC-48</td>
<td>2488.32</td>
</tr>
<tr>
<td>STS-192</td>
<td>OC-192</td>
<td>9953.28</td>
</tr>
<tr>
<td>STS-768</td>
<td>OC-768</td>
<td>≈40 Gbps</td>
</tr>
</tbody>
</table>

SONET and SDH multiplex rates (columns interleaved, # columns in a row is multiplied by n).
Concatenated carrier (e.g. OC-3c, rather than OC-3) → the entire SPE belongs to just one user → highest efficiency (96.667% for OC-192c)
Virtually all long-distance telephone traffic in the US, Japan, Europe, etc. is carried over SONET … but Internet telephony (VoIP) is changing this!

**VoIP Growth**

- The global mobile VoIP (mVoIP) market to grow at an impressive CAGR of around 28 percent during the forecast period, 2016-2020. [Source](http://thevoipreport.com/article/cold-hard-voip-stats/)
- The VoIP services market is expected to grow to $140 billion USD by the year 2021. [Source](http://thevoipreport.com/article/cold-hard-voip-stats/)
- Telecoms are losing an average of 700,000 landline customers per month. [Source](http://thevoipreport.com/article/cold-hard-voip-stats/)
- There will be 1 billion VoIP users by the end of 2017. [Source](http://thevoipreport.com/article/cold-hard-voip-stats/)
- It’s projected that the VoIP services market will expand 10 percent every year until 2021. [Source](http://thevoipreport.com/article/cold-hard-voip-stats/)
FDM on long-haul optic fiber

Wavelength Division Multiplexing

Dense WDM = DWDM
2.6.5 Circuit and Packet Switching

Circuit switching

Packet switching
Circuit switching vs. Packet switching (note pipelining!)

Long setup delay (~10s for local phone calls)

“Speed of light” delay (~5µs/km for copper)
## Comparison of switching technologies

<table>
<thead>
<tr>
<th>Item</th>
<th>Circuit-switched</th>
<th>Packet-switched</th>
</tr>
</thead>
<tbody>
<tr>
<td>Call setup</td>
<td>Required</td>
<td>Not needed</td>
</tr>
<tr>
<td>Dedicated physical path</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Each packet follows the same route</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Packets arrive in order</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Is a switch crash fatal</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Bandwidth available</td>
<td>Fixed</td>
<td>Dynamic</td>
</tr>
<tr>
<td>When can congestion occur</td>
<td>At setup time</td>
<td>On every packet</td>
</tr>
<tr>
<td>Potentially wasted bandwidth</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Store-and-forward transmission</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Transparency</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Charging</td>
<td>Per minute</td>
<td>Per packet</td>
</tr>
</tbody>
</table>
SKIP the remainder of Ch.2:
• 2.7 The Mobile Telephone System
• 2.8 Cable TV

Homework for Ch.2
Due Tue, Oct 1

End of chapter: 4, 8, 17, 25, 28, 34, 37, 46