Issues with just increasing frequency:

Increasing frequency requires increase in processing speed

→ cost

Wireless: above 10 GHz requires line-of-sight (LOS)

For a given frequency band (say 2.4–2.5 GHz) want to pack as many bits as possible

→ utilize the band as much as possible

→ also called "bandwidth"

→ multiple lanes, i.e., broadband

→ if one lane per user: multi-user communication

Issues with just increasing frequency (cont.):

Wireless: simultaneous uplink (to base station) transmission by multiple clients (from mobiles)

$\rightarrow$ problem of multi-user communication

$\rightarrow$ also referred to as multiplexing

Simple solution to multi-user communication:

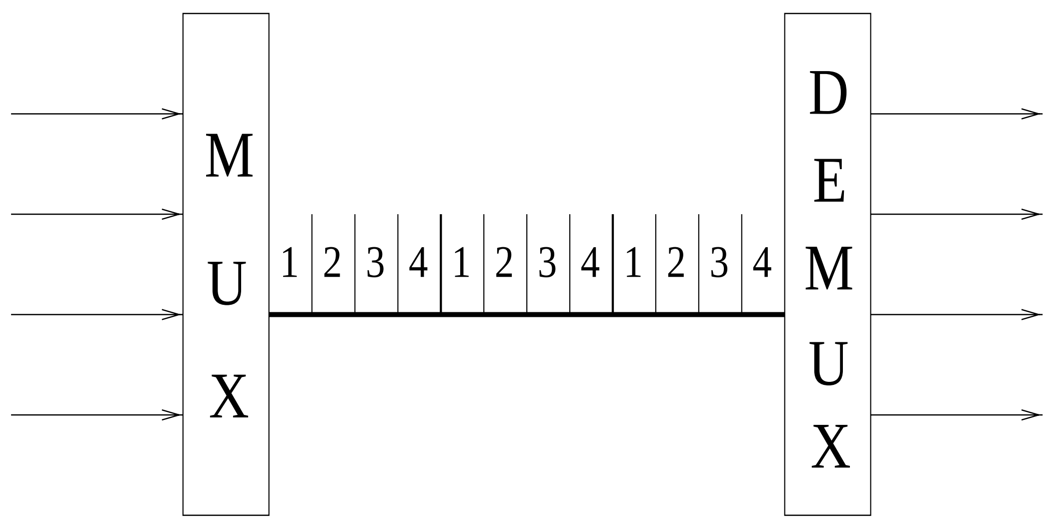
→ share a single lane by time reservation

→ time division multiplexing (TDM)

Ex.: 4 users sharing a single lane, i.e., frequency

→ divide time into blocks

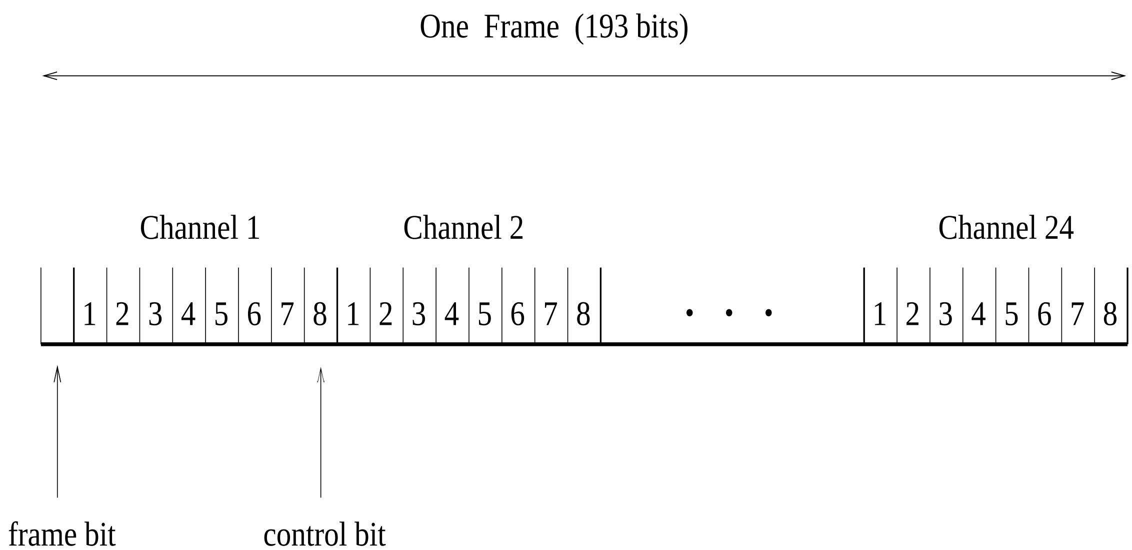
→ reserve blocks to 4 users: 1, 2, 3, 4, 1, 2, 3, 4, . . .



→ each block can carry multiple bits: block size

→ 1, 2, 3, 4: frame or packet

Real-world example: T1 carrier (1.544 Mbps)



- 24 simultaneous users
- 8-bit block size
- squeeze 8000 frames into 1 second

  $\rightarrow$ frame duration: 125 μsec
- bandwidth: $8000 \times 193 = 1.544$ Mbps
- drawbacks of using TDM for multi-user communication?

TDM allows sharing of single lane—called carrier frequency—by multiple users

→ baseband communication

→ users alternate in time: not truly simultaneous

→ what we want is broadband: multiple lanes

→ increase the "size of the pie"

→ truly simultaneous

Key problem of broadband or high-speed networks:

Given a frequency band (wired or wireless), how to create as many parallel lanes as possible

→ frequency band or "bandwidth" (Hz): scarce resource

→ especially wireless

→ utilize multiple frequencies for parallel transmission

→ frequency division multiplexing (FDM)

→ how many lanes are possible?

State-of-the-art: OFDM (orthogonal FDM)

→ ubiquitous in wireless networks

→ IEEE 802.11g/n WLANs (not 802.11b)

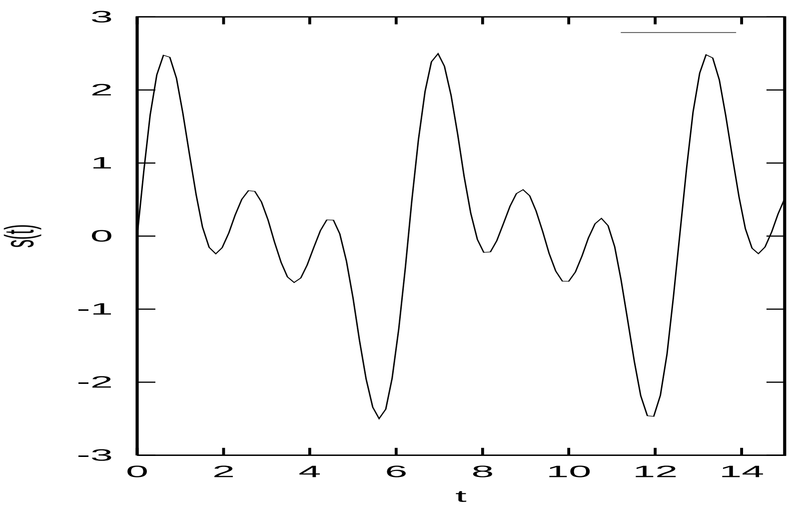
→ WiMAX, cellular, etc.

Practical dilemma:

- three wireless hosts are sending bits to base station
- each host uses its own carrier frequency

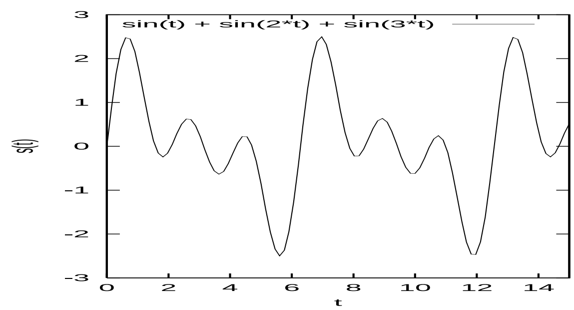
  → f_1, f_2, f_3

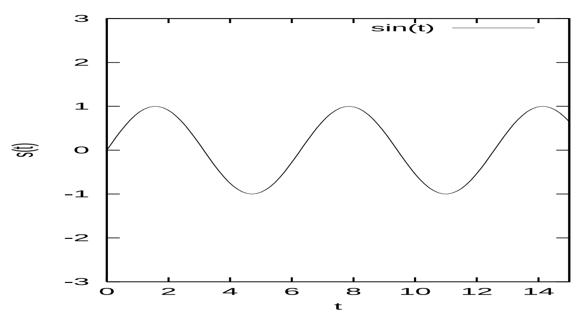
  → e.g., 2.42 GHz, 2.44 GHz, 2.46 GHz
- base station receives

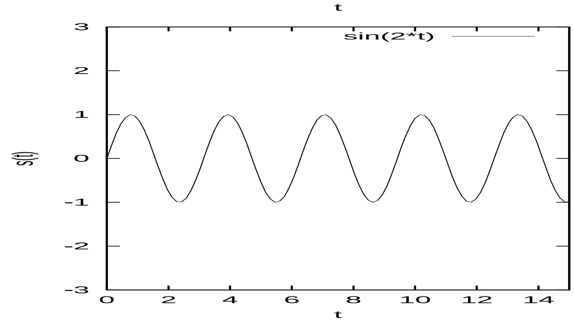


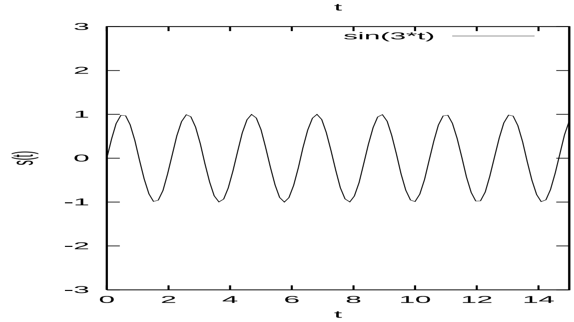
→ what bits did the 3 hosts send?

The signal received is the sum of









A receiver only sees the combined signal

→ to recover the bits sent requires recovering the shape of the individual carrier waves

→ with hundreds, thousands of carrier frequencies, how to do that?

Note: same problem applies to wireline broadband communication

Ex.: point-to-point link from A to B

→ A transmits bits to B over 3 parallel lanes

→ faster file exchange

Root of FDM solution: Joseph Fourier

→ 18th century idea ("old technology")

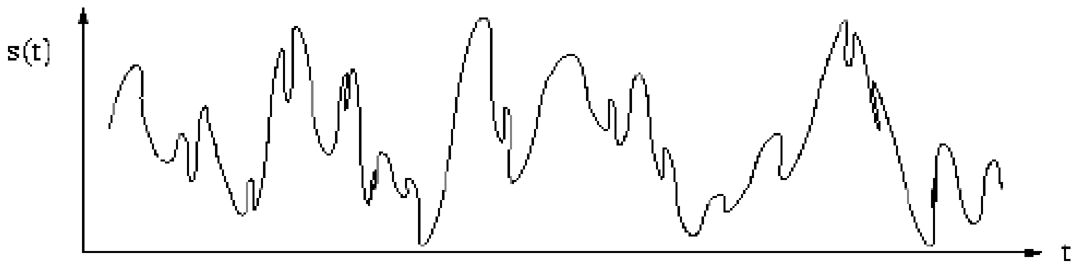
→ Fourier analysis

→ engineering bread and butter

→ worth knowing for its own sake (great idea)

Fourier's key insight:

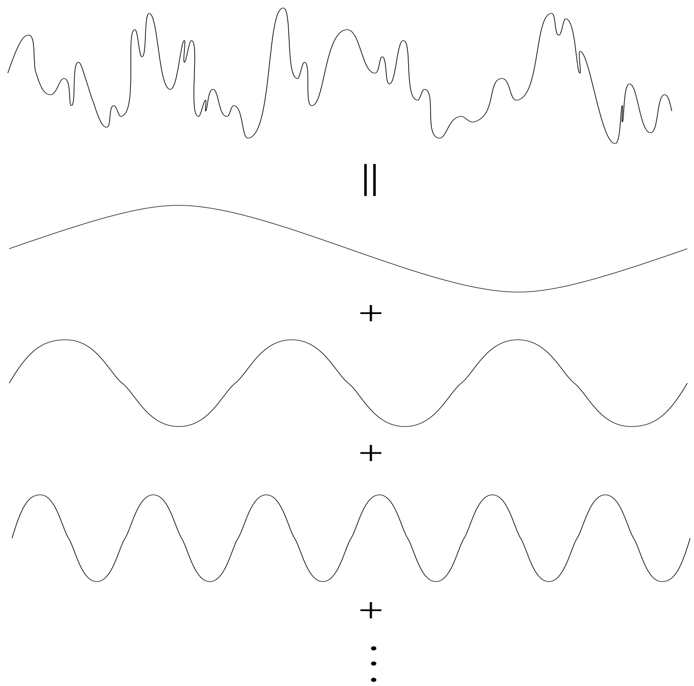
A complicated looking signal $s(t)$ whose shape (i.e., strength) varies over time



is just the sum of very simple building blocks

$\rightarrow$ sinusoids

Thus:



→ may require adding many sinusoids of different frequencies

→ key caveat: before adding sinusoid with frequency f, multiply its magnitude by a weight α

→ therefore complicated looking $s(t)$ is just the weighted sum of sinusoids

Some conceptual similarity to periodic table and matter

→ elements of periodic table: building blocks (sinusoids)

→ matter: complicated looking signal

→ H_2O: 2 parts H and 1 part O

→ $C_8H_{10}N_4O_2$

→ of course, matter has additional structure: not simple weighted sum

Obvious consequences:

- The value of the weight α_f of sinusoid f indicates how important sinusoid f is
- For example, if $\alpha_f = 0$ then sinusoid of frequency f is not needed at all for creating $s(t)$
- Since there are an infinite number of frequencies (from 0 to ∞) the weighted sum may entail an infinite number of sinusoids

  $\rightarrow$ not relevant for FDM: why?

Fourier's key insight is accompanied by a key technical contribution:

If given some complicated looking signal $s(t)$, then for any sinusoid f Fourier provides a simple formula for finding its weight α_f

$\rightarrow$ a way to decompose into building blocks

Let's make use of Fourier's insight for enabling broadband communication: point-to-point link from A to B

A wishes to send 3 bits to B in parallel using three carrier frequencies f_1, f_2, and f_3

→ say 3 bits: 1, 0, 1

→ carrier frequencies: 1 Hz, 2 Hz, 3 Hz

→ how to do it?

Fourier's conceptual and technical contribution in more precise language (aka math):

1. Complicated looking signal $s(t)$ is weighted sum of sinusoids

$$s(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \alpha_f e^{ift} df$$

$\rightarrow$ called Fourier expansion

$\rightarrow$ integral "$\int$" is just continuous sum

$\rightarrow$ recall: $e^{ift} = \cos ft + i \sin ft$

$\rightarrow$ Euler's formula

$\rightarrow$ why complex sinusoids involving $i = \sqrt{-1}$?

2. Given $s(t)$ and frequency f, how to find weight α_f:

$$\alpha_f = \int_{-\infty}^{\infty} s(t) e^{-ift} dt$$

$\rightarrow$ another weighted sum

$\rightarrow$ called Fourier transform

$\rightarrow$ algorithm to compute Fourier transform quickly: fast Fourier transform (FFT)

$\rightarrow$ see algorithms book