The Telephone Network

An Engineering Approach to Computer Networking

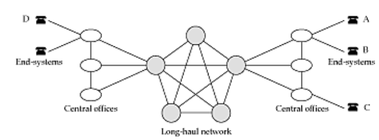
Is it a computer network?

- Specialized to carry voice
- Also carries
  - telemetry
  - video
  - fax
  - modem calls
- Internally, uses digital *samples*
- Switches and switch controllers are special purpose computers
- Principles in its design apply to more general computer networks

Concepts

- Single basic service: two-way voice
  - low end-to-end delay
  - guarantee that an accepted call will run to completion
- Endpoints connected by a *circuit*
  - like an electrical circuit
  - signals flow both ways (*full duplex*)
  - associated with bandwidth and buffer *resources*

The big picture



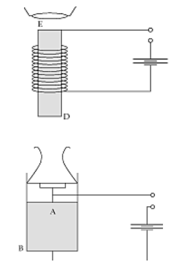
- Fully connected core
  - simple routing
  - telephone number is a hint about how to route a call
    - but not for 800/888/700/900 numbers
  - hierarchically allocated telephone number space

The pieces

1. End systems
2. Transmission
3. Switching
4. Signaling

1. End-systems

- Most end-systems analogue
- Transducers
  - microphone and speaker
- Dialer
- Ringer
- Switchhook (…dialtone)
- Powered from exchange…



Sidetone

- Transmission and reception circuit need two wires each
  - => 4 wires from every central office to home
  - Can we do better?
- Use *same* pair of wires for both transmission and reception
  - Keep it simple for field engineer!
  - Try and cancel out what is being said
  - However, unavoidable leads to sidetone (local) and echo (far end)
- Ergonomics,
  - Actually want some sidetone to stop users shouting

Echo

- Shared wires
  - => Some received signal is transmitted back
- Leads to echo (why?)
  - OK for short-distance calls
  - For long distance calls, need to put in echo chancellors (why?)
    - "Expensive"
- Lesson
  - keep end-to-end delays as short as possible

Dialing

- Pulse
  - sends a pulse per unary coded digit
  - collected by exchange (US = central office)
- Tone
  - key press sends a pair of tones (4 * 3 grid) = 12 digits
  - also called Dual Tone Multifrequency (DTMF)

2. Transmission

- Link characteristics
  - bandwidth:
    - analogue – range of frequencies link can support
    - digital information carrying capacity
    - related through Shannon's work
  - delay
    - time for signal to reach other end
    - light travels at 0.7c in fiber ~8 microseconds/mile
    - NY to SF => 20 ms; NY to London => 27 ms
  - attenuation
    - degradation in signal quality with distance
    - long lines need amplifiers, repeaters or regenerators

Transmission: Multiplexing

- *Trunks* between exchanges carry hundreds of conversations
  - Not cost effective to run thick bundles!
- Instead, send many calls on the same wire
  - *multiplexing*
- Analog multiplexing
  - bandlimit call to 3.4 kHz and frequency shift
  - obsolete (except WB900 <shudder>)
- Digital multiplexing
  - first convert voice to *samples*
  - 1 sample = 8 bits of voice
  - 8000 samples/sec => call = 64 kbps
  - Interleave samples from different calls

Transmission: Digital multiplexing

- How to choose a sample?
  - 256 *quantization levels*
    - logarithmically spaced (why?)
    - sample value = amplitude of nearest quantization level
  - two choices of levels (mu law and A law)
- Time division multiplexing
  - trunk carries bits at a faster bit rate than inputs
  - *n* input streams, each with a 1-byte buffer
  - output interleaves samples
  - need to serve all inputs in the time it takes one sample to arrive
  - => output runs *n* times faster than input
  - *overhead* bits mark start/end of *frame* (why?)

Transmission: Multiplexing

- Multiplexed trunks can be multiplexed further
- Need some standards! (why?)
- Europe and others, various G series standards
- This group is the PDH hierarchy…

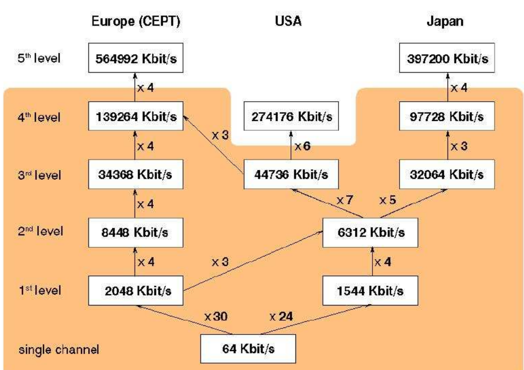
Standard (Common name)	Number of previous level circuits	Number of voice circuits	Bandwidth
(E0)		1	64 Kbps
G.704 (E1)	32	30	2.048Mbps
G.742 (E2)	4	120	8.448 Mbps
G.751 (E3)	4	480	34.368 Mbps
G.751 (E4/H1)	4	1920	129.264 Mbps

Transmission: Multiplexing

- US standard is called *Digital Signaling* hierarchy (DS)

Digital Signal Number	Number of previous level circuits	Number of voice circuits	Bandwidth
DS0		1	64 Kbps
DS1	24	"24"	1.544Mbps
DS2	4	96	6.312 Mbps
DS3	7	672	44.736 Mbps

PDH Interoperability



SDH

- SONET defined by Bellcore to be simplify things
  - SDH standardised by CCITT/ITU as the same but different

Level	SONET STS-n	SDH STM-n	Bandwidth
0	3	1	155.52 Mbps
1	12	4	622.08 Mbps
2	48	16	2488.32 Mbps

Transmission: Physical media

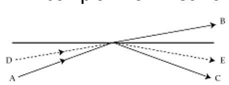
- Many in use today
  - twisted pair
  - coax cable
  - terrestrial microwave
  - satellite microwave
  - optical fibre
- Increasing amount of bandwidth and cost per foot
- Popular
  - twisted pair (CAT 1…7)
  - fiber
  - satellite

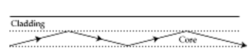
The cost of a link

- Should you use the cheapest possible link?
  - No!
  - Cost is in installation, not in link itself
  - Builders routinely install twisted pair (CAT 5), fiber, and coax to every room
  - Even if only one of them used, still saves money
- Long distance
  - often overprovision physical media
  - unless undersea cable….

Transmission: fiber optic links

- Wonderful stuff!
  - lots of capacity (>10 Pbps = 10^{16} bps)
  - very little attenuation (e.g. 0.5db/km – handy hint 3db = 50% loss)
  - low noise – low error rate
  - optical tap requires somewhat more specialized gear..
- A long thin strand of very pure glass
  - simple view – near total internal reflection
  - complex view – solve the wave equation





More on fibers

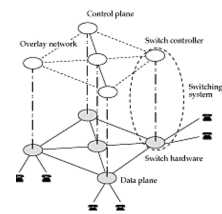
- Three types
  - step index (multimode)
  - graded index (multimode)
  - Single / mono mode (refers to only one solution to wave equation)
- Multimode
  - cheap
  - use LEDs
  - short distances (up to a few kilometers)
- Single mode
  - expensive
  - use lasers
  - long distances (up to hundreds of kilometers)

Transmission: satellites

- Long distances at high bandwidth
- Geosynchronous
  - 36,000 km in the sky
  - up-down propagation delay of 250 ms
  - bad for interactive communication
  - slots in space limited
- Nongeosynchronous (Low Earth Orbit)
  - appear to move in the sky
  - need more of them
  - handoff is complicated
  - e.g. Iridium

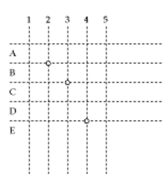
3. Switching

- Problem:
  - each user can potentially call any other user
  - can't have direct lines!
- Switches establish temporary *circuits*
- Switching systems come in two parts
  - switch and switch controller



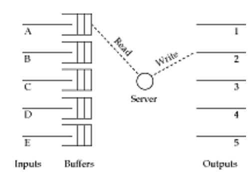
Switching: what does a switch do?

- Transfers data from an input to an output
  - many ports (up to 200,000 simultaneous calls)`
  - need high speeds
- Some ways to switch:
  - *space division*
  - if inputs are multiplexed, need a *schedule* (why?)



Switching

- Another way to switch
  - *time division (time slot interchange* or *TSI)*
  - also needs a schedule (why?)



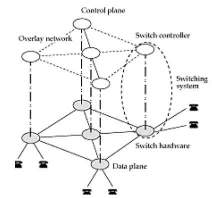
- To build larger switches we combine space and time division switching elements

4. Signaling

- Recall that a switching system has a switch and a switch controller
- Switch controller is in the *control* plane
  - does not touch voice samples
- Manages the network
  - call routing (collect *dialstring* and forward call)
  - alarms (ring bell at receiver)
  - billing
  - directory lookup (for 800/888 calls)

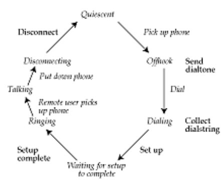
Signaling network

- Switch controllers are special purpose computers
- Linked by their own internal computer network
  - *Common Channel Interoffice Signaling (CCIS) network*
- Earlier design used *in-band* tones, but was severely hacked
- Also was very rigid (why?)
- Messages on CCIS conform to *Signaling System 7 (SS7)* spec.



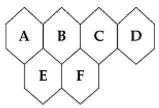
Signaling

- One of the main jobs of switch controller: keep track of *state* of every endpoint
- Key is *state transition diagram*



Cellular communication

- Mobile phone talks to a *base station* on a particular radio frequency
- Aren't enough frequencies to give each mobile a permanent frequency (like a wire)
- *Reuse*
  - temporal
    - if mobile is off, no frequency assigned to it
  - spatial
    - mobiles in non-adjacent *cells* can use the same frequency



Problems with cellular communication

- How to complete a call to a mobile?
  - need to *track* a mobile
  - on power on, mobile tells base of its ID and home
  - calls to home are forwarded to mobile over CCIS
- How to deal with a moving cell phone?
  - nearest base station changes
  - need to *hand off* existing call to new base station
  - a choice of several complicated protocols

Challenges for the telephone network

- Multimedia
  - simultaneously transmit voice/data/video over the network
  - people seem to want it
  - existing network can't handle it
    - bandwidth requirements
    - *burstiness* in traffic (TSI can't skip input)
    - change in statistical behavior
- Backward compatibility of new services
  - huge existing infrastructure
  - idiosyncrasies
- Regulation
  - stifles innovation

Challenges

- Competition
  - future telephone networks will no longer be monopolies
  - how to manage the transition?
- Inefficiencies in the system
  - an accumulation of cruft
  - special-purpose systems of the past
  - 'legacy' systems
  - need to change them without breaking the network
- Critical systems have been built that rely on the characteristics
  - alarms systems
  - power grid control…