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
    - bandwidth: 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 interleave 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...

<table>
<thead>
<tr>
<th>Standard (Common name)</th>
<th>Number of previous level circuits</th>
<th>Number of voice circuits</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E0)</td>
<td>1</td>
<td>64 Kbps</td>
<td></td>
</tr>
<tr>
<td>G.704 (E1)</td>
<td>22</td>
<td>30</td>
<td>2.048 Mbps</td>
</tr>
<tr>
<td>G.742 (E2)</td>
<td>4</td>
<td>120</td>
<td>8.448 Mbps</td>
</tr>
<tr>
<td>G.751 (E3)</td>
<td>4</td>
<td>480</td>
<td>34.368 Mbps</td>
</tr>
<tr>
<td>G.751 (E4/H1)</td>
<td>4</td>
<td>1920</td>
<td>129.264 Mbps</td>
</tr>
</tbody>
</table>

Transmission: Multiplexing
- US standard is called Digital Signaling hierarchy (DS)

<table>
<thead>
<tr>
<th>Digital Signal Number</th>
<th>Number of previous level circuits</th>
<th>Number of voice circuits</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS0</td>
<td>1</td>
<td>64 Kbps</td>
<td></td>
</tr>
<tr>
<td>DS1</td>
<td>24</td>
<td>&quot;24&quot;</td>
<td>1.544 Mbps</td>
</tr>
<tr>
<td>DS2</td>
<td>4</td>
<td>96</td>
<td>6.312 Mbps</td>
</tr>
<tr>
<td>DS3</td>
<td>7</td>
<td>672</td>
<td>44.736 Mbps</td>
</tr>
</tbody>
</table>

PDH Interoperability

PDH Interoperability

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

<table>
<thead>
<tr>
<th>Level</th>
<th>SONET STS-n</th>
<th>SDH STM-n</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>1</td>
<td>155.52 Mbps</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
<td>4</td>
<td>622.08 Mbps</td>
</tr>
<tr>
<td>2</td>
<td>48</td>
<td>16</td>
<td>2488.32 Mbps</td>
</tr>
</tbody>
</table>
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 over provision 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…