The Public Switched Telephone System
## Historical perspective

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1876</td>
<td>invention of telephone</td>
</tr>
<tr>
<td>1915</td>
<td>first transcontinental telephone (NY–SF)</td>
</tr>
<tr>
<td>1920’s</td>
<td>first automatic switches</td>
</tr>
<tr>
<td>1956</td>
<td>TAT-1 transatlantic cable (35 lines)</td>
</tr>
<tr>
<td>1962</td>
<td>digital transmission (T1)</td>
</tr>
<tr>
<td>1965</td>
<td>1ESS analog switch</td>
</tr>
<tr>
<td>1974</td>
<td>Internet packet voice</td>
</tr>
<tr>
<td>1977</td>
<td>4ESS digital switch</td>
</tr>
<tr>
<td>1980s</td>
<td>Signaling System #7 (out-of-band)</td>
</tr>
<tr>
<td>1990s</td>
<td>Advanced Intelligent Network (AIN)</td>
</tr>
<tr>
<td>1992</td>
<td>Mbone packet audio</td>
</tr>
</tbody>
</table>
Telephone service in the U.S.
Price of phone calls (NY – London)
# Transatlantic cable systems

<table>
<thead>
<tr>
<th>System</th>
<th>19xx</th>
<th>cost</th>
<th>circuits</th>
<th>$/circuit</th>
<th>$/minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAT-1</td>
<td>56</td>
<td>C $49.6M</td>
<td>40</td>
<td>213,996</td>
<td>2.443</td>
</tr>
<tr>
<td>TAT-2</td>
<td>59</td>
<td>C 42.7M</td>
<td>44</td>
<td>167,308</td>
<td>1.910</td>
</tr>
<tr>
<td>TAT-3</td>
<td>63</td>
<td>C 50.6M</td>
<td>79</td>
<td>111,027</td>
<td>1.267</td>
</tr>
<tr>
<td>TAT-4</td>
<td>65</td>
<td>C 50.4M</td>
<td>62</td>
<td>140,238</td>
<td>1.601</td>
</tr>
<tr>
<td>TAT-5</td>
<td>70</td>
<td>C 70.4M</td>
<td>648</td>
<td>18,773</td>
<td>0.214</td>
</tr>
<tr>
<td>TAT-6</td>
<td>76</td>
<td>C 197.0M</td>
<td>3,200</td>
<td>10,638</td>
<td>0.121</td>
</tr>
<tr>
<td>TAT-7</td>
<td>83</td>
<td>C 180.0M</td>
<td>3,821</td>
<td>8,139</td>
<td>0.093</td>
</tr>
<tr>
<td>TAT-8</td>
<td>88</td>
<td>F 360.0M</td>
<td>6,048</td>
<td>10,285</td>
<td>0.117</td>
</tr>
<tr>
<td>TAT-9</td>
<td>92</td>
<td>F 406.0M</td>
<td>10,584</td>
<td>6,628</td>
<td>0.076</td>
</tr>
<tr>
<td>TAT-10</td>
<td>92</td>
<td>F 300.0M</td>
<td>18,144</td>
<td>2,857</td>
<td>0.033</td>
</tr>
<tr>
<td>TAT-11</td>
<td>93</td>
<td>F 280.0M</td>
<td>18,144</td>
<td>2,667</td>
<td>0.030</td>
</tr>
<tr>
<td>TAT-12</td>
<td>96</td>
<td>F 378.0M</td>
<td>60,480</td>
<td>1,080</td>
<td>0.012</td>
</tr>
<tr>
<td>TAT-13</td>
<td>96</td>
<td>F 378.0M</td>
<td>60,480</td>
<td>1,080</td>
<td>0.012</td>
</tr>
<tr>
<td>Gemini</td>
<td>98</td>
<td>F 520.0M</td>
<td>214,920</td>
<td>371</td>
<td>0.004</td>
</tr>
<tr>
<td>AC-1</td>
<td>98</td>
<td>F 850.0M</td>
<td>483,840</td>
<td>304</td>
<td>0.003</td>
</tr>
<tr>
<td>TAT-14</td>
<td>00</td>
<td>F 1500.0M</td>
<td>4x2.5M</td>
<td>&lt;75</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Overview of telephone system

- analog narrowband circuits to “central office”
- 64 kb/s continuous transmission, with compression across oceans
- $\mu$-law: 12-bit linear range $\rightarrow$ 8-bit bytes
- everything clocked a multiple of 125 $\mu$s
- clock synchronization $\leftrightarrow$ framing errors
- AT&T: 136 “toll” switches in U.S.
- interconnected by T1 and T3 digital circuits $\rightarrow$ SONET rings (AT&T: $\approx$ 50)
- call establishment “out-of-band” using packet-switched signaling system (SS7)
The basic analog telephone

- Switchhook
- Ringer
- Microphone
- Receiver
- Loop equalizer circuit
- Balance network
- Pulse dialer
Telephone load measurements

- 0.1 erlang = busy 10% of the time
- CCS = hundred call seconds/hour  ➞ 36 CCS = 1 Erlang
- signaling: BHCA = busy hour call attempts
Telephone load variation

Call load as a function of weekday

- 7am - 7pm: Total 56.7%
- 7pm - 7am: Total 43.3%

<table>
<thead>
<tr>
<th>Day</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
<th>Sunday</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of call minutes</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>13</td>
</tr>
</tbody>
</table>

Graph shows call load with percentage of call minutes for each weekday from Monday to Sunday.
Call duration

- functional vs. social calls
- local call: 2.4 minutes
- business call: 3.5 minutes
- residential toll: avg. = 8.9 minutes, with a median of 3 minutes
- international calls: 5.1 minutes (U.S.-originated are longer)
Telephone call duration

![Graph showing telephone call duration distribution with data and exponential curves.](image-url)
Residential toll call distribution and duration as a function of distance

<table>
<thead>
<tr>
<th>distance (mi)</th>
<th>% calls</th>
<th>duration (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 10</td>
<td>5.1</td>
<td>4.6</td>
</tr>
<tr>
<td>11 – 22</td>
<td>20.2</td>
<td>5.1</td>
</tr>
<tr>
<td>23 – 55</td>
<td>23.2</td>
<td>5.9</td>
</tr>
<tr>
<td>56 – 124</td>
<td>13.3</td>
<td>7.7</td>
</tr>
<tr>
<td>125 – 292</td>
<td>12.1</td>
<td>9.4</td>
</tr>
<tr>
<td>293 – 430</td>
<td>4.6</td>
<td>10.4</td>
</tr>
<tr>
<td>431 – 925</td>
<td>9.7</td>
<td>11.9</td>
</tr>
<tr>
<td>926 – 1910</td>
<td>8.5</td>
<td>11.9</td>
</tr>
<tr>
<td>&gt; 1910</td>
<td>3.2</td>
<td>11.2</td>
</tr>
<tr>
<td>average</td>
<td>310 mi.</td>
<td>7.8</td>
</tr>
<tr>
<td>median</td>
<td>60 mi.</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Telephone call attempts

completed (70.7%)

- did not answer (12.7%)
- busy (10.1%)
- customer error (1.6%)
- equipment failure (1.9%)
- no response (2.6%)
- number invalid (0.4%)
Signaling System #7
Signaling System #7

**SSP**: service switching point = voice switch + adjunct

**STP**: signal transfer point \(\approx\) router

**SCP**: service control point = interface to databases
  * call management service database
  * line information database
  * home location register
  * visitor location register

* traditionally, 64 kb/s leased lines
* future: IP (→ IETF Sigtran WG)
ISDN protocol stack

ISDN = BRI (2B+D in 192 kb/s “raw”) or PRI (23B+D)
SS7 protocol stack

OSI layers

layer 7
- TCAP

layer 4,5,6
- ASP
- TUP
- ISUP
- BISUP

layer 3
- SCCP

layer 2
- MTP L2

layer 1
- MTP L1

CCS7 levels

Level 1
- MTP L1

Level 2
- MTP L2

Level 3
- MTP L3

Level 4
- Layer 4
ISUP MTP format

transmission order

<table>
<thead>
<tr>
<th>8</th>
<th>7</th>
<th>7</th>
<th>6</th>
<th>8</th>
<th>variable</th>
<th>16</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>flag</td>
<td>BSN</td>
<td>FSN</td>
<td>LI</td>
<td>SIO</td>
<td>SIF</td>
<td>checksum</td>
<td>flag</td>
</tr>
</tbody>
</table>

**BIB**: backward indicator bit
**FIB**: forward indicator bit
**BSN**: backward sequence number
**FSN**: forward sequence number

**SIO**: service information octet
**SIF**: service information field

SIF: 8 bits variable
SS7 protocol stack

Level 1 (physical): DS0A = 56/64 kb/s in DS1 facility

Level 2 (data link): error detection/correction, link-by-link

Level 3 (network):
  - routing
  - message discrimination  “point codes”
  - distribution

Level 4 (user parts):
  - basic signaling: TUP → ISUP
  - Transaction Capabilities Application (TCAP)
  - Operations, Maintenance, Administration (OMAP)
  - Mobile Application Part (MAP)
ISDN and SS7 call

**Calling user**

1. **Q.931**
2. **TE**
3. **SETUP**
4. **Alert**
5. **Call Proceeding**
6. **Answer Message (ANM)**
7. **Conn**
8. **DISC**
9. **RLSE**
10. **RLCOM**

**Exchanges**

- **ISUP**
- **TE SSP SSP**
- **Initial Address Message (IAM)**
- **Address Complete Msg. (ACM)**
- **Answer Message (ANM)**
- **Setup**
- **Alert**

**Called user**

1. **Q.931**
2. **TE**
3. **SETUP**
4. **Alert**
5. **Call Proceeding**
6. **Answer Message (ANM)**
7. **Conn**
8. **DISC**
9. **RLSE**
10. **RLCOM**
ISUP message format

- **Subservice field**
- **Service indicator**
- **DPC member**
- **DPC cluster**
- **DPC network**
- **OPC member**
- **OPC cluster**
- **OPC network**
- **Signaling link selection**
- **CIC (low-order octet)**
- **CIC msb**
- **Message type**

*depends on message type*
ISUP messages

→ Initial Address Message (IAM): called number *en bloc*

→ Continuity Message (COT): loopback test successful

← Address Complete Message (ACM): callee being rung

← Call Progress Message (CPG): report call set-up event

← Answer Message (ANM): callee has answered the phone

↔ Release Message (REL): request release of connection, with cause

↔ Release Complete Message (RLC): confirm REL
ISUP messages

← **Suspend Message (SUS):** suspend call, but keep connection

↔ **Resume (RES):** resume suspended call

↔ **Forward Transfer Message (FOT):** outgoing operator requests incoming operator

↔ **Information Request Message (INR):** terminating exchange wants more information

↔ **Information Message (INF):** response to INR

↔ **Pass-along Message (PAM):** tunnel another message
Reliability: “Nines”

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90%</td>
<td>36.5 days/year</td>
</tr>
<tr>
<td>2</td>
<td>99%</td>
<td>3.65 days/year</td>
</tr>
<tr>
<td>3</td>
<td>99.9%</td>
<td>8.8 hours/year</td>
</tr>
<tr>
<td>4</td>
<td>99.99%</td>
<td>53 minutes/year</td>
</tr>
<tr>
<td>5</td>
<td>99.999%</td>
<td>5 minutes/year</td>
</tr>
<tr>
<td>6</td>
<td>99.9999%</td>
<td>32 seconds/year</td>
</tr>
</tbody>
</table>
Reliability indications

- FCC incidents: ≥ 90,000 customers, ≥ 30 minutes (972 between 1992 and 1997)
- FCC ARMIS (Automated Reporting Management Information System)
- ANSI T1A1: logarithmic outage index = f(duration, # affected, time, functions, ...)
- call defects per million (e.g., AT&T 173 ppm)
Outage Statistics

- median outage lasts 2.9 hours (natural disasters: 13.4 hours)
- causes: facilities (45%), local switches (18%), CCS (13%), CO power (7.3%)
- facility failures: dig-ups (“back-hoe fade”, 58%), cable electronics (8%)
- ARMIS example: Bell Atlantic 1998: 180 switches, combined downtime of 628 minutes, or $6.6 \cdot 10^{-6}$