Remembering the BBN ARPANET Project

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Outline

1. Circa 1960: the time was ripe
2. 1966-1968: the procurement
3. 1969-1972: initial ARPANET implementation – irrefutable demonstration
4. The IMP design and implementation
5. 1973 to ca. 1994: evolution of ARPANET, testbed of Internet, ubiquity of packets
6. Reflections

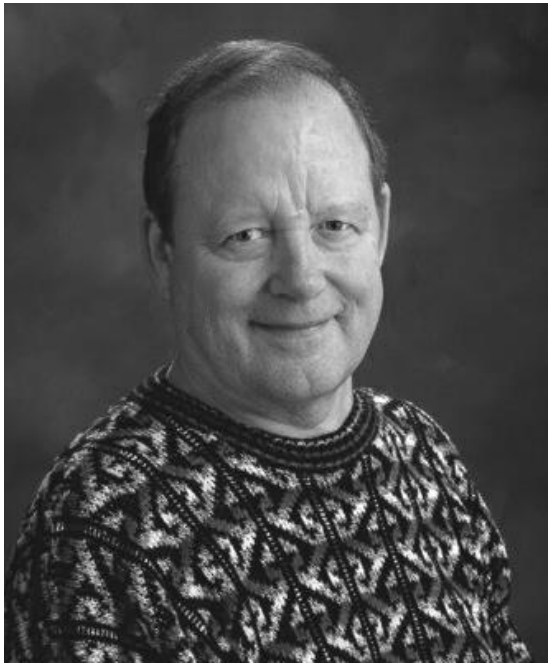
1. Circa 1960s: the time was ripe

- Circuit switching, message switching, specialized nets
- Licklider on man-machine symbiosis (1960)
- Kleinrock network-queuing-analysis thesis (1961-1962)
- Baran reports at RAND (early 1960s)
- Davies packet-switching prototype at NPL (later 1960s)




ARPA and IPTO

- Licklider at ARPA IPTO (1962-1964)
- Sutherland at IPTO funds Roberts and Merrill's TX-2 to Q-32 connection experiment (1965)
- Taylor got funding for network (1966)
- Roberts went to IPTO and planning began

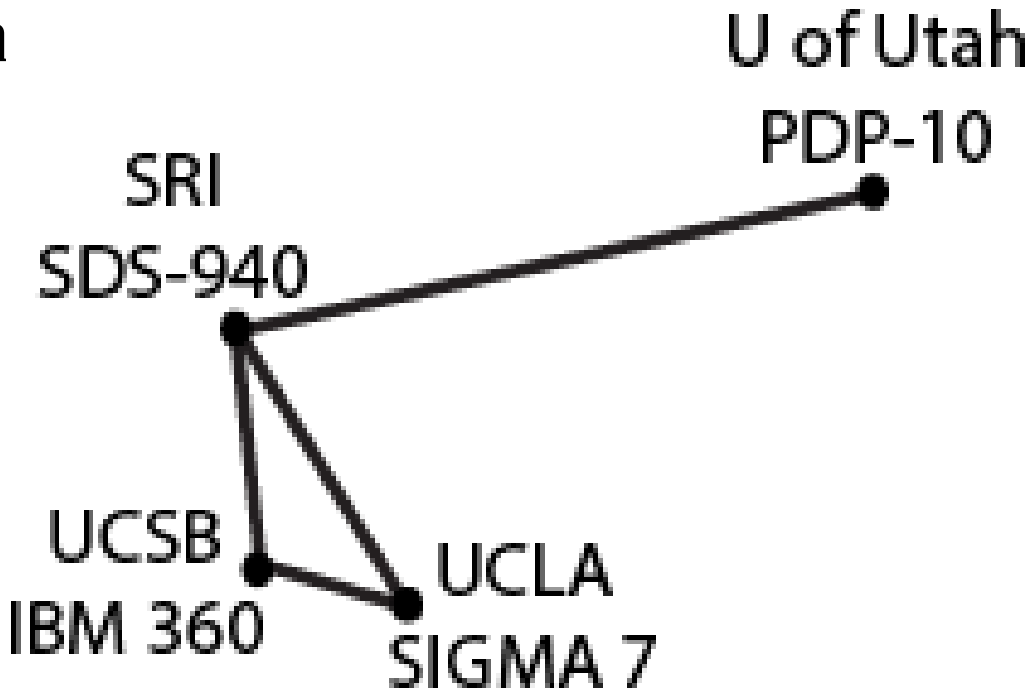


2. 1966-68: the procurement

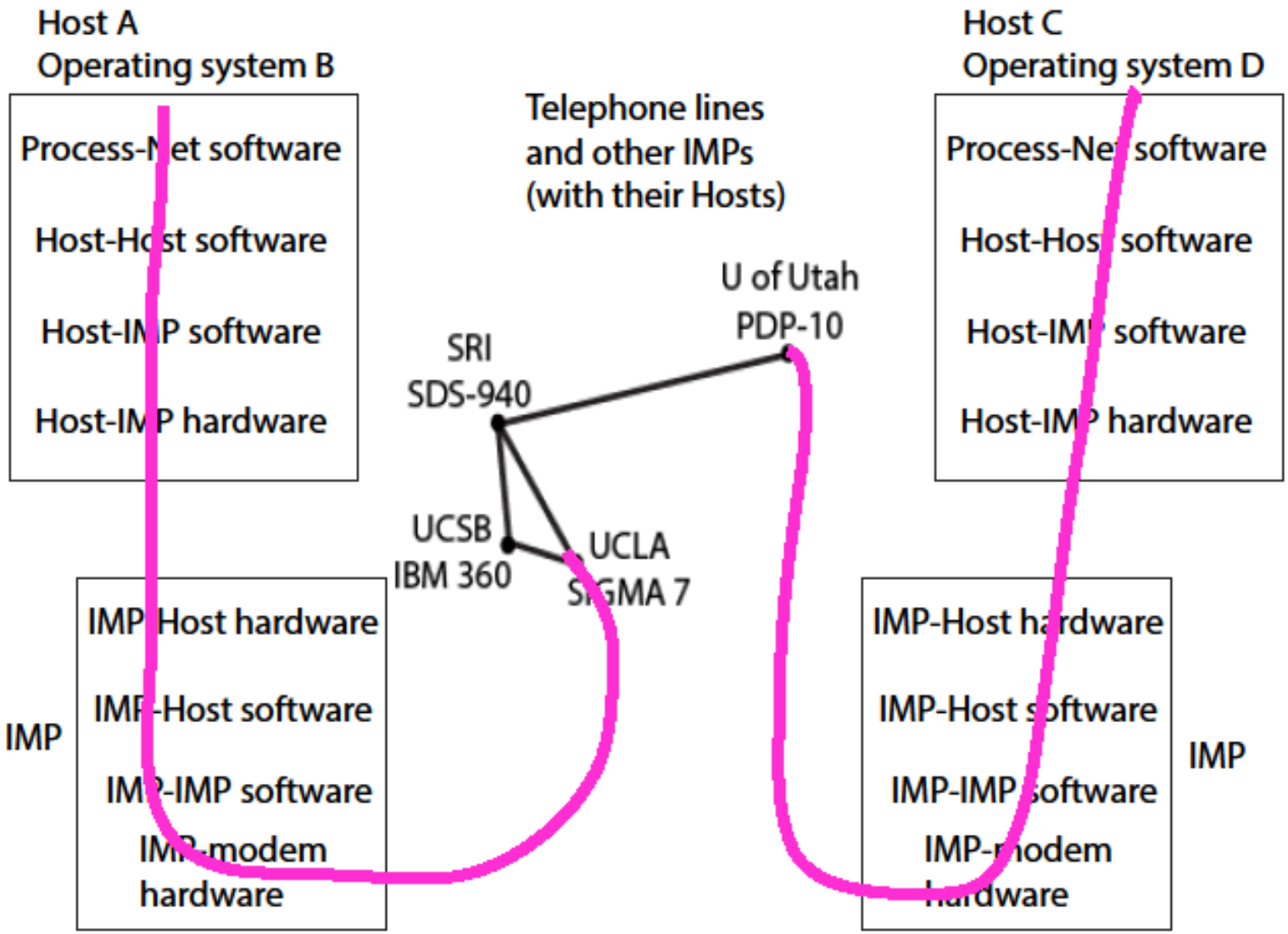
- Meetings of IPTO contractors; Shapiro study
- 29 July 1968 RFQ with 9 September due date; sent to lots of companies
- A few months earlier in 1968, we at BBN had begun doing preliminary design
- A dozen (?) bidders
- BBN bid: complete, highly detailed system (re)design with emphasis on performance and robustness

3. 1969-1972: initial ARPANET implementation; irrefutable demonstration

- BBN awarded contract to develop the IMP subnetwork, starting 1 January 1969 (4 IMP network due Sept.-Dec.)
- Other ARPA contractors were funded to develop interfaces to the IMP and to begin Host-Host communica



How it was supposed to work



Messages and packets

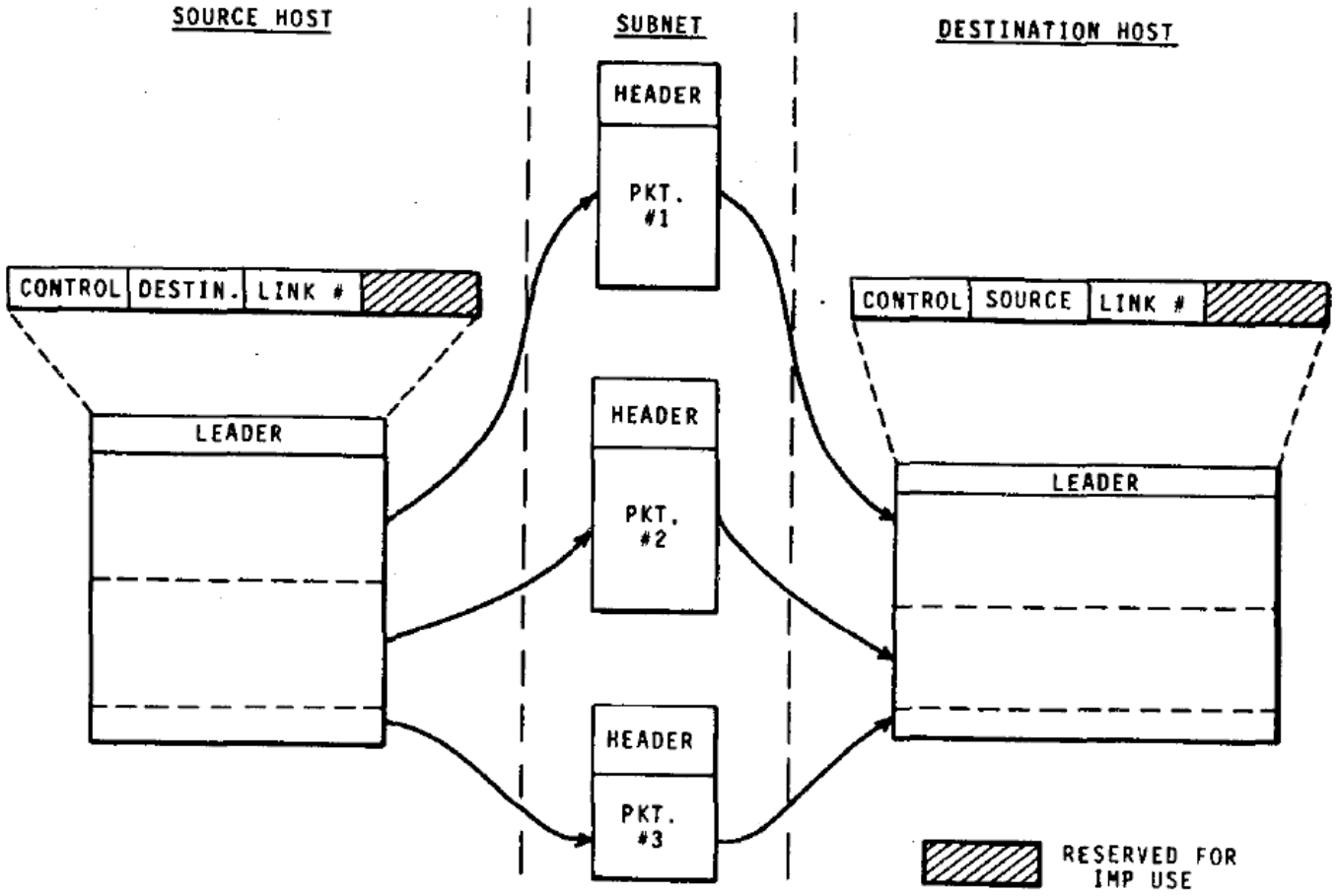
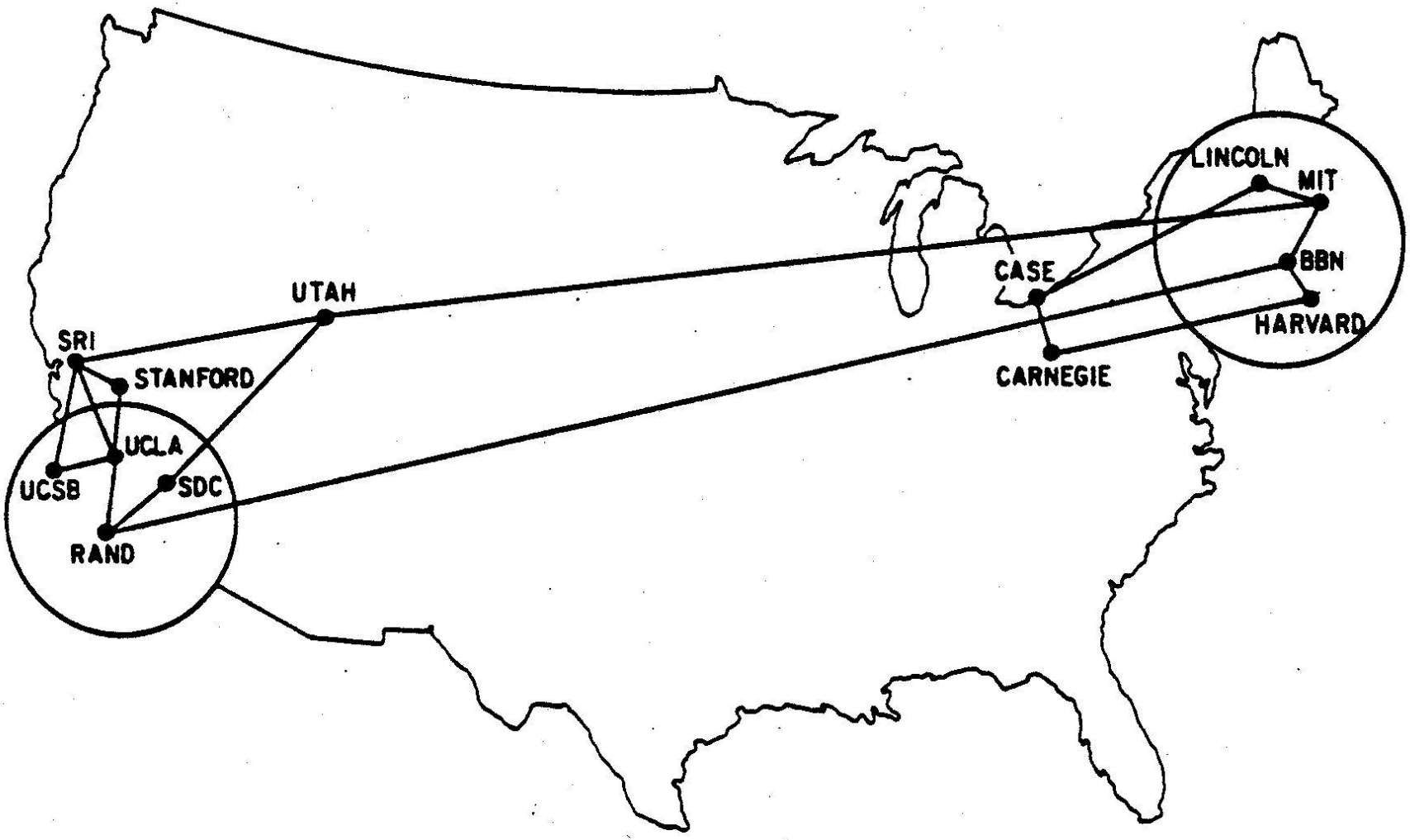


Figure 3—Messages and packets

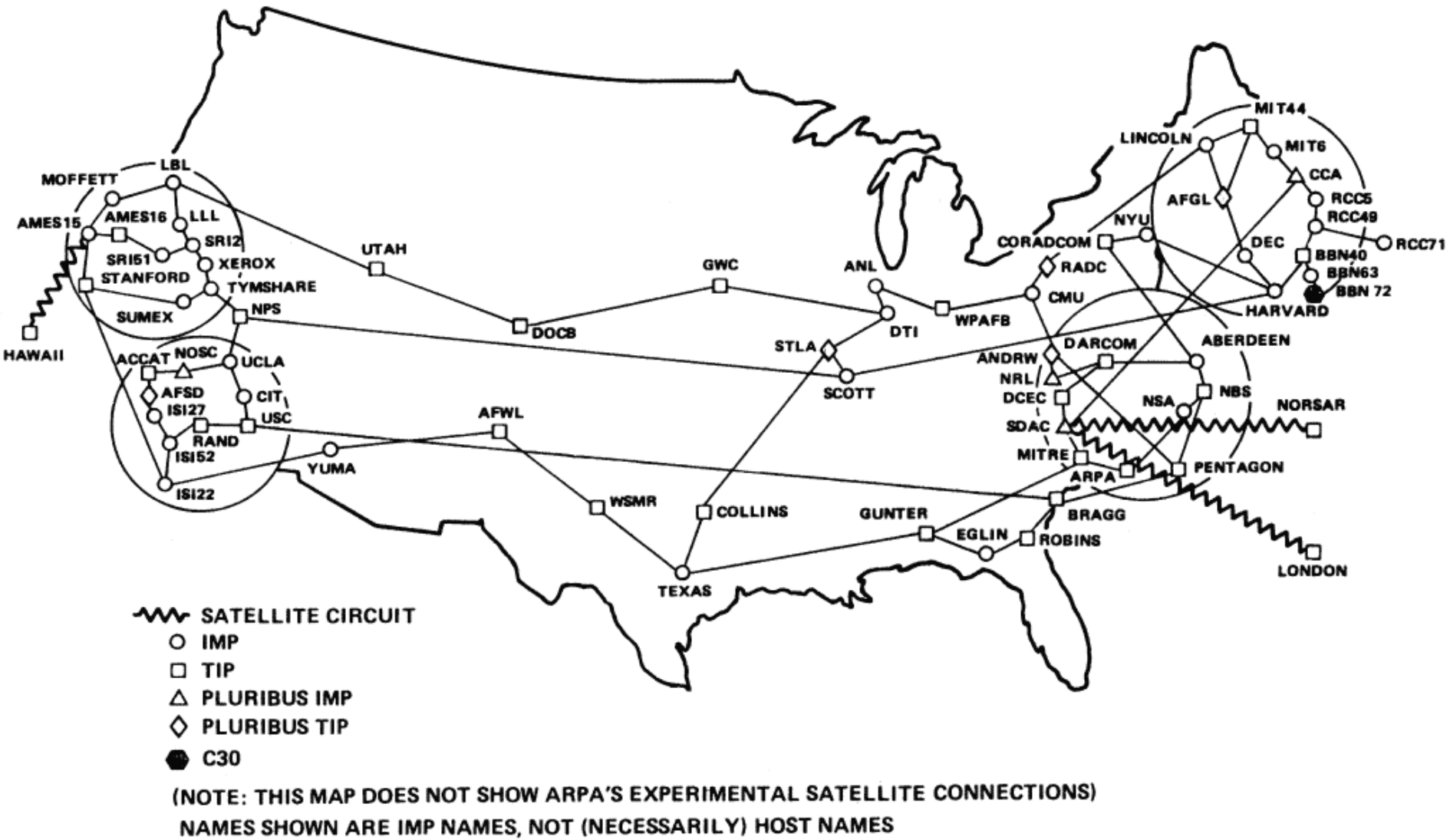
Parallel efforts at other organizations

- Network hardware/software at four original Host sites
- Network Analysis Corporation/topological design
  - Minimizing delay, maximizing reliability, and minimizing cost
- Contract to ATT Long Lines via the Air Force

Topological design



ARPANET GEOGRAPHIC MAP, OCTOBER 1980



(NOTE: THIS MAP DOES NOT SHOW ARPA'S EXPERIMENTAL SATELLITE CONNECTIONS)
NAMES SHOWN ARE IMP NAMES, NOT (NECESSARILY) HOST NAMES

Parallel efforts at other organizations (continued)

- ARPA IPTO itself
- UCLA -- Network Measurement Center
- Stanford Research Institute -- Network Information Center
- Network Working Group -- Request for Comments (RFCs)

BBN contract to develop an initial subnetwork of 4 IMPs, due Sept.-Dec.

- Honeywell 516 computer, 12 kilowords of core memory (16-bit words, 24 kilobytes, approximately microsecond cycle times for instructions)
- At right, the first IMP delivered (on display still at UCLA's Boelter Hall)
- Notice the eyes for cable hooks


INTERFACE
MESSAGE
PROCESSOR
The Origin of the Internet


INTERFACE
MESSAGE
PROCESSOR

We delivered 4 IMPs on time; and the subnetwork of IMPs worked!

- A BBN person went with each delivery (first to UCLA on August 30, 1969; then October, SRI; November, UCSB; December, U. of Utah)
- UCLA and SRI communicated once SRI IMP was installed
- Software development continued with new releases of paper tapes
- Four IMP test also done from UCLA (demonstrated a problem anticipated by Kahn)

29OCT67	2100	LOADED OP. PROGRAM EOI2 BEN BARKER BBN	CSK
	22:30	talked to SRI Host to Host	CSC
		Left op. imp. program running after sending a host dead message to imp.	CSK

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It worked (continued)

- The IMP subnetwork wasn't bug free in terms of network algorithms, but it *ran fast and didn't crash*; it ran well enough to take off the table the question of whether the ARPANET was going to work; the focus moved to host communications and applications on top of the IMP subnetwork
- IMP deliveries continued in 1970 at 1 per month; BBN was #5 permitting remote monitoring and control
- Much intra-site traffic
- IMP software was improved and extended; distant host interfaces were developed

How could we do so much so fast?

- No legacy to deal with
- Not much memory in IMP
- Single subnetwork contractor and cooperative user community
- Distributed system architecture supported on-going evolution
- Small, highly-integrated development team with much real-time system development experience
- *I think we were a good choice; but others could have done it, albeit perhaps differently*

4. IMP design and implementation

a. System design
b. Hardware
c. Software
d. Example problems

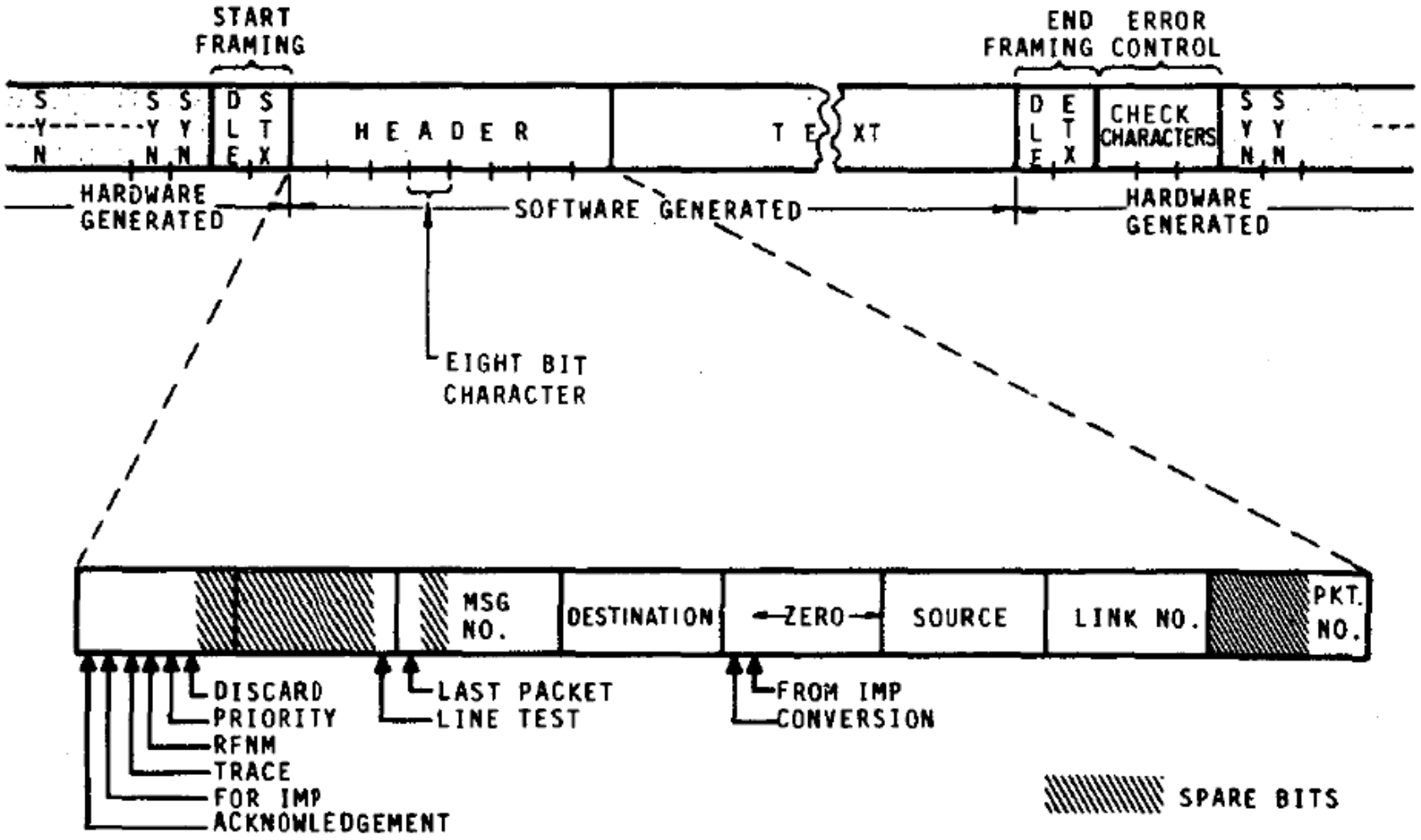
4a. System design (ARPANET characteristics)

a. Reliable transmission
b. Network transmitted binary data (application independent)
c. Dynamic routing
d. In-band monitoring/control, down-line loading, etc.
e. Host/host protocols partitioned from communications subnetwork -- protocol stack
f. Network Working Group and RFCs
g. Pay for fixed transmission capacity

a. Reliable transmission

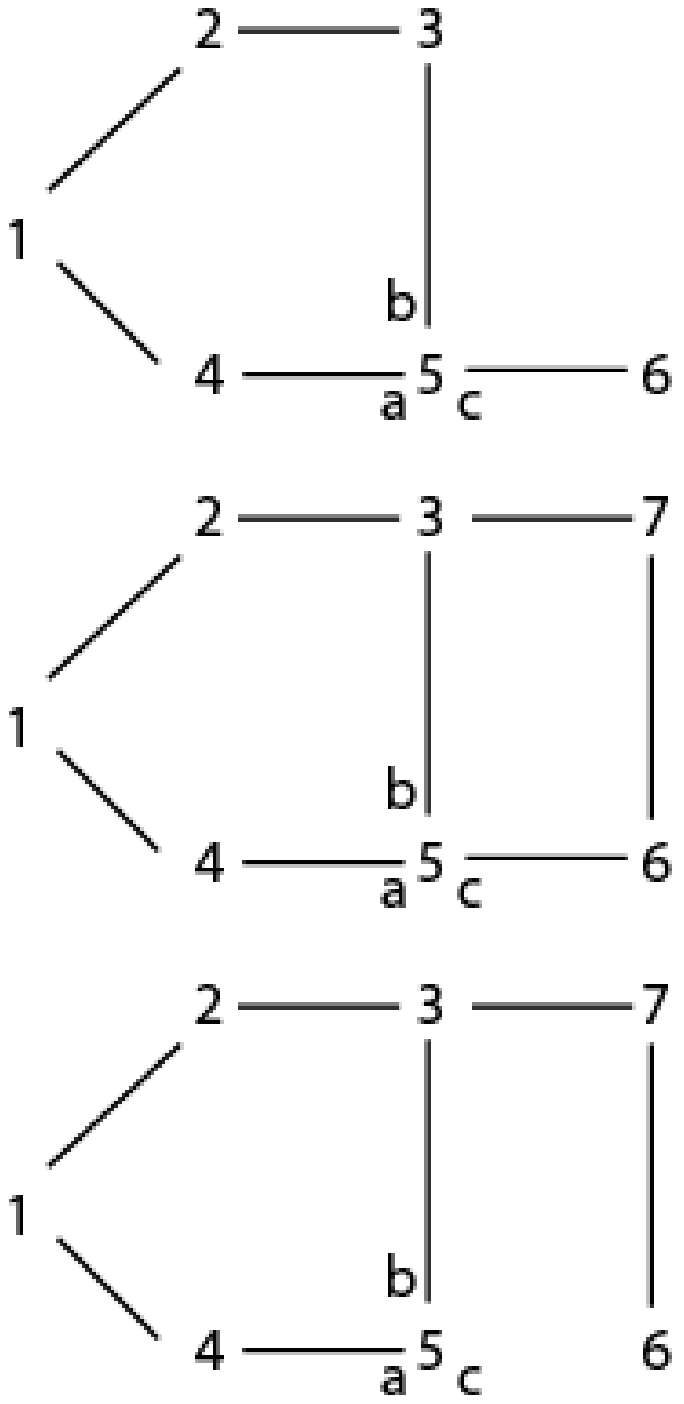
- IMP store-and-forward in face of flakey phone lines: CRCs, ACKs, and retransmission
- Ideally packet gets received and ACK sent back
- But, either data packet or ACK packet can be lost
- If ACK is received, discard packet
- If ACK is not received for too long, what does it mean?
  a. packet lost (correct action is to retransmit)
  b. ACK lost (all one can do is retransmit)
- Must detect and discard duplicate packets

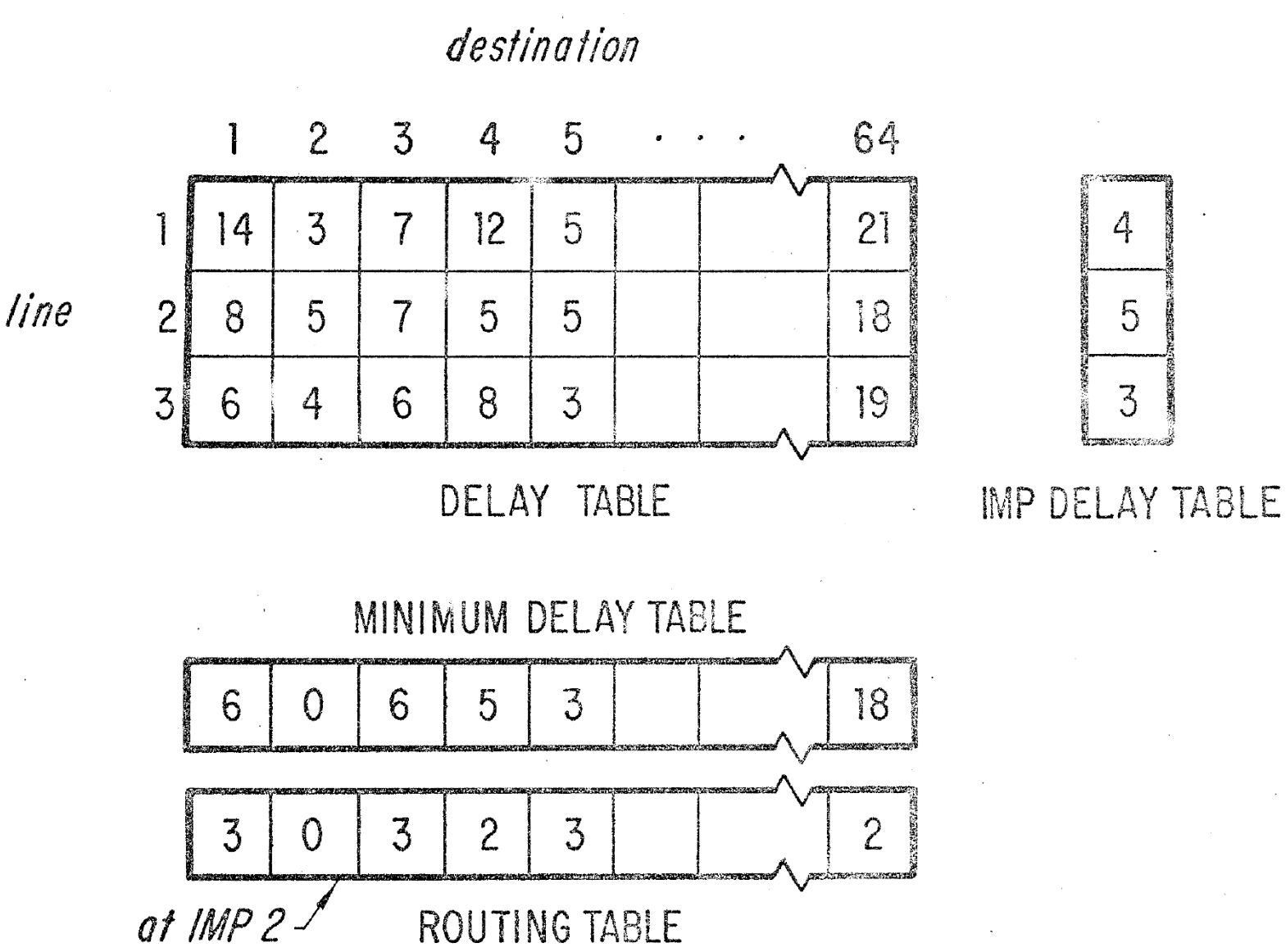
b. Network transmitted binary data (application independent)



c. Dynamic routing

- Automatically adapts to new IMPs
- Automatically adapts to new IMPs and/or lines
- Automatically adapts to temporary lines loss
- Automatically adapts to IMPs temporarily being down
- Distance-vector later replaced by link-state routing

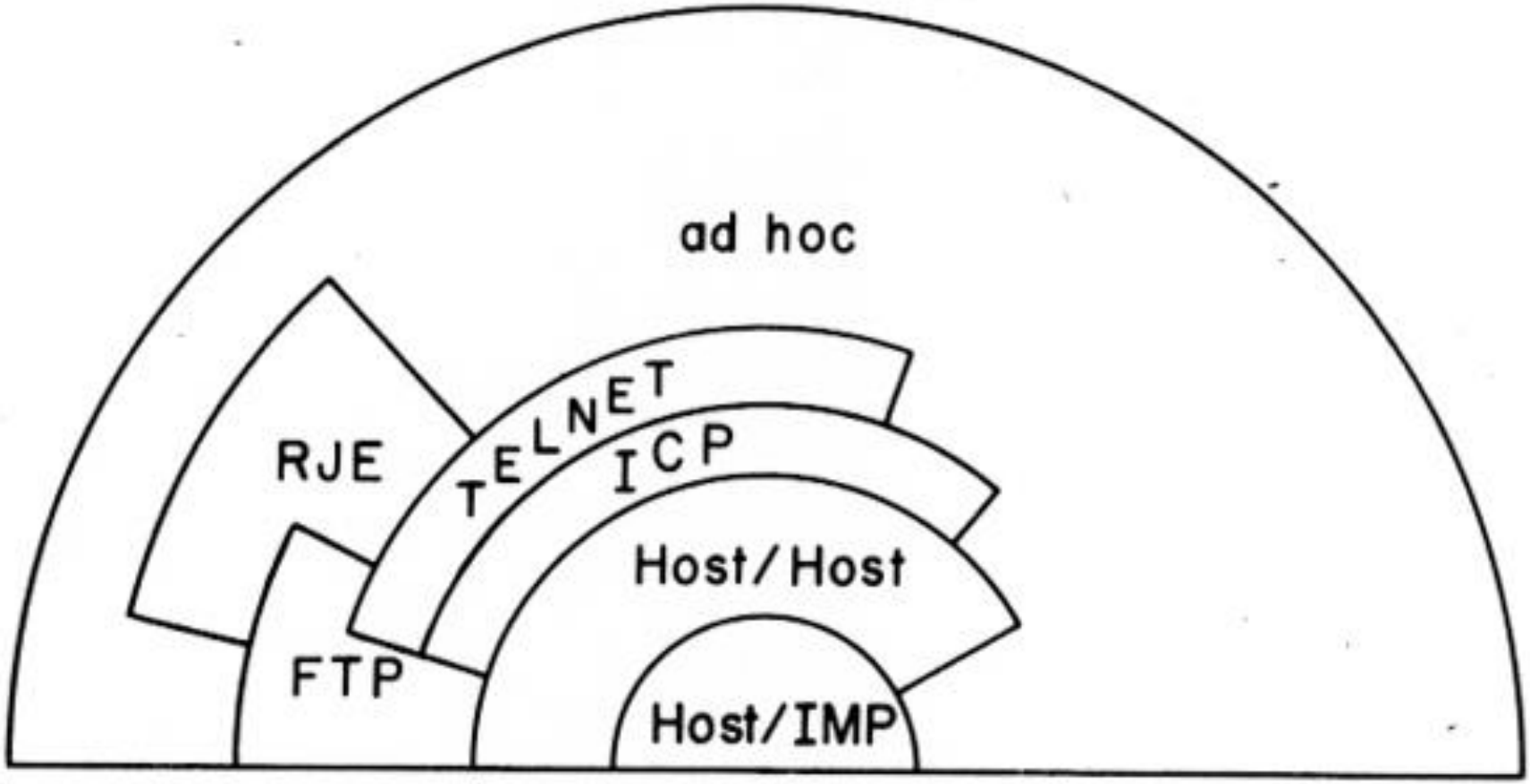



destination
1 2 3 4 5 . . . 64
line
1 14 3 7 12 5 21
2 8 5 7 5 5 18
3 6 4 6 8 3 19
DELAY TABLE
4
5
3
IMP DELAY TABLE
MINIMUM DELAY TABLE
6 0 6 5 3 18
3 0 3 2 3 2
at IMP 2
ROUTING TABLE

d. In-band monitoring/control, down-line loading, etc.

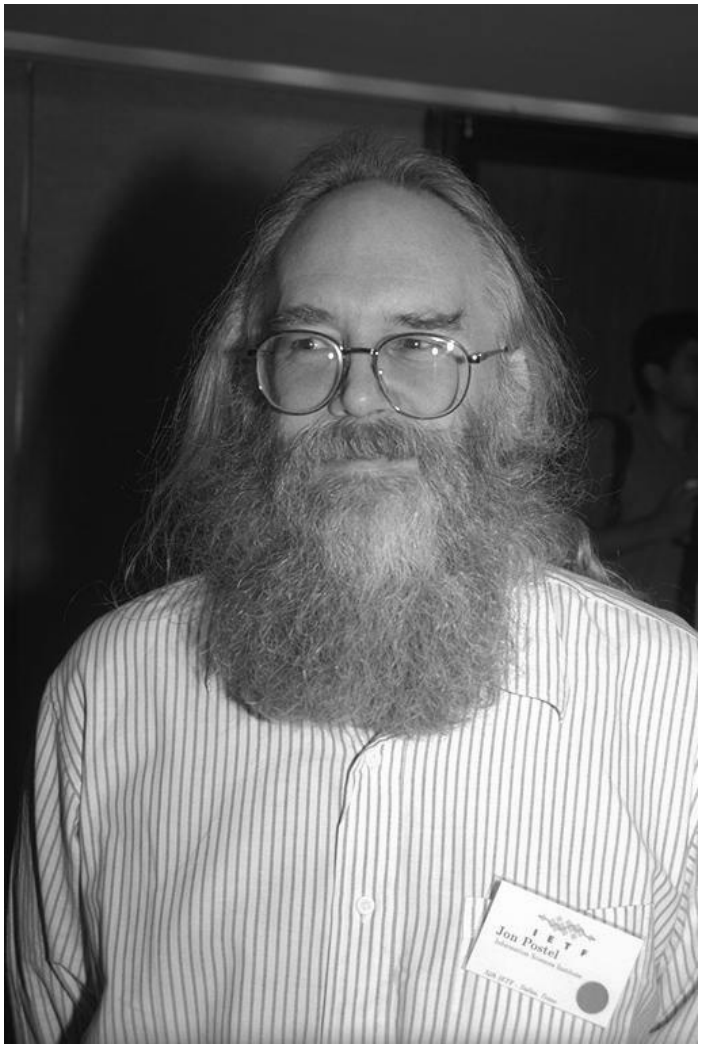
- 63 IMPs (numbers 1 to 63, 0 reserved); 6 bits
- 1 host interface
- almost immediately 4 host interfaces; 2 bits
- 4 "fake hosts" a trivial extension; 1 more bit
  - TTY in/out
  - debug in/out
  - statistics control/stats
  - trace control/reports

e. Host protocols partitioned from communications subnetwork



IMP/IMP stuff was down a level

f. Network Working Group and RFCs



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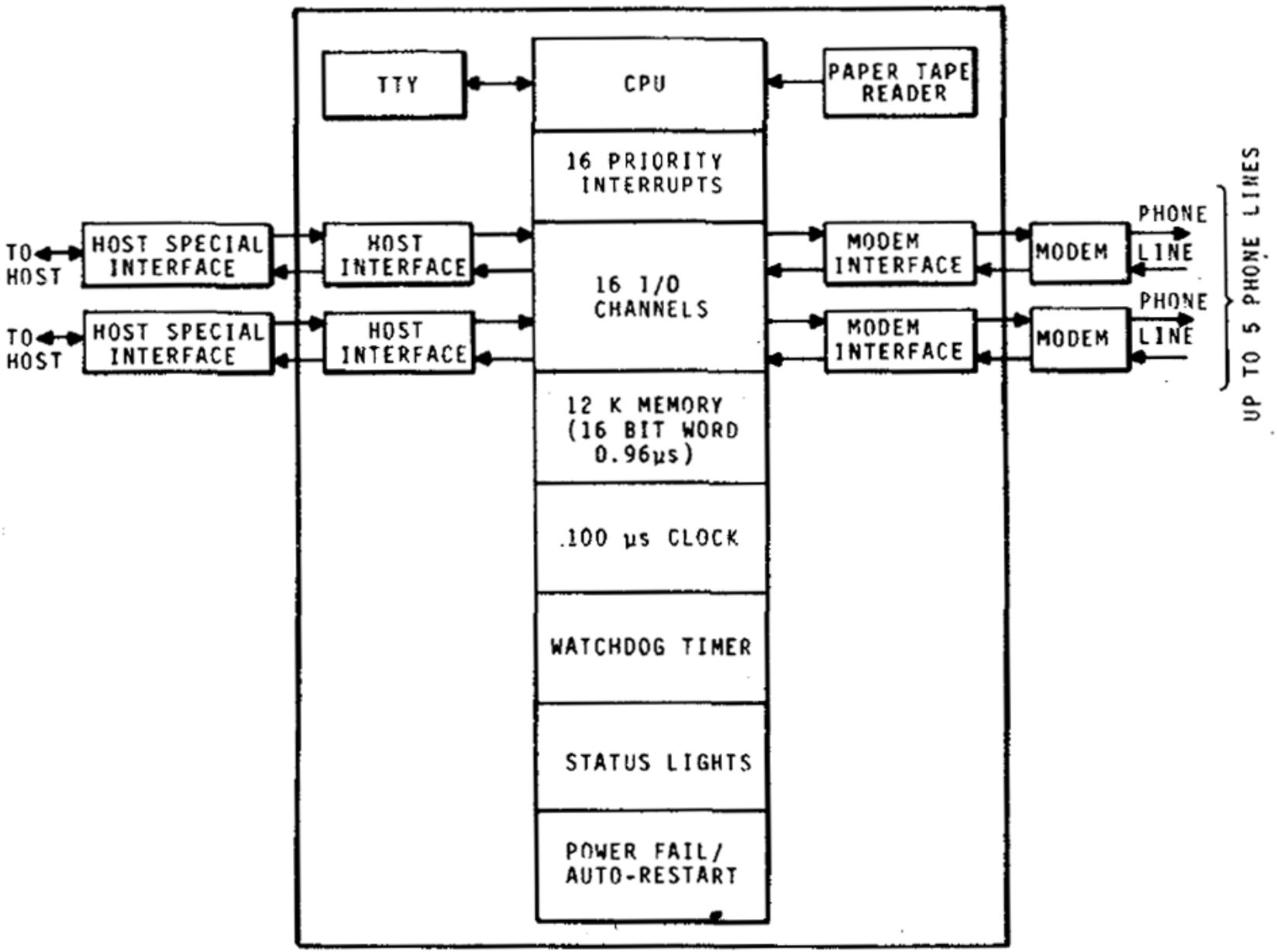
4b. IMP hardware – H-316/516 base



Electronics

- RTL (bipolar transistors to 0V; resisters for +5V)
- Circuits on small modules/cards plugging into blocks of 8 connectors
- Wire wrap pins on back of a block of connectors
- 1 to 3 blocks for our interface logic
- CPU, memory, etc., used same technology

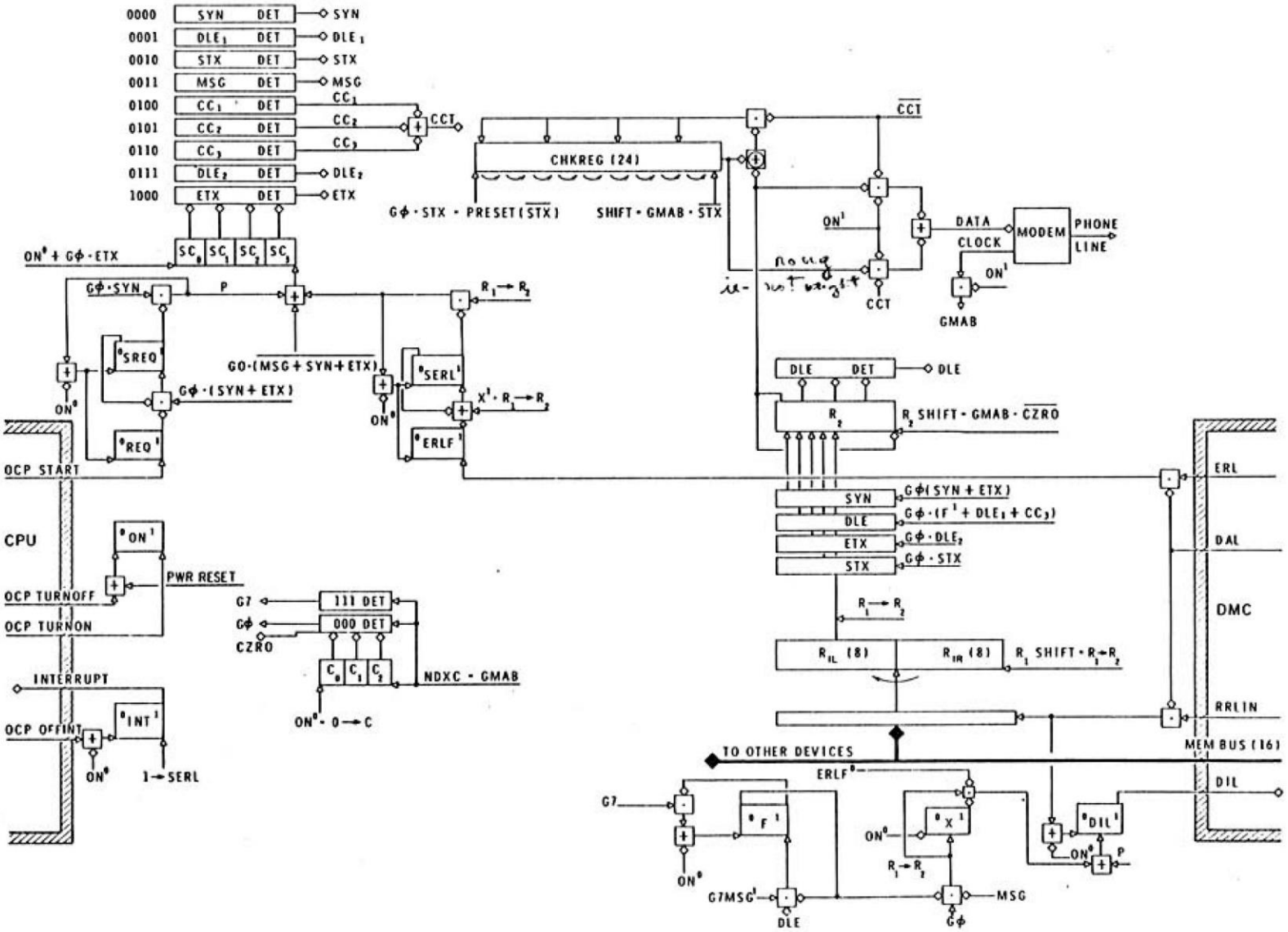


FIG. E-5 IMP/MODEM INTERFACE OUTPUT SECTION.

4c. IMP software (in other words, coding for 316)

- 1969 implementation environment
  - PDP-1 based time-sharing system
  - Model 33 TTY terminals
  - TECO editor
  - PDP-1 Midas assembler modified (with macros) to assemble Honeywell 316 code
  - Binary output on paper type
  - Paper tape reader on IMP
  - Octal DDT in IMP for looking at memory locations, setting breakpoints, typing in patches, etc.

Example page of IMP system assembly listing

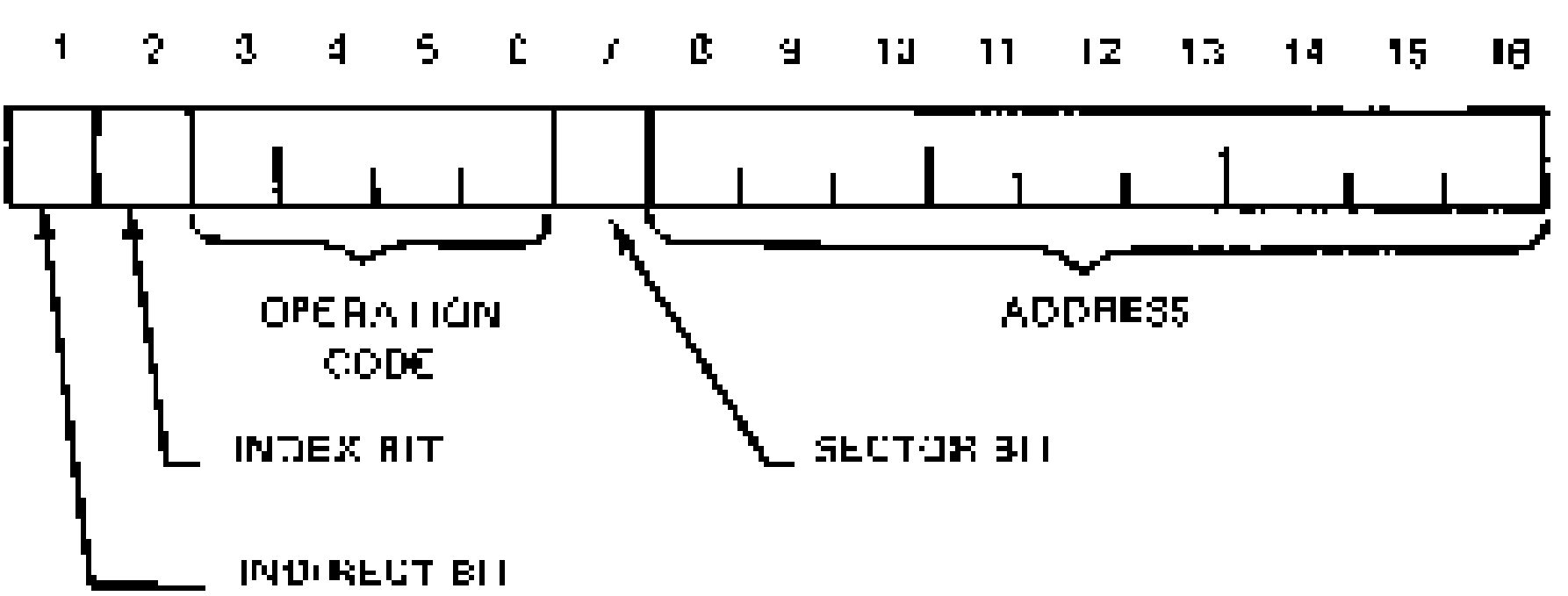
```
 *** THIS DOCUMENT MAY CONTAIN BBN PROPRIETARY INFORMATION. ***
 ***      FURNISHED FOR U. S. GOVERNMENT END USE ONLY.       ***
PAGE  168   IMP,3050,IMP   7:20 PM 9/16/1973

                    LEV T,0
20464 000000 5      JSRT:     0
20465 004112 5                LDA SIGN          /TURN OFF I2MTC CLOCK WAKEUP
20466 050440 5                STA NONE X        /FOR DEAD OR NON-EXISTENT LINES
20467 004000 5                LDA 0
20470 014127 5                ADD MICH
20471 023544 5                CAS VDHNO
20472 100000 5                SKP               /IS THIS MODEM STOLEN BY VDH?
20473 103464 5                JMP JSRT I        /YES
20474 023545 5                CAS MODNO
20475 103464 5                JMP JSRT I        /IS THIS MODEM STOLEN BY HOST?
20476 103464 5                JMP JSRT I
20477 115631 5                ADD (SATNO) I
20500 101040 5                SNZ
20501 103543 5                JMP SATGCI I
20502 064265 5                IRS SLT X         /YES, TIME TO START BRINGING IT UP?
20503 103464 5                JMP JSRT I        /NO
20504 001001 5                INH I2M
20505 033546 5 2              STX SENR
20506 005632 5 2 JSRT2:       LDA (SMPQ)
20507 021547 5 2 JSRT3:       JST JSRTS
20510 005633 5 2 JSRT4:       LDA (SMQ)
20511 021547 5 2              JST JSRTS
20512 073546 5 2              LDX SENR
20513 005634 5 2              LDA (ACKTAB)
20514 050646 5 2              STA RSEX X
20515 050653 5 2              STA CHFREE X
20516 044622 5 2              LDA I2MTAB X
20517 111635 5 2              STA (I2MLST 0 X) I
20520 050627 5 2              STA I2MEND X
20521 005636 5 2              LDA (-NACH)
20522 050634 5 2              STA I2MNXT X
20523 140040 5 2 NACKL:       CRA
20524 050641 5 2              STA TSEX X        /ZERO THIS - LOOP UNNECESSARY
20525 050440 5 2              STA NONE X        /ZERO THIS - LOOP UNNECESSARY
20526 166627 5 2              IMA I2MEND XI
20527 010000 5 2              STA 0
20530 023637 5 2              CAS (1777)
20531 021557 5 2              JST RQSUB
20532 101000 5 2              NOP               /NOTHING THERE OR JUST A DUMMY
20533 073546 5 2              LDX SENR
20534 064627 5 2              IRS I2MEND X
20535 064634 5 2              IRS I2MNXT X
20536 003523 5 2              JMP NACKL
20537 005640 5 2              LDA (JMP+0+1000+M2I0"A"777)
20540 111641 5 2              STA (M2IOK 0 XI) I
20541 000401 5 2              ENB T,0
20542 103464 5                JMP JSRT I

                    LEV VAR
20543         V     SATGCI:   SATDEF [0 0 JSRT I]
02264 020543 V
02314 120464 V
02344 120464 V
20544         V     VDHNO:    BSS 1             /0 FOR NO VDH, ELSE M,N=5
20545         V     MODNO:    BSS 1             /0=5 MODS, -1=4 MODS, -2=3 MODS
20546         V     SENR:     BSS 1
```

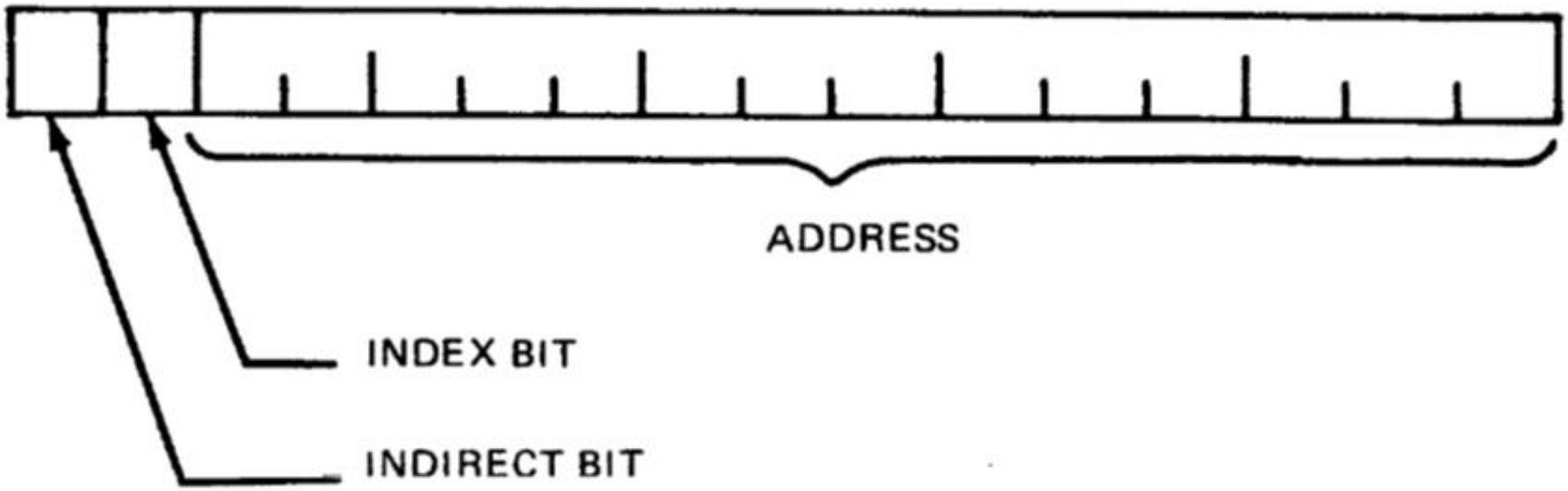
Example page of concordance


```
.ASCII  -         7,7,7,7,7,7,7,7,18,18,20(C),24(C),256(C),256(C),
                   256(C),256(C),256(C),256(C),256(C)
.DODXA  157(0)    23(C),157(0)
.ENB    2         12
.INH    2         12,108(2)
.TA.    7,7,7,8,9,10,10,18,20(C),24(C)  7,7,7,7,7,7,8,8,9,9,10,10,
                   18,18,20(C),24(C)
.TB.    8,9,10,18,18  8,9,10,18,18
.TC.    9,10      9,10
.VERS.  1         1,19(C)
0IF     -         1,9,10,12,12,12,13,13,13,14
15SECS  260(V)    261(1 0)
1IF     -         1,8,8,9,9,12,12,13,13,13,14,18,257(C),258(C)
2.5SEC  260(V)    267(2),269(5)
30SEC   14        19(C),114(C)
5SECS   260(V)    265(1)
8PKTS   24(C)     38(7 0),52(7),52(7),71(6 0),71(6 0),71(6 0),71(6 0),
                   75(6 0),76(6 5),78(6 4),174(5 0),174(5 0)
A       -         8,8,8,9,9,10,10,10,18,18,18,18,18,18,75(6 0),75(6 0),
                   121(4),129(4 0),133(4 0),154(3)
ACA     2         101(2 0)
ACCEPT  -         93(0)
ACK     -         94(0),95(0),265(1 0)
ACK1    96(0)     95(0)
ACK2    96(0)     95(0)
ACK3    96(0)     95(0)
ACK4    96(0)     95(0)
ACK5    96(0)
ACK567  96(0)     95(0)
ACK6    96(0)     96(0)
ACK7    96(0)     96(0)
ACKBIT  62(V)     63(6),63(6),70(6 0)
ACKBTS  15        110(2)
ACKCH   62(V)     65(6),65(6)
ACKGUD  95(0)     95(0)
ACKH    14        34(0),58(7),58(7),63(6),63(6),65(6),65(6),68(6 4),
                   68(6 4),69(6),88(0),88(0),89(0),89(0),90(0),91(0),
                   92(0),92(0),92(0),92(0),92(0),93(0),94(0),96(0),
                   100(0),107(2),107(2),107(2),107(2),107(2),107(2),
                   107(2),107(2),107(2),107(2),107(2),107(2),107(2),
                   108(2),108(C),108(C),110(2),110(2),110(2),111(2),
                   131(4),151(3),232(C),248(2),248(2),254(V),254(V),
                   254(V),254(V),254(V)
ACKLOP  95(0)     96(0)
ACKP    62(V)     63(6),63(6),63(6)
ACKS    95(0)     96(0),96(0),96(0),96(0),96(0),96(0),96(0)
ACKS1   96(0)     96(0)
ACKSYN  96(0)     95(0)
ACKT    97(V)     94(0),94(0),94(0),94(0),95(0),95(0),95(0),95(0),
                   96(0)
ACKTAB  17,17     94(0),168(5 2
```

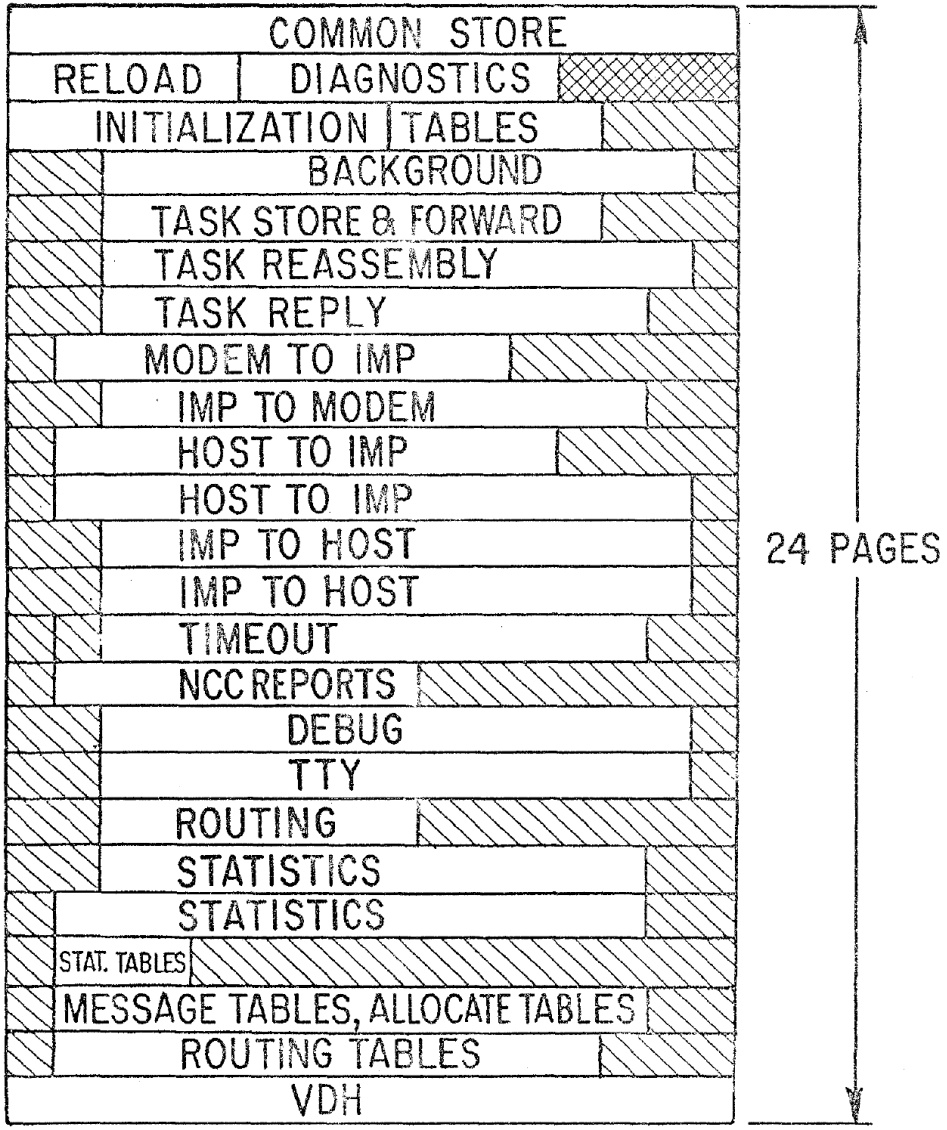
Other information from the assembler

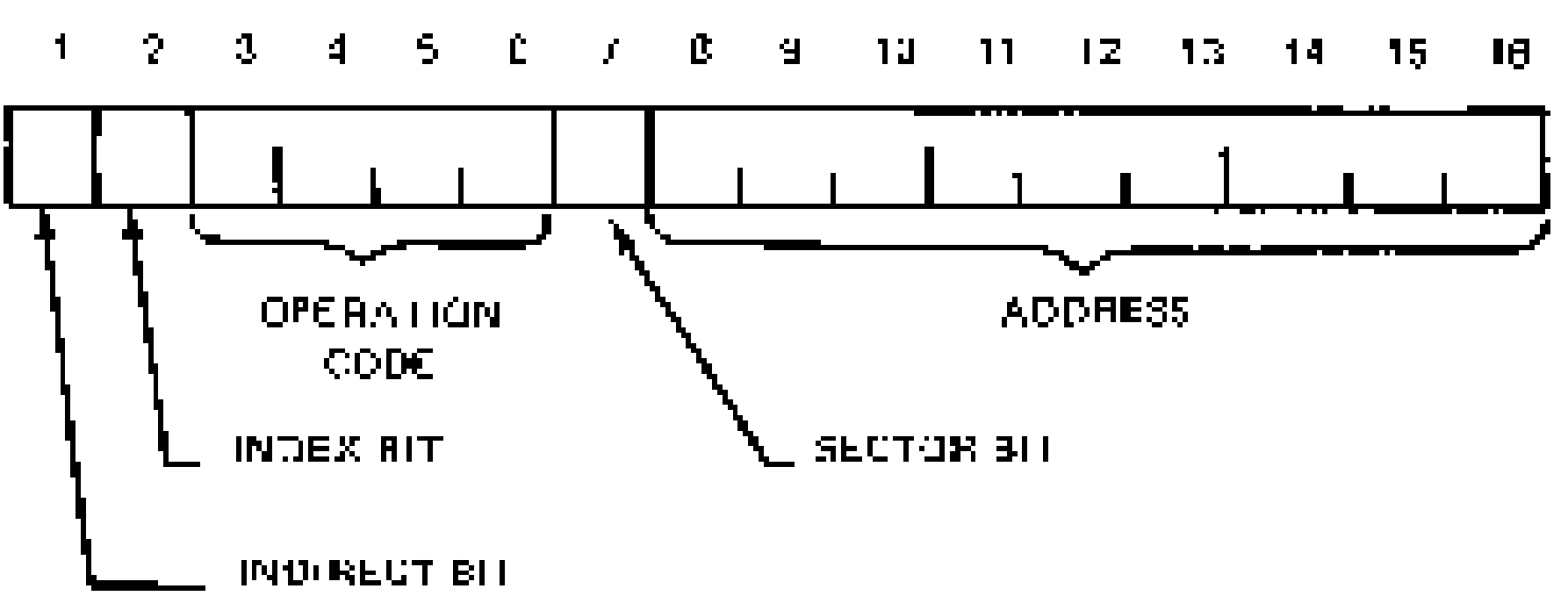
- For each segment of memory: beginning of code, end of code, patch space, buffer num.
- Halt locations
- Useful locations
- Crash reload locations
- List of segment and the locations of buffer in that segment

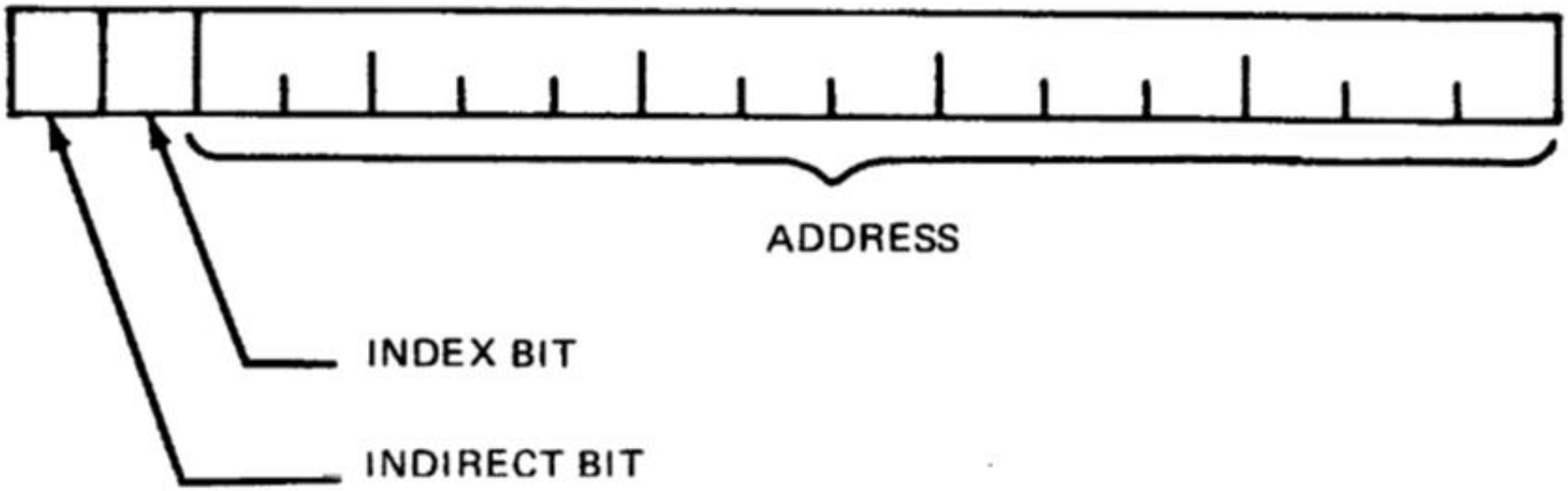

OPERATION CODE
ADDRESS
INDEX BIT
SECTOR BIT
INDIRECT BIT


ADDRESS
INDEX BIT
INDIRECT BIT

Storage allocation




OPERATION CODE
ADDRESS
INDEX BIT
SECTOR BIT
INDIRECT BIT


ADDRESS
INDEX BIT
INDIRECT BIT

316 registers and subroutine calls

- Registers: accumulator, index register, location counter, etc.
- Subroutine call:
  Jump-and-Store-location to address; puts location counter +1 at address; put address +1 in the location couter
- Nothing was saved automatically; subroutine saves registers it is going to use, e.g., accumulator, index register; end of subroutine restores saved registers and does indirect jump through first location of subroutine where the return address was stored

Honeywell 316 priority interrupt system and its use by the IMP

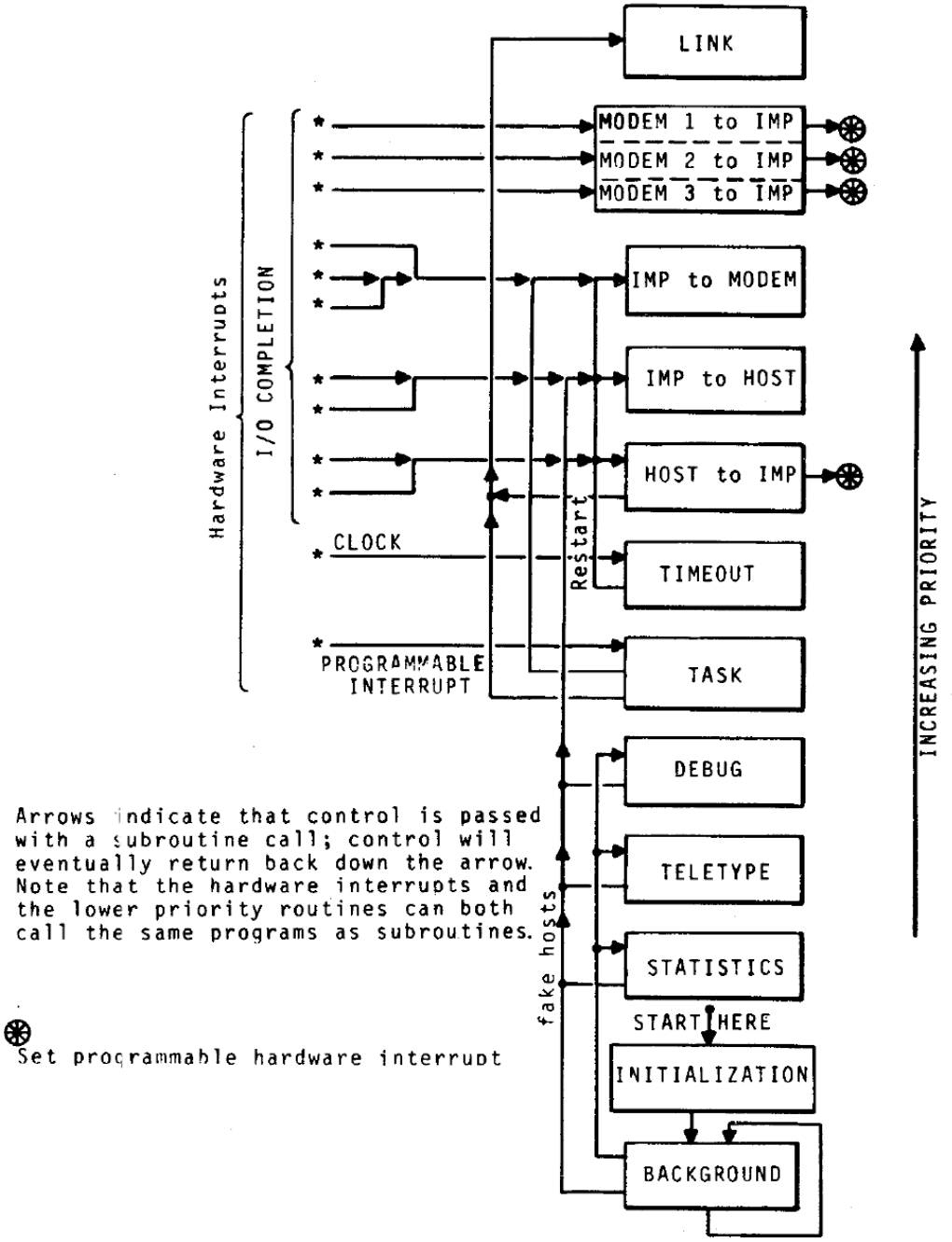


Figure 10—Program control structure

4d. Examples of problems

- Algorithmic, e.g., reassembly lockup, the limitations of distance vector routing
- Hardware, e.g.: failed bit in Harvard IMP memory; failure in a modem interface checksum – fixed by software checksums on routing tables and routing code
- Software, e.g.: “spurious ACKs”; other occasional interrupt bugs – reduced by assembly time automation of interrupt bug identification

Cross network maintenance

- Regular reports from IMPs to a computer on the BBN IMP (IMPs, phone lines, attached computers)
- Interface looping capability; TIP reporting
- Control of network data generation and collection for statistical analysis
- Cross network inspection and changing of memory locations
- Reloading from neighbor IMP
- New software releases across the network (sometimes required two steps)

Those who managed and governed us

- Roberts at ARPA IPTO and contracting agency
- Young PhDs as IPTO program managers
- With Craig Fields as program manager, operational management transferred to DCA; IPTO still directed development
- Kahn and Cerf called the shots of internetworking experiments
- Caught in an ARPA interoffice conflict; we also had our own BBN interdivisional stresses
- ARPANET became DDN and DCA still operated it
- And, of course, network users

5. 1973 to ca. 1994: internetworking and the evolution of the Internet

- Dissemination of the technology
- Prototypes and experiments

First demonstration of networked email (the first killer app)

Ray Tomlinson plus many others over the following years, e.g., Dave Crocker (plus the pre-network email developers)

ICCC 72

INTERNATIONAL CONFERENCE ON COMPUTER COMMUNICATION

24-26 OCTOBER 1972

WASHINGTON HILTON HOTEL, WASHINGTON, D.C. U.S.A.

- User-Oriented
  - Interdisciplinary
    - International
      - Stimulating Program

- User-Oriented

  This conference is not just another rehash of the technology of bits and bandwidths. It will deal with what all this is good for -- what the user problems and results are.

- Interdisciplinary

  The program will stress the user. Thus it is for lawyers, medical men, economists, and government men as well as engineers and communicators.

- International

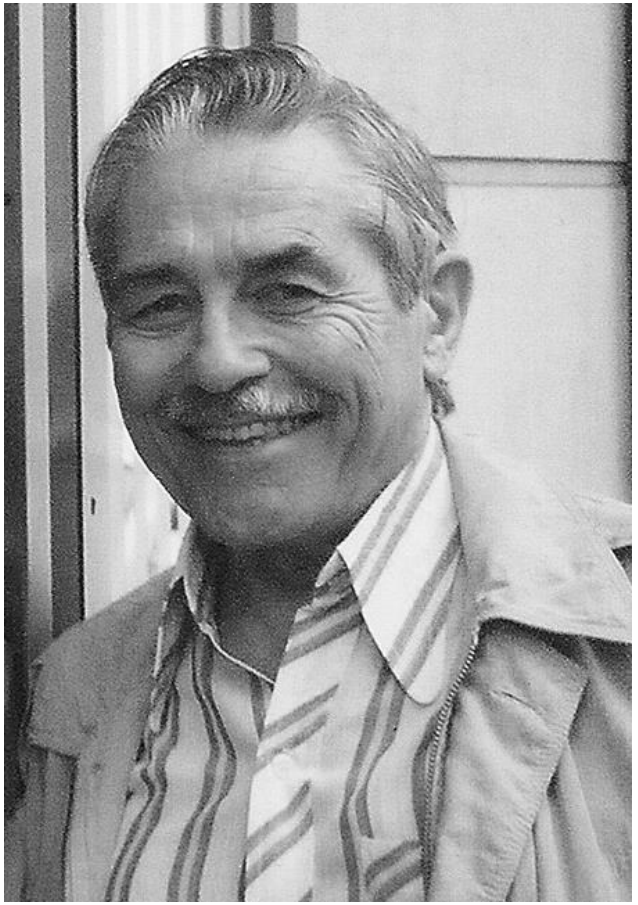
  The conference has been organized by a committee including representatives from 12 nations; the program will include papers reporting the state of computer telecommunication usage from most of these.

- Stimulating Program

  The program will have a strong tutorial orientation in view of the interdisciplinary emphasis of the conference. One session of particular interest is the Keynote session which will survey "Computer Communications in the Industrially Advanced Nations". Speakers from Japan, the USA, the USSR and Western Europe have been invited. Among other session topics expected to draw special interest are "The Wired City", "Data Banks and Individual Privacy", "Public Data Networks", and some twelve others.

Louis Pouzin and his Cyclades team

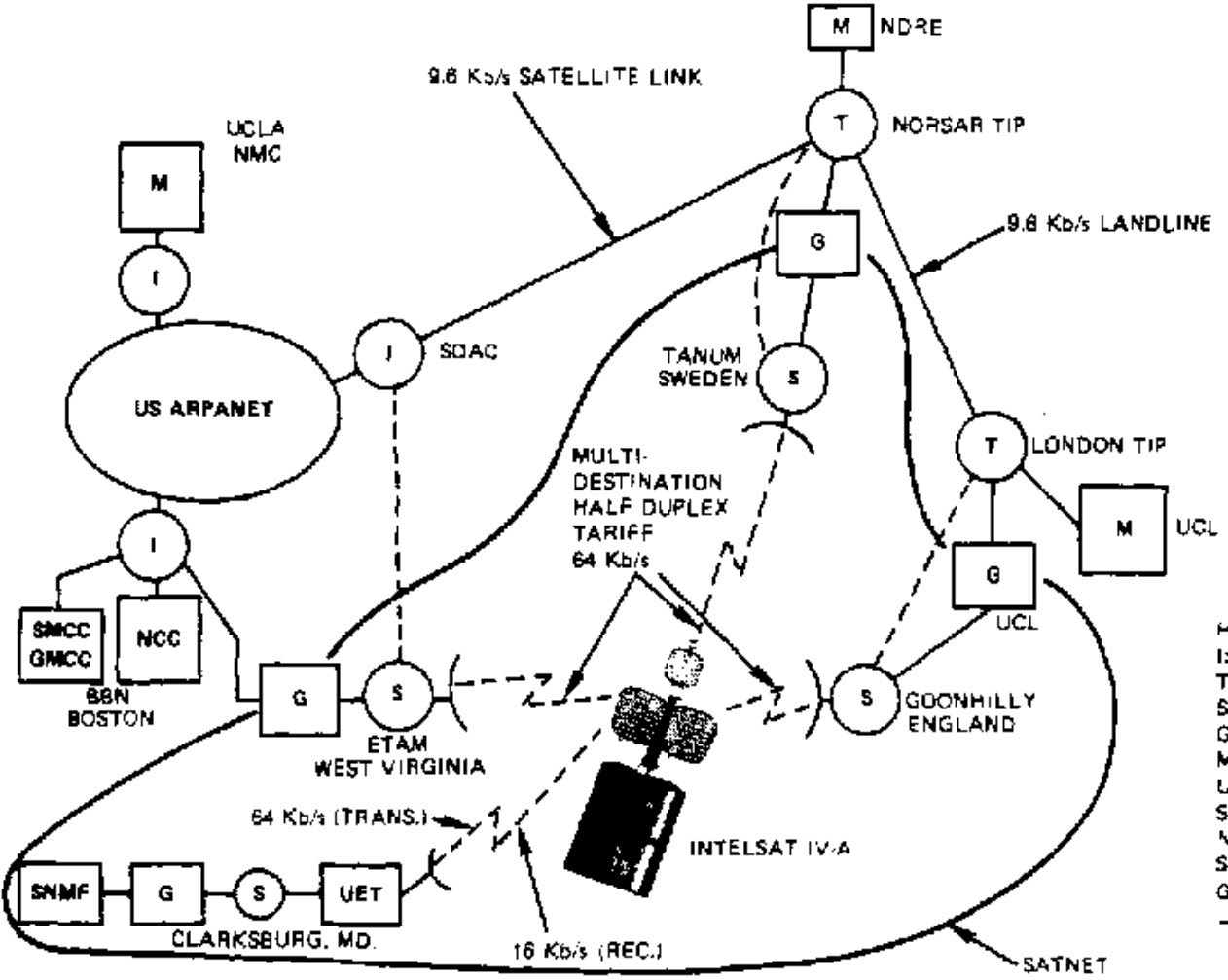
- From 1972
- Datagrams without reliability concerns in the packet subnetwork
- End-to-end reliability moved to the host level
- We consulted and taught them about how the IMP worked



Starting circa 1973 -- conception, development, and widespread implementation of TCP and later TCP/IP

- Vint Cerf, Bob Kahn
- *Many* others, e.g.,
  - Xerox PUP
  - 3-net experiment
  - Danny Cohen, et al.
  - Van Jacobson
- BBN deeply involved

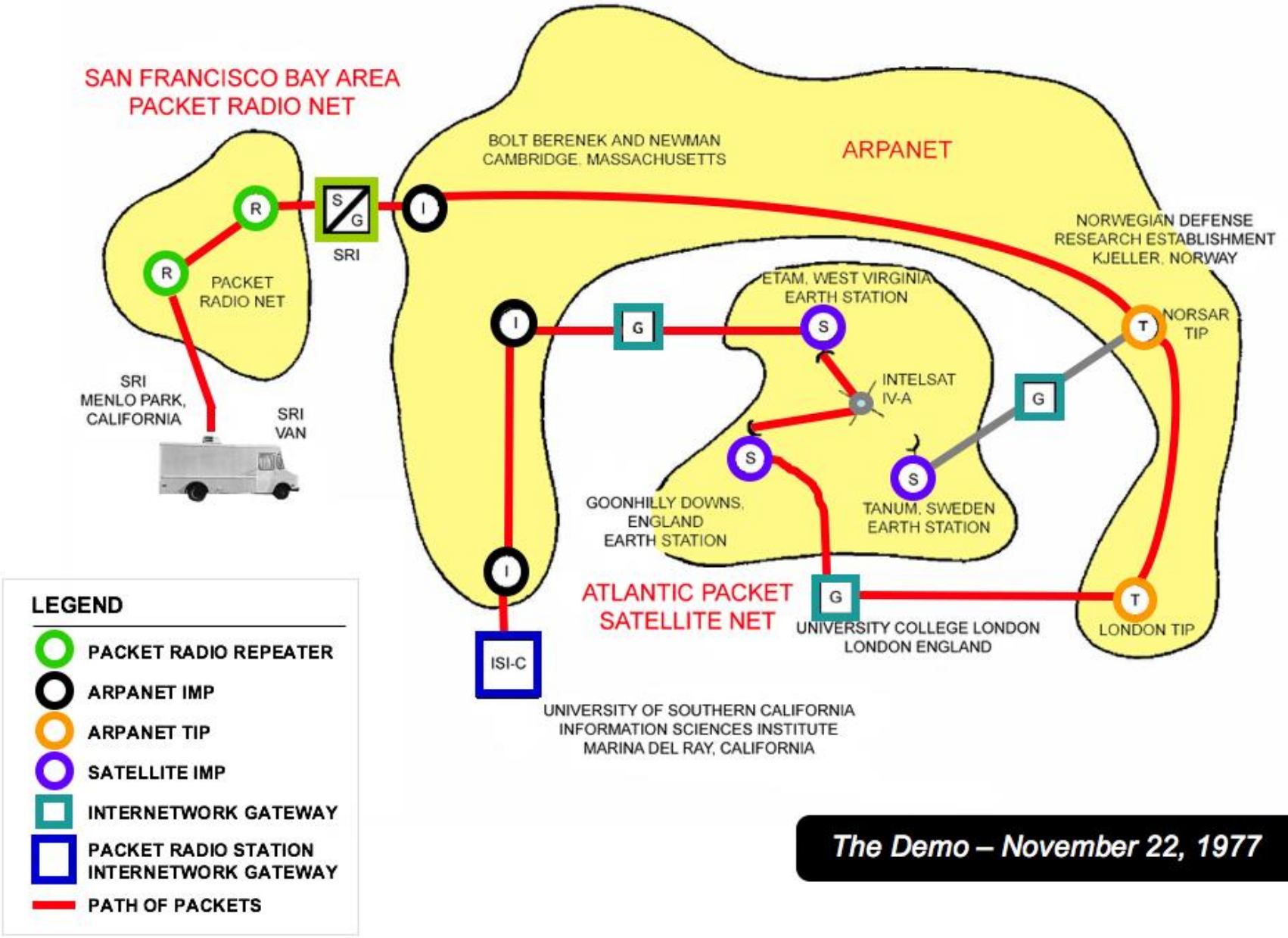
Packet satellite



H: HOST
I: INTERFACE MESSAGE PROCESSOR (IMP)
T: TERMINAL INTERFACE MESSAGE PROCESSOR (TIP)
S: SATELLITE INTERFACE MESSAGE PROCESSOR
G: GATEWAY COMPUTERS
M: NETWORK MEASUREMENT FACILITY
UET: UNATTENDED EARTH TERMINAL (G/T=29.7)
SNMF: SATELLITE NETWORK MEASUREMENT FACILITY
NCC: NETWORK CONTROL CENTER
SMCC: SATELLITE MONITORING AND CONTROL CENTER
GMCC: GATEWAY MONITORING AND CONTROL CENTER
— — DEBUGGING LINES

Fig. 4. Schematic of Atlantic Packet Satellite Experiment.

Packet radio

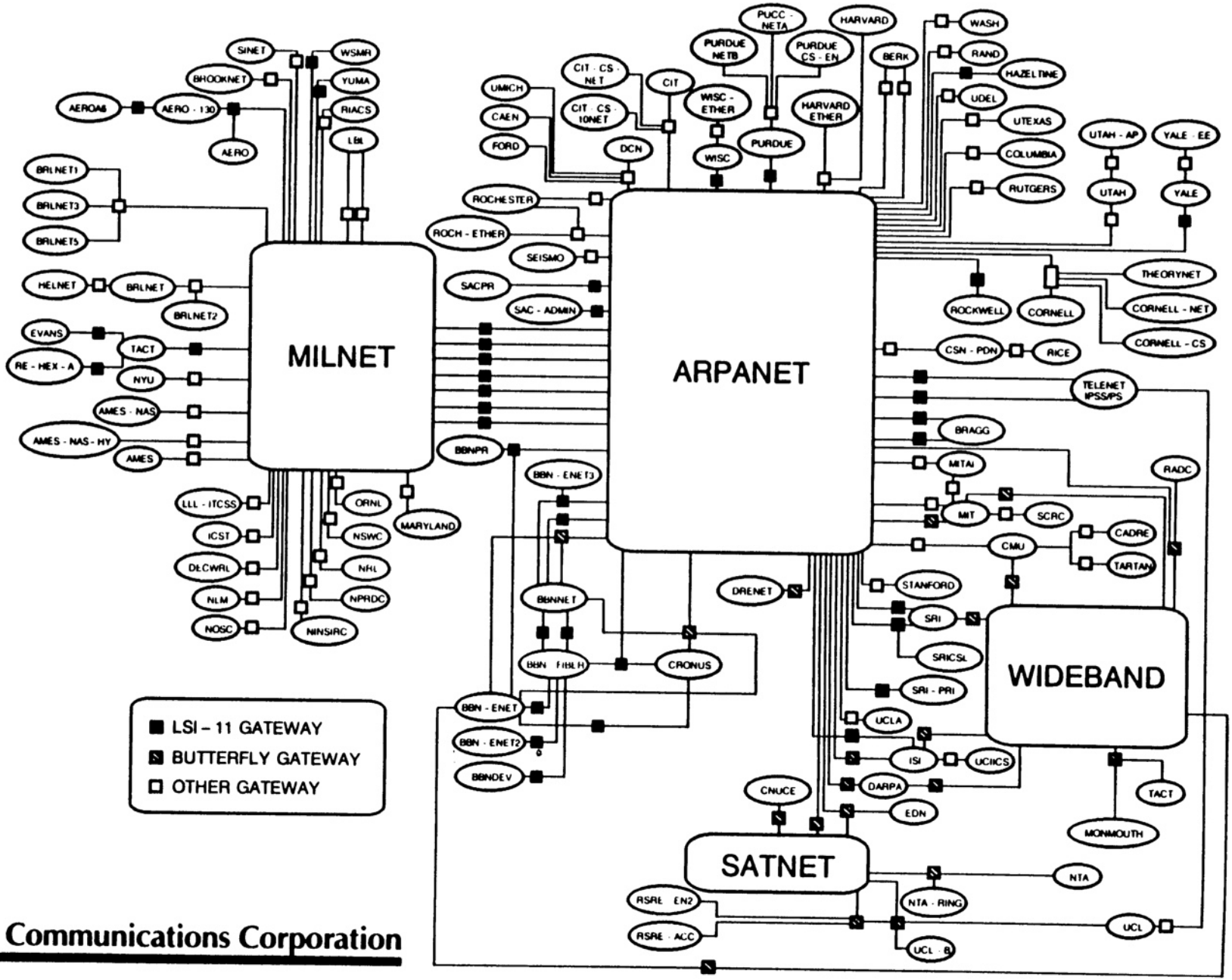


The Demo – November 22, 1977

Packet voice and video conferencing

447793-45D

Gerald O'Leary, Eric Evans, Mostafa Kaveh, Harold Heggestad, Peter Blankenship, Cliff Weinstein, Steve Blumenthal, Stephen Casner, Randy Cole, Earl Craighill, John Makhoul, Don Johnson, Peter Staecker, Robert Kahn, Joe Tierney, William Kantrowitz, Duane Adams, Connie McElwain, Carma Forgie, Gil Falk, Karen Panetta, Bruce Hecht



BBN Communications Corporation

JULY 1986

Some reflections

- People ask me if I knew ARPANET would be big deal
- The Internet disrupted then existing businesses; disruption has been turned back on the Internet
- It was a great time for me to get involved with packet switching.
- Resurrection of the 1973 IMP code (2013)

Thank you