Telecom Networks and Switching: Network Architecture

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Classification of Communication Networks

- By topology
  - point-to-point link
  - one-way (simplex) or two-way (duplex)
  - point-to-multipoint or star
    - all traffic goes through a Base node which performs switching
    - e.g., cellular Base Station, VSAT network

Remote Base

Star

( VSAT (Very Small Aperture Satellite) network

- mesh
  - fully connected vs. partially connected
    - traffic routed by each node
    - nodes also perform repeater function for other nodes not directly linked
    - e.g., trunk exchanges in a telecom network

- ring
  - all nodes perform repeater function
  - e.g., multiple telephone instruments on a single rural line connected to an exchange

- bus
  - only one pair communicates at a time, but signal is broadcast to all nodes
  - e.g., Ethernet LAN segment

- tree
  - like partially-connected mesh, but only one route between any two pair

Classification of Communication Networks (contd.)

- By scope of connectivity
  - local area
  - wide area

- By type of switching
  - circuit-switched: a dedicated channel (with a fixed bandwidth or bitrate) is assigned on demand
  - constant delay, fixed-capacity channel established
  - packet-switched: no dedicated channel assigned
  - variable delay, variable bitrate, occasional loss of packets, packets can traverse different links out of sequence
Public Switched Telephone Network (PSTN)

A wide area, circuit-switched, mesh (partially-connected) network of star-connected subnetworks

- started out historically as a tree network
- vulnerable to failure
- high-traffic routes can be directly connected
- requires sophisticated routing strategy

Telecom Networks & Switching

PSTN Today

- mesh connected Trunk exchanges at the state/regional level
- mesh connected local exchanges at bottoms in metropolitan areas
- a large number of direct routes between Area-level trunk exchanges

⇒ hierarchical route selected only if direct route is not available

PSTN Building Blocks

- subscriber terminal: telephone instrument
- simple, robust, low-cost, powered by exchange
- local loop (LL): a pair of wires from telephone to local exchange
- carries power to telephone, voice and signals both ways
- local exchange (LE): a switching node that switches calls from one subscriber to another, as well as to/from trunks
- complex equipment:
  - call processing
  - subscriber administration
  - configuration/health monitoring
  - battery
- LE terminations (Main Distribution Frame)
- Trunk terminations (Remote Distribution Frame)

PSTN Network Topology: a summary

- Fully mesh-connected TAXs at highest level
  - international gateways also connected to this subnetwork
- Second-level TAXs for states/regions/metros: connected to level-1 TAXs, but also partially amongst themselves
- Third-level TAXs (often, TAX-cum-local) also deployed at times
- LEs (sometimes, LE-cum-TE) at lowest level connect to subscribers
- Size of trunk group between any two TEs, depends on amount of traffic
  - trunks often segmented as outgoing and incoming, but can also be bothways
Numbering plan

- Semi-open plan: length of number differs by one or two digits (India, U.K., ...)
- Closed plan: uniform numbering (U.S., France, ...)
- International plan: country code + national number

Max = 12 as per ITU

Country code: world divided into 9 zones
- N. America: 1, Africa: 2xx
- S. America: 5xx, S. Asia: 9xx, and so on.

Example:
- India: 91, Srilanka: 941

Numbering plan (contd.)

- National number: Access code + Exchange code + Line number
- India: 7-9 digits in all: [2-6] + [3-1] + [4-2]

Example 1: 44 + 491 + xxx, Chennai Adyar
Example 2: 452 + 88 + xxx, Madurai Trunk
Example 3: 4367 + 00 + xxx, Thanjavur Trunk

India is divided into regions for STD codes
- Maharashtra: 2
- West Bengal: 3
- Tamil Nadu: 4

Dialling Procedure

- Dial full international number for all calls
  - 11 digits every time
- Use special prefixes for international and national calls, and dial only exchange code + telephone number for local calls
  - 5-7 digits only for local calls
- Prefix for national calls: 10 for international calls
  - 0 makes LE route call to TAX, second 0 goes to TAX which routes calls to International Gateway Exchange

Group Dialling: a separate dialling procedure for calls to neighbouring areas
- E.g. calling Kollam from Thiruvananthapuram: 0471 + 10 + xxx
- Routed through Thiruvananthapuram TAX as STD call
- Or: 0471 + 10 + xxx
- Access code for neighboring call areas
- Routed by LE or tandem (with local call charges)
- Exchange code cannot start with 9, thus reducing number space

PSTN Architecture: an Example

Tamil Nadu circle (excluding Chennai) has 16 TAXs
- Coimbatore TAX has trunks to other TAXs as well as to TAXs in many other circles (e.g., Agro, Bangalore, Chennai, Delhi, Hyderabad, Patna...)
- Madurai, Coimbatore, Tirunelveli have trunks to other TAXs in the circle, and a few to major TAXs in other circles (Mumbai, Hyderabad, Delhi)
- Other TAXs have trunks only to local XXX and to Chennai
- Every TAX has trunks to other TAXs and trunks to so-called dependent exchange: exchanges that can route STD calls only through the TAX
- Decision to add direct trunks to other circles based on traffic measurements

18 Secondary Switching Areas (SSA)
- Kumbakonam and Karulakudi do not have separate TAX
- Some LEs can have trunks to 2 TAXs if both are nearby and traffic warrants it

Each SSA has several Short Distance Charging Areas (SDCA)
- Typically 8-10, sometimes as low as 2, or as high as 14
- SDCA is a local calling area for metering purposes
SSA and SDCAs: an Example

SSA: Chengalpattu (Kanchipuram 3000 line TAX): next to Chennai, beyond Tambaram

SDCA: Shriramkulam (6), Chengalpattu (14), Tiruvattur (14), Thiruvallur (14), Maduranthakam (12), Kanchipuram (10) [number in parenthesis is the number of dependent LEs]

- main exchange at each town of same name
- STD codes: 4111/12/14/15/16/18/19
- Total of 86 exchanges, ~60,000 lines

⇒ Total of 86 exchanges, ~60,000 lines

Number Space

- 0 is used as prefix for STD, 00 for ISD
  - no telephone number can start with 0
  - first digit 1 is reserved for special service numbers like ambulance, police, fire, railway information, etc.
- when anyone dials 100, call is routed by LE (as programmed) to a central control room located anywhere
  - no telephone number can start with 1
- first digit 9 is reserved for value-added services etc.
  - cellular numbers start with 98
  - no local number can start with 9
  - with n-digit local number, available local telephone numbers = 7 x 10^{n-1}

⇒ Total of 86 exchanges, ~60,000 lines

Cellular Overlay

- Mobile Switching Centres (MSC) are like large local-cum-trunk exchanges
  - MSCs handle all cellular subscribers
  - MSCs are connected to TAXs on trunks
- All cellular numbers start with 98
  - an operator is given an access code pqr and a cellular number is 98pqr xxxxx
  - 10^5 subscribers per access code
- PSTN subscriber dials 98… if in same circle, and 098… if in another circle
  - e.g. Chennai PSTN subscriber dialing Chennai cellular → 98…
  - Chennai PSTN subscriber dialing TN circle cellular → 98…
  - TN circle PSTN subscriber in Vellore dialing TN circle cellular subscriber → 98…
  - TAX treats cellular number 98pqr as any other access code for routing

⇒ Total of 86 exchanges, ~60,000 lines

Cellular Overlay (cont'd.)

- Cellular subscriber dialing any PSTN subscriber ⇒ dial full national number i.e., access code + telephone number
- “Local Call” : within circle
- “STD Call” : call to a party in another circle
- if cellular subscriber roams to another cellular circle,
  - incoming call goes to home circle first and then is forwarded
  - cellular subscriber pays for STD charges between home circle and current location
  - outgoing call made just like cellular subscriber of the circle
  - accounting between cellular operations for billing
- Cellular Network is a circle-level overlay with one or more interconnects to corresponding TAXs in each circle

⇒ Total of 86 exchanges, ~60,000 lines

Telecom Networks and Switching: The Local Loop

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⇒ Total of 86 exchanges, ~60,000 lines

The Local Loop

- A pair of copper wires connecting subscriber terminal to the exchange line interface port
  - the pair is twisted (~ 3-4 twists every foot or so) to reduce induced coupling to other pairs in same bundle
  - characteristic impedance is 600 ohms
  - if subscriber terminal draws less than 20 mA into a 600 Ω termination (~250 mW), exchange can power the terminal
    - the (comes in various gauges (diameters)
      - 28 gauge → 0.4 mm
      - 20 gauge → 0.3 mm
      - typically 0.5 mm dia is used to get of exchange (primary cable), dropping to 0.4 mm dia for the last segment to the subscriber

⇒ Total of 86 exchanges, ~60,000 lines
Subscriber Terminal
- Telephone
- Fax Machine / Modem
- PCO

- like a telephone in 0-4 kHz band
- metering pulses at 12/16 kHz

Mic
Speaker
Push buttons or rotary dial: 0-9, *, #, Flash

2W/4W Conversion
- Sense $v_{AB} = (v_1 - v_2) / 2$
- Subtract $v_2$ from $v_1$ using a subtractor: $v_2$ (called hybrid)

Echo
- $600 \Omega$ terminations are not exact, or characteristic impedance of line varies or due to other component (subtractor, etc.) tolerances,
- extraction of $v_2$ not perfect
- $v_2 = \alpha v_1$
- an echo of one's own speech is heard
- called talker echo
- this is desirable in a telephone instrument 2W/4W hybrid, as one wants to hear oneself speak
- avoid "plugged ears" effect
- $\alpha$ made small but significant in telephone (called sidetone)

Twisted Pair Frequency Response
- Frequency response is bandpass
- Isolation transformer/capacitor blocks around d.c.
- $g_0$ causes increasing attenuation with frequency
- on very long loops, (>5 km) loading calls placed periodically to improve flatness of frequency response till ~3 kHz, but sacrifice beyond 4 kHz
- more prevalent in analog 2W trunks in the old days
- voice band in telephony = 0.3 - 3.4 kHz
- in-band loss increases with distance, and more for thinner $g_0$

Line Interface in exchange
- isolation transformer to isolate line from rest of exchange
- 48V battery (with current limiting to 30 mA) power feed
- C is "short" for voice band from 150 Hz upwards, but "open" for 25 Hz
- $v_r$ is a 75V 15V ± 5V, 25 Hz, sine wave ringer (superposed on 48V d.c)
- fuse and gas-discharge tube (GDT) surge arrestor at MDF protects exchange from 230V and lightning
- opto-isolated sensor for sensing current flow
- detecting telephone activity
- when GDT fires, loop is closed, and d.c current flows
Out-of-band Signalling

- **On-Hook/Off-Hook**
  - When telephone handset is lifted from cradle, the local loop, which is normally open, is closed
  - Current flows, value depends on a loop resistance, but limited to 20-30 mA
  - Voltage drops from 48V (on open circuit) to ~ 12V (~600Ω x 20mA) across telephone
  - Ringing is caused by 75 r.m.s, 25 Hz a.c signal
    - Cadence (ON period / OFF period) varies with country
    - 75 V r.m.s not needed these days for piezo electric buzzers, but this is a legacy of the days when the telephone had a bell
    - Current drawn by ringing phone is small

- **Out-of-band signalling**: << 100 Hz or >> 4 kHz
  - Pulsing caused by flowing/stopping of current due to closing/opening loop
  - 12 or 16 kHz pulses used for metering to PCOs
  - Battery polarity reversal to indicate that metering has begun

- **In-band Signalling**: 0.3 - 3.4 kHz
  - Touch-tone dialling
  - Dial tone, busy tone, ring back tone, announcements, etc. fed by exchange towards subscriber
  - Calling Line Identification (CLI) tones

Out-of-band Signalling (contd.)

- **Pulse, or decimal, dialling**
  - Break : Make : 2 : 1
  - Make + Break duration is 100 ms
  - Inter-Digital Pause > 1 sec

Out-of-band Signalling (contd.)

- **Battery reversal**
  - Used to indicate starting of call (i.e., beginning of metering)
  - Implemented with a bridge at line interface

Dual-Tone Multi-Frequency (DTMF) Signalling

- **Pulse Dialling** too slow
  - 10-digit number takes average of 0.5 x 10 + 1 x 9 = 14 sec.
  - Inter-exchange signalling changed from pulse to tone-based
  - Low-cost electronic tone generation possible in telephone instrument
  - Change subscriber dialling to tone-based (DTMF)

- **Dual-Tone Multi-Frequency (DTMF)** signalling
  - Frequency table
    - Pulse Duration 4 ms, Inter-Pulse Gap 3 ms
    - IDP > 400 msec, but once it exceeds \( \frac{1}{8} \times 125 = 62.5 \) ms, we can declare digit
  - Maximum IDP = 5 sec, to declare dialling complete
  - Tolerances for telephone instrument are obviously tighter
  - In rotary-dial phones, min. IDP ensured by time taken to rotate dial
  - In push button phones, pulsing controlled by electronic timer
  - Off-Hook → On-Hook (clear signal): min. 250 msec
  - Hook-Flash : Off-Hook → On-Hook → Off-Hook, with maximum On-Hook duration = 2000 msec (many telephones have >250 msec flash duration)
    - Used for "interrupting" exchange for some special service

- **Tolerance at Exchange**
  - 8-12 pps
  - Break/Make Ratio : 1:1 to 4:1
  - IDP > 400 msec,\( \left( \frac{1}{8} \times 125 \right) = 62.5 \) ms, we can declare digit
  - Maximum IDP = 5 sec, to declare dialling complete
**DTMF Specifications**

- Main problem is talk-off: false detection of digit due to speech, or failure to detect digit in background speech/noise
  - To reduce probability of talk-off
    - Most telephones cut mic path when keys are pressed
    - DTMF receivers in exchange are connected to a line only on demand
- When one goes off-hook, or one presses FLASH

**Choice of frequencies and amplitudes to minimise talk-off**

- Probability of talk-off cannot be made zero
  - Problem of any in-band signalling scheme

**DTMF Specifications (contd.)**

- Error in frequencies: $< 1.5\%$
  - Low-cost oscillator in telephone
- Large LCM among frequencies both within band and between bands
  - Reduce talk-off due to harmonics
- Minimum tone duration as large as possible, consistent with average human dialling speed
  - $40\text{ msec}$
- Minimum IDP = $40\text{ msec}$
- Nominal dialling speed $= 10\text{ digits/sec}$ (e.g., when redial button is pressed)
  - Typically user presses each button for $160\text{ msec}$ and IDP $= 250\text{ msec}$

**DTMF Receivers**

- Sophisticated spectral estimation devices that look for
  - One and only one frequency in each band
    - Near to tolerance limit
    - Power in 2 tones $> \text{rest of power}$
    - Frequencies within tolerance limit
    - High-resolution frequency estimation from $30\text{ msec}$ signal
    - Minimum tone duration, IDP, ...
- Typically, no need for one per subscriber line
  - Connected 'on demand' via the switch itself, this also reduces talk-off

**Comparison of Decadic and DTMF Dialling**

<table>
<thead>
<tr>
<th>Decadic</th>
<th>DTMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow ($&lt; 1\text{ digit / sec}$)</td>
<td>Fast (upto $10\text{ digits / sec}$)</td>
</tr>
<tr>
<td>Out-of-band ($&lt; 100\text{ Hz}$)</td>
<td>In-band</td>
</tr>
<tr>
<td>Signalling from end to end not possible</td>
<td>End-to-end signalling possible</td>
</tr>
<tr>
<td>False digits due to speech not possible</td>
<td>False digits possible</td>
</tr>
<tr>
<td>One-on-one detector per line</td>
<td>Assigned on demand by exchange</td>
</tr>
</tbody>
</table>

**Metering Pulses**

- "Home" metering introduced
  - Enables PCOs and PBX to provide individual billing
- Out-of-band $16 \pm 1\%$ kHz ($12\text{ kHz}$ in some countries) pulses used
  - One pulse indicates one meter unit
  - Not audible, can be additionally filtered by subscriber equipment
  - Pulse durations $= 125\text{ msec} \pm 25\text{ msec}$
  - Pulses detected by subscriber-end equipment for billing purposes
Calling Line Identification

- tones sent by exchange before feeding ring voltage
- tones led to "open" line:
  - high impedance termination (>20 kohms) on subscriber-end
  - no off-hook current detected
- always 10 digits are sent
- subscriber terminal detects tones (no talk-off problem) and displays digits

Subscriber Line Interface

- Performs the following functions:
  - Battery Feed
  - Overvoltage protection: GDT + fuse on MDF for primary protection, isolation transformer + varistor on interface card for secondary protection
  - Ring Feed
  - Supervision: detection of line status - On/Off - hook
  - Codec: analog-to-digital conversion and vice versa, in digital switches
  - Hybrid: for 2W/4W conversion in digital switches
  - Test: built-in capability for measuring line capacitance, insulation resistance, interference voltage, "click test" (reverse polarity in On-hook state)

Subscriber Line Interface Circuit

- A SLIC is a highly integrated, low-cost device that provides all the required line interface functions (except primary protection)
- controlled typically by a microcontroller / DSP
- often also has programmable gains and codec
- some universal SLICs have programmable terminating impedance — 600Ω, 900Ω, complex impedance, ...
- some generate 75 ringfeed, some need external input, some need a low-voltage a.c. drive (from switch via codec!)
- metering pulses require additional circuitry (cannot support via codec!)

Typical Architecture of Line Interface card

- N=8/16/32
- processor bus controls SLICs
- PCM bus is connected to switch matrix
- processor also communicates with central call processing unit
- built-in-test permits each local loop in turn to be physically connected to measurement devices

Main Tasks of Line Processor

- detection and validation of On-hook/Off-hook status and decadic digit detection
- de-bounce and validate make and break to reject when outside tolerance limits
- setting of gains, etc.
- assist in conducting line tests; increase speed of testing
- test 100’s lines in 24 hours
- take actions (feed ring, reverse polarity) & report events
  - on-hook / off-hook flash
- in general, offload low level tasks from central processor and parallelise the operations

Echoes in the Telephone Network

- Talker echo from distant exchange:
  - audibility depends on level of echo at hybrid and on losses in local loop and on gains in SLIC
  - echo at A = L_a G_t, a G_r, b E_b G_t, b G_r, a L_a x (Transmit Level)
- Listener echo: echo heard by B when A speaks, due to double reflection:
  - level = L_a G_t, a G_r, b E_b G_t, b G_r, a E_a L_b
- Echo Return Loss (ERL) = signal level / echo level
  ⇒ ∞ for perfect hybrid
Problems Caused by Echoes

- If round-trip delay < 20 msec, echo not heard distinctly
- Not a problem in terrestrial links except transoceanic links
- To reduce echo, \(G_t\) and \(G_r\) programmed such that typical end-to-end loss ~ 7-10 dB
  - Higher when \(L_a\) is less
- If round-trip delay is large, possibility of oscillation exists at a low frequency for which ERL is not good
  - Called singing
- Echo suppressors/cancellors used if round-trip delay is large, e.g., via satellite links
  - Echo suppressor cuts in/out 9-12 dB attenuation in A's receive-path based on whether A is talking/listening respectively
  - Echo canceller is an adaptive digital filter that learns the echo impulse response and subtracts the echo

ISDN: Local Loop goes Digital

- Unloaded tp has a bandpass frequency response
  - For high frequencies, attenuation is \(\propto f^{-2}\)
  - Delay distortion: \(\propto f^{-1}\)
  - A wideband pulse will get distorted
    - Both amplitude and phase distortion: \(\propto f^{-1}\)
- Employ digital transmission with adaptive equalization
  - Equalizer adapts to channel and tries to become \(\approx H(f)\)
  - Beyond this, main impairment is cross-talk from other pairs in same cable also carrying wideband digital transmission

Digital Transmission in ISDN

- Pulse transmission at 80,000 pulses/sec
- 4 amplitude levels (±2, ±1) employed
  - 4 “symbols” : quaternary alphabet : 160 kbits/sec
  - ±1 kbps / ±1 Quarternary Symbol
- Pulse shape chosen to minimise inter-symbol interference on ideal channel
- Equalizer in the receiver compensates for channel-induced distortion
- Duplex transmission on 2 wires, as in analog telephony
  - 2W/4W hybrid necessary
- Fixed analog hybrid not good enough: echo is undesirable interference
  - Employ adaptive echo canceller

ISDN Receiver

- Receiver is primarily DSP based
- Adaptive equalizer and echo canceller get trained at link set-up using special training signals that sound the channel, and echo path, respectively
  - Subsequently, the two blocks track slow changes based on the detected data

ISDN Payload

- 160 kbits/sec = 2 x 64 + 16 + 16 kbps
  - 2B1Q
  - D channel
- B channels: two 64 kbps user payload channels
  - Circuit-switched
- D channel: one 16 kbps channel used for signalling
  - A between ISDN terminal and network
  - User equipment and network
  - Packet switched
- Packet switched data paths between
  - User and network
  - User and user
  - Send digits, get metering information, temporary suspension of circuits (type i)
  - Send message to user terminal at other end (type ii)
**ISDN Addressing**

- International ISDN number + Subaddress
  - 14 digits (max)
  - 40 digits (max)
  - ISDN number allowed more digits than PSTN number
- International ISDN number: country code + national ISDN number
  - National ISDN number can be longer than PSTN number
  - Allows a prefix for indicating multiple networks (PSTN, X.25 messaging network,...)
- Subaddress is used for user-to-user messaging
  - E.g., to identify a specific device at user termination
  - Transparent to network

**Telecom Networks & Switching**

**Implementation of ISDN**

- Existing local loop can be used
  - Bridge taps (open tips that are “hanging off the loop”) must be disconnected
- New interface card in exchange
  - Two 64 kbps B channel circuits from each line to/from circuit switching matrix
  - Messages to/from D channel sent from/to packet switch
- Messages/packets travel between exchanges on SST network
  - SST is a pre-requisite for ISDN services

**An Example of a Sophisticated ISDN service**

- Always-On, Dynamic ISDN
  - Internet access using ISDN port
  - 9.6 kbps packet-switched link to ISP on D channel is always on
  - 64/128 kbps circuit-switched B channel set up when required by user terminal
  - Suspended when traffic is less
- Results in better utilisation of PSTN circuits for Internet access

**From Local Loop to Access Network (AN)**

- Copper pair getting costlier by the day
- Concentration can effectively reduce the number of lines needed form a cluster of subscribers
- New multiplexing and transmission technologies can be leveraged to efficiently carry the N concentrated lines to the exchange
  - Concept of Remote Line Unit (RLU)

**RLU - Exchange Interface**

- Physical interface usually standard
  - Permit standard transmission equipment to be used
- Signalling protocol proprietary
  - Brand X exchange works only with Brand X RLU

In 1996,

- V5.2 Signalling protocol standardised for interfacing Access Network (AN) to Local Exchange (LE)
  - Brand X exchange with V5.2 supports Brand Y AN (RLU is one type of AN)
- V5.1 protocol is for AN without concentration

**Telecoms Network and Switching: New Developments**

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**VS.1/VS.2 Protocol**

- Message-based protocol for subscriber signalling
  - events generated by subscriber (ON Hook / OFF Hook, Digits...) and exchange (ring, tests, ...) are mapped to messages
  - ISDN D-channel messages also transported between LE and AN
- in VS.2, AN's port number has to be mapped to PCM channel number for each call due to concentration
- a bundle of up to 16 E1s constitutes one VS.1 / VS.2 interface
  - some PCM channels can be configured for VS.1 / VS.2 signalling protocol
  - in case of failure of an E1 being used for signaling, PCM channels on another E1 take over, based on prior configuration

**Fibre Access Network**

- RT is like RLU is functionality
- Several RTs connected to a Multiplexer (MUX) with Central Office (or Exchange) using optical fiber
- Dual fiber-ring ensures survivability against single node/link failure
- Interface to exchange uses VS.2 signalling protocol

**Wireless Access Network (also called Wireless Local Loop, WLL)**

- Telephone connected to a Remote Station (RS)
- RS communicates on radio to Base Station (BS)
- BS controller (BSC) controls several BS
- Radio channels assigned on demand
  - concentration occurs on air link
- Quick deployment, no wires / cables (except may be for a few BS - BSC links)
  - but telephone now powered locally

In Summary,

- The AN
  - reduces (or eliminates) copper pair length
  - concentrates teletraffic
  - typically converts to digital from closer subscriber
  - interface to LE using VS.2 protocol
- For LE without VS.2 support,
  - either proprietary signalling to proprietary AN (e.g. WLL/RLU mated to a specific switch)
  - or: expand again (e.g. CD-MUX or BSC) to a standard subscriber interface, usually analog 2W
    - e.g. Digital Loop Carrier