TDM and T-Carriers

This lecture describes the earliest commonly-used time-division multiplex (TDM) scheme for transmission of digitized speech signals. The T1 signal carries 24 64 kb/s channels. First introduced in the early 1960's it is still used today.
After this lecture you should be able to: multiplex/de-multiplex a PCM channel to/from a T1 bit stream; compute the payload and channel bit rates for T1 and T3 carriers; compute the time between frame slips; convert between a bit stream and B8ZS coded waveforms.

Introduction

Time Division Multiplexing shares a transmission channel by interleaving data from different sources in time.

The best-known example is probably the T1 TDM system developed in the 1960s for transmission of multiple PCM speech signals between central offices.

A TDM system combines bits or bytes from multiple "tributaries" into one signal. A "frame" is the smallest time interval that contains data from all tributaries.

The term "synchronous" has three different meanings in the context of multiplexing:

- Synchronous receivers derive their bit timing from signal level transitions. Asynchronous receivers require start and stop bits.
- Synchronous data sources operate at a constant rate. Asynchronous sources can start and stop or can change their data rates.
- Synchronous clocks remain phase-locked to each other. Asynchronous clocks can drift with respect to each other; even if they are nominally at the same frequency.

T1 systems are synchronous in the first two meanings and often asynchronous in the last.

The hardware that interfaces a T1 line to a computer is called a CSU/DSU (Channel/Data Service Units). The CSU interfaces to the twisted pair and the DSU to a DTE (typically a router).

The original T1 design was meant for PCM speech only and would periodically "rob" the LS bit for signalling. The more modern T1 configuration described below is often used for data and can pass arbitrary 8-bit values.

T1/E1 Multiplex

The T1 TDM system time-division multiplexes 24 64 kb/s PCM channels by sequentially transmitting 8 bits from each PCM channel. Each set of 24 $\times$ 8 bits/channel = 192 bits per 125 μs frame is followed by a single synchronization bit resulting in an overall bit rate of 193×8 kHz = 1.544 Mb/s

The data stream delivered by a T1 carrier signal is called a DS1 (digital signal 1).

The main purpose of the framing bit is to detect correct framing. The receiver looks at this bit to see if it is still frame synchronized.

The framing bits can also be organized into a 24-frame "Extended Super Frame" (ESF) structure. In this case framing bit positions carry interleaved framing, error-checking and data link bits. This allows a 4 kb/s data channel in addition to a 2 kb/s of bits used for framing and 2 kb/s used for error-checking.

The framing and error-checking bits allow the CSU to detect an out-of-frame condition and to monitor the error rate. Alarms (visual, audible, relays, SNMP, ...) can be raised under different conditions such as loss of frame sync, too many errors, and frame slips.

The bits in the 4 kb/s signalling channel can be used for reporting alarms to the remote end or turning loopback on and off. This channel can also be formatted using an HDLC-like protocol that can be used to send arbitrary messages.

Outside of North Americal a similar TDM scheme called E1 is used that multiplexes 30 payload channels and 2 synchronization and signalling channels per frame with a total of 32×8 = 2.048 Mb/s.

T1 Physical Layer

T1 operates over twisted pair with 6000 foot repeater spacing and one pair in each direction. The nominal signal level is 0 dBm and the CSU has to be tested for compliance with PSTN (EIA-968).

Since no scrambler is used, a line code with high transition density is required to allow the receiver to recover bit timing.

The original T1 systems used AMI (alternate mark inversion), but long strings of 0's result in no transitions so modern T1 systems use a line code called B8ZS.

This line code is similar to AMI: there are 3 voltage levels, and alternate marks (1's) reverse their polarities to obtain zero DC balance. The pulse width is 50% of the bit duration.

However, the transmitter substitutes a special sequence if it detects a sequence of 8 consecutive zeros. These special sequences, 00-+0+- if previous pulse was a - or opposite if previous pulse was a +, include coding violations so they can be recognized and zeros substituted.

Exercise 1: Convert the sequence 0100 0000 0000 0100 to a B8ZS waveform assuming the previous mark was transmitted as a positive pulse.

Note that each sequence is balanced and includes two coding violations (one initial and one embedded).

The HDB3 line code is used by E1. It is similar but substitutes for sequences of four consecutive zeros and thus has a higher guaranteed transition density.

The transmit clock can either be generated from the receive clock or supplied by a data source (such as the CO's switch).

Frame Slips

T1 lines often transmit data to a device that has it's own clock. An "elastic store" (a FIFO buffer) is used where the clock recovered from the T1 is used to write into the buffer and the destination's clock is used to read from the buffer.

This can compensate for short-term variation in two clocks, but if there are multiple independent clock sources (e.g. a link between two COs) then their clocks will be unsynchronized and the frequency difference will eventually leads to underflow (empty buffer) or overflow (full buffer).

When this happens the receiver can duplicate (for underflow) or drop (for overflow) a whole frame. This avoids loss of frame sync but corrupts the output by duplicating or deleting one byte on each channel.

If the number of bits per frame is N and the clock rate difference is ΔR, the time between slips is:

$$\Delta T = \frac{N}{\Delta R}$$

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Slips are undesirable because they cause:

- audible glitches in speech
- bit errors in data systems (typically handled by higher-level protocols)
- visible errors due to bit errors in voice-band data or fax communication

It is possible to achieve low rates of bit slip by using high accuracy clocks. For example, many COs have "Stratum 1" clocks derived from GPS signals with errors of less than 1 part in 10^{11}.

Exercise 2: How often do frame slips happen for an error of 10^{-11}?

Higher-Level T-Carrier Multiplexes

If higher-speed channels are available, it is possible to time-multiplex multiple DS1 streams. For example 28 DS1's can be combined into a DS3. These higher speeds are usually transmitted over fiber.

Unlike T1, higher-level T-carrier multiplexes interleave bits from different channels rather than bytes since the framing bit needs to be transmitted along with the data bytes.

Since DS1 frames are not aligned to DS3 frames, it is not possible duplicate or drop frames during slips. Instead, the DS3 multiplex includes "stuffing" bits that can be used to carry extra data to reduce the amount of data in the buffer. Special bits in each frame indicate whether the stuffing bits contain data or not.

The stuffing bits as well as the DS3 framing and signalling overhead push the DS3 bit rate to 44.736 Mb/s instead of 28×1.544=43.232 Mb/s.

Similar multiplexes are defined by the ITU (e.g. E3 is 34.368 Mb/s).