Introduction

In August 1986 the T1D1.3 (Now T1E1.4) technical subcommittee of the American National Standards Institute chose to base their standard for the ISDN Basic Access on the Network Side of the NT1 on an echo cancelling technology (over Time Compression Multiplexing) using the 2B1Q line code. This decision culminated over 12 months of intensive study during which the properties of various line codes such as Biphase, AMI, MDB, 4B3T and 3B2T as proposed by some of the world's leading research organizations were compared. These codes were compared on the basis of theoretical analysis, as well as actual performance measurements conducted with prototype systems operating on 15 test loops. These test loops were chosen from a data base representative of the entire North American loop plant. After this exhaustive program of measurement and analysis, 2B1Q was chosen as the optimum code based on the best performance/complexity trade-off of all the evaluated line codes. 2B1Q was found to provide the greatest loop plant coverage for a given level of transceiver design complexity of any code studied.

These advantages of the 2B1Q line code were first recognized by British Telecom Research Laboratories (BTRL) and proposed by Mitel after extensive comparison of various codes in their search to find the optimum digital subscriber line technology. The line code is based upon Pulse Amplitude Modulation (PAM) technology which takes multiple binary bits and converts them into a multi-level signal. In the case of 2B1Q, two binary bits are converted to one of four symbols, the effective transmission rate on the line is reduced by the ratio 2:1 (i.e., half the transmission rate) or from 160 kbit/s to 80 kbit/s. This principle is called baud rate reduction. The advantages of baud rate reduction is to lower the frequency component on the transmission line allowing the transmission to benefit from reduced line attenuation and improved immunity to near end crosstalk and noise (can filter the energy at the higher frequencies).

Line Coding

Two broad classifications of line codes exist; block codes, and linear codes. Of the block codes, 4B3T and 3B2T are the most prominent. Biphase, and AMI are the leaders in the linear field. 2B1Q can be considered to be either a block code, or a linear code, depending on one's definition of a block code. For the time being, we can call it a "linear block code".

In the strictest sense, block codes make use of look-up tables to perform conversion from binary bits in a 2 level system to X-nary bits in an X-level system. Using a multi-level line code has the effect of reducing the transmit spectrum of the transceiver by a factor dependent on the line code used. Figure 1 shows an example of a 4B3T conversion where 4 binary bits are converted into 3 ternary bauds (3 level). The same principles apply to 3B2T, except the ratios are different. For 4B3T, the effective transmission rate is reduced from 160 kbit/s to 120 kbaud/s (160 * 3/4).

2B1Q line code has baud rate reduction from 160 kbit/s to 80 kbaud/s, but it does not make use of look-up tables in order to perform this reduction. It is the use of these tables which differentiates block codes from linear codes. Baud rate reduction is not enough to label a line code a block code.

Linear codes such as Biphase and AMI, allow the system to determine the next output baud without resorting to conversion look-up tables. Based on the current bit stream, the next output baud can be determined. 2B1Q falls into this category. Knowledge of the two current bits (dibit) results in a prediction of the next output baud. A bit represents 2-level decisions (either 1 or 0), but a baud can represent several levels. If the transmit rate is equal to the incoming rate, such as with Biphase or AMI, then bit and baud can be used interchangeably, However, when there is baud rate reduction, bit and baud cannot be interchanged.
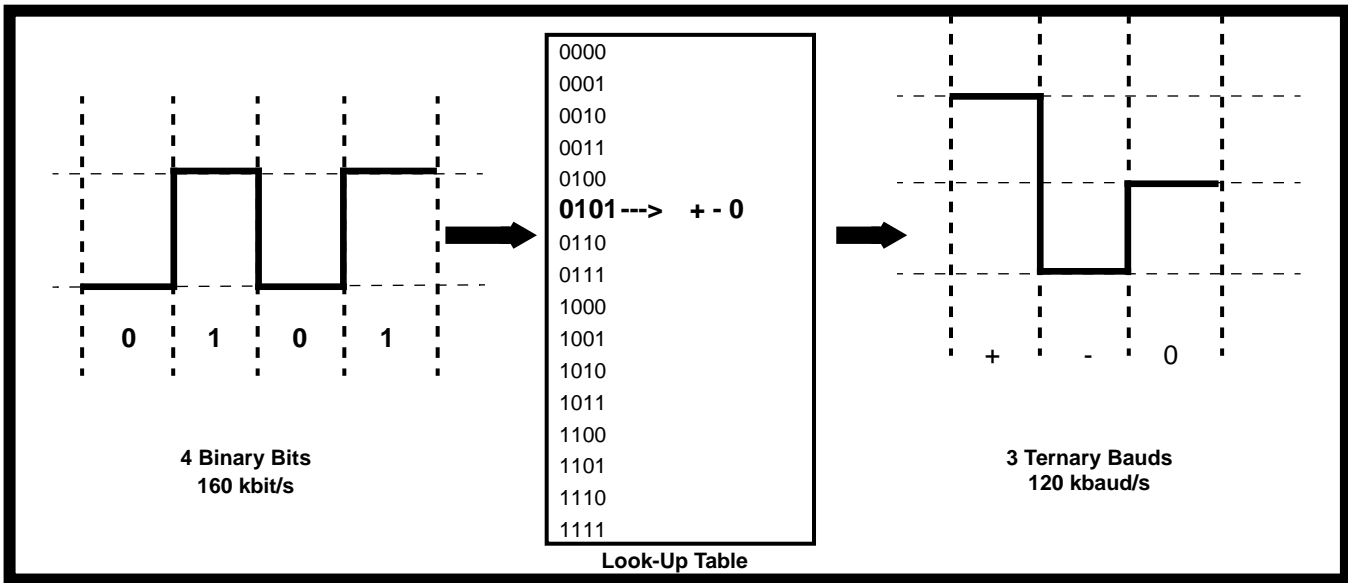
Figure 1 - 4B3T Line Coding Example

2B1Q Coding Rules

2B1Q is a 4-level code. It takes two 2-level bits and converts then into one 4-level baud (quat) as indicated in Table 1. This conversion effectively doubles the period of the symbol. Since the period is inversely proportional to frequency (i.e., f=1/T) the frequency on the line is reduced. With every advantage there are always drawbacks and the 2B1Q is no exception. A 4-level code results in reduced distance between decision levels, thus increasing the required SNR for a given performance level (BER). However, the baud rate reduction and narrower bandwidth results in performance gains which outweigh this drawback.

The important elements of the transmit quat are its sign, and its amplitude. The values assigned to the levels are set so that there is equal spacing between the four levels. Levels can be chosen to be +1, +0.33, -0.33 and -1. In order to eliminate the decimals, we'll choose the four levels to be +3, +1, -1, and -3.

The 2B1Q conversion table is shown in Table 1.

The first bit of the dibit is called the "sign-bit". If it is 0, the output quat will have a negative sign. If the first bit is 1, then the output quat will have a positive sign. The second bit of the dibit is called the amplitude bit, and it determines the magnitude of the output quat If it is 0, then the output level has an amplitude of 3. If the second bit of the dibit is 1, then the output amplitude is 1. This provides for a very simple means of encoding a binary bit stream into a 4-level code.

An example of 2B1Q coding is shown in Figure 2.

DIBIT	OUTPUT QUAT
10	+3
11	+1
01	-1
00	-3

Table 1. 2B1Q Coding Rules

Performance

The transmit baud rate of the 2B1Q system is one-half the rate of linear codes (80 kbaud/s vs 160 kbaud/s). This puts the bandwidth of the 2B1Q system in a lower frequency region of the Power Spectral Density (PSD) graph. It also produces a bandwidth which is much narrower than that for Biphase. See Figure 3 for a comparison of the filtered PSD plots. Telephone transmission lines act as a low pass filter with attenuation varying directly with frequency. Lower bandwidth codes will experience less attenuation, thus achieving greater reach.

A limiting factor to most linear line codes is the performance in the presence of Near End Crosstalk (NEXT). NEXT is generated onto a transmission line from the adjoining twisted pairs that are found in a bundle of cable. The signal on the adjoining pair will induce a signal on the line. The magnitude of the induced signal will increase proportionally with frequency. Therefore, if you lower a signal bandwidth (i.e., lower frequency content) you reduce the effect of NEXT.
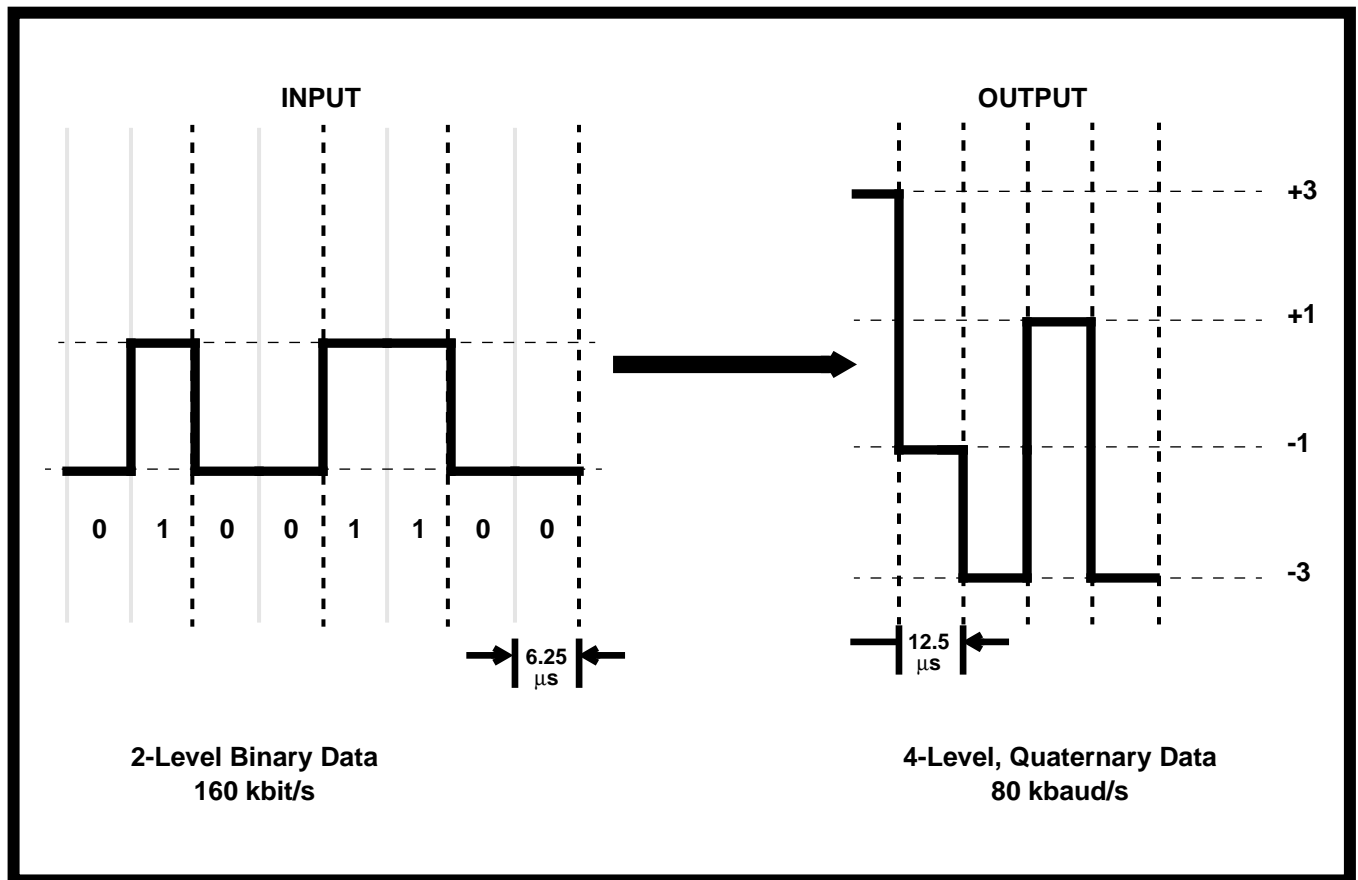
INPUT

OUTPUT

+3

+1

-1

0   1   0   0   1   1   0   0

-3

6.25
µs

12.5
µs

**2-Level Binary Data
160 kbit/s**

**4-Level, Quaternary Data
80 kbaud/s**

Figure 2 - 2B1Q Line Coding Example, 2 Binary, 1 Quaternary

POWER

2B1Q

4B3T

BIPHASE

TCM $\rightarrow$ 640 kHz

40 kHz   80 kHz   120 kHz   160 kHz   320 kHz
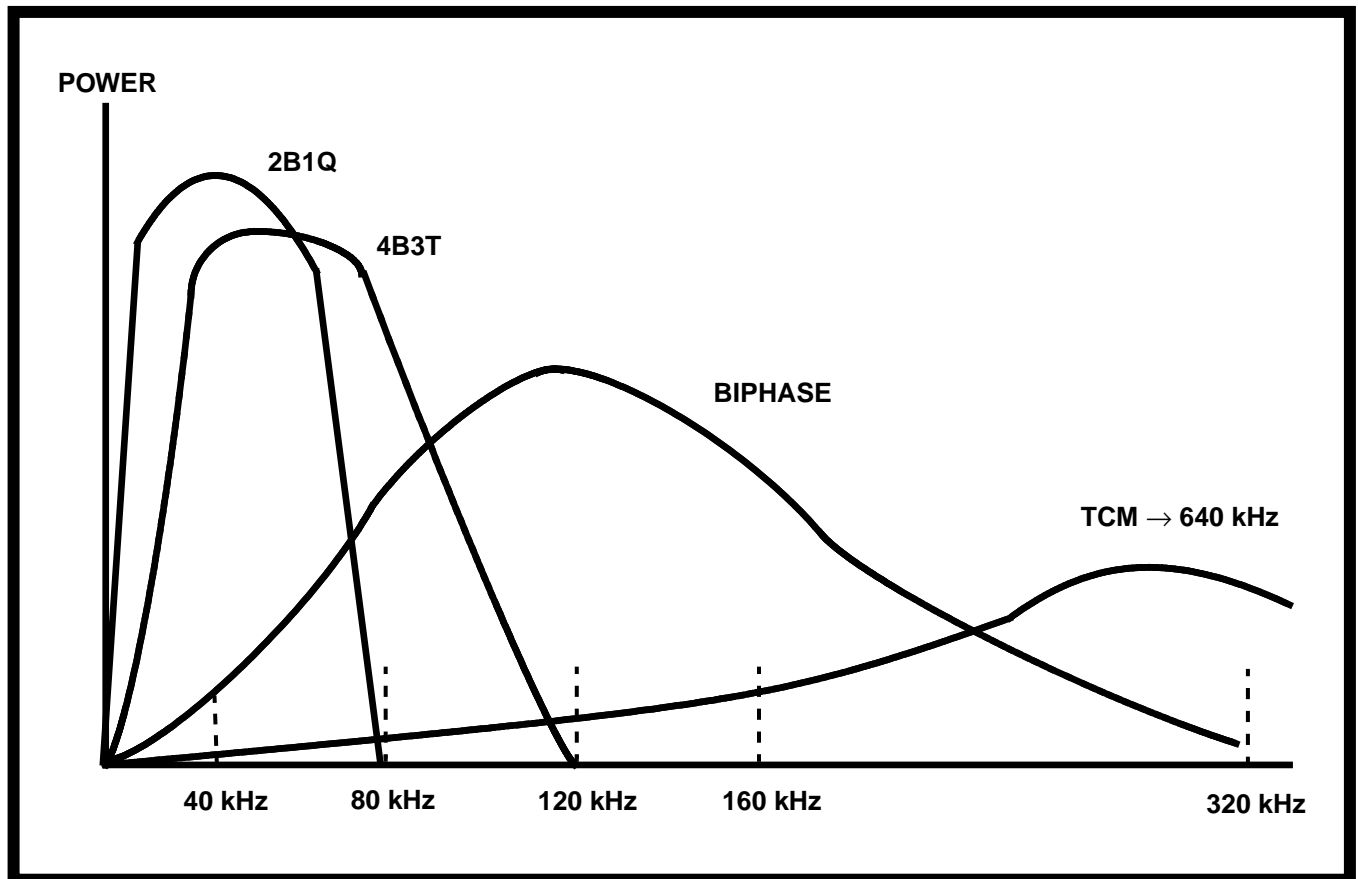
Figure 3 - 2B1Q Power Spectral Density Comparison

Complexity

One drawback of low frequency transmission is that the pulses output on the line tend to develop long "tails", or pulse responses caused by excessive group delay. Several consecutive pulses will tend to have effect on its neighbours, resulting in Intersymbol Interference (ISI). This ISI must be compensated for in order to ensure valid data recovery. Decision Feedback Equalization (DFE) is a technique which can be used to remove the effects of ISI. A DFE is simply a finite impulse response filter which performs a convolution of the loop impulse response with the received data. This convolution will provide an estimate of the effects of ISI which can be removed from the receive signal.

Implementation

A block diagram of a 2B1Q transceiver is shown in Figure 4. The 2B1Q transceiver has two ports consisting of a serial system interface (Mitel's standard ST-BUS), and a line port which interfaces directly to the single twisted pair via a passive termination hybrid and a line pulse transformer.

The two B-channels and the D-channel to be transmitted on the line are input to the DSLIC (on the ST-BUS) into the transmit interface block. The sync word and maintenance bits are added to the data which is then formatted, scrambled and digitally encoded into 2B1Q symbols. This digital representation is passed through a finite impulse response filter which converts the digital representation into an analog waveform. The transmitted pulse is then passed through a smoothing filter whose output is passed to a differential line driver which is capable of driving the line directly through a passive hybrid and line pulse transformer.

On the receive side, the precancelled signal drives a balanced receiver which feeds the input to an over-sampled second-order delta sigma A/D converter. The digital representation of the received signal yields a Pulse Density Modulated (PDM) stream which is digitally filtered and decimated to the 80 kHz baseband. Intersymbol interference (ISI) introduced by the loop is cancelled by a decision feedback equalizer. This is achieved by taking a convolution of the received pulse with the estimated impulse response of the loop. The cancellation of ISI is performed in parallel with the echo cancellation. Estimated received echo is obtained by taking the convolution of the transmit signal with the estimated impulse response of the loop. Feedback from the jitter compensator and the non-linear corrector
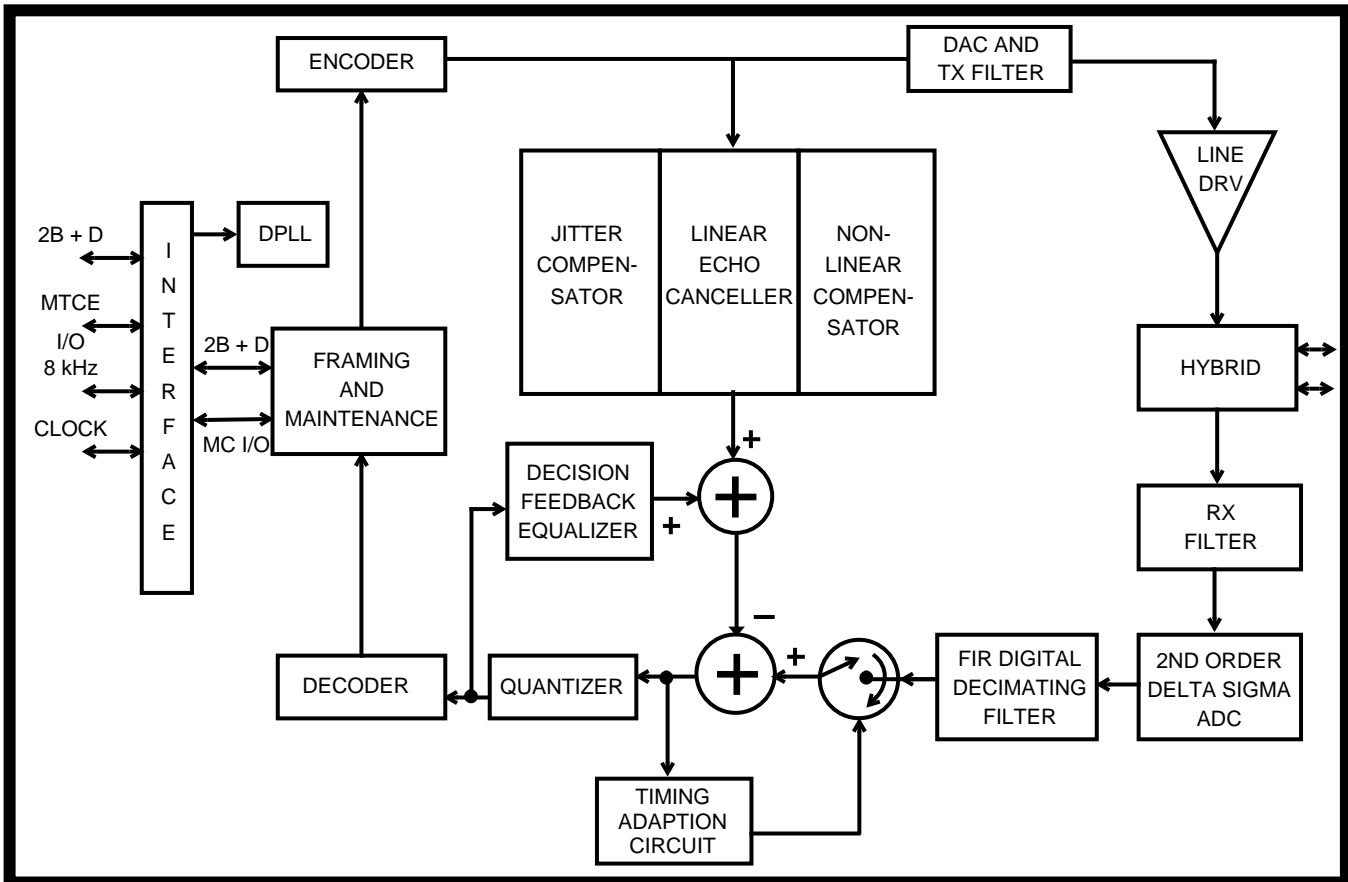
Figure 4 - 2B1Q Transceiver Block Diagram

interact with the coefficients of the echo canceller to reduce the error introduced by jitter and non-linearities in the analog circuitry. The output of all these blocks is summed together and the result is the received data which is passed through a decoder and descrambler before being sent out in TDM bursts on the ST-BUS.

Echo-Canceller (EC)

The 2B1Q chip uses a transversal filter compensator to cancel out the signal echo. This principle is shown in Figure 5. The number of bits needed by the echo-canceller is greater than for the DNIC. The DNIC uses five bits of transmitted signal prehistory. It is expected that the 2B1Q code will need between 30 and 40 bits. The number of bits of prehistory corresponds to the number of "taps" in the Echo-Canceller. These taps carry coefficient values (C_i), which are multiplied with the corresponding Tx bits (B_i) and the product of all the bits/coefficients is summed. This yields an approximation of the signal echo. Tap coefficients in the Echo-Canceller are updated based on an analysis of the error following the quantizer.

Decision Feedback Equalizer (DFE)

The main purpose of the DFE is to compensate for any ISI which is introduced into the system. Major sources of ISI are the pulse response of the transmitted samples, and bridged taps in the network. The Decision Feedback Equalizer operates on a similar principle to that described for the EC above except that it operates on the receive bit stream. It has taps and coefficients which are multiplied with the bit Rx stream in order to generate an approximation of the amount of ISI in the network. This is subtracted from the composite received signal as well. The DFE is expected to require in the range of 20 to 30 taps.

Quantizer (Slicer)

This block establishes which of the four levels is present at the sampling instant. The incoming data is sampled once per baud interval i.e., at a 80 kHz rate. The 4-level signal is converted to binary, based on the inverse of the 2B1Q encoding rules discussed earlier.

Analog to Digital Converter (ADC)

One implementation of the 2B1Q line code makes use of a "delta-sigma" ADC. This is sometimes referred to as an "oversampled" or "noise shaping" ADC. The principle is that the analog waveform is sampled at a very high frequency (10 MHz), and the samples are encoded. This information is then passed through a decimation filter which averages the data collected at the high frequency over a specified period of time and filters out the high frequency quantization noise. This method of doing the analog to digital conversion results in a highly accurate digital representation of the received signal.
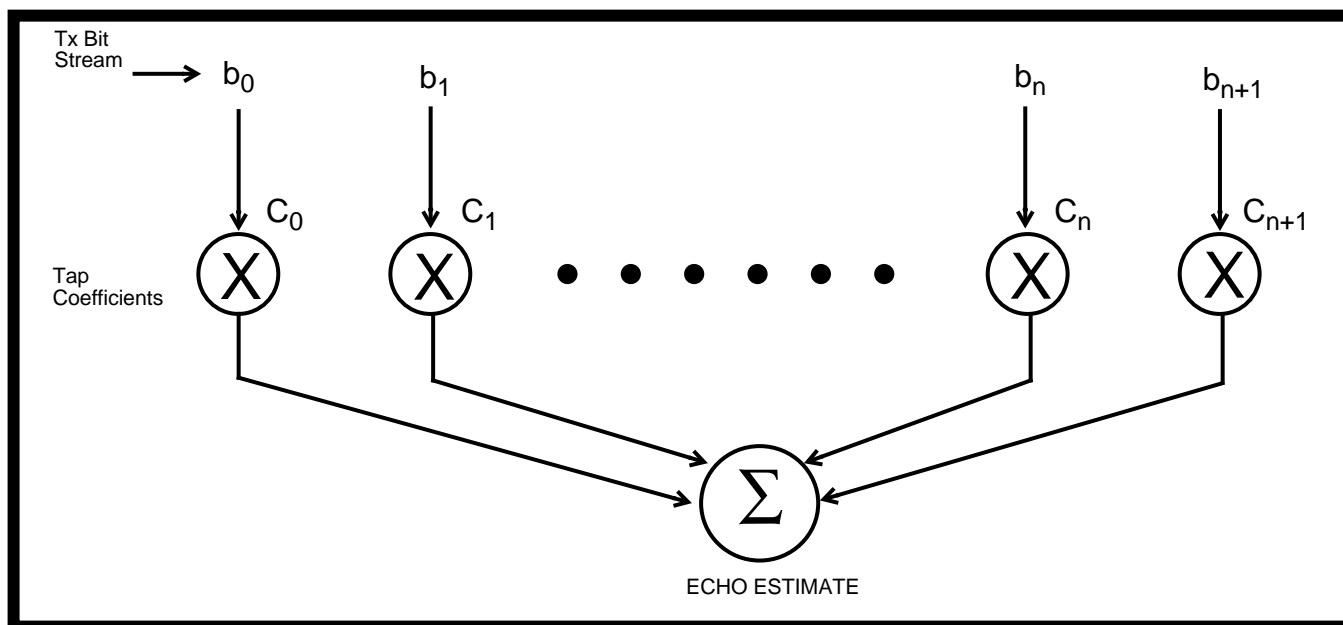

Figure 5 - Transversal Filter Compensator

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