PULSE-INTERVAL MODULATION SIGNAL TRANSMISSION

By J.N. Tripathi*

ABSTRACT

Pulse-interval modulation (PIM) is derived from asynchronous binary - slope quantised pulse - code modulation (ABSQPCM). In ABSQPCM and PIM, the input information signal is approximated by a series of positive decaying steps of equal amplitude and a simple differentiation of these steps provides a series of on-off pulses of varying periods. Pulse-interval modulation system has been experimentally tested for transmission of sinusoidal, data, FSK and speech signals (on tapes supplied by British Post Office Research Station) and the quality of reproduced signals was very good. Pulse-interval modulation belongs to the family of pulse-time modulation systems which have recently been used for video transmission in optical fibre local networks.

1.0 INTRODUCTION

Pulse-interval modulation (PIM) is derived from asynchronous binary-slope quantised pulse-code modulation (ABSQPCM) by modifying the inner loop so that the no-signal oscillations are established and maintained [1,2,3,4,5]. Therefore, all the waveform approximation and modulation principles of ABSQPCM are applicable to pulse-interval modulation. In a ABSQPCM and a PIM system, the input message signal f(t) is approximated by a series of positive decaying steps of equal amplitude $\Delta / 2$ and a slope ρ_o; then a simple differentiation of these steps provides on-off pulses with varying intervals between them.

The instantaneous time interval between the two successive pulses of short duration d_o is given by:

$$T(t) = \frac{\Delta}{\rho_o + f'(t)} = \frac{1}{f_i} \qquad (1)$$

where f_i is the instantaneous pulse-repetition frequency (PRF) of the modulator.

The no-signal pulse-interval repetition frequency f_{io} is obtained by substituting f(t) = 0 in equation (1), and is related to the no-signal pulse interval T_{io} as:

$$f_{io} = \frac{1}{T_{io}} = \frac{\rho_o}{\Delta} \qquad (2)$$

The modulation index m is defined as:

$$m = \frac{|f'(t)|}{\rho_o} \qquad (3)$$

Then, the maximum time-interval T_{max} and the minimum time-interval T_{min} are given by (6,7):

$$T_{max} = \frac{T_{io}}{1 - m} \qquad (4)$$

$$T_{min} = \frac{T_{io}}{1 + m} \qquad (5)$$

Pulse-interval modulation is an asynchronous pulse-modulation system which is self-oscillating and provides output pulses of short duration with large time interval between them. The time interval between two successive pulses varies with the modulating signal.

A pulse-interval modulation system is shown in **Figure 1**. The actual circuit diagram is shown in **Figure 2**. The input signal f(t) and the periodically varying pulses are linearly added and integrated by a two-section RC integrator. Duration of pulses is very much smaller than the interval between pulses. Two

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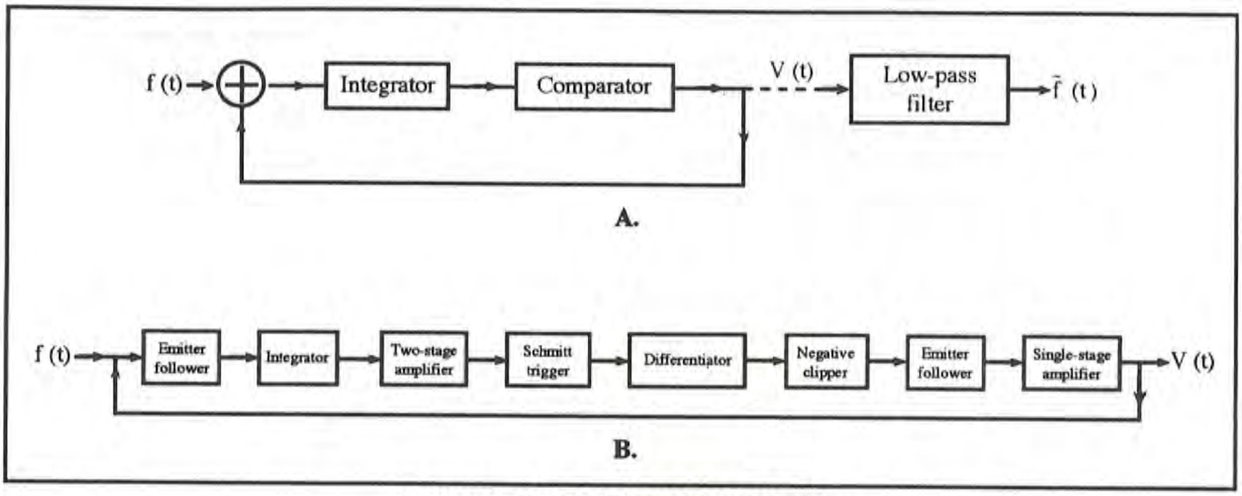
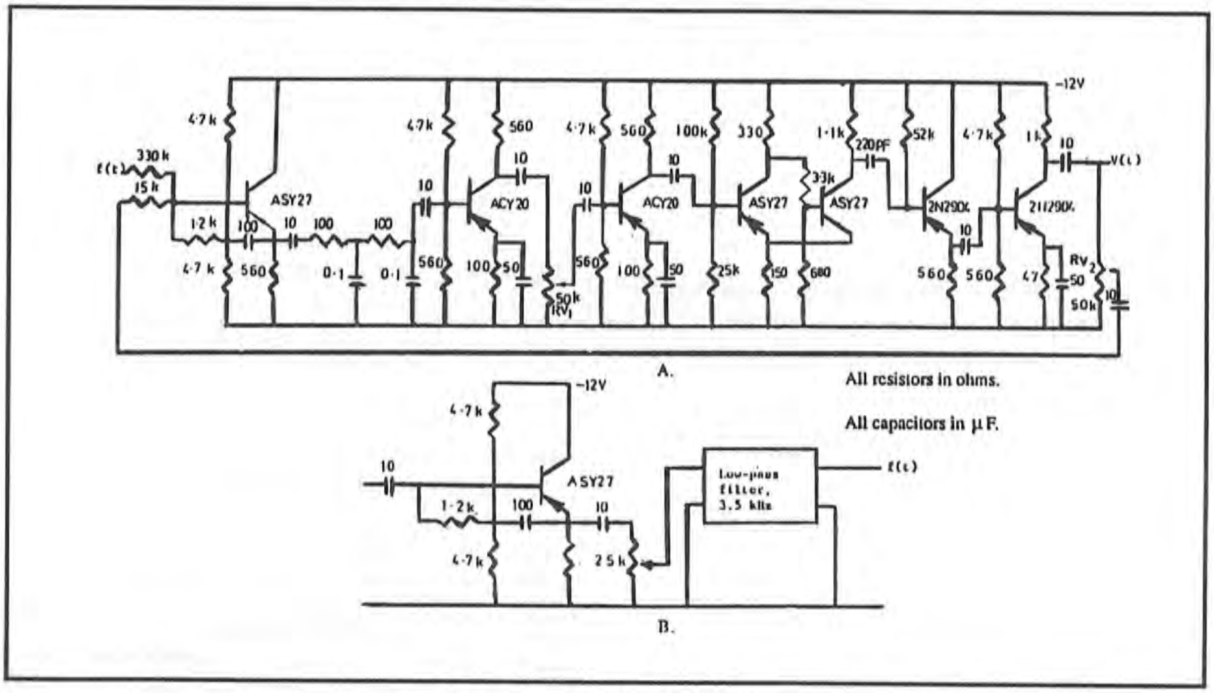


Figure 1: **Pulse-interval Modulation**
A. Principle of Operation
B. Block Diagram



All resistors in ohms.

All capacitors in µF.

Figure 2: **Circuit Diagram**
A. Modulator
B. Demodulator

amplifier stages were used to drive the Schmitt trigger comparator circuit. A differentiator circuit produces short duration (3 microseconds) pulses which are amplified and fed back to the input terminals to maintain continuous oscillations in the closed loop [4].

The demodulator is an impedance matching stage followed by a low-pass filter of input signal bandwidth.

Pulse-interval modulation waveforms are shown in **Figure 3**. The time interval between two successive pulses varies with the amplitude of a sinusoidal modulating wave as shown in **Figure 3B** and **3F**.

2.0 FREQUENCY SPECTRUM

The frequency spectrum of pulse-interval modulated signals is expressed by the following equation (6). The modulation index is m, the modulating frequency is f_m, the no-signal pulse-repetition frequency (PRF) is f_{io} and the PRF to the modulating frequency ratio is

$$\beta = \frac{f_{io}}{f_m}$$

The duty cycle angle is $\theta = \pi \frac{d_o}{T_{io}}$

Since the interval between the pulses varies, the duty cycle angle θ also varies, hence pulse-interval modulation belongs to the family of pulse time and frequency modulation.

Consider an infinite PIM periodic pulse train of amplitude V, pulse duration d_o and a PRF of f_{io}. The frequency spectrum is given by [4, 5].

$$V\,(t) = Vd_o f_{io} + mVd_o f_{io} \cos w_m t$$

$$+ \frac{2V}{\pi} \sum_{n-1}^{\infty} \frac{1}{n} J_o(nm\theta) \sin n\theta \{ J_o(nm\beta) \cos w_{io} t$$

$$+ \sum_{p=1}^{\infty} J_p(nm\beta) \cos\left(nw_{io}t + pw_m t\right)$$

$$+ \sum_{p=1}^{\infty} (-1)^p J_p\,(nm\beta) \cos\left(nw_{io}t - pw_m t\right)$$

$$+ \frac{2V}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sum_{q=1}^{\infty} J_q\,(nm\theta) \sin\,(n\theta + \frac{q\pi}{2})$$

$$\text{x} \left\{ J_o\,(nm\beta)\left[\cos\,(nw_{io}t + qw_m t)\right.\right.$$

$$\left. + \cos\,(nw_{io} - qw_m t)\right]$$

$$+ \sum_{p=1}^{\infty} J_p(nm\beta)\left[\cos\left(nw_{io}t + pw_m t + qw_m t\right)\right.$$

$$\left. + \cos\,(nw_{io}t - pw_m t + qw_m t)\right]$$

$$+ \sum_{p=1}^{\infty} (-1)^p J_p(nm\beta)\left[\cos(nw_{io}t - pw_m t - qw_m t)\right.$$

$$\left. + \cos(nw_{io}t - pw_m t + qw_m t)\right] \qquad (6)$$

where the J's are the Bessel functions of the first kind.

The second term contains the desired modulation frequency component and can be recovered by a low-pass filter.

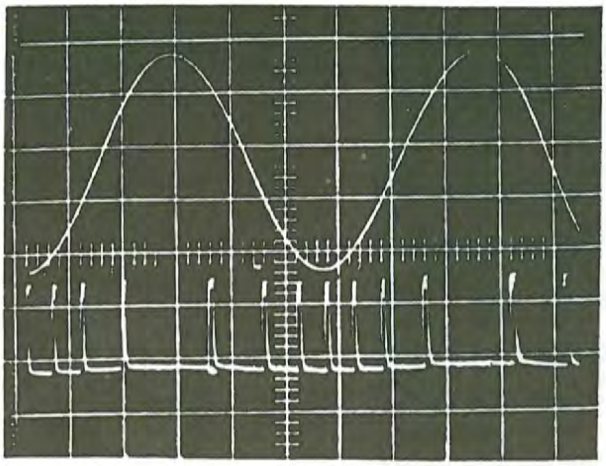
The oscillograms of the frequency components present in PIM are shown in **Figure 4**.

The theoretical expression of eqn. (6) is experimentally verified and there is a fair agreement between the experimental and the theoretical values.

The spectrum is uniform comprising all the odd and even harmonics of the PRF and the sidebands around them. The amplitude of the successive harmonics decreases with the progressive multiple values of f_{io}.

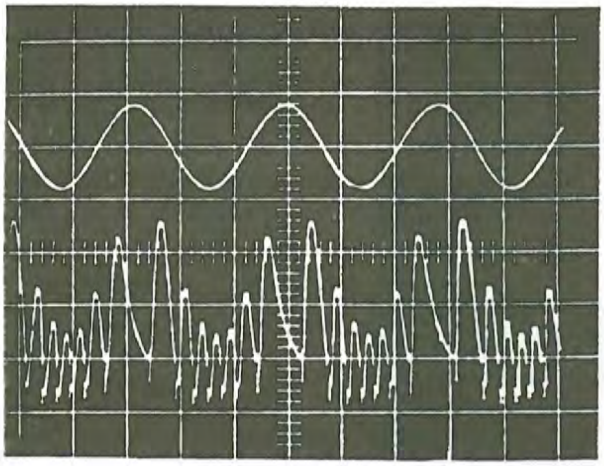
3.0 SIGNAL-TO-NOISE RATIO

Theoretical calculations of noise power in pulse-interval modulation were made for the ideal case when the pulse duration d_o was negligible in comparison to the pulse-time interval T_{io}. However, this may not be correct in the actual case, and therefore it is necessary to take into account the finite pulse duration d_o. Hence, the pulse-interval modulation turns into a pulse-length



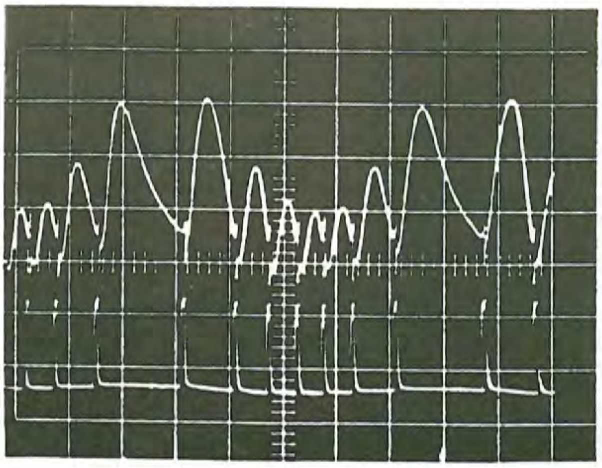
A. Modulating signal
Amplitude = 1 Volt/cm
Time = 50 μsec/cm

B. Modulator output
Amplitude = 5 volt/cm
Time = 50 μsec/cm



C. Modulating signal
Amplitude = 2 Volt/cm
Time = 100 μsec/cm

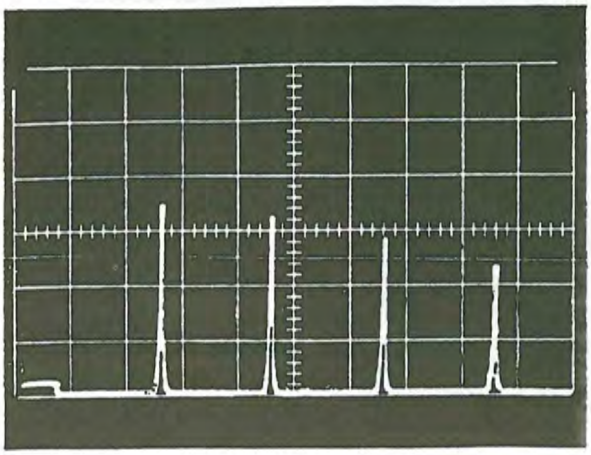
D. Input to the Schmitt trigger circuit
Amplitude = 0.5 Volt/cm
Time = 100 μsec/cm



E. Same as D.
Amplitude = 0.5 Volt/cm
Time = 50 μsec/cm

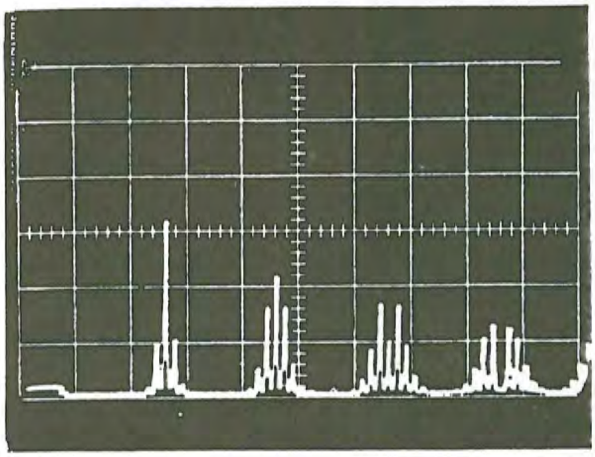
F. Modulator output
Same scale as in B.

Figure 3: **PIM Waveforms**



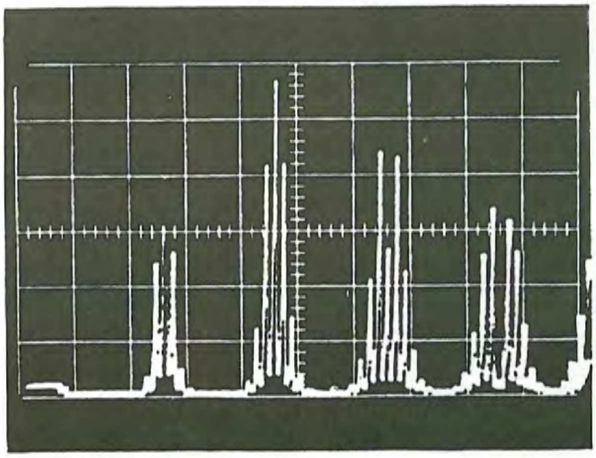
A. Spectrum of unmodulated PIM pulses

Amplitude = 0.05 Volt/cm
Frequency = 20 kHz/cm



B. Spectrum of modulated pulses

Amplitude = 0.05 Volt/cm
Frequency = 20 kHz/cm



C. Same as B but

Amplitude = 0.001 Volt/cm
Frequency = 20 kHz /cm

Figure 4: **Frequency Spectrum**

(or duration or width) modulation (PLM/PDM/PWM) system.

Signal-to-noise ratio expressions are known for pulse-length (duration/width) modulation. Jelonek's signal-to-noise ratio (SNR) formula is [4,6,8]:

$$\frac{V_s}{V_n} = \frac{(2BL-1)}{2\sqrt{2}} \frac{V}{N} \sqrt{\frac{f_{io}}{f_m}} \tag{7}$$

where,

V_s is the RMS audio frequency modulating signal voltage,
V_n is the RMS audio frequency modulating noise voltage,
f_{io} is the pulse repetition frequency (PRF),
f_m is the audio modulating frequency recovered by a low-pass filter of bandwidth f_m,
B is the transmission channel bandwidth before the slicer,
L is the duration of the transmitted pulse,
V is the peak pulse amplitude at the slicer,
N is the RMS noise voltage amplitude at the slicer.

At the slicer, a peak noise voltage N produces a time shift Δt on a pulse of peak amplitude V, and the noise power due to this time shift is given by Das [7]:

$$\left[\frac{V^2\Delta t^2}{T_{io}^2} + \frac{4V^2}{\pi^2}\sum \frac{1}{n^2}\left\{J_1^2\left(\frac{n\pi\Delta t}{T_{io}}\right)\cos^2\left(\frac{n\pi do}{T_{io}}\right) + J_2^2\left(\frac{n\pi\Delta t}{T_{io}}\right)\sin^2\left(\frac{n\pi do}{T_{io}}\right)\right\}\right]$$

Considering equal noise power contributions from the lower and the upper sidebands total noise power becomes $8V^2/\pi^2$.

The validity of Jelonek's SNR formula and Das' SNR expression has been checked for rectangular-wave modulation (RWM), which is a closed loop pulse-length modulation having a pulse duration of the half square-wave period T_{io} [4].

The experimental arrangement used for the measurement of signal-to-noise ratio of a pulse-interval modulation system is shown in **Figure 5**.

The audio frequency signal bandwidth is measured in the absence of channel noise and the noise power falling in the audio signal power is measured in the absence of modulation. The Elgenco noise generator had a bandwidth of 5 MHz. The linear adder consisted of two 220 ohm resistors and followed by one section of a filter used as a channel filter to control channel bandwidth. The slicer worked at one half of the pulse peak amplitude.

The V/N ratio can be measured at the points shown in **Figure 5**. The peak pulse amplitude V can be measured on an oscilloscope and the RMS noise voltage amplitude N is read directly on the noise generator with no attenuation in its path to the linear adder. Another section of the filter was used as a low pass filter of 3.5 kHz (fm) bandwidth. The power measuring unit consisted of a Dynamco AC-DC converter and a digital voltmeter.

The experimentally measured variation of V_s/V_n with V/N is shown in **Figure 6**. From the **Figure 6** at the threshold level of 17dB (V/N = 7) the output signal-to-noise ratio is found to be 18 dB:

For the same circuit value of

$$L = 7\mu s,\ f_{io} = 25\text{ kHz},\ B = 160\text{ kHz},$$

at the threshold level of V/N = 7,

$$\frac{V_s}{V_n} = 8.34 \quad \text{(using Jelonek's formula)}$$

which corresponds to a signal-to-noise ratio of 18.4 dB. Thus, the experimentally obtained value of the SNR (18 dB) is slightly lower than the theoretical value of SNR (18.4 dB) but it is quite close to the latter. Therefore, the theoretical SNR results are experimentally confirmed [4,6].

4.0 OPTICAL FIBRE SIGNAL TRANSMISSION

Optical fibre networks are being used to provide broadband telecommunication services that utilise multiplexes of video, data and voice channels. The choice of a modulation format on the optical carrier is therefore a principal factor in realising a high performance bandwidth efficient system at an

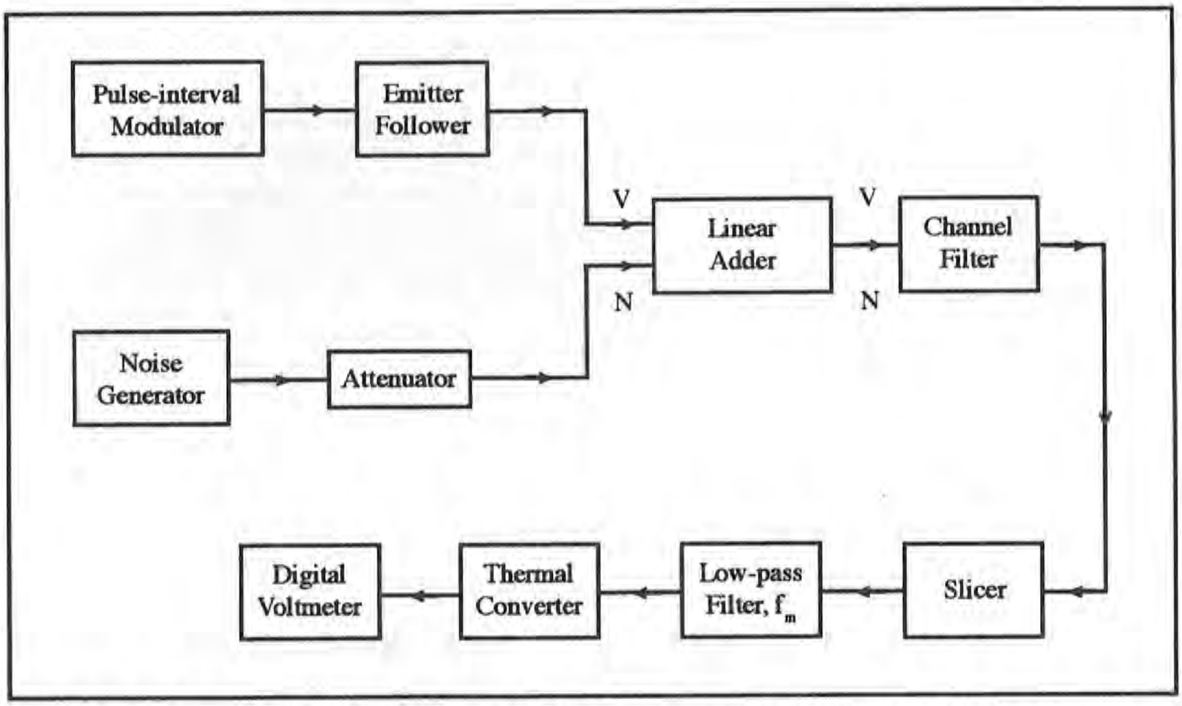


Figure 5: **Experimental Arrangement for the Measurement of Signal and Noise Powers**

acceptable cost. Even though the bandwidths offered by new fibre installations are very high, they are still limited by fibre dispersion and carrier incoherence over practical distances [9].

Analogue modulation schemes, in which the optical source is modulated in a continuous manner are both simple and bandwidth efficient, but often cannot deliver the required signal-to-noise ratio. In addition, these schemes suffer to a certain extent from nonlinearity of the optical channel and associated circuitry severely limiting the quality of the received information through intermodulation and crosstalk. In contrast, digital schemes such as pulse-code modulation (PCM) have been demonstrated to be substantially immune to channel nonlinearity and are capable of producing the required signal-to-noise ratio. However, digital schemes are significantly more complex and costly than analogue schemes, largely due to their coding circuitry and large bandwidth overhead [9].

Pulse-time modulation (PTM) represents an alternative approach that occupies an intermediate position between analogue and digital schemes. Modulation is simple, requiring no digital coding and the pulse format of the modulated carrier renders the scheme immune to channel nonlinearity and allows routing through logic circuits and switching nodes in a network. Moreover, PTM is unique in its ability to trade performance with bandwidth. Large bandwidth is a significant feature of fibre systems.

For short distance applications such as local area networks (LAN'S) may use multimedia or monomode fibre with a dispersive optical carrier which imposes a significant bandwidth limitation in the optical channel. In these applications, low speed optical sources such as light emitting diodes (LED's) can be used, while still achieving the required signal-to-noise ratio. In contrast, the available bandwidth on long distance terrestrial and undersea routes may be very much larger, employing optical amplification and soliton techniques. This additional bandwidth can be readily exploited by PTM to improve performance and signal-to-noise ratio.

The ability to exchange signal-to-noise ratio performance against bandwidth is a property unique to PTM modulation techniques, and is of increasing importance in high-speed networks. PTM techniques are of particular interest where short pulses such as solitons may be employed [9,10,11,12,17].

The adoption of PTM techniques has certain beneficial consequences from the stand point of

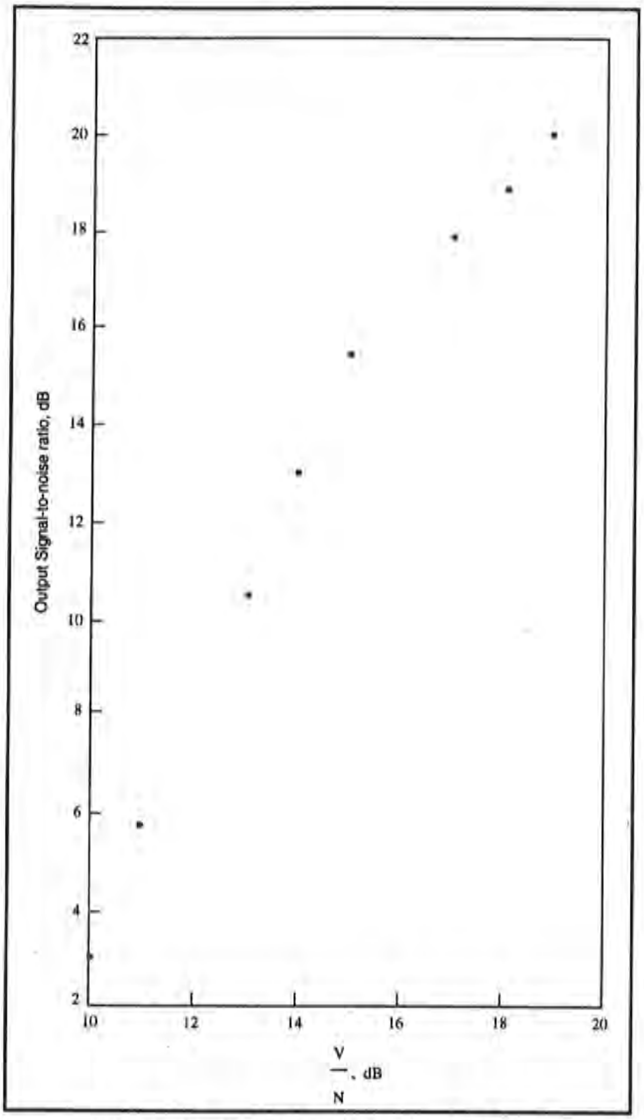


Figure 6: **PIM Signal-to-noise Ratio as a Function of V/N**

optoelectronic subsystem specifications. As PTM deals exclusively with a pulse format, there are no concerns over LED or laser diode linearity as would be the case with direct intensity modulation or subcarrier multiplexing techniques. In addition, for narrow pulse PTM formats, the peak optical output may be maintained at a high level to ensure good noise performance at the receiver without compromising device lifetime through elevated mean transmitted power levels.

An optical transmitter for a PTM system may be chosen primarily for its maximum peak power level to maximise transmission distance [9,11,12,17].

PTM techniques have been reported since the 1940's and it is only recently that a revival of interest has been shown, with the development of optical fibre transmission system. In all PTM, one of a range of time-dependent parameters of a pulsed carrier is used to convey information. The PTM family consists of the following modulation schemes [9-17].

PTM TYPE	VARYING PARAMETER
1. Pulse-position modulation (PPM)	Position
2. Pulse-duration (length) modulation (PDM/PLM)	Duration
3. Pulse-interval modulation (PIM)	Interval (space)
4. Pulse-interval and duration modulation (PIDM)	Interval and duration
5. Pulse-frequency modulation (PFM)	Frequency
6. Square-wave frequency modulation (SWFM)	Frequency

PDM and PPM are both long-established techniques and have been widely adapted for use in optical fibre applications [9]. PFM has been used extensively for optical fibre transmission of video and broadcast quality TV signals. SWFM has been used for the fibre transmission of HDTV (high-definition television) and other wideband instrumentation signals [9,]. Comparatively little work has been published on PIM and PIDM applied to wideband fibre transmission [9].

5.0 CONCLUSIONS

Analogue pulse communication techniques were developed during the second world war for RADAR (radio detection and ranging). Pulse-interval modulation was reported in late Sixties and it was investigated in early Seventies by the author for sinusoidal, FSK data signals and band limited speech signals. Experimental measurements were made of the PIM frequency spectrum. Theoretical analysis of the PIM signal-to-noise ratio (SNR) performance as well as experimental SNR measurements were carried out. Jelonek's SNR formula for PLM/PDM was found correct and applicable to finite duration pulses of pulse-interval modulation. Fundamental basic principles of pulse communication using electrical energy remain the same and these principles are equally valid now in the case of optical carrier communication.

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