All about Pulse Modulation

How Ultra narrow band Modulation works

7/10/07

Pulse modulation is well known in many forms. In communications it first appeared as **"Morse Code"**, otherwise known as "**ON/OFF keying" with "Pulse Width Modulation" (dots and dashes)**. It is quite simple and easy to understand. It was first used on telegraph wires, and later by others (Marconi) in wireless applications.

More recently, if 50-60 years ago can be considered recent, it was applied to microwave links to transmit digital data. Three possible modulation methods were used –**"Pulse Position", "Pulse Amplitude", and "Pulse Width".**

Basically these are amplitude modulation methods when considering their signal to noise relationships. It is a question of, "is it a signal, or is it noise"? The C/N for an ideal amplitude modulation method is 13.5 dB for a 10^{-6} bit error rate. Nearly the same values apply to FM when the same bandwidth is used. An extensive analysis is given in Schwartz (1).

End to End Pulse Widths:

Instead of relying on ON/OFF keying, polarity or phase can be introduced. **"Unipolar" vs "Polar"** keying. Instead of applying + 48 volts ON/OFF, +48 volts can be used for ON and - 48 Volts can be used for OFF. Polar keying, or antipodal signaling, results in a 3 dB improvement in the C/N for a given BER. C/N = 10.5 dB for 10^{-6} BER. See "Bellamy" (2) Fig. 4.25.

Applied to wireless, polar keying is more familiar as **"Bipolar Phase Shift Keying", or "BPSK".** This is referred to as a 2 level method utilizing 180 degree phase shift as opposed to some higher level methods where the data bits are combined into symbols. **"Biphase Phase Shift Keying"** is also possible where the phase is shifted less than 180 degrees. It can be shown mathematically that a phase shift of 90 degrees can have the same C/N as a 180 degree shift (Taub and Schilling (3)). This is commonly accepted, since **QPSK and BPSK have the same C/N for a given BER,** although one is a 180 degree method, the other a 90 degree method.

The NRZ Code.

Data is generally available in the **"Non Return to Zero"** (NRZ) code, which basically is holding the signal ON as long as a digital one sequence is present and OFF as long as zeros are present (in the unipolar format). In the bipolar format it is +V for a one and –V for a zero. Since ones and zero occur in a random format, this amounts to **"End to End Pulse Width Modulation". There is a positive pulse of a variable width as long as there is a one, or string of ones, present and a negative pulse as long as there is a zero, or string of zeros, present.**

These pulses can be analyzed individually as baseband pulses using the Fourier transform. When applied to a modulator as amplitude pulses, the same spectrum applies, but spreading to both sides of the carrier. **(Double Sideband)**. When the RF phases are reversed, as in Bipolar PSK, the carrier is cancelled over time, leaving **the energy in the sidebands. (DSB-SC). This is a specific unique case.** It would not apply to FM or PM, or if the average time on the phases for bit period is not equal.

Suppose for example the pulse widths are changed. Instead of ones and zeros of equal period, assume the use of the **RZ (return to zero)** code. This code has a pulse ON for ½ bit period for a one and OFF for the remainder of the bit period and for zeros. In this case at RF, the carrier does not disappear and both carrier and sidebands are present in the spectrum. With RF modulation this amounts to a carrier with alterations periodically to indicate the presence of a digital one. There are ultra narrow band methods based on this concept. (FK (9) and 3PRK (5)).

"The idea is to find ways to slightly mark the carrier wave with the modulation so that the least distortion of the carrier wave is achieved." (Wm C.Y Lee, (4))

Pulse Position Phase Reversal Keying. (3PRK) alters the carrier for only one or two cycles in the carrier wave stream. (Walker (5)).

Or, the conditions can be reversed. If the data is coded, (**Coded BPSK**) as in **VMSK,** (9) the data can all be carried in the sidebands with the carrier nulled. Only one sideband need be transmitted, **(Single Sideband - Suppressed carrier)**, since all the necessary signal information is carried in that sideband in the form of phase reversals. It is not necessary to restore a carrier, since the sideband itself can serve as the carrier to restore a reference. This concept applies to **VWDK and VMAK** as well. (Wu (6)).

The carrier does not null when the phase shift angle is 90 degrees instead of 180. This is the basis of NRZ-MSB, which uses NRZ baseband coding and quadrature RF modulation.

The pulsed carrier carries the same modulation information as the sidebands. What most people do not realize, and many do not accept, is that the carrier and sidebands are separable under certain conditions, with both carrying the modulation information. This is obvious in the case of VMSK (9), VWDK and VMAK (6) where there is no carrier and only one sideband remains. Single Sideband Suppressed Carrier technology is a very old technology. **The carrier alone can also be used.**

There are preconditions for all ultra narrow band modulation methods. **There must be no FM, hence the signal must be pulse width modulated AM, or equivalent. The phase change $\Delta\Phi$ must be instantaneous. The filter must be able to respond in amplitude and phase to a single RF cycle — that is, have zero group delay, which means having infinite Nyquist bandwidth.**

There are several mathematical papers which show this possibility. (Howe (7) and Hund (8)).

The mathematical description for BPSK of the carrier signal as generally accepted in most texts, is given as:

$I_t = I_m[(\cos(2\pi ft)]$ for phase one, and $I_t = I_m[(\cos(2\pi ft)+\theta]$ for phase two. **Eq. 1.**
θ can be any value from 180 degrees to 90 degrees +-.

This applies to the ultra narrow band methods as well.

Professor Howe's Analysis (7):

Professor Howe published a paper in 1939 analyzing Armstrong's modulation method that utilized PM to create FM. The main point resulting from his analysis is that using abrupt phase change pulses instead of sine waves produces quite different results. There is no Δf for most of the bit period.

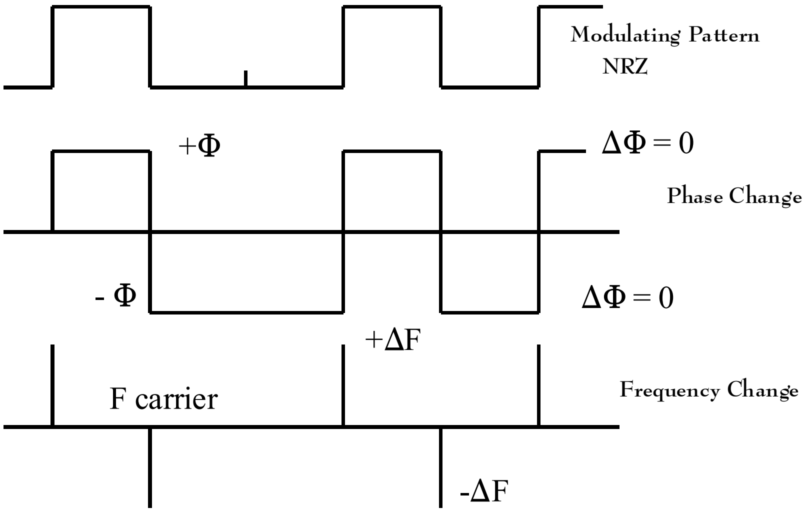

Figure 1. The Change in Frequency Caused by Abrupt (Near Instantaneous) Phase Changes.

Abrupt phase change digital modulation utilizes a rectangular coded baseband with abrupt edges, that is, the rise/fall times are as abrupt, or as near zero, as possible. Some RC rise time is inevitable, due to RC slew rates in the ICs and other parts of the circuitry.

The frequency resulting from a rectangular phase change input is: $F = F_{carrier} + \Delta f$. Δf can be calculated from the basic relationship $\omega t = \Phi = 2\pi ft$.

This can be rewritten in derivative form as $\Delta f = \Delta\Phi/2\pi\Delta t$. The rise and fall time t is fixed by the the circuit parameters. During the rise and fall times (pulse edges), there is a large $\Delta\Phi/\Delta t$., which causes a large Δf of very short duration.(about 1 RF cycle). At other times, $\Delta\Phi$ is zero and the frequency is constant at $F = F_{carrier}$. A phase detector using $F_{carrier}$

as a phase reference will detect the phase changes as positive and negative voltages. **A required bandpass filter delay time (group delay) can also be calculated from the same** $\omega t = \Phi = 2\pi ft$ **relationship:**

$$T_g = \Delta\phi / 2\pi\Delta f$$

Eq 2.

If $\Delta\Phi$ in the filter is zero, there is no group delay time T_g, or frequency change caused by the filter. ($\Delta f = \Delta\Phi/2\pi\Delta t$).

Hund (8) comes to the same conclusion. According to Hund:

For PM, applicable to abrupt phase changing PM and BPSK:

$$I_t = I_m \sin([2\pi Ft] + [\Delta\theta \sin(2\pi\, ft)]) \qquad \text{all} \qquad \text{Eq. 2.}$$

Sine or cosine can be used.

This equals $F = F_{carrier} + \Delta f$.

With PM, the carrier frequency $I_t = I_m \cos[2\pi Ft]$ remains fixed, but the phase θ can change. There is a **true relative phase part** $I_t = [\Delta\theta\cos(2\pi\, ft)]$ **relative to the un-modulated carrier.** If only the variation $\Delta\theta$ is considered, it is $I_t = [\Delta\theta\cos(2\pi\, ft)]$. There is an apparent frequency of $F_t = F + f\Delta\theta\cos(2\pi ft)$. If $\Delta\theta = 0$, there is no frequency variation. **But the fixed phase θ in the carrier (Eq. 1) can be altered at the start by phase switching in the modulator in accordance with a coded data pattern.**

Repeating, --- to preserve the zero Δf and zero rise time, ΔΦ must be zero. $\Delta f = \Delta\Phi/2\pi\Delta t$ and

$$T_g = \Delta\phi / 2\pi\Delta f$$

In order to preserve the rectangular pulse shape, the filter must have zero rise time, which is equivalent to zero group delay T_g, which also means **ΔΦ must be zero. Communications systems are analyzed according to the BT = 1 rule. (Bandwidth x Rise Time = 1).** A zero group delay filter for T = 0 must have an infinite bandwidth B. This bandwidth B is called the **"Nyquist"** bandwidth (10). **It is not necessarily the noise bandwidth of the filter.** BT can have values other than 1 in practice.

A system can be built in which the carrier is switched in phase as in BPSK with near zero rise time, hence no Δf.

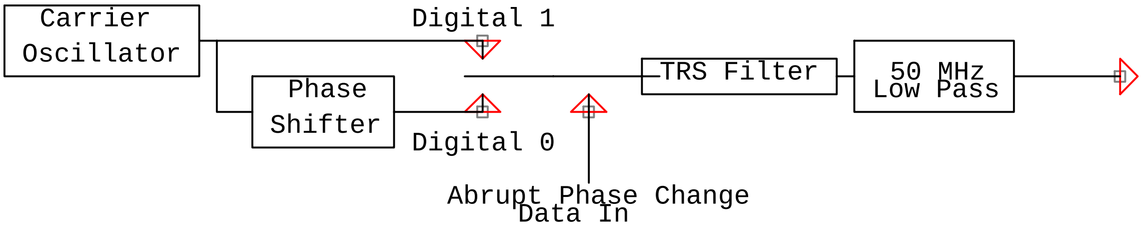

Figure 2. Abrupt Phase Change Modulator.

It is obvious from Fig. 2 above that abrupt phase change is possible, and also from practice where BPSK is acknowledged to be an AM method with no FM present. **PM is retained in the carrier when the phase angle is not 180 degrees.**

It remains to be shown that the carrier alone can carry the necessary information without sidebands. The necessary precondition for a system involving the carrier alone is **the filter, which must have zero group delay. That is, ΔΦ must = zero for the single frequency of the carrier.** Such a filter does exist. This filter has a Nyquist bandwidth = the filter frequency, and a very narrow noise bandwidth. The two are not the same as with most conventional filters. The filter is the well known half lattice crystal filter (and variations) which exhibit near zero group delay at a single frequency. This is due to the unusual phase shift at the crystal resonant peak.

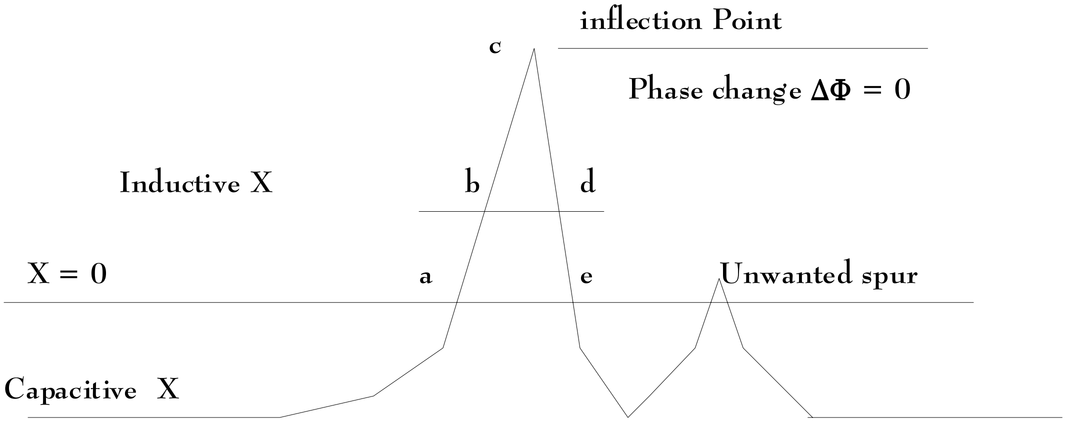

Figure 3. Characteritics of the Crystal Resonator. The phase change with frequency depends upon the change of impedance with frequency. (From File “FilterS” and UNB Textbook)

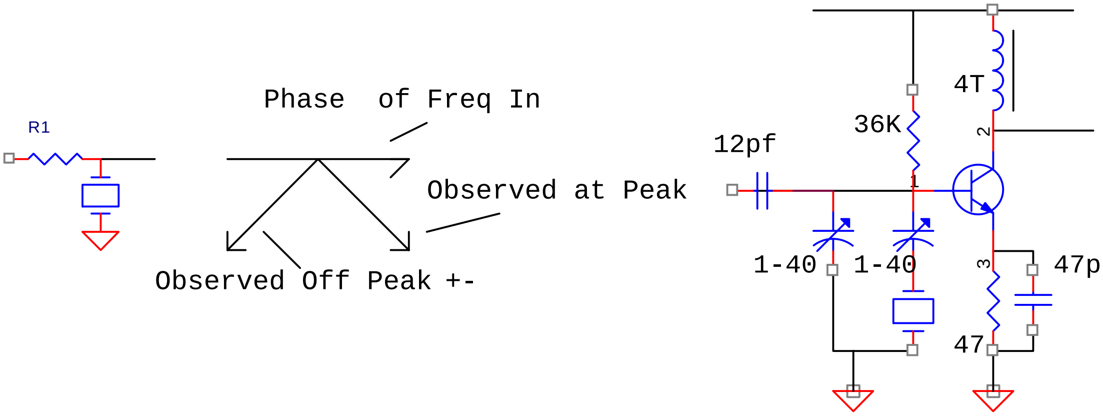

Fig. 4. First Test -- Inflection point confirmation. The phase shift through a shunt filter can be observed using the circuit above. The phase is non linear, having an inflection point (Fig. 3).

The circuit shown is a derivative of the half lattice crystal filter without the transformer. The 3 dB bandwidth of this filter is 1-2 kHz (Fig. 6), while the Nyquist BW can be up to 100 MHz or more...

The filter shown has a burst response equal to one IF cycle as seen in Fig. 5. The rise and fall time is seen to be 1 RF cycle, hence the group delay is 1/f.

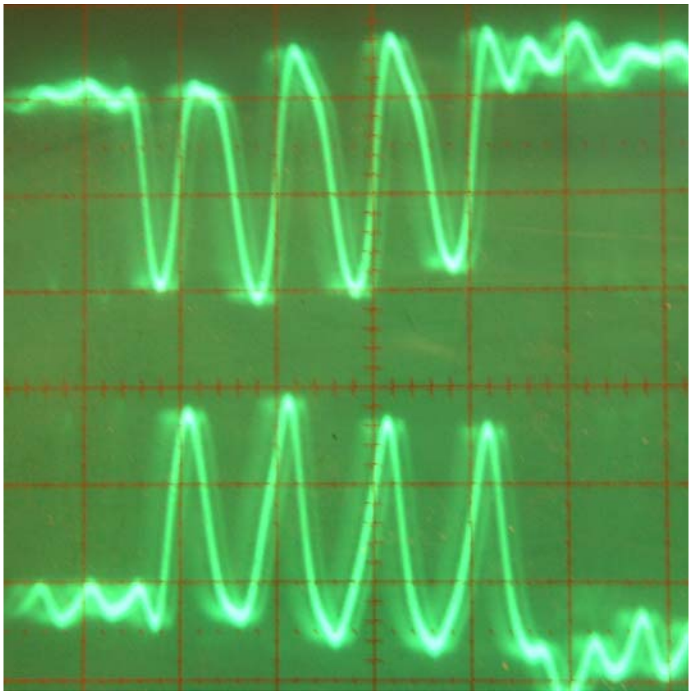

Figure 5. Burst test of the Half Lattice filter. The top trace is the pulsed input to the bandpass filter, the lower trace is the filter output. Note that there is no rise/decay time and there is no ringing to cause inter-symbol interference. Phase change is instantaneous.

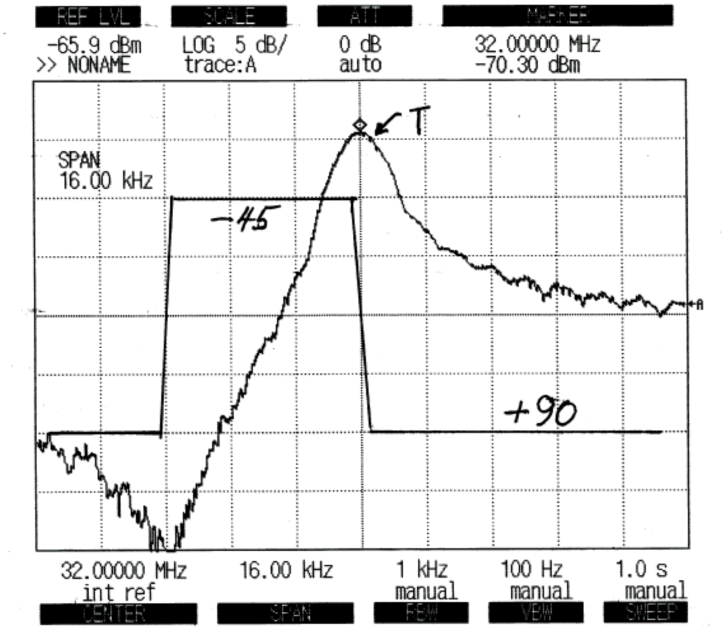

Figure 6. The Amplitude and Phase Response of the Half Lattice Filter. The filter is operated best just off the peak at the point marked T.

When only a single frequency is to be transmitted, the methods become single frequency 'Ultra Narrow Band' methods. Sidebands can be removed when the carrier alone is transmitted.

The UNB methods do not differ greatly from the well known 'Binary (bipolar) Phase Shift Keying' (BPSK) method, except for the special narrow bandpass filters used. The old VMSK method is referred to as coded BPSK. The newer NRZ-MSB is the same as standard BPSK, except that the shifted phase angle with binary data is less than 180 degrees. **The methods are analyzed as amplitude modulation methods**, just as BPSK is analyzed as an AM method in all the standard texts. **They do have a phase shifted carrier** (Fig. 2), which qualifies them as **phase modulation** <u>**after the filters**</u>, and which is detected as such, but they remain **basically amplitude modulation methods with end to end pulses on the different phases through the filters.** The spectrum seen is a Fourier spectrum typical of AM, with nulls at the carrier +- bit periods. The sidebands that are created are of the same polarity as the carrier and do not cause any phase modulation of the carrier itself, as is done in the Armstrong method to create PM. All sidebands merely change the amplitude of the carrier and have no effect on phase. They can be removed.

To illustrate, a simple 1010101 data pattern will be used with the modulator of Fig. 2.

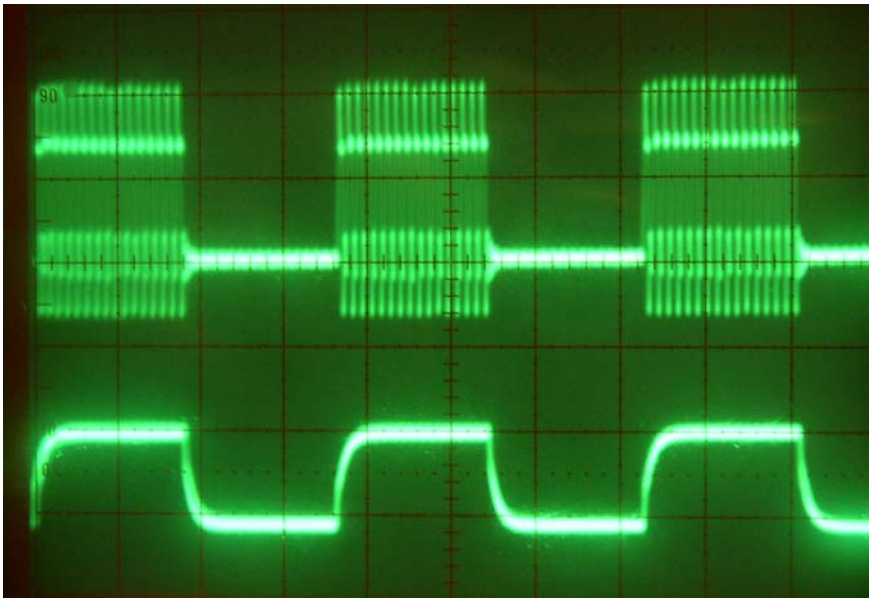

Figure 7. The pulses using the carrier phase modulator shown in Figure 2 with only one phase activated, the RF output shows ordinary amplitude pulse modulation with a burst of 16 IF cycles for a digital one. The IF frequency is 32 MHz, the data rate 2 Mb/s. This is the output of the abrupt phase change modulator prior to any filtering. There is no rise time, no phase slew rate and no ringing. The ON/OFF is instantaneous.

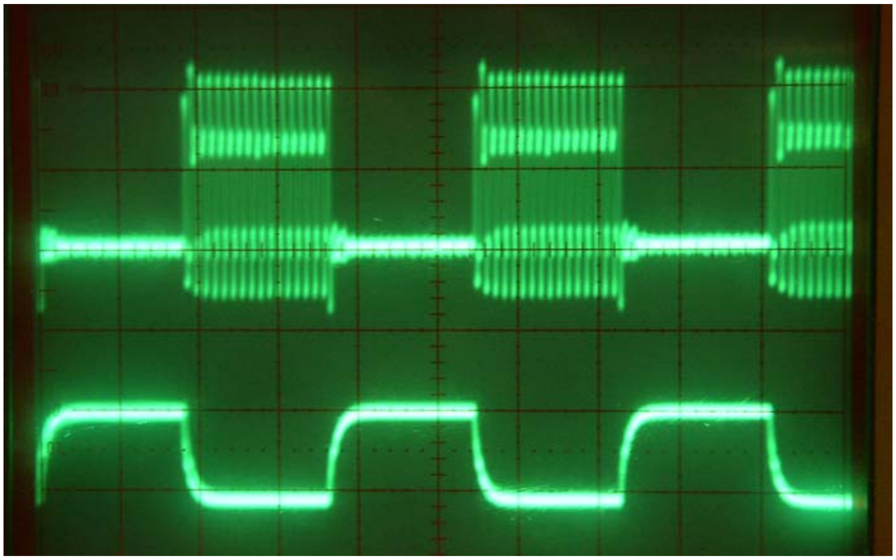

Figure 8. The pulses with only the opposite phase activated to produce an amplitude pulse on the digital zeros. The IF cycles in Figures 7 and 8 differ in phase by 90 degrees.

When pulses are added sequentially **(end to end pulse width modulation)**, the pattern below appears. This is nothing more than two AM pulses being added end to end in time. Phase one is switched ON to create an AM pulse for digital ones, then phase two is switched on to create an AM pulse for digital zeros. The UNB modulator is an abrupt change switch between phases one and two (Fig. 2). **No ordinary PM is involved at this stage, only AM pulses of varying phase.**

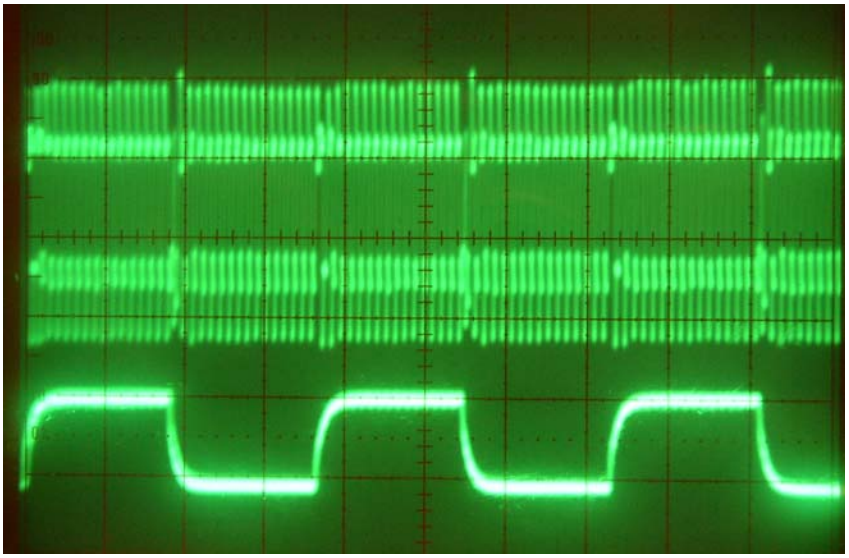

Fig. 9. The end to end amplitude modulation pulses for a 101010101 pattern. There are 16 cycles for the digital one and 16 cycles for the digital zero. The phase difference between the end to end pulses is 90 degrees. The transitions can be seen in Fig. 9. The carrier phase switching circuit is seen in Fig. 2

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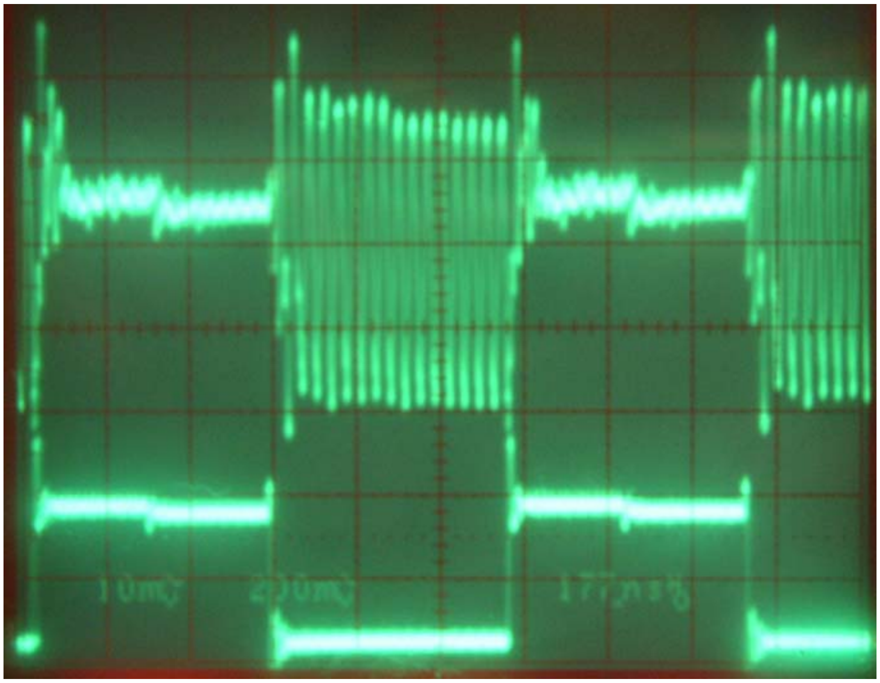

Figure 10. The amplitude response at the TRS, or other half lattice type filter output, when the pulses are for the zeros only. With one and zero pulses end to end of different phase, the blank space is filled in as in Fig.9. The filter rise time is approximately one IF cycle, so the group delay is approximately 1/(IF) sec.(30 nanoseconds for a 32 MHz IF). The pulse response shows almost no rise or slew time for the IF cycles to be exactly in phase with the data pulse as transmitted to arrive at a steady state in amplitude and phase. The date rate is 2 Mb/s, 1010101 pattern, 32 MHz IF.(16 cycles per pulse). The TRS filter has near zero group delay and can resolve the individual IF cycles.

Nyquist's Bandwidth Theorem:

Theorem: If synchronous impulses, having a symbol rate of f_s symbols per second, are applied to an ideal, linear phase brick wall filter, having a bandwidth = f_s, the response to these impulses can be observed independently, that is without inter-symbol interference. (10).

Nyquist's relationship is often expressed in a more obvious manner.
"The bandwidth 'B' need not exceed the reciprocal of the pulse width period 'T' ". That is B = 1/T. As an example, a RADAR pulse 1 microsecond wide requires a bandwidth of 1 MHz. This merely states that BT need not exceed 1. It does not preclude a lesser value.

This is usually interpreted to mean that the filter need not have a bandwidth greater than the symbol rate = $1/T_s$. Or, in the case of BPSK, = the data rate. Some methods combine several bits into a symbol. (MPSK, QAM, QPSK). Nyquist's theorem does not exclude the use of a narrower bandwidth. The symbol rate = $1/T_S$ cannot be changed, but the bandwidth B is variable. BT = .3 is a commonly used example.

If the filter has group delay, the cycles seen in Fig. 5 will rise to reach a peak value at the time T_g. Similarly, they will decay to reach a near zero value after the period T_g. The 'Ideal' filter has a group delay (rise/fall time) according to its bandwidth B. (from BT = 1). Thus the information from pulse 1 will carry over into the period of pulse 2 due to the decay period. This causes inter-symbol interference, which is the basis of Nyquist's theorem. To have zero interference, that is pulse one must not extend into the time period of pulse 2, the filter must have zero rise and fall time, which means zero group delay, which comes from **ΔΦ = zero.**

If the pulse on phase one does not extend over in time to the pulse of phase two, there is no inter-symbol interference. The pre-conditions are that the Nyquist bandwidth B be greater than 1/f. This does not apply to the noise bandwidth of the TRS or Shunt filter, which as can be seen from Fig. 6 is very narrow.

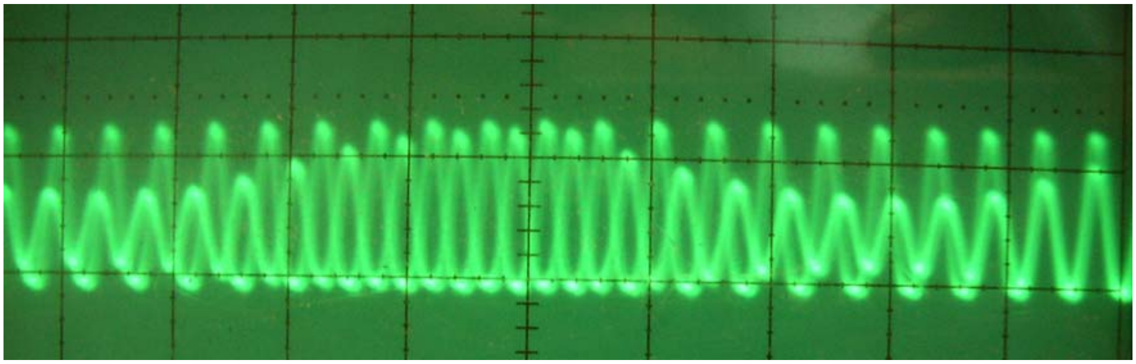

Fig. 11.

The slow phase shift that occurs with a filter having a **normal group delay** T_g.when used with BPSK. The maximum data rate possible depends on this phase slew rate, which is related to filter group delay, or rise time. Notice that there are no abrupt phase changes as in Figs.7, 8 and 9. Fig. 11 shows a continuous phase frequency shift keying system (CPFSK). A finite ΔΦ/Δt has been introduced by the filter. This in turn creates a Δf, and the resulting sidebands that are normally observed. If the TRS filter (Fig. 6 above) had group delay, there would be both amplitude rise time and phase slewing to arrive at a steady state. This does not happen as can be seen in Fig.10.

From the above it can be seen that carrier pulses containing the phase shift **can be passed through a narrow bandpass filter, if the filter has near zero group delay.** The resulting system is almost identical to ordinary BPSK. The expected C/N for a given BER is the same as for BPSK. This has been verified by measurements. This method is **"End to End Pulse Width Amplitude Modulation".** It is not ordinary PM and the equations normally applied to FM/PM do not apply. The amplitude PWM equations given in Schwartz (1) do apply. There are no Bessel or equivalent sideband modulation products in the spectrum which are in quadrature to the carrier. There are Fourier amplitude products of the same polarity in the spectrum that represent the sidebands. Since the phase change is retained in the carrier, these sideband products can be removed.

In systems utilizing both sidebands, any noise level that exceeds one sideband in level will cause an error. When only a single frequency is used, as in VMSK or NRZ-MSB, the noise level must exceed the level of that single frequency. This can result in a 3 dB improvement in C/N compared to BPSK. VMSK has been measured to have a C/N of 7.5 dB for a 10^{-6} BER. A partial explanation is found in Bellamy (2) Eq. C.34.

In this method **the carrier pulses create the AM sidebands**. The sidebands are not necessary to cause a phase shift in the carrier as is required for the Armstrong method to generate PM. The phase changes can be detected from the carrier alone, the sidebands alone, or the combination of both. If only the carrier is retained, the carrier phase shift must be passed without frequency shift or inter-symbol interference through the narrow band filter. Once past the filter and limiter (if used), the phase changes can be detected with an ordinary phase detector.

Shannon's Limit:

Shannon's channel capacity equation is based on the Nyquist BW. If the Nyquist BW equals 1/T = 1/f, (from BT = 1), then the channel capacity is determined by the Nyquist BW of the filter, which is not the noise bandwidth of the filter seen in Fig. 6.

Do not attempt to use the actual filter noise BW in Shannon's equation for this or any other modulation method. To do so yields false results. Always use the Nyquist bandwidth.

References:

(1) Mischa Schwartz, *" Information Transmission, Modulation and Noise*" McGraw Hill.1951.
(2) Bellamy, J.C., "Digital Telephony" John Wiley. 1991.

Quote, *" Except for a few relatively uncommon frequency modulation systems, digitally modulated carrier systems can be designed and analyzed with baseband equivalent channels".* Most Ultra Narrow Band methods fit into this **exception** category where filtering is involved, since there are no zero group delay baseband filters.

(3) Taub and Schilling, "Principles of Communications Systems", McGraw Hill. 1986.
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(5) H.R. Walker, U.S. Pat 6,445,737 " Digital Modulation Device In a System and Method of Using the Same". Covers the MSB methods 3PRK and MCM.
(6) K. H. Saywood and Lenan Wu, "Raise Bandwidth Efficiency With Sine-Wave-Modulation VMSK". Microwaves and RF Magazine, April 2001.
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(8) Hund, August, *"Frequency Modulation*", McGraw Hill 1942
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(10) H. R. Walker, U.S. Pat. 5,930,303 Covers VMSK and VMSK/2. PCT filings cover this patent internationally.
(10) Nyquist, H., "Certain Topics in Telegraph Transmission Theory", Transactions of the AIEE, Vol. 47, pp 617-644, Feb. 1928.
(11) *Transmission Systems for Communications,* 5th Ed., AT&T Bell Labs. 1982. pp756.