

Ultra Narrow Band Modulation

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The transmission of digital data over wireless links **without useful sidebands** is possible using abrupt phase change modulation and zero group delay filtering. The underlying principle has been known for more than 65 years, but has not been physically realizable until recently. The method presently in use, called 'MSB', or 'Minimum Sideband', **transmits a spectrum that is a single frequency line.** This method can greatly improve the performance of the commonly used GMSK modulation. See end note.

To understand how this is possible, it is necessary to study the basis of phase and frequency modulation.

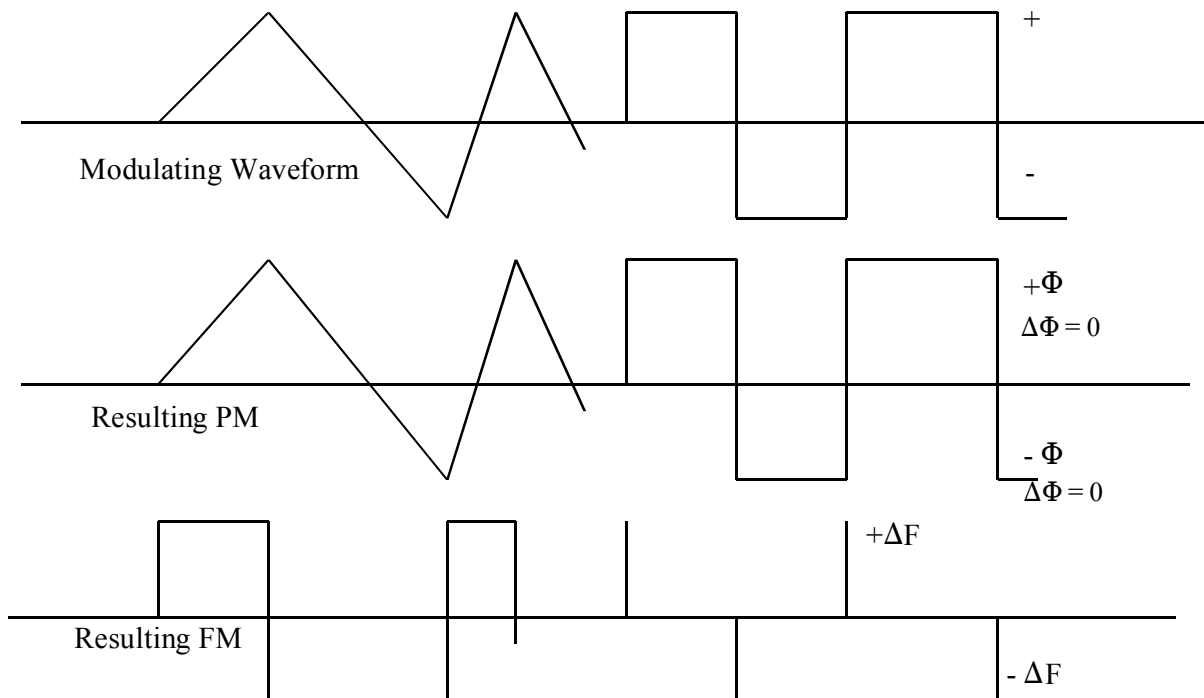


Figure 1.

The frequency change resulting from a modulating input is: $F = F_{\text{carrier}} + \Delta f$. Δf can be calculated from the basic relationship $\omega t = \Phi = 2\pi f t$, which 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 and baseband code.

During the rise and fall times, there is a phase change $\Delta\Phi$, which causes a frequency change Δf . A phase detector using F_{carrier} as a phase reference will detect the phase changes as positive and negative voltages. At the left in Figure 1, the change in $\Delta\Phi$ is

gradual and there is a change in frequency ($\Delta\Phi$ has a finite value). FM is differentiated PM. This modulation with changing $\Delta\Phi$ causes both frequency and phase modulation and can be detected by either means. A sine wave input creates a cosine wave FM output.

When the phase change is abrupt, as in Fig 1 at the right, the rise and fall times are near zero, and there is a large $\Delta\Phi/2\pi\Delta t$ value, which causes a very large Δf of very short duration.(about 1 RF cycle). At all other times, it can be seen that $\Delta\Phi$ is zero and the frequency $F = F_{\text{carrier}}$. A phase detector using F_{carrier} as a phase reference will detect the phase changes as positive and negative voltages conforming to the input, **Even though there is no FM, and there are no Bessel sidebands, during most of the bit period.**

This abrupt PM characteristic was noted by Prof. Howe in 1939 [1]. It was not utilized at the time since digital modulation was not being used and there were no zero group delay filters available. It was put into practice in the lab. at Pegasus in Dec. 2000, and one embodiment of the concept was placed on a microwave link in Denver in March 2002. It has since been used on Cable TV systems and RF links as well.

In practice, using GFSK/MSK, the CPFSK method associated with the commonly used Global System for Mobile Communications (GSM), a rectangular waveform (NRZ - upper right) is applied to a phase modulator. The phase-modulated output is an abrupt phase change as seen at the center right. The signal is then passed through an LC or Gaussian pulse shaping filter, which has group delay, or a definite rise time, which changes the phase shift to that seen at the left center. This in turn causes frequency modulation, seen at the lower left, which would not be there if the pulse-shaping filter had not been used. Removing the harmonics results in changing the triangular wave shape to a distorted sine wave. **Changing the bandpass filter to a flywheel vector adding filter transmits the signal without the FM sidebands that accompany the GSM method, which is a CPFSK method.**

MSB modulation is the same concept as BPSK modulation. The FCC designation is G1D. The difference is in the time on phase one vs the time on phase two. 50% duty cycles are avoided with 180 degree modulation, but acceptable with 90 degree phase shifts. The zero group delay filters must be used to avoid CPFSK modulation.

Vectors:

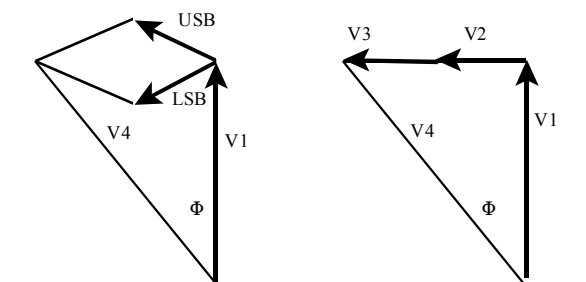


Figure 2.

When using the Armstrong Method [2] to generate sine wave FM, a carrier and two sidebands, an upper and a lower, are required. The vectors for the sidebands counter rotate, reaching a peak in either direction when they are of the same phase. The upper sideband is a frequency higher than the carrier by an amount equal to the modulation frequency. The lower sideband is lower in frequency by the same amount. This gives rise to the Bessel sideband products, which are necessary to cause the vector V4 to shift in phase. There are three or more different frequencies involved to produce the phase shift Φ . (Hund [7]).

The vector relationship is different for the abrupt phase change modulation method. The equivalents of the USB and LSB are seen as V2 and V3 when using abrupt phase modulation. They must maintain the phase shift Φ at a constant angle, hence they cannot rotate, but can only reverse. They are not at different frequencies, but are **at the same frequency as the carrier V1** if they do not rotate,

Abrupt phase change angle modulation does not require any frequencies other than that of the carrier. **There are no Bessel products or other sideband frequencies required to produce the phase shift in the carrier, which is perfectly detectable from the carrier alone with a conventional phase detector and zero group delay filters.**

Mathematically, if $\Delta f = \Delta\Phi/2\pi\Delta t$, then Δf is zero when $\Delta\Phi$ is zero. The level of the Bessel J_n products, as taken from a Bessel function table, is determined by $\Delta\Phi = \beta$. If $\beta = 0$, **there are no Bessel, or equivalent sideband products other than the J_0 product.** [7]. Hence there are no sidebands for nearly all of the bit period. **Ultra Narrow Band filtering removes any remaining sidebands in any case.**

The modulation angle can be +90 degrees or +45 degrees. The rectangular input used can be the NRZ baseband coded signal, or a signal that uses abrupt phase change pulses less than a bit period wide.

Using 90 degree modulation (+45) with an NRZ input, a Gaussian Minimum Shift Keying equivalent can be transmitted without sidebands. See end note. The resulting method has a better C/N and much higher allowable data rate than conventional GMSK using correlative detection and filtering.

When the modulation phase shift is in pulses much less than a bit period wide for a digital one, the spectrum is improved. Typically, the pulse is less than 1/10 bit period wide. Two coding methods (3PRK, MCM) reduce the pulse width to one or two IF cycles.

When using a coded baseband signal to produce an abrupt rectangular waveform with 90 degree abrupt phase change modulation, the spectrum is seen in Figure. 3. Pulse position coded information from a CMOS driver is used to provide unequal time periods on phase 1 and phase 2. The Φ_1/Φ_2 period difference in Fig. 3 is 40/1. The data rate is 270 kb/s, using random data. The method does create Fourier $\sin x/x$ spikes that can be filtered off.

NOTE: Taub and Schilling [11] explain the absence of Bessel products and the presence of Fourier amplitude products---" The power spectral density and the correlation function of a waveform are a Fourier transform series pair". Result- sinc/x spectrum.

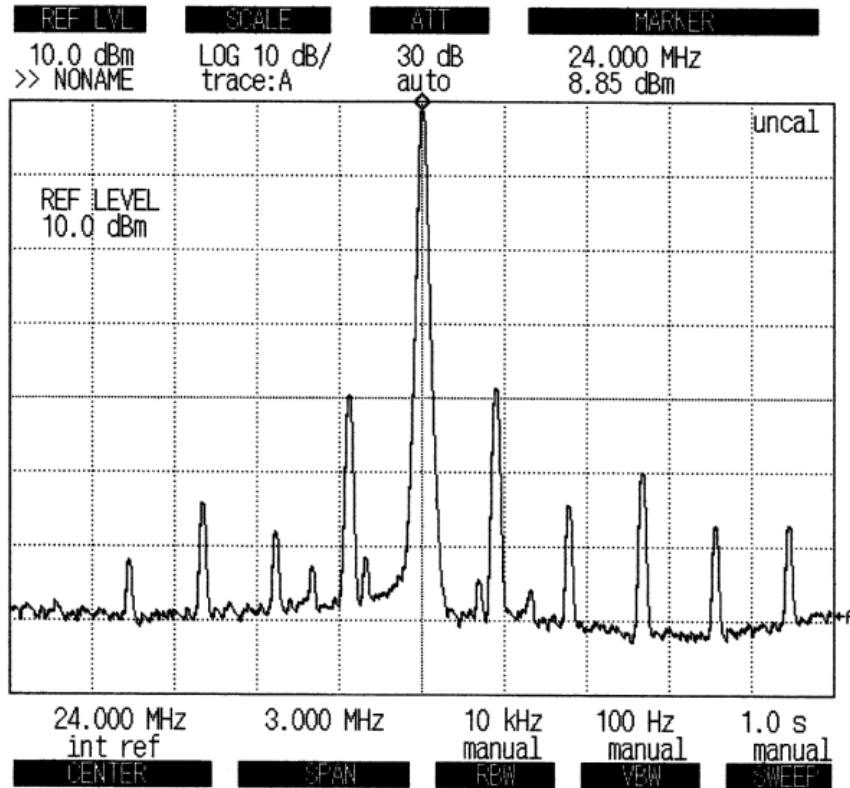
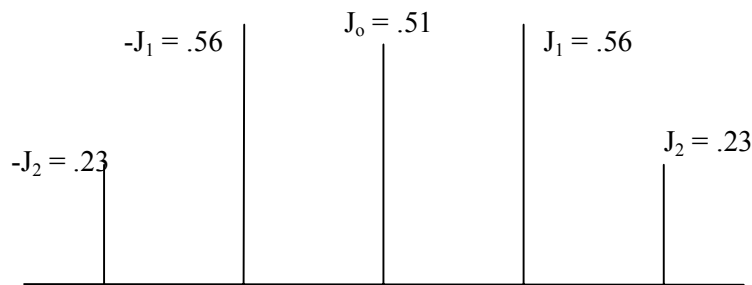


Fig.3. Shows MSB ± 90 degree modulation with no filter at the transmitter. To meet Cable TV specifications, the sinc/x spikes at right and left must be down -35 dB if the MSB injection level is 10 dB below the adjacent analog channel video. It is clear they exceed that. The Scale is 10 dB per div. **The spikes at this level meet FCC Cellular (Part 22) limits, since the RMS level of the spikes is below -60dB.**



Bessel Spectrum for $\text{Beta} = 1.5$

Figure 4. The Bessel products normally associated with FM/PM modulation. Obviously these products are not seen in Fig. 3. Only Fourier sinc/x products are seen. This same spectrum (Fig. 3) is seen if 1 cycle in 40 is removed (Missing Cycle AM).

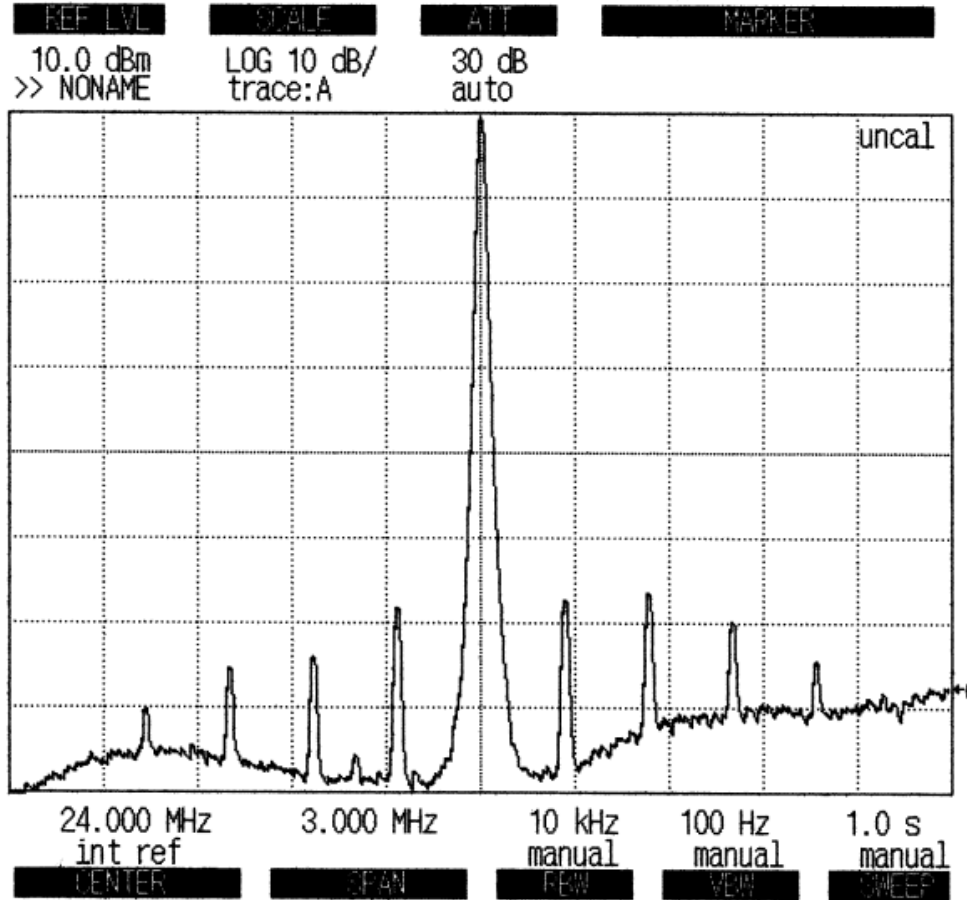


Figure. 5. Shows MSB modulation after one stage of zero group delay filtering to reduce the Fourier sinc/x sidebands an additional 20dB. This sinc/x shoulder reduction does not change the detected phase change output.

This MSB variation is referred to as 3PRK. After one stage of zero group delay filtering, this example has 20dB lower Fourier spikes at right and left. This is 10 times better than required for Cable TV in peak terms. The RMS value is less than 1/1000 the peak value, or better than -90 dB in this example. This is far better than the FCC's most stringent Microwave requirement, or for Cellular telephones.

The baseband waveform, ON for 97.5% of the time and OFF for 2.5% of the time, can be analyzed using Fourier methods for repetitive pulses. The result is a series of weaker frequencies, separated at multiples of the repetition rate from the predominant carrier. Unfortunately, these Fourier sinc/x products do carry over in the phase modulated spectrum. They are present for PM or missing cycles. They are amplitude products

however, and have no effect on the modulation phase as detected. **The peak level of these products is $-20 \text{ Log}_{10}(T/t)$. The RMS value is $-40 \text{ Log}_{10}(T/t)$.**

With ones only changes in phase, the average voltage is 6 dB lower and the RMS level is **$[-40 \text{ Log}_{10}(T/t) -12] \text{ dB}$** , since a change is present only 50% of the time..

These sinc/x products can be removed, or reduced, by zero group delay filtering with no effect whatever on the detected phase change. Being amplitude products, they are rejected by a phase detector.

When the spectrum at Fig. 3 (no filter) is applied directly to the phase detector with the reference phase locked to the carrier, a ± 90 degree output is obtained.. When a zero group delay filter that reduces the sinc/x products by an additional 40 dB (Fig. 5) is used, the detected phase change output level is the same.

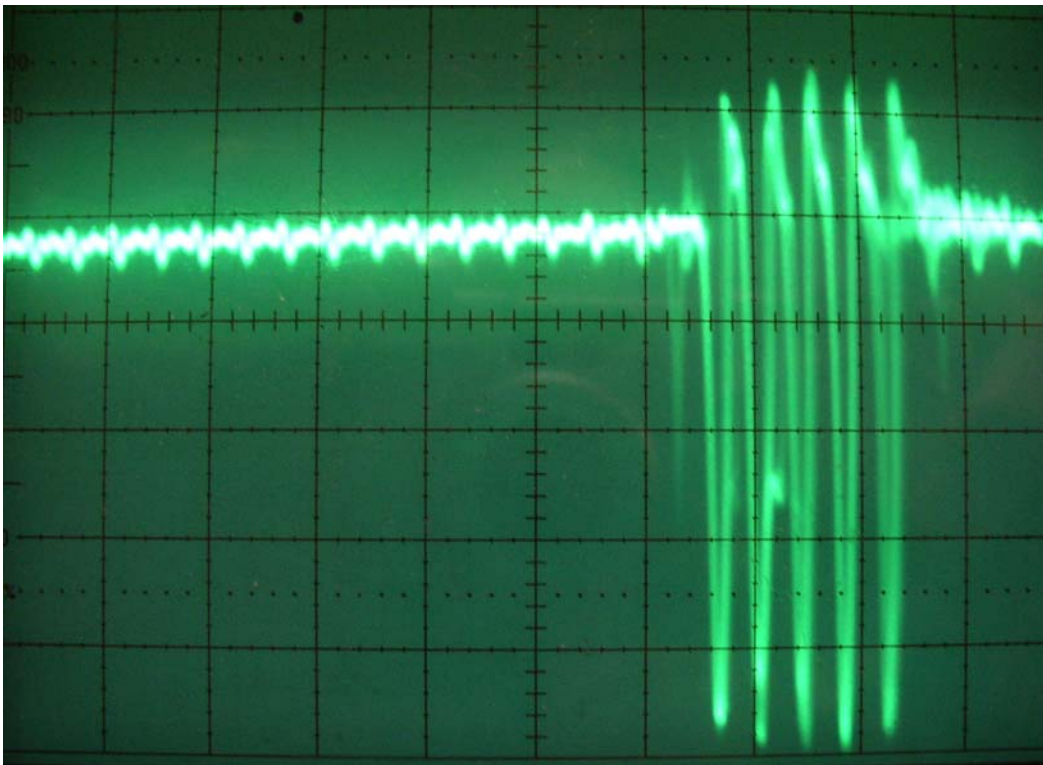


Figure 6.

Figure 6 shows the detected signal after two stages of zero group delay filtering. The modulation angle was 180 degrees (± 90). The detector is an XOR gate, which has a peak to peak response for 180 degrees from V_{cc} to 0. The scale is approximately 1 volt per division, so it can be seen that 180 degrees of phase shift has been retained - despite the loss of Fourier sidebands through the filter. Similar results are obtained using a quadrature detector built in as part of a limiter/detector chip, or when using a D flip flop as phase detector.

Energy in Sinx/x Spikes:

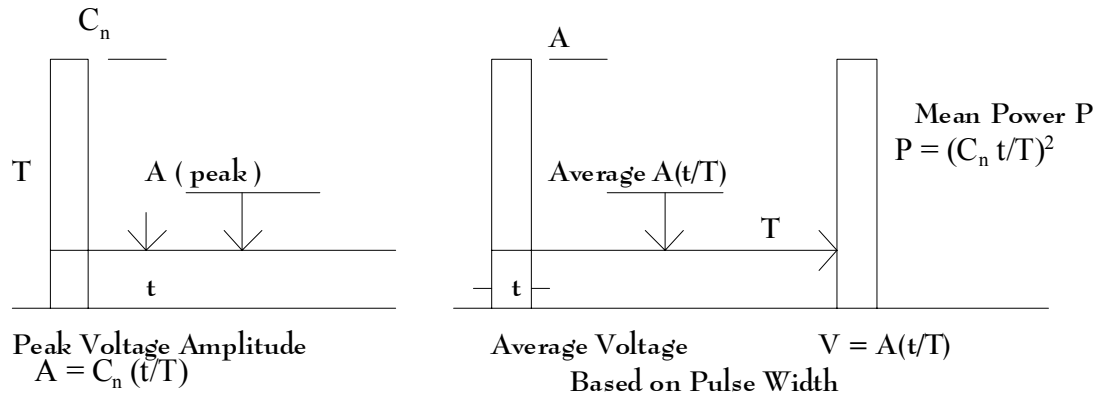


Figure 7.

The FCC is interested in these sinc/x spikes, and regulates their maximum RMS level. If the peak level of the sinc/x spikes is -30 dB, the RMS level is -60dB, which allows the spectrum in Fig. 3 to be used on a Cellular system with almost no further filtering at the transmitter. If one's only modulation is used, the RMS level is lower by an additional 12 dB -(60 + 12) dB. These spikes can be reduced further by filtering, as in Fig. 5, without having any effect on the detected phase output level. A typical receiving filter has 40 dB additional shoulder rejection. Figure 7 above shows the peak and RMS relationship.

Zero Group Delay Filters:

Conventional filters, based on the Nyquist filter, or ideal filter concept, have an inherent group delay, or rise time. The group delay for conventional filters is traditionally calculated to be:

$$T_g = [\Delta\Phi / (2\pi \Delta f)]$$

For LC or Gaussian filters, this is:

$T_g = [1/(4\Delta f)]$ and $T_g = [Q/4(\Delta f)]$ * Obviously, a very narrow $[\Delta f]$ bandwidth filter (high Q) has a very large group delay. * Corrected from earlier.

There is an associated equation for the **rise time of the conventional filter:**

$T_r = 0.7/B$, where B is the 3 dB bandwidth $[\Delta f]$ of the filter. This is the time from 10% to 90% on the RC curve. Bandwidth, rise time and sampling rate are mathematically linked in all previously used modulation methods. In generally utilized practice, **$T_r = 1/B$. This relationship is commonly used with filters in the $BT = 1.0$, or $BT = 0.3$ expressions. Filter bandwidth $B = 1/T$, where B is both the "ideal sampling rate" and a "Nyquist Bandwidth", due to the associated Δf , because the signal has reached an integrated peak level through the filter.** GSMK uses conventional filters, which cause Bessel or similar Sidebands by causing $\Delta\Phi$. MSB is unique in that filters that do not obey these rules are used. The zero group delay filter is used. If the filter has group delay and rise time, the

abrupt phase change will be smoothed over by the rise time (CPFSK), and the spectrum will have a ΔF , including Bessel or equivalent sideband products.

Figure 8 shows one variation of the zero group delay filter. A crystal is tuned to resonate at its parallel frequency, causing the various circuit reactances to cancel, leaving the crystal functioning as a shunt, which presents an extremely high resistance at the single resonant frequency. At all other frequencies, it is a complex reactive shunt load. At resonance, it functions like an RC differentiator, as seen at the right. It passes the phase changes without time delay loss as seen in Fig.6. The secret of zero group delay filtering is not to allow the signal to pass through the filter reference element, but to use the filter crystal as a reference only. There are other more effective filters, such as the TRS filter.

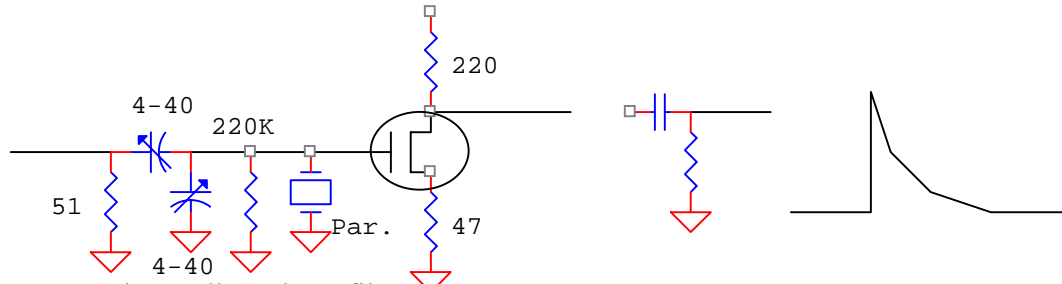


Figure 8. The Walker Shunt filter.

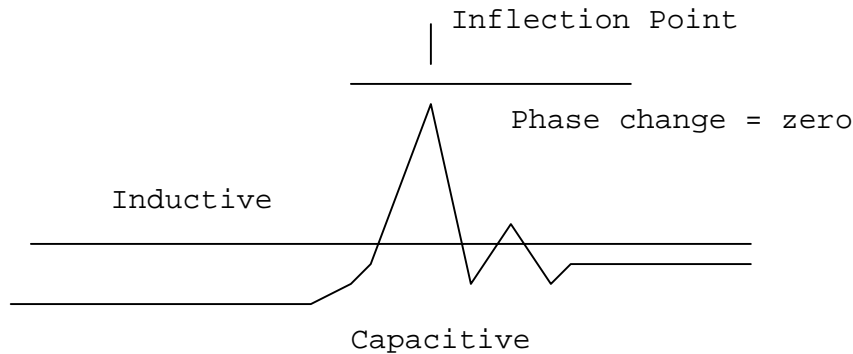


Fig. 9. Impedance of a Crystal

The group delay of a filter is given by $T_g = [\Delta\Phi / (2\pi \Delta f)]$. In Fig 9, there is an inflection point at the peak of the inductive reactance region where a resonant $\Delta\Phi$ is zero for a single frequency. If $\Delta\Phi$ is zero, there is no group delay. Since MSB modulation transmits only a single frequency, the group delay for that frequency is zero and phase transitions in 1 IF cycle are possible. The 'peak point/inflection point' becomes a pure resistance when resonated with a shunting capacitor as seen in Fig. 8.

There are no zero inflection points with conventional LC or multi-pole crystal filters that can be used. The $T_g = [\Delta\Phi / (2\pi \Delta f)]$ relationship applies so that there is group delay).

There are several different variations of MSB modulation in use, which have different names. The difference is in the baseband code used, the phase modulation angle, and whether the method uses the carrier, or is a single sideband method. All methods are patented and subject to further patents and PCT filings. References [4] and [8].

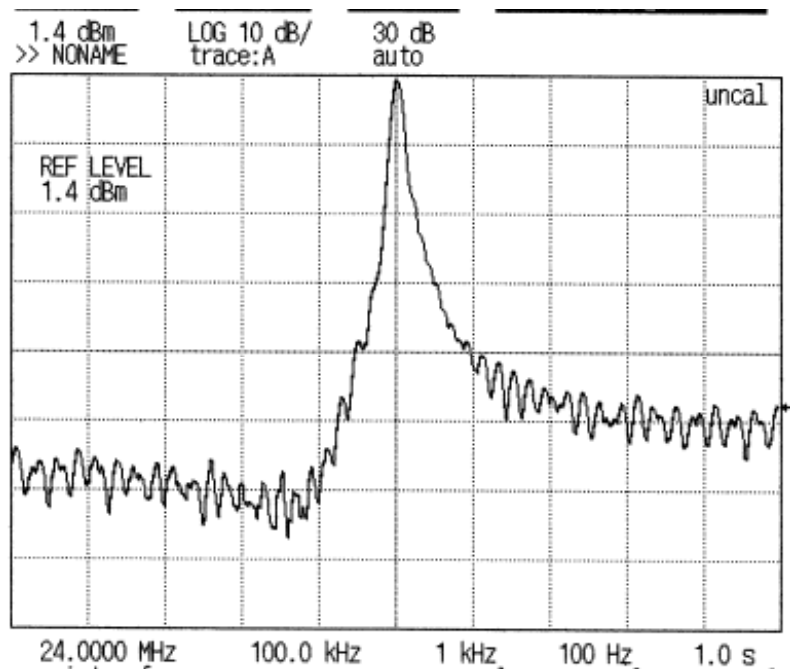


Fig. 10. Swept bandpass of 3 stages of zero group delay IF filtering. 3dB bandwidth is less than 2 kHz. The scale is 10 dB and 10 kHz per division.

The MSB signal is the **carrier without sidebands**. Where is the modulation energy? It is obviously to be found in the carrier alone as shown by Prof. Howe in Fig. 1. If there are J_1 or J_2 equivalent spikes there, reducing them with sideband removing filters should change the detected modulation angle. It does not. There are no Bessel sidebands visible in Figs. 3 and 5. The detected output remains nearly constant, equivalent to ± 45 degrees, or ± 90 degrees. It is thus shown that **MSB modulation has no Bessel, or equivalent, sidebands. Any Fourier amplitude sidebands can be removed, since they do not change the detected phase angle.**

Shannon's Limit:

$$R = W \log_2 (1+C/N) \text{ or as: } R = (1/\tau) \log_2 (1+C/N)$$

It is necessary to understand the meaning of W . **It is not the filter noise bandwidth used**, but the Nyquist Bandwidth, which is and must be equal to the sampling rate. One cannot violate the Nyquist sampling theorem. The general practice is to use $1/(\text{filter rise time})$ as the Nyquist bandwidth $B = (1/\tau)$. Quoting Schwartz:

"The system channel capacity 'R' is obtained by multiplying the number of samples per second (W) by the information per sample". (Schwartz, [5] pp324 and equation 6-134). The sampling rate for MSB is the intermediate frequency, or SubBit rate. Thus W is = to the Intermediate Frequency.

It is also obvious from the hardware and Fig. 6 that a data rate equal to the Intermediate Frequency can be received and decoded. The actual data rate used is lower, since multiple SubBits are used for one data bit.

Assume a 48 MHz IF, then

$$48\text{MHz} = 48\text{MHz} \text{Log}_2 (1+C/N)$$

The equation will balance when $C/N = 1 = 0\text{dB}$. (Shannon's Limit)

Using a lower R, it appears C/N could be below 0dB as in OFSK.

Error Probability:

The error probability for any two phase (2 level) method can be calculated from:

$$P_e = \frac{1}{2} \text{erfc} [\text{SNR}]^{\frac{1}{2}} \quad (\text{Sq. root of SNR is used to get voltage ratio})$$

$$P_e = \frac{1}{2} \text{erfc} [(E_s/\eta)\tau]^{\frac{1}{2}} \quad (\text{energy ratio})$$

$$P_e = \frac{1}{2} \text{erfc} [(E_b/\eta)]^{\frac{1}{2}}$$

$$P_e = \frac{1}{2} \text{erfc} [z] \text{ where } z = V_p/1.4E_N \quad (V_p = \text{peak signal level and } E_N = \text{noise RMS})$$

The probability of error is given by: $P_e = \frac{1}{2} \text{erfc} [\text{SNR}]^{\frac{1}{2}} \quad \text{SNR} = (\sin \beta)^2 E_b/n$

$$P_e = \frac{1}{2} \text{erfc} [z] \text{ where } z = V_p/1.4E_N \quad (V_p = \text{peak signal level and } E_N = \text{noise RMS})$$

This equation applies to double sideband suppressed carrier signals where each sideband carries half the energy and any noise equal to either sideband will cause an error.

When using MSB, there is only one vector, the noise level can be twice as high and the equation becomes: $P_e = \frac{1}{2} \text{erfc} [2\text{SNR}]^{\frac{1}{2}}$

Assuming V_{sig} and E_{noise} are both measured as true RMS values. This is verified by measurement.

Note the second of these equations. [$\tau E_{\text{signal}}/\eta$],

so $\tau E_{\text{signal}} = E_b$. = signal power ON for one SubBit period using 3 PRK. This is true energy per SubBit. One SubBit is being detected.

$$P_e = Q \left[\frac{A}{\sqrt{Nt}} \right] = Q \left[\frac{A}{\sigma} \right] = Q \left[\frac{\text{Cvolts}}{\text{Nvolts}} \right] = \frac{1}{2} \text{erfc} \left[\frac{A}{\sigma} \right]$$

From Feher [2], where A is the peak signal value at the sampling instant and σ is the RMS voltage of the noise power at the threshold detector input. When using a cycle to cycle comparison, noise peak voltage must be compared to signal peak voltage.

$$Q_{(z)} = \frac{1}{2} \text{erfc} \left(\frac{z}{\sqrt{2}} \right) = \frac{1}{2} \text{erfc} \left(\frac{V}{\sqrt{2N}} \right) = \frac{1}{2} \text{erfc} \left(\frac{E_s}{\sigma} \tau \right)^{\frac{1}{2}}$$

Bellamy, Eq C.19, Rappaport D.11

This equation assumes a peak signal voltage V and an RMS noise voltage, which would have peaks at 1.4 times the RMS level. Using a true RMS meter, the relative peak and RMS volts are the same as measured, so the 1.4 correction is not used.

$$Q = \left(\frac{E_s}{\sigma} \tau \right)^{\frac{1}{2}} \text{ determines the BER for MSB. } \tau = 1 \text{ for 3PRK.}$$

Utilizing a correlating detector with integrating filter in a post detection circuit, or in the detection circuit, the E_b can be increased by increasing τ .

The theoretical and measured BER follows the $Q(z)$ curve.

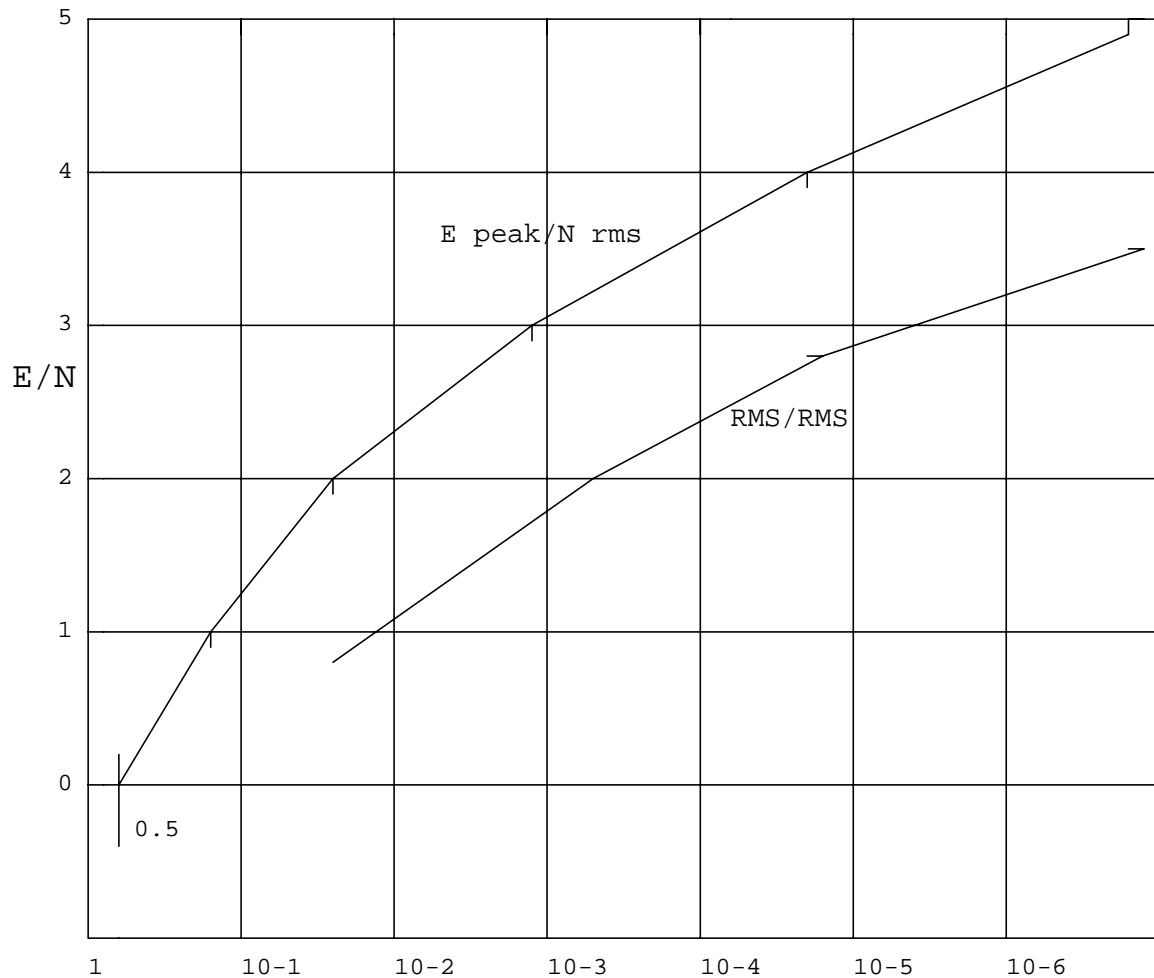


Figure. 11..

Percent of time probability that the noise will exceed signal for given SNR. With E signal measured as peak and Noise measured as RMS, use upper curve, which is the Q curve. For both measured RMS, or both peak, use lower curve, which includes the 1.4 correction. This becomes Bit Error Rate. The curves are approximate only.

These are voltage ratios, not power ratios.

The textbook 'Ultra Narrow band Modulation' offers a more complete explanation of BER and the measurement methods.

Now there is another inconsistency with the theory that Bessel sidebands are necessary. The phase detected output is always the equivalent of the transmitted phase modulation angle (Phase change = +90 degrees, for example) See Fig. 6 above. **There is no detected level change when the $\sin x/x$ (amplitude) sideband spikes are raised or lowered.** When passed through a zero group delay filter that reduces the $\sin x/x$ spikes by 30 or 40 dB, the detected output level is almost unchanged.

The signal is now the carrier without sidebands. Where is the modulation energy? It is obviously to be found in the carrier alone as shown by Prof. Howe in Fig. 1. If there are J_1 or J_2 equivalent spikes there, reducing them with sideband removing filters should change the detected modulation angle. It does not. There are no Bessel sidebands visible in Figs. 3 and 5. The detected output remains nearly constant, equivalent to +/- 45 degrees, or +/-90 degrees. It is thus shown that **MSB modulation has no Bessel, or equivalent sidebands. Any Fourier amplitude sidebands can be removed.**

PM theory says the phase angle should be equal to $2J_1 = \sin \Phi$ for small phase angles.[Hund, 7]. The present modulation method results in a large detected $\Delta\Phi$ (90 or 180 degrees) that completely disregards any changes in J_n levels. There are no J_n Bessel products with MSB modulation, and Fourier $\sin x/x$ products, which are amplitude products, do not change the phase.

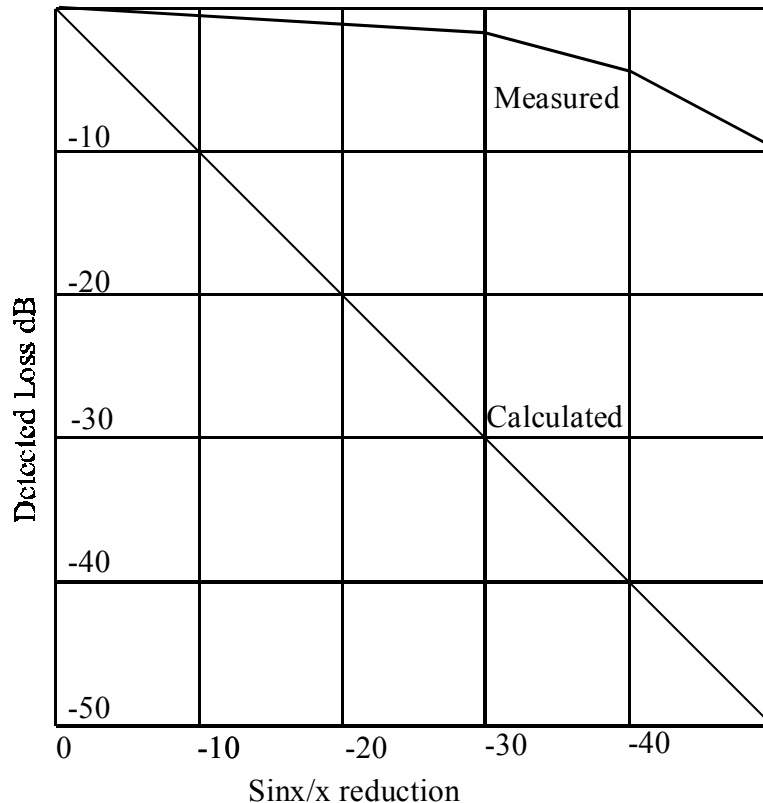


Figure 12 shows the detected output level (top) vs the reduction in $\sin x/x$ level (calculated). The Fourier $\sin x/x$ products have been assumed to cause PM as Bessel products do, and **the assumed phase angle as calculated is assumed to be dependent upon those $\sin x/x$ product levels. Obviously it is not.**

The zero group delay filters are not perfect and can introduce some phase loss. This loss is the cause of the measured roll off seen in Fig. 11.

Appendix:

When the NRZ baseband code is used with 90 degree ($\pm 45^\circ$) abrupt phase change modulation, the initial baseband signal is the same as that for Gaussian Minimum shift keying. To reduce sidebands **using conventional GMSK**, abrupt phase changes are avoided. The resultant method, using smooth phase changes, is referred to as "Continuous Phase Frequency Shift Keying" (CPFSK). This is easily reproduced using FM with a precise deviation control. ($\beta = .5$). **There are widespread Bessel sidebands.**

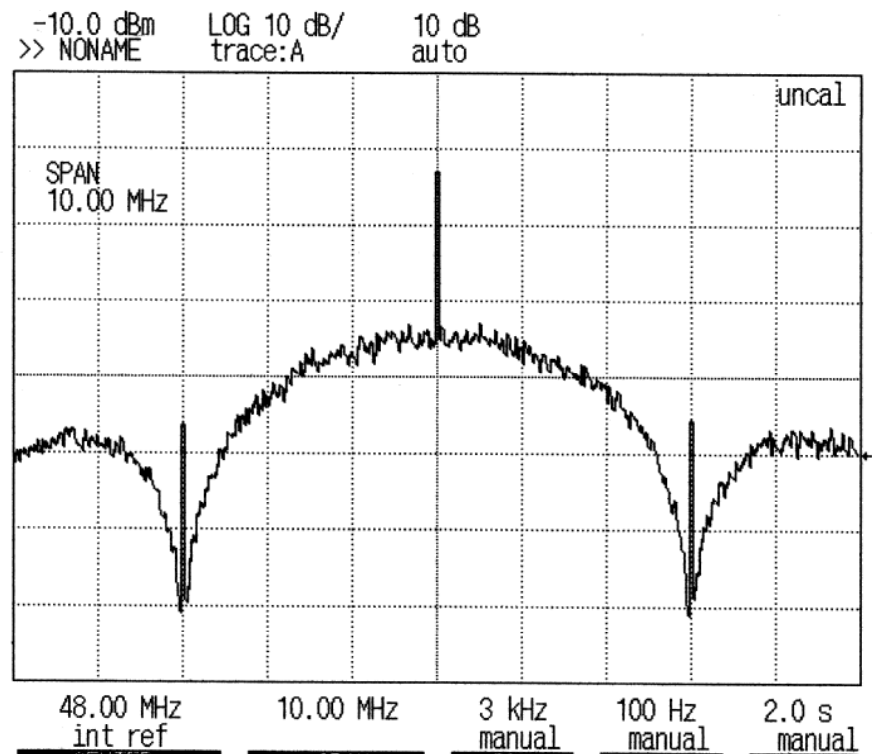


Figure 13. Spectrum of the abrupt phase change modulator output using NRZ random data as the input. The modulation angle is 90 degrees ($\pm 45^\circ$). The low level hump is "DC Creep" caused by the average DC level shift of the data pattern, plus unbalanced modulator sections. If the power level of the modulator output with all ones is made equal to the level with all zeros, this hump can be reduced about 30 dB. These "Creep" products do not contribute to the detected phase modulation angle, they are Amplitude Modulation products that can be reduced or filtered off. This is a sinc/x pattern.

90 degree modulation must be used in order to restore an unambiguous carrier. With 180 degree modulation, the carrier phase is ambiguous and differential coding of the data must be used. Certain modulation patterns, such as 55Hex using 180 degree modulation,

will produce a spectrum with no carrier, therefore 180 degrees cannot be used. 180 degrees was used with the earlier VmaxSK method now abandoned.

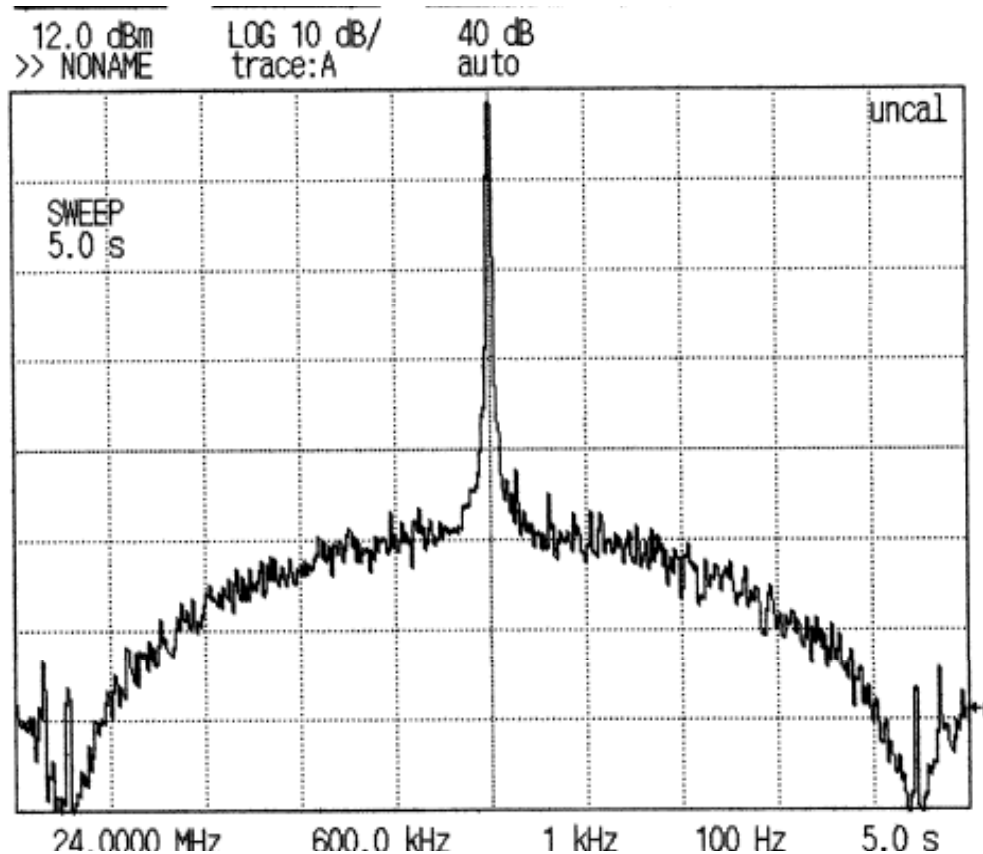


Figure 14. The spectrum of Figure 12 after 2 stages of zero group delay filtering, *or when the modulator sections are balanced*. This spectrum meets FCC requirements for Part 22. It is theoretically 1 Hz wide above the -50 dB level of the grass (lower hump). The data rate is 270 kb/s. (note dip at +-270 kHz).

This data rate can be increased to 3 to 4 Mb/s using the same filter / detector. The only spectral difference is that the sinc/x pattern hump nulls at $F_c \pm F_b$.

References:

- [1] Howe, Prof., As published in -- K.R. Sturley, " *Frequency Modulation*", Chemical Publishing Co., Brooklyn, N.Y. From "Wireless Engineer", Nov. 1939. pp 547.
- [2] E.H. Armstrong, " Proc. I.R.E"., May,1936.
- [3] K. Feher, " *Wireless Digital Communications*", Prentice Hall.
- [4] H.R. Walker, U.S. Pat 6,445,737, " Digital Modulation Device in a System and Method of Using the Same". Covers 3PRK and MCM.
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- [6] T.S. Rappaport, " *Wireless Communications*", Prentice Hall
- [7] Hund A., " *Frequency Modulation*", McGraw Hill

- [8] J. Pliatsikas, C. Koukourlis, J. Sahalos and H.R. Walker, "VMSK Modulation BOOSTS Wireless Communications Efficiencies." Wireless Systems Design Magazine, Jan 1998.
- [9] Dr. J. Pliatsikas, Dr. C Koukourlis, Dr. J. Sahalos and H.R. Walker, "Wireless Communications Using Spectrally Efficient VMSK/2 Modulation, "In Third Generation Mobile Telecommunication Systems" Springer Verlag, Berlin, Edited by Dr. P. Stavroulakis.
- [10] H.R. Walker, "Understanding Ultra narrow band Modulation", Microwaves and RF Magazine, Dec. 2003.
- [11] Taub and Schilling, "Principles of Communications Systems", McGraw Hill.

Circuitry for encoding and decoding can be found in [4], which covers one embodiment of this modulation method presently in use on microwave links. It is also posted on the web site <VMSK.org>, where several different versions are explained. SNR and BER measurements, comments on Shannon's Limit, and other topics are also discussed. A complete textbook is available for downloading.

Note 1:

Ordinary Minimum Shift Keying is a frequency modulation method that employs a modulation index of 0.5 ($2\Delta f/\text{Bit Rate} = 0.5$). A modulation index of 0.5 corresponds to the minimum frequency spacing that allows two FSK signals to be coherently orthogonal [6] - that is at 90 degrees from one another. Gaussian Minimum Shift Keying is derivative MSK that employs a Gaussian pulse shaping filter to smooth the phase change trajectory of the MSK signal. This is referred to as "Continuous Phase Frequency Shift Keying" (CPFSK), because the otherwise abrupt phase changes are removed. (and sidebands are created).

Frequency and phase modulation are convertible to one another according to the formula $\Delta f = \Delta\Phi/2\pi\Delta t$. This concept was used by Armstrong to build the first practical FM transmitter. This paper makes the CPFSK assumption they they are equally convertible and that 90 degree (+-45) phase modulation is the same as frequency modulation with an index of 0.5.

If the abrupt phase change modulation with an NRZ input is passed through a conventional pulse shaping RF filter, the frequency deviation Bessel sidebands are restored and the spectrum looks exactly like the GSM / GMSK spectrum. When the non pulse shaping zero group delay filter is used, there is no frequency deviation.

NOTE 2:

Taub and Schilling [11] explain the absence of Bessel products and the presence of Fourier amplitude products---" The power spectral density and the correlation function of a waveform are a Fourier transform series pair". Result- sinc/x spectrum.

It has been argued that the full Fourier spectrum is needed to restore the rectangular waveshape used at the modulation input. **This is true if it is desired to restore that waveshape.** However, the present method is not trying to restore that waveshape, only to detect a change in the phase of one or more RF cycles. The Fourier harmonic products have no influence when looking a single RF cycles. See Fig. 17.

frequency. The XOR gate compares the two, resulting in a negative spiked output one cycle wide when the phases match. In Figure 6 there has been a phase match for 5 cycles.

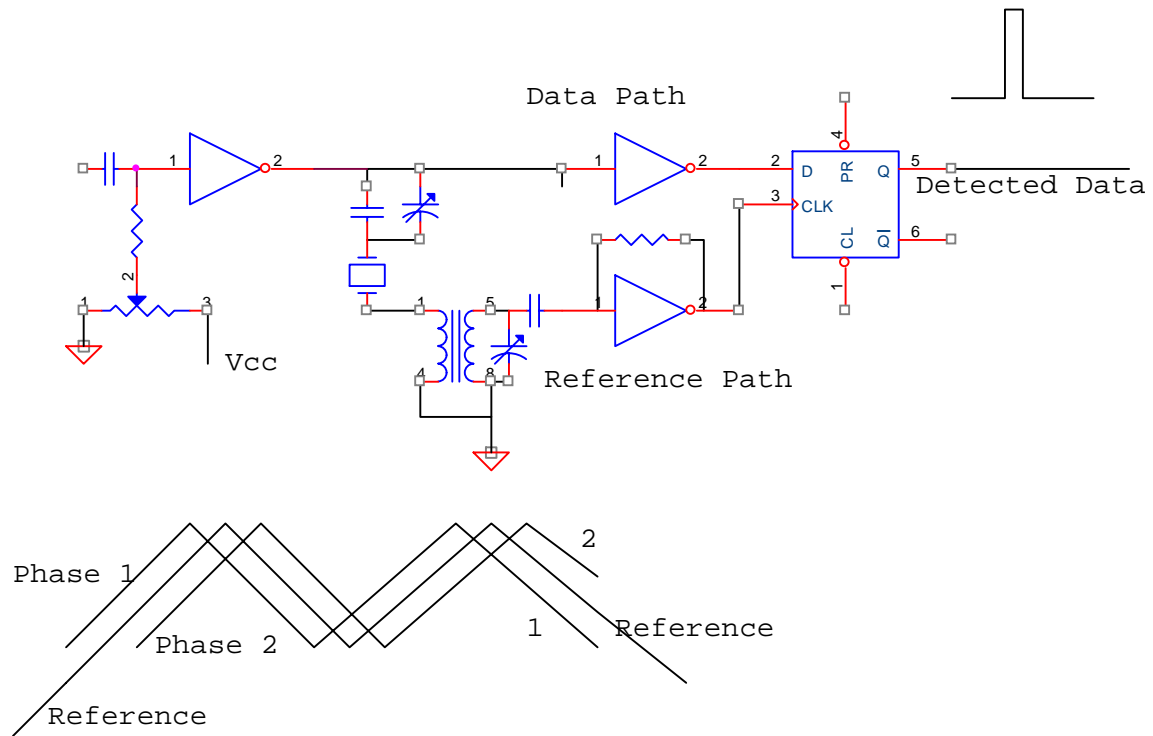


Fig. 17. The phase detector establishes a reference midway between phase 1 and phase 2 of the modulated signal. The shift in phase appears as a pulse as the signal phase passes through the reference zero.