Multipath Simulation With VMSK Modulation

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7/01/02

Abstract:

This report shows that VMSK is vastly superior to the presently used, or proposed, modulation methods for 3G mobile communications. VMSK, Pi/4DQPSK and GMSK all act differently when confronted with signals coming from 2 or more paths. The nature of π/4DQPSK and GMSK modulation restricts the weaker path to a level less than -12 dB before it destroys the desired modulation totally. VMSK on the other hand has no such restriction and tolerates a much higher level of interference once it is gated to the stronger signal. Even at a 0 dB difference in level between the paths, VMSK continues to function except when the delay path time is within a very narrow time boundary as seen in Fig. 8.

Pi/4DQPSK:

This is an oversimplified explanation as to why π/4DQPSK has an extremely high error rate at -10dB. π/4DQPSK modulation is used with the IS54/-136 cellular standard.

One method of detecting π/4DQPSK is to use a quadrature phase detector. The phase shifts possible are 45 degrees and 135 degrees. Figure 1a shows that +- voltage output levels are obtained from the phase shifts, which must then be decoded to obtain symbols of 2 bits each. If the second path is a 135 degree change while the primary path is a 45 degree change, the 45 degree change can be overshadowed, or masked out. The ratio is 3/1, or approximately 10 dB.

A graph showing the effects of multi-path interference on π/4DQPSK modulation is given in Fig. 2. This graph is from AWireless Communications@, T.S. Rappaport, Prentice Hall. Fig. 5.59. It shows clearly the serious effects of multi-path on π/4DQPSK links, and by implication, GSM links. This is to be compared with the measured results for VMSK to be given later in Fig. 5.

GMSK:

GMSK (used with GSM) uses a Gaussian filter with BT = .3. This means that a 101010 pattern will have 1/3 the voltage output level of a 000111000111 pattern. Again, this ratio is approximately 10 dB. Although not linear, the term BT refers to the ratio of filter bandwidth to data rate. In this case it is 1/3. The filter is not wide enough to pass a 101010 pattern without level loss. Long strings of ones and zeros have high voltage output levels, while rapid changes have an attenuated output level.

See Fig. 1b. GMSK can also be considered as a FM signal, where the capture ratio determines the level of tolerance. The capture ratio is generally about 12 dB for an FM signal.

8PSK:

8PSK has been proposed for IS136 use. 8PSK is about 3-4 dB worse than either GMSK (used with GSM) or the present IS136 π/4DQPSK.

VMSK:

With VMSK modulation, the interfering signal overlaps the desired signal in both level and time change, but the time changes occur at separated (delayed) times and, although additive, can be gated to separate them from one an another. The detected time change from each path is a spike, which is observed for only a tiny fraction of the bit period. This gating, along with peak detection, make VMSK the preferred method by a considerable margin. Outside the gate, a zero dB interference level can be tolerated, which is far better than a -10 dB ratio that cannot be tolerated (as with GMSK or π/4DQPSK).

Testing:

π/4DQPSK and GMSK tests require long and short delay periods, from zero out to 40 microseconds, to obtain the full effect of long one and zero bit strings. With VMSK this time period is immaterial. It is only if the interfering signal is exactly at one bit period, or a multiple of one bit period, that interference has any effect. This can be observed at one bit period +-, or 2 bit periods +-, hence delays longer than 2 bit periods are not necessary for testing.

Using VMSK modulation, the encoding waveform locked to the clock is seen in Fig. 3a. . The early spikes reset the clock (3b) and close the gate until the gate delay period (3c) runs out, at which time it reopens. Fig. 3d shows the detected waveform without a second path. Fig 3e shows the detected waveform with a -10 dB second path added. Detection is at the peaks of the negative going spikes. Pulses, which are outside the gate cannot reset the clock. Note that for the -10 dB case, the larger spike peaks of the desired path are still clearly distinguishable in amplitude.

The effect of the delayed multipath at -10 dB is to add or subtract a new set of peaks at 1/3 of the base level. Note that when the delay path is between 1 and 2 bit periods, the delay path peaks invert.

The effect can be seen more clearly during testing, when all ones or zeros are used and the delay path time varied. Figure 4 shows the related patterns. Figure 4b shows the delay to be at a delay time outside the gate. Note that the level shifts when the interference is directly over the desired or primary path as seen in Fig. 4c. A -10 dB delayed signal is assumed. With the delay equal to odd bit periods, the signals subtract. At even bit periods they add. As long as the negative peaks are discernable, the signal can be detected.

Another test that can yield good results is to use the clock as the signal timing source for the delay path instead of the modulated E-data pattern. This provides only one pulse, as in the all ones or zeros pattern for the delay path, but keeps normal modulation in the desired path so that error counting with random data is possible. Delaying this pulse through the critical points gives a better test for circuit effectiveness and makes corrections easier to implement.

The final test must simulate the real world, hence must use the same random modulated data on both paths. VMSK and the other methods all require wide range limiters to overcome fades. They do not differ in this regard. Doppler has little or no effect on VMSK since the detector frequency tracks.

Bell South has made measurements using VMSK modulation in a multipath environment. Report appended.

Problems:

There are specific time delays and data patterns that can cause problems if no compensation is used. These occur primarily when the delayed signal is very strong and overlays the desired signal just following the desired early spike at odd bit intervals, or overlays the early spike on even bit intervals.

As long as the gate does not lose lock, overlays on even bit periods generally do not cause a problem. If the gate should unlock, it could re-lock to the late spikes and decoded data will be false.

On odd bit periods, a strong multipath signal occurring at the time of the desired early pulse, within the gate, will decrease the desired early spike level. This could cause the gate to shift to the negative going late spikes and the decoded data will be false. Tests show this almost never occurs.

A very strong interfering signal occurring at just the right time is required for these problems to occur. The gate is automatically reset to the proper position when the first pulse to occur within the gate is the early pulse. After that, late pulses are ignored.

The time period at which there is a problem is only about .03 bit period wide. Outside this very narrow period, the signal can usually be detected and separated, even at 0 dB difference in levels, since the differentiation is in time, not level. 0 dB is 1/1 signal to interference ratio.

Amplitude detection of the peaks was assumed. The detecting problem described above arises when the echo pulse interferes in amplitude with the desired early pulse. There are cases where it has no effect.

Pulse Amplitude Expansion:

Pulse amplitude expansion offers a solution to some of these problems. For a delayed path signal lower than -6 dB in level, the problems listed above can be overcome. If expander circuitry reduces the amplitude factor (adding a diode and resistor to the differentiator Op. Amp. feedback), the negative peaks will all have equal negative amplitudes. Peaks less than -6 dB will not be expanded, while those greater than -6 dB will be expanded to reach the lower op. amp rail. These peaks can then be voltage clipped to ignore the weaker delay path peaks.

Assume the circuit is adjusted for a -6 dB delay path level. (It could probably be adjusted for -3 or -4 dB). Any negative going spike, of normal amplitude or greater than 50% of the normal amplitude, will be expanded to reach the maximum peak value. On odd bit delay periods, where the delay path exactly overlays an early desired bit in timing, the delay path level must exceed -6 dB to have any effect. If less than -6 dB, the negative early spike will reach the normal full voltage swing and there will be no interference, since the clipping level will ignore weak signals.

Note that there is a problem here only if the delay time is a multiple of the bit periods and exactly overlays the early pulse with a level exceeding -6 dB. This would be a very rare condition. The desired VMSK pulse is typically 1-2 % of the bit period. Hence major interference occurs only for 1-2 % of the possible path time differences.

For even bit period delays, all spikes are negative and any overlays will add to the level. Since the output level after expansion is already at the negative rail voltage, level is of little importance. If the negative going peaks at the input are less than 2 (6 dB) that of the desired spikes, they will not be expanded and the voltage clipper will ignore them. If they are greater than -6 dB, there will be two sets of spikes at the op. amp output. The gate circuit will select the earliest occurring pair and attempt to ignore the later pair. Thus the circuit should continue to function even at a 0 dB interference level. (Equal signal and echo). It will track one pair or the other unless there is an overlay in a very narrow range. There may be a few bits lost during any change in gate timing.
Fig. 5 shows the BER measurements made with VMSK and varying delay ratios (τ/T). Compare this with

Fig. 2 for GMSK and π/4DQPSK. Only when there is an exact timing overlay of the delay path on the bit periods, will there be a noticeable effect on the decoded signal (t/T = 1, 2, 3, --N).

Fig. 6 shows the test circuit used. The actual output mixing method used has been changed to provide better isolation between modulators.

This circuit also allows the carrier phase to be varied. The measurements were made with the phase shifted to give the greatest amount of interference. Shifting the phase 90 degrees reduced the interference level by a significant amount. As an approximation, the measured results are 3-4 dB worse on average than would be expected in the field, since the phase will shift as the time difference changes.

Fig. 7 shows the LR differentiator and amplifier used to increase the detected spike levels and the DC restorer or expander in the feedback circuit that holds the negative going peaks at a constant voltage level. The detector and decoding circuits are given in other reports.

Adaptive Filtering:

Thus far, only voltage levels have been used together with gating in a hardware solution to reduce the multipath problem. Adaptive filters can be designed to establish the desired pattern and use it as a reference. If the multipath signal has positive or negative swings outside the gate, these could be used as inputs to a DSP program, which could prevent the gate being shifted falsely. They can also be used to correct for a misread bit or a missing early bit.

If the gate delay is set by a counter that prevents fast changes, it is much less likely to lose lock than if a one shot time delay is used. This could be programmed into the DSP.

Adaptive filters as used for GSM or IS136 are not applicable to VMSK.

ERROR CORRECTION:

All BER measurements were made without any error correction. VMSK can be detected as a form of 'Coded BPSK'. This coding removes the need for Viterbi error correction, which is dependent upon Differential Coding of the data and loses 2 dB in C/N. Most other error correcting methods can be used. Almost any BCH code is applicable

Summary:

Even though the present VMSK hardware may have difficulty with multipath C/I stronger than -6 dB in a very narrow delay time interval, the overall results shown in Fig. 5 are far better than the alternative as shown in Fig. 2.--- **The other proposed modulation methods cannot function at all below approximately -15 to -18 dB.** ("Mobile Communications Enginering", McGraw Hill). VMSK is clearly superior, even without adaptive filtering and /or error correction. With adaptive filtering, the tolerated C/I could approach -1 or -2 dB.

Add to this the low C/N of VMSK compared to the others, 6-7 dB vs 13-14 dB for the same BER, and VMSK becomes a clear choice for 3G systems.

Multipath testing was done by Bell South. Their report is appended.

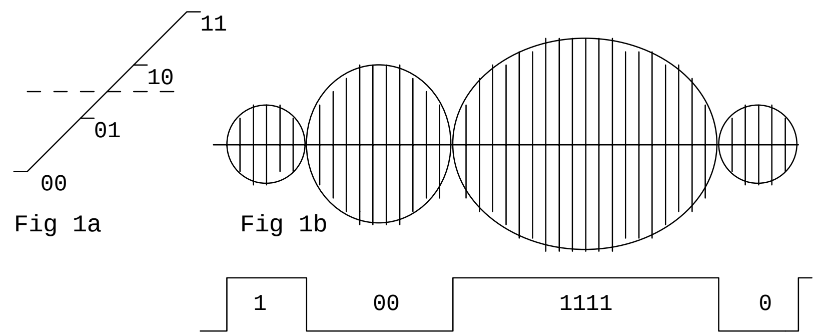
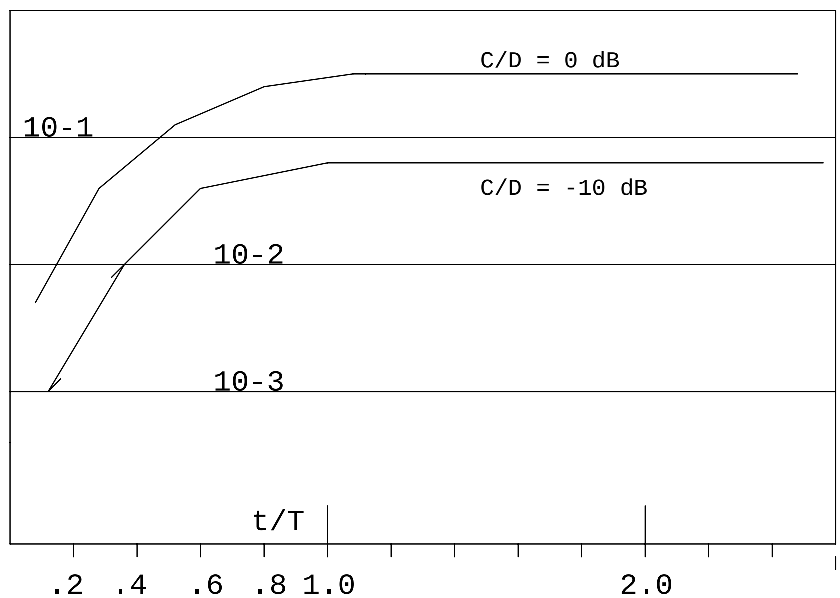


Fig. 2.



BER Performance in Rayleigh fading channel (delay path)

Fig. 3.

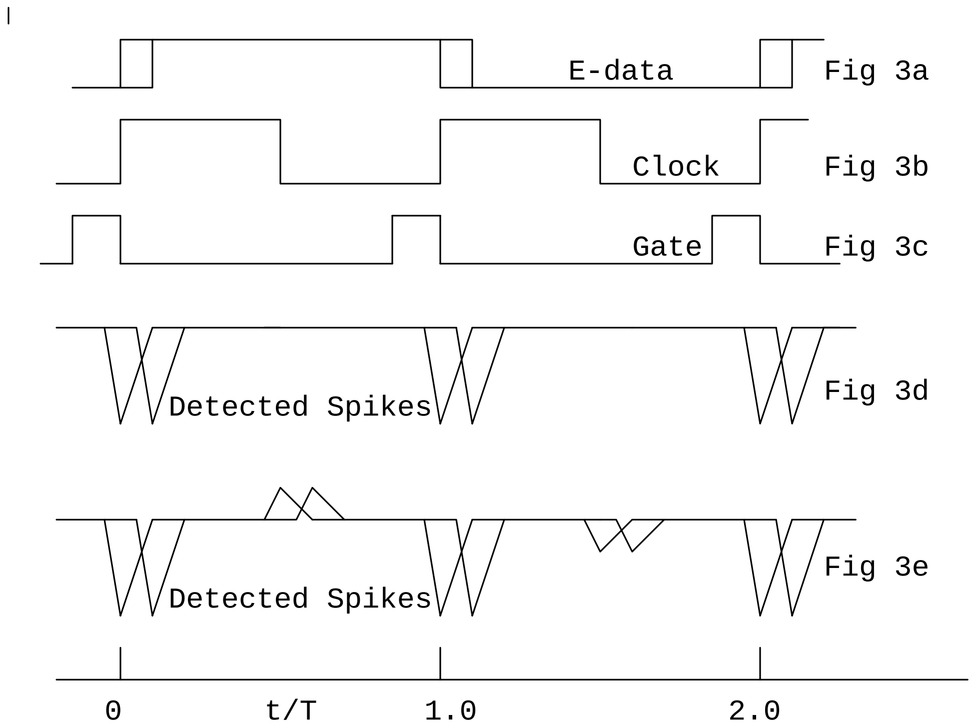
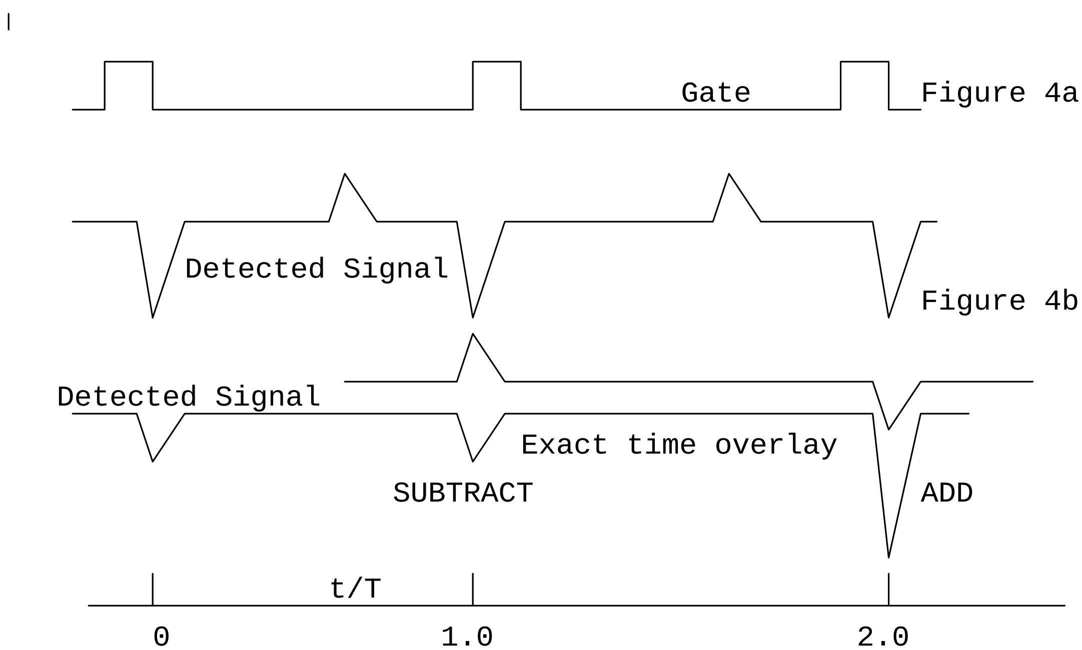


Fig. 4



There was no interference at any delay period at -6 dB. On half the exact overlay periods, a level of -3 dB C/D was tolerated. This critical time period is less than 1/50 the bit period. At all other delay periods the interference was negligible regardless of delay time.

Under most circumstances, VMSK would deliver an acceptable voice BER down to -(2-3) dB and data at 10-6 or better with minimal further correction at 3-5 dB C/D.

Bear in mind there is a problem only at this narrow time period. Otherwise the method operates down to almost 0 dB.

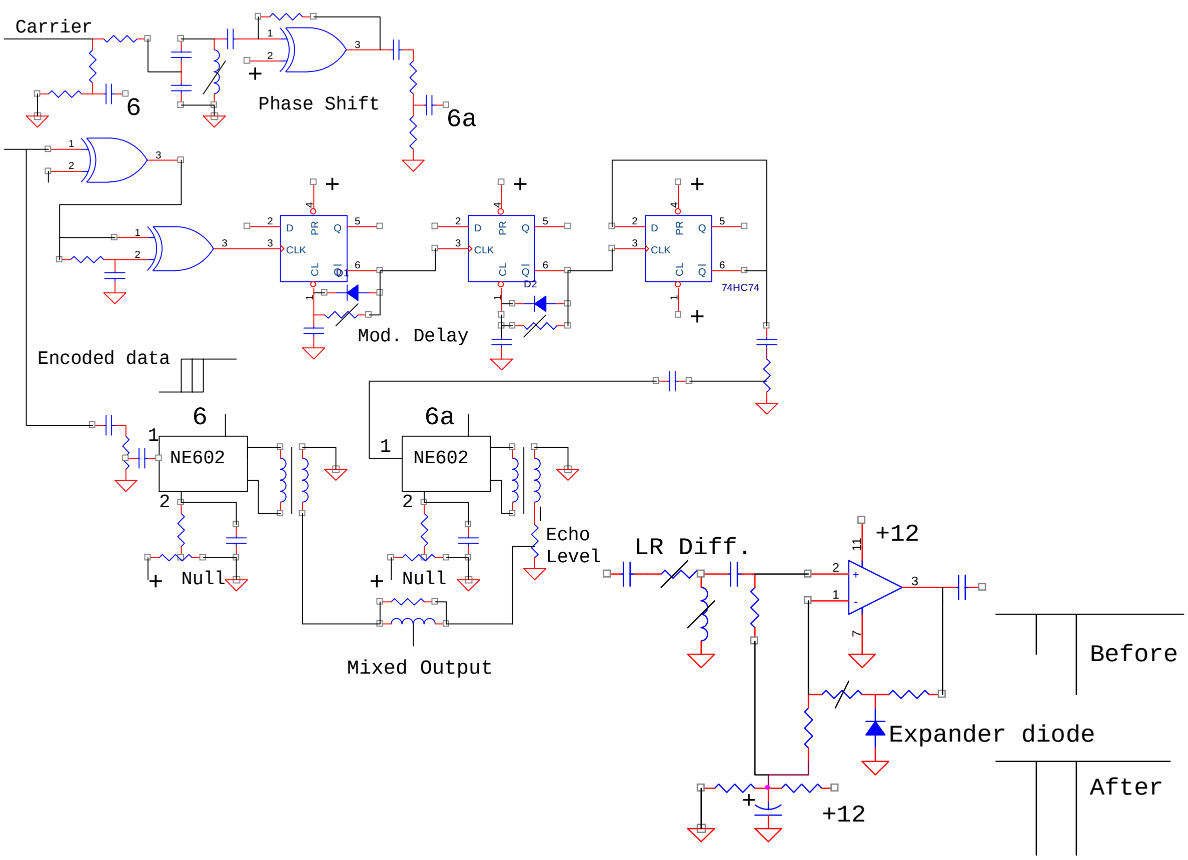
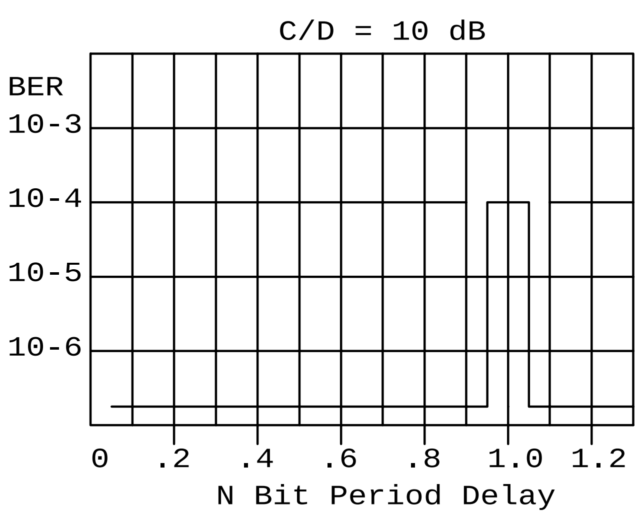


Fig. 6

Fig. 7



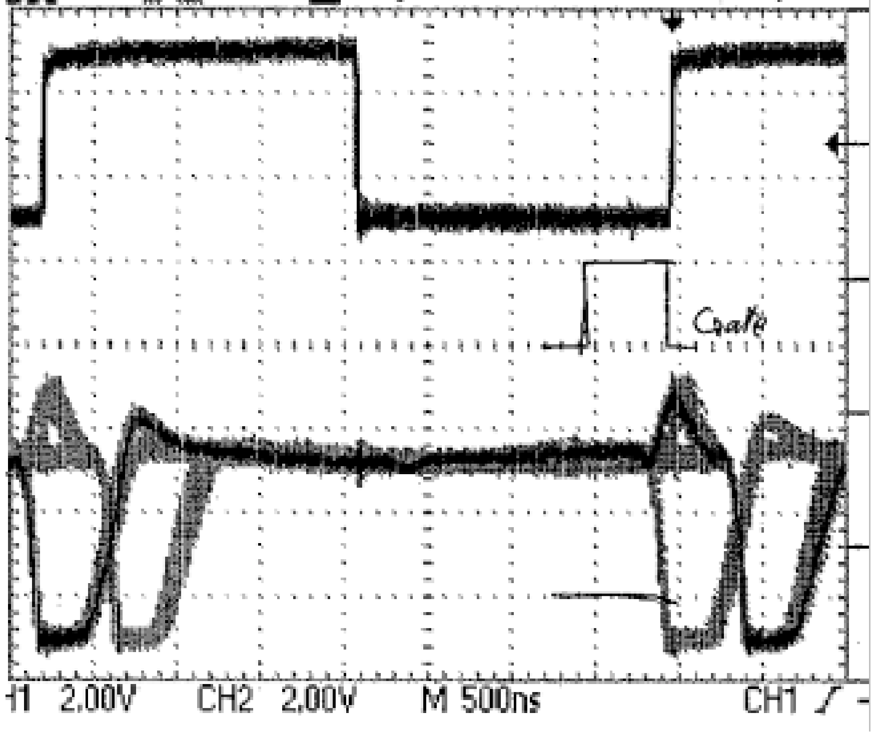


Fig.9. Echo Level -10 dB, delay time = **1 bit period.**

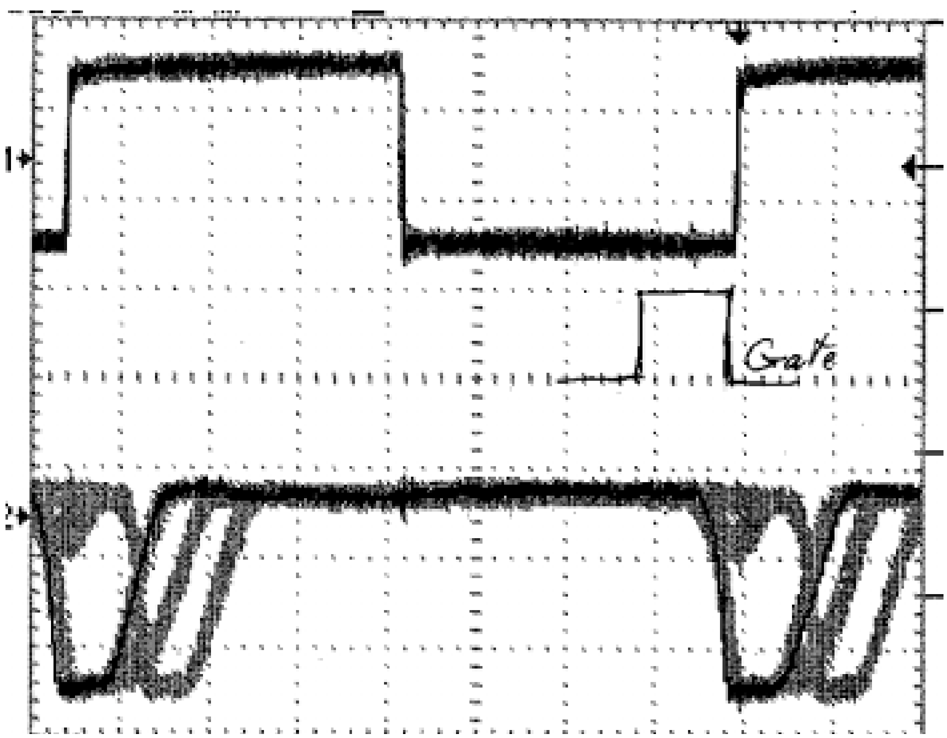


Fig.9. Echo Level -10 dB, delay time **= 2 bit periods.**

The detector circuit responds only to the lower negative peaks. The peaks are gated. In Figs. 9 and 10, the negative peaks at the lower right hand corner are within the gate and will be detected as digital ones. The minor pulses will be rejected. This multipath signal is now being detected without errors.

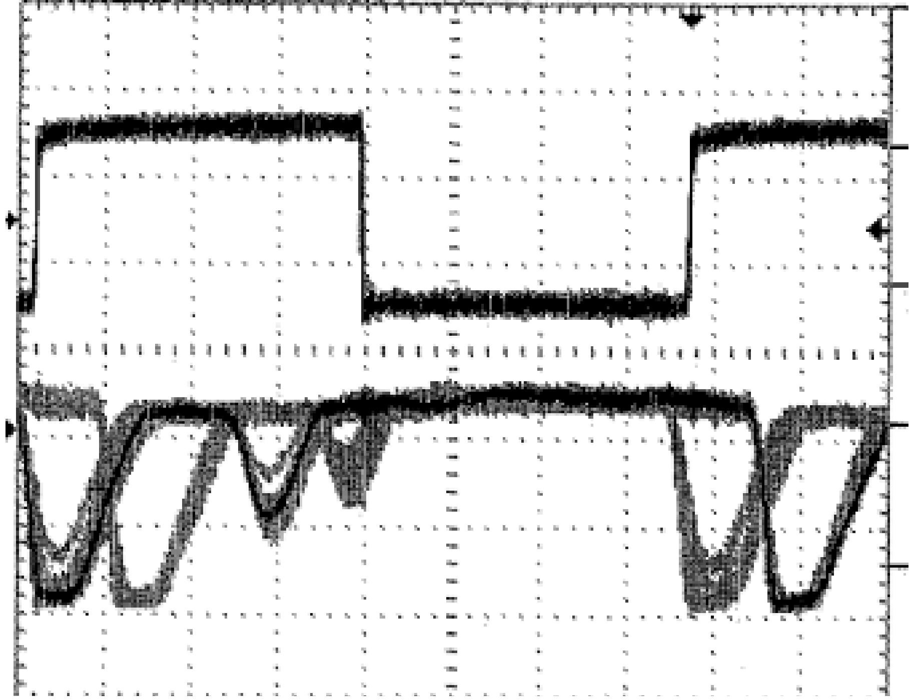


Fig. 11. Echo at -5 dB. Echo delay = .35 bit period. Detector will accept only negative spikes at the lower right which appear within the gate. Smaller spikes at center will be ignored. The detector works on negative peaks (clipped level) only.

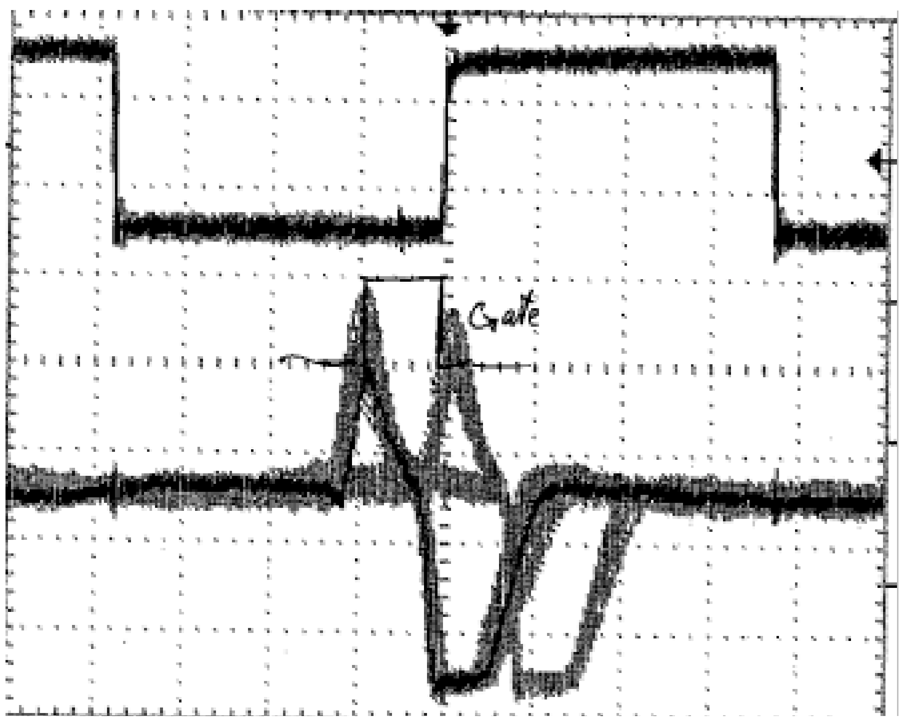


Fig. 12. Echo level -5 dB, delay time = .9 bit period. Detector responds only to negative going spike at the center that is within the gate. Gate closes once pulse is acknowledged. Echo is positive and has no effect on detected data.

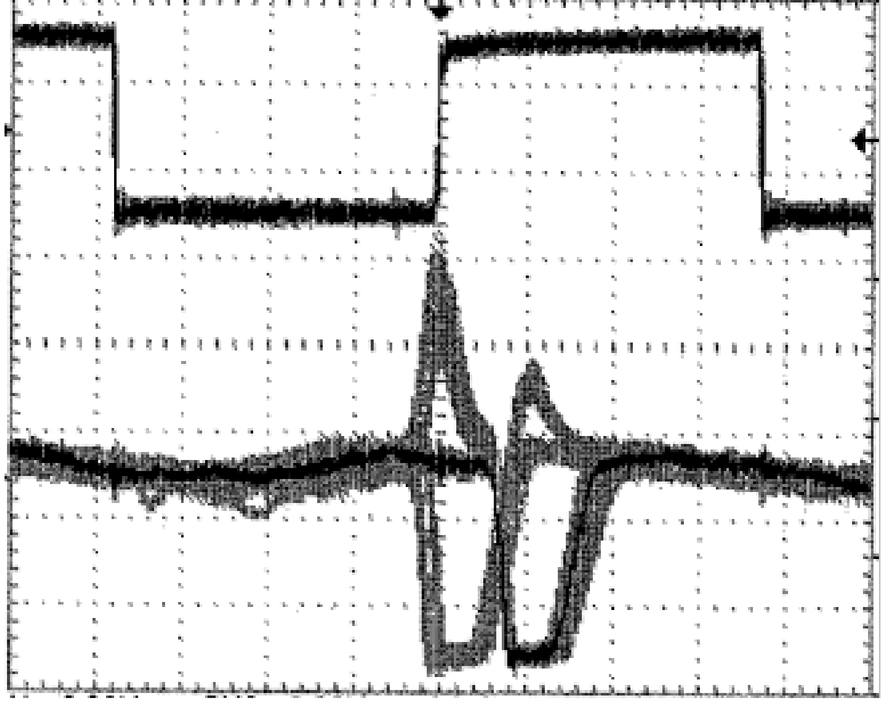


Fig. 13. Echo at -5 dB. Delay = 1.0 bit period. Echo can cancel desired pulse. When echoes are exactly at or near 1.0 or 2.0 bit periods, they cause trouble. In between the echoes are gated out or too weak to have any effect.

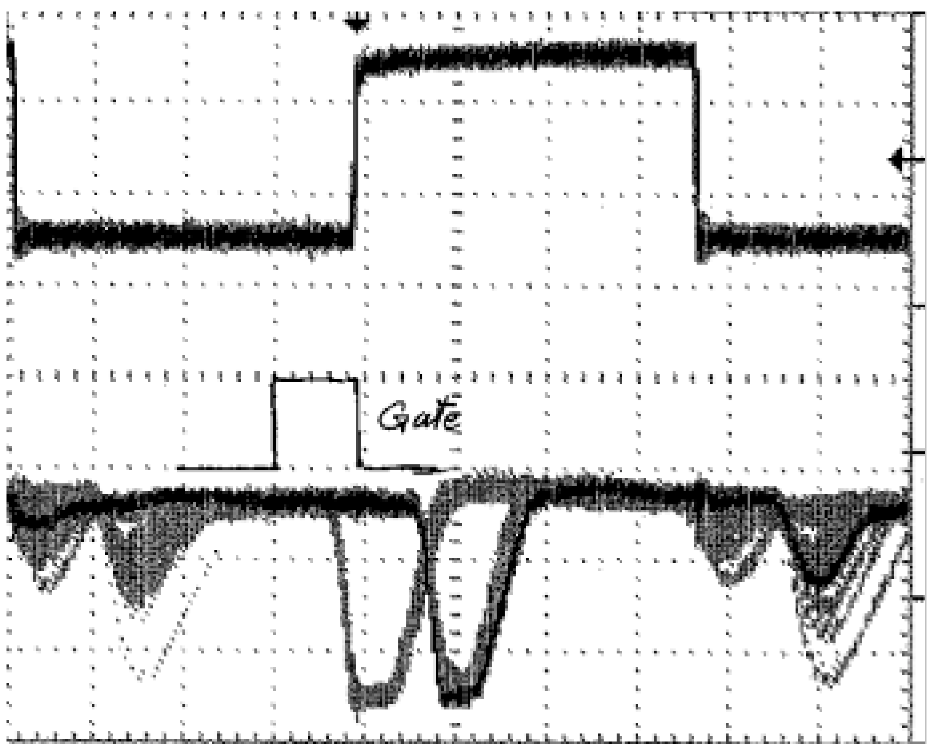


Fig. 14. Echo at -5 dB, delay time = 1.5 bit period. Detector response is to negative peak within the gate only. Other peaks are rejected.

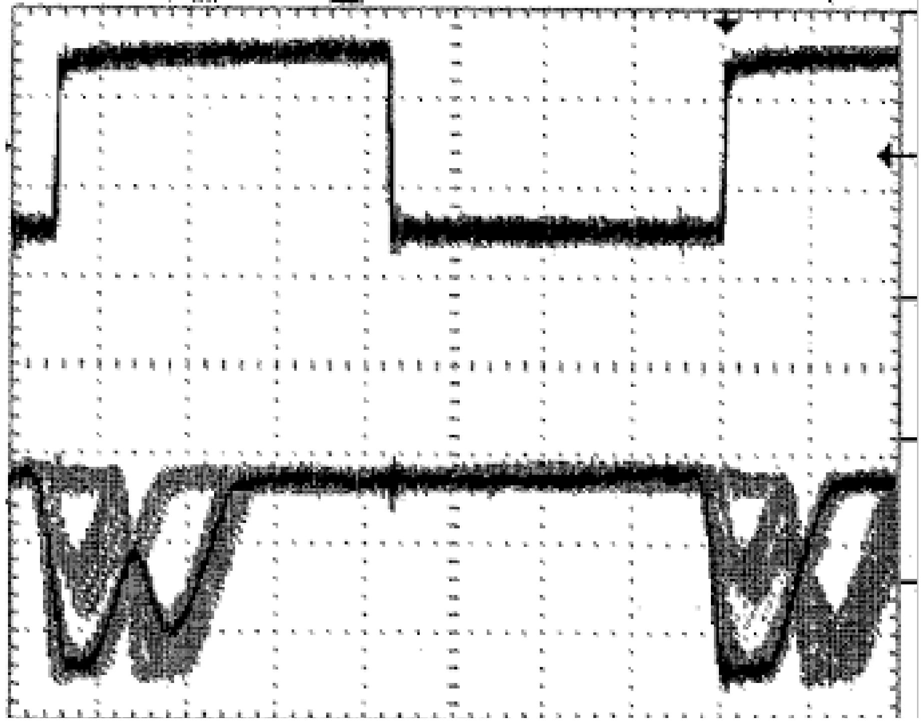


Fig. 15. Echo at -5 dB, delay time = 2.0 bit periods. If clip level is too high, the spikes at -5 dB will be detected giving an error. Both appear within the gate. First signal to appear within gate at the proper level will reset the gate.

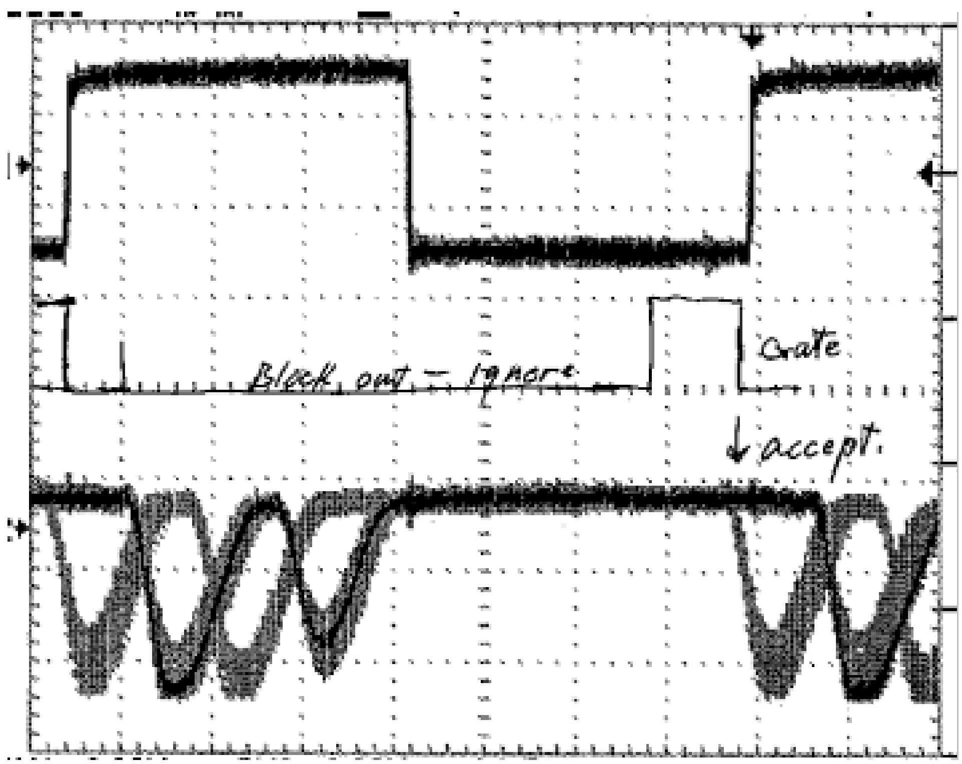


Figure 16. Echo and desired path at same level (0 dB). Delay time = .25 bit period. Detector locks to first negative going spike within gate. Will detect this without error.

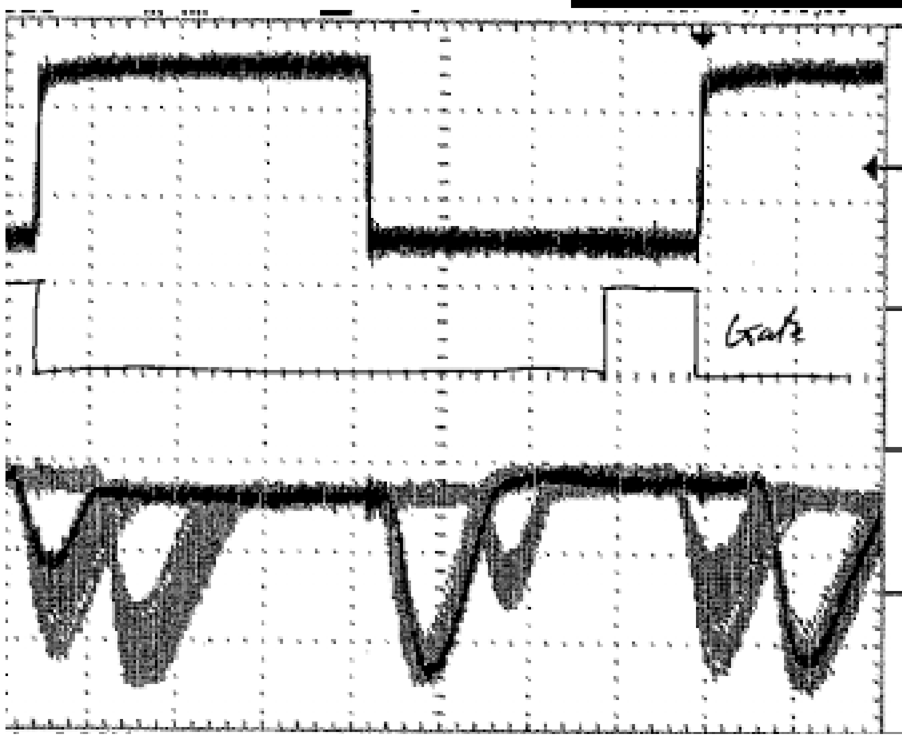


Fig. 17. Echo at 0 dB (Equal level with desired signal.). Delay period .5 bit rate. May or may not detect on signal within gate as seen. Would probably jump (move gate to stronger more reliable signal at center).

Signals at or near a multiple of the bit period (1.0, 2.0, 3.0 etc will not be detectable).

Figs. 9 to 17 were recorded without the differentiator and expander (Fig. 7.). After adding the differentiator and expander, the peak up at bit period delays of exactly 1, 2, 3,-- etc. bit periods is not seen at 10 dB C/D. It is barely perceptible at -6 dB and probably as seen here at -3 dB.

Adding this circuit makes it possible to operate close to 0 dB C/D except for a very small time period when the pulses exactly overlay one another.

A report prepared by Bell South is appended showing measurements made using a more sophisticated test set that also measured Rayleigh fading. These tests were made prior to adding the expander circuit of Fig. 7.

No error correction was used in these tests.

Title

To: *Blanked Out*
From: *Blanked Out*

CC: Hal Walker, (***I have added comments in italics-HRW)***

Date: June 12, 2000
Re: Testing of the VMSK modem (Pegasus Data) June 9, 2000 -At Bell South Lab., Atlanta

The equipment was set up, aligned and allowed to settle in before testing started. The setup was a little cleaner than it was for the earlier testing in March. Data rate is 270 kb/s. ADPCM encoded music.

Fade Testing
Testing of the fade margin required additional tweaking to get it down to 50 dB. This was the best that the limiter could provide. They need to improve the dynamic range and they are looking for a better limiter. ***We have a new limiter that is nearly 40 dB better. This will be used in future tests.***

Delay testing

This was the primary purpose for coming down and re-running the tests. Pegasus made changes in the detector slicing threshold and tightened up the gating window.

Two unfaded paths were set up in the fading simulator to verify the predicted improvement, as a result of the above changes, in reducing the susceptibility of the detector to multipath signals.

Test 1

Path 1 0 microsecond delay 0 dB attenuation

Path 2	***1 microsecond delay***	***10 dB attenuation***	***OK***	
"	***2 "***	***"***	***OK***	
"	3 "	"	OK	
"	4 "	"	Poor(one time slot = 3.769 μs)	
"	5 "	"	OK	
Path 2	6 microseconds	10 dB attenuation		Slightly Scratchy sound
"	7 "	"	OK	
"	8 "	"	Scratchy sound	
"	9 "	"	OK	
"	10 "	"	Slightly Scratchy sound	
"	11 "	"	Scratchy sound	
"	12 "	"	Scratchy sound	
"	13 "	"	OK	
"	14 "	"	Slightly Scratchy sound	

No other modulation method can operate at all at 10 dB. The fact that we are able to at some delay periods and with scratchy sound at the critical points puts us far ahead of any competition.

<u>Test 2</u>

Path 1	0 microseconds	0 dB attenuation		
Path 2	4 microseconds	<u>10 dB attenuation</u>	Bad	***(Critical time delay t/T =1).***
“	“	8 dB “	Bad	
“	“	6 dB “	Very bad	
“	“	12 dB “	Very scratchy	
“	“	14 dB “	Less scratchy	
“	“	16 dB “	Slightly scratchy	

Adjusted gate timing before test 3 started

Multiples of 3.8 microseconds are the bad spots.

<u>Test 3</u>

Path 1	0 microseconds	0 dB attenuation	
Path 2	3 microseconds	<u>6 dB attenuation</u>	Scratchy
“	8.02 microseconds	6 dB	Very Bad almost no music

At 7.9 microseconds the music was OK and again at 8.1 microseconds the music was good. At 8.01 to 8.06 microseconds the decoded music was bad to very bad with 8.02 being the worst .

The competition cannot even dream of operating at 6 dB. Scratchy sound means 1 in 1,000 errors. This is considered acceptable for digital voice with error correction using other methods. 10-3 is the cut off point. <u>We did not use error correction or adaptive filtering.</u>

<u>Test 4</u>

Path 1	0 microseconds	0 dB attenuation	
Path 2	9 microseconds	<u>6 dB attenuation</u>	OK **(this delay is in between gates)**
“	“	4 dB “	OK
“	“	3 dB “	Scratchy ***(Interference 70% of desired)***
“	“	2 dB “	Bad ***(80%)***

This test was to see how high the echo path strength could be raised to cause <u>trouble between the known bad time delay spots</u>. 3 dB means the echo is 70% as strong as the desired path. We measured 10-3 errors, and worse at 80%. 10-3 is considered -correctable/minimum acceptable -with error correction. Any other modulation method would be totally useless at 10 dB, or 30% level. They usually consider -15 to -18 dB as the absolute minimum for the other methods (10%). Bell South had to readjust the test set to get to the higher levels needed to cause us trouble.

Path 1	0 microseconds	0 dB attenuation	
Path 2	8.02 microseconds	7 dB attenuation	almost complete loss of music

Path 2 8.05 microseconds 7 dB attenuation music broken up but not nearly as bad as at 8.02 microseconds

8 dB " scratchy

9 dB " music clearing up and less scratchy

12 dB " Clean

These are tests at the bad spot- namely a very narrow range between 7.95 and 8.05 microsecond delay- We did not retune prior to this run. The bad spot area is 2-3% of the delay range. For other modulation methods it is 100% of the delay range. This shows a 10 $^{-3}$ bit error rate at 8 dB in the critical range only. A graph is appended to show the relative performance of other methods.

Pegasus:

1. Further clean up the modem cabling/shielding ***(In progress)***
2. Install TCXO oscillator(s), and eliminate some of the up/down conversion steps. ***(In progress)***
3. Clean up the transmitted (cellular) signal to meet the FCC emissions mask ***(In progress)***
4. Increase the receivers' dynamic range to approximately 70 dB from the present 50 dB***. (now at 95)***

BellSouth:

1. Provide Pegasus with the interface specifications/documentation for connecting their equipment to the receive antenna. This is in preparation for a one-way over the air field trial of their modem in Atlanta. ***(Believe they mean transmit antenna and power amp.)***

2. Coordinate the test with Region 2 .

3. Schedule another lab trial with Pegasus, prior to the field testing, to verify the FCC emissions compliance and the modem operation in the presence of Rayleigh fading.

Obviously Bell South wants to see this method succeed and is willing to help where they can.

We have a new receiver in preparation. It is a built from scratch unit that operates at GSM rates (270 kb/s) We can interchange it with a unit at 812.5 kb/s. Operating in an AMPS channel at 812 kb/s is the equivalent of 5.0 Mb/s in a GSM channel. Cabling will be kept to a minimum to reduce the cable pick up problems with weak signals.

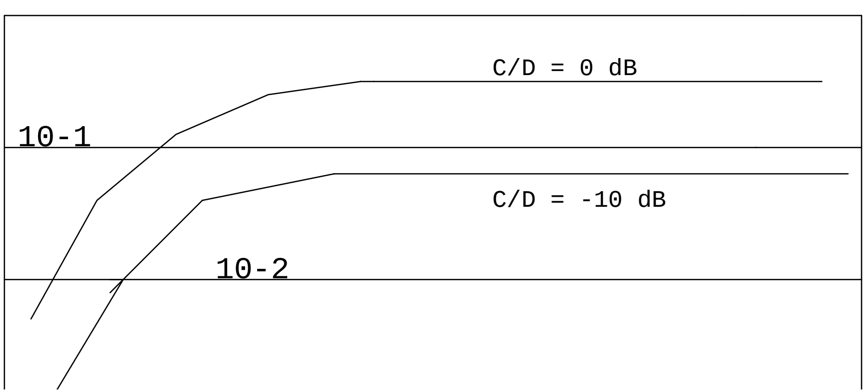
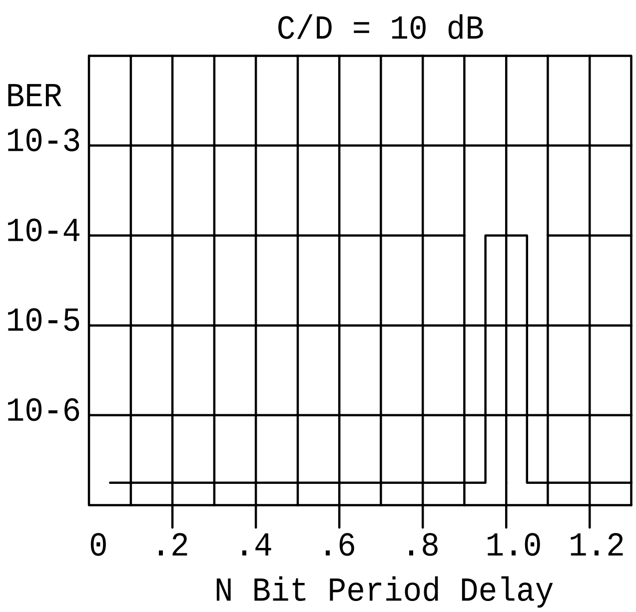


Fig.1.

Fig. 1. From Rappaport " Wireless Communications", Fig. 5-59. Applies to GSM and IS136.

This plot shows that a C/D greater than 18 dB is required for a usable signal using either GSM or pi/4DQPSK, whereas we can approach 0 dB for most of the echo time differences. This is at least a 10 to 1 difference.(power ratio).

We are obviously operating - without error correction or adaptive filtering - at better than** 10^{-3} **BER (probably at 10-4 bit error rate) in the critical spots at 1.0 and 2.0 t/T. Any other method requires 15-18 dB to get to 10-3. We fail at high echo levels only at critical spots, not across the whole range of t/T. The probability that operation will occur in one of these critical spots is very slight.



Our measurements are approximately as shown above. There is a narrow band of interference near t/T = 1 and t/T =2. Otherwise, we can approach 0 dB C/D for the areas in between. We have no trouble operating at C/D = 10 dB. As can be seen, our problem is in a very narrow delay period region and does not extend a cross the band. Gating the signal pulses greatly improves the system.

This is **without error correction or adaptive filtering**. We are still trying to get an understanding of the adaptation needed, but it appears to be an amplitude shift related problem that can be largely overcome. We foresee our operating at 6 dB C/D without problems.(with gating and 'R' correction).