IEEE P802.15
Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	**PHY Recommendation--Ternary AM DSB SC (with partial response pulse shape)**
Date Submitted	10 September, 2004
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Re:	TG4A Call for contributions, Jason Ellis, August 2004
Abstract	This paper recommends PHY modulation ***ternary AM double-sideband with suppressed carrier and with partial response pulse shaping***. Its properties are fully described. Background is given comparing it with other alternatives, and a brief description of an implementation.
Purpose	This proposal is a candidate for entry into the down-selection process for the TG4A.
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PHY Recommendation—Ternary AM DSB-SC (with partial response pulse shaping)

Chandos A. Rypinski with
Bob Ritter (builder & simulator) and John Armanini (math & logic)

Table of Contents **Page**

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SUMMARY

An uncommon digital modulation technique is recommended for short-reach, scalable data rate personal area as an alternative to widely used GMSK, BPSK, DPSK and OQPSK modulations. The targeted applications are those requiring a combination of properties which include: 1) high like-signal interference resistance to enable extensive frequency reuse over a large area, 2) low sidelobe levels to enable better use of adjacent channels and 3) the flexibility to trade off channel coding schemes and occupied bandwidth for the best fit to the specific application

The recommended baseband modulation is ternary DSB-SC (double-sideband suppressed carrier) with three amplitude levels. A specific unit-pulse shape (now referred to as "**Sym-pulse**") is used which provides minimized use of low frequencies with zero dc component, and which is relatively efficient in bit/Hz.

This modulation resembles two-level "Manchester" which has zero dc content in the generating symbol, but uses twice the baseband spectrum as NRZ. The use of three amplitude levels doubles the resulting bits/Hz property to achieve the same or better bandwidth utilization as for NRZ. This modulation is also like Lender's "duo-binary" in the use of three amplitude levels and partial response over lapping but with unlike power density spectrum at dc and at low frequencies.

An example use of Gold codes at 15 and 31 bits would enable code division separation of 12 and 20 channels which would be best used for resolving overlapping coverage's where equal level desired and interfering signals could be separate. The coding gain would bring the noise bandwidth back to that of the information transferred rather than the occupied bandwidth.

Unique properties are: 1) independence of match between transmitter and receiver rf phase and frequency, and 2) a material frequency diversity benefit from the second sideband.

There are two further possibilities, each enabling a doubling of spectrum utilization: 1) use of quadrature phase to send a second independent bit stream in the same bandwidth, and 2) single sideband transmission of the same video signal.

The recommended possibility has been simulated in great detail and many models built and tested.

Advantage Summary

This modulation has several advantages compared with others is summarized as follows:

- ***Zero dc and reduced low frequency energy*** density below 10% of the high edge frequency of the power density spectrum enables baseband amplification with video rather than dc amplifiers.
- ***Independence of rf phase or frequency at demodulation*** creates:
  1) great tolerance to motion of the user station, and
  2) it provides decreased susceptibility to phase reversal errors with frequency dependent or time domain fades.
- ***Low adjacent channel and second channel emissions*** are the result of using the right pulse shape in the first place, rather than filtering a high side lobe signal.
- ***Copper pairs can transport the baseband waveform large distances without equalization.***

The combination of all of the above advantages is important relative to alternatives which may not be equivalent on one or more considerations. There other lesser advantages.

- ***Overhead time used for acquisition is greatly reduced*** by the absence of the need for rf synchronization.
- ***Twice the average power allowed for BPSK may be used*** with the specified channel coding. Half the bits are 0's transmitted at zero amplitude creating a 50% duty cycle.
- ***Implementation is a relatively simple combination of analog and digital techniques*** not requiring A/D or D/A converters or fast DSP. Proprietary art is minimal since all functions, taken one at a time, are prior art.
- ***Low power drain, complexity and ease of implementation*** are also claimed.
- ***Theta-theta angle positioning*** can be provided as an extension of this radio system for users station location—a description, if of interest, will be separately provided.

Property Summary for Ternary DSB-SC

Feasible data rates:	10 Kbps to 32 Mbps	
Spectrum zero's:	Zero's at 0, 0.8 x bit-rate, 1.0 x bit-rate	
Occupied bandwidth:	@ -10 dB	0.16 to 1.28 x bit-rate
	@ -20 dB	0.08 to 1.4 x bit-rate
	@ -30 dB	0.04 to 1.5 x bit rate
Acquisition time:	zero time for rf synchronization 120 bits for AGC setting, bit clock acquisition and start delimiting	

It is believed that the quadrature phase can be used to double bits/Hz property with moderate degradation of the like-signal interference resistance, but will lose the frequency independence property.

This modulation, demodulation and implementation are described in further detail below.

DESCRIPTION OF THE RADIO MODULATION AND DEMODULATION

The properties of the data link requires complementary operation of transmitter and receiver. The transmitter is optimized for spectral efficiency and low emissions out-of-band and the receiver must be optimized to resist overload from strong signals on adjacent channels and interference from co-channel signals re-using the channel at the least possible separation.

Most important, is the system arrangements for frequency reuse, area coverage and total capacity. In this area, the capabilities of the basic radio channel have a big effect on capacity expressed as Mbits-per-MHz-per-acre of area. Within this heading is path diversity which can do more for reducing errors that any amount of forward error correction.

The functions of each element is best realized with careful distribution of functional burden between these parts. There are usually many different ways to implement, but the principles to be implemented are sorted with experience to a very limited list.

Transmit Modulation

The modulation is built up from a mathematically defined unit pulse which has the desired spectral power density characteristics. The unit pulse is defined over a number of bit intervals as shown in **Figure 1** below (blue-solid). The serial data stream is formed by overlapping these pulses each either up-right or inverted which forma a ternary waveform with values +1, 0, -1. The bit interval is the distance between zero crossings either side of center.

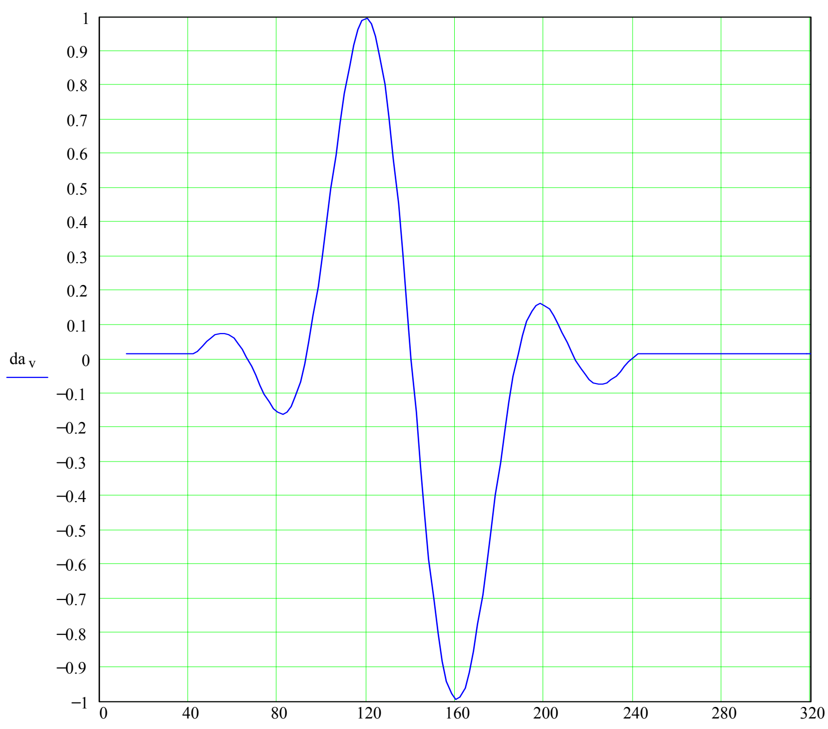


Figure 1 Wave shape for isolated pulse (Sym-pulse)

Serial bit stream waveform for Sym-pulse

Using the concatenated unit pulses to form a serial data stream, the following properties are obtained. At any instant, the amplitude is determined by two successive bits. The possible values for Sym-pulse are +1, 0 and -1. ***Differential channel coding*** is used as shown where a transition in either direction in source data is represented as bit-stream 1and absence of transition as bit-stream 0.

In **Figure 2** below, a sample random bit stream (130 bits out of 4,096) is shown, and the corresponding video waveform.

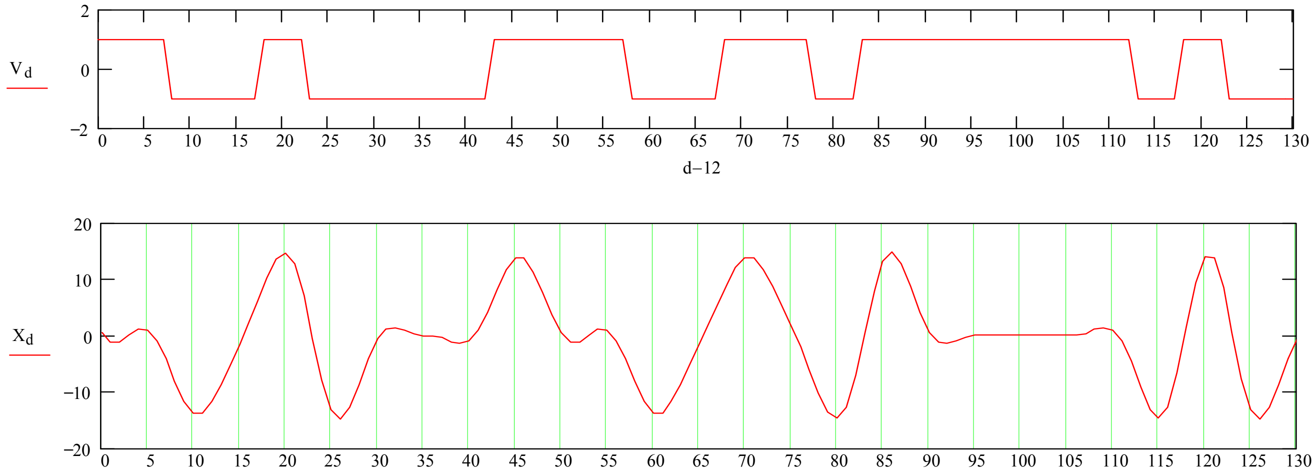


Figure 2 Above is 130 bits of data input producing the video waveform below

The “eye” diagram for this modulation is shown in **Figure 3** below. The traces represent every possible trace between consecutive pulses.

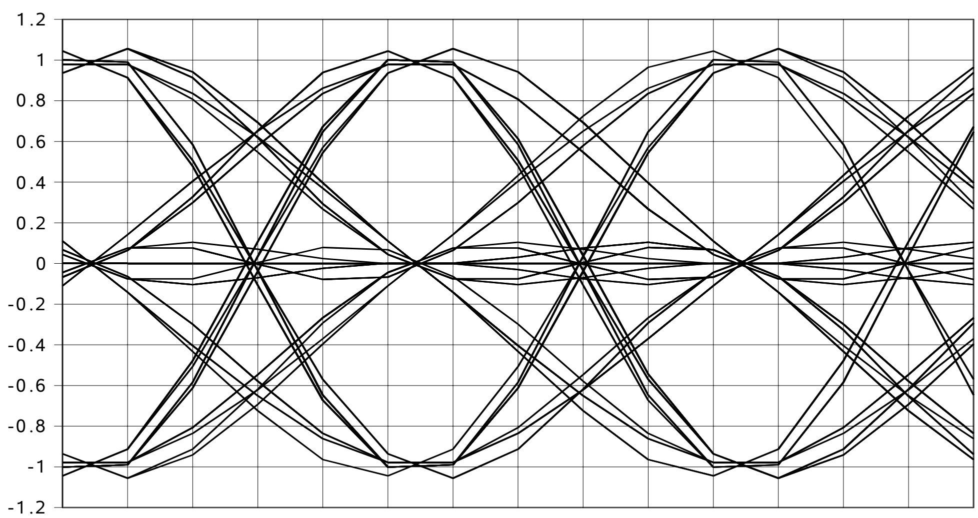


Figure 3 “Eye” diagram for ternary vdeo data stream

Figure 4 below shows the power density spectrum (mathematical simulation) for the data burst from which the above segment was taken. Notice that the first null is at 20 MHz for 25 Mbps data rate. Non-partial response generated spectrums usually have the zero at the bit rate.

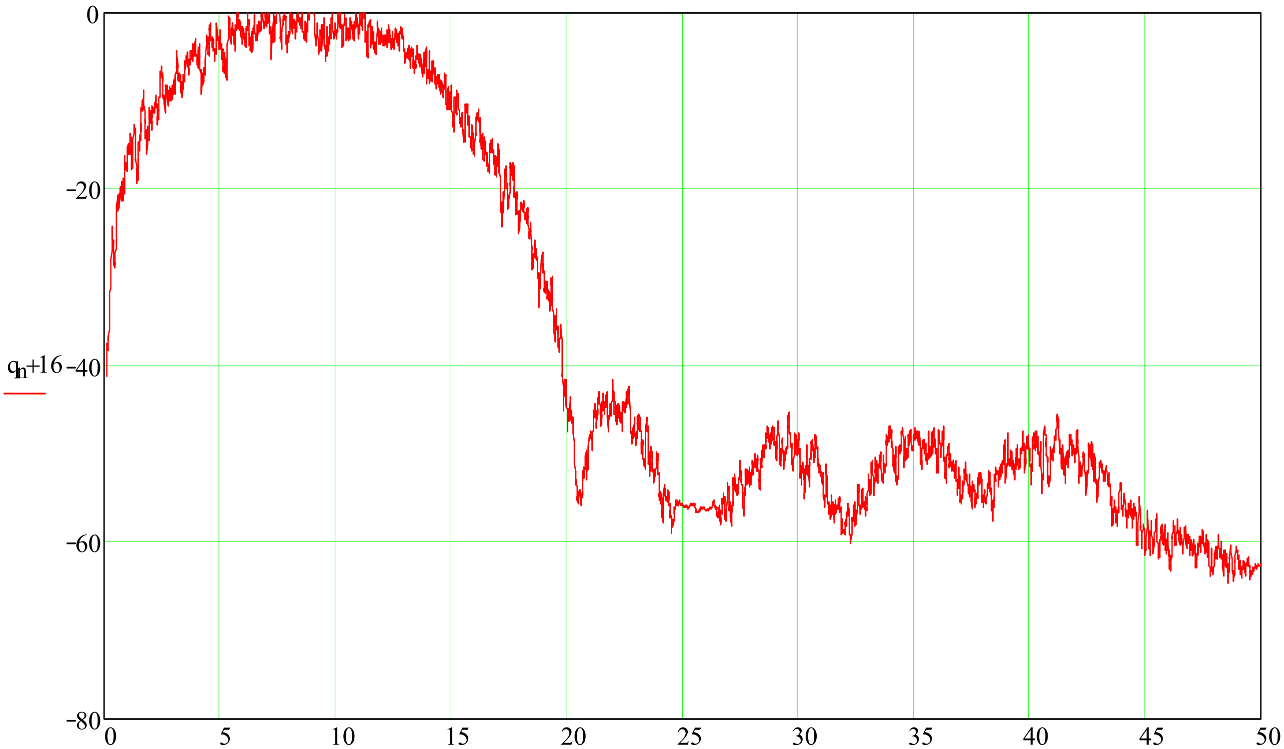


Figure 4 Power density spectrum for psuedo-random 4,096 bits (math simulation)

The vertical grid lines are at intervals of 5 MHz up to 50 MHz. The horizontal grid lines are at intervals of 20 dB. The low sidelobe level in this figure represents the potential of the process that creates the Sym-pulse. Later below, the resulting DSB spectrum at radio frequency is shown from both a simulation and a measurement.

Detail channel coding

As above described, the information is coded as transitions rather than absolute state. A 1 of either polarity is defined as a transition 1>0 or 0>1). A self-synchronizing scrambler is desirable. Under consideration is the use of a bit stuffing method (similar to IBM HDLC), where after 15 consecutive 0's, a data 1 is inserted. The same procedure could apply to 1's, but it is not necessary. The value of insuring the presence of 1's is to provide refreshing of the automatic gain control function.

The preferred preamble starts with all 1's which provides a sine-wave at half the bit frequency. Sequential bit stream 1's are always reversed in polarity independent of the number of interposed 0's. This avoids a spectral line at the bit rate in the data stream. This line would decrease the peak-average power ratio, and might reduce the noise tolerance in the demodulation.

Translation From Baseband to Radio Frequency

After modulation of the baseband signal on a carrier frequency, the double sideband suppressed carrier signal is created.

Spectral power density from system simulation

The figure below shows the output of a system simulation which uses a model of the present schematic circuit design. This is a very different input than the previous math simulation. The x-axis grids are space 20 MHz, and the y-axis grids are spaced 10 dB. The center frequency is 5.25 GHz.

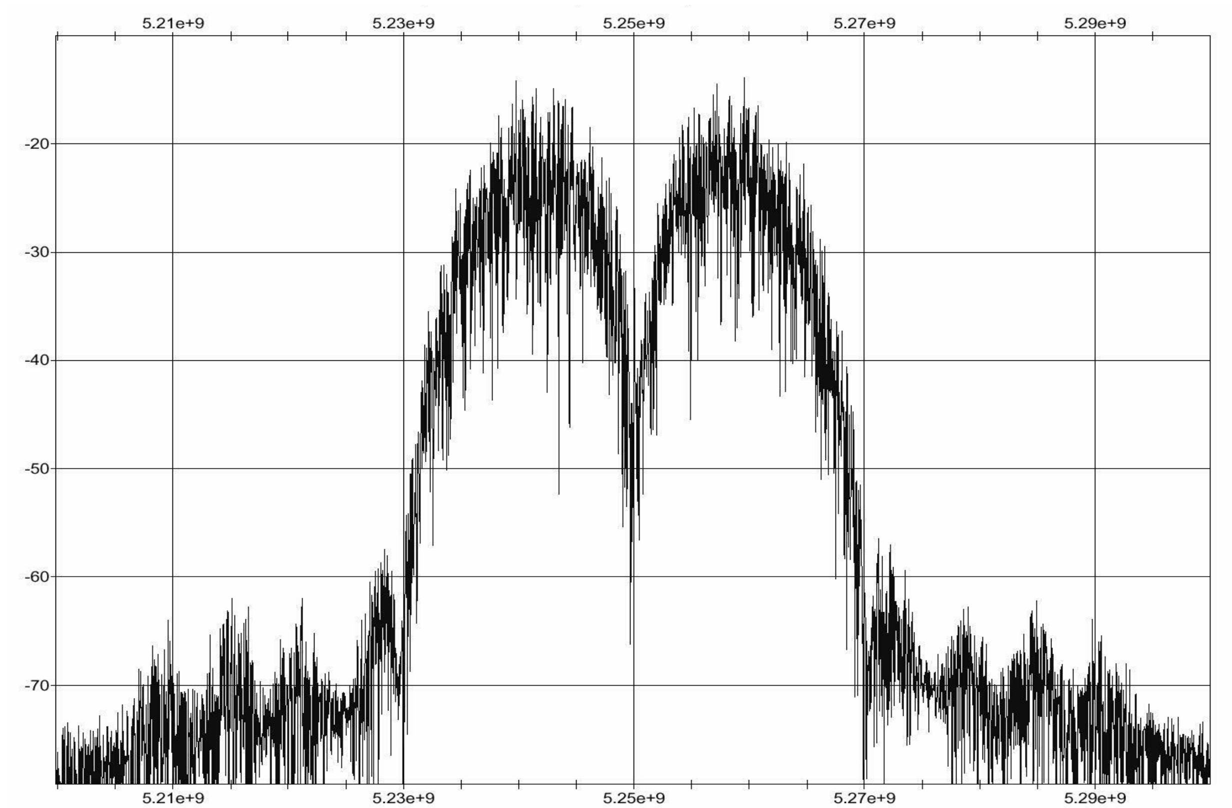


Figure 5 DSB Spectral Power Density from Circuit Simulation

Measured spectral power density

A screen capture from a spectrum analyzer is shown below. The point observed is at the output of the transmit up-converting diode ring mixer with 5.250 GHz local oscillator modulated by the 25 Mbps Sym-pulse data signal. This is a good picture, but it is probable that it can be further improved beyond the -30 dB points.

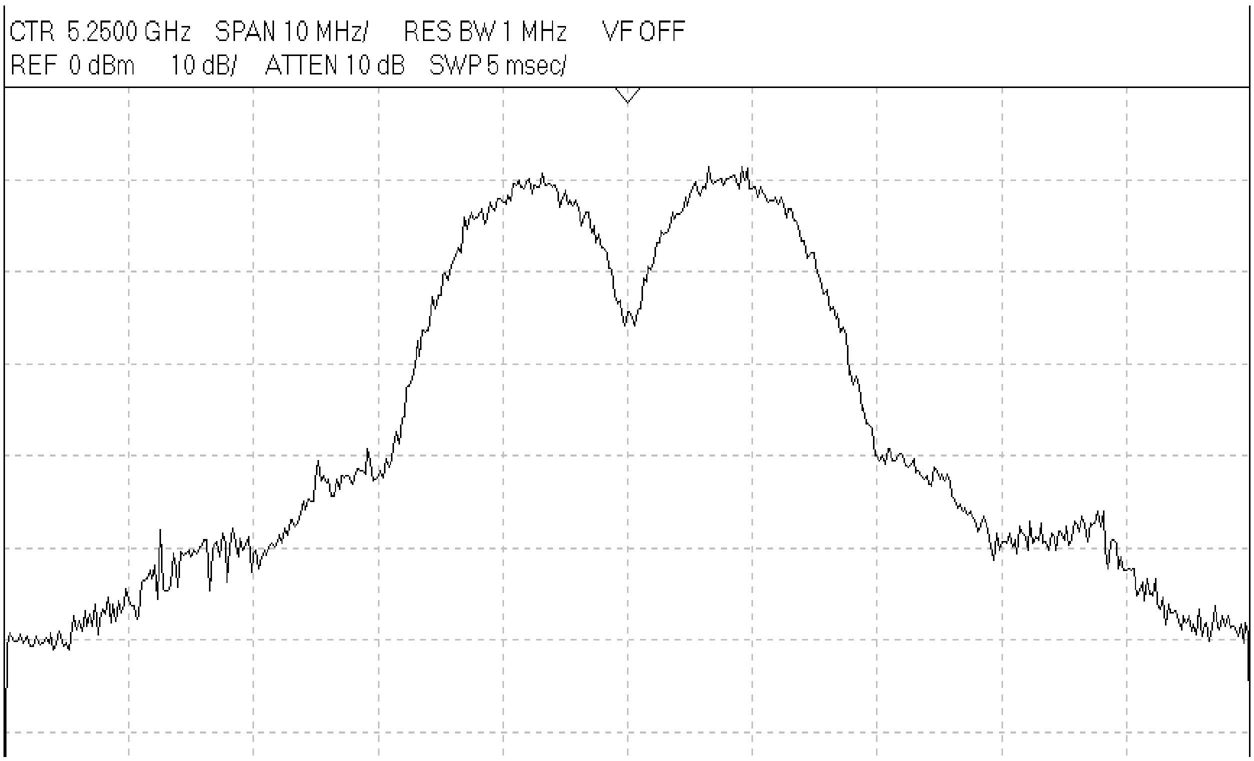


Figure 6 PSD screen capture at 5.25 GHz center frequency for DSB-SC radio

In mixing up to the signal frequency, some art is required to avoid mixer products, carrier leak and above all distortion of the video waveform. In this picture, the carrier leak appears as the raised point at the exact center.

It will be seen that this spectrum shape does not have the "shoulders" (24-30 dB down) found on multi-carrier modulations. Usually the back-off and linearity of the final transmit power amplifier is the cause of the shoulders. Such amplifiers may need more back-off than would the **Sym-pulse** spectrum shown above. The multi-carrier modulations are likely to show the shoulder out of the waveform generating circuitry because of imperfections in the generation from minimized sampling frequency or other circuit limitations.

There is an advantage in using an intermediate frequency in the transmitter architecture. At 400 to 1000 MHz, it is possible implement a bandpass filter selective enough to considerable reduce the unwanted spectrum more than one bandwidth (90+ % energy enclosed) off the center frequency.

Receiver Demodulation

The demodulation uses a vector demodulator which is better realized at an intermediate frequency.

There is usually 60-80 dB of gain (for data rates of 10-100 Mbps) between the antenna and the vector demodulator where ***the ultimate channel bandwidth is defined.*** Filters closer to the antenna cannot provide enough selectivity aid adjacent or next to adjacent channel rejection.

For narrower spectral bandwidths <12 MHz, a 900 MHz SAW bandpass filter can be used, but only the central 50% of its bandwidth. This is because of group delay spread limitations for common 25 MHz wide types. A FIR filter could have the desired amplitude and group delay characteristics, but not the low noise required for very low signal levels.

The simplest approach appears to be moderately reducing the gain ahead of the vector demodulator until the noise limitation is approached, and then adding video gain after the vector modulators. Use of material video gain is far easier with data waveforms that do not have dc content, and make small use of very low frequencies. Also, the radio design is much easier without too much gain at any one frequency. These are important advantages of Sym-pulse.

Each dB reduction of gain ahead of the vector modulators may increase the close-in large signal overload point by that much or more.

These circuits are shown in block diagram later below when the radio implementation is described.

The value of phase/frequency independent AM modulation

In moving station service, it is immediately necessary to calculate rate of change of rf phase as a function of velocity, and then determine if the de-rotation circuit or the PLL loop can keep up with it. Since the offered technology has no dependence on that property, it is a non-problem.

An experiment to test the coverage on access point will soon discover that there are many small spots where a signal cannot be recovered even though it is an unobstructed optical path. Further investigation will reveal that increased transmitter power may reduce the size of many of these holes, but it will not eliminate them. There are many cases where the signal level is high enough but not readable. These are the symptoms of multiple propagation paths where the vector sum is a null relative to the average level.

> What may not be recognized is that a cancellation null always generates a phase reversal whether it is traversed in time, frequency or space. Those modulations which depend on the rf phase as a bearer of information are degraded by such nulls.

When a cancellation null is encountered, there may be a substantial recovery time if PLL loops are use to recover virtual carrier (e.g., Costas loop). This difficult can be overcome by using differential QPSK where the phase reference for the current pulse is the preceding pulse. Since the reference has the same noise as the signal there is a small loss S/N threshold, but many have thought it worthwhile for the reduction in size of hit errors.

Multiple antenna diversity is of great benefit for reducing lost cover from cancellation nulls. Space diversity also reduces the average power require for a given area coverage. There would be a benefit using Sym-pulse as with other modulations.

The proposed modulation is double sideband with a potential for a two channel frequency diversity effect at high microwave frequencies. The complete information is carried by each of the sidebands. This is helpful when the signal bandwidth is wide enough and the frequency selective null is narrow enough to be in one of the sidebands and not the other.

When there is little difference in vector sum of the paths over the bandwidth of the signal, the situation is described by Rayleigh fading. With this type of signal, the amplitude can be several dB higher for a vector sum of multiple paths than for the isolated optical path. The received signal is modified from that transmitted by Doppler effect—typically in ppm. This is assured phase rotation that may be interpreted as variable path length/delay.

Most of the paths that cause Rayleigh fading have nearly the same length as the optical path. The additional rays are mainly from floor, wall and ceiling reflectors. There are usually a few of them that are dominant. Directive antennas and path diversity are almost the only effective ways of mitigation.

Increased transmitter power will shrink the size of coverage holes. In land mobile services that cover city streets, signal levels are used that 30 to 50 dB above free space. The interference range is many times that of the coverage.

No matter what the situation, the phase/frequency independent modulation will make the best of it.

Frequency independent amplitude demodulation

The amplitude detector is based on using an vector (I-Q) demodulator which may be at an intermediate or signal frequency. The output processing is based on the identity:

$$\sin^2(\theta)+\cos^2(\theta) = 1$$

The I and Q outputs are separately squared and the two results summed to obtain a phase-independent measure of the signal amplitude. The squaring operation yields a single positive output for either phase in the source signal, and ***it provides an amplitude indication proportional to signal power and independent of phase angle.*** It is possible that this function can be provided using the logarithmic transfer function of diode rectifiers at low level. Experiments have used commercially available analog multipliers which have been found satisfactory. The squaring circuits are range limited to input values less than unity. The available squaring circuits may be stretched at rates above 30 Mbps.

The data demodulator assumes use of an approximate AGC which is set at the start of the burst preamble and refreshed during the message. A second forward acting level compensator sets the threshold in relation to the peak signal level. The threshold is set at about 70% of the reference level for a comparator device which at sampling time determines the level to be above or below threshold.

There is an integrate-and-dump circuit which sums the areas of the central half of the incoming bit-pulse. The integration capacitor is sampled at the end of the charge interval and it is discharged during the non-integrate interval.

The block diagram of this type of demodulator appears in the radio block diagram of **Figure 8** below. This block diagram has been simulated end-to-antenna-path-antenna-to-end in same simulator as used for **Figure 5.**

Reason for avoiding primary use of quadrature phase

Now explained, is the reason for not using the quadrature phase. In a Rayleigh propagation environment, a path delay in one of the principal rays, corresponding to a 45° phase shift, will distribute its energy equally between the I and Q phase demodulators. It is not hard to imagine a delay of $1/8^{th}$ cycle at radio frequency, and this is enough to destroy the phase-based isolation on which QPSK rests. This degree of delay spread may not be frequent, but is also inevitable.

If a high percentage of first time success in packet transfer is desired, it is important to correct or mitigate a number of factors which appear a small percentage of the time.

RADIO IMPLEMENTATION

All of the work development described above has been in the context of making complete radios in the context of system concepts optimizing capacity for large scale, coordinated systems. The modulation selection is unaware of the context in which it is used, but some of the properties are essential to interference-limited system design.

Disclaimer: No assertion is made that the methods described are either the only way or the best way that the design can be achieved. It is intended to demonstrate that the concepts are sound both by simulation and by working models. The description is also intended to be helpful for independent cost estimates.

The complete radio is organized in the fashion shown in the block diagram below:

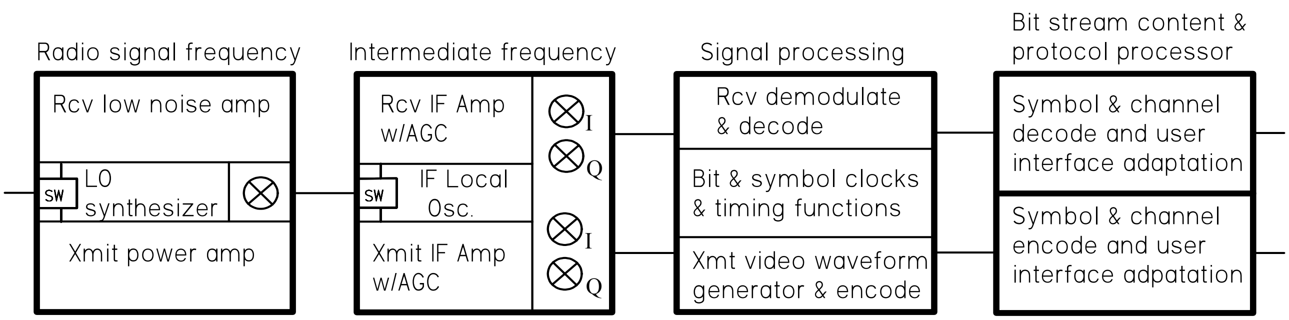
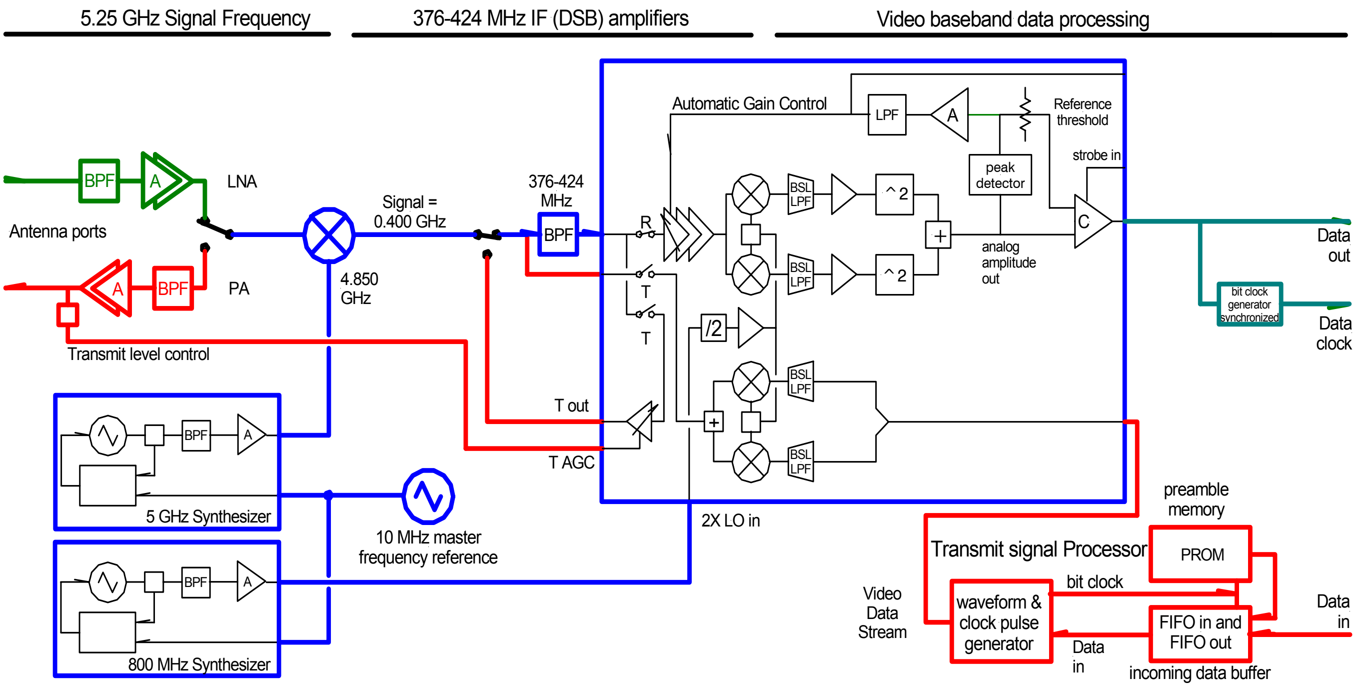


Figure 7 Generic block diagram data radio

The engineering in each of these blocks requires its own particular knowledge and skill set. It also suggests a partitioning if parallel development was undertaken.

Figure 8 Radio block diagram emphasizing signal path and IF ASIC



Preliminary Radio Block Diagam

There is also a way of looking at the radio from the point-of-view of gathering together the functions which would use a similar silicon process. The following block diagram is helpful in this sense.

This block diagram was intended to represent a 32 Mbps radio in a 48 MHz channel bandwidth at 5.25 GHz. It would be little different for a 1920-30 MHz radio with a 600 Kbps chipping rate. Only the detail frequency and rate numbers would change.

All of the functions related to the radio and to a lesser extent the logical data path are shown. The area within the large rectangle contains the circuits that implement the above describe modulation and demodulation. The current model uses one part with the vector transmit and receive mixers and all of the intermediate frequency functions that are shown. The detector with one comparator, sample and hold AGC level sensor, integrate-sample-and-dump detector and miscellaneous amplifiers are executed with simple components. Everything shown within the blue box could be a very useful ASIC

A large part of the function is in logic mostly implemented on a programable logic array. This part touches almost the entire radio.

The components shown in blue are used for both transmitting and receiving. Green is for receive-only and red is for transmit-only. The supporting logic functions are not diagrammed. The figure is intended to describe the radio PHY functions which are the subject of this document.

Logic support functions

The logic functions can be divided into functional categories. Since these categories and their exact function are programmable, the description is evolving with changes and additions as the need is recognize. The following tabulation illustrates the scope of this logic implementation.

The *clock and LO group* uses a shared 10 MHz accurate crystal oscillator to provide all required local oscillator function and the bit clock rate for data functions. It is assumed that the clock rate is accurate. At acquisition during the preamble the only adjustment is to step the phase if the bit clock in steps of $1/16^{th}$ of a bit until the received and local clock are matched.

The *transmit waveform generator group* generates the Sym-pulse video data signal that modulates the transmitter. The method closely resembles an FIR filter with a 20-tap shift register and resistor weighting of the taps. There are 5 taps/bit. Also, all of the bit steam modifications are applied within this group.

The *transmit bit stream PHY conditioning group* provides the preamble defined patterns, scrambling, start delimiter, basic channel coding functions and some miscellaneous functions. This group may be extended to provide spreading codes sufficient for code division channelization.

The *receive bit stream PHY processing group* provides preamble processing, unscrambling, delimiter detection, channel decoding functions and some miscellaneous functions. This group also provides the logic functions which are part of the signal demodulation function. This group may be extended to provide channel separation for code division channelization.

The *transmission evaluation group* provides a program for sending sequences of 64 and 1024 octet long pseudo-random packets which will measure packet and bit error rates.

The *interface adaptation group* provides necessary application interfaces including MMI (multi-media interface used between IEEE 802.3 MAC and PHY) and PCI.

The *medium access control group* providing MAC functions sufficient for transmission performance demonstration and to interface a desktop computer via the PCI bus.

Bandwidth and rate adaptation

The above block diagram assumes a 48-50 MHz channel bandwidth and a data rate of 30 Mbps. If the channel width is changed to 5 MHz, then the available data rate would be 3 mbps and IF filter bandwidth would have to be reduce to about 6-8 MHz. Also the IF gain would have to be increased 10 dB before the IF band filter to use the 10% increase in available sensitivity. In addition, a new intermediate frequency would have to be chosen and the various local oscillators and logic-involved clocks reset.

For rate adaptation on a scale of order of magnitude will require many detail changes, but not changes in principles.

At a later date, a paper design will be carried out for a set of rf and data dimensions useful to IEEE 802.15.3 TG4A.

SIMULATION

The radio link has been simulated end-to-end data input via the radio link using Elanix *System View*. The big problem in this type of simulation is collecting and understanding a large number of different tokens (component and function models) and verifying their validity

Some of the tokens were created on simulations on spice type software (Intusoft I-CAP/4 Pro) and others on E-M software (Zeland) usually converted to S-parameters. While this straightforward for one-each-input-and-output, it is not so simple for multi-port devices a number of which are used. Stock propagation models supplied in the system simulation were used. This work has generated a large, multi-layer document set.

LABORATORY VERIFICATION

This radio/logic group has been built as a bench-top model with a number of connectorized modules including antennas for receiver and transmitter. The component modules have been redone when advantage is recognized so that the resulting architecture has evolved considerably to enable implementation.

Each module is built with the smallest available components. The schematic is developed (captured) after which all of the documentation steps are automated. These include the schematic documents, bill-of-material, circuit board layout (4 metal layers), computer readable board fabrication instructions and pick-and-place assembly documentation. The circuit boards are milled on site in small numbers. This type of verification exposes production problems that might not appear in computer electrical simulation.

In this environment, it has been possible to go back and forth between bench measurement and simulation results. The simulation has gotten sufficiently good that this step is more for comfort than as a means of problem detection.

Everything described in the preceding sections on DSB-SC has been through this process. Not only do rf considerations have importance, but the interfacing of the radio to widely used data interfaces is a substantial task for a small development group.

APPLICATION RECOMMENDATION

For low rate channels, it is recommended that the widest available bandwidth be used for a shared channel, and that narrow band channels be derived by code division. Example:

5 MHz is available providing a chipping rate of 3 Mcps. A spreading code of 31 chips will provide 25 channels (Gold codes). Each channel will have a data rate of 97 Kbps and the noise bandwidth appropriate to that rate. The best use is to have one or more codes assigned to each access point using code separation to resolve overlapping coverage's. Multiple codes can be used to increase the transfer rate at any access point as may be needed for increased time sharing.

With 100 KHz per channel, it would also be an excellent choice for an FDM system at 60 Kbps.

CLOSING SUMMARY

We[1] propose that the TG4A committee accept Ternary AM DSB-SC with partial response pulse shaping as a candidate for the opening PHY layer selection.

It is well understood that anyone can propose, but only a majority constituency can select. It is also well understood that any opening recommendation is likely to be substantially modified before it is acceptable for incorporation in the standards document.

If selected, we will do everything necessary to enable a multi-vendor environment according to IEEE Standards Rules.

We plan to build a small number of technology demonstrator's which are now being designed. These could be available for independent verification of properties in December 2004 or soon after.

Some 802 Committees have gotten into a contest to over which proposal has the most service function. This proposal offers a competent function, implemented with smallest and simplest circuit function.

Others may then see as we do that this modulation is ***simple*** and one of the best for:

- transmitter power utilization,
- resistance to like and foreign signal interference,
- minimal out-of-band side lobe levels,
- resistance to errors from Doppler multipath including moving reflectors (one of only a few modulations with this property)
- accurate transmission without forward error correction
- fast and simple clock acquisition

We hope that others will join us in urging the choice of this modulation for the starting selection.

=end=

[1] "We" is the author, Chandos A. Rypinski and partner Bob Ritter, MicroTech Specialist, owners of the described technology development