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Abstract	The intent of this paper is to explore certain possible ways to do frequency modulation for short reach data transmission under the regulatory limitations on power and power density for ultra-wide-band transmission. The possibilities described are intended to be as simple as possible. With a 25 Mbps transfer rate, the following modulation strategies are considered and listed in reverse order of preference: 1) Direct high index FM modulation of a baseband waveform 2) Direct FM with multi-amplitude baseband waveform 3) Wide band FM sweep with superimposed FM data modulation 4) Wide band FM sweep with narrow band AM data modulation	
Purpose	The opinion expressed is that a relatively simple implementation is possible with performance equaling that of many more complex alternatives.	
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Very Wide Band Data Transport with Frequency Modulation

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Overview

This paper is to explore the possibilities of frequency modulation for short reach data transmission under the regulatory limitations on power and power density for ultra-wide-band transmission. The possibilities described are intended to be as simple as possible to implement. With a 25 Mbps transfer rate, the following modulation strategies are considered and listed in reverse order of preference: The demonstration rate may be scaled as needed,

1) Direct high index FM modulation of a baseband signal
2) Direct high index FM modulation with a multi-level baseband waveform
3) Wide band FM sweep with superimposed baseband FM data modulation
4) Wide band FM sweep with narrow baseband AM data modulation

FM Technology and Tradeoffs

Edwin Armstrong conceived wideband FM for noise free audio reception and reduced it to practice in the late 1930's. His concept included a mathematical description. His demonstration broadcast transmitter was on the New Jersey Palisades overlooking Manhattan. This work was so well thought out that little has been added to the theory since, but there has been an enormous decrease in the size of the apparatus to use it. This is the first tradeoff of occupied bandwidth to obtain a quieter, low distortion analog channel.

The problem addressed is mainly a tradeoff between several criteria, not all of which are fully appreciated. This part is the groundwork for the selection and weighting of optimization factors.

Basics

For clarity and consistency, some well known relationships of legacy FM will be stated.

Modulation Index and FM Advantage

The limit on the reduction of power density reduction from energy spreading is this ratio:

occupied bandwidth **:** information bandwidth

This limit is independent of the means used to spread the power.

The FM modulation index value of **5** means that the maximum deviation of the carrier frequency from channel center is five time the highest modulation frequency. The higher the index, the greater the FM advantage. This advantage is the degree (dB) of noise suppression in the FM receiver when the signal level is just high enough for full limiting, relative to what the noise would be in a linear AM radio, The other side of this relationship is that at a signal level just above noise, there is no FM advantage.

This is true when the receiver IF bandwidth will accept the full deviation of the transmitted signal (and a little more). The (Foster-Seely) discriminator compares the phase of the incoming signal shifted 90º with that of a reference tuned circuit in a non-coherent diode detector multiplier. When the frequencies match, there is zero output. A polar dc value is obtained when there is a frequency difference. The polarity is determined by signal frequency being high or low relative to the reference.

Typical modulation index for broadcast FM is 5. Land Mobile radio since channel splitting is 2 or lower. At low index, there is little FM advantage as is the case for current land mobile radios..

Reducing FM Noise Bandwidth

For a high index modulation, a phase-locked loop may be employed. A discriminator is employed to generate the error signal which is fed-back to a voltage controlled oscillator (VCO). The DC voltage applied to the VCO is a measure of the frequency. The rate at which this control signal changes is determined by the recovered waveform modulated at the source transmitter. The VCO tracks the received signal frequency. The low pass filter at the output of the phase detector determines the effective noise bandwidth. That bandwidth is matched to the source modulating signal. This method of FM demodulation was known in the late 1950's.

There is a lot to be careful about with this circuit. At output of error detector from which the received data is extracted, there is a lowpass filter. This filter needs to have near flat time delay across the passband. ***More subtle is that PLL detection dislikes phase reversals in the received signal induced by multipath propagation.***

The art is finding a way to detect the modulation in its own bandwidth independently of the bandwidth of the transmitted signal.

Optimization Factors in Using Frequency Modulation

Inducements

The attraction of frequency modulation is the constant amplitude level. Minor non-linearity in the transmit power amplifier will have small affect on spectrum shape. Moreover, all of the transmitted power can by used at the receiver.

Also, the receivers can be limiting avoiding a need for an AGC function. This sets a threshold above which the signal level is sufficient to realize the noise suppression advantage of FM.

Waveform Restrictions for FM Use

Possible baseband modulations for the FM transmitter must avoid constant-frequency which will create spectral lines with power concentrations. For direct FM, the baseband must have no dc content and no amplitude flat-tops.

Power Utilization

There is a direct and unavoidable relationship between power utilization and the capability factors including range, speed ceiling and bandwidth used. The necessary transmitter power is proportional to the information transmission rate.

Since there is a ceiling on power spectral density, it is necessary to devise means of working as close to the Shannon limit as is feasible. This utilization depends not only on the transmitter but also the refinement level of the receiver demodulation.

The application that minimizes the necessary transfer rate is well rewarded in range and accuracy of transmission.

Interference Susceptibility from Legacy Users

Once a foreign radio signal causes overload or capture of a limiter, the basic communication function is broken. The interfering signal is the power sum of all of the signals in the radio passband. The last two sweep methods have reduced working bandwidth reducing exposure to such signals. Also, they will have somewhat more gain which dilutes the improvement.

For this reason the level at which the noise bandwidth is determined, should be as close as feasible relative to the signal level at the antenna—not more than 40-50 dB.

Discriminators

Conventional discriminators will have a bandwidth equal to the spectrum width of the received radio signal, and therefore accept more noise than is necessary. A discriminator must be used which measures the error between the received and local estimate of the instantaneous frequency, and that must be a polar operation for the polarity of the signal to define whether to move the frequency up or down.

Using a PLL and VCO to track a high-index modulation, the bandwidth necessary to track the incoming frequency is smaller compared with the occupied bandwidth.

A known discriminator circuit generates a frequency error voltage using the variable frequency signal and a second locally generated reference frequency which anticipates the frequency of the incoming signal. This avoids a problem with the fixed reference frequency of common discriminators.

Model FM Systems

Following are technical descriptions of possible FM systems. All of these will support a 25 Mbps transfer rates, though they are scalable to other rates.

Direct FM Baseband Transmission

This method is ***straight forward with discriminator demodulation***, but the shift to ***PLL demodulation*** is probably unfeasible high data rates. It may be difficult to make a VCO that can go back and forth between the frequency limits ***25 to 50 times in one µsecond.***

Baseband Waveform Definition

This technique applies a baseband data signal to the voltage-control input of a VCO. The VCO must be designed to operate between over a specified high-low frequency range. It is desirable, but not required, that the voltage-frequency function be a straight line. This signal can be directly demodulated with a conventional discriminator.

A suitable 2-level baseband signal may consist of a either a full cycle or a half-cycle of sine wave in one bit interval. The polarity of the next symbol is an approximate continuation of the slope and direction of the prior symbol.

If two consecutive symbols are alike, the current *logic value is **0***. If the two consecutive symbols are opposite polarity, the current *logic value is **1***.

Apart from the small discontinuity between consecutive bits, the highest frequency is a sine wave at the full bit rate generated by *all data one's*. The full sine wave is the same frequency at baseband the bit rate. The first zero in the spectrum may be at twice the bit rate. It is unlikely that this is the best modulation, but it is a solution that is sure to work.

To double the bits/Hz, it is probably necessary to go to a 3-level modulation (ternary). The 3-level modulation may create spectral lines if this is no consideration from the beginning of the development.

Modulation Parameters

If the highest modulation frequency is the bit-rate and conventional limiter-discriminator circuits are used, the resulting properties are shown in the following Table:

Parameters—Direct FM Data Modulation

Modulation bit rate:	25 Mbs
Highest baseband frequency:	25 MHz
Available RF Bandwidth:	± 250 MHz
Available modulation index:	**10**
Available transmitter average power:	-14 dBm
Noise bandwidth with conventional discriminator:	700 MHz
Noise Figure (includes some implementation loss):	10 dB
Sensitivity at 16 dB quieting:	tbd

It is estimated that at 16 dB quieting demodulation of the baseband waveform would be successful. Bandwidth beyond the first null is necessary because energy in the sidelobes must be captured to recover a low distortion copy of the baseband waveform.

If a PLL type of discriminator were used, the noise bandwidth would be narrowed to 60 MHz. This should improve sensitivity by 10 dB. However, the VCO is required to sweep from edge-to-edge in a half-bit time interval. For this reason, ***high-rate UWB is considered unfeasible for simple radio designs.***

Direct FM Modulation with Multiple Amplitude Baseband Waveform

A further possibility for direct modulation is the use of a baseband wave form that has multiple amplitudes which translate to multiple frequencies with FM. The radio is little different than the previous radio except that the speed of frequency change will be much decreased. The example below will illustrate the method.

Assume a 16-amplitude pulse or symbol which will convey 4-bits of information. With 60 MHz channel spacing, 960 MHz of spectrum would be required. This channel spacing would support a 25 pulses-per–microsecond rate with some headroom. That is 100 Mbps.

All possible 16 baseband amplitudes will translate to 16 different channel frequencies. The worst case frequency step would have four times longer to change frequency than the binary system.

If 16 pulse detectors were to operate in parallel, the noise bandwidth would be close that of the individual detector. That bandwidth would be $1/16^{th}$ of the wideband detector.

It will be hard to make a detection system that is unaffected by values of prior and following pulses.

Baseband Waveform

No attempt will be made to define this waveform beyond the essential properties. It is essential to limit sidelobes and harmonic content as with the other modulations. Abrupt transmissions as slight as a change in slope between component wave forms will generate unwanted sidelobes. In general, a satisfactory result comes only from application of partial response principals.

There may need to be on extra amplitude state. In some cases, it is required that consecutive identical states are spectrally harmful. To overcome this difficulty an extra state is necessary. There then always 16 possible states other than the initial one.

Modulation Parameters

Using the modulation information shown above, the resulting parameters are shown in the following Table:

Parameters—Direct FM with 16-Amplitude Pulses

Modulation bit rate:	50 Mbs
Highest baseband frequency:	12.5 MHz
Available RF Bandwidth:	± 480 MHz
Selected modulation index:	2
Occupied bandwidth for one 4-bit symbol:	±30 MHz
Noise BW with non-coherent detector (worst case):	60 MHz
Available transmitter average power:	-11 dBm
Noise Figure (includes some implementation loss):	10 dB
Sensitivity at 16 dB quieting:	tbd

Above values include quick estimates that may not be accurate or unambiguously interpreted.

Swept Frequency Spreading With Normal FM Data Modulation

This modulation scheme separates the spreading and data transmission functions. The data transmission is relatively narrow band, and therefore may make good use of power and bandwidth.

The baseband modulation used does not have the constraint of avoiding a bit pattern that creates a spectral line as an energy concentration, since the signal is spread regardless of the information.

The Radio Configuration

The radio receiver is envisioned as a first mixer with a sweeping LO, a fixed frequency intermediate amplifier (IF) and a demodulator which will use a discriminator to recover:

1) fast changing frequency which is the recovered data signal, and
2) slow changing frequency used to correct and minimize the difference between the sweeping local oscillator and the received signal center frequency.

The transmitter uses the same sweeping oscillator for the receiver LO and with superimposed frequency modulation.

The Spreading Function

The center frequency of the transmitted signal moves at a constant rate of change from one limit of the pass band to the other limit. One sweep might take one millisecond. The sweep will be a slow change of frequency relative to that of the data modulation.

Consecutive scans could be in opposite directions creating a triangular frequency vs. time pattern, but this is not recommended for reasons to be described. The advantage of this type of sweep is that all sweeps start with the VCO already at the starting frequency.

Frequency Modulation of the Data

At the transmitter, the baseband video data signal is added to the control voltage of the VCO. The magnitude of data waveform is proportioned to a modulation index of 3:1 (tentative).

As in other cases, the modulating waveform should have the lowest possible top frequency for the data transfer rate provided.

The Baseband Modulating Waveform

For this appraisal, a ternary waveform[*] is selected in which data **0** is amplitude 0 and data one is amplitude **±1**. The 0 amplitude does not create the spectral line problem that would be present without a sweep function..

With the chosen waveform at baseband, it is known that 25 Mbps does not require transmission at or above 20 MHz or below 2 MHz. The absence of low frequency spectral energy enables some amplification at baseband before the noise bandwidth determining steps in the circuitry.

Modulation Parameters

Using the modulation information shown above, the resulting parameters are shown in the following Table:

Parameters—FM Sweep and FM Data Modulation

Modulation bit rate:	25 Mbs
Highest baseband frequency:	20 MHz
Available RF Bandwidth:	± 500 MHz
Selected modulation index:	3
Occupied bandwidth:	±60 MHz
Swept carrier RF bandwidth:	± 440 MHz
Noise BW with non-coherent detector (worst case):	120 MHz
Available transmitter average power:	-11 dBm
Noise Figure (includes some implementation loss):	10 dB
Sensitivity at 16 dB quieting:	tbd

There are several important improvements relative to the previous example. The sweep bandwidth is doubled—because it is easy when the frequency does not have to be moved with speed of the data handled. Doubling the spread enable doubling of the available transmit power under the regulatory limits..

[*] The **"Sym-pulse"** baseband waveform is described in **IEEE P802.15-04-0491-00-004a** more detail. Waveforms and spectral attributes are shown in this reference. There is also a web site for Sym-pulse.

The noise bandwidth is narrowed because in part of a reduction of the modulation index. This reduction is what is just sufficient to get a moderate gain in the FM quieting advantage. A further important factor is the change in the baseband modulation where there is a lower dependence on sidelobe energy.

The discriminator circuit can be conventional even though it may be non-optimal. For the frequency tracking error signal, the discriminator only needs bandwidth to accommodate the worst case difference in the transmitter and receiver averaged center frequency when the two frequencies are approximately synchronized.

Not considered above, is the pre-emphasis ordinarily used to make the effective index the same at all transmitted frequencies**.** This factor might reduce the apparent noise degrading the signal.

Swept Frequency Spreading With Ternary AM Data Modulation

This modulation uses the same linear sweep as described above, however the data modulation is applied to the carrier amplitude rather than frequency. The baseband ternary waveform is also the same.

The Radio Configuration

The first mixer and intermediate frequency amplifiers operate at the same frequencies as in the FM modulated radio above. The IF amplifier is different in that it is linear and variable gain controlled to limit the amplitude variation of the received signal at the point of detection.

The tracking discriminator can be simpler since it is the only discriminator. The amplitude detector can be a simple envelope detector for both data recovery and feedback AGC input.

Amplitude Data Modulation

Without frequency sweep active, the transmitted data signal is double sideband suppressed carrier ternary amplitude modulation.

Since the amplitude of the incoming signal approximates 0 or low when data **0** occurs, amplitude sensing must be “sample-and-hold” or have a “fast-sense-slow-release.” Intervals of up to 10 consecutive data **0** can occur, and these no signal intervals must be bridged.

The zero amplitude pulse has a 50% probability of occurrence producing a an average 50% duty cycle. This will diminish the average power which may then be increased reach the regulatory limit.

> ***The non-coherent envelope detection does not require phase or precise frequency match between transmitter and receiver.***

Modulation Parameters

Using the modulation information shown above, the resulting parameters are shown in the following Table:

Parameters—FM Sweep and Ternary AM Data Modulation

Modulation bit rate:	25 Mbps
Highest baseband frequency:	20 MHz
Available RF Bandwidth:	± 500 MHz
Occupied bandwidth:	±20 MHz
Swept carrier RF bandwidth:	± 490 MHz
Noise bandwidth with non-coherent DSB detector (worst case):	40 MHz
AM ON duty cycle:	50%
Available transmitter average power:	-8 dBm
Noise Figure (includes some implementation loss):	10 dB
Sensitivity at 1 x 10^-6 BER:	tbd

Further gains in range and receiver sensitivity appear in this table. The basic modulation is 0.6 bits/Hz. The noise bandwidth of the non-coherent detector is reduced to less than 40MHz.

Channelization for System Use

The functions which channelization provides within a common, shared radio spectrum include:

1) Separation of work groups with overlapping radio coverage
2) Increasing capacity in one coverage with parallel access
3) Enabling virtual duplex operation
4) Separation of backbone relay communication from that of users

The scheme for this type of modulation requires common timing control for all users, and a common access protocol for the top level functions.

The concept of multiplexing with identical stations is that the timing of sweep start is coordinated. If two stations start sweep a time difference greater than the time it takes to sweep two-channel-widths, the transmissions can be simultaneous and non-interfering. With a 1 GHz sweep width and a working channel width of 40 MHz, 250 channels can be defined by starting time. At one location, it would be unwise to space channels less than every 24th channel which would enable 10 channels at one location.

For virtual duplex operation, it possible to reserve up-sweep for station originated traffic and down-sweep for access-point originated traffic.

At 25 Mbps, one millisecond is enough time to transfer up to 24,000 bits or 3,000 octets. It quite possible to tailor the packet length to the needs of the traffic carried.

The regulators have often resisted coordination of different users primarily because parallel operation might be used to carry much more traffic in one place than is the intent of license-exempt operation. This problem can be addressed if and when it is important.

Central coordination of many overlapping coverage's is not within the scope of "layer-2" bounded IEEE 802.

Recommendation

The simplest means of getting radio advantage from a modest enlargement of occupied bandwidth is by using a high index (2-5) deviation frequency modulation. P802.15 should explore this possibility for short reach radio.

The FM sweep and Ternary AM (Sym-pulse") for data is a recommended as a good and feasible compromise between many conflicting optimization criteria.

It is recommended that efficiency and functionality be sought and defined, before tackling problems arising from excessive speed to market and repositioning of marketing channels. Then may be the useful life may exceed a year or two for communication products.

The Author is very much aware of the need for group consensus before anything gets further than a presentation. We will work constructively with anyone with like views on the objectives.

END