Wireless Communications Using Phase Modulation-Orthogonal Frequency Division Multiplex (PM-OFDM) Modulation

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Abstract
Described is a communication system designed for transmitting data in dynamic channels with poor signal-to-noise, such as are encountered with traveling vehicles. This modulation technique can be described as Phase Modulated-OFDM (orthogonal frequency division multiplexing) or PM-OFDM. While OFDM(A) is a linear modulation method, this new method is a nonlinear modulation technique. A complex baseband OFDM signal is converted into a real-only analytic signal, which is then used to rotate the phase of a constant-amplitude carrier. Because it has a constant amplitude with a crest factor of zero dB, RF power generation can be very efficient using a class-C amplifier. The modulation technique inherits the characteristics of FM/PM transmissions, including a threshold effect and a capture effect which mitigates interference. The signal can be band-limited and orthogonal to other signals, such as linear OFDM/OFDMA/SC-FDMA signals. Linear Precoding (LP) can be used to limit peak phase excursion. Receiver phase recovery can be assisted by a strong continuous wave (CW) component in a received signal.

Background
Mobile communications present special problems for communications engineers. These problems include dynamically varying signal strength, Doppler shift, rapidly changing multipath, fading, and a need to frequently hand off between base stations. This system can be used for conventional applications, such as LTE (long term evolution) systems and Rural Broadband delivery systems. It can also be used for optical communications.

A traditional goal of designing a transmission system is to approach as closely as possible the Shannon capacity for a channel, achieving a maximum number of bits per second in a given bandwidth with a given transmit power. This is a reasonable goal where there is a limited amount of bandwidth, RF bandwidth is expensive, or signals propagate in all directions, interfering with each other. Two examples are cellular radio handset signals which are generally omni-directional, and cable TV signals which suffer from high coaxial attenuation and limited booster amplifier dynamic range. But other channels don't have these constraints. For example, in Rural Broadband applications there is not much radio interference, but there is high attenuation due to long distances and foliage. In millimeter wave microwave, directional antennas can limit off-axis interference. In fiber optics, there is very wide bandwidth available and low fiber attenuation, but cost of terminal equipment is high and phase recovery for coherent optics is challenging.

Discussion
Figure 1 is a block diagram of a transmitter. Input bits are converted into complex baseband symbols, and complex conjugates are added, using Hermitian symmetry. After an Inverse Fast Fourier Transform (IFFT), a resulting real-only sequence is used to phase modulate a carrier wave. The resulting signal is amplified, up-converted and transmitted. A power-efficient class C amplifier can be used in place of an inefficient class A amplifier.

Figure 2 is a plot of real-only voltage vs. time sequence, which is converted into a phase vs. time sequence by the phase modulator. Because the input baseband signal is OFDM, the signal will generally have a Gaussian distribution.

Figure 3 is a polar plot of in-phase vs. quadrature voltage at the output of the phase modulator. Because phase modulation is used, the signal trajectory will be along the outside of a circle and sample voltages will land on the circle. A modulating factor “K” is used to convert phase modulator input volts to radians on the phase modulator. K was chosen to limit the phase rotation to plus or minus 180 degrees. This is not a requirement, but a phase angle must be tracked as crosses the negative X-axis to prevent errors when demodulation occurs.

Demodulation occurs in the receiver by converting a received phase angle to a voltage vs. time sequence. This can be done by computing an arc-tangent of the quadrature voltage samples divided by the in-phase voltage samples.

Figure 4 is a spectral plot of amplitude vs. frequency. Most notable on this plot is a strong CW (continuous wave) component in the center. This CW subcarrier is useful in the receiver to recover phase and frequency. Visible on the plots are first order modulation bandwidth and second order modulation bandwidth. When the complex symbols were formed, the lower order coefficients those near zero Hertz) were set to zero (nulled). This has an effect of reducing energy near the CW component, which facilitates CW recovery. The bandwidth of the original baseband real-only OFDM modulating signal has been expanded at Radio Frequencies (RF) because phase modulation is a nonlinear technique.

If during a block reception there is phase noise or a frequency error between a transmitter and a receiver, and if the error frequency is less that the number of zeroed subcarriers situated near the CW, a recovered bandpass-filtered CW can used as a local oscillator in the receiver. This compensates for phase noise, Doppler shift, and frequency error. At millimeter wave frequencies and optical frequencies phase noise is expected to be high.

By truncating sidebands, the occupied bandwidth of a transmitted signal can be limited. This can be done by converting the IF or RF signal into the frequency domain at point C in Figure 1, and then symmetrically forcing sideband energy to zero. Then the bandwidth-truncated signal is converted back into the frequency domain and transmitted. This process is illustrated in Figure 5, which is the spectral plot of Figure 4, but with sideband truncation. This truncation, if it is less than a few percent of total signal energy, can have only a minor effect on a MER (modulation error ratio) of a received signal, but reduces interference with adjacent band signal. It also has another non-obvious characteristic: this block transmission can be made orthogonal to other similar transmissions using adjacent subcarriers in a Fourier transform.

In mathematics, two functions are orthogonal if the integral of one basis function times another basis function over a time interval equals zero. In OFDM(A) modulation, the basis functions are integer multiples of sines and cosines. For two phase modulated blocks:

$$\int_a^b f1(x) \times f2(x)\, dx = 0 \qquad (1)$$

where f1(t) is one phase modulated signal (or block) and f2(t) is the other phase modulated signal (or block) that is orthogonal to f1(t). Between block time limits a and b, an integer number of cosine wave cycles of subcarriers occur. f1(t) and f2(t) may be referred to as blocks of exclusively allocated subcarriers.

Furthermore, if the OFDM frame rate is made similar to other signals and the subcarriers are assigned by a central base station, this orthogonal signal can be used in an OFDMA (Orthogonal Frequency Division Multiple Access) or SC-FDMA (Single Carrier-Frequency Division Multiple Access) upstream (or downstream) transmission system. A multiplex of three signals is shown in Figure 6.

An obvious disadvantage of phase modulation is the greater occupied bandwidth relative to linear OFDMA or SC-FDMA, but when bandwidth is available and signal attenuation is large, a radio link can be better maintained.

At point B in the signal chain, a cyclic prefix can be added to facilitate echo cancellation, and equalization. If mixed with OFDMA or SC-FDMA signals, a same cyclic prefix duration and block timing should be used.

At point A in the signal chain, linear precoding can be added to the signal, similar to the linear precoding used on SC-FDMA LTE upstream transmissions. This involves an additional FFT operation, but allows subcarriers to be re-aligned in frequency. In particular, the subcarriers next to the strong central CW component can be shifted up in frequency. The advantage to linear precoding for LP-OFDMA is that phase angle crest factor is reduced, relative to the Gaussian distribution of an OFDM signal.

At the receiver linear, channel equalization should be used before phase recovery. Echoes and signal dispersion will have a negative effect on phase angle recovery. That is, without echo cancellation a recovered vector diagram will not have a circular trajectory.

Optionally, the PM signal can also be amplitude modulated (AM) to increase the data capacity of a channel. This requires a linear class A amplifier.

Conclusion

This article describes PM-OFDM modulation. Optionally, the signal can be linearly precoded (LP) making a LP-PM-OFDM signal. Generating this signal for transmission is power efficient and reception can occur at poor signal to noise ratios. It is also designed to operate in a multiplex of upstream signals, such as LTE (long term evolution). Applications for this communications signal includes mobile communications with dynamic mult-path and Doppler shift, millimeter wave, transmission over fiber optic cable, and other radio links with poor transmission characteristics. This system can be used to transmit symbols with high order constellations at relatively poor signal to noise ratios.

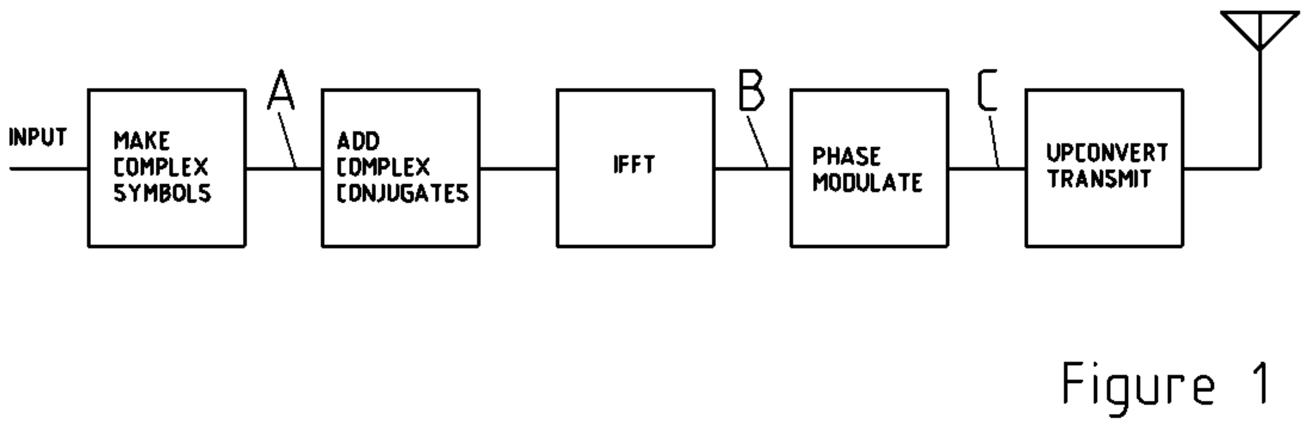

Figure 1 Transmitter block diagram.

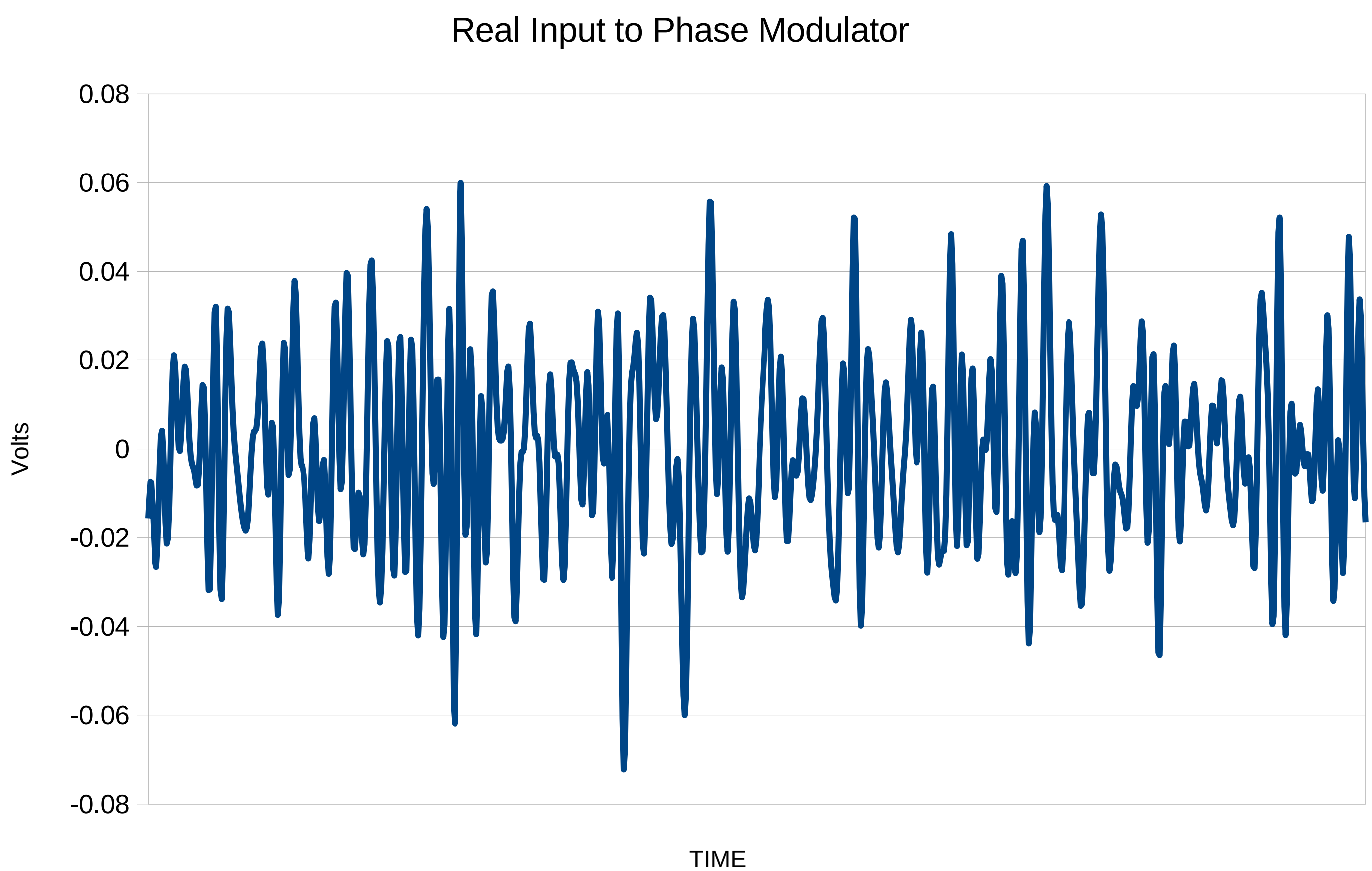

Figure 2. Input voltage into a phase modulator

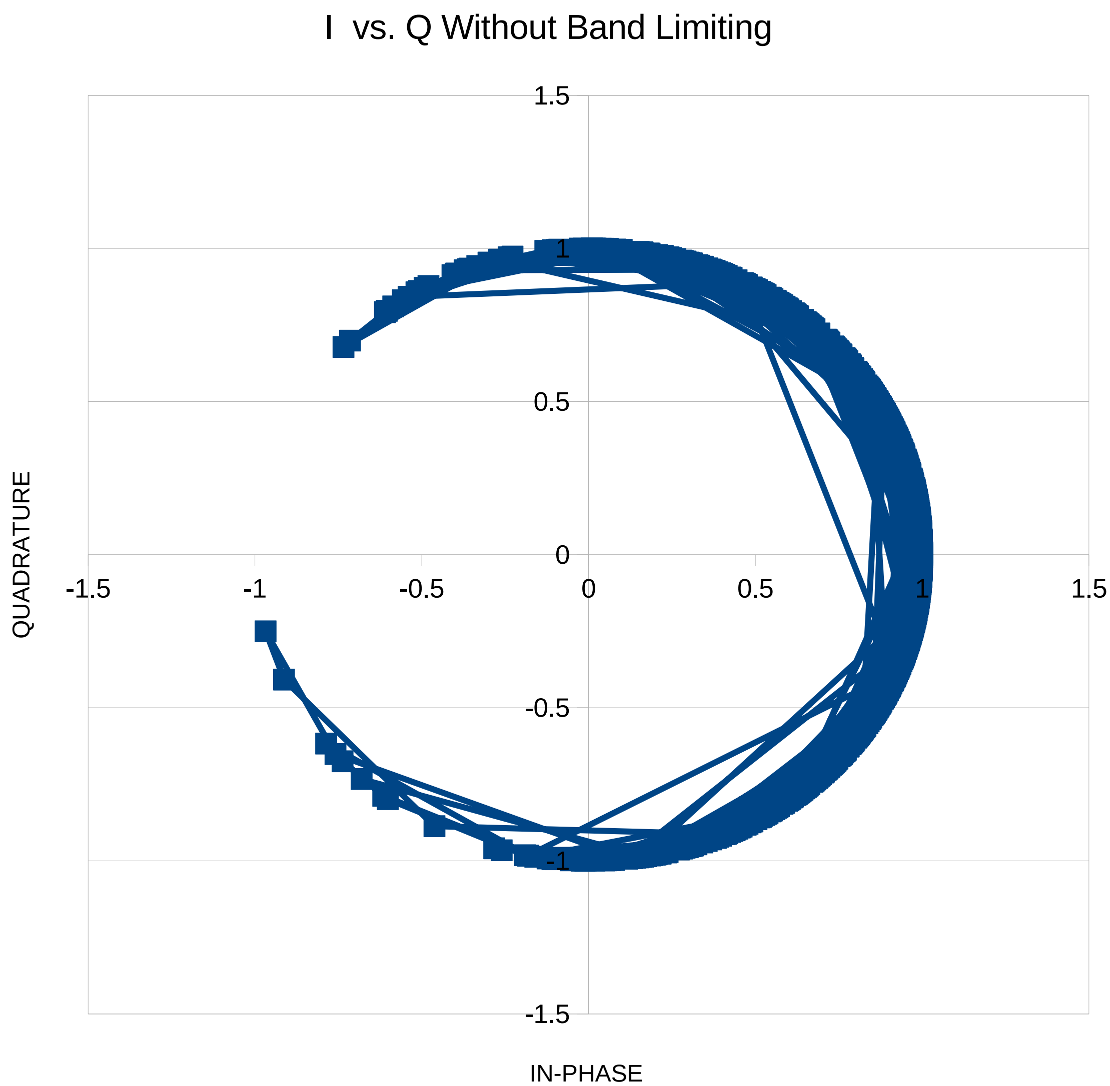

Figure 3 Vector diagram of transmitted signal

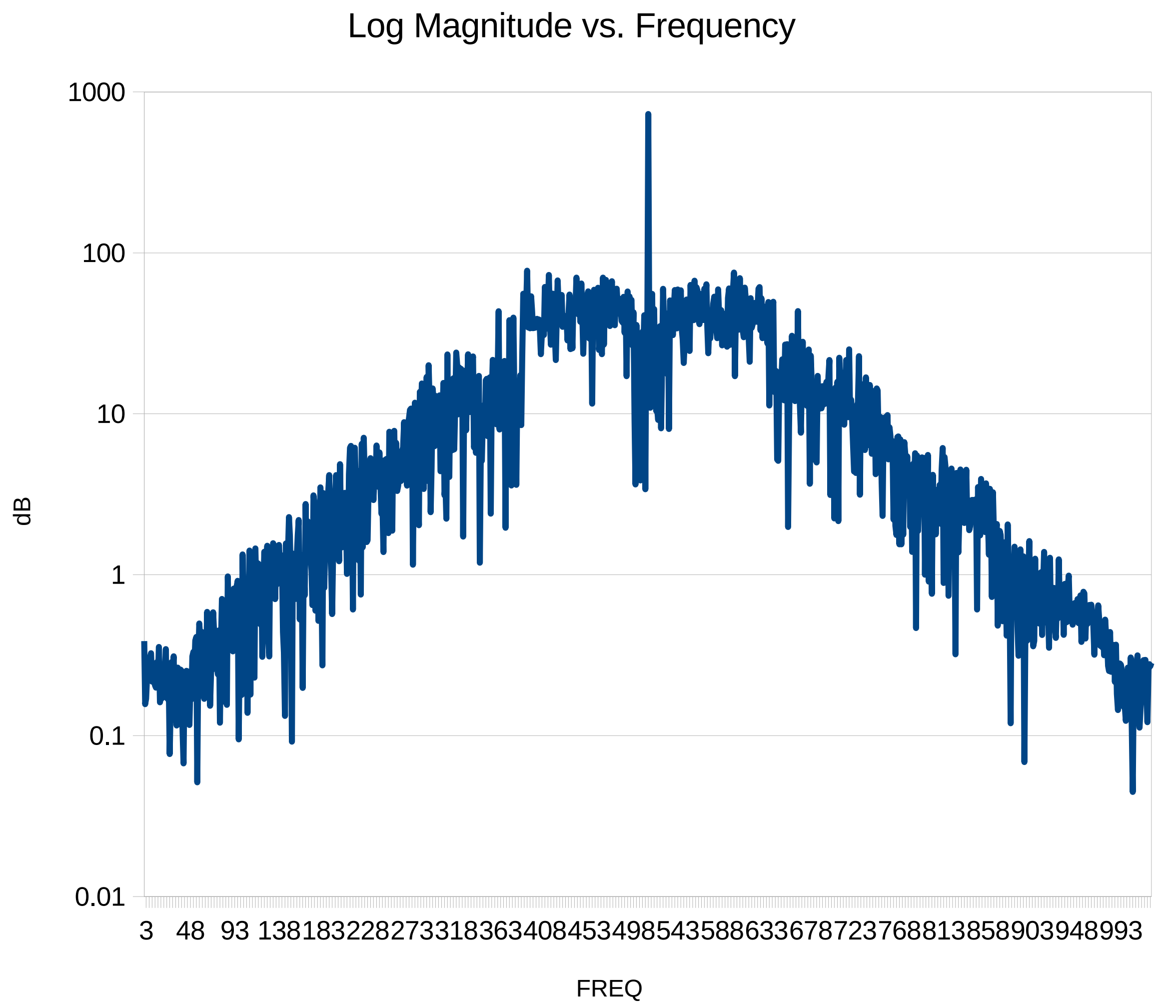

Figure 4 A spectral plot of a PM-OFDM signal.

Figure
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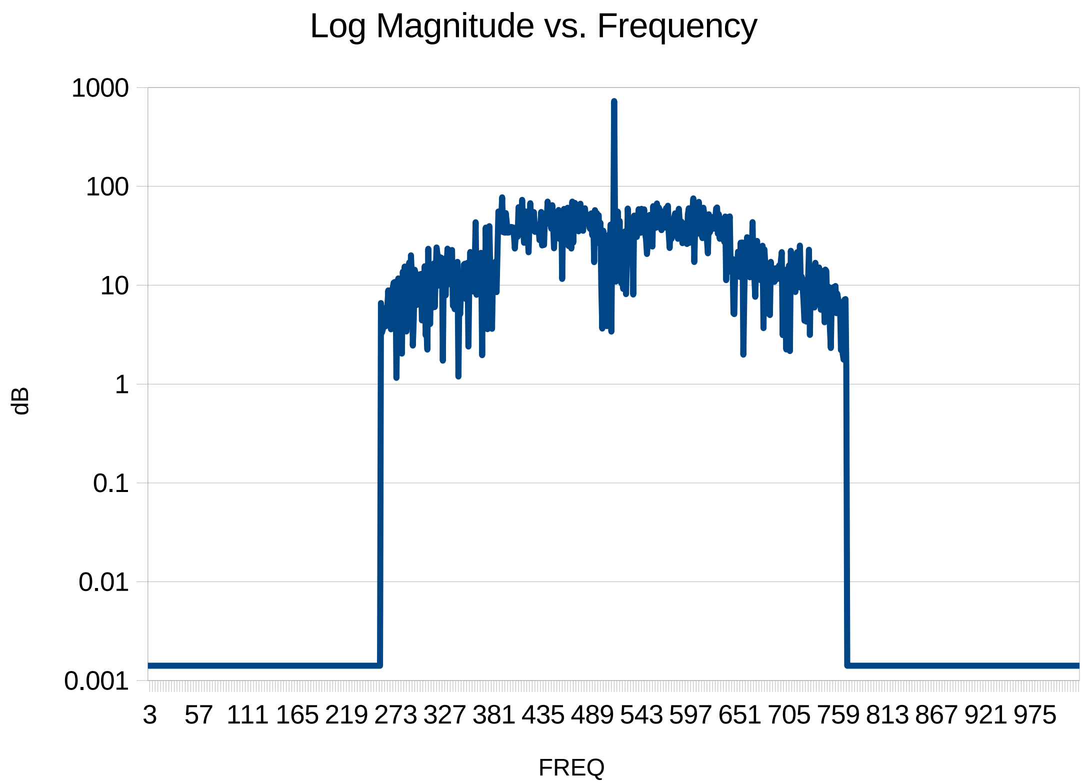

Spectral plot with truncation of higher subcarriers, making a signal orthogonal to adjacent similar signals, or to OFDMA or SC-FDMA upstream signals.

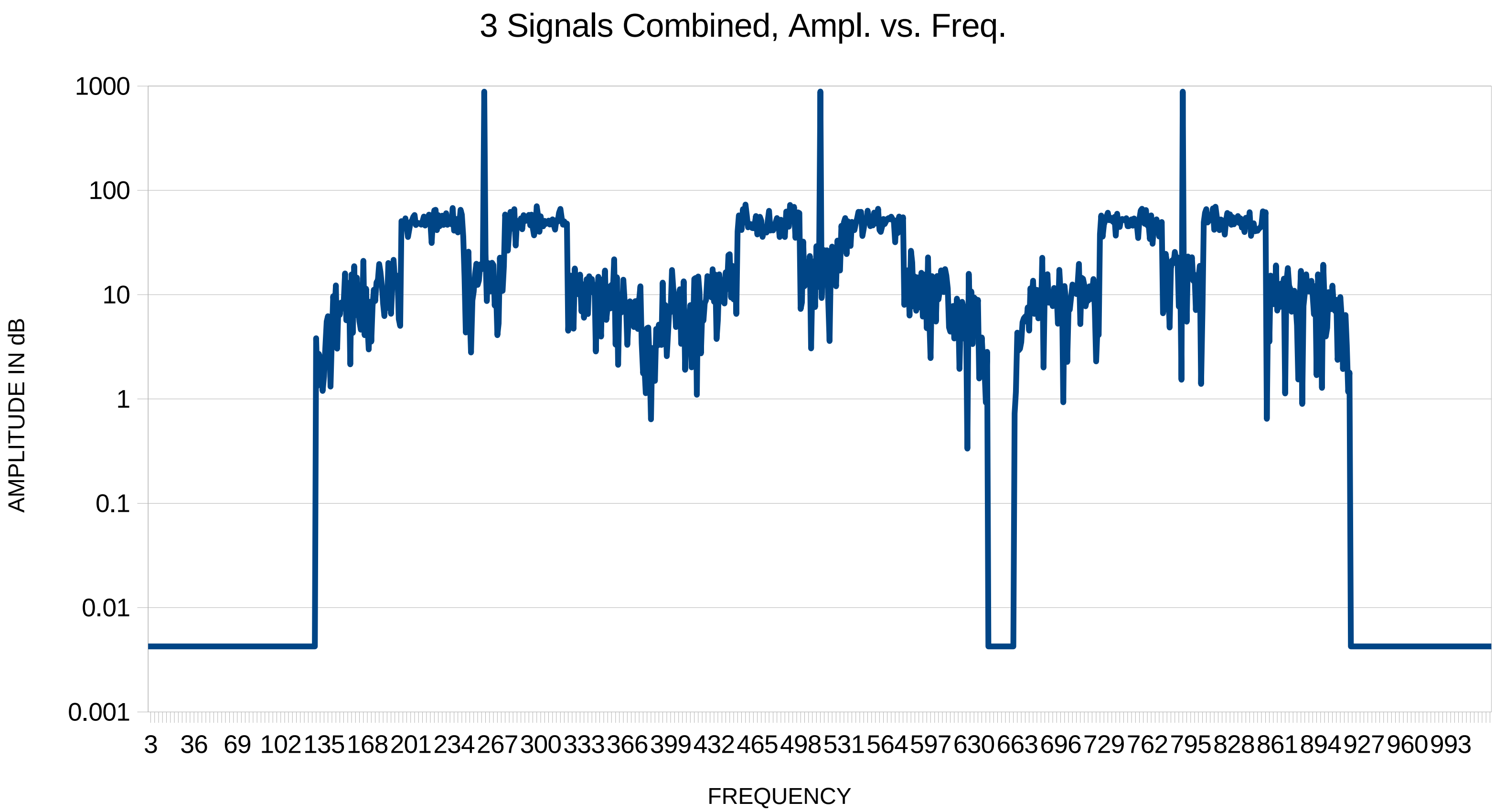

Figure 6 Three PM-OFDM orthogonal signals. A vacant band has been intentionally left by the central controller between the 2nd and 3rd transmissions.