Increasing Bandwidth Efficiency By Means Of Analog Modulation On Top Of Digital Modulation

J. C. Pliatsikas[1], C. S. Koukourlis[1] and J. N. Sahalos[2]

[1]Department of Electrical and Computer Engineering,
Democritus University of Thrace,
B. Sofias 12, GR-671 00, Xanthi
GREECE

[2]Department of Physics,
Aristotle University of Thessaloniki,
GR-540 06, Thessaloniki
GREECE.

Abstract: - A method of contemporary use of digital and analog modulation on the same bandwidth is described. In this method the phase of the carrier of an analog AM modulated signal is also modulated by a digital one with a rate depending on the RF bandwidth of the analog broadcasting. Measurements and results of a full hardware implementation will show the applicability of the method.

Keywords: - Digital modulation, bandwidth re-use, spectral efficiency, bandwidth efficiency, amplitude modulation, AM.

1. Introduction

The need for digital data transmission through existing analog channels led to the development of various techniques which, at fist, targeted only to the transformation of the digital information into forms suitable to be transmitted through the existing channels. Nowadays, the increasing demand for greater transmission capacity necessitates the use of spectral efficient modulation techniques that allow more efficient use of the available bandwidth, at the cost of higher SNR (Signal to Noise Ratio) [1]-[3].
An alternative technique of increasing the efficiency is the transmission of digital data in the allocated bandwidth for *analog* transmission, e.g. AM radio broadcasting, without interfering with it. The idea of the transmission of analog and digital information in the same channel is not new, since it has been used for commercial applications in the past e.g. the Radio Data System (RDS) and the Teletext [4], [5]. Nevertheless, the proposed method differs from the above because it utilizes the whole analog bandwidth at all times to transmit digital data.
In this paper the proposed digital modulation method will be presented along with the theoretical analysis of the phase modulated signal at the baseband. Moreover, a presentation of a proposed modulator – demodulator circuitry will be made together with the experimental results of an implemented prototype.

2. Basic concept

The concept of simultaneously transferring digital information over an AM radio channel is to properly phase modulate the reference carrier of the AM radio signal in order to carry the digital information without interfering to it.

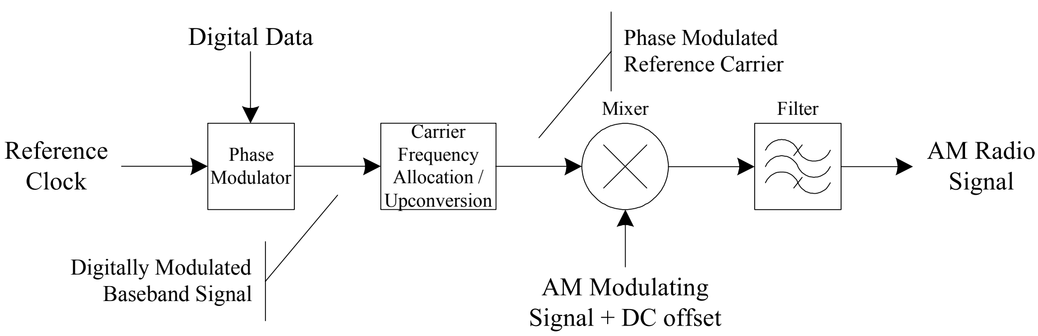


Fig. 1. Block diagram of the combined transmitter.

A rough block diagram of such an AM modulator is shown in Fig. 1.

Initially a reference carrier (clock) is phase modulated with the use of a specific phase modulation. The above carrier is subsequently fed to a mixer along with the AM modulating signal. Finally, the transmitted signal that carries digital information in its phase and analog information in its amplitude is obtained from the mixer output after a bandpass filter.

The phase modulation of the digital data at baseband is implemented by the use of a programmable logic device. In order to do so, a higher than the data rate clock is required. Assuming that the frequency of the high clock is k times the data rate, the encoding algorithm of the digital data signal $d(t)$ is given in Table 1.

Table 1. Encoding rules of the data waveform.

INPUT WAVEFORM		ENCODED WAVEFORM
Data transition from logic 0 to 1	→	Change of logic state to the opposite, one high-clock cycle after the middle of the bit.
Data transition from logic 1 to 0	→	Change of logic state to the opposite, one high-clock cycle before the middle of the bit.
Preservation of either logic state	→	Change of logic level state at the middle of the bit.

As it will become clear later, k is related to the phase changes of the modulated signal. It has been estimated that for $k \geq 8$ the phase changes of the signal are small enough not to cause significant disturbance to the AM receiver, which normally assumes that the frequency and phase of the carrier are constant.

3. Analysis of the signal

In order to analyze the modulated signal, it is convenient decomposed it into two basic ones: a *decomposed carrier* and a *decomposed data signal*, Fig. 2.

The first one consists of alternating pulses with period $2T_b$ and duration $((k\text{-}1)/k)T_b$. The second one comprises of pulses with period T_b and duration equal to $(1/k)T_b$.

Re-examining the decomposed data signal, it can be considered as an *inherently* encoded digital data signal, $e(t)$ with duration $(1/k)T_b$.

With the use of the Fourier series [6], [7] and utilizing only the first terms, the digitally modulated baseband signal is expressed by:

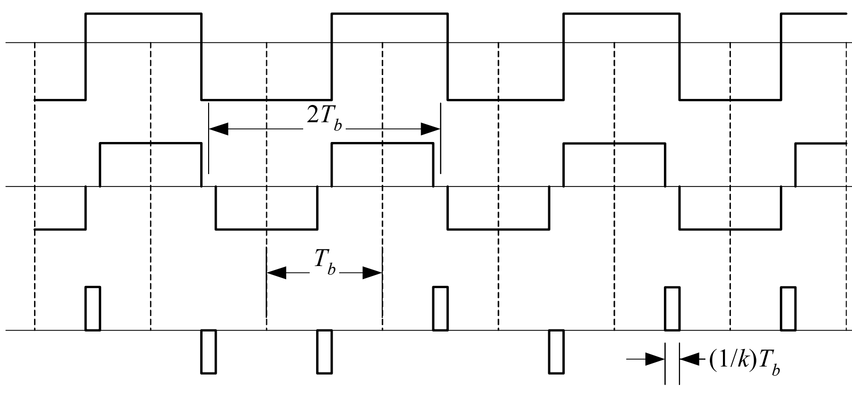
$$\upsilon(t)_{Modulated} = \frac{e(t)}{k} + \frac{2}{\pi}\sin\left(\frac{\pi}{k}\right)e(t)\cos(\omega_b t) + \frac{4}{\pi}\cos\left(\frac{\pi}{2k}\right)\sin\left(\frac{\omega_b}{2}t\right) \qquad (1)$$

where $e(t)$ takes the values ± 1.

From the three terms of Eq (1) only the second, with angular frequency ω_b, and third, with angular frequency $\omega_b/2$, ones are used for the recovering of the digital data at the receiver. The first term, having a spectral component near dc, is suppressed by filtering.

The vector representation of the digitally modulated baseband signal based on Eq. (1), at a time somewhat after t=0 is given in Fig. 3.

The amplitude of the signal varies between $(4/\pi)\cos(\pi/2k)\text{-}(2/\pi)\sin(\pi/k)$ and $(4/\pi)\cos(\pi/2k)+(2/\pi)\sin(\pi/k)$ while the phase, as it will be proven later, from $-\sin(\pi/2k)$ to $\sin(\pi/2k)$. The above variations occur during one full period of the decomposed data vector, $2T_b$.



Digitally Modulated Baseband Signal (1)

Decomposed Periodic Signal (2)

Decomposed Data Signal (3)

Fig. 2 Decomposition of the modulated signal as a sum of two signals: a decomposed periodic signal (carrier) (2), and a decomposed data signal (3).

According to Fig. 3, the modulated signal can be considered as phase modulated, carrying all the required information in its phase. Therefore its amplitude variations can be ignored or suppressed (limited).
Reconsidering Fig. 3, the phase of the modulated signal can be expressed in the following form:

$$\theta = \tan^{-1}\left(-\frac{e(t)\sin\left(\frac{\pi}{k}\right)\cos(\phi)}{2\cos\left(\frac{\pi}{2k}\right) - e(t)\sin\left(\frac{\pi}{k}\right)\sin(\phi)} \right) \quad (2)$$

where φ is the angle of the decomposed data vector

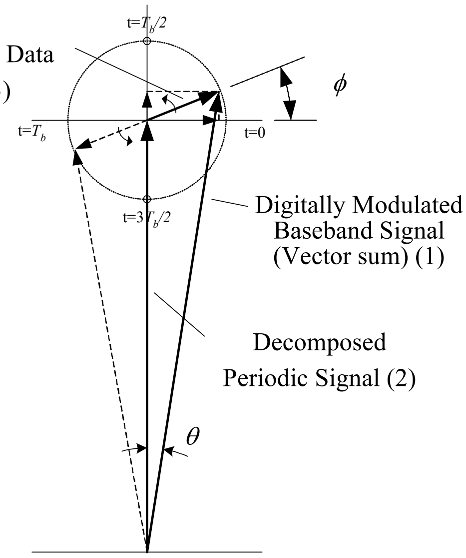


Fig. 3. Vector presentation of the digitally modulated baseband signal. The numbers in parenthesis correspond to Fig. 2.

and $e(t)$ the encoded digital data, taking values ±1.
As mentioned before, the decomposed data vector performs a full cycle every $2T_b$. For that reason the angle φ can be substituted with $\omega_b t/2$. Taking into account that $k \geq 8$ and using the approximations $\tan^{-1}x \cong x$ and $\sin x \cong x$, which are valid for large k, gives:

$$\begin{aligned}\theta(t) &\approx -e(t)\frac{\pi}{2k}\cos\left(\frac{\omega_b t}{2}\right) \\ &\approx d(t)\frac{\pi}{2k}\left|\cos\left(\frac{\omega_b t}{2}\right)\right| \end{aligned} \quad (3)$$

As it can be seen from Eq. (3), the phase of the digitally modulated baseband signal is continues, changing sinusoidaly from 0 to $\pm\pi/2k$ to 0. Moreover, it is reversely proportional to the value of k.

Taking also into account the amplitude variations of the digitally modulated baseband signal, Eq. (1) can be expressed in polar form as:

$$\begin{aligned}\upsilon(t)_{Modulated} &= \sqrt{\frac{16}{\pi^2} - \frac{16}{\pi k} e(t)\sin\left(\frac{\omega_b t}{2}\right)} \cdot \\ &\sin\left(\frac{\omega_b t}{2} - e(t)\frac{\pi}{2k}\cos\left(\frac{\omega_b t}{2}\right)\right)\end{aligned} \quad (4)$$

It should be noted that the expression of the phase modulated signal is derived from only the first three terms of the Fourier series. This expression is equivalent to the filtering of the signal and therefore the same amplitude variations are expected if the analog modulated signal is indeed filtered.
The above amplitude variations will contribute as noise to the AM signal, reducing its *SNR*. The calculated value of the variation for k=8 is 19.6%. It seems to be unacceptably high and for that reason it should be reduced or preferably suppressed. The reduction is possible because, as noted above, the signal is a form of phase modulation.

4. Signal Recovery

4.1. Analog Signal Recovery

After suppressing the amplitude variations and unconverted to a higher frequency, the phase modulated signal is used as a carrier to a DSB-AM modulator. Its output is the transmitted AM signal carrying digital information in its phase and analog information in its amplitude:

$$\begin{aligned}\upsilon(t)_{AM} &= A\left(1 + m(t)\right) \cdot \\ &\sin\left(\left(\omega_c t + \frac{\omega_b t}{2}\right) - e(t)\frac{\pi}{2k}\cos\left(\frac{\omega_b t}{2}\right)\right)\end{aligned} \quad (5)$$

$m(t)$ is the AM modulating signal.
The demodulated AM signal, by the use of an envelop detector and after low pass filtering is:

$$\upsilon(t)_{AM\ \text{Αποδιαμ.}} = A'\left(1 + m(t)\right) \quad (6)$$

From Eq. (6) it is clear that the AM signal is recovered at the receiver without any other degradation.

4.2. Digital Signal Recovery

The digital data stream can be taken by mixing the DSB-AM signal with a recovered carrier, 90° out of phase. Carrier is a sine-wave with frequency equal to $f_c + f_b/2$.
Before mixing the received signal with the recovered carrier, it is limited to suppress all its amplitude variations. The output of the mixer, after low pass filtering is given by:

$$\upsilon(t)_{Demodulated} \approx -\frac{A\,A'}{2}\frac{\pi}{2k}e(t)\cos\left(\frac{\omega_b t}{2}\right) \approx \frac{A\,A'}{2}\frac{\pi}{2k}d(t)\left|\cos\left(\frac{\omega_b t}{2}\right)\right| \quad (7)$$

$\upsilon(t)$ is a time varying waveform, changing its values at $t=(2n+1)T_b/2$, where it is zero. If the sampling of the waveform is made at $t=(2n)T_b/2=nT_b$, the digital data $d(t)$ can be recovered directly from the demodulated signal. This is achieved due to the difference of $f_b/2$ in the frequency between the recovered carrier used at the demodulator and the carrier at the modulator.

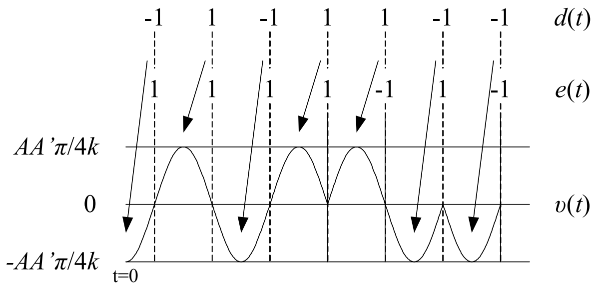


Fig. 4. Demodulated data waveform $\upsilon(t)$ in regards to digital data $d(t)$ and the encoded digital data $e(t)$.

5. Spectral and Power Efficiency

5.1. Spectral Efficiency

The spectral efficiency of the phase modulated signal is calculated based on Eq. (4). The modulated signal can be considered as a form of narrowband PM signal [6], [7], with modulating phase $\varphi(t)=-e(t)(\pi/2k)\cos(\omega_b t/2)$. For that reason the required minimum bandwidth for the transmission is $2f_m$, where f_m is the maximum frequency of the modulating waveform, $\varphi(t)$.

Taking the above into account, the power spectral density (*PSD*) of the modulating waveform $\varphi(t)$ is:

$$P_s(f) = \frac{2T_b}{k^2}\left(\frac{\cos(\pi f T_b)}{1-(2fT_b)^2}\right)^2 \quad (8)$$

5.2. Power Efficiency

The power efficiency of the proposed phase modulation is calculated by the probability of bit error for binary polar signals [8]-[10]. That is :

$$P_e = Q\left(2\sqrt{\frac{E_s}{N_o}}\right) \quad (9)$$

Using the expression of the baseband modulated signal (see Eq. (1)) the power E_s is:

$$E_s = \frac{2}{\pi^2}\sin^2\left(\frac{\pi}{k}\right)E_b \quad (10)$$

E_b is the bit power.

Combining Eqs. (9) and (10) gives the probability of bit error for the proposed phase modulation scheme:

$$P_e = Q\left(\sqrt{\frac{2E_b}{N_o}}\frac{2}{\pi}\sin\left(\frac{\pi}{k}\right)\right) \quad (11)$$

6. Hardware Implementation

In order to demonstrate the applicability of the proposed method a prototype system has been implemented. A modulator and a demodulator circuitry are used in order to transmit digital data over an analog AM signal. The phase modulation used by the system is for k=8, with a bit rate equal to 20 kbit/sec and carrier frequency 465 kHz. The above values are selected in order to be suitable for the commercially available ceramic filters.

6.1. Modulator

Fig. 5 shows the block diagram of the implemented modulator.

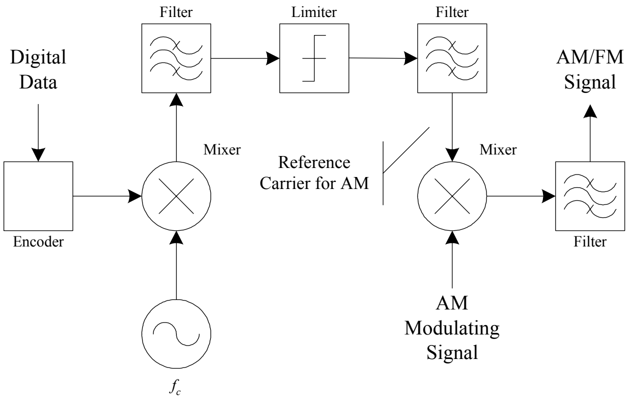


Fig. 5. Block diagram of the implemented modulator

Firstly, an encoder, incorporated into a Programmable Logic Device (PLD), Altera EPM 7064LC44 implements the necessary algorithm for the generation of the modulated digital data signal. Afterwards, a balanced modulator (Philips NE 602) transferred the baseband signal to IF. Consecutively two ceramic filters (Murata CFWS 455C) suppresses all the out-of-band frequencies. Finally, the DSB-AM modulation of the signal is realized by another modulator (Analog Devices AD 1496).

The transmitted signal that carries digital information in its phase and analog information in its amplitude is shown in Fig. 6(a). As an AM modulating input a sweep function from 0 Hz to 15 kHz was used.

Fig. 6(b) shows the spectrum of the above AM modulated signal. As it can be seen, the suppression of the out of band frequencies is sufficient while the blur of the spectrum is due to the AM modulation of the signal by the sweep function.

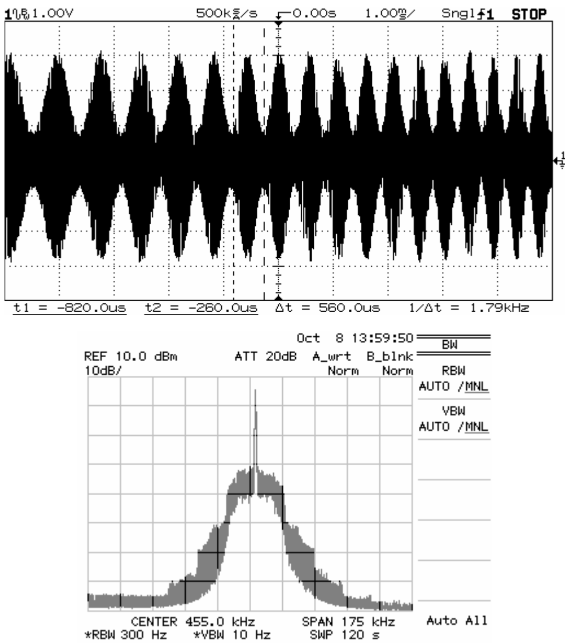


Fig. 6. (a) AM modulator output with the use of a sweep function from 0 Hz to 15 kHz as modulating input.
(b) Spectrum of the above AM modulated signal.

6.2. Demodulator

The block diagram of the implemented demodulator is shown on Fig. 7.

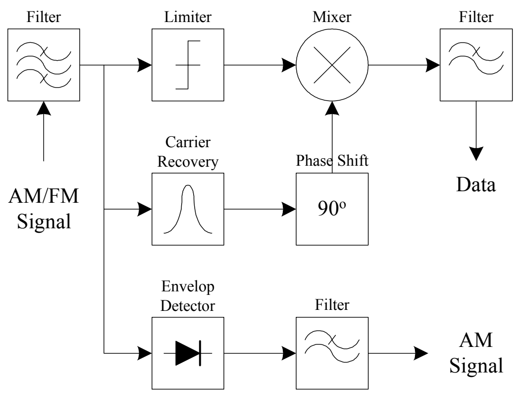


Fig. 7. Block diagram of the simulated demodulator.

The received signal, after the filtering is split into two paths, one for the demodulation of the AM signal and one for the recovering of the digital data. The recovering of the AM signal is done by the use of an envelop detector. Fig. 8 shows the demodulated AM signal after low pass filtering (upper trace) along with the modulating AM signal (lower trace). As it can be seen the two signals are identical.

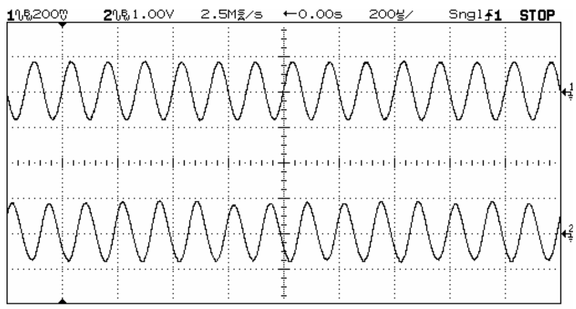


Fig. 8. Demodulated AM signal (upper trace) along with the modulating one (lower trace).

For the demodulation of the digital data a coherent detector is used, implemented by a balanced modulator (Philips NE 602). The necessary 90^{o} out of phase carrier is recovered by the use of a proprietary narrowband band-pass crystal filter with Q≈4000. Finally, the digital data signal is retrieved by the use of a demodulator (Philips NE 602). The eye diagram of the demodulated data signal, after low pass filtering, is shown in Fig. 9(a).

The digital data signal $d(t)$ can be recovered from the demodulated signal by the use of a level transformation circuit. An example of a recovered digital data stream along with the one at the modulator are shown on Fig. 9(b).

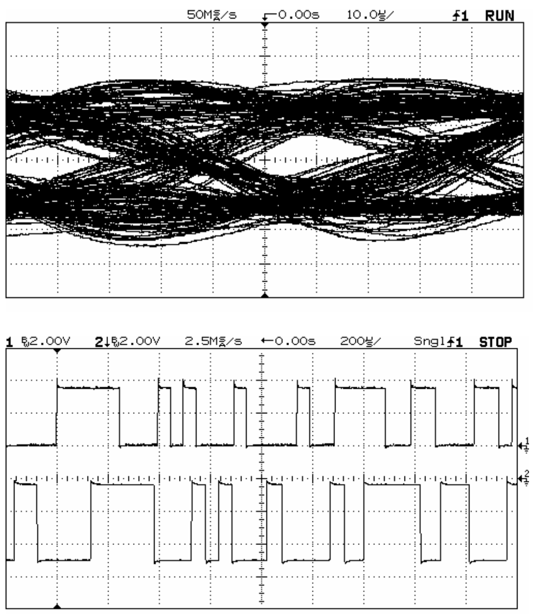


Fig. 9. (a) Eye diagram of the demodulated data signal.
(b) Recovered data stream at the demodulator (upper trace) along with the digital data stream at the modulator (lower trace).

7. Conclusions

This paper proposes a phase modulation method that enables the simultaneous transmission of analog and digital information. This is done by properly modulating the phase of an AM signal's carrier in order to carry digital information with little or no interference to the signal itself. This way an already occupied bandwidth is re-used, which it can be considered as an overall increase to the bandwidth efficiency of the system.

Care is taken in order the proposed method to be compatible with commercially available AM receivers. This is one of the main advantages of the proposed method along with the achieved bit rate, $2f_m$, which is much higher than that given by other methods [11]-[13].

Finally, the relative simplicity in the implementation of the modulator and demodulator is another advantage of the proposed method.

References:

[1] G. D. Forney, Jr. Les Brown, M.V. Eyuboglou, J.L. Moran, "The V.34 High-Speed Modem Standard", IEEE Communications Magazine, pp. 28-33, December 1996.

[2] K. Maxwell, "Asymmetric Digital Subscriber line: Interim Technology for the Next Forty Years", IEEE Communications Magazine, pp. 100-106, October 1996.

[3] J.A.C. Bingham, "Multicarrier Modulation for Data Transmission: An Idea Whose Time Has Come", IEEE Communication Magazine, pp. 5-14, May 1990.

[4] CENELEC, "Specification of the radio data system (RDS)", European Standard EN 50067, March 1992.

[5] World System Teletext and Data Broadcasting System Technical Specification, Department of Trade and Industry, UK, 1987.

[6] Leon W. Couch II, "Modern Communication Systems, Principles and Applications", Prentice Hall International, N.J., 1995.

[7] Taub and Schilling, "Principles of Communications Systems" McGraw Hill, 2nd edition, 1986.

[8] B. Sklar, "Digital Communications, Fundamentals and Applications", Prentice Hall International, 1988.

[9] S. Pasupathy, "Minimum Shift Keying: A Spectrally Efficient Modulation", IEEE Communications Magazine, pp. 14-22, July 1979.

[10] S. Gronemeyer and A. McBride, "MSK and Offset QPSK Modulation", IEEE Transactions on Communications, pp. 809-820, August 1976.

[11] Y. O. Al-Jalili, G. B. Lockhart, "Towards Real-Time Implementation of a Radio-Data-System for AM Sound Broadcasting", IEE Proceedings, Vol. 136, Pt. 1, No. 1, pp. 20-24, Feb. 1989.

[12] Y. O. Al-Jalili, A. A. Al-Obaidi, M. K. Habib, "Characteristics of Reduced Bandwidth Envelop Detected Minimum-Phase Signals", IEE Proceedings, Vol. 137, No. 6, pp. 345-354, Dec. 1990.

[13] G. B. Lockhart, Y. O. Al-Jalili, "Analysis and Simulation of a Hybrid Modulation Scheme for Embedding Data in Amplitude-Modulated Signals", IEE Proceedings, Vol. 138, No. 3, pp. 426-436, Oct. 1991.