SP-QPSK: A NEW MODULATION TECHNIQUE FOR SATELLITE AND LAND-MOBILE DIGITAL BROADCASTING

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ABSTRACT

A new modulation technique, "SP-QPSK" (sinusoidal shaped π/4-QPSK) suitable for land-mobile and satellite digital broadcasting systems applications is introduced. In digital data and/or sound broadcasting systems, which may have a relatively low bit rate transmission requirement, the residual phase noise introduced by the Doppler shift of moving vehicles presents a high bit error floor in coherently demodulated systems. To avoid this problem, non-coherent detection methods may have to be employed. Even though these systems require a higher C/N than their theoretical coherent counterparts in stationary AWGN environments, the overall performance of non-coherent systems is frequently superior in a mobile radio environment. In addition, to satisfy the high power and spectral efficiency requirements of emerging digital broadcast systems, nonlinear, saturated amplifiers may become essential subsystems.

We introduce a new modulation technique, SP-QPSK, which combines the advantages of the IJF-OQPSK narrowband satellite systems and of the π/4-QPSK systems which have been adopted as the second generation land-mobile cellular standards, i.e., the US digital cellular standard.

The performance of our new generation of SP-QPSK systems is investigated by computer simulations and experimentally. Digital signal processing implementation techniques have been used in the experimental prototype design.

We demonstrate that nonlinearly amplified SP-QPSK has a 10 dB lower out-of-band radiated power than conventional QPSK and it is suitable for differential and discriminator detection. Improved performance and simplified (non-coherent hardware) receivers could lead to novel digital broadcasting applications of this powerful modulation technique.

1. INTRODUCTION

Digital data and sound broadcasting have been proposed for future satellite and/or terrestrial broadcasting system applications [8]. Some of the most important modulation-demodulation (modem) requirements include: (1) non-linear power amplifier to attain increased power efficiency of the transmitter; (2) discriminator or differential non-coherent detection for Doppler shift-caused phase noise-controlled mobile radio systems.

Two-symbol-interval (TSI) QPSK modulation techniques [1], such as IJF-OQPSK, SQAM, etc., have been developed and are in use in several satellite communication systems which require efficient non-linear power amplification and reduced out-of-band radiation. However, these schemes need coherent detection due to the fact that they have "offset" I and Q baseband channels by half a symbol duration. This "offset" mode is not suitable for conventional differential non-coherent reception. On the other hand, for differential or discriminator detection, π/4-QPSK [2; 3 and 6] is an improved QPSK-based modulation technique proposed for the US digital cellular standard. However, it has a major drawback in nonlinearly amplified systems, i.e., a significant out-of-band spectral radiation. We invented a new modulation technique, sinusoidal shaped π/4-QPSK, or for short, "SP-QPSK," which has the combined advantages of the TSI-QPSK and also of the π/4-QPSK systems.

2. TSI-π/4-QPSK Systems

Even though the π/4-QPSK modulator is basically a QPSK (four state) modulator, it has eight signaling phase states as illustrated in Fig. 2.1. The principles of this modulation technique are described in [2; 3 and 6]. The

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phase shift as a function of the information symbols is illustrated in Table 2.1. At every sampling instant each orthogonal axis may have a value of (1, 0, or -1) or (0.707 or -0.707). In our new modulation scheme we propose to connect both these values with an appropriate smooth curve which realizes TSI-based ±4-QPSK schemes. Fig. 2.2 shows the block diagram of an SP-QPSK modulator. In our design Nyquist filters used in conventional ±4-QPSK are replaced by TSI waveform shaping circuits [1].

Table 2.1 Phase shift as a function of information symbol

<table>
<thead>
<tr>
<th>(i, j)</th>
<th>shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1, 1)</td>
<td>π/4</td>
</tr>
<tr>
<td>(0, 1)</td>
<td>3π/4</td>
</tr>
<tr>
<td>(0, 0)</td>
<td>-π/4</td>
</tr>
<tr>
<td>(1, 0)</td>
<td>-π/4</td>
</tr>
</tbody>
</table>

Fig. 2.2 Block diagram of SP-QPSK modulator

Fig. 2.3 and Table 2.2 show illustrative wave shapes which could be suitable for this design. A TSI wave shape may be regarded as the product between a binary on-off signal and the wave shaping circuit. The theoretical spectral density of these wave shapes is illustrated in Fig. 2.4 and Table 2.3 [4; 5].

Table 2.2 Expression of TSI wave shape [Ref. 1]

<table>
<thead>
<tr>
<th>Wave Shape</th>
<th>y(t) = D(i) - D(i-1) t/T + D(i-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>y(t) = D(i-1) - D(i-1) t/T + D(i)</td>
</tr>
<tr>
<td>Triangle</td>
<td>y(t) = D(i-1) - D(i) t/T + D(i)</td>
</tr>
<tr>
<td>Sineoidal</td>
<td>y(t) = D(i-1) - D(i) t/T + D(i)</td>
</tr>
<tr>
<td>Parzen</td>
<td>y(t) = D(i-1) - D(i) t/T + D(i)</td>
</tr>
<tr>
<td>Blackman</td>
<td>y(t) = D(i-1) - D(i) t/T + D(i)</td>
</tr>
</tbody>
</table>

Note: T symbol duration
1 current sample instance
D(i) current sample value (-1, -0.707, 0.707, 1)

Fig. 2.4 Theoretical characteristics of TSI wave shape (in Frequency domain)

Table 2.3 Theoretical characteristics of TSI wave shape

<table>
<thead>
<tr>
<th>Wave Shape</th>
<th>2nd side lobe</th>
<th>-3dB width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>-13dB</td>
<td>1.18 T</td>
</tr>
<tr>
<td>Triangle</td>
<td>-27dB</td>
<td>1.28 T</td>
</tr>
<tr>
<td>Sineoidal</td>
<td>-33dB</td>
<td>1.44 T</td>
</tr>
<tr>
<td>Parzen</td>
<td>-53dB</td>
<td>1.62 T</td>
</tr>
</tbody>
</table>

The computed results of linearly and nonlinearly (hardlimited) amplified spectra are shown in Fig. 2.5 to Fig. 2.9. In these figures one sideband of the modulated signal and/or corresponding demodulated baseband are is illustrated. Fig. 2.5 represents a conventional ±4-QPSK. Even though it has a narrow band-limited spectrum in a linearly amplified channel, the out-of-band spectrum is restored (spread) to approximately -25 dB relative to the in-band spectrum. Rectangular shape, i.e., no wave-shaping
Fig. 2.5 Simulated Nyquist filtered ($\alpha=0.2$) power spectrum

Fig. 2.6 Simulated rectangular shaped power spectrum

Fig. 2.7 Simulated triangle shaped power spectrum
Fig. 2.8 Simulated sinusoidal shaped power spectrum

Fig. 2.9 Simulated Partzen shaped power spectrum

Fig. 2.10 Baseband waveform on one orthogonal axis of SP-QPSK

Fig. 3.1 Block diagram of FM discriminator
shown in Fig. 2.6, has the same spectrum as a conventional binary PRBS signal. Triangular-shaped waves, Fig. 2.7, have a lower out-of-band spectrum. However, as there are discontinuities, it may not be suitable for specific band-limited channel applications. Sinusoidally shaped waveforms have a low out-of-band spectrum both in linear channel and in nonlinear channels. It has approximately a 10 dB spectral improvement at $A_f = 1.6/T_b$ from the carrier frequency. In addition it has a smooth waveform which has continuous derivatives. The Partzen shape, illustrated in Fig. 2.9 based on Ref. [4], also has a smooth waveform and has a low out-of-band spectrum. However, the second peak at $f = 2.5/T_b$ is larger than that of the sinusoidally shaped signal. Hence sinusoidal shaping is the best one among the investigated TSI π/4-QPSK waveforms. The sinusoidal shaping rule is rewritten here:

$$U(t) = \frac{1}{2} \left[ (I(i-1) - I(i)) \cos(\pi t/T) + I(i-1) + I(i) \right]$$ (1a)

$$V(t) = \frac{1}{2} \left[ (Q(i-1) - Q(i)) \cos(\pi t/T) + Q(i-1) + Q(i) \right]$$ (1b)

where $U(t)$ and $V(t)$ are the orthogonal signals of SP-QPSK, $I(i)$ and $Q(i)$ are the values at the sampling instants $i$, and $T$ is symbol duration.

Fig. 2.10 shows a computer generated baseband waveform of an SP-QPSK modulator.

3. DEMODULATION METHODS

For power efficient applications, saturated amplification may be required. This mode of operation is frequently used in numerous communication applications, especially in satellite broadcasting. Because of nonlinear amplification of non-constant envelope bandlimited QPSK type of signals, the received demodulated signal is distorted as compared to the constellation shown in Fig. 2.1. The information is contained in the phase shift between two symbol durations. Hence the combination of a hard limiter (extremely fast AGC) and an FM discriminator is suitable for stable reception. In Fig. 3.1 a block diagram of the demodulator, based on FM discrimination, is illustrated. Instead of Integrate and Dump filtering, which is often used for analysis of FM discriminators, Butterworth lowpass filters are used because band-limited channels are assumed in this case.

The output of the discriminator becomes four-level; each level expresses $3\pi/4, \pi/4, -\pi/4, -3\pi/4$ phase shift between two-symbol duration. Therefore gray encoded signals can be decoded. Data is regenerated from differentially detected phase information. Transmitted data is recovered with parallel/serial conversion and gray code conversion recovers the original information from these four levels. The analysis of the output of the discriminator is as follows:

The input signal of the discriminator is

$$S(t) = A \cos \left\{ 2\pi f_c t + \phi(t) \right\}$$ (2)

where $f_c$ is a carrier frequency. When $\epsilon$ is a small amount of delay the output of the differential detector after lowpass filter is

$$O(t) = \sin \left\{ \phi(t) - \phi(t-\epsilon) \right\}$$ (3)

In this case as $S(t)$, formula (2), is the sum of two orthogonal signals, phase information satisfies the next.

$$\tan \left( \phi(t) \right) = V(t) / U(t)$$ (4)

Here, $U(t)$, $V(t)$ correspond to (1). As $U(t)$ and $V(t)$ have sinusoidal waveform, output signals can be easily computed. Substituting (4) for (3)

$$O(t) = \frac{U(t-\epsilon) V(t) - U(t) V(t-\epsilon)}{\sqrt{U^2(t-\epsilon)+V^2(t)} \sqrt{U^2(t)+V^2(t-\epsilon)}}$$ (5)

The computed waveform of (5) is Fig. 3.2. As shown in this figure, four phase states are detected. Therefore a three-level baseband threshold detector can distinguish these four symbols [3, 6].

![Fig. 3.2 Simulated output of FM discriminator](image)

![Fig. 3.3 Block diagram of differential detection](image)
in Fig. 3.4. As it needs only a two-level threshold detector, accuracy of the detection is more improved than the F+1 discriminator detection using the three-level threshold decision mentioned above. Except for the difficulty or long delay line, the differential detection may also be suitable for the demodulator.

![Fig. 3.4 Simulated output waveform of differential detection](image1)

4. EXPERIMENTAL RESULTS

Performance of our SP-QPSK is measured with experimental hardware designed at UC Davis. DSP techniques have been used in this 250 kb/s modem design. Fig. 4.1 and Fig. 4.2 illustrate the measured baseband waveforms of one orthogonal axis and a constellation diagram generated mutually from this modem.

Spectrum spreading is also measured. Fig. 4.3 shows the comparison of spread spectrum among IJF-OQPSK, SQAM and SP-QPSK. SP-QPSK has 10 dB advantage compared with QPSK and has the same spectrum as the IJF-OQPSK nonlinearly amplified system [8].

For demodulation an FM discriminator was designed. Fig. 4.4 is the band-limited spectrum at the IF input of the demodulator. Fig. 4.5 is the experimental waveform at output of the FM discriminator.

![Fig. 4.1 Baseband waveform of SP-QPSK](image2)

![Fig. 4.2 Constellation of SP-QPSK](image3)

![Fig. 4.4 Received spectrum](image4)
Fig. 4.3 Measured spectrum

bit rate: 250 kb/s
horizontal: 100 kHz/div
vertical: 10 dB/div
5. CONCLUSION

A new modulator "SP-QPSK" is described. It has a good performance in nonlinearily amplified channels. It can be realized with simple hardware. Therefore it is useful for power and spectrally efficient systems, especially digital broadcasting. As a demodulator an FM discriminator is suitable for eliminating the Doppler-caused phase noise effect of mobile receivers.

6. REFERENCES


