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DESIGN ISSUES OF A DIGITAL BASEBAND GMSK-MODULATOR FOR AN AUTONOMOUS WIRELESS COMMUNICATION SYSTEM

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Abstract. *In wireless communication systems the available spectrum is limited, and avoiding adjacent channel interference is often an issue. The power spectrum must be as compact as possible. At the same time, wireless systems are often autonomous systems fed by batteries or fotovoltaic energy. To minimise the power consumption, power efficient, non-linear amplifiers are used. These amplifiers require signals with a constant envelope. Using GMSK as modulation form is a good choice to fulfil these requirements. In this paper first the general properties of MSK and GMSK signals are recapitulated. Then the quadrature structure of a GMSK modulator is given. Finally, the design of the digital base band GMSK modulator is discussed in detail. The described design is part of a base station of a fixed wireless system for a mountainous area, fed by fotovoltaic energy. The GMSK modulator has a normalised bandwidth of 0.5, but the design results can easily be generalised to other situations.*
Keywords: *wireless communications, digital modulation, minimum shift keying.*

Introduction

Gaussian Minimum Shift Keying (GMSK) is often used as modulation form in digital wireless systems. In wireless systems the available spectrum is limited and adjacent channel interference must be avoided, which means that the main lobe of the power spectrum must contain most of the energy and the side lobes must be very low. Wireless systems are often autonomous systems fed by a battery or by photovoltaic energy (solar energy). This implies that the power consumption is of primary interest. The modulator design described in this paper is part of a base station for a fixed wireless communication system to be used in a mountainous area and it should be fed by photovoltaic energy. To optimise the power consumption, efficient power amplifiers are used in these systems e.g. class C amplifiers. These power efficient amplifiers are non-linear amplifiers, so the amplified signals should be constant envelope signals, to avoid spectral broadening and hence adjacent channel interference.
A GMSK modulated signal has a constant envelope and can make a good trade-off between bandwidth and intersymbol interference (ISI).

Properties of GMSK modulation

Constant envelope signals can be straightforward obtained with simple phase modulation techniques like Binary Phase Shift Keying (BPSK) or Quadrature Phase Shift Keying (QPSK). These signals contain abrupt phase changes. If a QPSK modulated signal is filtered to reduce the spectral side lobes, then the abrupt phase changes are removed and the resulting waveform no longer has a constant envelope. Abrupt 180° shifts in phase will cause the envelope to drop to zero momentarily.
Minimum Shift Keying (MSK) modulation avoids this problem because it has a continuous phase [1]. An MSK modulated signal can be described as

$$s_{MSK}(t) = A\cos(2\pi f_c + b_n \frac{\pi}{2}(\frac{t-nT_b}{T_b}) + \theta(nT_b)),$$
$$nT_b \le t < (n+1)T_b \qquad (1)$$

with A : amplitude of the signal
f_c : carrier frequency
b_n : n-th information bit (+1 or -1)
$T_b = 1/R_b$: bit duration
$\theta(nT_b)$: phase at the end of the (n-1)th bit period (and at the beginning of the n-th bit period)

This means that the phase of the signal linearly increases or decreases 90° during each bit period as shown in Figure 1.

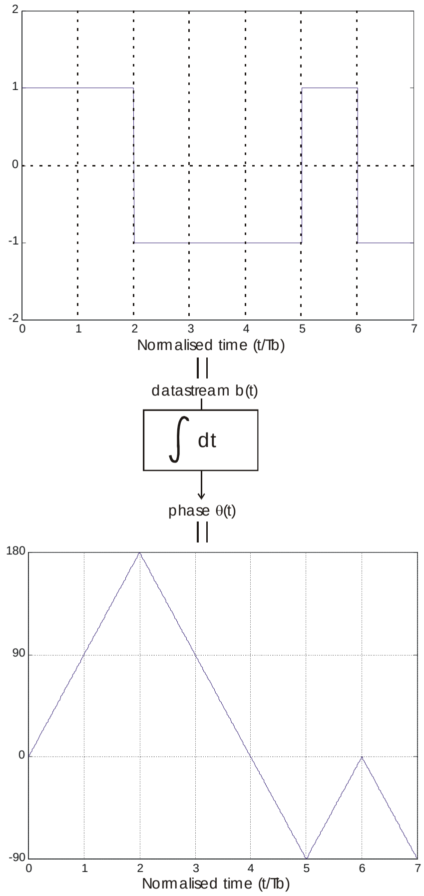

Figure 1. GMSK phase

The phase θ(t) can be formed by integrating the bitstream b(t). In fact, MSK is a form of Frequency Shift Keying (FSK) that follows from a carefully designed Phase Shift Keying (PSK) which can be seen in the following formula:

$$s_{MSK}(t) = A\cos\left[2\pi\left(f_c + b_n\frac{1}{4T_b}\right)t - b_n n\frac{\pi}{2} + \theta(nT_b)\right],$$
$$nT_b \le t < (n+1)T_b \qquad (2)$$

So the modulator switches between two frequencies:

$$f_1 = f_c - \frac{1}{4T_b}$$
$$f_2 = f_c + \frac{1}{4T_b} \qquad (3)$$

The difference between the frequencies used in this FSK modulation is the minimum distance such that the signals does not interfere with each other i.e. that the signals are orthogonal over T_b.

The power spectrum of QPSK and MSK is shown in Figure 2. Due to the continuous phase, MSK has a 50% wider main lobe (±0.75 R_b versus ±0.5 R_b for QPSK) and the energy in the side lobes is much lower. This is advantageous for the adjacent channel interference.

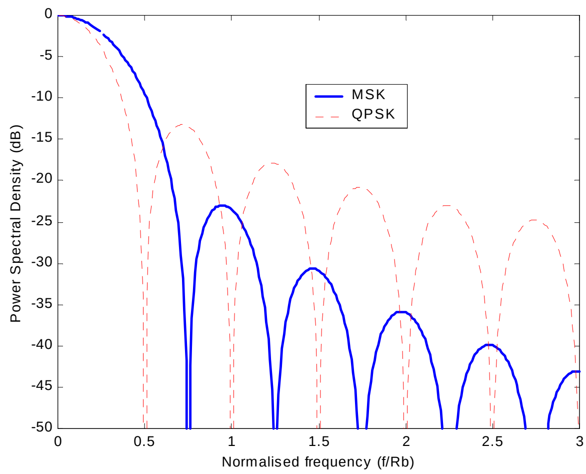

Figure 2. Power spectral density of an MSK and GMSK signal

GMSK starts from the MSK signal and applies a Gaussian filter to the phase (Figure 3(a)) [2]. This generates a spectrum with lower side lobes. The bandwidth B of the Gaussian filter is defined with respect to the bit rate R_b, the product BT_b is called the normalised bandwidth. Figure 4 and Figure 5 show the time and the frequency response of a Gaussian filter for various BT_b (Remark: MSK corresponds to $BT_b = \infty$ and the time response is rectangular).

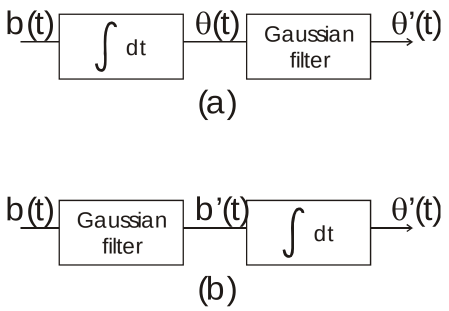

Figure 3. GMSK phase

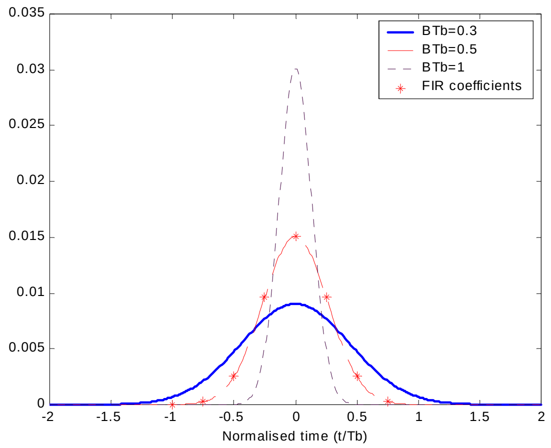

Figure 4. Time response of Gaussian filter for several BT_b.

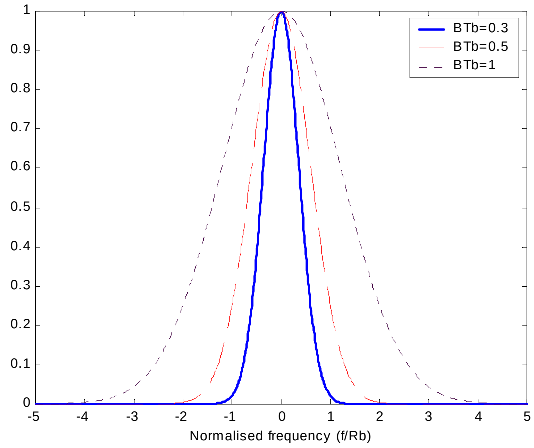

Figure 5. Frequency response of Gaussian filter for several BT_b.

The Gaussian filter introduces intersymbol interference (ISI). The bits are spread out in time by the filter and therefore overlap. This can be seen in Figure 3(b): the integration and filtering can be switched. Figure 6 shows the overlap of the bits for the bit sequence [1 -1 1 -1 1 1 1 -1 -1] for $BT_b = 0.5$; each bit occupies an interval of about $2T_b$ in this case.

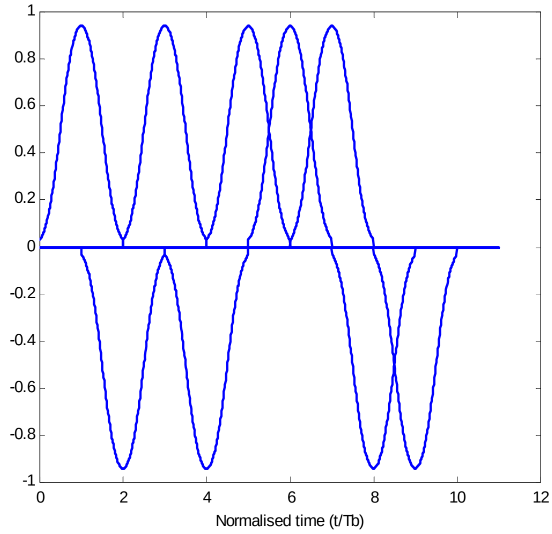

Figure 6. Individual pulses representing the filtered datastream b'(t)

Figure 7 and Figure 8 show the filtered signal b'(t) and the phase of the GMSK signal θ'(t) respectively. The phase of the GMSK signal is smoother than the phase of the MSK signal; this explains the more compact spectrum of a GMSK signal.

The ISI results in degradation in the BER (Bit Error Rate). A lower BT_b results in a higher spectral efficiency but also in a higher BER, so a compromise is necessary. In the GSM system for example, a BTb = 0.3 is used (datarate is 270.8 kbps), this gives a degradation of about 1 dB in BER with respect to MSK [3][4].

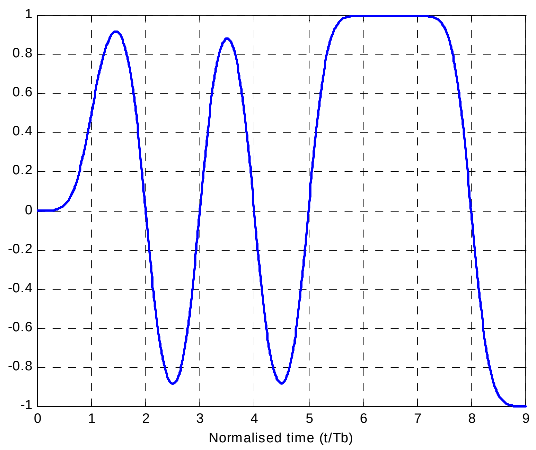

Figure 7. Total signal b'(t)

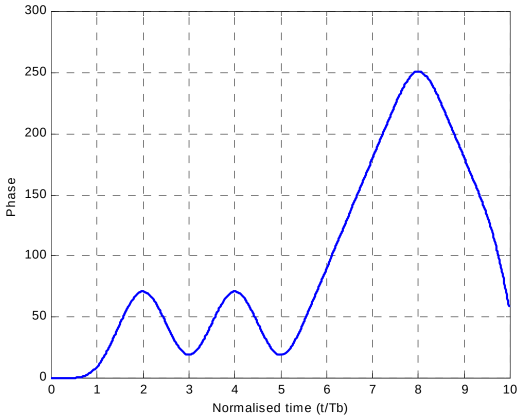

Figure 8. Total signal θ'(t)

Applying the filtering to the phase signal, i.e. before the modulation, guarantees that the modulated signal keeps a constant envelope.

GMSK modulator architecture

A VCO-modulator architecture can be used for the GMSK modulator, but this simple architecture is not suitable for coherent detection due to component tolerance problems. The frequency deviation factor of the VCO must exactly equal 0.5, however the modulation index of conventional VCO based transmitters drifts over time and temperature.

Therefore, a quadrature modulator is used. The I and Q signals are digitally generated. The configuration for the base band modulator is shown in Figure 9.

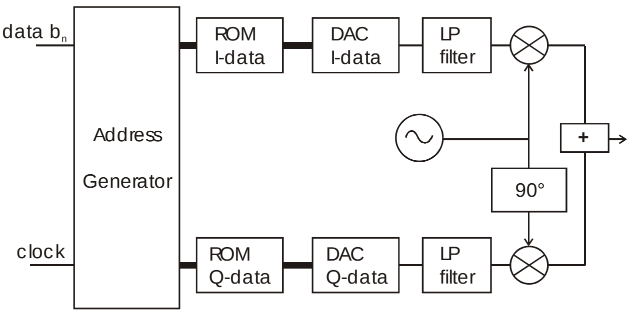

Figure 9. Transmitter modulator

The next paragraph describes the design of the base band part of the modulator: the generation of the ROM data and the design of the address generator. As an example, the design of a GMSK modulator with a normalised bandwidth of $BT_b = 0.5$ is used.

Baseband modulator design

The quadrature modulator architecture is based on the following formula:

$$\begin{aligned} s_{GMSK}(t) &= A\cos[2\pi f_c t + \theta'(t)] \\ &= A\cos[\theta'(t)]\cos[2\pi f_c t] - A\sin[\theta'(t)]\sin[2\pi f_c t] \\ &= I(t)\cos[2\pi f_c t] - Q(t)\sin[2\pi f_c t] \end{aligned} \tag{4}$$

The I(t) and Q(t) data must be sampled and stored in ROM. The number of samples taken in each bitperiod T_b is called the oversampling factor. A higher oversampling factor makes the low pass filters after the A/D converter simpler. In the design example the oversampling factor is chosen to be 4.

In theory, the length of the impulse response of a Gaussian filter is infinite, which means that each bit will cause ISI with all other bits of the data signal. However, only the neighbouring bits suffer severe ISI and practically the length of the impulse response can be truncated. To generate the ROM data the impulse response of the Gaussian filter is turned into a digital finite impulse response filter (FIR). Therefore, the impulse response is truncated symmetrically around zero. The length of the FIR response depends on the normalised bandwidth BT_b. For $BT_b = 0.5$ the length of the impulse response can be limited to $2T_b$. Then the edge of pulse envelope falls below 60 dB with respect to the peak envelope amplitude. With an oversampling of 4 the FIR filter in the design example has only 8 coefficients. The samples are marked in Figure 4.

In this approximation it is important to normalise the filter coefficients such that each data bit causes a phase shift of exactly ±90°. Then the I and Q signals can be generated by filtering the linear phase from the MSK signal with the FIR filter and then taking the sine and cosine function of the filtered phase.

The I and Q signals can also be generated from data stored in a ROM, because the phase function θ'(t) can have only a very limited number of shapes in each bit interval. With the above described FIR filter for BT_b=0.5, each bit interferes only with the next bit and so the phase variation in the n-th bit interval depends on the current bit b_n and the previous bit b_{n-1}. There are only 4 possibilities for the shape of the phase variation in each bit interval. The net phase variation between the start and the end of a bit interval can be either 0°, +90° or –90°. So at the beginning of a bit interval the phase can have 4 values. This is shown in Figure 10.

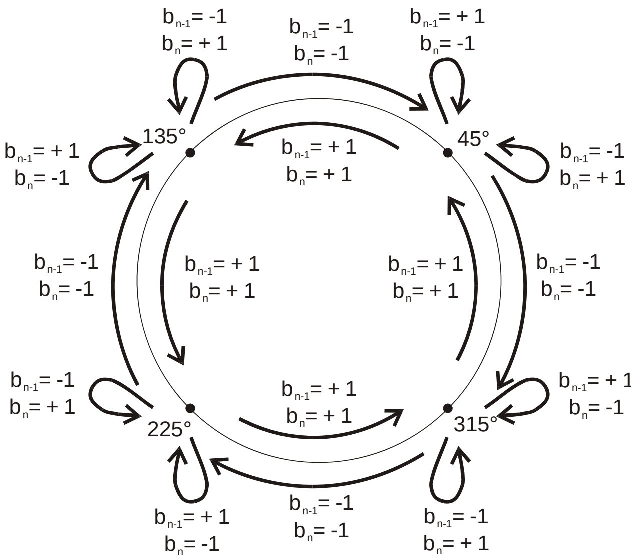

Figure 10. Phase variations for a GMSK modulator BT_b = 0.5

The conclusion for our design example is that for the phase function θ'(t) there are 16 possible waveforms in each bit interval. So 16 waveforms for I and Q must be stored in the ROM. With an oversampling factor of 4, each waveform is described by 4 samples and a total number of 16 x 2 x 4 = 128 samples must be stored in ROM. The number of samples can be further reduced because some of the waveforms for the I and Q component are the same (cos(90°-θ') = sinθ', cos(-θ') = cos(θ'), sin(180°-θ') = sin(θ')). In fact, we need to store only 8 different waveforms (shown in Figure 11). So the two ROM's in Figure 9 could be merged and one ROM containing 8 x 4 =32 samples would be sufficient. This requires however a ROM with two access ports and the design of the address generator becomes more complex, so there is no clear practical advantage in doing so.

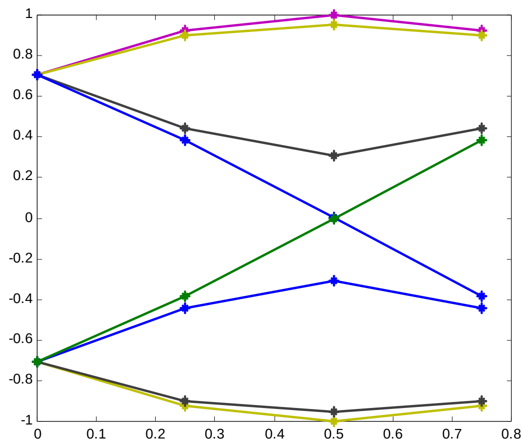

Figure 11. Waveforms stored in ROM

The address generator in Figure 9 selects the correct waveform based on the incoming bits b_n. The address generator can be a digital finite state machine. Figure 10 can be used as a state diagram to design the address generator. The address generator can also be described by Table 1.

Present state	θ'(nT_b)	b_n	b_{n-1}	New state	Wave form number
0	45°	-1	-1	3	1
0	45°	+1	-1	0	2
0	45°	-1	+1	0	3
0	45°	+1	+1	1	4
1	135°	-1	-1	0	5
1	135°	+1	-1	1	6
1	135°	-1	+1	1	7
1	135°	+1	+1	2	8
2	225°	-1	-1	1	9
2	225°	+1	-1	2	10
2	225°	-1	+1	2	11
2	225°	+1	+1	3	12
3	315°	-1	-1	2	13
3	315°	+1	-1	3	14
3	315°	-1	+1	3	15
3	315°	+1	+1	0	16

Table 1. Description address generator

Conclusion

In this paper the detailed design process of a digital GMSK base band modulator is presented. The digital approach results in a straightforward design with a very high accuracy. The design process is explained for a GMSK modulator with a normalised bandwidth $BT_b = 0.5$ and an oversampling factor of 4, but the design can easily be repeated for other parameters. Based on the detailed analysis in this paper a software program can be written that has input parameters like normalised bandwidth, oversampling factor and number of bits per sample, and that automatically generates the ROM samples and a description of the address generator.

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