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Title: **Simple Gaussian Filter Design for FH-SS Applications**

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Abstract

An elegant look-up table implementation of Gaussian filter with BT_b=0.5 based on Feher's Filter (FF) patented technology[1] is presented. Control logic and encoder functions are introduced in the implementation to reduce the storage size of Read-Only Memory (ROM) by 50%. A normalized low bit rate filtered baseband signal with a data rate of 50 kbit/s is compared with the intersymbol interference and jitter free (IJF) filtered baseband signal (also known as the FQPSK-1[2,3] baseband signal) in the time domain and frequency domains. The same technology was also evaluated at rates of 2Mbit/s and 10Mbit/s. The digital filter described here was implemented using the inexpensive CMOS digital components.

Intellectual property disclosure statements were submitted to IEEE 802.11, JTC-TIA and other standardization committee by Dr. Feher Associates during 1993-1994[4]. To request technology transfer and licensing package information, contact: Dr. Feher and Associates, Digcom, Inc. 44685 country club drive, El-Macero CA 95618, U.S.A.,Tel:(916)753-0738; Fax:(916)753-1788 or Dr. Kamilo Feher at (916)752-8127.

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Introduction

The rapid growth in the number of users of wireless communications has imposed a great demand on efficient modulation schemes in the recent years. Gaussian filter has become the baseband filter in many wireless technologies. Gaussian Filtered Minimum Shift Keying (GMSK) modulation is the European Standard for both digital cellular landmobile system and personal communications services systems due to its attractive narrow spectrums with much reduced side lobes. The advantage of GFSK with any modulation index m is attributed to the Gaussian filter. Thus, an efficient implementation of a Gaussian filter is one of the major tasks in improving the power efficiencies of the personal communications systems (PCS). A Gaussian filter can be either analog or digital. However, a digital filter has an advantage over an analog filter in the size and precision. Compared to the previous methods of look-up table, the implementation of Gaussian filter with BT_b=0.5 described here has the advantage of reduced ROM size. However, for BT_b=0.5, eight different kinds of segments are required at the filter output in each one-bit duration T_s. The structure of such a Gaussian filter is still complicated.

The baseband filter of FQPSK-1, a leading modulation candidate for IEEE 802.11 standards, has a simple structure because only four different segments of one bit duration T_s are required at the filter output, and can provide an alternate solution since its output signal has almost the same shape as the output signal of Gaussian filter in both time and frequency domains.

Gaussian Filter

The cascade of a Gaussian low-pass filter (GLPF) with an FM modulator VCO leads to a GFSK with variable modulation index, typically $0.1 \le m \le 1$. When m=0.5, it becomes GMSK modulator. A block diagram of the GFSK modulator is shown in Fig.1.

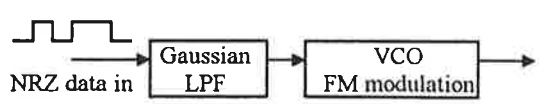

Figure 1. Voltage controlled oscillator (VCO)-FM modulator

The pulse response of the GLPF is given by [5]

$$g(t)=B\sqrt{\frac{2\pi}{\ln 2}}\exp\left[-\frac{2\pi^2B^2}{\ln 2}t^2\right] \qquad (1)$$

where B is the 3dB bandwidth of the GLPF. The pulse response g(t) of Gaussian low-pass filter is shown in Fig.2 for various BT_b (T_b is a unit bit interval) product. Smaller BT_b leads to more compact spectrum, but at the same time introduces more intersymbol interference (ISI)[5].

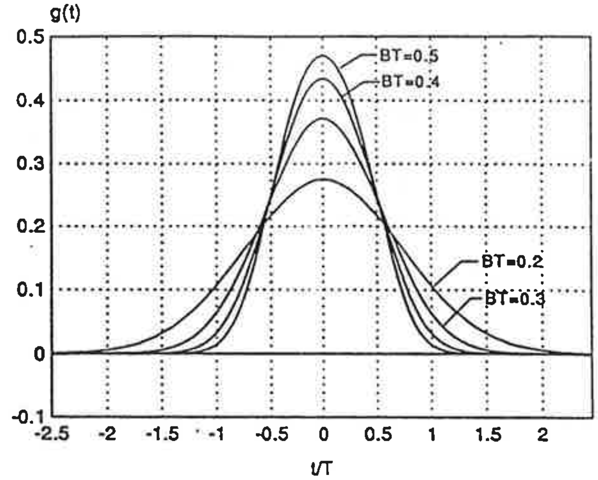

Figure 2. The pulse response g(t) of Gaussian filter

Hardware Implementation

a) General Description

A block diagram of the look-up table implementation is described in Fig.3. This schematic illustrates the use of control logic and encoder in the look-up table scheme, which results in reduced ROM size. In our implementation BT_b product was chosen to be 0.5, and the eye diagram at the Gaussian filter output is plotted in Fig.4. It consists of eight segments during one bit duration, as shown in Fig.5. The output signal of GLPF in one-bit duration is completely determined by three successive input data, namely the present, previous and future bits. The relationship between the output signal and input data is listed on table 1. Its principle is the same as that of FQPSK-1 baseband filter, in which the output signal is determined by two successive input data, namely the present and previous bits. The eye diagram of FQPSK-1 baseband signal is also shown in Fig.4. Input and output relationship is listed on table 2. Figure 6 shows the spectrum of the modulated signal, obtained using the GFSK of Fig.1, with the Gaussian filter and the FQPSK-1 baseband filter. The carrier frequency is 915MHz and modulation index is 0.5. It can be seen from the Fig.4 that their eye diagrams are very similar, in addition their spectral shapes being identical in Fig. 6.

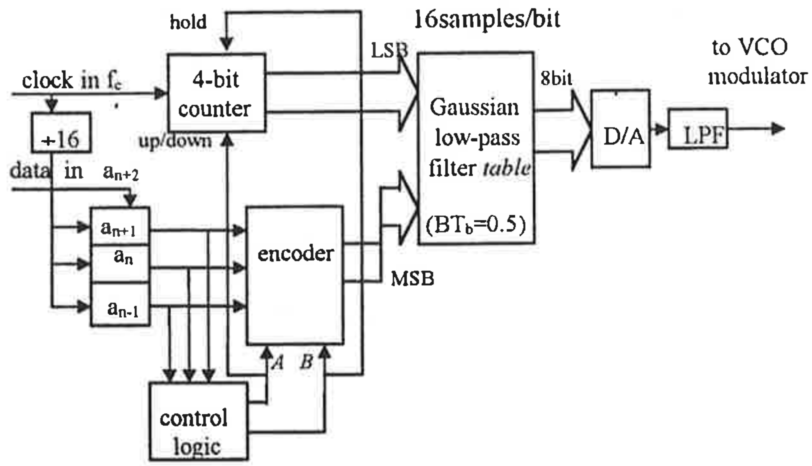

Figure 3. Block diagram of look-up table for a Gaussian low-pass filter

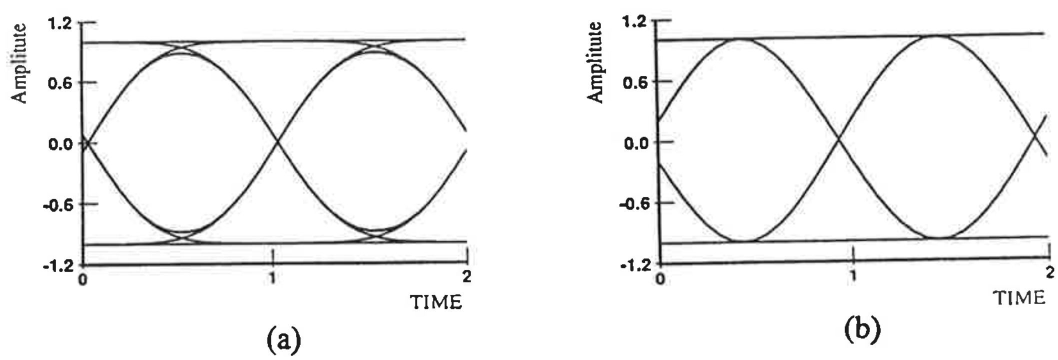

Figure 4. Tx baseband eye diagram
(a) after Gaussian filter (BT_b=0.5)
(b) after FQPSK-1 baseband filter

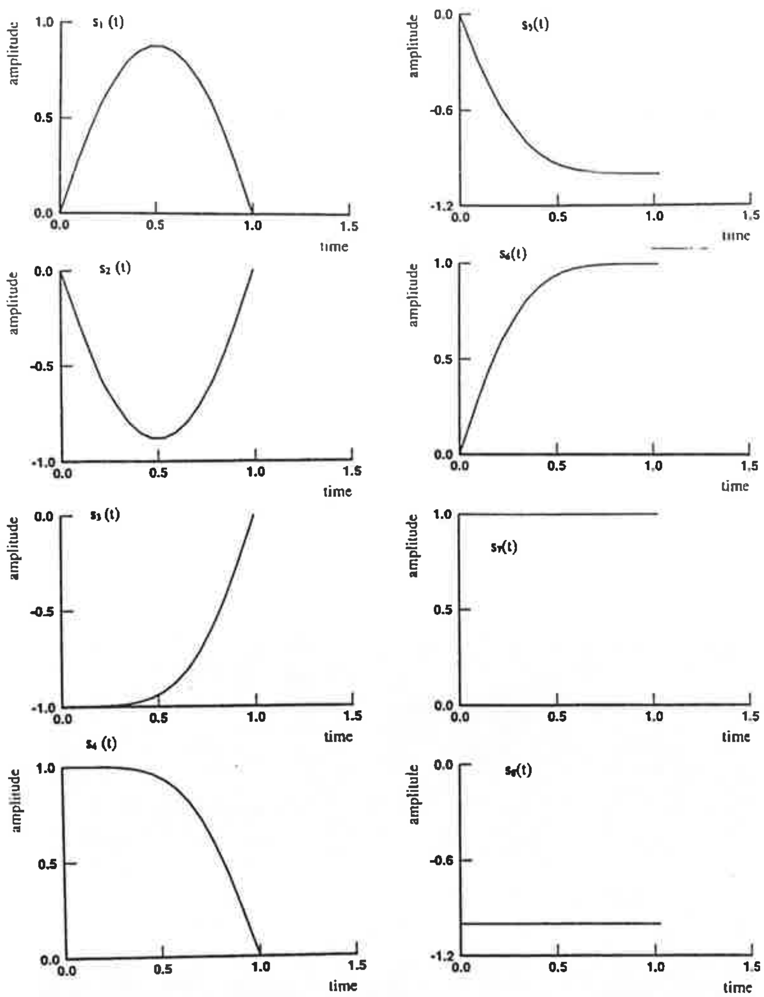

Figure 5. Baseband segments of Gaussian filter output

Table 1. Relationship between output signal and input data for Gaussian filter

order n	input data a_{n-1}, a_n, a_{n+1}	output signal s_i (t)
1	0 1 0	s_1 (t)
2	1 0 1	s_2 (t)
3	0 0 1	s_3 (t)
4	1 1 0	s_4 (t)
5	1 0 0	s_5 (t)
6	0 1 1	s_6 (t)
7	1 1 1	s_7 (t)
8	0 0 0	s_8 (t)

Table 2. Relationship between output signal and input data for IJF filter

order n	input data A_{n-1}, A_n	output signal y_i (t)
1	0 0	y_1 (t)
2	0 1	y_2 (t)
3	1 0	y_3 (t)
4	1 1	y_4 (t)

where: y_1 (t)= -1, y_2 (t)= $-\cos(\pi t/T_s)$
y_3 (t)=$\cos(\pi t/T_s)$, y_4 (t)=1, $0 \le t \le T_s$

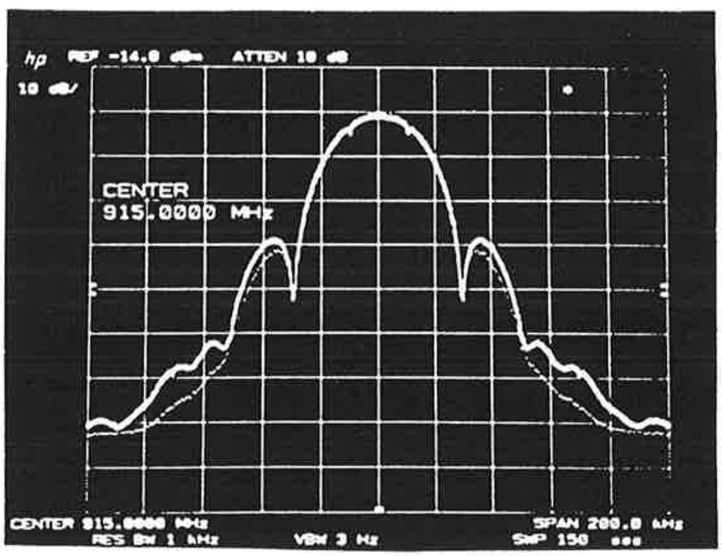

Figure 6. The spectrum of modulated signal in Fig.1
upper curve: using FQPSK-1 baseband filter
lower curve: using Gaussian filter with BT_b=0.5

The principle of comparison among three successive input bits used in Gaussian filter is based on the Feher's filter. In the Feher's filter, the key is ***bit-comparison,*** and ***the output signal of the Feher's filter depends on the correlation of the present binary input signal A_n and with the previous binary input signal A_{n-1}.*** In FQPSK-1 baseband filter, the comparison between the present bit A_n and previous bit A_{n-1} is carried out once during each bit duration T_s, and the output signal can be determined. In the Gaussian filter, the comparison is also carried out during each bit duration T_s, but among the three bits a_{n-1}, a_n, and a_{n+1}, the output signal is determined based on the net result of two two-bit comparison, between a_{n-1} & a_n, and a_n & a_{n+1}.

b) Control logic and encoder

Fig.5 shows four kinds of basic segments: s_1 (t),s_2 (t),s_3 (t) and s_4 (t), other segments can be obtained from them by means of control logic and encoder. For example, for the 16 point samples of one bit duration, s_5 (t) can be derived from s_3 (t) when the counter counts down. s_7 (t), a DC level, can be obtained from the first sampled value of s_4 (t) when the counter holds. A detailed circuit is shown in Fig.7. The control logic generates two signals, *A* and *B*, in response to the 3-bit input from the shift register. These signals control the encoder and counter. When the input state corresponds to n=1,2,3 or 4 in Table 1, the signals *A* and *B* are both at logic 0 level, and the encoder does not encode its input data, and the counter counts up. When n=5 or 6, *A* is a logic 1 level and *B* is still a logic 0 level. In this case, the encoder encodes the input data and the counter is forced to count down, as signal s_5 (t) or s_6 (t) is read out from s_3 (t) or s_4 (t) in reverse order. When n=7 or 8, *A* becomes a logic 0 and *B* is logic 1, the encoder encodes its input data and the counter holds, as signal s_7 (t) or s_8 (t) is read out from the first sampled value of s_4 (t) or s_3 (t) continuously.

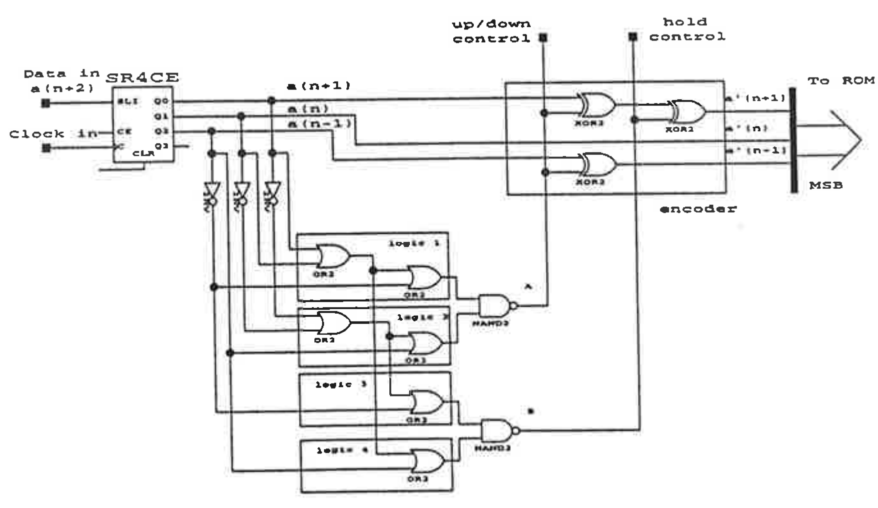

Figure 7. The control logic and encoder

Figure 8 shows the experimental eye diagrams at the outputs of Gaussian and FQPSK-1 baseband filters based on above principle. They are exactly the same as the mathematical curves in Figure 4. In our improved implementation of Gaussian filter only four state segments s_1 (t), s_2 (t), s_3 (t) and s_4 (t) are required to be stored in the ROM instead of eight state segments, so the ROM size is reduced by 50%.

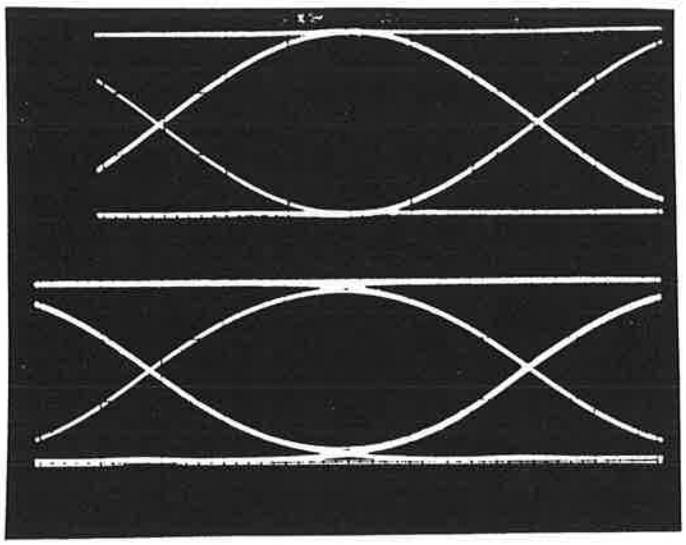

Figure 8. Experimental eye diagram
upper curve: after FQPSK-1 baseband filter
lower curve: after Gaussian filter

Conclusion

Based on the principle of the FQPSK-1 baseband filter, an improved implementation of Gaussian filter with reduced memory size ROM has been presented. It is noted that the symmetry of the signal segments can be utilized to further reduce the ROM size by 75% at the cost of more logic circuit complexity.

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