FPGA-Based MSK DS-SS Modulator for Digital Satellite Communications

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ABSTRACT

Minimum shift keying (MSK) modulation fits in satellite communications links due to its superior performance in providing low sidelobe spectral energy and reduced sidelobe regrowth. This paper investigates design, implementation and testing of MSK modulator on FPGA. Direct sequence spread spectrum (DS-SS) modulation is also considered because it provides low power spectral density and allows accurate ranging of the satellite. Direct digital synthesis (DDS) is employed to generate the modulated signal. A novel technique for digital implementation of type II MSK modulator is shown. The MSK modulator is designed and simulated using VHDL language and then implemented on Xilinx XtremeDSP Development Kit Pro (which contains Xilinx FPGA XC2VP30-4FF1152 and Analog Devices AD9772A digital to analog converters (DAC)). Evaluation of the implemented modulator is done by comparing the resultant MSK modulation spectrum and the modulated waveform to the theoretical ones, which showed good performance.

INTRODUCTION

In low earth orbit (LEO) satellite communication links it is required to employ modulation techniques to achieve transmission with minimum power (the high power amplifiers (HPA) onboard satellite and in ground station have to operate in the saturation mode) which requires using constant envelope signal to avoid spectral regrowth. It is also required to make efficient usage of spectrum (according to international telecommunication union (ITU) and consultative committee for space data systems (CCSDS) regulations and recommendations) and minimum bit error rate (BER) at the receiver. MSK modulation meets all these requirements. It is required also to measure the varying distance (range) between the satellite and the ground station and the radial velocity of the satellite (range rate) to facilitate the tracking of the satellite by the ground station antenna tracking system. Ranging can be implemented using DS-SS technique. Thus, MSK DS-SS modulator is chosen in this paper for LEO communication links.

The relevant characteristics of MSK modulation with DS-SS technique are first described. Then digital implementation of the MSK modulator is shown. Prototyping by FPGA is used due to its superior performance over analog implementation. Some benefits of the former over the latter are: parallel manipulation of functions, precision, stability, high integration, reconfigurability and availability of digital function libraries. Results and performance evaluation are finally presented.

MSK MODULATION

When considering MSK as a phase modulation, the phase of the carrier advances or retards, according to the data stream, linearly with time by 90° w.r.t. the carrier phase over the course of each symbol period T_s.

\[ x(t)_{\text{MSK}} = \cos \left( \omega_s t + \frac{\pi}{2} \frac{t}{T_s} + \phi_0 \right) \] (1)

where \( \phi_0 \) is the initial phase and the sign of the second term of the phase argument changes only at the keying instants (i.e. every T_s) according to the modulating data.

Since the phase will continue to advance or retard linearly with time over the course of each symbol period, the derivative of the phase, or the frequency, may have one of two values, where:

\[ \omega(t) = \frac{dx(t)}{dt} \] (2)
In this way MSK can also be considered as frequency modulation with two different frequencies. The effective frequency difference due to advance or retard of phase by $\pi/2$, w.r.t. the carrier phase, is\(^1\):

$$\Delta f^+ = \frac{\Delta \omega}{2\pi} = \frac{\Delta \varphi(t)}{2\pi} = \frac{\pi}{2\pi} = \frac{f_s}{4}$$

(3)

$$\Delta f^- = \frac{-f_s}{4}$$

(4)

$$\Delta f = \Delta f^+ - \Delta f^- = \frac{f_s}{2}$$

(5)

where $f_s$ is the symbol rate, $\Delta f^+$ and $\Delta f^-$ are the frequency differences between the two MSK symbols’ frequencies and the apparent carrier frequency $f_o$ of MSK modulated signal (located at the mid point between the two MSK symbols’ frequencies), and $\Delta f$ is the frequency difference between the MSK symbols’ frequencies.

During each symbol duration $T_s$, one of two frequencies $f_1$ or $f_2$ is generated and we can represent $f_1$ and $f_2$ as an integer multiple of $\Delta f^2$,

$$f_1 = \frac{n}{T_s} = n\Delta f$$

(6)

and

$$f_2 = \frac{n+1}{T_s} = \frac{(n+1)}{T_s}$$

(7)

where $n$ is an integer number equal to the number of half cycles of the lower frequency symbol $f_1$ during the MSK symbol period $T_s$.

In random data transmission, the resulting spectrum will be centered on an apparent carrier, i.e. the spectrum is symmetric around it, located at:

$$f_o = \frac{f_1 + f_2}{2} = \frac{(2n + 1)}{4T_s} = \frac{(2n + 1)}{2}$$

(8)

**MSK Spectral Occupancy**

The power spectral densities of MSK and OQPSK signals are given by\(^3\,4\,4\):

$$\text{PSD}_{\text{MSK}} = \frac{16A^2T_s}{\pi^2} \frac{\cos 2\pi T_s f}{1 - 16f^2T_s^2}$$

(9)

$$\text{PSD}_{\text{OQPSK}} = A^2T_s \left( \sin \frac{\pi T_s f}{s} \right)^2$$

(10)

where $f$ is the frequency offset from the apparent carrier $f_o$.

MSK exhibits no abrupt changes in the signal phase which lowers the signal power in the sidelobes of the spectrum compared to the spectrum of the rectangular-pulse QPSK and OQPSK, Fig.1. Although the phase is continuous in MSK, the frequency is not and this widens the main lobe of MSK spectrum\(^1\,5\).

![Figure 1: MSK and OQPSK Power Spectral Densities](image)

**Type II MSK Modulation and its Implementation**

Using Type I MSK Modulator

MSK can be generated by modulating the I and Q channels of a quadrature modulator, Fig.2, by sinusoidal weighting functions. These weighting functions $\cos(2\pi t/4T_s)$ and $\sin(2\pi t/4T_s)$ are of period $4T_s$, while each data bit occupies $2T_s$ period. The half cycles of these waveforms are analogous to the staggered square waves used in OQPSK.

There is a special type of MSK modulation, referred to as type II, which is obtained if the weighting functions on the quadrature symbol streams are always positive half cosines or positive half sines\(^5\). Its MSK signal can be represented in the form:

\[\text{MSK}_{\text{II}} = \cos(2\pi f_s t + \varphi(t))\]

where $f_s$ is the symbol rate and $\varphi(t)$ is the phase of the carrier. This type of modulation is used in many communication systems due to its simplicity and performance characteristics.
\[
s(t)_{\text{MSK/Type II}} = d_I \cos \left( \frac{2\pi}{4T_s} \right) \cos(\omega_o t) + d_Q \sin \left( \frac{2\pi}{4T_s} \right) \sin(\omega_o t) \tag{11}
\]

where \(d_I\) and \(d_Q\) are the in-phase and quadrature data streams (or are obtained from the even and odd numbered bits of a single serial input data stream), respectively.

\[d_I \cdot K(t-T_s) = D_I \quad \text{and} \quad d_Q \cdot K(t) = D_Q\]

Eqn (12) can be rewritten in the form:

\[
x(t)_{\text{MSK/Type II}} = \cos(\omega_o t) + \sin(\omega_o t)
\]

where the linearly time varying retarding or advancing phase depends on \(D_I\) and \(D_Q\) as,

\[
\theta(t) = \tan^{-1} \left( \frac{D_Q(t)}{D_I(t)} \right)
\]

Instead of multiplying the conversion functions \(K(t)\) and \(K(t-T_s)\) by the sinusoidal weighting functions they are now multiplied by the data stream, (13), in the data manipulation block shown in Fig.4. Thus, type I MSK modulator can be used as a building block for type II MSK modulator.
Type II MSK modulation has an important advantage over type I MSK; in that the polarities of the modulating data streams are not altered by the polarities of the weighting functions. This advantage is important in the demodulation process.

**DIRECT SEQUENCE SPREAD SPECTRUM MODULATION**

One method of spreading the spectrum of a data-modulated carrier is to first modulate a very wideband spreading codes SC_I and SC_Q using the data (Info_I and Info_Q) then the resulting stream modulates the carrier. This modulation spreads the data energy over a bandwidth much greater than the data bandwidth. The spreading code can be generated using linear feedback shift register (LFSR)\(^7,\)^\(^8\). The spreading signal is chosen to have properties that facilitate demodulation of the transmitted signal by the intended receiver, whereas it makes demodulation by an unintended receiver as difficult as possible. These same properties will also make it possible for the intended receiver to discriminate between the communication signal and jamming. If the bandwidth of the spreading signal is large relative to the data bandwidth, the spread spectrum transmission bandwidth is dominated by the spreading signal and is nearly independent of the data signal\(^7\).

Spreading the data spectrum by the spreading code is implemented as follows. The input data (i.e. Info_I and Info_Q) modulates pseudo random sequences (namely, the spreading codes SC_I and SC_Q of period \(T_c = 2T_s\)) constituting the signals \(d_I\) and \(d_Q\). This can be done if we replace \(d_I\) and \(d_Q\) in (12) by the result of multiplication of the input data and the spreading codes as follows:

\[
\begin{align*}
  s(t)_{\text{MSK}} &= d_I K(t - T_s) \cos \left( \frac{2\pi}{4T_s} \cos(\omega_s t) \right) \\
  &+ d_Q K(t) \sin \left( \frac{2\pi}{4T_s} \sin(\omega_s t) \right)
\end{align*}
\]

The periods of Info_I, Info_Q and SC_I, SC_Q are related by:

\[ T_{\text{Info}} = N_c \cdot T_c \]  \hspace{1cm} (15)

where \(T_{\text{Info}}\) is the information data period, \(T_c\) is the chip period and \(N_c\) is an integer.

**IMPLEMENTATION**

The MSK modulated signal is constructed by generating the phase \((\theta(t))\) where \(\theta(t)\) is generated according to (14) and (15). This linearly varying phase is used to generate the MSK modulated signal. The type I/II MSK modulator is constructed from three parts. The first part is the sinusoidal waveform LUT which implements phase to amplitude conversion, Fig.5 part I. The second part consists of a phase generation circuit consisting of two synchronized (i.e. start operation at the same time) phase accumulators and an adder. One of the phase accumulators is used to generate ascending carrier phase ramp \((\omega_{ot})\) and the other is used to generate ascending or descending weighting function phase ramp \((2\pi t/4T_s)\), i.e. does addition or subtraction of the weighting function phase to the carrier phase according to the control signal from digital data manipulation part, Fig.5 part III.

The sampling frequency \(f_s\) and the phase accumulator’s word length \(N\) define the phase increments \(WPI\) and \(CPI\) (in Fig.5) to generate the synthesized frequencies \(f_s\) and \(1/4T_s\) according to\(^9\):

\[ f_s = 2^N f_{\text{synthesized}} \]  \hspace{1cm} (16)

where PIR stands for either WPI or CPI with their corresponding synthesized frequencies.

In the third part, three functions are done to generate the control signal that is used in part II to control the addition or subtraction of the weighting function phase. These functions are; first, to modulate the spreading codes, SC_I and SC_Q, with the input data, Info_I and Info_Q, that implements DS-SS. The second function is determining the type of MSK signal, i.e. type I if the conversion functions are equal to unity and type II if they are as defined in Fig.3. The third function is to process the data in the quadrature channels (Xoring \(D_I\) and \(D_Q\)) to generate the signal that controls the addition or subtraction of the weighting function phase thus,

\[
= \text{Info}_I \cdot SC_I \cdot K(t - T_s) \left( \cos \left( \frac{2\pi}{4T_s} \cos(\omega_s t) \right) \right) + \text{Info}_Q \cdot SC_Q \cdot K(t) \left( \sin \left( \frac{2\pi}{4T_s} \sin(\omega_s t) \right) \right)
\]  \hspace{1cm} (14)
RESULTS AND DISCUSSION

The MSK DS-SS modulator was implemented using XtremeDSP Development Kit Pro which contains Xilinx FPGA XC2VP30-4FF1152 and two DACs. ISE 7.1 software was used for developing the VHDL project.

The spreading codes period $T_c$ is chosen to be 2μs (or equivalently the symbol frequency $f_s = 1$MHz). The design parameters are chosen as follows; $f_o = 5.75$ MHz, $n = 11$ thus, symbol frequencies are $f_1 = 5.5$ MHz and $f_2 = 6$MHz, (6), (7) and (8). The phase accumulator word length $N$ equals 32 and the sampling frequency $f_{sa}$ equals 50MHz.

The used DAC (Analog Devices, AD9772A) in the XtremeDSP Development Kit Pro has an input word width $L = 14$ bits which is fully used to allow using the full swing of the DAC’s analog output. This is done to improve the amplitude quantization noise of the generated signal. This value of $L$ is equal to the output word width from the LUT. The LUT is implemented with minimum resources using a Xilinx IP core that implements trigonometric functions. The conversion functions $K(t)$ and $K(t-T_s)$ are implemented as two clock signals (with period of 4μs) staggered by 1μs.

The two independent spreading codes, $SC_1$ and $SC_0$, are obtained from the output of two independent LFSRs with arbitrary feedback coefficients and fed to the $SC_1$ and $SC_0$ inputs of the type II MSK DS-SS modulator where the two streams are staggered by 1μs, i.e. half-chip period. In order to verify the MSK spectrum, Fig.1, the data should be random. The Xilinx IP core that implements LFSR has a maximum length of 168 and thus we use the LFSR length to be 168 to produce a very long random sequence. Due to the pseudorandomness of the spreading codes the input information (InfoI and InfoQ) are not needed to be random and are selected to be constant equal to logic ‘1’.

The main signals to be examined are the modulated MSK signal and the output of Xoring of $D_1$ and $D_0$ signals which controls the modulated signal’s symbol frequency, Fig.5. These two signals are driven to DAC1 and DAC2 on the XtremeDSP Development Kit Pro to display their outputs on a spectrum analyzer and a digital storage oscilloscope (DSO), respectively. The 10 MSBs representing the input phase to the LUT accumulator output are debugged using the Xilinx ChipScope Pro core, and are displayed later. The total bit file that contains the designs of type II MSK modulator and the debugging ChipScope Pro core is downloaded to the main FPGA on the kit.

To analyze the generated spectrum for the modulated signal (the analog output of DAC1 with rms value of 0.707V) the signal is fed to the input of the Rohde & Schwarz FS300 spectrum analyzer and snapshot for the MSK spectrum was taken through FS300-K1 remote control/PC software screen, Fig.6. The spectrum analyzer is adjusted such that the resolution bandwidth (RBW) is 10 KHz (to obtain low noise floor at the spectrum analyzer display) and the video bandwidth (VBW) equal to 100Hz (smoothes the displayed spectrum). Fig.6 shows that the main lobe bandwidth is equal to ≈1.5MHz and the difference between the peak power in the main lobe and the first sidelobe is equal to ≈23 dB, which agrees with the expected theoretical spectrum shown in Fig.1. The center frequency of the shown spectrum is equal to ≈5.75MHz.

The MSK signal (taken from DAC1) and the phase control signal (i.e. $D_1 \oplus D_0$ taken from DAC2) are
displayed on DSO (Agilent model DSO06034A), and snapshots are taken through the Quick Print capability to investigate them, Fig.7 and Fig.8. Fig.7 shows snapshot taken for the higher frequency symbol $f_2$ with 6 cycles $(n+1)/2 = 6$ of frequency $f_2 \approx 6\text{MHz}$ within one symbol period of $1\mu\text{s}$, (7), together with the output of the XOR operation (the signal that controls the addition or subtraction of WPI, Fig.5) which is constant during one symbol period and equal to +1V corresponding to logic ‘1’. Fig.8 shows the lower frequency symbol $f_1$ with 5.5 cycles $(n/2 = 5.5)$ of frequency $f_1 \approx 5.5\text{MHz}$, (7), at the same symbol period together with the output of the XOR operation which is equal to -1V corresponding to logic ‘0’, (8).

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