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Analysis and implementation of Minimum Shift Keying (MSK) modulation on FPGA platform

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***Abstract*— Most of the communication techniques for telemetry applications are analog modulation techniques like PCM/FM in earlier years. Increased data rates and increased number of platforms requires more bandwidth efficient modulation techniques to avoid losses, interferences in information transfer. MSK has been introduced as part of continuous phase modulation technique and more bandwidth efficient technique as well. Telemetry is an automated communications process by which measurements and other data are collected at remote or inaccessible points and are subsequently transmitted to receiving equipment for monitoring. Motivation and an objective behind study of MSK scheme is described with an overview of digital modulation schemes. This paper is an exclusive analysis and implementation of MSK modulation technique on FPGA platform. Simulation results of MSK modulation technique are verified with implementation of same on Xilinx virtex-4 FPGA board.**

Keywords*— *Telemetry, MSK modulation, FPGA

Introduction

These days wireless application requires bandwidth efficient digital modulation techniques for communication. The basic digital modulation techniques are amplitude shift keying (ASK), frequency shift keying (FSK) and phase shift keying (PSK). PSK modulation techniques are power and bandwidth efficient for narrowband and wideband applications. The most frequent PSK schemes are binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), offset quadrature phase shift keying (OQPSK), minimum shift keying (MSK), Gaussian minimum shift keying (GMSK), multi-h CPM (continuous phase modulation) etc., The MSK, GMSK and multi-h CPM are varieties of continuous phase modulation schemes (CPM), which are memory modulation schemes..

I. Introduction of telemetry

Telemetry is the process by which characteristics of the objects are measured remotely, and the results transmitted through link to a distant station where they are displayed, recorded, and analyzed. The telemetry process involves measuring different parameters like Video, audio, pressure, speed, and temperature etc. In the modern era, these measurements are not enough and there is a requirement of putting together audio, video and analog sensor data along with the earlier mentioned parameters and transmitted using digital modulation techniques.

Once received, the data stream is separated into the original measurements. In present days Most of the telemetry schemes currently functioning are analog schemes like Pulse Code modulation (PCM) preferred for telemetry applications as against PAM and other formats comprising of inputs from analog video and audio, analog vibration sensors and digital PCM parameters from various other inputs. These are multiplexed and analog FM modulation is carried out prior to transmission on two independent communication links, one specifically for video and the other for various data inputs [1].

However, bandwidth constraints and other limitations have been imposed with regard to CCSDS and IRIG 106 standard, and increased demand of communication resources by the increased data rates and number of aircrafts using the channels simultaneously have necessitated consideration of a digital scheme for the these applications [2].

II. Motivation

a) Restrictions on the bandwidth in the available frequency spectrum for telemetry applications.

b) Available analog modulation schemes like CPM/FM are less bandwidth efficient, which restricts the number of flights to operate simultaneously.

c) Cross channel interference is a dominant in the analog modulation scheme. The recommended digital modulation scheme should minimize the co-channel and cross-channel Interferences.

d) The digital modulations should be designed, which are more bandwidth and power efficient and low bit error rate (BER) according to the IRIG and CCSDS standards of telemetry applications.

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III. OBJECTIVE

MSK is a continuous phase modulation scheme. The modulated carrier does not contain phase discontinuities and frequency changes at carrier zero crossings. It is typical for MSK that the difference between the frequency of logical 0's (f0) and 1's (f1) is equal to half the data rate. MSK modulation makes the phase change linear and limited to ± (π/2) over the symbol interval. Due to the linear phase change effect, better spectral efficiency is achieved. That means that MSK is ordinary FSK with the modulation index set to 0.5,

The MSK modulator can be realized by using a direct MSK approach or the I-Q based concept. In both types of modulators the straightforward means of reducing the Out Of Band (OOB) energy is pre-modulation filtering or pulse shaping. Direct MSK modulation can be realized by direct injection of NRZ data into the frequency modulator with the modulation index set to 0.5.

IV. AN OVERVIEW OF DIGITAL MODULATION SCHEMES.

Some of the most widely used digital modulation techniques are shown in the following Table 1.1 [3] [7].

Table I Digital modulation techniques.

Linear modulation Techniques	**Constant envelop modulation techniques**	**Combined linear and constant envelope modulation techniques**	**Spread spectrum modulation techniques**
BPSK (Binary phase shift keying)	BFSK (Binary frequency shift keying)	MPSK (M-ary binary phase shift keying)	DS-SS (Direct Sequence spread spectrum)
DPSK (Differential phase shift keying)	MSK (Minimum shift keying)	QAM(M-ary Quadrature amplitude modulation)	FH-SS (Frequency hopping spread spectrum)
QPSK (Quadrature phase shift keying)	GMSK (Gaussian minimum shift keying)	MFSK(M-ary frequency shift keying)	

In BPSK the bits are modulated with two different phase carrier signals, which give narrow main-lobe and high power levels in side lobes. The 180° phase shift at each and every bit leads to destroy the constant envelope property and it won't allow using efficient high power amplifiers. The combination of two bits is used to form one symbol in case of QPSK, which leads to band-width efficiency of BPSK by factor of 2.

In QPSK two BPSK schemes are used with orthogonal carrier frequencies, this makes not to interfere the two signals with each other. Even band width efficiency may increase; the bit error probability is same as BPSK.

In QPSK the 180° phase shift is not fixed in all cases, the phase shift may be 90° or 180° depending on the transmit bits. But the zero crossing of symbols in constellation diagram still not avoided completely which destroys the property of constant envelope property. To avoid the zero crossing of symbols in constellation one of the channel in QPSK is staggered, which makes to avoid the zero crossings completely, because only one bit changes at a time, this leads to 90° phase shift always [4]. But the constant envelope property is not maintained because of sudden change of 90° phase shift, with the same bandwidth and power efficiency as the QPSK. The pulses used to shape the bits in the case of BPSK, QPSK and OQPSK are rectangular pulses of one bit duration, this leads to sudden phase shifts at the end of the each bit. By prior pulse shaping of the input bits leads to smooth phase transition from one bit to another bit with no phase offset at the end of the bits and this can maintain the constant envelope property of the signal.

These types of modulations are called continuous phase modulation schemes (CPM). The constant envelope property allows using high power more efficient non-linear amplifiers which are suitable for high power applications.

V. MSK MATHEMATICAL ANALYSIS

The phase changes at symbol transitions in QPSK can be further can be reduced by OQPSK which is at most ± π/2 .This reduces the out-of-band interference due to band limiting and amplifier non-linearity. This suggests that further improvement is possible if phase transitions are further smoothed or even become completely continuous between two symbols or bits. Minimum shift keying (MSK) is a form of continuous phase modulation scheme, which can be derived from OQPSK by shaping the pulses with half sinusoidal waveforms, or can be derived as a special case of continuous phase frequency shift keying (CPFSK) [8].

When considering MSK as a phase modulation, the phase of the carrier advances or retards, according to the data stream, linearly with time, by π/2 w.r.t the carrier phase over the course of each symbol period *Ts*. MSK signal can be represented as [9].

$$S_{MSK} = \cos(2\pi f_c t \pm \frac{\pi}{2T_s} t + \emptyset_0) \qquad (1)$$

Where $\emptyset_0$ 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 [6].

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$$w(t) = \frac{\varphi(t)}{dt} \tag{2}$$

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 π/2, w.r.t. the carrier phase.

$$\Delta f+ = \frac{\Delta w}{2\pi} = \frac{\Delta w(t)}{\Delta(t)}\frac{\varphi_1(t)}{2\pi} = \frac{\frac{\pi}{2}}{T_s}\frac{1}{2\pi} = \frac{f_s}{4} \tag{3}$$

Similarly,

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

The total frequency deviation is

$$\Delta f = \Delta f + - \Delta f - = \frac{f_s}{2} \tag{5}$$

where f_s is the symbol-rate, Δ+ and Δ- are the frequency differences between the two MSK symbols' frequencies and the apparent carrier frequency f_0 of MSK modulated signal (located at the midpoint between the two MSK symbols' frequencies), and Δf is frequency difference between the MSK symbols' frequencies. During each symbol duration Ts, one of two frequencies f_1 or f_2 is generated and can be represented as f_1 and f_2 as an integer multiple of Δf [5].

$$f1 = \frac{n}{2T_s} = n\Delta f \tag{6}$$

And

$$f2 = \frac{n+1}{2T_s} = (n+1)\Delta f \tag{7}$$

where n is an integer number equal to the number of half cycles of the lower frequency symbol $f1$ during the MSK symbol period T_s. With the integer multiples, the signal is guaranteed to have continuous phase at the bit transition. The phase-continuous signals in general have better spectral properties than signals that are not phase-continuous; it is preferred to transmit signals that have this property. In random data transmission, the resulting spectrum will be centered on an apparent carrier, i.e. the spectrum is symmetric around it, located at

$$f0 = \frac{f1+f2}{2} = \frac{2n+1}{4T_s} = \frac{2n+1}{2}\Delta f \tag{8}$$

where $f0$ is the center frequency of operation.

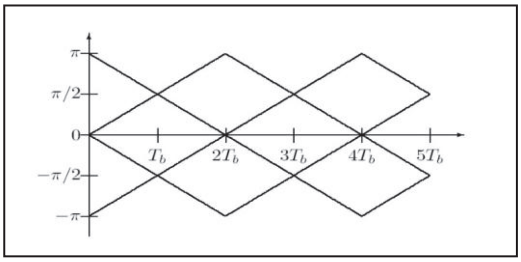

Fig 1. Phase trellis of MSK

The phase variation over time is phase trellis here, the modulation index for MSK is h =½ and $\theta(0) = 0$ or $\theta(0) = \pi$. At every multiple of the bit time the phase can only take on one of two values, the values being 0 and π for $t=2k\ Tb$, and ± π/2 for $t = (2k+1)\ Tb$ and is CPFSK with deviation ratio for h = ½ is the smallest possible difference if the signals of the two frequencies are to be orthogonal over one bit interval. The phase variation in MSK is linearly varying as shown in the Fig. 1.

VI. MSK MODULATION

MSK can be viewed as OQPSK modulation scheme, in which the staggered $I(t)$ and $Q(t)$ channels are directly modulated on two orthogonal carrier signal after weighting with the half sine and cosine waves with period of 4T, i.e. $A\cos(\pi/2T)$ or $A\sin(\pi/2T)$ respectively. Then modulate with one of the orthogonal carrier signal $\cos(2\pi fct)$ or $\sin(2\pi fct)$. The MSK signal can be viewed as follows and the block diagram is shown in the Fig 2.

$$s(t) = AI(t)\cos\left(\frac{\pi t}{2T}\right)\cos(2\pi f_c t) + AQ(t)\sin\left(\frac{\pi t}{2T}\right)\sin(2\pi f_c t) \tag{9}$$

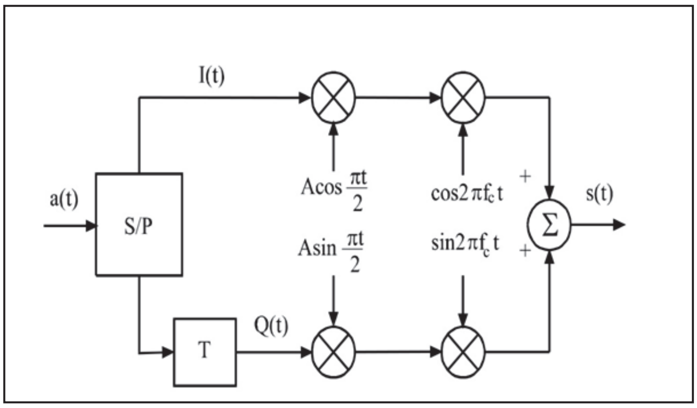

Fig 2. MSK modulator

where T is the bit period of the data. From the final output of

MSK signal the following properties can be observe.

- Envelope is constant
- Phase is continuous between the bit transitions
- This is a form of FSK signal, which involves two frequencies.

MSK signal has the symbol duration of T instead of 2T which is same for the OQPSK despite the symbol duration is 2T in QPSK. The above equation can be written in different form as In the kth bit period of T seconds, *I(t)* and *Q(t)* is either 1 or -1, and denote them as I_k and Q_k , thus

$$s(t) = \pm A\cos\left(\frac{\pi t}{2T}\right)\cos(2\pi f_c t) \pm A\sin\left(\frac{\pi t}{2T}\right)\sin(2\pi f_c t) \quad (10)$$

$$s(t) = \pm A\cos(2_c t) + \frac{d_k \pi}{2T}t \quad (11)$$

$$s(t) = \pm A\cos(2_c t) + \frac{d_k \pi}{2T}t \quad + \varphi_k \quad (12)$$

$$s(t) = A\cos\left(2\pi(f_c + \frac{d_k}{2T}\right)t + \varphi_k),\ kT \le t \le (k+1)t \quad (13)$$

where d_k = 1 when I_k and Q_k have opposite signs (i.e., successive bits in the serial data stream are different), and d_k = -1 when I_k and Q_k have same signs (i.e., successive bits in the serial data stream are same) or equivalently

$$d_k = -I_k Q_k \quad (14)$$

φ_k = 0 or π are corresponding to $I_k = 1$ or -1 or equivalently

$$\varphi_k = \frac{\pi}{2}(1 - I_k) \quad (15)$$

Both $d_k$and φ_k are constant in a bit period of T seconds since I_k and Q_k are constant in T. From the above equations it is clear that MSK signal is a special FSK signal with two frequencies. $f+ = f_c + \frac{1}{4T}$ And $f- = f_c - \frac{1}{4T}$, where $f+$ is called space frequency, and *f* is mark frequency, and f_c is carrier frequency. The frequency separation is $\Delta f = \frac{1}{2T}$ .This is the minimum separation for two FSK signals to be orthogonal, hence the name minimum shift keying.

Ordinary coherent FSK signal could have continuous phase or discontinuous phase at bit transitions. MSK carrier phase is always continuous at bit transitions. The excess phase of the MSK signal, referenced to the carrier phase is given by,

$$\theta(t) = \frac{d_k \pi}{2T}t + \varphi_0 \quad (16)$$

$$\theta(t) = \pm\frac{\pi}{2T}t + \varphi_0 \quad (17)$$

Where φ_k is constant in the interval [*kT, (k +1)T*] and $\theta(t)$ is linear and continuous always in the interval [*kT, (k+1)T*].

The above equations show that the excess phase $\theta(t)$ is always continuous between the bit transitions. The phase of the carrier is $2\pi f_c t$ which is also continuous at any time. Therefore the total phase, $\pi f_c t + \theta(t)$, is always continuous at any time. In other words, for the MSK signal phase to be continuous, no specific relation between f_c and 1/T is required. However f_c should be chosen as a multiple of 1/4T, but it is for orthogonality of its I-channel and Q-channel signal components, not for continuous phase purpose. If f_c is a multiple of 1/4T (i.e., f_c =m/4T) for a positive integer m, then $2\pi f_c$ kT = mkπ_2, which is a multiple of π/2. Thus the total phase at bit transitions is also a multiple of π/2. If f_c is not a multiple of 1/4T, then the total phase at bit transitions is usually not a multiple of π/2. Consequently, the total phase at bit transitions is a multiple of π/2. The excess phase (t) increases or decreases linearly with time during each bit period of T seconds. If d_k = 1 in the bit period, the carrier phase is increased by π/2 by the end of the bit period. This corresponds to an FSK signal at the higher frequency *f*+. If d_k= 1 in the bit period, the carrier phase is decreased by π/2 by the end of the bit period. This corresponds to an FSK signal at the lower frequency *f*.

VII. SIMULATION RESULTS

a) Multiplexer implementation of MSK modulation in MATLAB:

MSK is forms of CPFSK, in which two frequencies are involved, which are called f+ and f- also known as space and mark frequencies respectively. And the phase is increasing or decreasing in the bit period according to the respective bits. From the above information it can be implement the MSK more efficiently and effectively based on the multiplexer logic. In which the possible signals are generated and stored in look up table (LUT), depending on the present bit and previous bit information the appropriate signal is selected and the selected signal is concatenated at the output. Before concatenate the signal is inverted accordingly to maintain continuous phase between bit transitions.

The four possible signals are Fmaxcos, Fmincos, Fmaxsin and Fminsin, where Fmax is the mark frequency and the Fmin is the space frequency generated as the sine and cosine pattern. The Fmax is the maximum frequency, which is more than the operating frequency f_c by 1/4T and the Fmin is the minimum frequency, which is less than the operating frequency f_c by 1/4T i.e.

$$Fmax = f_c + \frac{1}{4T} \tag{18}$$

$$Fmin = f_c - \frac{1}{4T} \tag{19}$$

These two frequencies give ± π/2 phase shift in one bit period. The block diagram of the multiplexer based MSK is as shown in Fig 3.

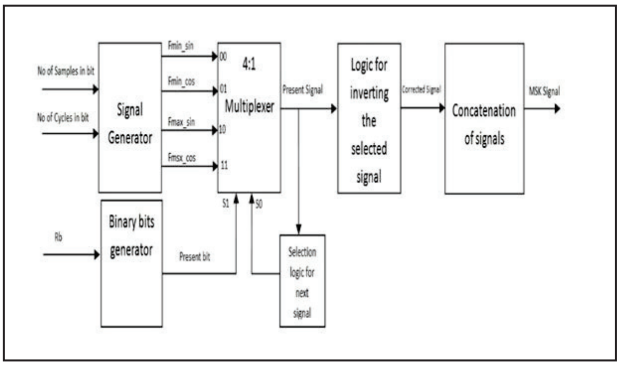

Fig 3. Multiplexer based MSK implementation.

All these generated waveforms are used to concatenate with continuous phase in between the two bits. In the pre-generated time waveforms the signal is achieved π/2 phase shift at the end of the bit interval. This gives the ¼ of the extra cycle for maximum frequency and reduces the 1/4 cycle. This leads to attain Fmax and Fmin frequency in particular bit as shown in Fig 4.

The timing waveform of MSK is as shown in the Fig 5. From the figure one can observe the frequency change of the signal which is a form of the frequency shift keying having the continuous phase.

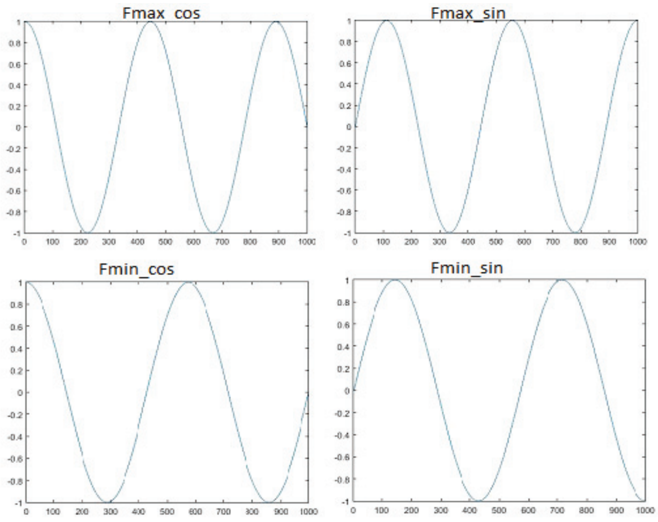

Fig 4. MSK signals stored in LUT

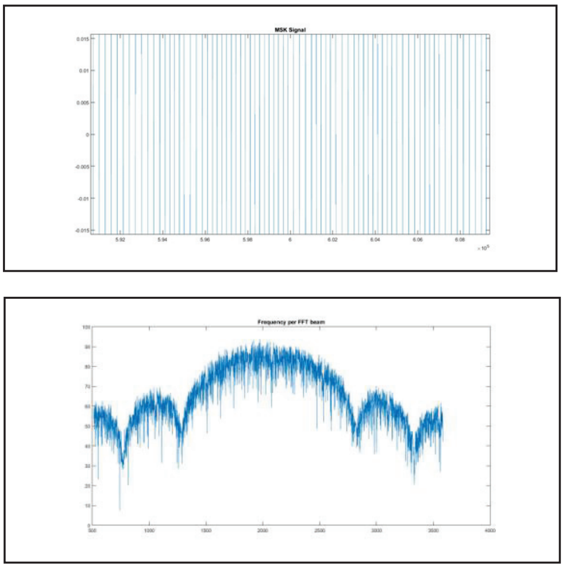

Fig 5. MSK time waveform and frequency spectrum

Further this work is implemented on Xilinx Virtex - 4 FPGA. Clock rate of 105MHz achieved data rate of 52.5 Mbps. Depending upon number of samples per one sine cycle, 1Mbps to 4Mbps bitrate can be achieved.

b)MSK modulation implementation on FPGA:

The number of samples per bit and number of cycles in bit are given as input to signal generator. 4-LUT's has been selected for implementation of 4:1 Mux. An Algorithm has been developed for inverting the selected signal coming from the LUT as per present and previous bit. The selected signal is passed through DAC is the modulated MSK signal. The GUI is also developed for user which will give the information on waveform parameters e.g. bit rate, FPGA clock frequency.

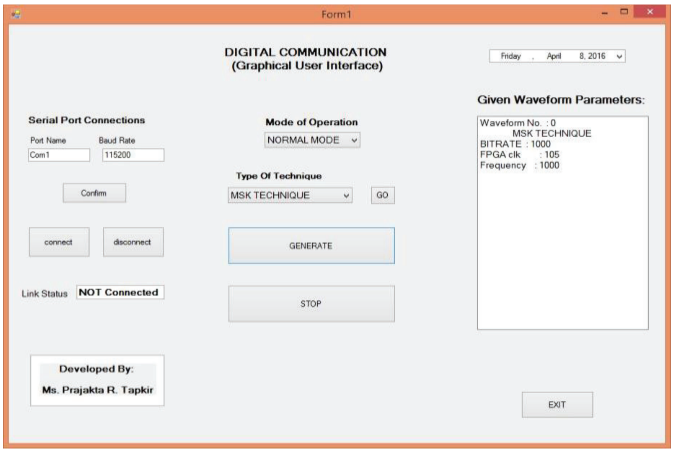

Fig 6. GUI for user information

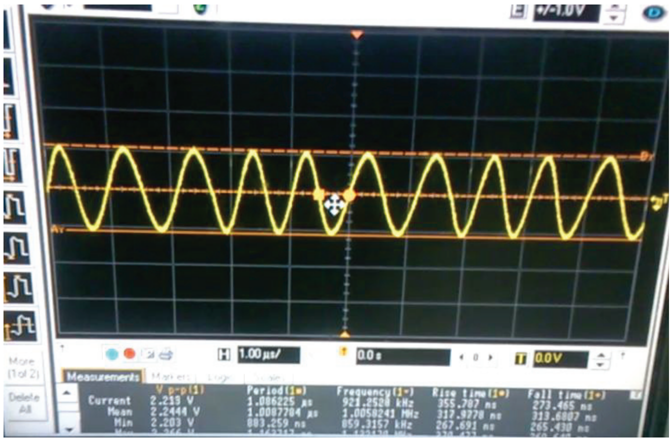

Fig 5. MSK modulated signal

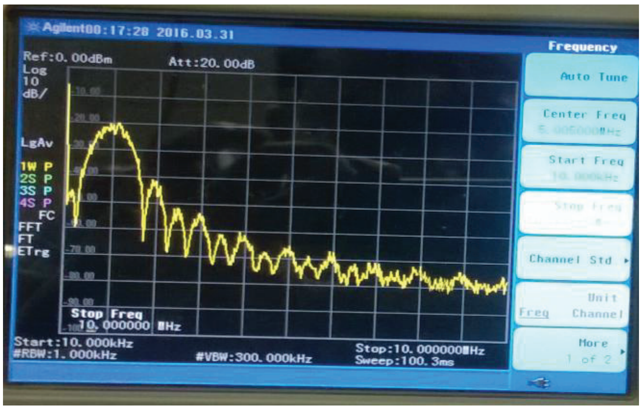

Fig 6. MSK spectrum.

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