Dynamically tuneable pre-modulation filter for an airborne PCM/FM telemetry system

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Abstract
In the conventional airborne telemetry system, the pre-modulation filter with a multipole active Bessel filter is preferred to use in Pulse Code Modulator (PCM)/FM transmission. In the existing system, it is not possible to change the cut-off frequency for different data rates dynamically as required in the launch scenario of a long-range aerospace vehicle. In general, aerospace vehicle has multiple propellant stages to travel a desired trajectory path. Each stage gets separated from the vehicle at different instances. Each stage measurement plan is defined and correspondingly the PCM format is generated with an optimum data rate. Hence, the telemetry system is required to transmit variable data rates at various instances of a long-range aerospace vehicle from launch point to end point of a vehicle. This can be addressed by designing a dynamically tuneable pre-modulation (DTPM) filter. Here, a suitable DTPM filter scheme is proposed to mitigate variable data rate transmission in the telemetry system. The scheme is analysed as per IRIG-106 standard and simulated using MATLAB. The same has been modelled using VHDL and implemented targeting 28 nm technology Xilinx Zynq FPGA device.

1 | INTRODUCTION
An airborne telemetry system is being used during the development phase of an aerospace vehicle. In the trajectory path of a vehicle, the telemetry system transmits real-time vehicle information into free space and the ground receiving station receives [1] it. This information is most essential for the post-flight analysis which in turn is used to evaluate the performance of an aerospace vehicle. The telemetry system captures various parameters like vibration, temperature, strain, battery voltages, navigation data and all transactions of standard bus [2] data. It consists of Sensors, Telemetry Encoder, FM transmitter and Antenna system as shown in Figure 1. The sensors are used to capture physical information of systems or sub-systems of an aerospace vehicle. The sensors physical measurement values are in the order of milli volts. Hence, it needs a Signal Conditioning Circuit (SCC) to provide impedance matching to the sensors, to band limit the sensor signals and to normalize the measurements. Since the SCC output is analogue signal, it is given to the analogue and then to the digital converter of the Pulse Code Modulator (PCM) encoder. The PCM encoder is capable of handling analogue and digital signals and multiplexes data. The PCM encoder multiplexes all the SCC signals along with MIL STD 1553 [2] data. The multiplexed data is converted into a serial data and then coded as a NRZ-L or Bi-phase data [1] in the PCM encoder. The serial data is further applied to the pre-modulation filter (PMF) as recommended by IRIG-106 [3]. This continuous serial data passes through a lowpass Bessel filter [1] called as a PMF to suppress higher order harmonics and thus band limit the signal. This band limited signal is applied to FM transmitter which modulates signal to S-band frequency and then it is transmitted to the ground station through antenna system. This technique is called as PCM/FM transmission [1]. In the launch scenario, the telemetry system has to transmit data from the launch point to the end point of a vehicle. The system has to meet the link margin [1,3,4] of a long-range aerospace vehicle with respect to the ground receiving stations. As the data rate increases, the required bandwidth also increases, resulting in a decrease in signal to noise ratio (SNR) for a defined bit error rate.
1.1 Conventional architecture of a PMF

In the conventional airborne telemetry system shown in Figure 2, PMF is used as an analogue filter with fixed cut-off frequency. This filter is used to filter the harmonics of the serial data for a predefined data rate. In general, lowpass Bessel filter is optimized for maximally flat time delay (constant group delay) which indicates that it has linear phase characteristics and excellent transient response to a pulse input [5]. This comes at the expense of flatness in the passband and rate of roll off. In general, these filters are designed using Sallen-Key and MFB configurations [5], and it needs an operational amplifier, resistors and capacitors. The IRIG-106 also recommends multiple pole (min pole 6) Bessel filter [1] as a PMF in PCM/FM transmission. In the existing system, the cut-off frequency can be changed by adjusting resistors and capacitors of an active filter [6] in the telemetry hardware. The changes occur due to change in measurement plan or update rate of measurement of a vehicle. This in turn changes the data rate of the telemetry output. Hence, the cut-off frequency of PMF must be changed. These changes are set before integrating telemetry system into a vehicle. However, this architecture will not allow to change cut-off frequency for different data rates dynamically in the launch scenario of a vehicle.

1.2 Necessity of a variable data rate transmission

In general, long-range aerospace vehicle has multiple propellant stages to travel a desired trajectory path [4]. Each stage gets separated from vehicle at different instances. Each stage telemetry measurement plan is defined and correspondingly PCM format is generated with an optimum data rate [1]. A typical scenario of a three-stage aerospace vehicle trajectory with stage separations is shown in Figure 3. As number of stages increases, the measurement quantity of a telemetry system increases and thus data rate increases. At the initial phase of a vehicle, data transmission rate is more because of large measurement plan. Once the stage gets separated, the measurement parameters cutdown from the telemetry system. Hence, the data rate of a telemetry system decreases as propellant stages get separated from vehicle. Each stage avionics data bus [7] gets disconnected and the corresponding data is cut down from the telemetry measurement.

In the terminal phase of a vehicle, the update rate of measurement parameter in turn needs to be modified in the telemetry system. The requirement of increased update rate demands high data rate of transmission. Hence, the telemetry system is required to transmit variable data rates at various instances of a long-range aerospace vehicle from launch point to end point of a vehicle. These instances are well defined in the measurement plan to meet the long-range vehicle coverage for a defined RF link margin.

In the literature, it is noted that various digital filters [8–16] are designed with variable cut-off frequency. These filters are tuneable [9,10,17] with variable coefficient methodology or fixed coefficient with decimation [9]. These are designed with memory-based [10–12] or distributed architecture [9] and implemented on FPGA. The applications of tuneable filters and spectrum characterization have been discussed widely in [9]. The tuneable filters are primarily used in areas where the modulating signal needs to be band limited dynamically and finds its applications in speech/audio processing, bio-medical signal processing, range detection systems, acoustics, adaptive and tracking systems, spectrum characterization, speech synthesizers and so forth. In case of body monitoring systems, data rates may change when the person is idle or doing some physical activity where the heart rate may be a trigger to collect more data and accordingly modify the cut-off frequency. It also finds use in manufacturing industries where one may need more
information (more data) during a failure or during a particular period of the manufacturing process. The available tuneable filters in the literature are used to filter unwanted signal or harmonics with complex schemes.

In this paper, we present the architecture proposed to design a dynamically tuneable pre-modulation (DTPM) Bessel filter to achieve variable data rate transmission required in the launch scenario of the long-range aerospace vehicle with less complexity.

2 | PROPOSED ARCHITECTURE OF A DTPM FILTER

To meet the variable data rates transmission in real-time condition of a vehicle, a scheme is proposed as shown in Figure 4 to employ in the telemetry system. It consists of a programmable logic (FPGA), digital to analogue converter (DAC) and fixed cut-off active filter with maximum data rate. The FPGA generates different data rates of serial data for a predefined format of telemetry measurement plan. Here, variable cut-off frequency filter to be implemented on FPGA. It generates a digitally filtered serial data to be applied to DAC whose output is further passed to a predefined cut-off frequency filter. The DAC generates analogue signal. This analogue signal consists of switching harmonics that are filtered with a fixed cut-off frequency filter which suppress the switching harmonics of a signal. The variable cut-off frequency of a filter is dynamically tuned with the help of FPGA-controlled software. The magnitude response of overall DTPM filter is achieved by realizing the necessary logic circuit in FPGA for different data rates.

3 | MODELLING OF THE PROPOSED DTPM FILTER

The Bessel filter coefficients which are required in the proposed scheme are calculated using the rational transfer function [18] for different orders greater than six. These coefficients are convolved with step inputs. The step response output of a Bessel filter is normalized and stored. The stored data for raising and falling edges information is taken into consideration and applied on the input data. The input signal is digital in nature in the case of PCM/FM technique. It has raising and falling edges and also contains sequence of ‘1’ or ‘0’ s. Here, each bit duration is defined based on data rate of telemetry format. For example, the bit duration of 1 Mbps data rate of NRZ-L is 1 $\mu$s. The bit duration is segmented into the defined number of samples, and it is a pre-selectable number. Each sample of a segment is replaced with a stored information of a Bessel filter response. The algorithm for a DTPM filter is depicted below.

**Algorithm of a proposed DTPM filter**

```
Process DTPM (PresentBit, PreviousBit, SampleClk)
Begin.
    If (PresentBit = 1 and PreviousBit = 0)
        Samples = Replace(BitSamples, StepRaising)
    else if (PresentBit = 0 and PreviousBit = 1)
        Samples = Replace(BitSamples, StepFalling)
    else.
        Samples = Replace(BitSamples, LastSample)
    end if;
    Output(SampleClk, Samples)
End Process;
```

In this algorithm, the Bessel filter order is critically selected based on sampling frequency of input signal. In this design, tenth-order filter is selected because that the input signal is sampled 10 times for each bit of information. It is observed that DTPM filter is sensitive to sampling frequency rather than input cut-off frequency and also noted that a perfect relation between order and sampling rate.

3.1 | MATLAB simulation results and analysis

The DTPM filter is modelled using the and Bessel filter responses are studied for various orders as shown in Figure 5. As a case study, the tenth-order filter is selected. The Bessel filter response of a raising and falling edge coefficients are stored in a memory. The raising and falling edges of serial data are detected and replaced with the stored Bessel coefficients.

While simulating for the filter response, the input square wave of 5 MHz is generated and applied to the DTPM filter. The response of DTPM filter is shown in Figure 6. It can be observed that the sudden raising and falling edges on the input signal are smoothly replaced with Bessel response, thereby removing the high-frequency content present in the input signal. Hence, the input signal bandwidth will be reduced effectively.

The same observation can be reconfirmed from the plots of fast Fourier transform (FFT) of the input and output signals shown in Figure 7. It can be observed from the plot that harmonics present in the input which are expected in a square wave are reduced significantly. The first harmonic present in the input signal is suppressed to 9 dB from 32 dB. The rest of the harmonics of input signal are reduced significantly which can be concluded from the decrease in effective noise floor and therefore yielding better signal quality.
3.2 Analysis of conventional and proposed DTPM filter

A square wave input of 5 MHz is applied to the conventional Bessel filter. This filter order is chosen as 10, and its sampling frequency is set to 50 MHz. The same conditions are applied to the proposed DTPM filter. The output power spectral density (PSD) of both filters is plotted in Figure 8. It may be concluded from the observations that the DTPM filter response is better than the conventional Bessel PMF. The performance of the DTPM filter is significantly better at harmonics of the input signal compared to other frequencies. The filter performance even though degrades at frequencies greater than 45 MHz, the signal level is lower than 90 dB and these frequencies contribution to the signal can be ignored as they are weak.

The observations of PSD of both the filters are highlighted in Table 1. It may be noted that harmonics of the input signal are significantly reduced by the DTPM filter compared to Bessel PMF.

In Figure 9, noise analysis is performed by inducing additive white Gaussian noise (AWGN) in the signal and varying its SNR. Here, the peak of the second harmonic of input signal is considered as an effective noise floor [15] which is unwanted.
in the output. The effective noise floor of the input signal, Bessel PMF and DTPM, the filter outputs are compared with PSD plots of each of these signals. The induced noisy signal SNR is varied from 0 to 20 dB and effective noise floor of each of these filters are compared in Figure 9. Further increase in SNR of input signal beyond 20 dB does not change the filter outputs significantly.

These results are compared with the pure signal (without inducing any noise – SNR inf) and presented in Table 2. It is observed that the noise performance of DTPM filter is better compared to the Bessel PMF by around 12 dB at SNR 0 dB. It is also noted that the high-frequency components are suppressed significantly in the DTPM filter.

4 | HARDWARE IMPLEMENTATION AND RESULTS

The specifications of DTPM required for its implementation in hardware are derived as per the requirements of a long-range aerospace vehicle and presented in Table 3. The implementation of the proposed DTPM filter requires various
components. In that, the primary active components presented in Table 4. The implementation of a DTPM filter mainly requires FPGA, a high-speed DAC and a programmable gain amplifier with fixed cut-off frequency active filter. The block diagram of DTPM filter targeted to implement using FPGA is shown in Figure 10. Here, DTPM algorithm is implemented using VHDL model and ported on FPGA.

The step response of a Bessel filter coefficients is stored in an FPGA. The digitally programmable phased locked loop (DPLL) is used to generate clock for sampling PCM serial data. In ZYNQ FPGA, programmable logic related PLL called as IOPLL is used for generating sampling clock. The IOPLL output clock is programmed by the ARM controller of a ZYNQ FPGA [19] called as the Processing System. The PCM serial data rate is known to the ARM controller for a defined PCM format.

The PCM sampling format information for various instances and data rate for each sampling format are stored in application memory of an ARM controller. The clock generator module generates twice the data rate of clock from PLL clock. This clock is used as the bit detector module which detects raising and falling edges of the serial data. The sample generator module generates samples from previous and present bit information. It gets clock signal form PLL, which is used to segment bit period and also synchronizes each sample data.

The DAC AD9748 [20] takes 8-bit parallel data and clock and generates analogue data. The FPGA generates sampled data which goes to DAC circuit. The selected DAC provides current output which is converted into voltage with I-V converter circuit. This voltage signal applied to second-order butter worth filter with 10 MHz cut-off frequency to eliminate unwanted signals [15]. The gain of the filter is controlled by gain controller which is realized in the FPGA hardware. The gain is set as per the modulation signal voltage for FM modulation.

As the input data rate changes, the sampling clock and the update rate of samples at the input of DAC also change. The proposed design takes the input data rate and step response of a normal Bessel filter and then performs filtering for various data rates of the serial data. Hence, the proposed filter gets tuned dynamically with known data rate and performs filtering. The hardware setup used for verifying the functionality and

| TABLE 1 | Analysis of Bessel versus DTPM filter for a given square input of 5 MHz |
|---------|-----------------------------|
| Bessel Filter Response | DTPM Filter Response |
| 12.19 dB peak at 5 MHz | 10 dB peak at 5 MHz |
| −7.811 dB peak at 15 MHz | −10 dB peak at 15 MHz |
| −38.44 dB peak at 25 MHz | −39 dB peak at 25 MHz |
| −91.5 dB peak at 35 MHz | −91.0 dB peak at 35 MHz |

| TABLE 2 | Effective noise (dB) floor of Bessel and DTPM filter |
|---------|-----------------------------|
| SNR | Input Signal | Bessel Filter | DTPM Filter |
| 0 | −13.35 | −23.88 | −35.3 |
| 10 | −9.52 | −20.17 | −28.77 |
| 20 | −9.34 | −19.9 | −29.34 |
| Original signal | −9.42 | −19.9 | −28.74 |

**FIGURE 9** Noise analysis of Bessel and DTPM filter
TABLE 3  Hardware specifications of the DTPM filter

| Parameter         | Specification |
|-------------------|---------------|
| Input data        | NRZ-L         |
| Data rate         | 1–10 MHz      |
| Sampling clock    | 10 times the data rate |
| DAC update rate   | 100 MSPS      |
| Output voltage    | Maximum 10 V  |

TABLE 4  Hardware active components used for DTPM filter

| Hardware Device   | Part No            |
|-------------------|-------------------|
| FPGA              | ZYNQ 7Z020        |
| DAC               | AD 9748           |
| Active filter     | Op-amp LMH 6612H   |

FIGURE 10  FPGA implementation of DTPM filter

FIGURE 11  A snapshot of hardware test setup of DTPM Filter

performance of the proposed scheme is shown in Figure 10. The hardware results are recorded for an input of 5 MHz. The sampling clock is chosen as 50 MHz and for each sample the stored Bessel coefficients of the 8-bit data are read and applied to the DAC. The DAC output is applied to the active filter, the output of which is recorded on CRO as shown in Figure 11. The same procedure is repeated for 2.5 MHz which is shown in Figure 12. The filtered output results are verified with the MATLAB simulation results. The spectrum of final output signal is also recorded on spectrum analyser as shown in Figure 11. From the spectrum, it may be noted that effective noise floor [15] is approximately 20 dB as expected from the simulation results (Figure 11).

5  CONCLUSION

The conventional hardware configurable PMF filter can be replaced by the proposed DTPM filter for a variable data rate transmission of an airborne telemetry system. The proposed DTPM filter is implemented using FPGA and DAC and fixed cut-off frequency active filter. This has been simulated for various data rates and results are compared with conventional PMF filter. The DTPM filter dynamically adjusts with the incoming serial data. This is further integrated with telemetry hardware to meet a variable data rate transmission at various instances of a long-range aerospace vehicle.

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