

FPGA BASED POWER EFFICIENT CHANNELIZER FOR SOFTWARE DEFINED RADIO

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ABSTRACT

Multiple communication channel support in RF transmission, such as that in a Software Defined Radio (SDR) warrants the use of channelizers to extract required channels from the received RF frequency band and to perform follow-on baseband processing. This paper describes the process of channelization as it applies to low-power and high-efficiency applications in wireless and Satellite Communications (SATCOM) domains. Smaller bandwidths and changing requirements of bandwidth calls for a programmable channel selection mechanism whereby channels and the resulting bandwidth can be selected based on target application, which is the primary principle in the Software Defined Radio based systems. Evolving wireless standards, advances in FPGA technologies available at a much lower Non-Recurring Engineering (NRE) costs than those for a comparable custom designed ASIC make programmable channelizer a viable solution. Radiation hardness is an essential requirement for parts used in space systems. This paper addresses the importance of methods to meet radiation requirements: selection of robust technologies and hardening by design.

1. INTRODUCTION

Software Controllable Architectures (SCA) are more adaptable to multi-standard and multi-channel communication systems. FPGA based channelizers are essential components and enable channel selection to be configurable based on the end application. The goal is to obtain maximum use of a single design through software reconfiguration of hardware assets and dynamic configuration and selection of channels, while ensuring highest level of fidelity of signals received at the destination.

Multiple access systems are widely used in satellite and terrestrial communications (such as JTRS land mobile radio), paving the way for SDR, which promises interoperability and compatibility among disparate standards. The use of such systems in SATCOM reduces the power requirements and also allows frequency reuse

between the satellite beams. Wideband and narrow band techniques are two main categories. Power efficiency of any of these techniques can be improved by adding forward error correction coding (FEC) with a bandwidth penalty and improved bandwidth efficiency will become more and more relevant with congested channels. This has to be achieved without jeopardizing the data quality. Systems have to be designed to coordinate carrier frequency, phase and symbol timing. Synchronous CDMA, orthogonal FDMA and wavelet-packet multiple access are all viable options [7,31]. In this work, we will concentrate on the critical aspects of channelizer design itself, trade-offs for low-power requirements, programmability, implementation details and radiation effects.

2. BACKGROUND

2.1 Channel Coding

The primary goal of channel coding is to reduce impairments in a reconstructed signal that was affected by transmission errors and Automatic Repeat Request (ARQ) to further improve channel conditions. Various forms of channel coding are employed in a transmitter including Cyclic Redundancy Check (CRC) bits for error detection and Forward error correction (FEC) bits for error correction. These operations can easily be performed on a programmable device from commercially available FPGA vendors. For example, in the CRC function, configurable parameters include

- Variable length generator polynomial
- Variable data width from 1 to width of polynomial
- Specified initial value

2.2 Channelizer

Several techniques in channelization are suitable for RF communication channels including Digital Down Conversion, Polyphase Fast-Fourier Transform (Polyphase FFT) Filter Banks and Frequency Domain Filtering. A multichannel digital receiver is used typically to down-convert a set of frequency division multiplexed (FDM) channels from a sampled data signal stream. Conversely, a multichannel digital transmitter simultaneously up-converts a number of baseband signals to assemble a set of FDM channels and send them into a single data signal stream.

Figure 1 shows a basic wideband transceiver. The system has RF receivers on the front end which digitize the input channels (for example, ten 20 MHz channels). The frontend comprises of Analog to Digital Conversion (ADC) subsystem which forms the first part of the digital transceiver. Analog signals are mixed with locally generated signal, and bandpass filtered. In the process the received wideband signal is split into quadrature channels (I and Q) that is digitized. An IQ balancer is generally used prior to the channelizer or can be made a subcomponent of the channelizer itself. Each incoming channel is assigned a unique ChannelID. The digitized channels are fed to the channelizer which selectively extracts desired channels and desired number of channels. The digital section of the receiver is called a *channelizer* or *zero-IF* demodulator. The channelizer maps RF (or near RF) directly to baseband. For mobile/hand-held wireless applications for which SDR is considered to be increasingly suitable, a premium is also placed on power dissipation.

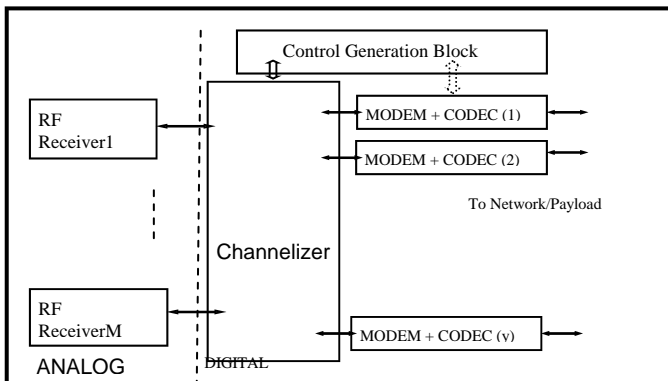


Figure1. Toplevel Functional Blocks in a Transceiver

The extracted channels both control and data portions are then post-processed in channel processors for demodulation and decoding of real data. During transmit, the payload data is encoded and modulated and then sent to the channelizer which generates necessary channels for onward transmission. The number of channel processors (y) depends on the number of active channels at the output of the channelizer. For programmability, both input frequency, output channels and bandwidth parameters can be set as desired, and can be changed at any given time.

3. DESIGN TRADE-OFFS FOR CHANNELIZER

During Digital Down Conversion, convergent rounding is used between stages to minimize DC biases into the processed output signal. The pre-processor in the architecture under consideration is a Hogenauer based Cascade Integrator Comb (CIC) filter which can enable higher decimation rate channelizations for higher input data rate, when compared to a conventional multiplier based mixer with Direct Digital Synthesizer circuits. With CIC

filters, the preprocessing stage essentially becomes Multiply Accumulate (MAC) free lowpass filter. This gives high signal processing speeds. Postprocessing filter which is normally needed in a CIC based filter do not need to be at such high rate and thus can be implemented with FIR filters. Thus even by reducing the complexity of design with use of CIC filters, we still have to deal with high power consumption due to the mixers and DDS logic that is necessary in a DDC based design. The downconversion process typically involves both FIR filters and a numerically-controlled oscillator (NCO), both of which are available as userconfigurable intellectual property (IP) for programmable logic users. For low-power applications we found that DDC may not be the best choice since it is also important to decrease the complexity of arithmetic operations in the Digital mixers and Direct Digital Synthesizers (DDS) in order to achieve lowest power.

Without having to deal with reducing the complexity of mixers and DDS logic, it can be overcome by “eliminating” the use of such components. The same functionality can be however gained by employing polyphase Fast Fourier Transform (FFT) filter bank segments that are multiplier-free [4,9,21,24].

Polyphase FFT filtering is suited for designs where (a) sampling rates that are power of 2 times the baseband bandwidth and (b) number of channels equal the decimation rate. Although these requirements make the flexibility of channelizer parameters hard to achieve, polyphase filter technique of channelization is efficient in terms of less area and less power. Polyphase filter banks also lead to reduced cost because of fewer system resources that are needed to implement. Certain transformations in terms of rearranging of functions can be performed to the standard Polyphase FFT based channelizer to achieve a modified and more efficient channelizer as shown in Figure 2.

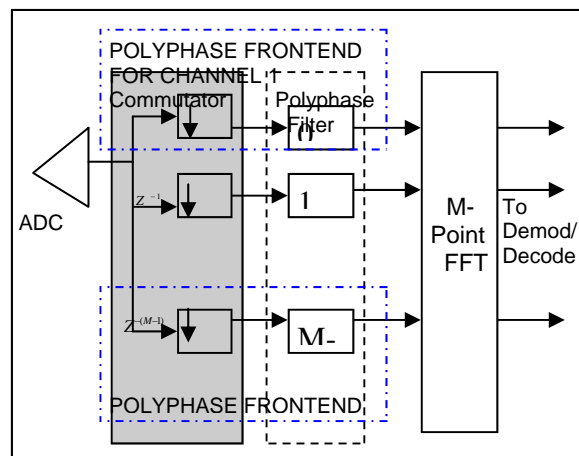


Figure 2. Commutator w/ Polyphase Filter Bank

In order to address the problem of full complex heterodyne at the output of bandpass filter, we can utilize sample rate reduction by retaining only one of M samples if it is decimation by M , thus enabling processing of only the retained samples. We can also take advantage of the fact that if we can select the center frequencies which alias to a DC value, then the entire heterodyne operation becomes a scalar value, thereby removing the need for heterodyne.

Polyphase FFT filter bank (PFFB) scheme assumes redundancy within the frequency plan of wideband channel. This scheme works best if the input consists of identically shaped and equally spaced channels. This mechanism requires one polyphase FIR filtering component to isolate and decimate various channels, followed by a FFT computation block. The polyphase segments can be made multiplier-free for low power applications. One optimization that has often been used in wireless communications is quantizing the input signal to such a level that it essentially becomes like a bandpass signal [4,9,30]. The heterodyne function is unnecessary, since there is no need for mixing with synthesized carrier as in DDC. Hence, there is no need for a DDS. This has its limitations in that the channel isolation is done on a per channel basis. Advantages of polyphase FFT over conventional window based FFT methods also include resilience to strong interference in passband ripple and spectral leakage

After studying various techniques to accomplish single or multiple channel extraction of signal bands from the bandwidth collected by high bandwidth converters, a modified version of the base polyphase system is chosen.

4. SYSTEM VIEW

FPGA technology provides the signal-processing engineer with the ability to construct a custom data path that is tailored to the application at hand. FPGA reconfigurable DSP system is shown in Figure 3.

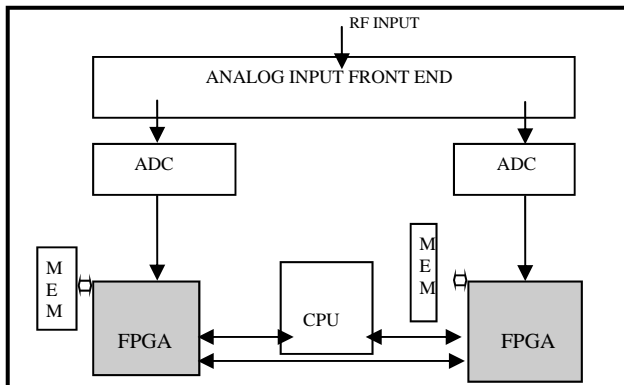


Figure 3. Reconfigurable DSP System

5. RADIATION EFFECTS IN VERY DEEP SUB-MICRON (VDSM) CIRCUITS

(A) Cumulative Effects: Two different types of cumulative effects, namely **Total Ionizing Dose (TID)** effects that cause increase of leakage currents, variation of transistor threshold voltage, and increase of transistor switching time. Therefore, the power supply currents increase, the switching and dynamic parameters degrade, and the noise margins are reduced; and **Displacement Damage (DD)** caused by high energy, is a main concern for optoelectronics devices, but it is not a concern for a CMOS devices.

(B) Single Event Effects (SEE): Prominent SEE effects are

- **Single Event Upset (SEU):** The current spike results of a bit flip in a memory cell or a latch. The effect is permanent as long as the correct information is not rewritten in the memory cell.
- **Multiple Event Upset (MEU):** A single particle causes an upset in several neighboring memory cells.
- **Single Event Latch-up (SEL):** A low resistivity path is triggered between V_{dd} and V_{ss} , and can destruct the chip if latch-up current is high enough. A power cycle is necessary to recover from a SEL condition.
- **Single Event Transient (SET):** A glitch occurs that may propagate in the circuit and cause errors.
- **Single Event Functional Interrupt (SEFI):** This event affects state machines and a circuit reinitialization is necessary to recover.

There are different ways to **mitigate radiation effects**. The first method is to work on the integrated circuits process. For example, the quality of oxides is a main driver for total dose hardness. Processes also have significant effect on SEE hardness. For example, CMOS/SOI technologies are immune to SEL. In general, all CMOS processes with an epitaxial layer are less prone to be sensitive to SEL, and are less sensitive to MEU than CMOS bulk processes. This, for example, is the solution that *Xilinx* proposes for the Aerospace applications. *Xilinx* space FPGAs are processed with a *special epitaxial layer* that makes them not sensitive to SEL.

Hardening by process may be very effective. However, this approach is only accessible to parts manufacturers. The only way for design engineers to harden a circuit against radiation effects is to perform hardening by design. **Hardening by design** can be performed at different levels:

- At the elementary transistor levels, layout techniques and *guardband* techniques improve the TID and SEL

tolerance. These techniques require the development of a specific library and can be quite time consuming.

- At the cell and function level, designs techniques like triple module redundancy, Error Detection and Correction codes (EDAC), CRC frame checks, and others can be very powerful to mitigate SEE.
- Other design techniques include complete initialization of state machines, defining all possible states, appropriate choice of state machine implementation, adding redundant logic (which has the downside of increasing on-chip real estate).

Testing is an essential activity to assess the sensitivity of a device to radiation effects and will be performed at specialized test facilities [10].

6. DESIGN APPROACH

The overall objective of this work has been to develop a low-power Channelizer design that can be implemented on FPGA device(s). The design consists of schematic entry and RTL descriptions in Verilog. Specific tasks include:

Step 1. Improvements of Polyphase Channelizer

Efficient M-Path Polyphase channelization architecture is designed for highly efficient and low-cost (power and area) designs. For providing a complete solution to the problem on hand, we need to address two aspects: 1) Programmability and 2) Low-Power and efficient design techniques. In a channelizer design, we need to perform basic channelization and secondary signal processing operations. The main functional blocks in a polyphase system are shown in Figure 2, with down conversion of the incoming channel with a complex heterodyne, followed by a digital low-pass filter and a down-sampling operation as required by the decimator.

Low power, low weight techniques: Reusability, software downloaded bit streams save area, weight and package size. Clocking biases conventionally have been used to reduce dynamic power. Selective operation of parts of the device is another method that can save power dissipation. In addition, Multi-layer, 3-D packaging techniques are paving the way into low-power and low weight implementations.

Resource sharing: It is clear from Figure 2 that the structure needed at the input of the M-point FFT is similar to all channels, except for channel co-efficients. These channel co-efficients can be generated on the FPGA, separately for each channel and passed to the FFT. Alternatively, the coefficients for all channels can be pre-calculated and loaded into a Content Addressable Memory (CAM) in the FPGA. The front-end processing units consisting of commutator and polyphase segment is grouped into what we are referring to as “Polyphase Frontend”. Programmable parameters include decimation rate, channel

Id, bandwidth and center frequency, are supplied to Channel Coefficient Generator (CCG) and Decimation Rate Generator (DRG). This design is capable of generating channel coefficients and decimation rates that are unique to each channel. The *polyphase frontend* is recursively called M times to perform the operation for M channels. Thus it has an interesting and a much desirable byproduct for programmable channelizers. We initially noted that polyphase channelizers support fixed set of frequency plans with equally spaced channels. However, this design enables us to overcome that obstacle thus supporting multiple frequency plans with the overhead of an extra FFT logic. Since low-power is our criterion, the decrease in speed due to this design is an acceptable trade-off. This improved architecture is shown in Figure 4.

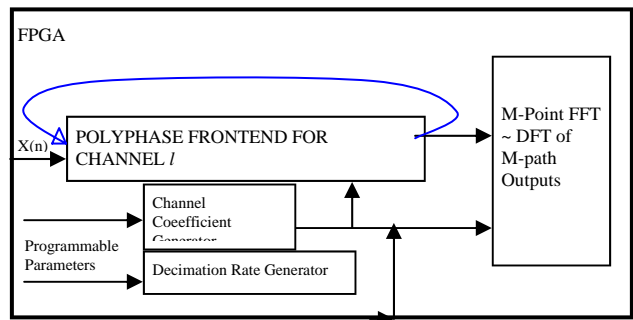


Figure 4. Resource Sharing of Polyphase Frontend Logic

Quantization: If accuracy of the data is not paramount, quantization of input samples prior to entering the polyphase section is recommended. The polyphase filters are multiplier-free since quantization leads to approximations of multiplication operations to basic additions and shift operations. This also is a feasible approach for low-power design, depending on amount of accuracy needed.

Implementation related improvements

- Segmented routing is essential in high performance and power efficient DSP based designs. Some Xilinx and Altera FPGAs can give sustained performance irrespective of device utilization. Segmented routing architectures also lead to lesser power and are more predictable.
- Board space reduction is accomplished by the use of a small outline Ball Grid Array (BGA) package, which results in a small footprint. In the case of FPGA based design, there are several suitable devices from vendors yielding efficient board designs.

The resource reduction translates into lesser power. For a typical application there can be resource savings of upto a

factor of 20 by moving from a standard DDC based approach to a polyphase filter bank approach. Further resource reduction can be performed by viewing the polyphase channelizer to be operating in two processing rate zones. The commutator alone operates at a much higher rate than the rest of the circuit. Except the commutator, all the blocks are operating at a rate which is M times lower than the input data rate. This implies that the commutator supply voltage can be at the required levels, whereas the supply voltage for the rest of the processing blocks can be lower. This leads to the usage of level converters between different voltage domains, but can lead to considerable power savings [6,7]. An asynchronous level converter is the simplest technique employed for converting signals from high V_{DD} to V_L . It is important to note that we are proposing the lower voltage V_L to be configurable such that it is lower than nominal voltage V_{DD} in steps of 0.5 v.

It is evident that optimizations in the channelizer thus far lead to dynamic power reduction in terms of switching transistors. However, along with dynamic power, **leakage power** is a key factor to consider while addressing low-power designs.

Total FPGA Power = $P_s + P_l$ where, P_s (switching power)

= $\sum kV_{DD}^2 F_{clk} C_L$, where k is usually 0.5, F_{clk} is the clock frequency and C_L is the load capacitance. The switching power is added for all nodes in the FPGA.

P_l (leakage power) due to supply voltage and leakage current. The leakage current for a supply voltage point is obtained for FPGA device from the vendor's device characteristics or through SPICE simulations.

Thus, with decreasing transistor dimensions and growing number of transistors, we cannot ignore leakage power. For this reason, we are using the approach for FPGAs called "Configurable V_{DD} ". This enables us to dynamically control the power supply to fast and slow portions of the channelizer, thereby reducing leakage power. By applying the power sensitivity calculation [18], we can formulate a simple algorithm as follows for determining the power supply.

For all CLBs in the Commutator,

Assign supply voltage = nominal V_{DD}

For all CLBs in polyphase segments and FFT filter bank,

- Calculate Power sensitivity (= Decrease in FPGA Power / Decrease in V_{DD})
- Calculate delay on the critical path with decreased

$V_{DD} (= V_L)$

- If design meets timing, Supply voltage = V_L
- Mark the CLB as done

The configurability of supply voltage comes at some cost in terms of additional transistor resources on the FPGA. For every CLB that needs configurability (in this case, for those CLBs in post-commutator portions of the channelizer), we need 2 P-transistors like those used for pre-charge in CMOS circuits as shown in Figure 5. These two act as 'power control switches' (PCS) [27].

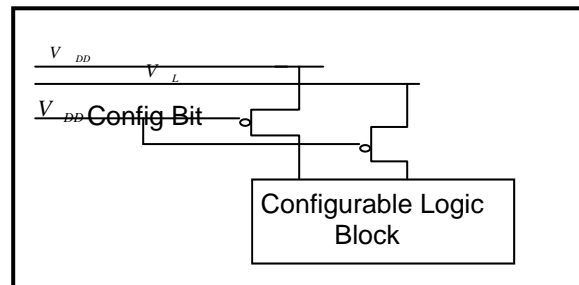


Figure 5. Programmable V_{DD} in a CLB of a FPGA

Additional low-power design techniques include

- Interleaving layout methods for CLBs with V_{DD} and V_L , thus creating easy access to power grid
- Higher V_L for SRAM intensive FPGA device if chosen
- Fine tuning of transistor sizes in level converter
- Gate-booted power controlling transistors in Figure 5.
- Clock gating to save dynamic power for portions of design that are not functional

Therefore, with the modified and enhanced channelizer, configurable parameters include Input frequency, Number of output channels, Output frequency bandwidth, Quantization Enable ('Q' to enable or disable quantization based on required accuracy of data), Supply voltage configuration bit ('S' to choose between V_{DD} and V_L).

Step 2. Generate a computer simulation model.

Simulation model is developed in Verilog for sub-components of the system. A subtask of this step includes generation of functional tests to verify the functionality. Block level and system level tests, with various configurations of programmable parameters are vital part of functional testing. This gives flexibility of modifying the frequency plans of a wideband channel and thus simulating different target applications.

7. APPLICATIONS

The programmable channelizer can be used for rapid prototyping and deployment of special targeted applications

in multi-standard and wideband civil defense and electronic warfare where variable channel selection is more suitable than a fixed channel selection and securing communications wherein the frequency plan can change on an as needed basis to prevent intrusion. The phrase 'Information War' is becoming increasingly relevant in this day where information is required to reach the correct destination with most efficient circuits. Packetized data communication with signal and radiation tolerant integrity and efficiency is required. Several aspects of internetworking that can be done in less area with less power and flexibility to change the design are therefore essential for Satellite Communications (SATCOM) to achieve reliable and scaleable multimedia communications. These small and cool devices can then be equally applicable in Department of Defense (DoD) as well as in commercial tactical network communications.

8. CONCLUSION

Efficiency in terms of architecture optimizations such as those made in the Polyphase FFT and implementation aspects leading to smaller area, low power, radiation hardness and low cost seem very promising. Innovative design enhancements from engineering community, coupled with process improvements from FPGA vendors can play a crucial role in satellite communications and in producing fast, small and efficient communications systems that can be used both in aerospace and commercial arenas.

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