Researching FPGA Implementations of Baseband MIMO Algorithms using AccelDSP

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Introduction

FPGAs offer an attractive set of hardware features for WiMAX systems that can be difficult for systems engineers with little FPGA design experience leverage. DSP oriented FPGAs such as the Xilinx Virtex™-5 offers up to 640 programmable DSP blocks capable of running at 550 MHz for a raw peak performance in excess of 350 GMACs. The linear algebra algorithms being investigated for use in baseband MIMO applications, such as matrix inversion, matrix factorization, single value decomposition (SVD), beamforming and adaptive filtering, are inherently complex to design in hardware. Companies will often task advanced research teams with determination of an optimal hardware approach. To assist these teams Xilinx provides a high-level MATLAB based design flow well suited for this type of research.

WiMAX Overview

WiMAX is a standards-based technology that enables the delivery of the last mile broadband access as an alternative to cable and DSL. The WiMAX forum (Worldwide Interoperability for Microwave Access) promotes conformance and interoperability of the IEEE 802.16 standard. WiMAX is a long range system that uses a licensed spectrum in contrast to Wi-Fi technology which is short range and uses unlicensed spectrum bandwidth to provided access to a local area network (LAN). WiMAX systems have the potential to cover up to 70 miles or deliver up to 70 Mbits/s.

The latest WiMAX standards, 802.16d and 802.16e are generating the most industry interest because they operate at lower frequencies and suffer less from inherent signal attenuation resulting in improved range and in-building penetration. More advanced versions of the 802.16e are using Multiple-input multiple-output (MIMO) techniques to improve data rates even further. The IEEE 802.16e-2005 standard provides an improvement on modulation schemes over previous WiMAX standards primarily by enhancing the OFDMA (Orthogonal Frequency Division Multiple Access) to create a Scalable OFDMA (SOFDMA). Coverage is increased through a variety of techniques including advanced antenna diversity schemes, Adaptive Antenna Systems (AAS) and Multiple Input Multiple Output (MIMO) technology.

Implementing MIMO Algorithms in FPGAs

The performance gains of MIMO technology comes at the expense of hardware complexity. A transmit/receive system that utilizes multiple antennas not only transmits data between the corresponding antennas but also between the adjacent antennas. The data is received in the form of a “MIMO Channel Matrix”.

![MIMO Channel](image)

Linear algebra techniques such as Singular Value Decomposition (SVD) or matrix inversion are required to decouple the channel matrix in the spatial domain and recover the transmitted data.

Developing a MIMO system prototype in hardware that performs at the actual system data rates often requires the use of an FPGA based hardware platform. The designer of this prototyping system, however, is faced with two considerable challenges; the first is to design something as complex as an SVD or matrix inverse in hardware and the second is tuning the implementation for optimal performance.

Implementing Matrix Operations on FPGAs

The specific matrix factorization or inversion algorithm selected for implementation will be a tradeoff between numerical stability and hardware efficiency. A high-level MATLAB model is typically developed to determine the most efficient algorithm for a particular application. MATLAB is a natural modeling language choice because of its inherent support for matrices, complex numbers and linear algebra functions. In the case of the...
SVD this may involve choices between adaptive estimation techniques, vector rotations or other simplifications that result from channel matrices with special properties such as symmetry.

Once an algorithm has been finalized the hardware performance will need to be tuned to overall system requirements. Maximizing the performance of a MIMO system in hardware requires that partial parallelism be implemented in key areas of the design that have the greatest impact on overall performance.

**Algorithmic MATLAB Synthesis using AccelDSP**

Xilinx supports an abstract FPGA design flow based on MATLAB that is well suited for research of FPGA based implementations of WiMAX MIMO algorithms through AccelDSP™ which takes algorithmic floating-point MATLAB as input and, using an algorithmic synthesis process, generates optimized fixed-point FPGA implementations. Users control the implementation process through a set of design directives and global settings.

### Typical MATLAB DSP Design Flow

<table>
<thead>
<tr>
<th>Floating-Pt. Algorithm</th>
<th>Fixed-Point Conversion</th>
<th>Architecture Definition</th>
<th>Create / Integrate IP Blocks</th>
<th>Create RTL Design</th>
<th>Refine Architecture</th>
<th>Verify RTL</th>
<th>RTL Synthesis</th>
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<tr>
<td><strong>Steps performed by AccelDSP</strong></td>
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### AccelDSP Design Flow

**MATLAB based Algorithmic IP**

AccelDSP offers an Advanced Math tool kit as part of its AccelWare IP libraries to assist developers in MIMO research. AccelWare is a library of floating-point MATLAB model generators can be synthesized by AccelDSP into efficient fixed-point hardware. The generated MATLAB models can be modified by the user to reflect unique algorithmic approaches to their systems problems and thus serve as reference designs. The table below includes a summary of the available functions in the AccelWare Advanced Math Toolkit.

<table>
<thead>
<tr>
<th>Category</th>
<th>Available Advanced Math AccelWare Models</th>
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<tr>
<td>Matrix Inversion</td>
<td>QR method, Cholesky method, triangular inversion</td>
</tr>
<tr>
<td>Matrix Factorization</td>
<td>QR method, Cholesky method, SVD</td>
</tr>
<tr>
<td>Adaptive Filters</td>
<td>QRD-RLS</td>
</tr>
<tr>
<td>Matrix Utilities</td>
<td>Givens-Array Rotation</td>
</tr>
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</table>

Below is a code example of a synthesizable a MATLAB model generated by AccelWare for a givens rotations function commonly used in a QR Decomposition matrix inverse.

```matlab
% multiplier-based implementation of a Givens Rotation
r_sqr = x(1)*x(1) + y(1)*y(1);
if (x(1) == 0) & (y(1) == 0)
  v = x*1;
  w = y*1;
else
  r_inv = 1/sqrt(r_sqr);
sin_phi = y(1)*r_inv;
cos_phi = x(1)*r_inv;
vt = x*cos_phi + y*sin_phi;
w = y*cos_phi - x*sin_phi;
end
```
Conclusion
Abstract modeling and design methodologies are necessary to explore an adequate segment of the hardware solution space for an advanced linear algorithm such as those used in WiMAX baseband MIMO applications. AccelDSP enables algorithm developers with limited hardware design skills to explore that space using the familiar MATLAB modeling environment. Bridging the gap between these two highly specialized development domains allows more degrees of freedom when determining the final solution.