FPGA-Based WiMAX System Design

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1. Introduction

The explosive growth of the Internet over the last decade has lead to an increasing demand for high-speed, ubiquitous Internet access. Broadband wireless access (BWA) is increasingly gaining popularity as an alternative "last-mile" technology to DSL lines and cable modems. Following the hugely successful global deployment of the 802.11 wireless local area network (LAN) standard, deployment of the IEEE 802.16d wireless metropolitan area network (MAN) standard is currently in progress. This technology aims to provide fixed broadband wireless access to residential and small business applications, as well as enable Internet access in countries without any existing wired infrastructure in place. Standardization efforts are also underway for the 802.16e version that attempts to provide mobility to the end user in a MAN environment. The WiMAX Forum (Worldwide Interoperability for Microwave Access) is an industry-led, non-profit corporation formed to promote and certify compatibility and interoperability of broadband wireless products. The organization is a non-profit association formed in 2003 by equipment and component suppliers to promote the adoption of IEEE 802.16 compliant equipment by operators of broadband wireless access systems [1].

2. IEEE 802.16-2004 Standard

This revised standard consolidates IEEE Standards 802.16, 802.16a, and 802.16c, retaining all modes and major features without adding new modes. This standard specifies the air interface of a fixed (stationary) point-to-multipoint (PMP) BWA system providing multiple services in a wireless metropolitan area network (MAN) [2]. It also specifies an optional mesh topology enhancement to the medium access control layer (MAC).

Table 1: Overview of the different variants within the 802.16 standard.

	802.16	802.16a/Rev d	802.16e
Completed	December 2001	802.16a: Jan 2003 802.16Revd: June 2004	Est. Mid-2005
Spectrum	10 - 66 GHz	2 - 11 GHz	2 – 6 GHz
Application	Backhaul	Wireless DSL & Backhaul	Mobile Internet
Channel Conditions	Line of Sight Only	Non Line of Sight	Non Line of Sight
Bit Rate	32 – 134 Mbps at 28MHz channelization	Up to 75 Mbps at 20MHz channelization	Up to 15 Mbps at 5MHz channelization
Modulation	QPSK, 16QAM and 64QAM	OFDM 256 sub-carriers QPSK, 16QAM, 64QAM	Scalable OFDMA
Mobility	Fixed	Fixed	Pedestrian Mobility – Regional Roaming
Channel Bandwidths	20, 25 and 28 MHz	Selectable channel bandwidths between 1.5 and 20 MHz	Same as 802.16a with UL sub-channels to conserve power
Typical Cell Radius	1-3 miles	4 to 6 miles; Max range 30 miles based on tower height, antenna gain and power transmit	1-3 miles

2.1 PHY Layer Overview

Figure 2 provides an overview of the typical PHY layer functions implemented in a WiMAX base station operating in the OFDM/OFDMA modes. Apart from the usual functions such as randomization, forward error correction (FEC), interleaving, and mapping to QPSK and QAM symbols, the standard also specifies optional multiple antenna techniques. This includes space time coding (STC), beamforming using adaptive antennas schemes, and multiple input multiple output (MIMO) techniques which achieve higher data rates. The OFDM modulation/demodulation is usually implemented by performing fast fourier transform (FFT) and inverse FFT on the data signal. Although not specified in the standards, other advanced signal processing techniques such as crest factor reduction (CFR) and digital predistortion (DPD) are also usually implemented in the forward path, to improve the efficiency of the power amplifiers used in the base stations. The uplink receive processing functions include time, frequency and power synchronization (ranging), and frequency domain equalization, along with rest of the decoding/demodulation operations necessary to recover the transmitted signal.

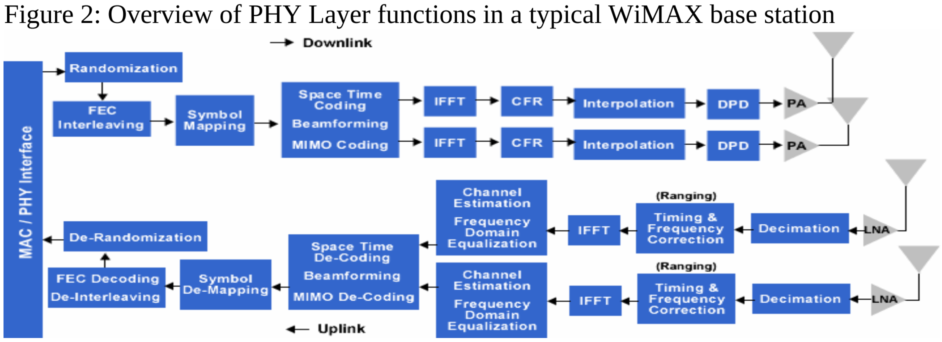
3. Hardware Platform for WiMAX Implementation

Designers of WiMAX systems need to meet a number of critical requirements such as processing speed, flexibility and time-to-market, and it is these stringent requirements that ultimately drive the choice of the hardware platform. Some of the major challenges are further described below.

3.1 Implementation Challenges

- **Processing speed**: Broadband wireless systems such as WiMAX have throughput and data rate requirements that are significantly higher than those in cellular systems such as WCDMA and cdma2000. In order to be able to support such high data rates, the underlying hardware platform must have significant processing capabilities. In addition, several advanced signal processing techniques such as Turbo coding/decoding, and front end functions such as FFT/IFFT, beamforming, MIMO, CFR and DPD are very computationally intensive and require several billion multiply and accumulate (MAC) operations per second.
- **Flexibility:** WiMAX is a relatively new market and is currently going through the initial development and deployment process. 802.16Rev d has just been standardized while the 802.16e mobile version is still in the works. Under this current scenario, having hardware flexibility/re-programmability in the end WiMAX compliant product is very important. This ensures that in-field programmability is possible, alleviating the risks posed by constantly evolving standards.

Figure 2: Overview of PHY Layer functions in a typical WiMAX base station



- **Time to Market:** Because WiMAX is an emerging technology, time-to-market is a key differentiator for OEMs looking for early success in gaining market share. This has a direct effect on the development cycle and choice of hardware platform, with designers requiring easy-to-use development tools, software, boards, and off-the-shelf IP and reference designs in order to accelerate the system design.
- **Cost Reduction Path:** Another important requirement to keep in mind while choosing the hardware platform is the availability of a long term cost reduction path. The evolving WiMAX standard/market is expected to stabilize after the initial uncertainty surrounding it, leading to a situation where cost of the final product becomes much more important than retaining flexibility. A hardware platform that has such a clear cost reduction path And enables a seamless flexibility, cost tradeoff is the need of the hour.

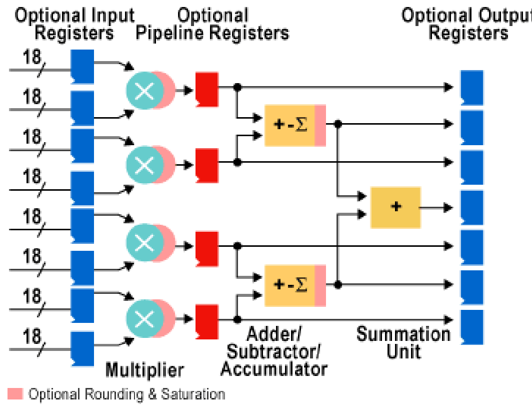
4. FPGA based WiMAX System Design

This section describes how each of the implementation challenges associated with WiMAX system design, as outlined in Section 3.1, can be effectively addressed with FPGAs. Altera's Stratix II and Cyclone II FPGAs are considered as a case study.

4.1 Processing Speed

High performance FPGAs such as Altera's Stratix II platform [2], contain embedded DSP blocks, TriMatrix™ memory architecture, innovative logic structure, and high-speed interfaces, providing a powerful and integrated platform to implement broadband wireless systems such as WiMAX. Each DSP block can support a variety of multiplier bit sizes (9x9, 18x18, 36x36) and operation modes (multiplication, complex multiplication, multiply-accumulation and multiply-addition) and can

Figure 3: Stratix II DSP Block Architecture



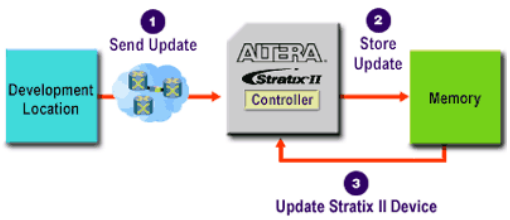
offer a DSP throughput of 2.8 GMACS per DSP block. Such high throughputs are required for implementing complex DSP techniques found in WiMAX systems including adaptive beamforming, MIMO, FFT/IFFT, FIR filtering, CFR etc. The largest Stratix II device, the EP2S180 device, has 96 DSP blocks that offer a throughput of 284 GMACS and can support up to 384 18x18 multipliers. The throughput in Stratix II devices is orders of magnitude higher than single-chip DSP processors available in the marketplace today. In addition, new rounding and saturation support has been added to the DSP block to facilitate porting DSP firmware code onto the FPGA.

4.2 Flexibility

As noted earlier, hardware flexibility/re-programmability in the end WiMAX compliant product is very important due to constantly evolving standards. Altera's Stratix II FPGAs provide the ability to easily evolve WiMAX systems in accordance with changing market demands. These devices allow remote system upgrades to be transmitted over any communications network, keeping products ahead of the competition, and also feature the dedicated recovery circuitry to ensure reliable updates. Remote system upgrades are enabled using Stratix II devices and flash memory. As shown in Figure 4, a user can perform a remote system upgrade in three simple steps:

1. Send an update from the development location through a network to the Stratix II device.
2. Store the update in the memory.
3. Update the Stratix II device with the new data.

Figure 4. Remote Upgrade Systems with a Stratix II Device in Three Steps



A Stratix II device-developed WiMAX system can be easily upgraded when:

- Additional protocol support is required to ensure compatibility with future products
- Enhancements or bug fixes are necessary

WiMAX systems that use Stratix II FPGAs can stave off premature obsolescence because they can support evolving standards and applications that were not known at the time of equipment deployment.

4.3 Time-to-Market

As with any new promising technology, time-to-market is a key differentiator for OEMs developing WiMAX compliant products. To achieve this, designers need access to off-the-shelf IPs and reference designs that help accelerate their own development cycle.

This section describes some of the PHY layer solutions available from Altera.

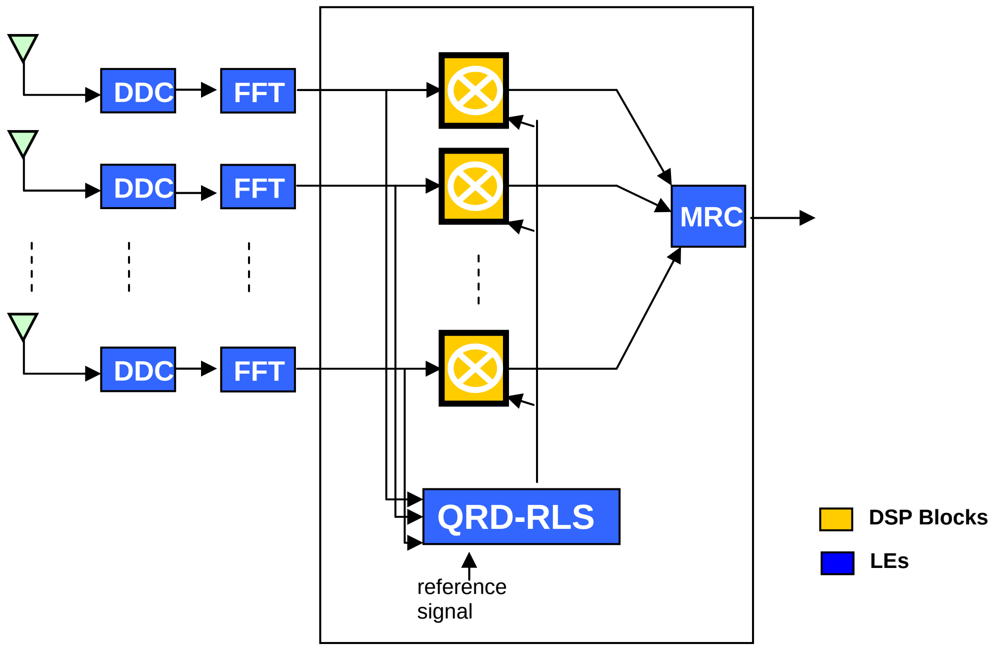
Forward Error Correction (FEC): 802.16Rev d specifies the concatenation of a Reed-Solomon (RS) outer code and a rate-compatible convolutional inner code, on both uplink and downlink. To implement these schemes, Altera provides the RS Compiler and Viterbi Compiler IPs that are fully parameterizable and have a user friendly interface [3]. The automatically generated code is highly optimized for Altera FPGAs, including Stratix II and Cyclone II devices.
Turbo convolutional codes and Turbo Block codes are specified as optional FEC schemes in the standard. Low density parity check (LDPC) codes are a new type of FEC codes that are gaining in popularity and might be specified as optional FEC scheme in 802.16e version. Altera, along with its IP partners, provides a complete portfolio of FEC schemes for WiMAX systems.

OFDM modulation/demodulation: As shown in Figure 2, the OFDM or OFDMA sub-carriers are generated by performing the IFFT operation at the transmitter, while FFT operation is done at the receiver to transform the signal back to the frequency domain. The FFT is a computationally intensive function requiring a large number of multipliers and Stratix II FPGAs, with embedded DSP blocks, offer an ideal scalable platform to implement FFT of various sizes. Altera also provides the FFT IP function that is a high performance, highly-parameterizable FFT processor [4].

Multiple Antenna Techniques: Multiple antennas techniques are specified in WiMAX systems to increase the range and reliability of transmission and reception. Multiple antenna schemes provide various benefits including array gain, diversity gain and co-channel interference suppression. 802.16Rev d currently supports several multiple antenna options including space-time codes (STC), multiple-input multiple-output (MIMO) antenna systems and adaptive antenna systems (AAS). These schemes involve computationally intensive

algorithms and operations that are well suited for implementation on FPGAs.
Figure 5 illustrates an example implementation of AAS to perform receive beamforming. The signals from different antennas are first downconverted to baseband using digital down converters (DDC) and then transformed back to the frequency domain using FFT operations. Complex weights are then applied to the signals before performing maximum ratio combining (MRC) to maximize the signal-to-noise ratio. The application of complex weights to the signals from different antennas involves complex multiplications that map well onto the embedded DSP blocks available in Stratix II devices. The weights are computed using the QR decomposition based recursive least squares (QRD-RLS) algorithm.
Altera provides IP cores to implement adaptive weight update algorithms such as the least mean squares (LMS), normalized LMS (NLMS), RLS and QRD-RLS algorithms. Altera also provides the Alamouti decoder core to implement the transmit diversity option using Alamouti space time codes as specified in the WiMAX standard. MIMO spatial multiplexing schemes usually require matrix decomposition algorithms such as the QR decomposition, Cholesky decomposition and Singular value decomposition (SVD). These cores are also provided by Altera to ease the implementation of MIMO techniques on FPGAs.

Figure 5: Beamforming Implementation with AAS schemes



4.4 Cost Reduction Path

Although flexibility is highly desired in initial WiMAX products (due to the evolving standards and market uncertainty), the standards will eventually stabilize, leading to a situation where flexibility of the WiMAX product needs to be traded for a low-cost ASIC implementation. Altera provides this cost reduction path for its FPGAs through HardCopy devices. Altera® HardCopy™ devices are the industry's first structured ASICs that offer a comprehensive alternative to traditional ASICs [5]. ASIC design today faces increasing product development costs and long design cycles, both due to shrinking process geometries and growing design complexity.

These challenges also demand first silicon success to avoid costly and time-consuming re-spins.Altera addresses the pain associated with traditional ASIC design by providing the FPGAs, development tools, intellectual property (IP), and a seamless migration path from the function-verified prototypes to high-volume production devices.

5. Conclusions

WiMAX is an emerging technology with significant potential and is poised to revolutionize the “broadband wireless internet access” market. The diverse hardware requirements including processing speed, flexibility, integration and time-to-market necessitate an FPGA based implementation platform. Altera’s high-density FPGAs and HardCopy devices provide WiMAX OEMs with significant competitive advantages by minimizing development time and resources, maximizing first-time success, and accelerating time-to-market.

6. References

[1] The WiMAX Forum. *www.wimaxforum.org*

[2] *Stratix II Device Family Features*. http://www.altera.com/products/devices/stratix2/features/st2-features.html

[3] *Error Detection & Correction*. http://www.altera.com/products/ip/dsp/error_detection_correction/ipm-index.jsp

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[5] *HardCopy Devices*. http://www.altera.com/products/devices/hardcopy/hrd-index.html

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