Architectural Decisions for SDR in MIMO Applications

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ABSTRACT

As commercial SDR products mature, new applications will look to the technology as a means to simplify future designs. At the same time SDR is gaining traction, so are MIMO consumer devices for 802.11n, 802.16e and LTE. This paper explores some of the trade-offs SDR System architects need to consider when designing next generation SDR MIMO RFICs for mobile devices and where the technology can enhance operation for these modes.

1.0 INTRODUCTION

Software Defined Radio (SDR) solutions are beginning to move into the commercial mainstream. Companies including Sandbridge, picoChip, BitWave and others have announced SDR components for handsets. SDR base stations by Alcatel-Lucent, ZTE, Huawei, Vanu and AirSpan have been announced and deployed worldwide. The inherent flexibility and programmability of SDR can accelerate time to market and is one key driver behind the move to SDR.

SDR Infrastructure has already been available for several years. Initially deployed by Mid-Tex Cellular in 2004, Vanu's Anywave Base Station has now been deployed several times in the US and elsewhere. Although the first deployment provided a single protocol (GSM) overlay on Mid-Tex's existing network, it one of the first commercial steps in executing on the promise of SDR. The Anywave Base Station provides software programmable implementations of complex waveform processing on general purpose hardware.

During that same time period, the US Government sponsored the Joint Tactical Radio System (JTRS). The JTRS program has been focused on replacing armed services legacy radios with a family of SDRs that can support the military mission using a wide range of frequencies and protocols (waveforms).

In 2008, ZTE has announced the ZXGW B8036 Base Station, which changes frequency bands by switching software instead of hardware. The base station currently supports simultaneous GSM and WCDMA, and can be modified to support CDMA and WiMAX in the future. The Base Station can also support the development of "long term evolution" (LTE).

Earlier this year, Huawei has announced a next generation radio access network (RAN) for Telia Sonera that will support GSM and UMTS services in the same frequency band using software configurable for GSM, UMTS and LTE functionality.

In developing SDR technology for base stations, designers have often relied upon wideband Analog to Digital Converters (ADCs) to sample sufficient bandwidth to extract the signals of interest. Without the capability to retune the ADC for different frequencies and bandwidths, the ADCs needed wide bandwidth to enable full base station performance across the desired spectrum. Power consumption of the required ADC is often greater than 1 watt, which may be an acceptable power benchmark for a base station but is much too high for a mobile device. Supporting mobile devices with SDR solutions will require a new architecture. Recently, 4G technologies have begun to be trialed and deployed. These 4G technologies which include LTE and WiMAX all offer a MIMO option but history has shown that entrenched legacy protocols are never eliminated early in the transition to a newer technology. The resulting multi-band multi-protocol radios which must be designed to support 4G and legacy protocols offer many challenges to the designer. MIMO adds another layer of complexity. This paper will explore some of the tradeoffs and design challenges that are considered when architecting next generation SDR MIMO RFICs for mobile devices.

2.0 THE MULTI-BAND MIMO CHALLENGE

With each new generation of technologies, wireless system designers have worked diligently to increase the capability of each new technology and keep pace with the growing demands for both voice capacity and data throughput. Many current efforts are focused on the implementation of MISO (multiple input single output) or MIMO (multiple input multiple output) wireless technologies for increased data rates. WiFi (802.11n), WiMax (802.16e), HSPA, EVDO and LTE all use various types of MISO or MIMO to create multiple parallel paths to increase the available data bandwidth between the network and a wireless client.

Unfortunately for designers, even as new technologies are developed to increase the available network bandwidth, the technologies themselves present designers with ever more challenging constraints.

One 4G technology, LTE, may be deployed into as many as 20 different frequency bands each of which may use any one of 6 bandwidths and 4 modulations. Furthermore, the LTE specification describes seven different downlink modes for the LTE UE which include both transmit diversity as well as spatial multiplexing.

If a wireless carrier only needed to support one particular bandwidth in only one operating frequency band, the challenge would be straightforward and the development of MIMO RFICs would follow the historical path of incremental integration. However, while there is clearly some overlap between the various combinations of frequency, bandwidth and modulation, the complexity necessary to satisfy carriers typical use cases is growing steadily.

The challenge in designing next generation RFICs which support MIMO is not in the specifics of a particular operating band or protocol. After all, designers have successfully addressed new protocols such as OFDM for several years. Rather the challenge is in supporting MIMO radios which operate across *multiple* frequency bands and *multiple* protocols while supporting SISO, MISO or MIMO in a single device. All of this must be achieved using best in class cost, power and performance to be commercially viable. SDR offers the means to achieve that goal.

3.0 SDR Implementations in MIMO Applications

When reviewing the requirements for a new LTE handset for a carrier such as Verizon, one can quickly assess the required coverage in both bands and protocols.

A new handset might include connectivity requirements such as:

- LTE in Band XIII using MISO
- EVDO in Bands I, II or IV
- WCDMA in Band XX
- WiFi in 2.4 GHz Band
- Bluetooth in 2.4 GHz Band
- GPS

The design challenge for this handset is to integrate a wide range of functionality, frequency bands and wireless protocols into a small form factor. MISO adds to the complexity. Spatial multiplexing requires at least two receive paths. Then, as the number of different bands increases the number of required RF inputs also increases. The experience of most RF designers is that one can improve the performance of a RF circuit by trading bandwidth and operating range of the device for performance. The design of a multi-band multi-mode terminal is then the result of multiple tradeoff analyses which minimize cost by minimizing the required number of unique RF paths in the device. Designers attempt to reuse the same circuits by switching in LNAs, filters or other elements as necessary for each use case. However designers have found that there is typically some minimum number of parallel RF circuits required to meet a particular use case because the performance of each RF chain can only be stretched to cover several adjacent frequency bands at best.

More paths and RF inputs increases the required die area to implement the required functionality. For example, satisfying a requirement for a dual band MISO LTE handset which also supports a single band of WCDMA would most likely require at least 5 parallel receive paths, each of which includes all circuitry from RF input to digital output (figure 1).

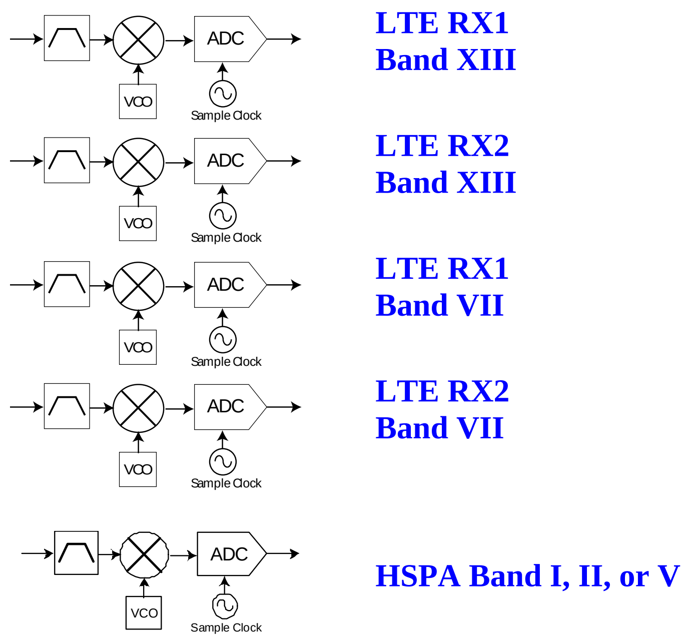

Figure 1 LTE/WCDMA Handset RF

Compounding the multi-band challenge, since each LTE Receiver may need to support modulations ranging from BPSK to 64 QAM, each of the parallel receivers must be designed to support the most aggressive set of performance requirements and may be relatively inefficient and power hungry when running with lower order modulations

4.0 ARCHITECTURAL CONSIDERATIONS FOR APPLICATIONS

Three key elements drive all decisions when architecting RFICs for mobile devices; cost, performance and power consumption. When designing RFICs for devices that have limited modes of operation and limited frequency bands of operation (i.e. quad-band GSM/GPRS/EDGE devices), the traditional architecture of a fixed transceiver with limited number of inputs consistently meets goals for cost, performance and power. As the number of frequency bands or modes has increased, designers have typically added several transceiver paths on the same die, each of which would support a limited set of the mode and frequency band combinations required by the application. While incrementally increasing the cost, this approach has worked well for 2G and 3G integration.

However as the number of frequency bands and wireless protocols required by a device grow, it becomes more and more difficult to support all of the required bands with a single RFIC. Not only is the chip more difficult to design but the profitability and potential market addressed by the solution is also inherently more dependent on a single use case. By "single use case", we refer to the desired combination of frequency bands and protocols which the carrier would like to integrate into supported devices. To the degree that a single use case can meet the needs of fewer customers (because it is frequency and protocol specific), the "reward" from the design may decrease. Additionally as the number of bands and protocols increases, risk increases for both schedule and performance since the design itself has become more complicated. Marketing professionals must therefore continually re-evaluate the risk/reward tradeoff of a particular product family since the profitability may decrease (due to increasing design complexity which raises costs) even as the target market shrinks (since the target market is narrower in focus). When the risk/reward analysis becomes poor, then the product team must attempt to rebalance the equation by either making the chip suitable for a wider range of use cases or by reducing its cost.

This has long been the promise and the potential downfall of SDR in commercial radios. Flexibility (of band, bandwidth, linearity, and mode) has been associated with increased cost, increased power consumption or decreased performance when compared to a fixed transceiver solution. SDR solutions must therefore demonstrate the flexibility required by multi-band, multi-mode and multi-receiver architectures while not degrading commercial metrics.

SDR radios must address the flexibility issue directly at the design level since the architecture only uses a single RF path (or two in the case of MIMO). With SDR architecture, operating frequency, protocol bandwidth and linearity performance are reconfigured, which can modify the overall performance of the radio as necessary to meet required customer specifications and minimize power consumption. Thus commercial cost, performance and power consumption can all be best in class for each of the supported bands and protocols.

A sampling of design and performance challenges for multi-band and multi-mode MIMO architectures include:

- ❑ Multi-band Support – There are over 20 currently defined LTE bands range from 698 MHz up to 2690 MHz
- ❑ Gain Imbalance – Best performance will result when there is minimal gain difference between MIMO receive path #1 and MIMO receive path #2
- ❑ Sensitivity – From 2G protocols like GSM to 4G protocols like LTE with 64QAM modulation requires a wide range of SNR in order to achieve the desired data throughput.
- ❑ ACP – Suppressing Adjacent Channel Power (ACP) while supporting multiple frequency bands (from 700 MHz to 2.7 GHz) is a challenge
- ❑ On Chip Isolation – managing 5+ receivers, as well as multiple transmit chains, on the same die requires a very effective isolation strategy.
- ❑ Operational Bandwidth – Narrow bandwidth with high stop band attenuation for legacy 2G protocol support. 3G protocols have medium bandwidth and 4G has multiple bandwidths including very wide bandwidths for LTE for example.
- ❑ On Chip Calibration – Required for each standard to maintain IQ balance and DC carrier suppression. Algorithms may vary with bandwidth, frequency and temperature
- ❑ Sampling – Clocks must be synchronized for multiple inputs and outputs as well as varying symbol and interface rates.

5.0 ARCHITECTURAL TRADEOFFS

In developing a RFFE reference design, such as the one shown in Figure 2 which includes the BitWave Softransceiver RFIC for SDR, design engineers considered several tradeoffs between conventional architectures and the SDR architecture to best manage the three key metrics; cost, performance and power when compared to more traditional fixed architectures.

- ❑ Multi-band Support – SDR transceivers do not eliminate the need for RF front end filtering. Thus, there is a tradeoff between number of parallel inputs (multi-band, low noise paths) and die area (cost). Most commercial phones operate today with 7 or fewer bands so designing an SDR RFIC for a maximum use case of 8 bands encompasses most uses cases without increasing cost. Using a multi-port single tunable LNA as BitWave does, further reduces the die area over the traditional approach of implementing 8 independent fixed function LNAs on chip.
- ❑ Sensitivity – Improved linearity and lower noise figures are essential to good receiver sensitivity. The design has to carefully balance bandwidth, noise contribution and device linearity. Allowing for each components bias to be set based upon mode of operation and performance requirements balances power consumption versus performance.
- ❑ ACP – Improved transmit linearity is essential to meeting ACP requirements. The RF design of a circuit which exhibits high linearity, moderate output power, a wide frequency band from 700 MHz to 2.7 GHz and operation without the usual transmit SAW filter is

difficult at best. Power consumption is also a limiting consideration. Successful design requires correctly balancing the rejection achievable using analog vs. digital sections of the radio. In particular, a survey of specifications including protocols from GSM to HSPA to LTE showed that a transceiver may need in excess of 50 dBm IP2 and 30 dBm IP3. After due analysis, it was concluded that the design of a purely analog circuit that delivered that performance would be prohibitive in size and power consumption. The solution was found in the use of digital pre-distortion. Since over 50% of the BitWave Softransceiver already consisted of digital circuitry, it was very area and power efficient to use those same circuits to implement a digital pre-distortion to improve the IP3 performance of the chip while minimizing size and power.

- Bandwidth – The ability to support multiple filter sizes with configurable cutoff is a key requirement. However ABB power consumption is a limiting consideration. Successful SDR design requires correctly balancing the rejection in both analog and digital sections of the radio. In particular, analog rejection can be traded off against ADC dynamic range and digital filtering, while ensuring the Softransceiver supported analog filter bandwidths up to 20 MHz.
- Calibration – Each protocol will require separate calibration values since the operating frequency bands and bandwidths change for each protocol. Chips such as BitWave's Softransceiver RFIC are capable of generating their own test tones however tone placement is critical to developing calibrations that consistently perform across the desired bands. In addition, each receive path must be separately calibrated which further complicates routing of the test signals.
- Channel Matching – Using two fixed function (fixed for carrier frequency, bandwidth and performance) receivers for MISO systems normally means using identical on-chip layouts to try to minimize differences which would then manifest themselves as issues for channel matching. Using an architecture that is programmable by nature means circuits can be laid out for optimal cost and then they can be measured and calibrated for ideal matching at minimal power consumption.

6.0 SUMMARY

Designers have worked diligently to increase the capability of each new wireless technology while keeping pace with the growing demands for both voice capacity and data throughput. Many current efforts are focused on the implementation of MIMO (multiple input multiple output) technologies for increased data rates. WiFi (802.11n), WiMAX, HSPA, EVDO and LTE all use various types of MIMO to increase the available data throughput between the network and a wireless client.

Unfortunately for designers, even as new technologies are developed to support the bandwidth intensive applications which consumers desire, the technologies themselves present designers with ever more challenging constraints. New MIMO technologies (in conjunction with existing legacy protocols) will drive demand for multi-band, multi-protocol devices and will raise additional challenges to minimize cost and size while maintaining performance.

The design challenges faced by RFIC and radio designers are the same for MIMO as for legacy radio designs and include sensitivity, isolation, adjacent channel power as well as MIMO specific goals such as gain imbalance and clock sync. MIMO simply makes these all more difficult as the designer now has even more radios to integrate. The multiple channels used by a MIMO radio also make on-chip isolation more difficult. SDR offers a solution both for legacy multi-band radios as well as MIMO applications.

MIMO technology integration risk and cost is reduced by utilizing programmable circuits in the RFIC design. Successful design of programmable RFICs (SDR) requires careful analysis of the performance tradeoffs possible when supporting multiple bands and protocols. Then architectural decisions can be made which will support a low cost, small, and power efficient SDR implementation. Today, such implementations are already being done at companies such as BitWave Semiconductor and are exemplified by their Softransceiver™ RFIC platforms.