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WiMAX

## RF System and Circuit Challenges for WiMAX

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## ABSTRACT

Broadband Wireless Access has occupied a niche in the market for about a decade, but with the signing of the 802.16d standard it could finally explode into the mass market. Intel's baseband transceiver chip is flexible enough to accommodate Radio Frequency Integrated Circuit (RFIC) architectures of today and the future. With the emergence of this standard an ecosystem is developing that will allow multiple vendors to produce components that adhere to a standard specification and hence allow large-scale deployment. One of the major challenges of the 802.16d standard is the plethora of options that exist; Worldwide Interoperability Microwave Access (WiMAX) will address this issue by limiting options and hence ensure interoperability. The result will allow manufacturers of Radio Frequency (RF) components and test equipment to have their products used for mass deployment.

In this paper, we focus on the various RF challenges that exist on a RF system-level and show how such challenges can translate into circuit designs. The RF is made more complicated by the fact that WiMAX indeed addresses wireless markets across the world both in licensed and unlicensed bands. Thus, solutions have to be flexible enough to allow for the many RF frequency bands and different regulations around the globe. Several major RF architectures are discussed and the implications for WiMAX specifications are explored, in particular both Intermediate Frequency (IF)- and I/Q-based structures are investigated.

Part of our discussion will provide insight into the cost and performance tradeoffs between Time Division Duplex (TDD) and Frequency Division Duplex (FDD) systems both in licensed and unlicensed bands. It is generally accepted that TDD systems offer cost advantages over their FDD counterparts; however, most licensed bands intended for data applications operate with FDD systems in mind. Some of the RF subsystem

blocks that have stringent WiMAX specifications are also elaborated upon: these include synthesizers, power amplifiers, and filtering. These fundamental subsystem blocks are where most of the transceiver costs reside; the same blocks are also responsible for most of the RF performance.

The industry is moving towards using Orthogonal Frequency Division Multiplexing Access (OFDMA) and either spatial diversity or beam forming techniques to enhance link margins. We touch on the RF challenges associated with these techniques. Finally, we view some of the important WiMAX specifications for RF and the implications for the design of RF circuits, which include SNDR, channel bandwidths, RF bands, noise figures, output power levels, and gain setting. Some important differences between WiMAX and 802.11 RF specifications are also highlighted.

## INTRODUCTION

As the RF challenges mount so do the costs of the Radio. For WiMAX to be successful the cost vs. performance equation has to be balanced carefully. Two extreme examples of this cost and performance equation are a Single In Single Out (SISO) system from Hybrid Networks (now defunct) requiring Line of Sight (LOS) radios. LOS radios result in truck rollouts utilizing experienced technicians to set the equipment up. However the cost of the radio is low due to its simplicity. In general, the SISO radio requires expensive installation and reliability is poor; link margins are typically 145 dB. On the other hand, Iospan Wireless (now defunct) demonstrated a Multiple In Multiple Out (MIMO) radio with a 3x2 system; i.e., three receive and two transmit chains. It was able to support link margins of 165 dB that could penetrate inside homes in multipath environments. With this ability, the issue of costly truck rollouts is eliminated; however, the cost of the multiple radio chains becomes a deterrent. Still, as Radio Frequency Integrated Circuit (RFIC) integration

improves, costs will head down. WiMAX, through the use of integration and advanced techniques to increase link margins, should be able to achieve reliable wireless systems at a reasonable cost.

## RF ARCHITECTURES

This section describes the plethora of tradeoffs and challenges for RF architectures for WiMAX-related radios. We discuss Frequency Division Duplex (FDD) and its cousin, Half FDD (HFDD) as well as Time Division Duplex (TDD). Intermediate Frequency (IF), Direct Conversion or Zero Intermediate Frequency (ZIF) as well as variants of these are presented. The interface between the Baseband (BB) chip and the radio must be carefully designed, so these challenges are exposed. Methods to improve Link Margins, namely MIMO, and beam forming can be used in WiMAX. In addition, OFDMA, which allows for subchannelization, improves capacity efficiency. We discuss the RF challenges inherent in the use of these methods.

### TDD/FDD and HFDD Architectures

#### TDD

Figure 1 shows a TDD radio. The darkened blocks are the most costly in the radio. TDD systems utilize one frequency band for both Transmit and Receive. This concept requires only one Local Oscillator (LO) for the radio. In addition only one RF filter is necessary and this filter is shared between the Transmitter (TX) and the Receiver (RX). The synthesizer and RF filters are major cost drivers in radios. Having one synthesizer saves on die area; a large part of the radio die size can be taken up by the LO, in particular the inductor, which is part of the resonant structure.

The RF filter in a TDD system is not required to attenuate its TX noise as severely as in FDD systems. The TDD mode prevents the TX noise from self jamming the RX since only one is on at any time. As well as relief of the RF filter specifications, having just one RF filter saves cost and space. It should be noted that to ensure Transmitting radios do not interfere with nearby Receiving radios, the specification for TX noise cannot be eased with abandon. The Transmission noise from Radio 1 will interfere with the Received signal of Radio 2. Thus, although self-jamming specifications are made easier, collocation specifications must be carefully considered. There is a notable savings in power from the TDD architecture, a direct result of turning the RX off while in TX mode and vice versa.

Several disadvantages exist, however. There is a reduction of data throughput since there is no transmission of data while in RX mode unlike FDD

systems. The Medium Access Control (MAC)-level software tends to have a more complicated scheduler than an FDD system since it must deal with synchronizing many users' time slots in both TX and RX mode. It must be noted that while the RF filtering specifications are relaxed, this tends to imply that subscriber stations will have to be spaced further apart from each other to avoid interference. In essence, the system must handle fewer users in a given area than in FDD systems.

TDD systems are most prominent in unlicensed bands; in these bands the regulations for output noise are more relaxed than in licensed bands. Thus, inexpensive RF filters can be specified. Since the unlicensed bands are free of cost there is competition to drive for the lowest cost architecture, TDD.

#### FDD

Figure 2 shows an FDD radio. A high-performance RF front-end is required in FDD systems. Collocation issues from a TX noise perspective are solved since the worst-case scenario of self jamming is not possible. FDD systems do not have to switch the RX or TX; this alleviates settling time specifications, which results in a simpler radio design. The MAC software is simpler because it does not have to deal with the time synchronization issues as in TDD systems.

The radio must be capable of data transmission while in Receive mode without incurring any degradation in Bit Error Rate (BER). To ease the burden on the filter there is a gap between the TX frequency band and the RX band; however, carriers wish to minimize this space. Typically this is a separation of 50 MHz to 100 MHz.

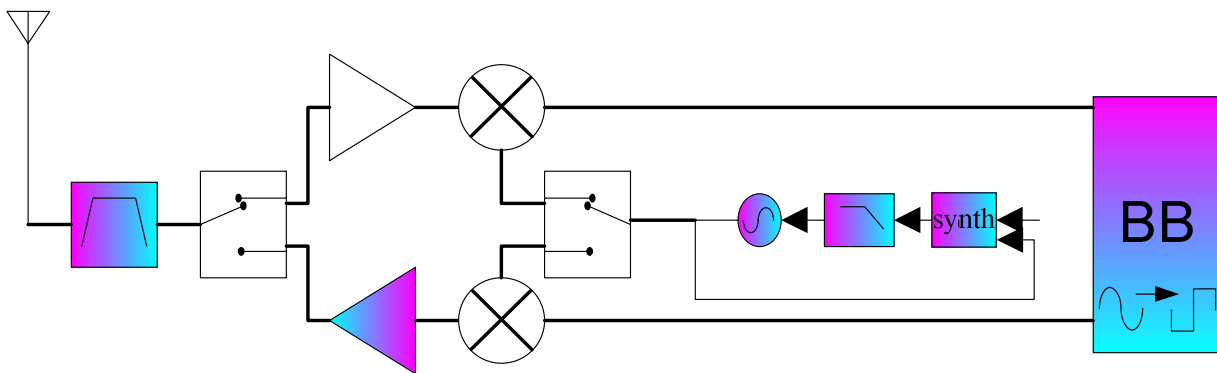


Figure 1: TDD radio

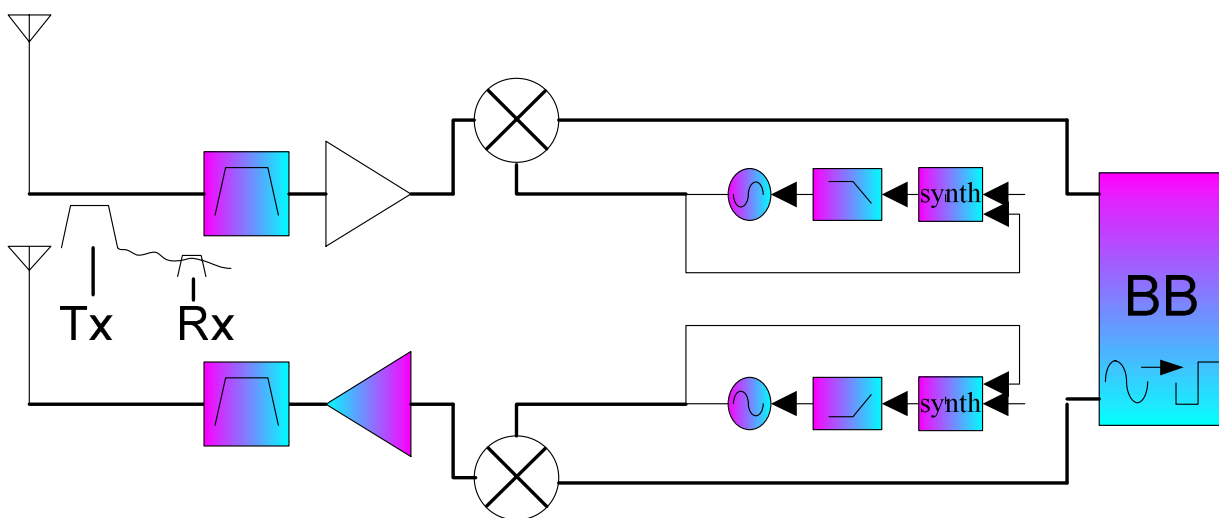


Figure 2: FDD radio

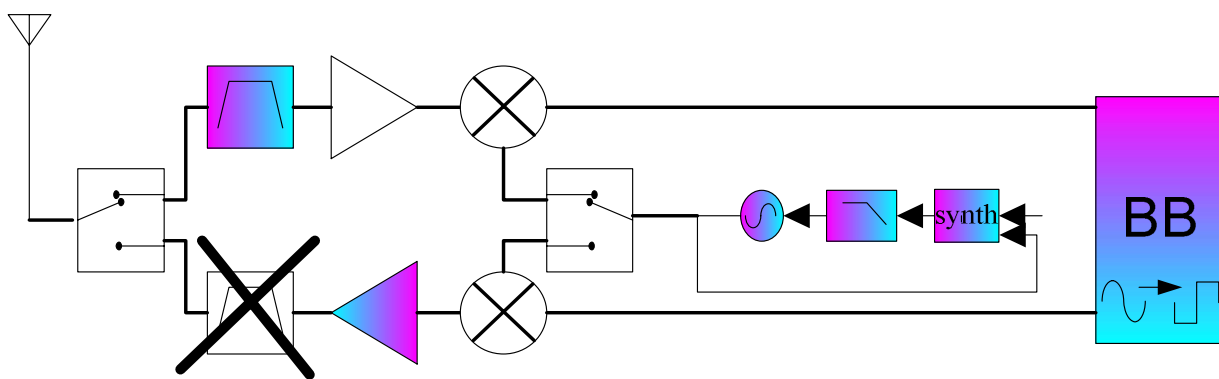


Figure 3: HFDD radio

We try to specify the TX noise to be 10 dB below the RX input noise floor, in which case the TX noise will only degrade the RX by 0.5 dB. Unfortunately the specifications usually tie FDD systems to using cavity

filters or 4-pole ceramic filters. Cavity filters run in the order of \$35 each while ceramic filters can be in the \$8 range. Most licensed bands do not have one standard structure but are flexible; i.e., the TX and RX could be

swapped in different geographical regions. This results in having to design several flavors of the filters, something that does not lend itself to mass production of the filters.

To give an idea of the filter requirements in FD:

$$\text{Filter\_rej (dB)} = \text{Po(dBm/Hz)} - \text{Mask (dBc)} - [174 + \text{NF-cochannel\_rej}]$$

For example, if power output  $P_o = -33$  dBm/Hz, in a 1 MHz signal bandwidth, output power is +27 dBm.

Mask of TX is = 60 dBc; i.e., the thermal floor of TX is 60 dB below the  $P_o$ .

NF is Noise Figure of Receiver = 5 dB.

CoChannel\_rej is how far in dB is the undesired signal below the desired signal. = 10 dB i.e., the undesired signal is 10 dB below the desired signal.

We get Filter\_rej at the RX frequency of 86 dB. If the RX is 100 MHz away from the TX, this filter is an expensive cavity filter.

The full-duplex nature of the circuit requires a separate TX and RX synthesizer. The RFIC die area is significantly impacted by the inductor of a resonant circuit; this is part of a Voltage Controlled Oscillator (VCO) which is used in the synthesizer. Thus, two of these have a large impact on the cost of the RFIC.

A final note on FDD systems is that they are power hungry; this also increases the cost of the power system. Thus, FDD is not an ideal platform to build portable or mobile radios.

FDD systems are typically deployed in licensed bands e.g., 5.8 GHz, 3.5 GHz, 2.5 GHz: the spectrum is expensive. The cost of the spectrum forces the carriers to serve as many users as possible. Capacity must be optimized, which results in carriers favoring FDD architecture. Clearly it is very desirable to have the Base Station work in FDD, but to reduce costs, the Subscriber Station could be a HFDD structure.

### HFDD

Figure 3 shows a HFDD radio. The HFDD architecture combines the benefits of the TDD systems while still trying to allow for frequency duplexing. The Base Station can operate in FDD and retain its capacity advantage over TDD systems. This can lower the cost of the radio significantly at the Subscriber Station where the unit cost must be driven down.

The cost reduction appears in the form of relief in the RF TX filter, and since there is one synthesizer the die area of the RFIC shrinks. Power savings are also realized as in TDD systems.

Once again the collocation issues have to be addressed carefully. Self jamming is not a problem as in TDD but then too much relief on the TX filter can result in interference between users.

There is also a capacity loss at the Subscriber Station since the radio cannot simultaneously Transmit and Receive.

The HFDD structure can be used in both licensed and unlicensed bands. The Transmit and Receive can be at the same frequency as in TDD systems or separated by a frequency gap as in FDD. This type of radio is very flexible. Its cost structure approaches that of a TDD radio.

In summarizing the duplexing schemes, Intel's baseband chip can support both TDD and HFDD modes. This takes care of most of the Subscriber Stations. In a typical deployment the ratio between the Base Station and Subscriber Stations is 1 to 100, due to the low volume of the Base Station. The Physical (PHY) and Media Access Control (MAC) layer need not be designed as a custom chip; a Field Programmable Gate Array (FPGA) could be cost effective. It is possible to connect two baseband chips together to support an FDD scenario for the Base Station.

We discuss various radio architectures in the following sections; these include IF- and I/Q-based architectures and some variants on these. Some of the interface between the radio and the baseband chip is deliberated.

### RF Interface

The baseband chip digitizes the analog signal and performs signal processing. This PHY layer chip contains the blocks for filtering, Automatic Gain Control (AGC), demodulation of data, security, and framing of data. The algorithms that do power measurements, such as AGC and RF selection can be taken care of by the lower-level MAC. As can be seen, there are common parameters such as AGC that are shared across the PHY, MAC, and radio.

The major blocks within a radio that need control from the baseband IC are AGC, frequency selection, sequencing of the TX/RX chain, monitoring of TX power, and any calibration functions e.g., I/Q imbalance. Each of these blocks are tightly coupled with the PHY and/or lower-level MAC.

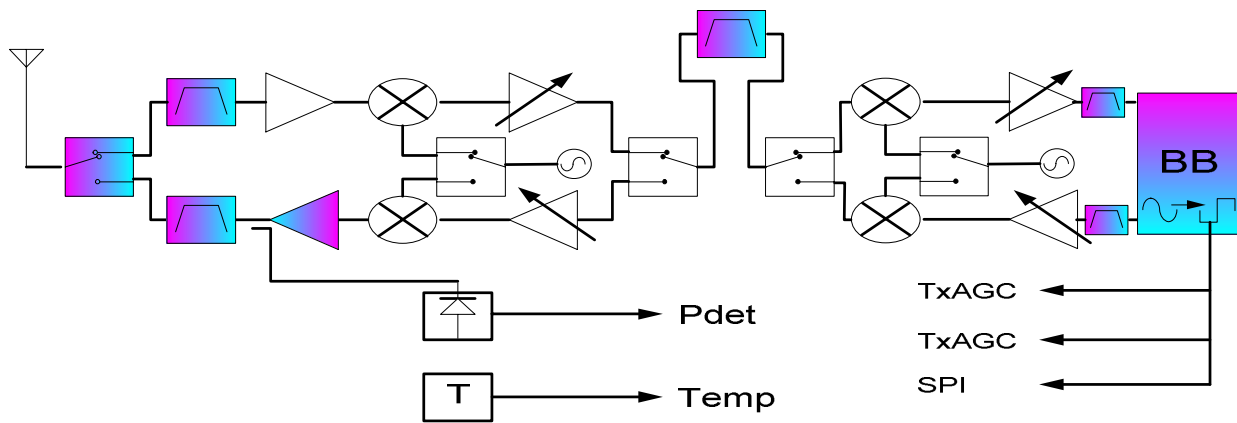


Figure 4: HFDD architecture

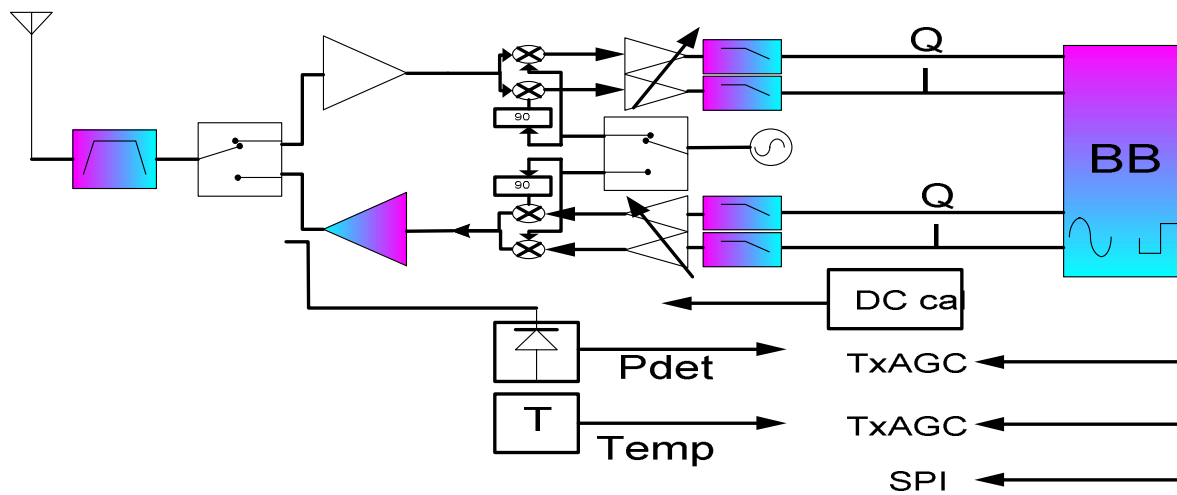


Figure 5: Block diagram of ZIF architecture

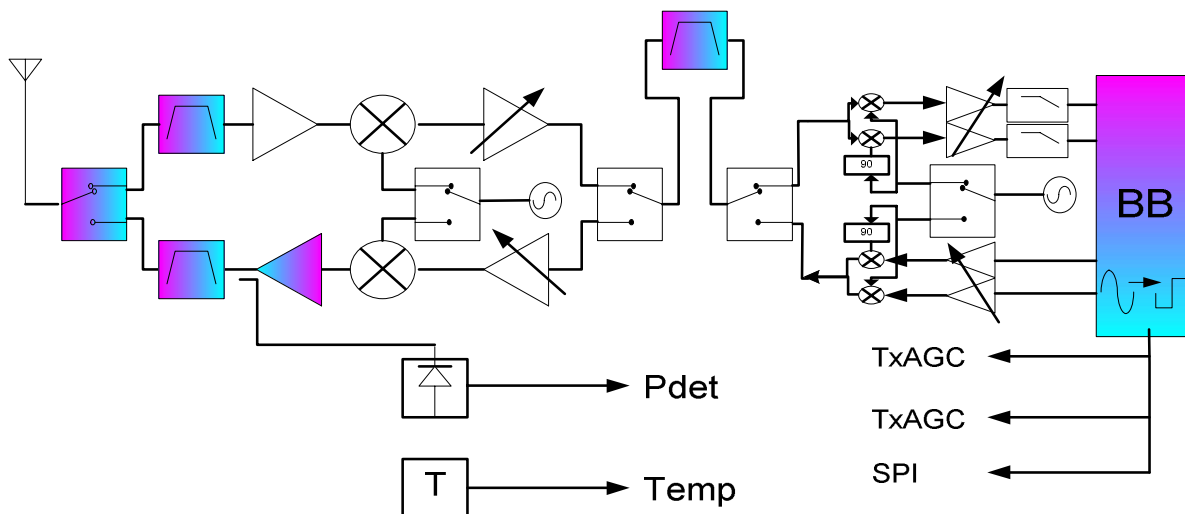


Figure 6: I/Q Baseband architecture 1

A reasonable way to communicate with the radio is through a Serial Peripheral Interface (SPI); it minimizes pins on the RFIC.

Usually the SPI is used to control the synthesizer. In order to make the interface more useful so that it can control the digital AGC of an RFIC and help perform measurements of power and temperature, the SPI needs to be a dedicated time-critical element. In this way, the SPI can respond to AGC, measurements, and frequency commands in a timely and predictable manner. A note of caution, however: traffic on the SPI could cause interference to the incoming signal and put spurs on the TX signal. Therefore all SPI communication should only occur in the TX to RX time gaps. Other interface blocks are General Purpose Input/Output (GPIO), Pulse Width Modulators (PWM), DACs, and ADCs.

The AGC is split into RX AGC and TX AGC. In the RX AGC, response times may have to be rapid to cope with the changing RF channel in a mobile environment, in the order of usec. However, in a fixed wireless application, the channel change is in the order of msec. The TX AGC can be relatively slow in steady state. However, in powering up the TX, the AGC may need to attain the correct power level in the usec time frame. Typically, the AGC is controlled through single-bit digital to analog converter, i.e., sigma delta converters. Either of these methods have clock noise that needs to be filtered out. The tradeoff here is that for a large slope of the RF AGC, the clock noise must be filtered to avoid distorting the signal. However, the filtering introduces a delay that slows down the AGC response. To increase the time response of the AGC, multibit DACs can be used.

The selection of the RF is done through the SPI. For HFDD systems there is a settling time from TX to RX frequency, and the loading of the SPI is part of the timing budget.

Monitoring the temperature of the radio is a slow process; however, power measurements either from TX or RX require synchronization with the TX/RX timing gaps. Interfacing to the radio must take into account the sequencing of the radio; for example, in the case of the Transmitter we need to switch the antenna, enable the TX and load frequency, change the TX gain, turn on the PA, and finally ramp the modulation. Switching to the RX requires sequencing the TX down to avoid spurious emissions.

Two fundamental parameters drive radio design: noise and linearity. The goal is to attain as much dynamic range in the presence of undesired signals. This requires a distribution of gain and filtering through the TX or RX chain. Many architecture designers struggle with the

placement of this gain and filtering. We look at some of these radio architectures in the next sections.

### **HFDD Architecture**

The details of the HFDD architecture are shown in Figure 4. There is a frequency separation between the TX and RX so separate filtering is necessary in the RF front-end. However, the IF is shared between the TX and RX. A Surface Acoustic Wave (SAW) filter provides for excellent adjacent/alternate channel rejection. There is a final frequency conversion to a lower IF that can be handled by an AD. Much of the AGC range is at the lower IF. An AGC range of 70 dB is required; the absolute gain is higher to overcome losses. For the TX AGC, a 50 dB range is required. The AGC can be controlled through PWMs for analog AGC or GPIO for step attenuators.

Two synthesizers are necessary for the double conversion. The low-frequency synthesizer is fixed and does not have to be switched during the RX to TX change. The high frequency synthesizer is the challenging block; it is required to settle within 100 usec. The step size could be as low as 125 KHz in the 3.5 GHz band.

Several signals are also sent to the Baseband IC: TX power level (sometimes RX power level), temperature, and synthesizer lock detect. The power level is most important since power output has to be as close as possible to the intended value and still within regulations.

### **TDD Architecture**

TDD is a good example of direct conversion transceivers or ZIF. Figure 5 is a block diagram of the ZIF architecture. The TX and RX frequencies are the same so the RF filter can be shared. The downconversion process is done with I/Q mixers; these consume a small area on the die. The issue with such mixers is they need to be matched; otherwise, distortion is introduced. Also LO feedthrough effects tend to increase due to dc imbalances. These effects are significant since most of the gain is at the final conversion. The dc offset results in a reduction in the dynamic range of the AD since extra bits are required for this offset. A dc calibration circuit can be implemented to reduce the effect. In addition, I/Q imbalance will result in distortion. The problems are aggravated by temperature, gain changes, and frequency. By going to dc, low-pass filters can be used that are selective to channels. These can be implemented on chip and can save on cost. It must be noted that the on-chip low-pass filters do consume a large die area. They can also introduce noise. WiMAX

has variable bandwidths ranging from 1 MHz to 14 MHz but as the cut-off frequency is reduced there are significant challenges in the on-chip filter. For such ZIF schemes there must be an Automatic Frequency Control (AFC) loop whereby the Baseband IC controls the reference oscillator of the RFIC. This ensures that any dc leakage terms stay at dc and do not spill over into the desired tones of the OFDM waveform.

### I/Q Baseband Architecture 1

A variant of the HFDD and TDD architectures mentioned above is a combination shown in Figure 6. This structure has the advantage that some filtering is done at an IF removing some of the strain on the dc filters.

In addition, power can be saved by having the final stage operate at lower frequencies. The issues related to I/Q mismatch and dc leakage are lessened by having less gain at dc and operating the mixers at an IF instead of an RF. Savings can be realized at the TX filtering: because the SAW can do most of the filtering there is no need for the TX low-pass filters. This has the added advantage that the I/Q mismatch from the low-pass filters is removed. One drawback is that two Digital to Analog (DA) converters and two Analog to Digital (DA) converters are required.

### I/Q Baseband Architecture 2

To address the problems of the I/Q baseband radios another architecture is considered. Figure 7 shows an RX where the signal is mixed to dc then mixed up to a near Zero IF (NZIF). By going to dc the IF filter is removed and filtering can be done on-chip. To avoid dc and I/Q problems the signal is mixed to an IF. The choice of IF is greater than half the channel bandwidth. This structure allows the gain to be distributed between the dc and IF stages. Also, as an added benefit, only one AD is required. For the TX stage, I/Q upconversion is used.

### RF Challenges for MIMO, AAS, and OFDMA

Antenna diversity is an important technique that can inexpensively enhance the performance of low-cost subscriber stations. It can help mitigate the effects of channel impairments like multipath, shadowing, and interference that severely degrade a system's performance, and in some cases make it inoperable. By using multiple antennas, a system's link budget can be significantly improved by reducing channel fading, and in some implementations, by providing array gain. There are several designs, all of which yield excellent gains, that can be implemented, ranging from low to high complexity. The basic designs are Selection

Diversity Combining (SDC), Equal Gain Combining (EGC), and Maximum Ratio Combining (MRC). SDC is a scheme of sampling the receive performance of multiple antenna branches and selecting the branch that maximizes the receiver signal to noise ratio. To work properly each antenna branch must have relatively independent channel fading characteristics. To achieve this, the antennas are either spatially separated, use different polarization, or are a combination of both. The spatial correlation of antennas can be approximated by the zero order Bessel function given by the equation  $\rho = J_0^2(2\pi d/\lambda)$  and shown in Figure 8. From Figure 8, it is seen that relatively uncorrelated antenna branches can be achieved for spatial separations greater than one-third a wavelength, supporting the requirement for small form-factor subscriber stations.

For optimal SDC performance the selection process and data gathering must be completed within the coherence time. The coherence time is the period over which a propagating wave preserves a near-constant phase relationship both temporally and spatially. After the coherence time has elapsed the antennas should be re-sampled to account for expected channel variations and to allow for re-selection of the optimal antenna. For a TDD system, where reciprocal uplink (UL) and downlink (DL) channel characteristics are expected, the selected receive antenna can also be used as the transmit antenna. Although the SDC technique sounds rather simple, surprisingly large system gain improvements are possible if the algorithms can be designed effectively.

There are two figures of merit for judging the gain enhancement of an antenna diversity scheme. These are diversity gain and array gain. Under changing channel conditions, diversity gain is equivalent to the decrease in gain variance of local signal strength fluctuations of a multiantenna array system when compared to a single-antenna array system. The result of increased diversity gain is the reduction in fading depth. This is due to each antenna of a multiantenna system experiencing independent fading channels over frequency and time. The second figure of merit, array gain, is the accumulation of antenna gain associated with increased directivity via a multiantenna array system. In a typical system, as the number of antenna array elements grows, the gain increases  $10 \cdot \log(n)$ , where  $n$  is the number of antenna array elements. This means a doubling of gain for every doubling of antenna elements.

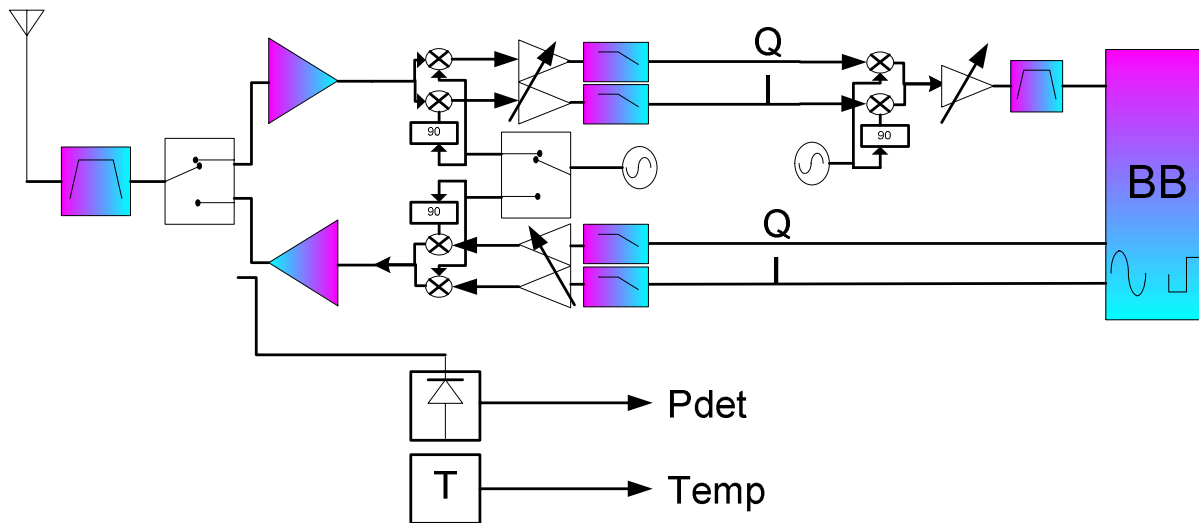


Figure 7: I/Q Baseband architecture 2

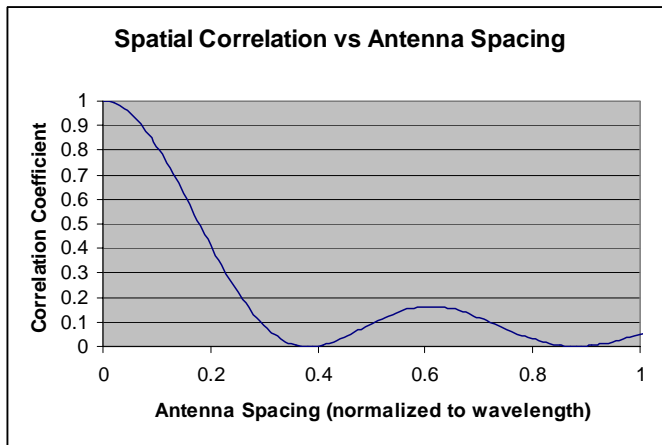


Figure 8: Bessel function approximation of the spatial correlation coefficient

The SDC scheme exhibits no array gain, as only one from  $n$  antennas is used at any instance. However, through spatial or polarization diversity, the SDC achieves stellar diversity gain, as shown in Table 1.

Table 1: Performance enhancement of antenna diversity

Antenna Scheme	Diversity	Antenna Gain (SUI3,SUI4 model w/100uSec Rayleigh delay spread)	Implementation Complexity
(4 Antenna Branches)			
Selection Diversity Combining		8 dB	Low
Equal Gain Combining (Analog)		9 dB	Mid
Maximum Ratio Combining (Analog)		10 dB	High
Maximum Ratio Combining (Digital)		14 dB	High

Another basic antenna diversity technique using multiple antennas is EGC. Instead of selecting one from  $n$  antennas, as in SDC, the algorithm combines the power of all antennas. The multiple independent signal branches are co-phased, the gain of each branch set to unity (equal gain), and then all branches combined. The EGC antenna diversity technique achieves diversity gain, while also producing array gain. Thus, EGC provides higher antenna diversity gain than SDC, as can be seen in Table 1. To achieve an antenna diversity benefit closer to optimal, MRC of the antenna elements

can be used. This technique is similar to EGC, with the exception that the algorithm tries to optimally adjust both the phase and gain of each element prior to combining the power of all antennas. The summation of the signals may be done in either the analog or digital domain. When summation occurs in the digital domain, RF hardware for each independent antenna branch is required from RF to baseband. When MRC is realized in the analog domain, summation may occur directly at RF. Performance is better when processing is done in the digital domain, as frequency selective channel characteristics are compensated for in each branch. In an analog MRC, only the average channel distortion over frequency is used to compensate for the amplitude and phase variation between array elements. In digital MRC, discrete frequency components across the signal bandwidth are co-phased and individually weighted based on SNR at the receiver. MRC realizes the highest antenna diversity gain compared to the other techniques discussed, (refer to Table 1). Although the complexity is high, MRC implementation costs are decreasing through better RF integration and reduced CMOS geometries of the baseband processor integrated circuit.

MIMO and AAS systems are used to improve link margins. Using MIMO requires multiple RF chains with multiple ADs. With integration, the cost of these multiple chains should come down. Isolation between the receive chains needs to be in the order of 20 dB, which is easy to accomplish. There are no matching requirements for the gain and phase between the RX chains, which means that the radio design is simplified. MIMO works well in TDD or FDD, and its improvements to link margins are observed in multipath environments.

In contrast, for AAS or beam forming systems, the TX and RX chain need to be matched across frequency and over gain and phase. However the subscriber station does not have multiple chains. Such systems work well in TDD mode since the TX frequency is the same as RX frequency. AAS estimate the TX channel based on information they get from the RX channel, so having the same frequency improves these estimates.

OFDMA allows the RF channel to be split into subchannels. As a result, the power can be boosted since fewer tones are used. For users that do not TX much data on the UL, a smaller bandwidth can be allocated. Thus, more efficient use of the bandwidth can be made on a per-user basis. This technique does pose some challenges for the radio. Interference and noise between subchannels must be carefully considered over the whole transmit gain range. This problem is similar to the FDD case except there is no frequency separation. Therefore, noise performance and linearity must be

excellent since there is no help from filtering. Another issue with OFDMA is that the RF must be maintained to <1% accuracy; otherwise, different users will collide with each other within the subchannels.

We have discussed various duplex schemes: RF architectures were outlined and some methods to improve link margin considered. Next, we discuss the particular circuit blocks within the RF system that are particular cost drivers.

## RF SYSTEM BLOCKS

There are three main areas of cost for a radio: synthesizer, power amplifier, and filter.

### Synthesizer

The synthesizer generates the LO that mixes with the incoming RF to create a lower frequency signal that can be digitized and processed by the Baseband IC. The WiMAX specifications call for a high-performance synthesizer. The synthesizer block takes up a large part of the RFIC die area and is therefore a costly component of the RFIC. The Integrated Phase Noise is <1deg rms with an integration frequency of 1/20 of the tone spacing to 1/2 the channel bandwidth. Thus, for the smaller bandwidths of 1.75 MHz, the integration of the phase noise can start as low as 100 Hz. For HFDD architectures, the TX to RX frequency has to settle within 100 usecs. The step size of the channel is 125 KHz in the 3.5 GHz band. In order to settle and maintain this step size, fractional synthesizers must be considered. It must be noted that as RF increases, obtaining phase noise <1deg rms becomes a challenge. As well as all the radio LOs, the clock for the AD must be also viewed as an LO that adds phase noise to the overall jitter specification.

### Power Amplifier

Wideband digital modulation requires a high degree of linearity. Linearity implies higher power consumption. The tradeoff between efficiency and linearity is a constant battle. For WiMAX, a power amplifier can work at 4 to 5% efficiency for about a 6 dB backoff from output P1 dB. Such a backoff results in about a 2.5% Error Vector Magnitude (EVM) or 32 dBc of Signal to Noise plus Distortion (SNDR). With a class AB Power Amplifier (PA) the efficiencies can run as high as 15 to 18% with similar EVM numbers.

A much overlooked parameter in PA design is settling time. When a PA is switched on from cold the power level will overshoot (or undershoot), then settle out. This settling time can be as poor as 100s of msec to get within 0.1 dB of the final value. For OFDM symbols,

the RX has to estimate the power of a tone from the beginning of a frame to the end of a frame. If there is a droop of power from the beginning to the end of  $>0.1$  dB across the frame, the BER for 64 Quadrature Amplitude Modulation (QAM) will increase. The primary cause for this power droop is that the bias circuits and the output power Field Effect Transistor (FET) are at thermally different points. Since this phenomenon is thermal the effect can last 100s of msec. To mitigate power droop the bias circuits have to be placed as close to the output FETs as possible so they see the same temperature. In some cases the PA may have to be turned on ahead of the TX cycle to allow the PA to stabilize and remove some of the droop. This implies having a trigger signal based on when data are to be transmitted. Having the MAC and PHY realize this trigger is not a simple matter. The budget of 100 usec for HFDD is taken up by the synthesizer settling and any PA turn-on issues. A possible solution is to design the PA so that the PA settling is  $<5$  usec.

## Filtering

Filtering is required to eliminate undesired signals from adjacent or alternate channels. Any noise from these immediate signals can leak noise into the desired band. Filtering at the receiver does not help; only a clean transmitted signal will prevent such degradation. Regulatory bodies control the transmitted mask.

For the adjacent channel problem the challenge is between linearity and filtering complexity. If the undesired channels are filtered out then less backoff in the radio is required and more of the AD bits are available for fading margin. SAW filters have depreciated in cost and are now in the  $<\$2$  range for high volume. SAWs provide the optimum filtering. A significant drawback is that the technology does not fix the maximum channel bandwidth that can be supported. Another issue is that it is difficult to support a large array of RF bands with a fixed IF. For spurious analysis, the optimum IF depends on the RF.

Filtering on-chip requires a large die area and as the channel bandwidth is reduced the die size increases. On-chip filters also produce more noise. A benefit is that the filter can be adjusted to accommodate the various bandwidths.

For I/Q-based designs, on-chip filters are necessary. The filters can be matched much more closely if on-chip. This minimizes the I/Q mismatch due to filtering. The final channel selectivity is performed in the Baseband IC using digital filters.

Filtering, like gain, must be distributed between the RF and subsequent down conversions. The RF filtering is

used to reduce the image and far blockers; i.e., out of the RF band. The RF front-end must be linear enough to support the largest in-band blocker. In addition, reciprocal mixing of the LO with the undesired signal must be considered. The RF filters are typically  $>50$  MHz wide and are constructed from various technologies each with different Qs. The larger the Q, the larger the size and the better filter shape. In FDD systems cavity filters may have to be used; these are large mechanical cavities and can cost  $>\$30$  in high volume.

## WIMAX SPECIFICATIONS

We highlight some of the WiMAX RF specifications and contrast them with 802.11 specifications where possible. The specifications are broken into RX and TX. It should be noted that most designs aim to do better than the standards, hence these numbers should be viewed as the minimum requirements. In addition we note the impact on the RFIC due to these specifications.

**Table 2: RX specifications**

Parameter	802.11*	WiMAX	Impact on RFIC
NF (dB)	10	7	The implication for the RFIC is that it may require an external LNA to meet a 5 dB NF.
SNDR-64-QAM (dBc)	<29	29	The implication for the RFIC is excellent phase noise for tone spacing of 5 KHz and linearity. For 802.11 the tone spacing is larger; i.e., 300 KHz thus phase-noise requirement is less stringent.
Alternate Channel Rejection (dBc)	NA	30	The AD bits may be used for allowing the adjacent channel through and some of the alternate channel. The digital filter would perform the bulk of the close-in channel filtering. Results in increase in linearity for RFIC.
HFDD mode	No	Yes	More complicated synthesizer to support dual frequency.
Channel BW (MHz)	10; 20	1.25 ;1.75;3.5 ; 7;14; 5;10;20;	The implication for the RFIC is that the smaller bandwidths result in a complicated synthesizer due to the smaller step size. Filtering for an array of bandwidths introduces adjacent channel compromises.

**Table 3: TX specifications**

Parameter	802.11*	WiMAX	Impact on RFIC
Licensed Band Operation	No	Yes	The implication for RFIC is that the regulations are tighter and increase cost.
AGC Range (dB)	NA	50	The implication for RFIC is that linearity must be maintained over AGC range for 64-QAM.
SNDR (dBc)	<31	31	The implication for RFIC is NF of TX chain, linearity and phase noise.
OFDMA	No	Yes	Noise and linearity must be maintained over the AGC range for in-channel cases.
Smart Antenna	No	Yes-Option	More RF chains for MIMO or matched RF chains for beam forming.
Power Output (dBm)	Restricted in unlicensed bands	<24 dBm	The implication for RFIC is PAs require higher efficiency, or even smart PA technology.

## SUMMARY

WiMAX poses significant challenges to the RF subsystem. Several RF architectures were discussed both in FDD, HFDD, and TDD modes. The cost-performance tradeoffs in the various architectures were deliberated: these included IF- and Baseband-type radios. Some of the more important RF system blocks, synthesizers, power amplifiers, and filtering that relate cost and specifications were discussed. Finally, some of the WiMAX radio specifications were highlighted and contrasted with 802.11, and the impact to RFIC development was noted.

## REFERENCES

- [1] 802.16 REV d/D5- 2004.  
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## AUTHORS' BIOGRAPHIES

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