Multiple Antenna Processing for WiMAX

Overview

Wireless operators face a myriad of obstacles, but fundamental to the performance of any system are the propagation characteristics that restrict delivery of signal power, and deployment scenarios that create interference. Broadband applications further exacerbate these problems and continue to create interesting challenges for system designers.

Numerous techniques are used to improve link performance, but the use of multiple antennas provides the best approach to realize the largest gains to address increased coverage or reduced transmit power.

Challenges to Improving Performance

Tremendous innovations have been made affecting communication systems, including modulation and coding concepts, organization of time and frequency resources, RF performance, materials, power consumption, batteries, and production capabilities. And so it is natural to ask what more can be done. As indicated in Table 1, an exciting frontier is space.

Table 1: Near-term potential for innovations and their impact on link performance.

Technology	**Likelihood of New Gains**
Communication Channel. There is a tremendous body of knowledge promoting coding techniques that perform very close to the theoretical bound provided by Shannon's Law.	Very small
Physical Layer Design. Extensive evaluation of time and frequency allocations have led to wideband and narrowband designs which are quite sophisticated and leave little that has not been considered. Some optimization is possible.	Small
MAC Layer Design. Methods for allocating resources have been analyzed. Some improvements in algorithm design may be possible due to processing advancements, or implementation due to protocol refinement.	Small
Frequency Allocation. Increasing channel bandwidth leads to increased channel capacity, but spectrum is typically a highly constrained commodity, especially spectrum suitable for non-line-of-sight scenarios associated with consumer services.	Modest
RF Enhancements. Designing inexpensive radios with performance meeting broadband needs is challenging but possible given the economies of scale that can be supported through consumer services.	Good
Space. Although spatial processing has been used for the past 30-40 years, implementation costs continue to fall such that including spatial technologies can be considered for mainstream consumer applications.	Excellent

RF enhancements and reduced processing costs further bolster this case as the trade off between cost and performance become more attractive. An important consideration is that while spectrum can be extremely expensive, space is free.	

The Cellular Problem

Providing sufficient range and capacity with a wireless link is a given problem that is made more challenging by channel variations. However, the overarching constraint with a multi-user deployment is interference. If this were not the case, the average throughput could be increased (or the range increased) by increasing the transmit power, or any frequency reuse could be lowered to achieve increased spectral efficiency. Techniques that provide good link quality and address interference are needed to provide meaningful improvement in a cellular environment, and as noted above, spatial techniques that do this provide the most likelihood of significant gain.

Multiple Antenna Processing

Using multiple antennas opens a number of possibilities that are unavailable when using a single antenna. The first possibility is spatial diversity, which unlike time and frequency diversity uses a resource that does not negatively impact capacity. Like time and frequency diversity, spatial diversity also provides enhanced system reliability by scaling signals across fades. The second possibility is beamforming, which focuses energy and thereby provides two beneficial factors: increasing signal energy to an intended user, and decreasing interference elsewhere. Both of these factors can be used to realize additional capacity or range across a network. The third possibility is exploiting multiple channels (spatial multiplexing), which greatly increases capacity.

Spatial Diversity

The improvement in signal-to-noise ratio (SNR) when using multiple antennas is a function of array and diversity gain. Beamforming provides array gain by coherently combining energy at each of the antennas, even if the channels are completely correlated. The theoretical array gain for N antennas relative to a single antenna is 10log(N) for the uplink and 20log(N) for the downlink. The gain in the downlink is higher since the power from each transmitter is also coherently combined. In this case the SNR is improved by the array gain, and the probability of a bit error is improved fractionally. Diversity gain results when independent channels exist between the transmitter and receiver such that the likelihood of all channels experiencing a deep fade simultaneously is greatly reduced. Here the probability of a bit error is reduced exponentially and so the amount of margin needed to pad a link budget allocation against fading is reduced.

Hence, there can be SNR gain when using multiple antennas even if the channels are completely correlated. This portion is the array gain, which is a linear gain in SNR. Additional link budget gain is possible if the channels are statistically diverse by reducing the fade margin, and this diversity gain is typically significantly greater than the array gain.

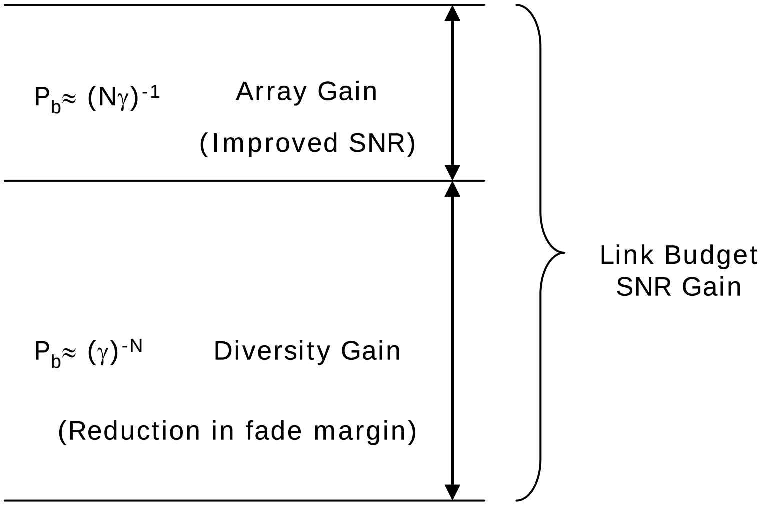

Figure 1: Spatial diversity can provide array and diversity gain. The probability of bit error is reduced fractionally with array gain, and exponentially with diversity gain.

Multiple antennas can be used at the receiver or transmitter, leading to opportunities for receive or transmit gains.

Receive Diversity

Selection combining and equal gain combining are well known approaches for realizing diversity gain, but have performance drawbacks that are easily overcome using the MRC (maximal ratio combining) algorithm. The MRC algorithm can achieve both array gain and diversity gain. Implicit in a standard MRC analysis is the assumption that any channel fading is flat such that each receive path can be modeled by a single complex channel weight, an assumption in WiMAX systems made reasonable by using OFDM with narrow bandwidth subcarriers. The MRC solution entails weighting each receive path proportional to its SNR.

With MRC, interference is considered noise and will therefore dramatically reduce the SNR. In the absence of interference, a beamforming solution can be shown to be equivalent to MRC. However, in the presence of interference a beamforming solution based on maximizing SNR or minimizing MSE (mean squared error) can reject the interference and thereby provide improved performance.

Transmit Diversity

While using multiple antennas at a base station is feasible, a user’s terminal is typically constrained by cost, size, and power such that adding multiple antennas is difficult. Since a base station does not have these same constraints, providing diversity using the base stations antennas during transmission is appealing.

Transmit diversity is often characterized as open or closed loop. Open-loop transmit diversity does not require knowledge of the channel at the transmitter, while closed-loop diversity does.

With open-loop transmit diversity, signals are sent from different transmit antennas, and because of this additional processing is required to achieve diversity and deal with the spatial interference introduced. The most popular processing scheme is space-time coding, where a code known at the receiver is applied at the transmitter. Of the many space-time codes studied, space-time block code (STBC) approaches are supported in WiMAX systems and easily implemented. (Space-time trellis codes can provide better performance but with much higher complexity.) In particular, the Alamouti code is an orthogonal STBC that is both easily implemented and provides optimal diversity order, but is limited to certain combinations of antenna numbers. WiMAX defines a capability with one or two transmit antennas and two receive antennas. Unlike MRC, STBC schemes provide diversity gain but not array gain.

Closed-loop transmit diversity takes advantage of channel information at the transmitter to make efficient use of the transmit antennas. In a TDD system, either channel reciprocity or feedback can be used to acquire this channel information. There are two effective approaches for implementing closed-loop transmit diversity: linear diversity precoding and beamforming. Either approach provides array gain, although only beamforming specifically addresses interference. .

Beamforming

Cellular systems employ orthogonality in time and frequency to distribute limited resources to multiple users. Adding space to the mix adds spatial diversity and allows higher spectral efficiency. Directional antennas (fixed sectors) and frequency reuse support limited spatial processing, but with significant drawback to spectral efficiency. On the other hand, beamforming allows enhanced signal power without a corresponding increase in interference. Although this isn’t free, the expense of increased processing requirements can be an attractive trade off given the benefits.

There are several approaches identified with beamforming:

Beam Switching. Switching between fixed beams has not been successful in cellular systems. Either the beams are too broad or too narrow, and in each case the benefit to cost ratio is low.

Beam Steering. Solutions that try to steer beams perform poorly in broadband applications. Determining a direction of arrival is not obvious due to scattering and multipath, and the solution changes with time.

Switched Diversity. Selecting an antenna has some advantage because of its simplicity, but for a base station it makes much more sense to use more advanced techniques requiring relatively little increase in resources but with significant gains in performance.

MRC (Maximal Ratio Combining). This approach combines the maximized SNR at each antenna. Because the SNR is not jointly maximized over all of the antennas (optimal beamforming), this approach is not optimal but is relatively easy to implement. By using channel state information or channel reciprocity, MRT (maximal ratio transmission) can be used to exploit spatial diversity and array gain on transmission.

Optimal Beamforming. This approach refers to using optimality criteria (maximizing SINR or minimizing mean-squared error) across all antennas. Results are typically formulated in terms of forming beams and nulling interference. The strength of this approach is that the interference reduction is based on the power of the interference. The stronger the interference, the greater it is suppressed. The optimal beamforming solution reduces to the MRC solution in the absence of interference and when the noise and interference are independent and identically distributed. By using channel reciprocity, the optimal beamforming solution can be used to exploit spatial diversity and array gain on transmission.

Figure 2 indicates that beamforming provides additional gain beyond what a wide-angle directional antenna provides. Although this gain can be meaningful, the significant benefit is a reduction in interference to others. As depicted in Figure 3, by limiting the interference energy directed to other users, and in some cases actively nulling this interference, the improved SINR can be achieved without reducing the spectral efficiency. Also, since the users are randomly spread, there is additional interference diversity gain as the beams track users.

Figure 2: Beamforming can provide gain beyond that provided by a single directional antenna. More importantly, omni and wide directional antennas are inefficient because power is distributed where it isn't needed and create interference for unintended users.

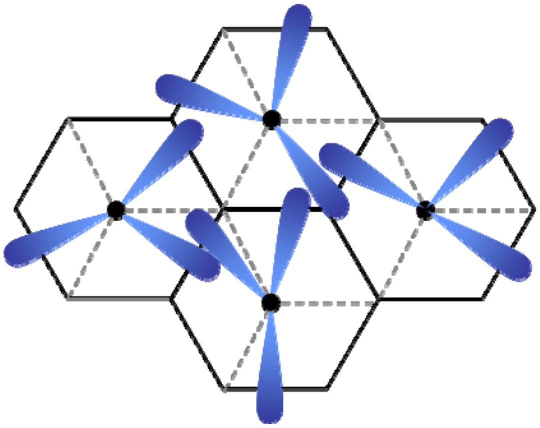

Figure 3: Beamforming limits the interference to other users and enables true frequency reuse of 1 across the network. If omni-directional antennas are used, virtual sectors can be created through SDMA. The number of sectors depends on the number of simultaneous beams that can be supported.

Spatial Multiplexing

Spatial multiplexing assumes that multiple antennas support multiple channels such that the capacity increases linearly with the number of channels supported. This capacity gain is far larger than the logarithmic capacity gain achieved by improving the SNR on a single channel. However, realizing multiple channels in a WiMAX system is typically restricted to special cases. Here are some of the challenges associated with spatial multiplexing and the impacts.

- **Multipath**. WiMAX deployments are expected to experience substantial multipath, leading to scenarios where the channels are not flat. Although MIMO theory assumes a flat channel, the OFDM physical layer effectively converts a frequency selective fading channel into many parallel flat-fading channels. Hence, with a WiMAX system both MIMO (and beamforming) can take advantage of reasonably flat narrow-bandwidth channels.

- **Antennas**. Spatial multiplexing gains are based on an assumption of many independent channels with equal power. In a WiMAX deployment with base stations high above scattering objects using sector antennas, the assumption of a scattering-rich environment is not likely. Furthermore, MIMO spatial multiplexing gains are limited to the maximum number of uncorrelated antennas at the base station *and* the subscriber station. Placing multiple antennas at a user's terminal is challenging, and making them uncorrelated even more so. Still, experiments have shown that modest spatial correlation is OK, and that two antennas at a subscriber unit close to each other can still provide benefit.
- **Interference**. Most throughput studies are based on a point-to-point link analysis, typcially assuming performance is limited by Gaussian noise. Even in these cases, spatial multiplexing performance gains are possible only if the SNR is rather large, on the order of 20 dB or more. Also, information and communication theory indicate that the capacity of a MIMO cellular system can actually decrease as the number of transmit antennas increase because of the additional interference. For these reasons, use of MIMO is typically restricted to subscribers that are near the base station where the SNR is high and the interference may be limited.

Since spatial diversity provides benefit at low SNR and spatial multiplexing requires high SNR and little or no external interference, effectively using spatial multiplexing requires adaptively selecting it when appropriate.

Conclusion

While many technologies provide improvements to wireless connections, the unique factor provided by spatial processing is the ability to distribute energy while limiting interference. This is fundamental to providing significant gains to existing wireless systems, and supports other equally important concerns such as frequency planning, deployment limitations due to public, cost, or geographical constraints, and service offerings. Employing the appropriate spatial processing techniques can provide significant cost and performance differentiators from systems using less advanced technology.