Understanding MIMO: Part II

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With MIMO, systems use multiple transmit and multiple receive antennas. Looking at various MIMO techniques (specifically the receive techniques) that use different approaches to antenna and signal optimization, note that each type of MIMO has advantages and disadvantages.

Selection diversity is the simplest diversity approach. Using multiple antennas with overlapping coverage, this approach selects the antenna with the highest received signal power, mitigating fading (Fig. 6). In this case, the outage probability with M antennas is equal to the outage probability of the single antenna raised to the Mth power. This substantially reduces outage probability, i.e., diversity gain.

![Selection diversity diagram]

Fig. 6: Selection diversity.

Selection diversity is the simplest technique to implement and requires only one RF chain, such as an LNA, filter, or down converter, independent of the number of antennas. However, it doesn't use all the signal energy available at the antennas, so the diversity gain is less than M and the array gain is limited. Interference suppression is also limited.

**Switched multi-beam**
A switched multi-beam antenna is an array with multiple fixed beams pointing in different directions (Fig. 7). The receiver picks the beam with the highest signal-to-noise ratio (SNR).
The switched multi-beam antenna can provide an array gain of $M$ with $M$ beams and a diversity gain. The signal processing needed to control the antenna is simple, as the receiver only has to search for the correct beam every few seconds. On transmit, using one beam can reduce interference into other users.

On the down side, an array gain of $M$ can only be obtained in a near line-of-sight environment (where the angle range of the arriving signals is less than the beam width), while a diversity gain can be achieved only when the range of angles is greater than the beam width. Also, interference reduction is achieved only under limited conditions (near line-of-sight and interference not arriving in the desired signal beam). On transmit, interference with other users isn't reduced in most multi-path environments.

**Adaptive Array**

With an adaptive array, the signals received by each antenna are weighted and combined to improve output signal performance. For example, if the signals are combined to maximize output SNR, the technique is referred to as maximal ratio combining. If the signals are combined to maximize the signal-to-interference plus noise ratio, the technique is referred to as minimum mean square error (MMSE) combining.

The maximum ratio combines all available signal energy at the receiver and thereby obtains a full array and diversity gain. With $M$ antennas, an array gain of $M$ and an $M$-fold diversity gain is realized. This gain is obtained independent of the environment. MMSE combining also can suppress up to $M-1$ interferers, regardless of their received signal power (except for equipment limitations). This is possible in a line-of-sight environment if the transmit antennas are spaced greater than the array’s beam width. But it's also possible in a multi-path environment if the fading at each transmit/receive antenna is independent.

Note that the adaptive array can require $M$ complete RF chains if digital signal processing (DSP) is used at the baseband. The weight calculation can require significantly more computational complexity than switched diversity/multi-beam approaches.

**MIMO-SM**

The ability to suppress up to $M-1$ interferers with $M$ antennas can also increase the data rate of a single link. If a user transmits different signals from each of $M$ antennas, then a receiver can weigh and combine the received signals $M$ different ways to obtain each signal (Fig. 8). That is, the receiver can combine the received signals to get the signal from the first transmitted antenna with
the other signals considered as interferers, and so on, to obtain all M signals. This is known as MIMO with spatial multiplexing (MIMO-SM). This can be done with DSP of the same set of received signals from the M antennas. In a multi-path environment, the only requirement is that the fading at each antenna is independent, or more specifically, that the multi-path environment is rich enough.

The data rate can be increased M-fold for the same transmit power and bandwidth. That is, the data rate can be arbitrarily increased to any level, without increasing the total transmit power or spectrum, by adding antennas at both the transmitter and receiver with increased DSP. This requires at least M antennas at both the transmitter and receiver, with M RF chains and complex signal processing. The maximum data rate increase is limited by the richness of the multi-path environment, although measurements have shown that a factor of 10 outdoors and 100 indoors is the typical limit. MIMO with spatial multiplexing can't be added to existing systems like other smart antenna techniques without changing the standards.

The various MIMO techniques can improve the user experience and system capacity in any wireless system by reducing interference, extending range, increasing data rates, and improving quality. There are certainly differences between the methods that MIMO can be applied to a given situation, but in general, unless you have a line-of-sight, adaptive arrays are the best option for overcoming a tough multi-path environment.

Smart antenna technology can be added to any existing wireless system to improve its performance. MIMO with spatial multiplexing generally is most useful when applied to systems that have reached maturity with respect to the ability of DSP to increase their performance. In this case, MIMO-SM can be the only technique that can provide an order of magnitude increase in link capacity. The areas where MIMO techniques add significant value to wireless systems include:

- **Wi-Fi**: Small devices with mainly indoor coverage generally favor adaptive arrays. The main benefits include range increase, interference mitigation (particularly with unlicensed band operation), and uniform coverage. Uniform coverage with multipath mitigation is of increasing interest for VoIP applications where QoS for voice applications is essential. Smart antennas can be implemented at either the client or access point alone as these systems use the same frequency for transmission or reception (allowing for the receive weights to be used for transmission), for equal gains in both directions. Coming higher data rates make MIMO an attractive solution.

- **WiMax (IEEE802.16), IEEE802.20**: Multi-beam antennas (perhaps in combination with adaptive arrays) are favored at base stations, while adaptive arrays are favored at the client. Here, the basestation smart antenna provides greater range and allows a capacity increase through spatial re-use, i.e., separate beams. Adaptive arrays on the client can provide gains comparable to building penetration losses, permitting use of WiMax for in-building clients, eliminating outside the building installation. Many of these systems use time-division duplexing, allowing for equal gains in both
directions with implementation on the client alone.

- Cellular: Like WiMax, multi-beam and adaptive arrays are useful at basestations, with adaptive arrays useful at the handsets. Increased coverage and higher system capacity, along with the higher data rates are the biggest gains. These systems use frequency-division duplexing. Hence, some ingenuity is needed to obtain gains with smart antennas on transmission.

- RFID: Smart antennas, either multi-beam or adaptive arrays, can be used on readers to increase range for which a response from an RFID can be received.

- Ultrawideband (UWB): Smart antennas provide one of the most promising methods for increasing UWB range. However, UWB’s low cost requirement and transmit power radiation limitations, along with the complications of severe frequency selective fading over a wide bandwidth, creates smart antenna implementation challenges.

- Mobile satellite TV: A multi-beam antenna permits a low-profile antenna that can track the received signal even while the vehicle is in motion and yet can also be incorporated into the roof of a vehicle, unseen from inside or outside the vehicle. Adaptive array technology can further improve performance by mitigating multipath and adapting to implementation/environmental variations.

- Satellite radio: Adaptive arrays can provide more uniform coverage, multi-path mitigation, and robustness on the satellite radio receiver. In addition, adaptive arrays can allow for low profile antennas that can be hidden on the vehicle with higher gain than existing antennas (even though each antenna element may have lower gain than the existing antenna). Furthermore, adaptive arrays can improve indoor reception and eliminate the need for manual pointing of the indoor unit.

- Digital AM/FM Radio: Adaptive arrays can provide more uniform coverage, multi-path mitigation, and robustness, along with permitting better performance with hidden antennas. Also, adaptive antennas can extend the range.

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