Whitepaper – MIMO & The MCMC Detector

Motivation

MIMO can enable massive increases in range and data throughput of wireless devices as seen since 2009 with 802.11n and 802.11ac WiFi. Though WiFi MIMO size has stagnated at 3x3 since 2010, by upgrading normal chipsets with MCMC, one of FARhang Wireless' technologies, a major technical barrier is removed allowing 8x8 and larger MIMO configurations.

Figure 1: 802.11 WiFi router using 3-antenna MIMO.

Background & Terminology – What is MIMO?

MIMO (multiple-input multiple-output antenna) communication technology uses multiple antennas for four main purposes: redundancy to enhance reliability, beamforming to increase range, MU-MIMO to increase data-rate to multiple users, and spatial-multiplexing to increase data-rate to individual users.

Redundancy is the simplest way to exploit MIMO. When a device such as a laptop or smartphone has only one antenna that is twisted to a bad angle or covered by a hand it can completely lose signal, dropping the connection. With multiple antennas some will remain in a strong position, so by always choosing the best antenna the redundancy leads to a much more reliable connection. Cost increases linearly as the number of components increases. Power requirements stay nearly constant since the unused antennas can be turned off.

In the **beamforming** configuration, the *same data* is sent over each transmitting antenna (and added together at the receiver), overlapping to create a *beam* of energy in a specific direction. This method is primarily used to increase range, but can marginally increase data rate by exploiting the improvement in signal strength. When a device connects with an unmatched numbers of antennas beamforming can still increase range, such as when an access point (AP) has 3 antennas and a smartphone has 1. Cost increases linearly as the number of components increases. Power requirements increase linearly as the additional components are constantly being used. This extra power use may be undesirable in a battery-powered mobile device.

An extension to beamforming called **MU-MIMO** (multi-user MIMO) is appearing in wave-2 802.11ac APs in 2014. It allows communication with multiple devices simultaneously, up to a maximum of the number of antennas because of a null-steering requirement. Without this ability, each device connected to an AP must communicate one at a time. This time-sharing means that the AP's maximum, continuous data-rate is split between the connected devices. Splitting the data-rate can cause problems in a home, airport, or cafe where many users are attempting stream large amounts of data simultaneously. MU-MIMO increases the total beamforming data-rate by the number of antennas at the AP.

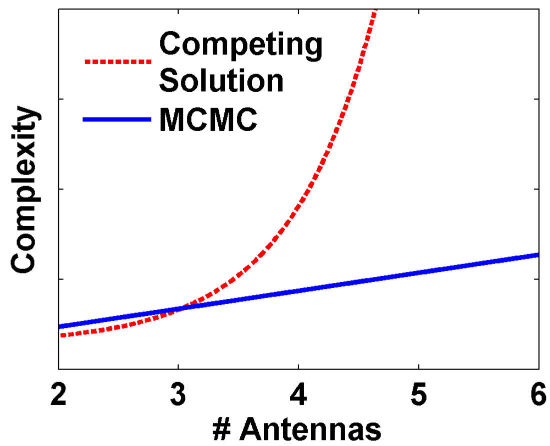

Figure 2: Comparison of complexity between MCMC and a typical competing detector solution.

For ***spatial-mutliplexing***, *different data* is sent over each antenna in separate parallel streams, thereby increasing the data rate by the number of antennas. The shorthand for this is *"# transmit antennas"* **x** *"# receive antennas"* **:** *"# spatial streams"*. So a 4x4:4 chipset fully exploits the 4 antennas to increase the data rate by a factor of 4, using 4 spatial streams. A 4x4:3 chipset has 4 antennas at each side, but only uses 3 data streams in the spatial-multiplexing mode. When two devices connect with unmatched numbers of antennas the multiplexing is limited by the smaller. So a 3x2 is limited to 3x2:2 and a 3x1 is limited to 3x1:1.

At first, cost appears to increase linearly as the number of components increases, but starting at roughly 3x3 the cost increase shifts to exponential. This is because the math to do the *detector* digital-signal-processing (DSP) in the receiver increases exponentially. After 3x3 this exponential increase in detector complexity begins dominating all other costs, requiring an exponentially larger and therefore more costly chip to perform the math. Likewise, power requirements initially appear to increase linearly until the exponential increase in math requires exponentially increasing power. This exponential increase in cost and power-consumption creates a barrier to the implementation of high quality MIMO systems beyond about 4x4:4 in size. Avoiding this massive complexity increase has been the motivation for designing chipsets such as a 4x4:3 with fewer spatial streams than antennas. Several manufacturers are in the process of releasing 802.11ac WiFi chipsets in this configuration.

Smartphones – Are there limitations to MIMO?

There are physical limitations to how large a MIMO system can be, regardless of whether it's being used for redundancy, beamforming, or spatial-multiplexing. The key requirement to get the full, expected performance increase from additional antennas is that each has an *independent* view of the world. If two antennas are so close together that they see the same signal there is little advantage to having two, since one can do the job. A good rule of thumb for estimating *how-close-is-too-close* is that the antennas should be at least ½ wavelength away from each other. This translates to a minimum of 2.5" separation for 802.11 at 2.4GHz and 1.25" at 5GHz. For a smartphone this suggests a maximum of 2x MIMO at 2.4GHz and 4x MIMO at 5GHz because of its small size. Note that as of 2014 the first high-end phones with 2x antenna 802.11ac

MIMO are being released.

Even if the number of MIMO antennas is limited in some small devices such as smartphones, increasing the number of antennas at the other end of the connection still increases performance. Adding antennas asymmetrically can dramatically improve range and connection reliability while maintaining high throughput. For example, an 8x2:2 AP-to-smartphone configuration can simultaneously use beamforming and multiplexing to increase range and double data-rate. Or, by using the MU-MIMO concept in an 8x1:1 configuration, up to 8 devices could be served simultaneously, effectively increasing the total data throughput by a factor of eight.

MCMC Detector – How to avoid exponential processing complexity?

To understand how our technology fits into the complex signal processing performed in modern communications equipment, it is convenient to think of it in the form of a flow chart. The data flows sequentially through the flow chart with a specific part of the processing being done in each block. Each block has a specific *core* set of *intellectual property (IP)* which determines its specific functionality and performance. For that reason this unit is called an *IP core* and it is common to sell them as enabling functional blocks to companies.

FARhang Wireless' IP cores target the **MIMO detector** block that translates the received signal into the individual binary 1/0's of the data. This math intensive operation can be done in different ways depending on the desired balance of performance and low complexity. Note that higher performance can provide a blend of longer range and higher data-rate. Low complexity requires less silicon in the chip, reducing cost and power-consumption.

At a high level, one can consider three general classes of detectors. There are older conventional methods, using **soft-MMSE** (minimum-mean-square-error), which have low performance and relatively simple, low complexity math. The newer **competing** methods, based on **ML** (maximum-likelihood) approximations, improve performance but have the drawback of exponentially increasing complexity. **FARhang Wireless'** technology, based on **MCMC** (Markov-Chain-Monte-Carlo), has similar high performance to the competing ML methods while keeping a low, linearly increasing complexity. See Figure 3 for a qualitative visual example of the differences between these three classes of detectors. The interested reader should refer to the many excellent technical journal articles published on these topics since MCMC's invention in 2005. A selected list of these articles is presented at the end of this document.

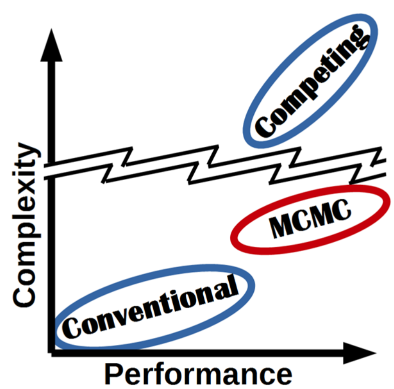

Figure 3: Detector comparison.

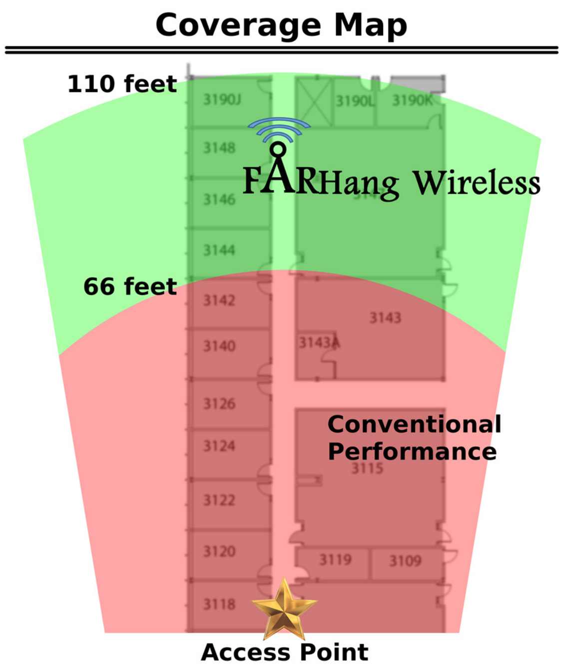

Figure 4: Real-world results showing performance in an office environment.

The conventional and MCMC detectors have been implemented and tested in a real office environment; see Figure 4. These initial results performed at 2.4GHz show a consistent 2-3 dB performance improvement over the soft-MMSE detector, which translated to a 67% increase in range.

Other Applications

Although this whitepaper has focused on the application of MCMC to 802.11 WiFi MIMO, there are several other applications worth noting. In particular cellular, backhaul, last-mile, and HD-video-screen streaming technology can benefit from the use of large MIMO systems to enable longer range, higher data-rate, and greater user-density. Therefore they are possible opportunities for MCMC implementation.

Summary

Wireless communications systems requiring higher performance can exploit MIMO for improvements that scale with the number of antennas. Unfortunately the detector, a key processing step in the receiver, has exponentially increasing complexity as antennas are added. Therefore, the dramatically increasing cost and power-consumption typically limit the realizable size of MIMO systems. By using the MCMC detector technology developed by FARhang Wireless this complexity barrier is reduced to a linear increase, allowing large MIMO systems with high performance to be developed.

Selected Publications on MCMC-MIMO Detectors

[1] B. Farhang-Boroujeny, H. Zhu, and Z. Shi, “Markov chain Monte Carlo algorithms for CDMA and MIMO communication systems,” *IEEE Trans. Signal Processing*, vol. 54, no. 5, pp. 1896 – 1909, May 2006.

[2] H. Zhu, B. Farhang-Boroujeny, and R-R. Chen, “On performance of sphere decoding and Markov chain Monte Carlo detection methods,” *IEEE Signal Processing Letters*, Oct. 2005, pp. 669-672.

[3] S.A. Laraway and B. Farhang-Boroujeny, “Implementation of a Markov Chain Monte Carlo Based Multiuser/MIMO Detector,” *IEEE Trans. On Circuits and Systems,* vol. 56, no. 1, Jan. 2009, pp. 246-255.

[4] Hansen, M.; Hassibi, B.; Dimakis, A.G.; Weiyu Xu, "Near-Optimal Detection in MIMO Systems Using Gibbs Sampling," *IEEE GLOBECOM* 2009, Nov. 30 2009-Dec. 4 2009, pp. 1-6.

[5] R-H. Peng, R-R. Chen, and B. Farhang-Boroujeny, “Markov chain Monte Carlo Detectors for channels with intersymbol interference,” IEEE Transactions on Signal Processing, vol. 58, no. 4, 2010, pp. 2206 – 2217.