Implementation of Quantum-inspired algorithm for MIMO detection

WINLAB | Wireless Information Network Laboratory

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Motivation

In the foreseeable future we expect continued increases in the number of wireless devices. This creates pressure to continuously increase network capacity and efficiency, but it is often too computationally expensive to find the optimal solution.

Quantum computing has the potential to address these bottlenecks, but is too far away for practical use. Instead our goal is to implement a MIMO detection algorithm that is quantum-inspired but runs on classical hardware.

Background

Modern wireless networks use MIMO (Multiple Input Multiple Output), which is when multiple transmitters and receiver antenna transfer multiple streams of data simultaneously for higher throughput.

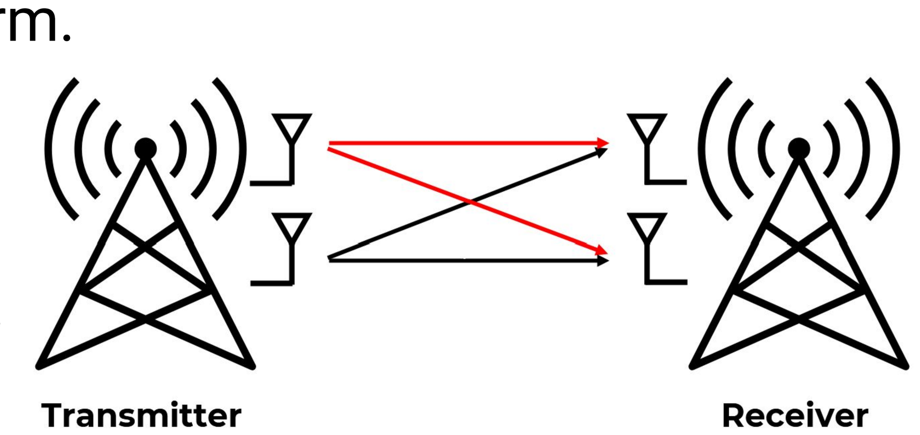
While MIMO provides performance advantages, it is susceptible to channel hardening: a phenomenon that decreases the variations in channel gains. This makes signals harder to distinguish and demultiplex. We combat channel hardening with MIMO detection algorithms, which attempt to the most likely transmitted bits based on the received bits and channel estimation. This process is equivalent to minimizing the expression $\| \mathbf{y} - \mathbf{H}\boldsymbol{x} \|^2$ by selecting the best $\boldsymbol{x}$ vector. Here $\mathbf{y}$ is the received symbols, $\boldsymbol{x}$ is the transmitted symbols, and $\mathbf{H}$ is the channel state matrix.

Our work is an implementation of a quantum-inspired MIMO detection algorithm, ParaMax[1], that performs close to the best algorithms, but at much lower cost.

ParaMax

ParaMax is a probabilistic algorithm based on simulated annealing and parallel tampering. It reformulates Maximum-Likelihood (ML) detection into an equivalent Ising form.

Fig 1: In realistic scenarios there is some amount of interference from the signals. MIMO detector seek to undo the effects of this interference.



ParaMax works by sampling possible solutions and attempting to find the best solution based on energy levels. This is similar to how quantum computers operate, hence this algorithm quantum-inspired.

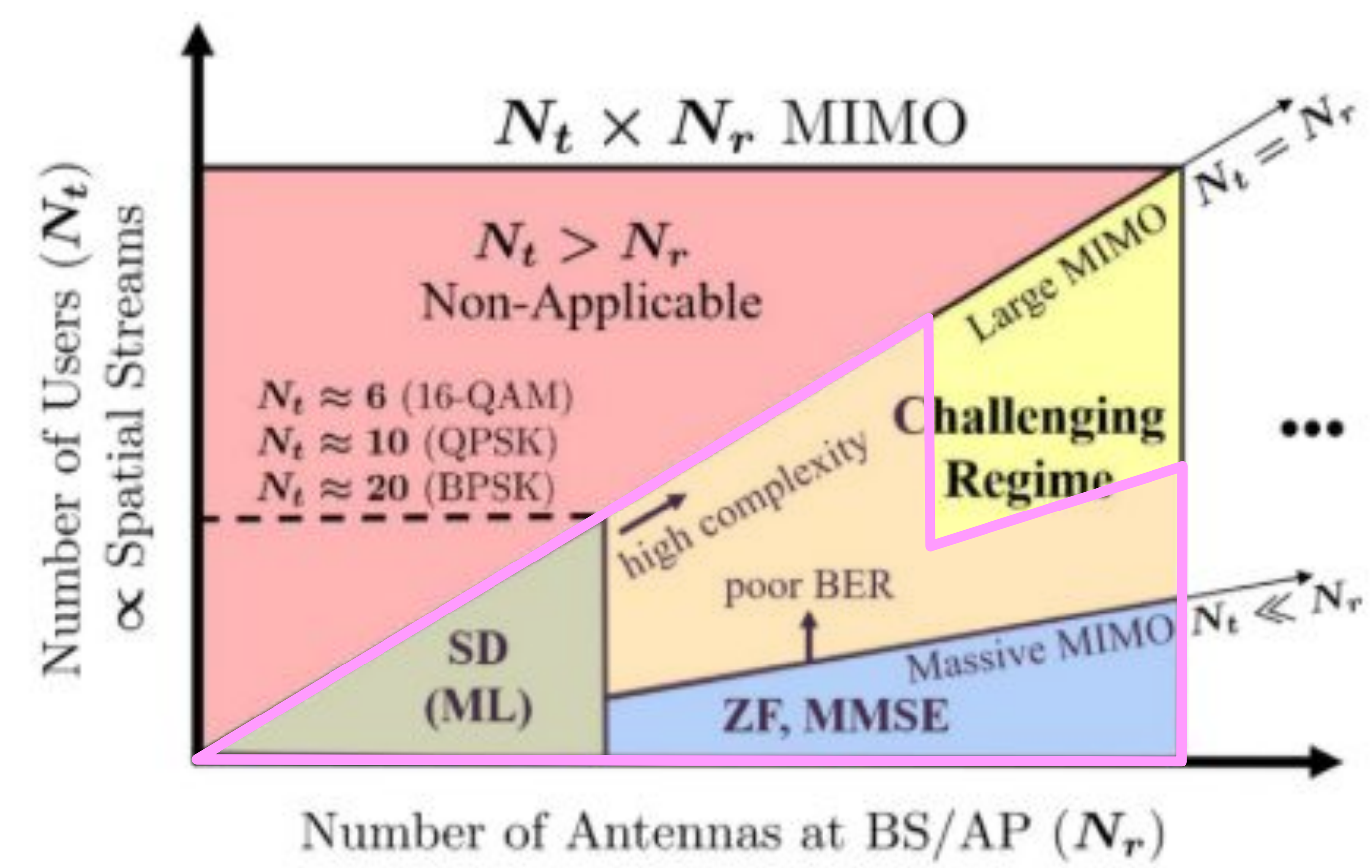


Fig 2: MIMO regimes in 5G New Radio, and approximate feasibility of various detection approaches. The pink region captures the MIMO feasibility of ParaMax (16-QAM) in Massive MIMO settings.

Design

Our plan is to implement a real MIMO system and use the received network samples as input for our MIMO detectors and provide a realistic baseline of performance. The data generation and processing of received data will both be done offline. Implementation includes frame synchronization, channel estimation, and comparison to other MIMO detectors based on bit error rate (BER).

ParaMax is a probabilistic detector; we calculate the probability based on the number of processing elements ($\mathbf{N}_{PE}$) and the probability of obtaining the optimal solution: $\mathscr{P}(\text{ParaMax}_{ML}) = 1 - (1-P_{ML})^{\mathbf{N}_{PE}}$. We determine the probability of the optimal solution heuristaically and determine the required $\mathbf{N}_{PE}$ via $log(1-\mathscr{P}(\text{ParaMax}_{ML}))/log(1-P_{ML})$.

We compare our performance to another parallel probabilistic detector: FlexCore[2]. FlexCore uses channel information to find the most probable transmitted symbols, where $P_c(\mathbf{p}) = \prod_{l=1}^{N} P_l(p(l))$ is the probability that a given full sphere decoder path $\mathbf{p}$ is correct, P_l is the probability that a level l is correct, and FlexCore does preprocessing to select the most likely sphere decoder paths before a transmission is received.

Results

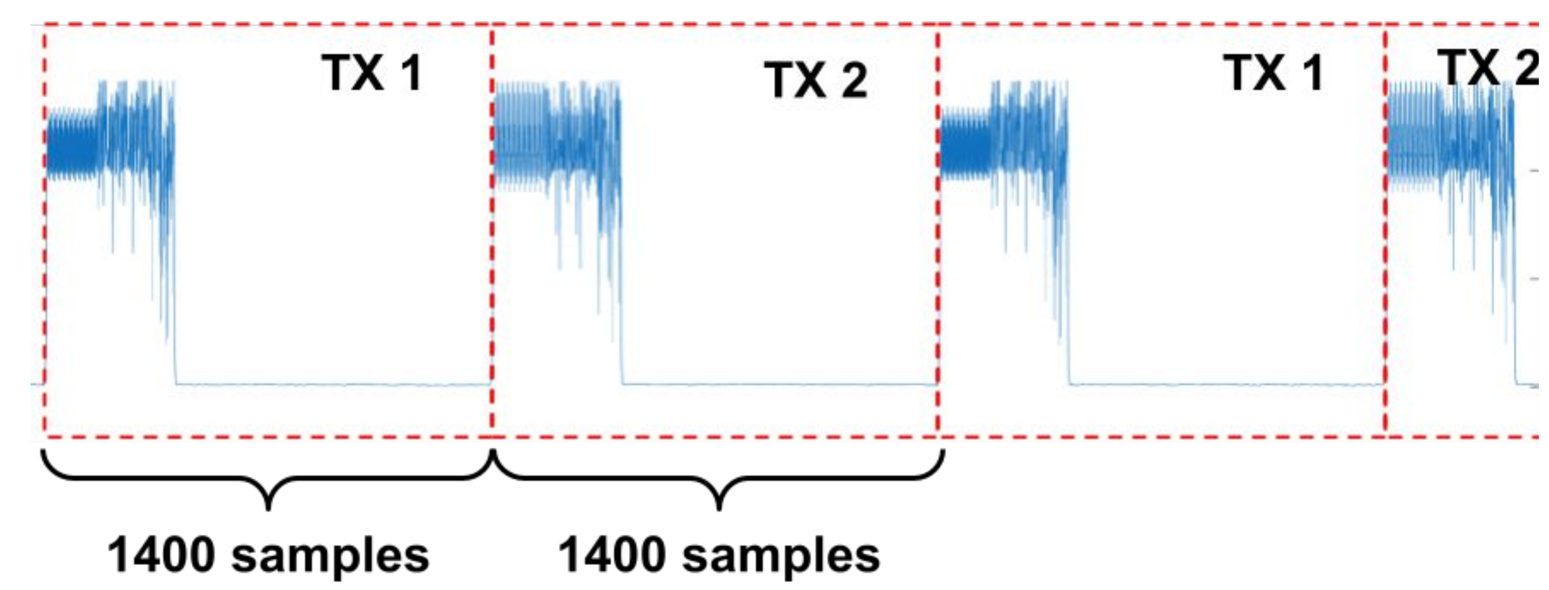


Fig 3: Data samples from 2 Tx that are frame synchronized.

Precise timing is critical in MIMO systems, so most of the internship was spent achieving exact frame synchronization. We used USRP X310 radios that were time synced to 2 ns of precision with a GPS pulse. Using a C++ driver we would schedule frames to be transmitted every 500 μs, where frames are scheduled to be 10 ns apart.

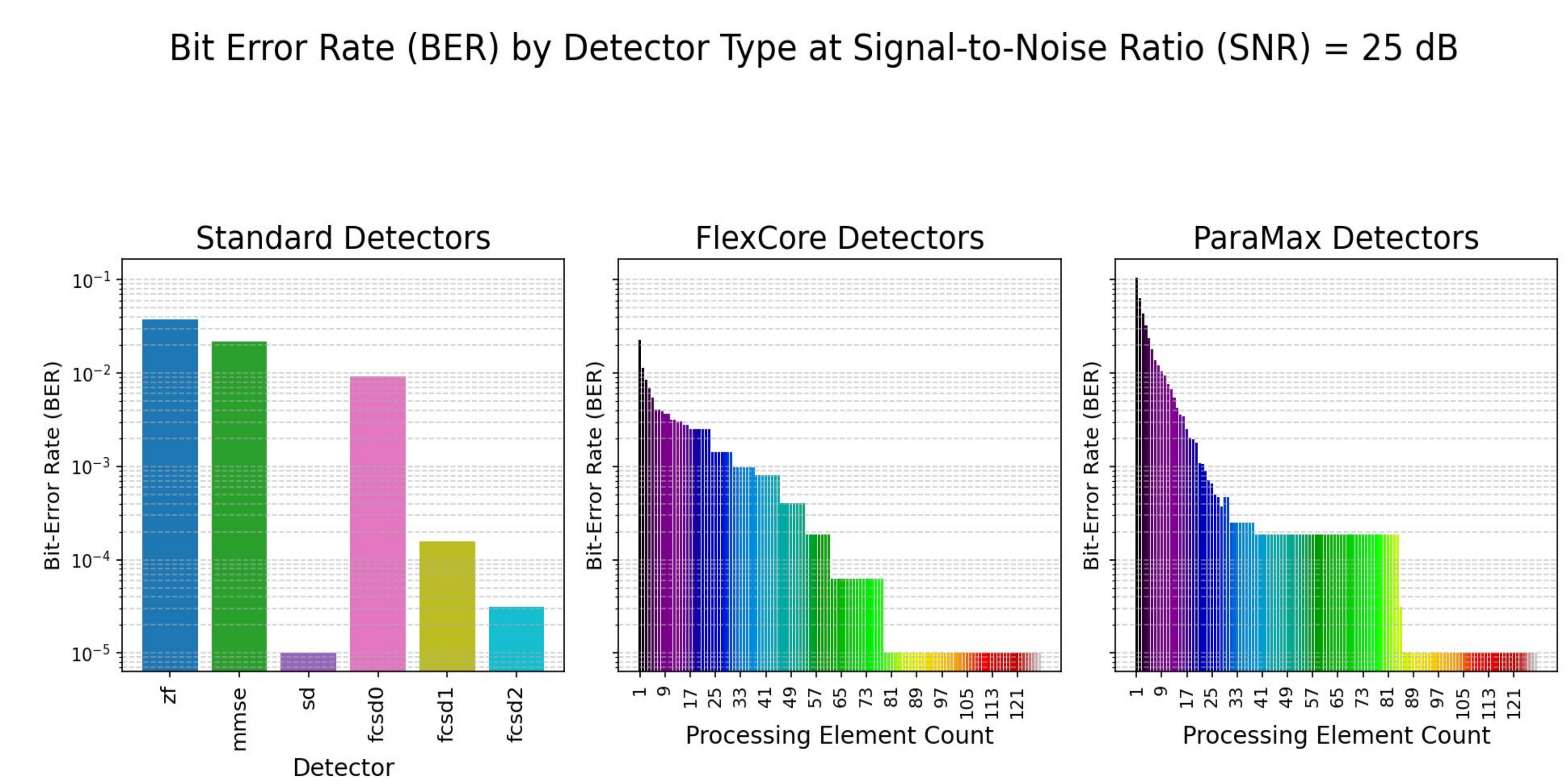


Fig 4: Bit-Error Rate (BER) vs MIMO detection approaches for 8x8 MIMO (16-QAM) at 25 dB Signal-to-Noise Ratio (SNR). Includes BER vs number of processing elements for FlexCore and ParaMax.

Our software simulation demonstrates parallel detectors achieving optimal BER with lower complexity than Sphere Decoding (SD). This highlights the potential of parallel processing for efficient scaling in massive MIMO architecture.

References

1. Minsung Kim, Salvatore Mandrà, Davide Venturelli, and Kyle Jamieson. "Physics-inspired heuristics for soft MIMO detection in 5G new radio and beyond." In *Proceedings of the 27th Annual International Conference on Mobile Computing and Networking (MobiCom '21)*, pages 42–55. Association for Computing Machinery, 2021.
2. Christopher Husmann, Georgios Georgis, Konstantinos Nikitopoulos, and Kyle Jamieson. "FlexCore: Massively Parallel and Flexible Processing for Large MIMO Access Points." In *14th USENIX Symposium on Networked Systems Design and Implementation (NSDI '17)*, pages 197–211. USENIX Association, March 2017.

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