Theoretical Study of Power Management of a MIMO Network using Antenna Selection Algorithm

Akash Bharadwaj B R*1, Samarth Athreyas*2

*1Software Engineering Analyst, Accenture PLC, Bangalore, Karnataka, India
*2Design Engineer, AMD, Fort Collins, Colorado, USA

Abstract—Multiple-Input-Multiple-Output(MIMO) networks are basically very power hungry systems. They offer a wide range of advantages like improvement in range, throughput and reliability without demanding an increase in the bandwidth and transmit power. MIMO is associated with the IEEE Standard 802.11n which is a Wireless Local Area Network (WLAN). The complexity of the MIMO systems increase as the transmitters and receivers employed increase and this is one of the issues which is being dealt with. This is facilitated with the help of an algorithm called Antenna Selection Algorithm which helps in choosing the subset of the antennas based on the energy per bit ($E_b$) values (which has to be minimum). The algorithm is simulated to obtain the optimal antenna configuration and transmit power with a data rate constraint for multiple data rates. This helps in switching off/on the particular RF chain based on the results and to make MIMO systems power efficient.

Keywords: MIMO, WLAN, WiMAX, OFDM, $E_b$

I. INTRODUCTION

In radio, multiple-input and multiple-output, or MIMO, is the use of multiple antennas at both the transmitter and receiver to improve communication performance. It is one of several forms of smart antenna technology. It is a spatial multiplexing antenna type, it offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. It achieves this goal by spreading the same total transmit power over the antennas to achieve an array gain that improves the spectral efficiency (more bits per second per hertz of bandwidth) and/or to achieve a diversity gain that improves the link reliability (reduced fading). Because of these properties, MIMO is an important part of modern wireless communication standards such as IEEE 802.11n (Wi-Fi), 4G, 3GPP Long Term Evolution, WiMAX and HSPA+. MIMO technology takes advantage of multipath behavior by using multiple, smart transmitters and receivers with an added spatial dimension, to dramatically increase performance and range. MIMO makes antennas work smarter by enabling them to combine data streams arriving from different paths and at different times to effectively increase receiver signal-capturing power. When there are more antennas than spatial streams, the antennas can add receiver diversity and increase range.

II. UNDERSTANDING MIMO

[1] By properly leveraging the multipath effect, MIMO can significantly boost channel capacity compared to a traditional single-input-single-output (SISO) link. In this work use of “antenna” refers to the passive antenna and the corresponding RF chain that powers it unless otherwise specified. To address the power challenge, novel power management solution called antenna management algorithm is made use of. Antenna management algorithm dynamically determines the number of active antennas and transmits power for each active antenna, in order to minimize the energy consumption for delivering each data bit, or achieve minimum MIMO energy per bit, while guaranteeing a required data rate. The key rationale behind antenna management is the mobility of mobile systems. As mobile systems move around, they encounter different propagation environments, which can lead to different capacity benefit from using multiple antennas. Since the circuit power cost of using one active antenna is fixed, different environments may lead to different capacity benefit from using multiple antennas. The below figure 1 represents the communication system of a 2X2 MIMO.

Fig. 1. 2X2 MIMO
Multiple Input Multiple Output (MIMO) systems—offer superior data rates, range and reliability without requiring additional bandwidth or transmit power. By using several antennas at both the transmitter and receiver, MIMO systems create multiple independent channels for sending multiple data streams. Due to the above reasons MIMO is becoming very popular and in near future it can become ubiquitous.

The number of independent channels and associated data streams that can be supported over a MIMO channel is equivalent to the minimum number of antennas at the transmitter or receiver. Thus, a 2x2 system can support at most two streams, a 3x3 system can support three streams and a 4x4 system can support four streams, as illustrated in The figure below. Some of the independent streams can be combined through dynamic digital beam-forming and MIMO receiver processing, as shown in the red oval, which results in increased reliability and range. A 4x4 MIMO system with dynamic digital beam-forming and MIMO receiver processing supports two maximum-rate data streams. Other configurations such as 2x2 and 3x3 MIMO are significantly less reliable, since they have fewer antennas and thus fewer extra spatial dimensions that can be combined.

![Fig. 2. 4X4 MIMO system supports up to four data streams.](image)

### III. METHODOLOGY

This is a theoretical study to optimize the energy utilized by the 4X4 MIMO by identifying those antennas with low energy per bit values. Here we simulate the antenna selection algorithm with the channel matrix generated by considering certain parameters. The figure 3 represents the 4X4 MIMO connected to a switch array and RF chains.

16 radio paths exist between the transmitter and receiver, and the path through which the data has to be passed is identified, using the channel matrix and antenna selection algorithm. Hence, selecting only a subset of it by finding the optimal antenna configuration.

The Channel State Information (CSI) or the coding techniques like Space Time Coding (STC) etc., is not considered but which could be further taken up in future as an extension of the project.

![Fig. 3. Channel Matrix](image)

### IV. HARDWARE AND SOFTWARE USED

#### A. MATLAB

In this project MATLAB is used to generate the channel correlation matrix by considering certain parameters. These parameters are used as inputs to the antenna selection algorithm.

#### B. Xilinx ISE

This section deals with the Spartan-3 FPGA family which is manufactured by Xilinx Inc. which helps in realizing the hardware implementation of the project.

### V. FUNDAMENTALS

To arrive at the results, we use the narrowband assumption, which implies that the signal seen at the receiver is a summation of all taps. This assumption is valid, for example, for systems based on the orthogonal frequency division multiplexing (OFDM) modulation. For the simulation, the following antenna configuration system (these parameters can be used for system simulations and performance comparisons) is used:

- 4 transmit and 4 receive antennas (4x4 MIMO system)
- Uniform linear array (ULA)
- λ/2 adjacent antenna spacing
- Isotropic antennas
- No antenna coupling effect
- All antennas with same polarization (vertical)

#### A. Specifications

[21, 22, 23, 20] IEEE 802.11n channel models for indoor Wireless Local area networks:

1) **BANDWIDTH**: of up to 100 MHz
2) **FREQUENCIES**: 2 and 5 GHz.
3) **PROFILE**: Residential which cover the scenarios of each channel model has a path loss model including shadowing, and a MIMO multipath fading model, which describes the multipath delay profile, the spatial properties, the K-factor distribution, and the Doppler spectrum.
4) **NO.OF CLUSTERS**: 2
5) **NO.OF TAPS**: 1ST CLUSTER -5, 2ND CLUSTER -7
6) **OVERLAPS**: 3
7) **TOTAL**: 9 TAPS EACH OF 10ns DELAY
   [0 10 20 30 40 50 70 80]
8) \( M = 2 \): Modulation order (BPSK)
9) \( R_{sym} \): 10e3 (Input symbol rate)
10) \( R_{bit} \): \( R_{sym} \log_2(M) \) (Input bit rate)
11) \( N_t \): 4 (Number of transmit antennas)
12) \( N_r \): 4 (Number of receive antennas)

**Element spacing at the Transmitter and Receive antennas (normalized by the wavelength)**:
- \( \text{TxSpacing} = 0.5\lambda \)
- \( \text{RxSpacing} = 0.5\lambda \)

**Spatial parameters on Transmitter side; see appendix A**
- \( \text{Angular spreads} : 14.4^\circ \) (Cluster 1)
- \( \text{Angular spreads} : 25.2^\circ \) (Cluster 2)
- \( \text{Mean angles of departure} : 225.1^\circ \) (Cluster 1)
- \( \text{Mean angles of departure} : 106.5^\circ \) (Cluster 2)

**Spatial parameters on receiver side; see appendix A**
- \( \text{Angular spreads} : 14.4^\circ \) (Cluster 1)
- \( \text{Angular spreads} : 25.2^\circ \) (Cluster 2)
- \( \text{Mean angles of arrival} : 4.3^\circ \) (Cluster 1)
- \( \text{Mean angles of arrival} : 118.4^\circ \) (Cluster 2)

Using these parameters the channel correlation matrix is generated using MATLAB.

### VI. ALGORITHM IMPLEMENTATION

To address the power challenge, a power management solution called antenna management algorithm is used. Antenna management dynamically determines the number of active antennas and transmit power for each active antenna, in order to minimize the energy consumption for delivering each data bit, or achieve minimum MIMO energy per bit, while guaranteeing a required data rate. The key rationale behind antenna management is the mobility of mobile systems. As mobile systems move around, they encounter different propagation environments, which can lead to different capacity benefit from using multiple antennas. Since the circuit power cost of using one active antenna is fixed, different environments may lead to different numbers of antennas to achieve the minimum energy per-bit. For example, an indoor environment with rich multipath effect can provide a MIMO channel higher capacity improvement than an outdoor environment with a dominant line-of-sight (LOS) path can. As a result, a larger number of antennas is more likely to be optimal for the indoor environment. The antenna management algorithm efficiently solves the MIMO energy per bit minimization problem with:

1) a pre-built mapping to identify the optimal transmit power and
2) antenna selection algorithms to obtain the optimal number of antennas. This system design of antenna management is 802.11n-compliant. Both one-ended and two-ended designs where the former is suitable for a MIMO link between a mobile node and an access point while the latter for that between two mobile nodes is proposed. We evaluate the system design of antenna management for two-ended design. The antenna configuration is identified by selecting subset of antennas (both Transmitter and Receiver) with data rate constraint and not considering the channel coding techniques.

#### A. Antenna Selection Algorithm

[1] Input to the antenna selection algorithm is the channel matrix \( H \) with minimum data rate constraint \( R_{min} \). The optimal transmit power \( P_{TX_{opt}} \) and the optimal antenna configuration \( w_{opt} \) is obtained as outputs from the algorithm. The algorithm is as follows;

1. \( Eb_{min} = +\infty \)
2. \( \text{for } I \leq nt \leq NT, I \leq nr \leq NR \)
3. \( \text{Identify } H(nt, nr) \text{ using antenna selection algorithms to identify the optimal configuration by finding the one with high norm.} \)
4. \( PTX = PTX (nt, nr, R_{min}) \) using the pre-built mapping
5. \( Eb = Eb (PTX, nt, nr) \)
6. \( \text{If } Eb < Eb_{min} \)
   \( \circ Eb_{min} = Eb, P_{TX_{opt}} = PTX, w_{opt} = w \)
7. \text{end}
8. \text{return } PTX, w_{opt}

In this algorithm both ends are optimised using the equation:

\[
Eb = PMIMO / R = Eb (PTX, NT, NR)
\]  

(1)

Where,

\[
Eb (PTX, NT, NR) = \frac{PTX + NT \cdot PT_{RF} + NR \cdot P_{RF} + P_{T_{shared}} + P_{R_{shared}}}{R}
\]

(2)

\( P_{T_{RF}} \) is the power used by the RF chains on the transmitter end and \( P_{T_{shared}} \) is the power consumed by the shared circuitry on the transmitter end. Similarly, it is also present on the received end as well.

#### B. MIMO Energy per Bit Minimization

In this section the energy per bit minimization problem for a MIMO link is analyzed. The question that is being answered here is: given the channel matrix \( H \), what is the number of active antennas and transmit power that yield minimum energy per bit?

1) **Objective Function**

The objective function, the MIMO energy per bit \( Eb \), can be calculated as the power consumption \( P \) divided...
by the data rate $R$. There were two observations regarding $P$ and $R$. First, the two ends of a MIMO link can be either a pair of battery-powered mobile nodes, or an infrastructure node and a mobile node. Because energy efficiency is only important to mobile systems, $P$ can be either the power consumption of both ends or that of a single end. Second, the data rate supported by the MIMO channel is function of the number of antennas at both ends. In practice, one or both ends may allow antenna management.

These two observations lead to nine cases of the MIMO energy per bit minimization problem, depending which end allows antenna management and which end desires energy efficiency optimization. When both ends are mobile nodes, $P=P_{\text{MIMO}}$; when only one end is mobile, $P=P_{\text{T}}$ and $P=P_{\text{R}}$ for the mobile node as a transmitter and a receiver, respectively. When both ends allow antenna management, $E_{\text{b}}=E_{0}$ ($P_{\text{TX,N_T,N_R}}$) from equation 1 and 2.

2) Constraint
The important constraint to the optimization problem is that $R \geq R_{\text{min}}$, $R_{\text{min}}$ being the minimum required data rate, because the optimization variables $P_{\text{TX,N_T,N_R}}$ have a direct impact on the data rate $R$ and wireless links usually have a data rate requirement.

3) Optimization Variables
Next is the optimization variables are considered. First, the given $H$ and $R_{\text{min}}$ is observed, there exists a finite optimum transmit power, $P_{\text{TX,OPT}}$, that yields minimum $E_{\text{b}}$. Second, we combine other optimization variables as one, namely the antenna configuration, $w$, which includes not only the number of antennas, i.e., $N_{\text{T}}$ and $N_{\text{R}}$, but also which subset of antennas is active. Apparently, each yields a unique channel matrix and thereby a unique optimal transmit power $P_{\text{TX,OPT}}(w)$.

C. Algorithmic Design of Antenna Management
It is an efficient solution to the optimization problem formulated above. The problem is non-trivial to solve for the following the following reason;

Given $H$ and $R_{\text{min}}$, no closed-form formulation of the optimal transmit power, $P_{\text{TX,OPT}}$, is obtainable.

Antenna management leverages two key techniques to tackle the above challenge. First, it identifies $P_{\text{TX,OPT}}$ with mappings built offline. For each pair of $N_{\text{T}}$ and $N_{\text{R}}$, antenna management employs multiple mappings to cope with large-scale channel fading introduced by significant movement of the mobile node. Second, for a small number of antennas, antenna management enumerates all the antenna configurations to find $w_{\text{OPT}}$, i.e., the optimal and the optimal subset of antennas; for a large number of antennas, it leverages existing antenna selection algorithms. The overall algorithm is summarized in Algorithm stated above and following are two techniques.

1) Pre-Built Mapping
It is observed that, without considering $R_{\text{min}}$, $P_{\text{TX,OPT}}$ is primarily determined by the dimension of $H$, i.e., $N_{\text{T}}$ and $N_{\text{R}}$. Therefore, a mapping from each $(N_{\text{T}}, N_{\text{R}})$ to $P_{\text{TX,OPT}}$ can be built offline using either synthetic or measured channels. In this work, the prebuilt mapping [1] is used to obtain the power transmitted for the corresponding data rate. This is shown in the Figure 4.

![Fig. 4. Mapping from the effective data rate to the optimal transmit power](image)

2) Antenna Selection
Given $N_{\text{T}}$ and $N_{\text{R}}$, minimizing $E_{\text{b}}$ is equivalent to maximizing $R$, since the power consumption is constant. Therefore, it turns into a capacity-maximization-based antenna selection problem where existing efficient algorithm, can be straightforwardly leveraged. As a result, we only need to identify the optimal number of antennas, with the lowest $E_{\text{b}}$.

The Figure 5 shows the 4X4 transmitting and receiving antenna array and explains how the antenna selection algorithm acts as feedback network and also optimisation of both transmitting and receiving antennas.

![Fig. 5. Optimizing both transmitter and receiver](image)
D. Flow Chart of the Algorithm

```
Compute norm of all possible configurations

Select the best pair in each configuration which gives total of 16 configurations.

If Eb < Eb(min)

Compute Eb for all the above different possible configurations.

Update the current configuration as the optimal configuration

Output the configuration with min Eb and power
```

Fig. 6. Flow-chart of the Antenna Selection algorithm

VII. IMPLEMENTATION

A. Software Implementation

1) VHDL using Xilinx-ISE

Simulation of the antenna management algorithm which is implemented using VHDL using Xilinx-ISE is shown in this section. Figure 7 below shows the H-matrix inputs in the simulated test bench window.

Fig. 7. Simulated test bench-H matrix inputs

The Figure 8 shows the optimal transmit power for a given data rate and antenna configuration obtained from pre-built mapping.

Fig. 8. Simulated code of optimal transmit power

The Figure 9 shows the optimal antenna configuration and power for the given H-Matrix and data rate.

Fig. 9. Simulated test bench – optimal antenna configuration
2) **MATLAB Simulation**

The Figure 10 explains how the signal fades in the channel and we are plotting samples versus amplitude in dB, which shows the amount of co-relation between the two fading envelopes, the one pair with least co-relation is chosen for high diversity gain.

![MATLAB Simulation Results](image)

3) **MATLAB Output**

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<tr>
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<th>-0.5094 - 0.7450i</th>
<th>-0.5094 + 0.7450i</th>
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</table>
B. Hardware Implementation

The Figure 11 shows the Spartan-3 FPGA kit connected to two GPIO (General Purpose Input Output) BUS where, in one board the 8-LEDs show the optimal antenna configuration and in the other the optimal power.

![Hardware Implementation Image]

VIII. CONCLUSION

The concept of MIMO, advantages and disadvantages are learned with the help of various sources which helped in the generation of channel matrix for 4X4 MIMO. This is generated by various parameters like the angle of arrival, angle of departure, angular spread and antenna spacing. With the knowledge of the channel matrix the antenna selection algorithm is implemented to obtain the optimal transmit power and the antenna configuration for the given data rate which is above the threshold value. This results in identifying the subsets of antennas instead of using all at a given time by identifying those antennas with low energy per bit values based on the information from channel matrix.

IX. FUTURE SCOPE

The existing work project could further extended in future by considering all the channel state information (CSI) and various channel parameters involved in the channel between transmitter and receiver. This is makes the project more practical than it is now as this project is only a theoretical study of MIMO and to identify the antenna configuration. Various channel coding techniques which are not considered could be dealt in future and the project could also be tested for outdoor communication by considering profiles other than B.
REFERENCES


Appendix

Appendix A – Model B

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<th>Tap index</th>
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