Antenna Power Allocation for Energy Save in MIMO 802.11n Networks

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Abstract- MIMO systems provide a method of improving the goodput of communication by either diversity or spatial multiplexing. However, multiple transmission antennas come at the increased cost of circuit power, and so it might not always be the best approach. In this project, we analyze the varying effect of noise and circuit power on the performance of 1x3, 2x3 and 3x3 MIMO systems, and predict the best configuration under the given conditions. We propose a method to optimally allocate power among multiple transmission antennas in order to obtain the minimum energy per bit values. We answer the following questions: Which MIMO mode should the system operate in Diversity or Spatial-Multiplexing; How many transmission antennas should be turned on and How much power should be allocated to each antenna. We propose an algorithm to optimally allocate transmission power for the best energy per bit performance. We also compare our power allocation approach to verify its utility. Simulations and numerical results show that our proposed approach works better than the naive equal power allocation method, and closely tracks the oracle.

Keywords- Power Allocation, Diversity, Multiplexing, MIMO systems

I. Introduction

Multiple-input-multiple-output (MIMO) systems are very significant in wireless communications. Recent advancement in wireless technology namely 802.11n utilize the advantages of MIMO system to provide better service. MIMO systems are defined as links in which both the transmitting and the receiving ends have multiple antennas. These multiple antennas can be used to improve either the quality of transmission (by reducing the bit error probability) or increase the data rate of transmission. These separately provide diversity gain (reduced bit error probability) or multiplexing gain (increased data transmission rate). Using the multiple antennas for transmission comes at the cost of the power which is needed to power the extra antennas. Each antenna which is operated requires a fixed power in order to operate its circuitry elements, apart from the power which is needed for transmission. However, just the power requirement increase cannot be used as a measure of performance in MIMO systems, since employing multiple antennas also reduces the time required for transmission. So the energy required per transmitted bit provides a more accurate heuristic to measure the usefulness of multiple antennas. In this project we propose a method for selecting the number of transmit antennas to power on in order to minimize the energy per transmitted bit. Further, in the case where channel gain is known, we propose a method of optimal power allocation amongst the active antennas. Since MIMO systems can operate in two modes, we also identify the conditions for switching between diversity and multiplexing modes and the optimal number of active antennas and power allocation in each mode.

II. Related Work

Prior work on energy saving in 802.11n MIMO has not specifically addressed the optimal transmission antenna selection problem, or the power allocation issue. [3] talks about power allocation for transmitter diversity systems and models the allocation based on the knapsack problem. However, it only considers the total power consumption with bit error rate constraints, and does not consider energy per bit as a defining factor, or the selection of an optimal number of transmission antennas. [1] considers the energy per bit heuristic and adopts a power modeling similar to ours, but the papers analysis is on the receiving antennas and identifying the most efficient energy chain setting at the receiver. In [4], the authors talk about the transmission energy per bit, but this comparison is done with respect to the transmission distance. They compare the energy efficiency of SISO with MIMO and use the results to analyze the effect of cooperation between sensor nodes. [5] considers the case of switching between MIMO and SIMO modes based on the energy efficiency. They propose a method of rate selection and adaptive switching. However, they do not address the question os operating in spatial-multiplexing or diversity modes, nor do they consider the power allocation issue.

III. System Model

We consider a MIMO system with N_T transmit antennas and N_r receive antennas. While deciding on an optimal antenna selection and power allocation, the aim is to minimize the total energy consumed per bit transmitted. The total energy consumed per bit can be obtained as:

$$E_b = \frac{P_{total}}{\text{Goodput}}$$

The total power consumption for transmission is divided into two main parts: the transmit power P_T and the power consumption of the other circuit blocks P_C. So total power consumption for a system with N_T transmitters can be obtained as:

$$P_{Total} = P_T + N_T P_C$$

The transmit power P_T is distributed amongst all the active antennas. We define H to be the channel gain matrix, where entry h_{ij} defines the path gain from transmit antenna j to receive antenna i. In the cases where H is unknown, each active transmitter is assigned the same power, i.e. $P_i = P_T/N_T$. When H is known, the P_i values are varied optimally.

A. Spatial-Diversity

Multiple antenna systems provide spatial diversity, wherein the same information symbols are replicated and sent in order to improve the reliability of the link. For a given diversity gain of d, the probability of error is known to decay at the rate of SNR^{-d}. Intuitively, we can see that the diversity gain corresponds to the number of independent paths the same data is sent via. So the maximal diversity gain is $N_T N_r$. The probability of error can then be written as:

$$P_e = \left(1 - \frac{1}{\text{SNR}^{N_T N_R}}\right)$$

and the rate of transmission as

$$R_b = \log(1 + SNR)$$

The goodput of the spatial diversity mode is obtained as:

$$G = R_b P_e$$

$$G = \log(1 + \text{SNR})\left(1 - \frac{1}{\text{SNR}^{N_T N_r}}\right) \tag{1}$$

In the case where no channel information is known and each active transmission antenna is assigned the same power for transmission, we can define the SNR(signal-to-noise) ratio at the receiver in terms of transmit power as:

$$\text{SNR} = \frac{P_T}{N_0}$$

When the channel gain matrix is known to the transmitter, the power allocated to each active antenna(P_i) is different and the SNR in this case is defined as:

$$\text{SNR} = \frac{1}{N_r}\sum_{i=1}^{N_T}\frac{P_i|H_i|^2}{N_0}$$

The energy required per bit transmitted while in diversity mode is then defined as:

$$E_b = \frac{P_T + N_T P_c}{\log(1 + \text{SNR})\left(1 - \frac{1}{\text{SNR}^{N_T N_r}}\right)} \tag{2}$$

B. Spatial-Multiplexing

Apart from spatial diversity, multiple antenna systems can also be used to provide a higher data rate than single antenna systems. This is done by sending independent information symbols in parallel through the separate channels. This is spatial-multiplexing. For a given spatial-multiplexing gain r, the rate of transmission obtained increases as $r \log \text{SNR}$. Since the information signals need to be sent by independent channels, the maximum possible spatial-multiplexing gain is given as $\min\{N_T, N_r\}$. When the channel gain is unknown, we divide the power equally among the active antennas to obtain a rate given as:

$$R_b = N_T \log(1 + \text{SNR})$$

The goodput in the unknown channel gain information case is then defined as:

$$G = N_T \log(1 + \text{SNR})\left(1 - \frac{1}{\text{SNR}^{N_r}}\right) \tag{3}$$

When the channel gain is known the power is distributed among the active antennas based on the channel gain for each path. The goodput in this case is defined as:

$$G = \frac{1}{2}\left(\prod_{i=1}^{N_T}\left(1 + \frac{P_i|H_i|^2}{N_0}\right)\right)\left(1 - \frac{1}{\text{SNR}^{N_r}}\right) \tag{4}$$

The energy per bit is defined as total power/Goodput where goodput is given by equation 3(or 4) for the case of channel gain unknown(or Channel gain known).

IV. Our Approach

In this section we use energy per bit as our heuristic and show our analysis. We carry out the analysis through several case studies for both diversity and spatial-multiplexing modes of MIMO operation. We also consider the case when the channel gain is unknown to the transmitter and when it is known. We show how the channel gain information can be used by the transmitter to smartly select the antennas and allocate power using our optimal power allocation scheme. We consider four different scenarios - i) Channel Unknown and Diversity mode, ii) Channel Unknown and Multiplexing mode, iii) Channel known and diversity mode and iv) Channel known and Multiplexing mode of operation. In our analysis, we consider the following 3 configurations: 3x3, 2x3 and 1x3 and compare the energy per bit over varying noise and circuit power.

This comparison with noise and circuit power is important. As different environments have different noise characteristics which is an important aspect and needs to be consider when we are dealing with performance of device based on 802.11n. Also since different devices have different internal circuitry which might consume different power for the same task, considering circuit power to switch between the modes and the configuration is thus important and adds to the performance.

V. Scenario 1 - Channel Gain Unknown and Diversity Mode of Operation

Here, we consider the case where we are operating in diversity mode and do not have channel gain information available at the transmitter. Each active antenna is allocated equal power, as there is no information available that can form a basis for unequal allocation.

Goal: To decide on an optimal number of active antenna(N_T) with varying P_C and N_0.

We will show our analysis through several case studies which we carried out. We will show how to minimize energy per bit.

Case Study 1: We compare energy per bit with varying noise power for $P_T = 1W$ and $P_C = 0.1W$. Table 1 show the values we chose in our case study to study the comparison between the configurations for diversity mode.

TABLE I
Channel unknown at Tx and Diversity Mode: Variation with N_0

N_0	$E_b^{1x3}(N_0)$	$E_b^{2x3}(N_0)$	$E_b^{3x3}(N_0)$
0.2	**0.429**	0.4643	0.5029
0.6	0.9915	**0.8895**	0.9281
0.8	1.927	1.39	**1.283**

The same can be seen from Figure 1. We can see that as noise power increase, operating in 3x3 mode provides a lower E_b. At higher noise power values, the diversity gain in 3x3 is sufficiently high to overcome the overhead of extra circuit power, and so is the better option.

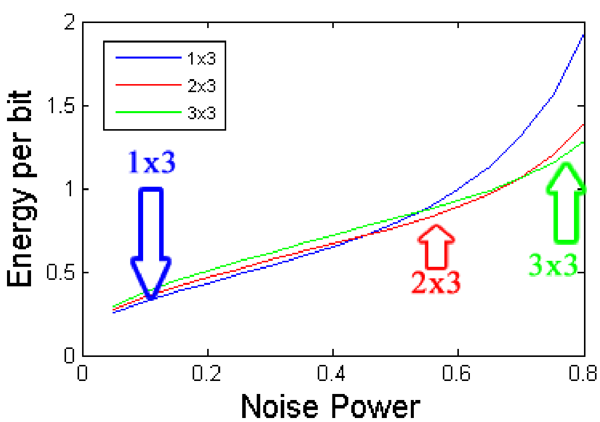

Fig. 1. Diversity mode with unknown channel, Energy per bit vs. Noise Power

Case Study 2: We compare energy per bit with varying circuit power for $P_T = 1W$ and $N_0 = 0.7W$. Table 2 show the values we chose in our case study to study the comparison between the different configurations for diversity mode.

TABLE II
Channel unknown at Tx and Diversity Mode: Variation with P_c

P_c	$E_b^{1x3}(P_c)$	$E_b^{2x3}(P_c)$	$E_b^{3x3}(P_c)$
0.05	1.248	0.9739	**0.9361**
0.4	1.665	**1.594**	1.791
0.8	**2.14**	2.302	2.768

The result of this case study can also be seen from Figure 2. As the circuit power increases, the overhead of using multiple antennas is much higher and the goodput gained is much lesser than the cost of activation.

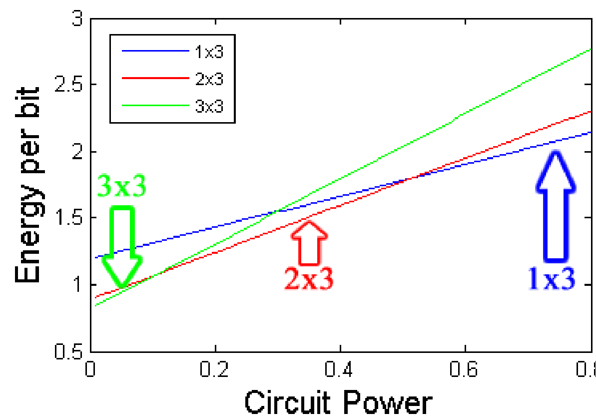

Fig. 2. Diversity mode with unknown channel, Energy per bit vs. Circuit Power

Case Study 3: From the above two case studies, we can see that there exist crossover points of N_T with N_0 and P_C. So, for any given N_0 and P_C, there exists an optimal N_T for which E_b is minimum. In this case study, we study the change in N_T for varying both N_0 and P_C. We see in Figure 3 and Figure 4, that for any value of N_0 and P_C, there exists an optimal value of N_T. For high noise and low circuit power values, 3x3 works best. As circuit power increases, for the same noise, the number of optimal N_T decreases. In low noise situations 1x3 works best. As the noise increase, the number of optimal N_T also increases, since the higher diversity gain reduces the bit error probability, leading to increase in goodput.

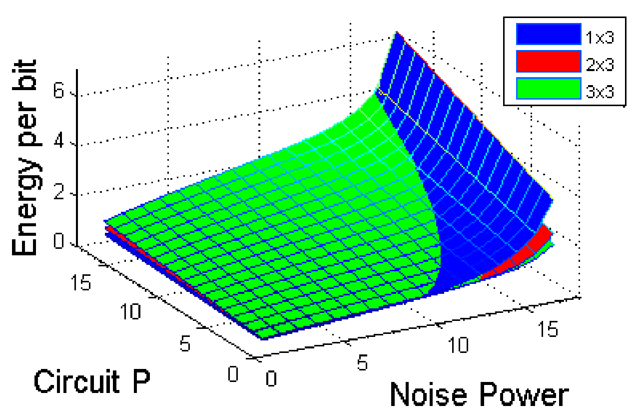

Fig. 3. Diversity mode with unknown channel, Energy per bit vs. Noise Power and Circuit Power

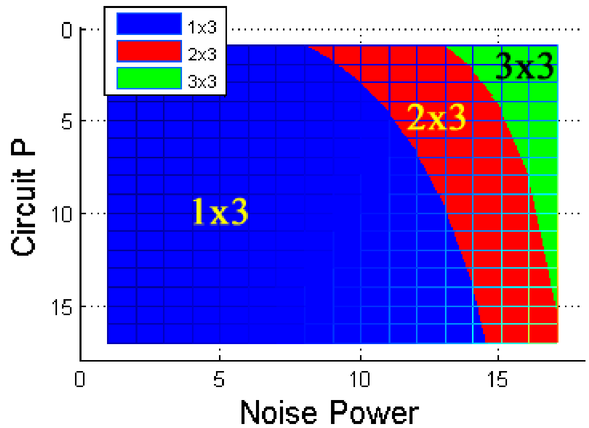

Fig. 4. Different view: Diversity mode with unknown channel, Energy per bit vs. Noise Power and Circuit Power

It is possible to mathematically find a solution to decide N_T based on the N_0 and P_C values. This can be written as:

$$
\begin{array}{l}
1\text{x}3 \rightarrow E_b^{1X3}(N_0, P_c) \leq \min(E_b^{2X3}(N_0, P_c), E_b^{3X3}(N_0, P_c)) \\
2\text{x}3 \rightarrow E_b^{2X3}(N_0, P_c) \leq \min(E_b^{1X3}(N_0, P_c), E_b^{3X3}(N_0, P_c)) \\
3\text{x}3 \rightarrow E_b^{3X3}(N_0, P_c) \leq \min(E_b^{1X3}(N_0, P_c), E_b^{2X3}(N_0, P_c))
\end{array}
$$

VI. Scenario 2 - Channel Gain Unknown and Multiplexing Mode of Operation

In this scenario, we consider the case where we operate in Spatial-Multiplexing mode and the channel gain is unknown at the transmitter. Each active antenna is allocated the same fraction of power. We compare the different configurations with varying P_C and N_0 and tell the optimal value which should be selected for minimizing energy per bit(E_b).

Goal: To decide on an optimal number of active antenna(N_T) with varying P_C and N_0.

Case Study 4: Here we compare the effect of varying N_0 on Energy per bit for different number of transmit antennas. As can be seen in Figure 5, when the noise power increases, the probability of error increases, and the energy per bit requirement increases in all cases. However, we also find that higher number of transmit antennas always result in lower Energy per bit values. This can be attributed to the fact that rate in 3x3 is very high, and hence capacity becomes high. The varying noise has the same effect for the different transmission antenna numbers, and so 3x3 always performs better.

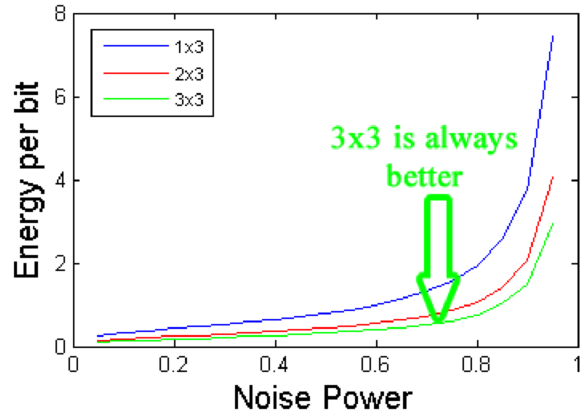

Fig. 5. Multiplexing mode with channel Unknown, Energy per Bit vs. Noise Power

Case Study 5: When we compare the E_b for different N_T with varying P_C, we find that 3x3 always works better. In Figure 6 we see that even with the increase in circuit power, the capacity of 3x3 is high enough to offset it, and so always performs better.

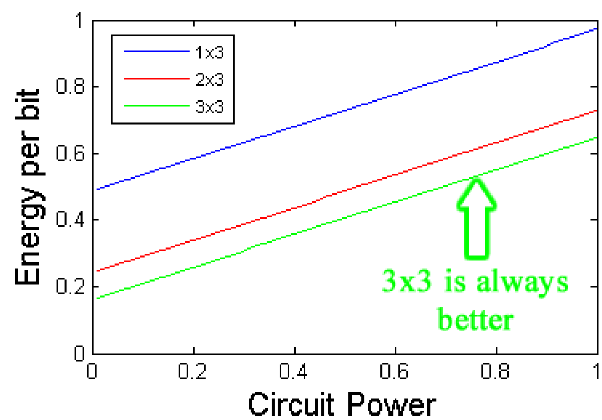

Fig. 6. Multiplexing mode with channel Unknown, Energy per Bit vs. Circuit Power

In both the case of varying P_C and N_0, we find that 3x3 configuration works the best. This can be attributed to the high capacity gain in case of higher number of transmission antennas, which can offset the overhead due to the extra circuit power. So in the case of spatial multiplexing, for any value of noise and circuit power, higher number of transmission antennas work best.

VII. Scenario 3: Channel gain known and Diversity Mode of Operation

Till now we considered the case where the channel gain is unknown. However, NICs now provide information about the channel gain, which can be used to improve the goodput. With the channel information, transmitter can smartly allocate the power to perform better than the unknown channel case. Each active antenna is allocated power in proportion to the channel gain thus maximizing the SNR.The SNR in this case is computed as the average SNR over all the receivers. **Our goals are:**

- Find optimal N_T for any N_0 and P_c
- Which antennas to select for transmission, N_T
- How much power to give to each active antenna

OUR OPTIMAL POWER ALLOCATION: We know goodput in the case of known channel while operating in Diversity mode is given as in [1]. The power distribution amongst the active antenna should be such that the goodput is maximized. Intuitively we see that we should assign maximum power to the transmitters which have the maximum channel gain. However, the optimal power allocation should not assign zero power to any of the other transmitters as that would be equivalent to switching of the antenna. Considering these two constraints, the optimal power allocation works as below:

- Allocate P_{min} power to all the N_T antennas
- Allocate the remaining $P_T - N_T P_{min}$ power to the antenna with the highest channel gain

We now use this optimal power allocation for deciding on the best value of N_T for varying circuit power and noise power. Our case study shows the optimal value of N_T which should be selected for any N_0 and P_c.

Case Study 6: In this case study, we see the effect of variation of N_0. Each active antenna is given power P_i using the optimal power allocation method described before. Table 3 shows the variation of N_0.

TABLE III
CHANNEL KNOWN AT TX AND DIVERSITY MODE: VARIATION WITH N_0

N_0	$E_b^{1x3}(N_0)$	$E_b^{2x3}(N_0)$	$E_b^{3x3}(N_0)$
0.5	**0.7**	0.7348	0.7831
1.0	1.152	**1.095**	1.152
1.5	2.264	1.715	**1.641**

We consider two cases separately: where the channel gain difference at each transmitter is very high, and where the channel gain information at each transmitter is low. Similar to case study 1, we find that there exist crossover points shown in Figure 7 and Figure 8. What is interesting is that for separate variations in channel gain the crossover points vary. As the difference in channel gains decreases, the region for 3x3 increases and 1x3 decreases. When difference in channel gain is high, selecting a higher number of antennas results in power allocation to even the weaker channels, which reduces the goodput.

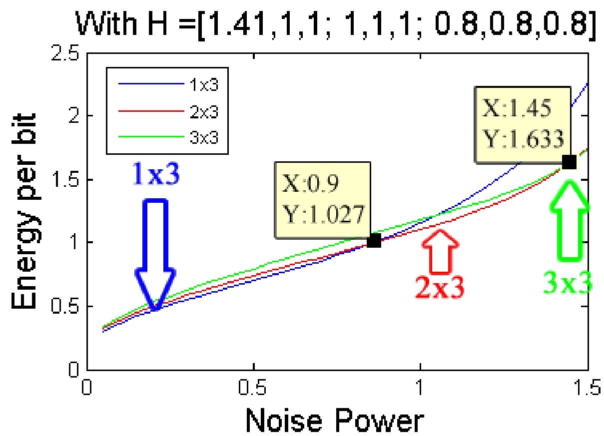

Fig. 7. Diversity mode with high channel gain variation, Energy per bit vs. Noise power

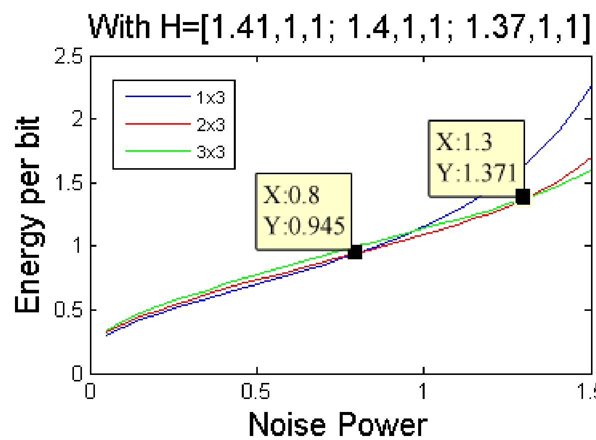

Fig. 8. Diversity mode with low channel gain variation, Energy per bit vs. Noise power

Case Study 7: In this case study, we see the effect of variation of P_c. Table 4 shows this variation of P_c.

TABLE IV
CHANNEL KNOWN AT TX AND DIVERSITY MODE: VARIATION WITH P_c

P_c	$E_b^{1x3}(P_c)$	$E_b^{2x3}(P_c)$	$E_b^{3x3}(P_c)$
0.01	1.361	1.134	**1.109**
0.1	1.442	**1.268**	1.304
0.45	**1.758**	1.79	2.065

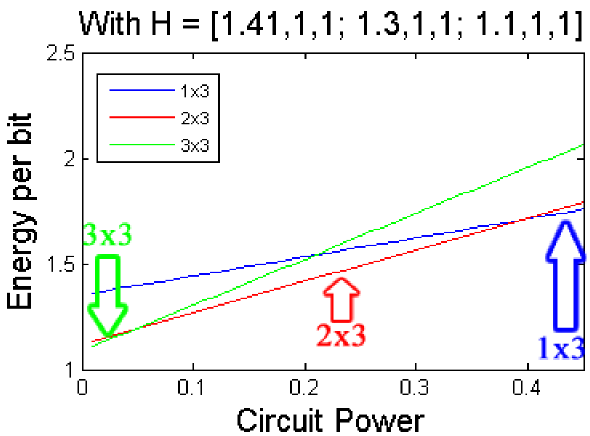

Fig. 9. Diversity mode with high channel gain variation, Energy per bit vs. Circuit power

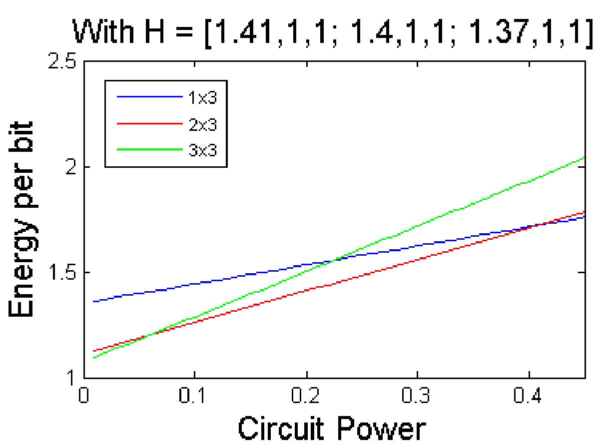

Fig. 10. Diversity mode with low channel gain variation, Energy per bit vs. Circuit power

Similar to case study 1, we see that increasing circuit power favors a lower number of transmission antennas. Next we compare the case of high channel gain variations and low channel gain variations shown in Figure 9 and Figure 10. Higher channel variation reduce the performance region of 3x3 configurations, as allocating power to the low gain channels will reduce the Goodput, thus increasing the Energy per bit consumption.

Case Study 8: Based on the previous two case studies, we see that there exist crossover points for the optimal number of transmission antennas based on both noise power and circuit power.

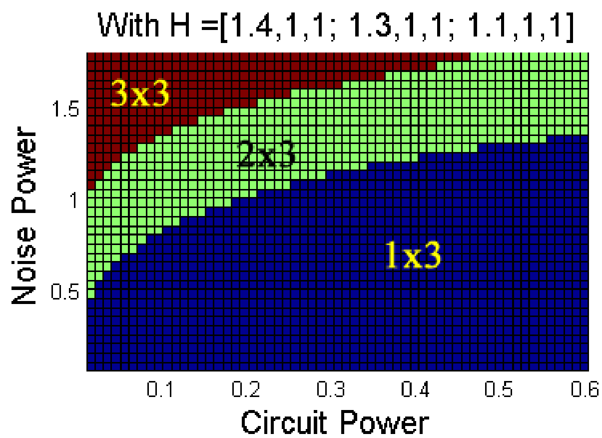

Fig. 11. Diversity mode with high channel gain variation, Optimal N_T for varying noise power and circuit power

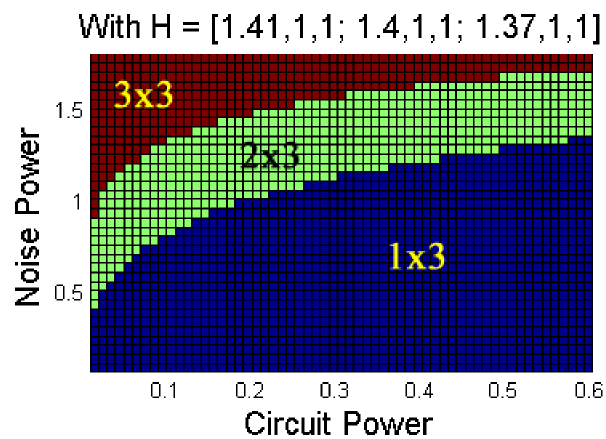

Fig. 12. Diversity mode with low channel gain variation, Optimal N_T for varying noise power and circuit power

In Figure 11 and Figure 12, we can see distinct regions for the optimal number of transmission antennas based on the noise and circuit power. When noise power is high, operating with multiple antennas is better due to the decreased probability in error and hence increased goodput. When the circuit power is low, this transition to higher number of antennas happens sooner as compared to higher circuit powers, since the goodput gain needed to offset the increase in power consumption is lower. When low variation and high variation channels are compared, we see that the region for 3x3 is higher in case of lower channel gain variations.

A. Performance Comparison - Diversity

Comparing our proposed optimal power allocation approach with the equal power allocation approach in figure 13, we find that our proposed solution always works better. Intuitively this is true, since the optimal approach allocates more power to higher gain channels, thus improving the SNR and consequently the goodput.

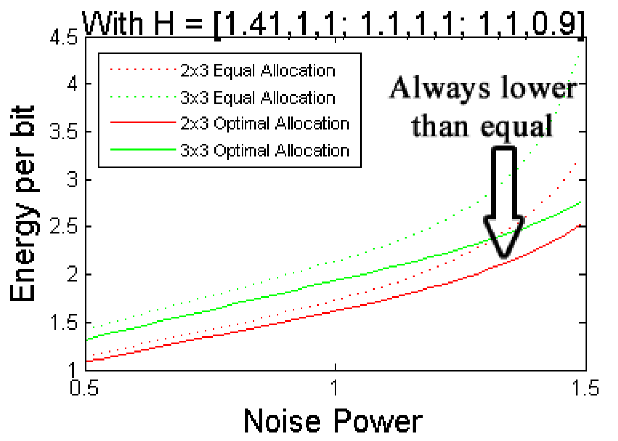

Fig. 13. Comparison of equal power allocation with our approach, Diversity mode

Next we compare whether our approach is actually the best possible power allocation method. We compare our method with an oracle approach as shown in figure 14, which always knows what the best possible power allocation. The proposed approach, always tracks the oracle, which is evident even mathematically.

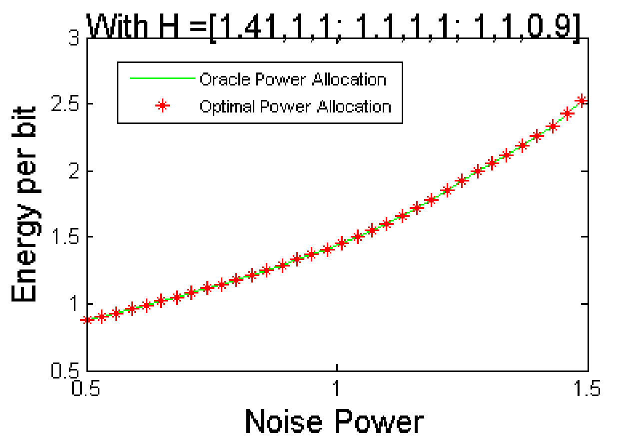

Fig. 14. Comparison of the oracle power allocation with our approach, Diversity mode

VIII. Scenario 4: Channel Gain Known and Multiplexing Mode of Operation

Similarly in the case of Spatial-Multiplexing mode, based on the channel gain information at the transmitter, power can be allocated such that the SNR increases and the Energy per bit decreases. Our goals are similar to scenario 3.

OUR OPTIMAL POWER ALLOCATION: We know goodput in the case of known channel while operating in Spatial Multiplexing mode is given as in (4). A water filling approach to maximize the capacity already exists. But since we have the constraint of total power while calculating energy per bit, just maximizing the capacity will not result in minimum E_b. In our proposed method, we first fix a value of N_T. Once this is fixed, we can use a variation of the water filling method to maximize the capacity and thus minimize Eb. In the standard water filling approach, power is allocated based on a minimum performance threshold. However, there might be some antennas which are not allocated any power in this approach, which actually will reduce the number of active antennas. Each active antenna must be allocated at least the minimum P_{min} power, after that water filling can be used to allocate the remaining power. The proposed power allocation works as below:

- Assign P_{min} power to all the active antennas
- The remaining power $P_T - N_T P_{min}$ is assigned using the water filling approach

Using this approach we can define the power allocated in 3x3 configurations as:

$$P_i = \left(\left(\frac{1+N_0\left(\frac{1}{|H_1|^2}+\frac{1}{|H_2|^2}+\frac{1}{|H_3|^2}\right)}{3} \right) - \frac{N_0}{|H_i|^2} \right)^+ (P_T - 3P_{min}) + P_{min}$$

Power allocate in 2x3 is defined as:

$$P_i = \left(\left(\frac{1+N_0\left(\frac{1}{|H_1|^2}+\frac{1}{|H_2|^2}\right)}{2} \right) - \frac{N_0}{|H_i|^2} \right)^+ (P_T - 2P_{min}) + P_{min}$$

Based on this optimal power allocation, we study the effect of varying P_C and N_0 on the optimal N_T value.

Case Study 9: In this case study, based on our optimal power allocation approach described above, we compare the effect of varying N_0 on the energy per bit requirements. Table 5 shows the value of N_0 we chose in our case to see the performance of various configuration. We fixed $P_T = 1.5W$ and $P_c = 0.9W$.

TABLE V
Channel known at Tx and Multiplexing Mode: Variation with N_0

N_0	$E_b^{1x3}(N_0)$	$E_b^{2x3}(N_0)$	$E_b^{3x3}(N_0)$
0.05	0.6938	0.5635	**0.5412**
0.5	1.318	**1.225**	1.311
1.1	**2.14**	2.219	2.516

Figure 15 and Figure 16 show this comparison for the cases of high channel gain variation and low channel gain variation. We find that at lower noise powers, 3x3 configurations work better, which changes with increase in noise power. As noise power increases, the capacity of all configurations decrease, but the rate of decrease in 3x3 configurations is higher than of 1x3. So at higher noise power, 1x3 works better. When high and low channel gain variation models are compared, we see that the performance region of 3x3 increases in lower channel gain variations. This can be attributed to the fact that at higher channel gain variations, allocating even small amount of power to low channel gain transmitters result in a sharp drop in capacity.

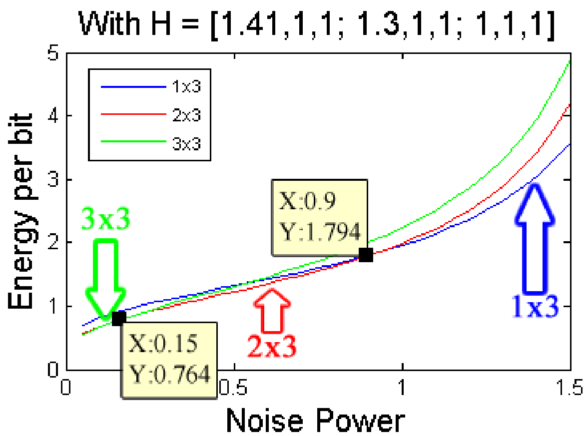

Fig. 15. Multiplexing mode with high channel gain variation, Energy per bit vs. Noise power

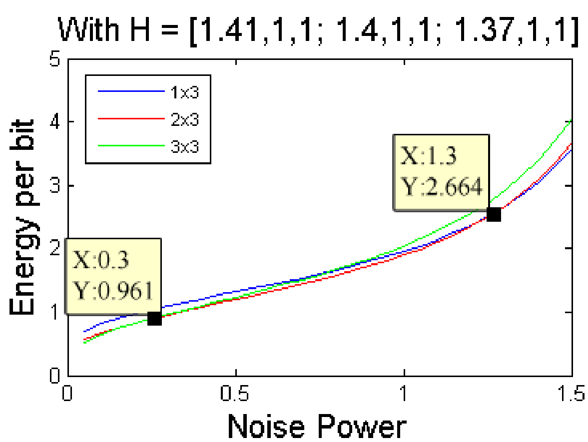

Fig. 16. Multiplexing mode with low channel gain variation, Energy per bit vs. Noise power

Case Study 10: In this case study, based on our optimal power allocation approach described above, we compare the effect of varying P_c on the energy per bit requirements. Table 6 shows the value of P_c we chose in our case to see the performance of various configuration. We fixed $P_T = 1.5W$ and $N_0 = 0.6W$.

TABLE VI
CHANNEL KNOWN AT TX AND MULTIPLEXING MODE: VARIATION WITH P_c

P_c	$E_b^{1x3}(P_c)$	$E_b^{2x3}(P_c)$	$E_b^{3x3}(P_c)$
0.1	0.9507	0.6959	**0.6373**
0.5	1.188	**1.023**	1.046
1.5	**1.783**	1.842	2.091

From Figure 17, we can see that lower circuit power favors a higher number of transmission antennas. When the circuit power is low, the cost of operating a higher number of antennas is easily offset by the goodput gains, which is not the case as the circuit power increases. Comparing the high channel gain variation case with the low variation case shown in Figure 18, we see a similar trend as in case study 7. Lower channel gain variations result in larger performance regions for a higher number of antenna.

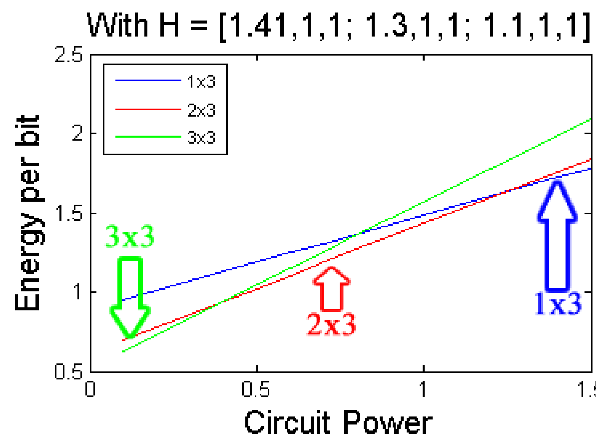

Fig. 17. Multiplexing mode with high channel gain variation, Energy per bit vs. Circuit power

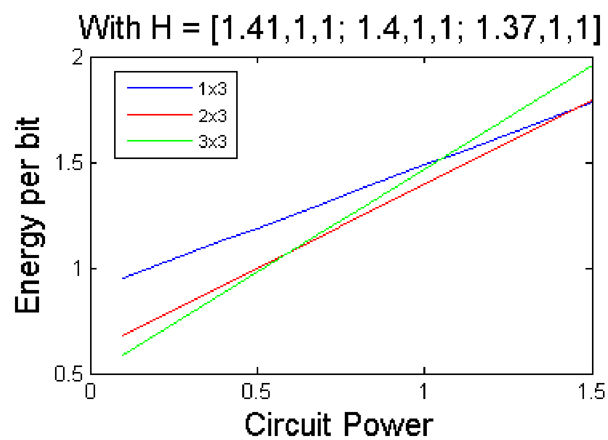

Fig. 18. Multiplexing mode with low channel gain variation, Energy per bit vs. Circuit power

Case Study 11: From case studies 9 and 10, we see that there exist crossover points for the optimal number of transmission antennas with varying Noise power and Circuit power. Figure 19 shows the variation of optimal N_T with N_0 and P_c. For low noise power and low circuit power, higher number of transmission antennas provide the best E_b. As the noise power increases, the capacity decrease for 3x3 case is high. Correspondingly if the circuit power also increases, the overhead of operating in 3x3 mode also increases. Thus at higher noise and circuit power values, 1x3 provides the best E_b values, whereas at lower circuit and noise power higher number of transmission antennas work better.

Figure 20 shows the variation of optimal N_T with N_0 and P_c for the scenario where channel gains variation is low. As seen in figure, in this case, performance region of 3x3 mode increases.

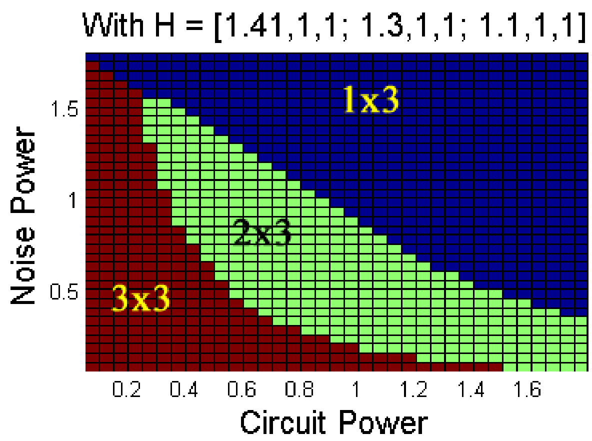

Fig. 19. Multiplexing mode with high channel gain variation, Optimal NT for varying noise power and circuit power

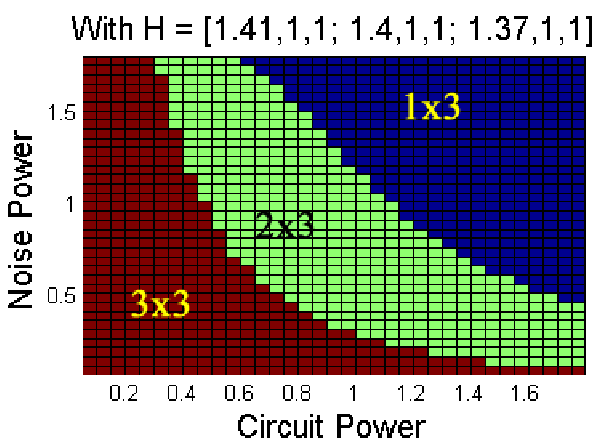

Fig. 20. Multiplexing mode with low channel gain variation, Optimal NT for varying noise power and circuit power

A. Performance Comparison - Multiplexing

Next we compare our scheme of minimizing energy per bit with the scheme where you allocate equal power at each active antenna. To find the upper bound on performance, we also compare our scheme with the best possible oracle approach which has all the information about the best configuration and best power allocation.

First, we compare our proposed power allocation and minimizing energy per bit approach with the naive approach of equal power allocation. Intuitively, we know that allocating unequal powers to antennas with different channel gains will provide an increased goodput as compared to the equal allocation and this is what is observed as shown in Figure 21

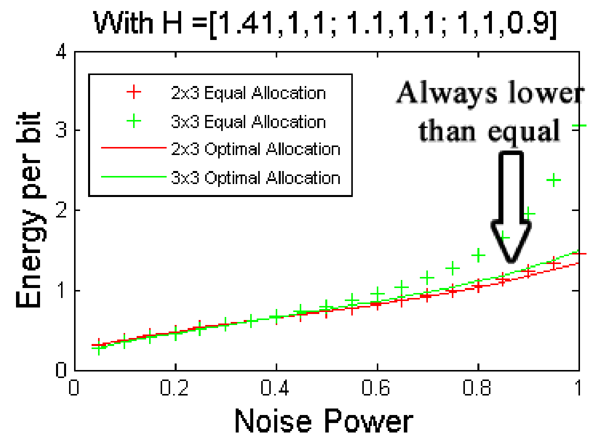

Fig. 21. Comparison of equal power allocation with our approach, Multiplexing mode

We now compare the proposed power allocation approach with the oracle approach. In Figure 22 we can see that the proposed approach tracks the oracle mostly. However there are some slight deviations. From equation (4) we see that for minimum Energy per bit we need to maximize the goodput. The rate of transmission must be increased and the probability of error decreased. The water-filling approach maximizes the rate of transmission calculation, but does not minimize the probability of error. This results in the slight deviation of the proposed approach from the oracle approach.

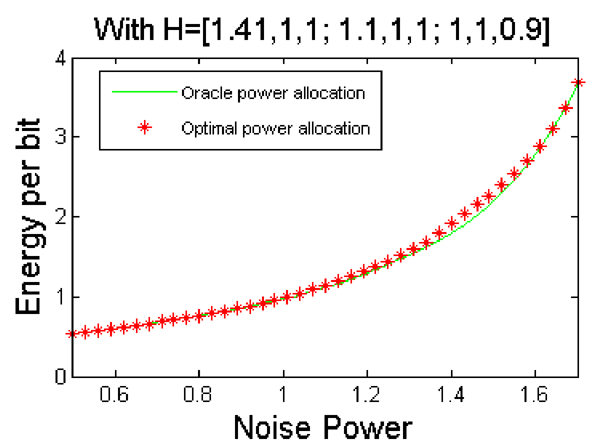

Fig. 22. Comparison of oracle power allocation with our approach, Multiplexing mode

IX. Diversity and Multiplexing Switching

From the case studies $1-11$ we have compared the optimal N_T values for different modes with varying noise power and circuit power. Based on these results we now try to decide on an optimal number of antennas as well as the optimal mode to operate in, which will provide the lowest Energy per Bit values. We expect that multiplexing will work in low noise and low circuit power scenarios with a higher optimal number of transmission antennas, since in this case the capacity of 3x3 configurations is really high. As the noise power increases, the diversity mode becomes more feasible due to the requirement of increased reliability. In Figure 23, as expected we find that low noise and low circuit power favors multiplexing with higher number of antennas, whereas higher noise and circuit power favors diversity mode.

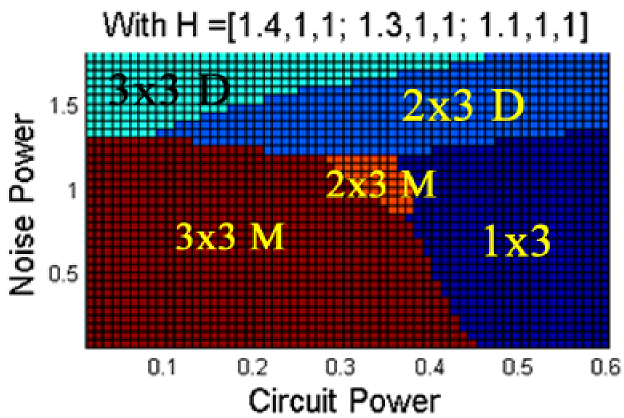

Fig. 23. Optimal mode and N_T with varying Noise Power and Circuit Power for high channel gain variation

When the difference in channel gain variation decreases as in figure 24, the performance region of multiplexing increases, and the crossover points shift. When channel gain variation is high, allocating even a small amount of power to the lesser gain channels increase the E_b drastically, so the region of operation of higher transmission antennas is lesser.

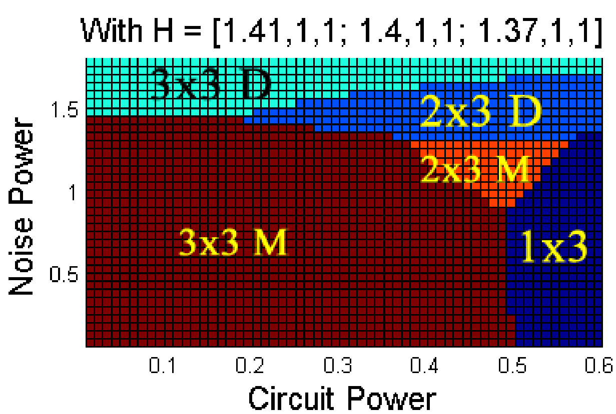

Fig. 24. Optimal mode and N_T with varying Noise Power and Circuit Power for low channel gain variation

Based on the above analysis, we find that for each combination of noise and circuit power, for given channel conditions, we can find an optimal operation mode - diversity or spatial-multiplexing. Once we know the mode, we also find an optimal number of transmission antennas to activate; which antennas to activate and the optimal power allocation in order to minimize the energy per bit.

X. Conclusion

We show that depending upon the noise power and circuit power, different number of transmission antennas configurations have different Energy per bit values, and an optimal number of transmission antennas exists for each value pair of N_0 and P_c. Diversity and Spatial-Multiplexing modes provide better performance under different conditions, and it is possible to decide on an optimal mode amongst the two. We also find that the proposed power allocation techniques to minimize energy per bit for both diversity and spatial-multiplexing modes work better than the equal allocation method and closely track the best possible oracle approach. We believe this project has numerous applications, most importantly in 802.11n MIMO networks. As the battery of the device is very important and saving energy is one of the fundamental problem. We addresses this issue in this project and successfully came up with an approach with provides the complete knowledge of - type of mode to choose, number of antennas to switch on, which antennas to switch on and how much power to allocate to each active antenna for minimum possible energy per bit value.

XI. Future Work

In our current system modeling, we have considered a simplified power model with only transmission power and circuit power components. This works well in our case since these two are the main varying factors influencing the total power and can be used to accurately model the Energy per Bit distribution. In the future we can extend this to consider a more sophisticated power model with higher level of detail.

In our proposed solution, we provide a method to switch between the Diversity and Spatial-multiplexing modes. We can extend this approach to operate in both modes simultaneously, with a fraction of the transmission antennas operating in diversity mode and the remaining in Spatial-multiplexing mode.

Also our analysis considers a varying number of transmission antennas with a fixed number of receiver antennas. Both transmission and receiver antennas can be analyzed together in order to obtain an optimal solution.

Acknowledgment

We would like to thank Professor Songwu Lu, for his guidance and direction. We are also grateful to Ioannis Pefkianakis and Scott Guan-Hua Tu for their valuable help.

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Our Response to Reviewers

We appreciate the attention of CS211 students that they have given to this project during our presentation. Their comments were very helpful in directing our attention to areas that required clarification.

Review Comment #1: Weighted powers both circuit and noise for different configurations
Response: For the different scenarios, case studies 3, 8 and 11 compare the effect of varying both noise power and circuit power on the energy per bit values. Optimal values of the number of active transmission antenna and power allocation to each have also been described.

Review Comment #2: I have no idea how the scenarios are evaluated
Response: As shown in the case studies, the various scenarios were evaluated based on the minimum Energy per bit values for varying noise power and circuit power. We consider Energy per bit as the heuristic to decide on an optimal number of active antennas as well as power allocation.

Review Comment #3: Where did the oracle power allocation come from
Response: The oracle power allocation values were found by extensive enumeration of all possible values and choosing the best combination.

Review Comment #4: Emperical results?
Response: Since the modeling is based on well known mathematical formula, we care confident that in actual experiments, the findings would still hold, with a few minor variations

Review Comment #5: No comparisions against current work
Response: In our related work section, we have included the current work. We have also compared our approach with an equal power allocation approach.

Review Comment #6: Didn't explain any assumptions/tools used for simulations.
Response: All the simulations were carried out in MATLAB. For each case study, we have also mentioned the values of all considered factors.

Other Research Topic Tried

We started with the topic Design, implementation, and performance evaluation of high-speed data transmission mechanism using heterogeneous wireless network We came up with an approach to implement the same and evaluate the performance in terms of bandwidth. Based on Prof. Lu's feedback we moved from the implementation aspect to finding a good, novel and interesting research issue.

The main issues we found in this context were related to goodput improvement, energy efficiency of transmission, scheduling of packets at transmitter and re-ordering at receiver. For many of the issues we thought of, we already found a lot of existing work in the area. We found that the case of energy efficient scheduling using multiple active interfaces had not been fully addressed. We wanted to address the challenges of taking into account the different BER and delay characteristics of the different interfaces and simultaneously reduce the energy consumption in transmission using multiple active interfaces. We modeled the problem as a Markov Decision Process in order to find the fraction of data to be sent along each active interface in order to minimize the energy consumption. Based on Prof. Lu's feedback, we kept the MDP approach on hold and started thinking of another approach/issue. We became interested in the correlation between frame aggregation and rate adaptation; and whether there exists a dependency between the two. We came up with a metric for adaptivity, and came up with an approach for frame aggregation such that the adaptivity remains high.

Simultaneously we started working on the power allocation issues in 802.11n MIMO networks. Eventually, based on the response from Prof. Lu, we concentrated our efforts on this topic, the results of which have been described in this report.