Adaptive RF Chain Management for Energy-Efficient Spatial-Multiplexing MIMO Transmission

Hang Yu, Lin Zhong, and Ashutosh Sabharwal
Department of Electrical & Computer Engineering, Rice University, Houston, TX, USA
{Hang.Yu, lzhong, ashu}@rice.edu

ABSTRACT

We present the theoretical foundation, implementation, and experimental evaluation of a novel power-saving mechanism for wireless transmission from multiple-input multiple-output (MIMO) transceivers, called *RF chain management*. RF chain management seeks to minimize the energy per bit for MIMO transmission, via adaptively choosing the optimal RF chain configuration, and satisfies the minimum data rate requirement at the same time. Our simulation shows that up to 45% and averagely 23% energy per bit reduction can be achieved. We have also built a prototype based on the WARP platform, and our experimental results have proved the feasibility of RF chain management in real systems and under realistic channels.

Categories and Subject Descriptors

C.2.5: Local and Wide-Area Networks

General Terms

Algorithm, Design, Measurement, Experimentation

Keywords

MIMO, RF chain management, Energy efficiency

1. INTRODUCTION

With the capability of improving channel condition (channel reliability or channel capacity), the MIMO technology has been considered as a promising candidate for the next generation of wireless broadband communication [1-3]. The multiple antennas in a MIMO system can be exploited in two ways. One is creating a highly effective antenna diversity system to improve channel reliability and increase the system's robustness; the other is the use of multiple antennas for parallel transmission of independent data streams, or increasing channel capacity. The latter, which supports significantly higher data rate, is called spatial multiplexing MIMO, or SM-MIMO. Seeking for high-throughput WLAN communication with the peak data rate up to 300Mbps, IEEE 802.11n has adopted SM-MIMO as the underpinning technology. Unless otherwise specified, we use MIMO to refer to SM-MIMO in this work.

The performance improvement of a MIMO system brings additional overhead at the same time. For example, compared to conventional single-input single-output (SISO) systems, a MIMO system incurs significantly higher circuit power consumption due to its use of multiple RF chains, especially for transmission. This has become a dominant technological barrier to the practical deployment of MIMO systems, particularly on battery and thermally constrained mobile systems.

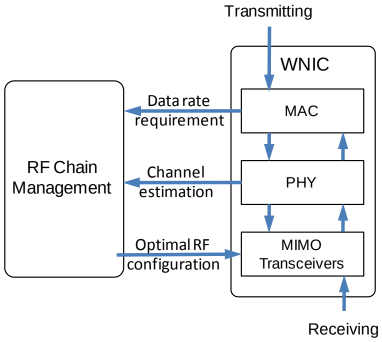


Figure 1. RF chain management is intended to be implemented inside the wireless network interface card (WNIC)

We address this challenge by applying power-saving modes to the RF chains of a MIMO transceiver in transmission, or *RF chain management*. It is motivated by the following observation. The gain in data rate by adding another RF chain depends on the channel condition while the power overhead is fixed. Therefore, whether using more RF chains improves energy efficiency is dependent on the channel. The goal of RF chain management is to achieve the optimal tradeoff between data rate and power consumption. That is, it minimizes the ***energy consumption per transmitted data bit***, by adaptively choosing the best RF chain configuration, including the optimal number of active RF chains as well as the optimal subset of antennas. Because different RF chain configurations lead to different available data rates, RF chain management must satisfy the data rate requirement.

In this work, we first provide the theoretical foundation of RF chain management and then an 802.11n-compliant system implementation. We also evaluate RF chain management with both MATLAB-based simulation and prototype-based measurement. Our evaluation clearly demonstrates its effectiveness, i.e. up to 45% and averagely 23% improvement in energy efficiency of MIMO transmission while meeting data rate requirements.

We intend RF chain management to be implemented inside the wireless network interface card (WNIC), as illustrated by Figure 1. It obtains data rate requirement from the MAC layer or above and channel estimation from the PHY layer, identifies and subsequently selects the optimal configuration for the MIMO transceiver.

It is important to note that while our evaluation is based on MIMO systems with a small number (two to four) of RF chains as used by

ISLPED'09, August 19–21, 2009, San Francisco, California, USA.

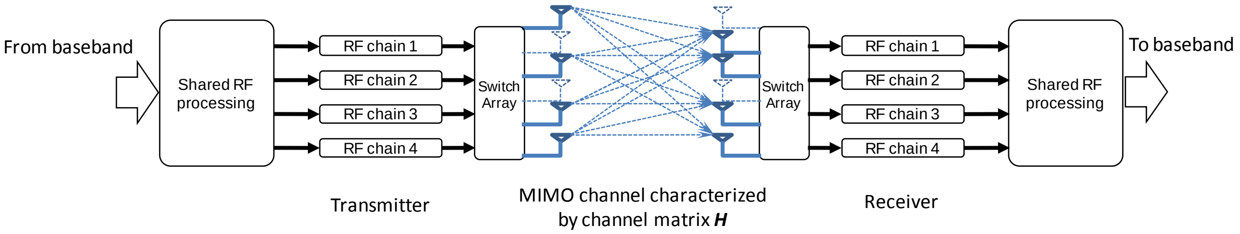


Figure 2. A MIMO system with transceivers with four RF chains and six antennas. While a MIMO transceiver can transmit and receive, the figure illustrates that one transmits to the other. Existing work has addressed antenna selection, i.e. which four out of the six antennas to use; RF chain management, in contrast, also addresses how many RF chains to use in transmission for improved energy efficiency.

existing standards, future MIMO systems operating at a high-frequency spectrum, e.g. 60GHz [4], can have more RF chains. In these cases, it will be even more important to adaptively configure the transceiver for improved energy efficiency, and we expect RF chain management to be more effective due to a larger number of possible configurations.

The rest of the paper is organized as follows. Sections 2 and 3 provide background of the MIMO technology and discuss related works, respectively. Section 4 presents the theoretical foundation of RF chain management. Section 5 offers an 802.11n-compliant system implementation. Section 6 and Section 7 provide simulation and prototype-based evaluations, respectively. Section 8 concludes the paper.

2. BACKGROUND

We first provide background for the MIMO technology. Figure 2 illustrates a representative architecture of a MIMO system with two transceivers as the transmitter and receiver respectively. Each pair of transmit antenna and receive antenna forms a sub-channel between the transmitter and receiver, and the MIMO channel is composed of these sub-channels. At the transmitter, each active RF chain sends out an individual data stream supplied by the baseband, from the associated antenna. At the receiver, each active RF chain receives the data streams from all transmit RF chains. The existence of multiple data streams in MIMO systems increases the channel capacity proportionally in comparison to SISO systems which only support a single data stream.

2.1 MIMO Channel Model

The MIMO channel can be characterized by a $N_R \times N_T$ complex matrix $\boldsymbol{H}$, as illustrated in Figure 2. N_R and N_T are the number of active RF chains in the receiver and transmitter, respectively. The time-varying channel model adopted by IEEE 802.11n [5] is described by

$$\boldsymbol{H}(t)=\sqrt{\frac{K(t)}{K(t)+1}}H_{LOS}(t)+\sqrt{\frac{1}{K(t)+1}}H_{NLOS}(t) \tag{1}$$

In the model, $H_{LOS}(t)$ and $H_{NLOS}(t)$ denote the line-of-sight (LOS) component and non-line-of-sight (NLOS) component of the channel, respectively. $K(t)$ is the *Ricean K* factor that indicates the scattering property, or fading distribution of the channel. By varying $K(t)$, the model can fit channels with various fading distributions. For example, $K=0$ and $K=\infty$ model the ideal *Rayleigh fading* and *Ricean fading* channels, respectively. The inclusion of time, t, indicates that the channel can be dynamic over time.

2.2 MIMO Channel Capacity

For a narrow-band, frequency-flat additive white Gaussian noise (AWGN) MIMO channel, with signals transmitted from individual antennas equally powered and independent with each other, the channel capacity C can be calculated as [1]

$$C=\operatorname{logdet}\left(\boldsymbol{I}_{N_R}+\frac{P_{TX}}{N_T N_0}\boldsymbol{H}\boldsymbol{H}^H\right) \tag{2}$$

where $\boldsymbol{H}$ is the channel matrix used in Section 2.1, $\boldsymbol{H}^H$ the conjugate transposition of $\boldsymbol{H}$, P_{TX} the total transmission power across all transmit antennas, N_0 the channel noise level, and $\boldsymbol{I}_{N_R}$ a $N_R \times N_R$ unit matrix.

The capacity model clearly indicates the channel capacity C depends on the transmission power P_{TX} and channel matrix $\boldsymbol{H}$, which changes with different N_T. To increase C, it is straightforward to employ larger P_{TX}, or using a bigger number of RF chains N_T. However, both ways will produce power overhead correspondingly. Sometimes bigger N_T, i.e., more RF chains, may not contribute too much to the capacity improvement, especially for the channel with a large *Ricean K* factor, i.e. the LOS component is dominant, because the sub-channels between the transmitter and receiver are highly correlated with each other. For such channels, it may not be cost-effective in terms of energy per bit, to employ a large number of RF chains with increased power consumption.

2.3 Power Model for a MIMO Transceiver

The power consumed by a MIMO transceiver for transmitting, $P_{Transmit}$, can be divided into that by all the power amplifiers, P_{PA}, and that by all other circuit blocks $P_{Circuit}$ [6]

$$P_{Transmit} = P_{PA} + P_{Circuit} \tag{3}$$

Note that P_{PA} depends on the total transmission power, P_{TX}, while $P_{Circuit}$ is independent of it. For simplicity, we assume that P_{PA} is linearly dependent on P_{TX}. Moreover, $P_{Circuit}$ can be divided into that contributed by each active RF chain, P_{RF_chain}, and that by circuit shared by all active RF chains, P_{shared}, e.g., the frequency synthesizer. We approximate the power consumption by a MIMO transceiver for transmitting, $P_{Transmit}$, as

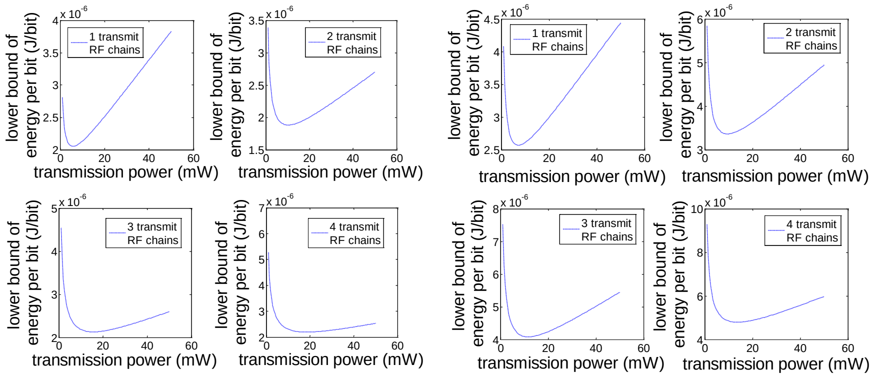
$$P_{Transmit} = (1+\alpha)P_{TX} + N_T P_{RF\_chain} + P_{shared} \tag{4}$$

where α is a intrinsic parameter of the power amplifier and N_T is the number of active RF chains.

In this work, we adopt the parameters for the power model from [6]. While different MIMO transceivers will have different power models, $P_{Transmit}$ is always a linear function of N_T, and the effectiveness of RF chain management is therefore only dependent on the relative size of P_{TX}, P_{RF_chain} and P_{shared}. Apparently, RF chain management will be more effective in saving power when P_{RF_chain} is relative larger. The relative size of P_{RF_chain} adopted from [6] is typical of realistic MIMO transceivers [7].

3. RELATED WORK

MIMO transceivers can employ more antennas than RF chains and dynamically select a subset of them to best leverage diversity, or *antenna selection* [8, 9]. Existing solutions assume all available RF chains active all the time thereby the power consumption is fixed



(a) ***Rayleigh fading*** **channel**

(b) ***Ricean fading*** **channel**

Figure 3. Lower bound of energy per bit with different numbers of RF chains and transmission power

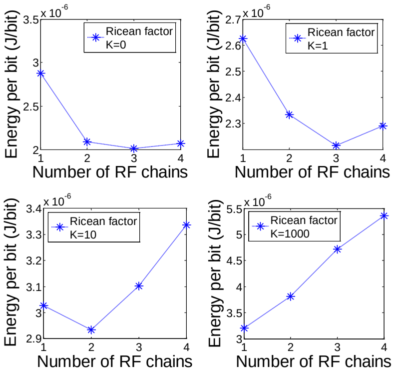


Figure 4. Lower bound of energy per bit with different numbers of RF chains and different channels

over time. In contrast, our work seeks to dynamically find the optimal number of active RF chains so that the circuit power consumption can be saved and even lower energy per bit can be achieved. Therefore, RF chain management is complementary to antenna selection.

Many have studied channel capacity improvement by optimally allocating transmission power into each antenna [10-12]. Such power allocation algorithms ignore the circuit power consumption, $P_{Circuit}$, and assume a fixed transmission power budget, P_{TX}. RF chain management can be regarded as a power allocation scheme that considers $P_{Circuit}$, optimizes P_{TX} , allocates zero power to inactive RF chains, and allocates equal power to active ones.

In [13], transmission modes (SISO or MIMO) and transmission power are dynamically adjusted on each node in a network, according to the distance for each pair of transmitter and receiver. This work, however, fixed the data rate and used MIMO to minimize BER with least power consumption. RF chain management, in contrast, allows dynamic data rate under the performance requirement and minimizes the transmission energy per bit.

4. THEORETICAL FOUNDATION

4.1 Energy per Bit for MIMO Transmission

We consider two key factors that affect the energy per bit of MIMO transmission, namely transmission power and RF chain configuration. For the following analysis we assume the MIMO transceiver has four identical RF chains and antennas. We also assume the channel ideally matches the model described in Section 2.1.

Transmission Power **($\boldsymbol{P_{TX}}$).** Figure 3 (a) and (b) show the theoretical lower bound of energy per bit over different transmission power P_{TX} for a *Rayleigh fading* channel ($K = 0$) and a *Ricean fading* channel ($K = \infty$). We assume a fixed number of RF chains (four) in the receive side, while a variable number of RF chains in the transmit side. It shows that there always exists an optimal P_{TX} that minimizes energy per bit, and as the number of transmit RF chains increases, the optimal P_{TX} increases as well. Another conclusion from our simulation results under many channel matrices is that the optimal P_{TX} is not sensitive to the change of channel fading distribution, i.e. it is almost independent with $\boldsymbol{H}$.

RF Chain Configuration **($\boldsymbol{\omega}$).** The number of configurations of a MIMO transceiver with N RF chains, each bound with a unique antenna, can be calculated as $\sum_{k=1}^{N}\binom{N}{k} = 2^N - 1$. We use ω to denote one of those configurations. When N is not large (e.g. four in our analysis), one can enumerate all configurations. Each configuration can provide a unique channel, with a unique channel matrix $\boldsymbol{H}(\omega)$. Note that the dimension of $\boldsymbol{H}(\omega)$ is determined by N_T. Figure 4 shows the lower bound of energy per bit for four configurations with one to four active RF chains respectively. We also investigate the impact of channel fading distribution, i.e., we choose channels with different *Ricean* factors (K equals 0, 1, 10, 1000 respectively), and then calculate the average energy per bit under 100 samples for each K (. It shows that there is always an optimal configuration that minimizes energy per bit, and the optimal configuration varies with the channel fading distribution.

Both the optimal transmission power and optimal RF chain configuration depend on the channel condition. For example, as *Ricean* factor K increases, the optimal P_{TX} increases, and those configurations with less RF chains are more capable of saving power. This is consistent with Section 2.2.

4.2 Problem Formulation

We aim to minimize the energy per bit of MIMO transmission, calculated as the power consumption $P_{Transmit}$ divided by the effective data rate R_{eff}. We employ the power model presented in Section 2.3 to calculate $P_{Transmit}$, under different configurations. With regard to R_{eff}, we consider $B \times C$ as its upper bound (therefore $\frac{P_{Transmit}}{B\times C}$ is the lower bound of energy per bit) where B denotes the bandwidth, and $B \times \beta C$ as the achievable data rate in practice, where $0 < \beta < 1$ is the indicator of the utilizing efficiency of the channel capacity. Therefore

$$E_b = \frac{P_{Transmit}}{R_{eff}} = \frac{P_{Transmit}}{B\times\beta C} \qquad (5)$$

Using the models in Section 2, we rewrite Equation (5) as

$$E_b = \frac{(1+\alpha)P_{TX} + N_T P_{RF\_chain} + P_{shared}}{\beta B \log\det\left(\boldsymbol{I}_{N_R} + \frac{P_{TX}}{N_T N_0}\boldsymbol{H}(\omega)\boldsymbol{H}(\omega)^H\right)} \qquad (6)$$

Recall that N_T and $\boldsymbol{H}(\omega)$ are functions of the RF chain configuration ω. α, P_{RF_chain} , P_{shared} , and B, are constants known to the transmitter. Therefore, we can denote the energy per bit as a function of P_{TX} and ω, or $E_b(P_{TX}, \omega)$.

Because different configurations have a direct impact on R_{eff}, we must minimize E_b under certain data rate constraint, or $R_{eff} \geq R_{eff\,min}$. The data rate constraint, $R_{eff\,min}$, can be set by the application, system, and user.

In summary, the optimization can be formulated as

$$\textbf{\textit{Minimize}}\ E_b(P_{TX},\omega),\ \textbf{s.t.}\ R_{eff} \geq R_{eff_{min}} \tag{7}$$

4.3 Solution

We minimize E_b by identifying P_{TX} and ω, under the constraint of $R_{eff_{min}}$. Theoretically, we need to examine $N_{P_{TX}} \times N_{config}$ possible combinations, where $N_{P_{TX}}$ is the number of possible values of P_{TX}, and N_{config} is the number of possible RF chain configurations. N_{config} is usually small, and we have also claimed that the optimal P_{TX} is almost independent on the channel matrix, while in fact it is mainly decided by N_T and the channel noise level N_0. Therefore, the optimal P_{TX} could be computed offline, with a lookup table with different N_T and N_0. Then it turns into a one dimensional optimization problem with the algorithmic complexity of $O(N_{config})$. We exhaustively search all configurations that can satisfy the data rate constraint, and choose the one with minimum E_b as the optimal. If none of the configurations satisfies the constraint, we leave all RF chains active to obtain the highest data rate. We have examined the computational overhead of this algorithm in the prototype-based experiment, and it shows that the computation latency is trivial compared to the mode transition of the transceiver thereby the overhead is negligible.

Note that one can estimate $\boldsymbol{H}$ either explicitly or implicitly. The transmitter can explicitly send training symbols to the receiver, and then the latter calculates $\boldsymbol{H}$ and feeds it back to the former. This method is accurate but incurs overhead for the training and feedback. On the other hand, when a transceiver receives frames in the receive mode, it calculates the channel matrix, and can use it as the estimation for next transmission. While incurring no overhead, this method is accurate only when the channel is largely reciprocal and the communication is bidirectional. Fortunately, both requirements are easily met for short range communication with the acknowledgement mechanism, e.g. 802.11.

5. SYSTEM IMPLEMENTATION

We now provide an 802.11n-compliant implementation of RF chain management.

5.1 Per-Frame Adaptation

Because 802.11 allows per-frame data rate adaptation, our implementation adapts the RF chain configuration for each outgoing frame. While it is possible to set the data rate constraint for each frame, practical systems often care more about the average rate of a short period of time. Therefore, we constrain the exponential moving average of the per-frame data rate, $R_{eff_{avg}}$, calculated as

$$R_{eff_{avg}}(n) = w \cdot R_{eff_{avg}}(n-1) + (1-w) \cdot R_{eff}(n) \tag{8}$$

where n is the frame index and w is the weight given to the history. Apparently, a larger w introduces more memory of the past. In our implementation, we adopt $w = 0.5$. As illustrated in Figure 1, the data rate requirement will come from the 802.11 MAC layer, which can translate the throughput requirement from application, system or user into the average data rate requirement.

RF chain management estimates the channel upon a frame reception. MIMO-based 802.11n transmitter includes training symbols for each outgoing frame so that the receiver can estimate the channel matrix, $\boldsymbol{H}$, for signal recovery. RF chain management leverages this channel matrix to estimate the channel capacity and effective data rate in order to identify the optimal transmission power and RF chain configuration for the next transmission.

5.2 Hardware Implementation

The transceiver can be in one of the three operational modes: transmit, receive and idle. RF chain management only applies to the transmit mode, and uses the receive mode to estimate the channel. It determines the RF chain configuration, or which RF chains should be active, and consequently manages the inactive RF chains to conserve power, using either the receive/idle modes or powering them off for maximal power saving. In our evaluation, we assume the inactive RF chains are powered off.

It is important to note that RF chain management can be overhead-free. 802.11 transceivers are half-duplex and will switch between transmit and receive modes for each frame transceiving. Therefore, there will be no overhead for using the receive mode for managed RF chains to save power. There will be an overhead only when inactive RF chains are powered off. Such overhead, fortunately, is very small in modern wireless transceiver implementation. For example, for the MAX2829 transceiver used in our prototype [14], the switching latency is only 50µs, and the energy overhead can be compensated by being powered off for as short as 100ns. Since frame transmission usually lasts hundreds of microseconds, the overhead is negligible in comparison to the energy saving. Moreover, we readily include such overhead in the calculation of E_b (Equation 6) and the same method still applies.

5.3 Protocol Compatibility

We next explain how RF chain management can be implemented without any protocol change and compatible with IEEE 802.11n.

Channel Estimation: RF chain management employs implicit channel estimation and obtains the channel matrix from the PHY layer when it is in receive mode. This is possible because of the acknowledgement mechanism inherent to 802.11. An 802.11 receiver immediately sends an ACK frame to the transmitter to acknowledge the reception of a data frame. This makes sure the transmitter will indeed have the free opportunity to obtain the channel estimation for RF chain management. Moreover, 802.11 provides a virtual carrier sense mechanism with RTS/CTS exchange before data frame transmission. While it is only used for large data frames, it guarantees the channel estimation is effective, especially for non-continuous transmission where a long interval may exist between the last ACK frame and the current data frame.

Noise Level Estimation: We also need to know the noise level N_0, or SNR to calculate channel capacity C, as indicated in Equation (2). RF chain management uses received signal strength indication (RSSI) to estimate the channel's SNR, which is directly available at the PHY layer of 802.11.

Dynamic Configuration of RF Chains: RF chain management can potentially change the number of RF chains on a frame-by-frame base. The receiver will need to know the number of RF chains used in the transmission to properly recover the signal. Fortunately, the Physical Layer Convergence Procedure (PLCP) header of 802.11n MAC frames specifies the number of transmit antennas (RF chains). RF chain management employs this field to notify the receiver about the number of active RF chains for each frame.

6. SIMULATION-BASED EVALUATION

To demonstrate the effectiveness of RF chain management, we have implemented it in both simulation and experiment. We first report a MATLAB-based simulation to evaluate its system design and power savings under generated channels.

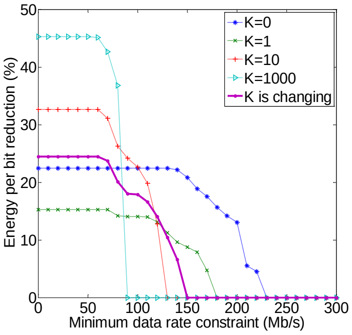


Figure 5. Energy per bit reduction of RF chain management in MATLAB-based simulation

6.1 MATLAB Simulation Setup

We employ MATLAB to simulate a MIMO system that includes two identical 802.11n-like MIMO transceivers each with four RF chains and antennas, denoted as Node 1 and Node 2. Only Node 1 implements RF chain management, which is supposed to transmit data frames and receive acknowledgements from Node 2. We also implemented an 802.11-like PHY layer in both nodes, with multiple modulation schemes, e.g., BPSK and square MQAM (M=4, 16, 64, and 256), as well as several coding rates, including 1/2, 2/3, and 3/4. We generate channels with different characteristics of multipath effect, by varying K in the channel model described in Section 2.1. All the channels are ideally reciprocal, with a 20MHz bandwidth.

6.2 Simulation Results

We compare the average energy per bit of RF chain management against that of a static configuration with all RF chains active all the time. For this comparison, we measure the average energy per bit on Node 1 for 1000 successive frames for RF chain management and the static configuration, under the same channel. We also investigate the influence of the data rate constraint on RF chain management.

We explore five scenarios for evaluation. For the first four scenarios we use a constant K which equals 0, 1, 10, 1000 respectively, to simulate different environments from ideal *Rayleigh fading* channel to ideal *Ricean fading* channel; and for the last scenario we assume K is randomly changing for each frame, among the values of 0, 1, 10, 1000 with equal possibility, to simulate mode mobility and environment changes. This is the fastest varying rate of the channel that RF chain management is able to cope with, while the change of real-world channels is much slower.

Figure 5 shows the energy per bit reduction of RF chain management against the static configuration. We make three key observations. First, RF chain management achieves significantly lower energy per bit than the static configuration. We observe an average 15% to 45% reduction in energy per bit for all five scenarios even when the minimum data rate requirement is 70Mbps. Second, when the minimum data rate increases, the energy per bit by RF chain management increases and gradually approaches that of the static configuration. This is because more RF chains are needed to satisfy the increasing data rate requirement. However, as observed in our prior work [15], wireless network interface cards usually only achieve a small fraction of the peak performance, due to low application demand or bottlenecks in the rest of the network system, therefore RF chain management will be highly effective most of the time. Finally, when K increases and the LOS component becomes more dominant, RF chain management becomes more effective in reducing energy per bit. This is because under such channels, adding more RF chains brings marginal capacity improvement. Therefore, the static configuration using all RF chains is least energy efficient, and one can expect RF chain management to reduce more energy per bit.

Table 1. Probability of correct decision making and corresponding increase of energy per bit over different noise level

Noise level N_0 (mW)	*Probability of making correct decision (%)*	*Increase of energy per bit (%)*
0.1	*99.8*	*0.02*
1.0	*97.7*	*0.44*
5.0	*93.4*	*0.79*
10.0	*91.6*	*1.11*

We also examine how RF chain management works when the estimated channel matrix $\boldsymbol{H}$ considerably deviates from its real value. Toward this end, we add channel noise of various levels to the simulation and obtain the exact optimal RF chain configuration by exhaustively searching and compare it with the one identified by RF chain management. Table 1 shows the probability of the two configurations are the same and the increase in energy per bit of RF chain management in comparison to that of the optimal configuration for five noise levels, from 0.1mW to 10mW. Even when the channel is very noisy ($N_0 = 10mW, SNR = 0dB{\sim}3dB$), RF chain management consumes only about 1% more energy per bit than the theoretical optimal configuration, which is negligible in comparison to the reduction achieved from a static configuration.

7. PROTOTYPE-BASED EVALUATION

To evaluate RF chain management under realistic channels, we also measure its performance with a prototype implementation.

7.1 Prototype Implementation

We have built a prototype of RF chain management using an open-access wireless research platform, called WARP [16]. WARP supports 2 × 2 MIMO system. Each WARP board contains two RF daughterboards. Each daughterboard has a MAX2829 transceiver [14] and is connected with one omni-directional antenna. We used a Lenovo ThinkPad T400 laptop to interact with the two WARP nodes via WARPLab, a MATLAB-based interface that enables the laptop to exchange information with the two nodes. Both input and output of RF chain management, e.g., the estimated channel matrix and noise level as the input, RF chain configuration and transmission power level as the output, are exchanged between the laptop and two WARP nodes via an Ethernet switch.

7.2 Experimental Setup

Figure 6 shows the experimental setup, with the laptop and two WARP nodes. The evaluation involved two communicating nodes: one as the mobile client which runs RF chain management and the other as the access point with both RF chains active all the time without optimization. The radio was at 2.4GHz, and the channel was 40MHz. We chose an indoor environment that both line-of-sight (LOS) and non line-of-sight (NLOS) components exist between the client and access point. Both nodes are stationary but we artificially change the scatters between them to form different scenarios. Besides, since there are unpredictable Wi-Fi interferences at the same frequency band, the noise level of the channel is assumed to be dynamic over time.

Similar to our MATLAB-based simulation, the client with RF chain management sends DATA frames to the access point and the access point acknowledges each DATA frame with an ACK frame.

7.3 Measurement Results

We compare the energy per bit of RF chain management against the static configuration that always uses two RF chains. We examine the performance of RF chain management under both NLOS and LOS scenarios. For the NLOS scenario we place two WARP nodes on the two sides of a wall, and for the LOS scenario we put two nodes close to each other (3 meters away from each other) and guarantee there is a dominant LOS path between them.

The WARP platform can only support 240Mbps. Therefore, we make the comparison under four different data rate requirements: 0, 50, 100, and 200Mbps. Figure 7 shows the energy per bit reduction of RF chain management in comparison to the static configuration, for the LOS and the NLOS scenarios, respectively. Even when the data rate requirement is 50Mbps, RF chain management still improve the energy efficiency by 32% and 8% for the LOS and NLOS scenarios, respectively. It also shows that RF chain management becomes less adaptive and the energy per bit is approaching that of the static configuration when the required data rate is higher. This is more prominent in our experiments than in simulation because our prototype only allows three possible configurations. Both observations are consistent with the results from our theoretical analysis and simulation.

Figure 6. One laptop and two WARP nodes in the prototype

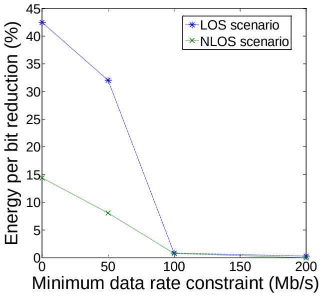


Figure 7. Energy per bit reduction of RF chain management in experimental evaluation

8. CONCLUSION

We presented a novel power-saving mechanism, *RF chain management*, for MIMO transmission. RF chain management adaptively optimizes the transmit RF chain configuration for minimum energy per bit while satisfying data rate requirement. We offered its theoretical foundation and an 802.11n-compliant implementation. Results from MATLAB-based simulation and WARP-based experiment showed its effectiveness on energy saving.

Our work is limited in the following aspects that can be addressed in future work. First, we only optimize the efficiency of MIMO transmission without considering the energy cost at the receive side. While this limits our solutions to mobile devices operating in the infrastructure mode, e.g. transmitting to an access point, the problem formulation in Section 4 can be extended to incorporate receiver energy cost too [17]. Second, this work only considers spatial multiplexing MIMO systems. Multiple antennas and RF chains are also used in other wireless systems, e.g. *Beamforming* systems. RF chain management can be potentially used in these systems should the energy efficiency become a concern.

ACKNOWLEDGEMENTS

The work was supported in part by NSF awards CNS/CSR-EHS 0720825, CNS/NeTS-WN 0721894, CNS-0551692, CNS-0551692, and support from the TI Leadership University program.

9. REFERENCES

[1] Paulraj, A.J., et al., *An overview of MIMO communications - A key to gigabit wireless.* IEEE Proc., 2004. **92**(2): p. 198-218.

[2] Gesbert, D., et al., *From theory to practice: an overview of MIMO space-time coded wireless systems.* IEEE Journal on Selected Areas in Communications, 2003. **21**(3): p. 281-302.

[3] Zheng, L. and D.N.C. Tse, *Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels.* IEEE Trans. Information Theory, 2003. **49**(5): p. 1073-1096.

[4] Smulders, P., *Exploiting the 60 GHz band for local wireless multimedia access: prospects and future directions.* IEEE Communications, 2002. **40**(1): p. 140-147.

[5] Erceg, V., et al., *TGn channel models*, in *IEEE document 802.11-03/940r2*. 2004.

[6] Cui, S.G., A.J. Goldsmith, and A. Bahai, *Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks.* IEEE Journal on Selected Areas in Communications, 2004. **22**(6): p. 1089-1098.

[7] Behzad, A., et al., *A Fully Integrated MIMO Multiband Direct Conversion CMOS Transceiver for WLAN Applications (802.11n).* IEEE Journal on Solid-State Circuits, 2007. **42**(12): p. 2795-2808.

[8] Sanayei, S. and A. Nosratinia, *Antenna selection in MIMO systems.* IEEE Communications, 2004. **42**(10): p. 68-73.

[9] Molisch, A.F. and M.Z. Win, *MIMO systems with antenna selection.* IEEE Microwave Magazine, 2004. **5**(1): p. 46-56.

[10] Telatar, E., *Capacity of multi-antenna Gaussian channels.* European Trans. Telecommunications, 1999. **10**(6): p. 585-595.

[11] Rey, F., M. Lamarca, and G. Vazquez, *Robust power allocation algorithms for MIMO OFDM systems with imperfect CSI.* IEEE Trans. Signal Processing, 2005. **53**(3): p. 1070-1085.

[12] Yoo, T. and A. Goldsmith, *Capacity and power allocation for fading MIMO channels with channel estimation error.* IEEE Trans. Information Theory, 2006. **52**(5): p. 2203-2214.

[13] Siam, M.Z., et al., *Adaptive multi-antenna power control in wireless networks*, in *Proc. Int. Conf. Wireless Communication and Mobile Computing (IWCMC)*. 2006, ACM: Vancouver, British Columbia, Canada.

[14] Maxim Integrated Product, *Data sheet for MAX2829 Single/Dual-Band 802.11a/b/g World-Band Transceiver ICs.*

[15] Liu, J. and L. Zhong, *Micro power management of active 802.11 interfaces*, in *Proc. Int. Conf. Mobile Systems, Applications, and Services (MobiSys)*. 2008, ACM: Breckenridge, CO, USA.

[16] *Rice University WARP: http://warp.rice.edu/.*

[17] Yu, H., L. Zhong, and A. Sabharwal, *RF Chain Management for Energy-Efficient Spatial Multiplexing MIMO Systems, Technical Report 06-15-09, Rice University, June 2009. (http://www.recg.org/publications.htm).*