Improving Energy Efficiency based Aware Link Adaptation for Multiple-Input Multiple-Output OFDM Wireless Networks

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Abstract—This paper presents the improving energy efficiency based aware link adaptation for multiple-input multiple-output (MIMO) Orthogonal frequency division multiplexing (OFDM) wireless networks. The practical link adaptation algorithm for MIMO-OFDM is presented. The proposed solution is based on sounding the channel periodically and choosing the optimal mode that will maximize the throughput or energy efficiency (EE) while satisfying the application’s quality of service (QoS) requirements. The computational complexity of the algorithm and determination of sounding period by novel closed form solutions and iterative algorithms are easily determined. Realistic link level simulations confirm that the proposed solution achieves significant improvement over existing link adaptation algorithms when the aim is to maximize the throughput, and provides orders of magnitude gain in energy efficiency compared to poorly chosen fixed modes when used for energy efficiency maximization purposes.

Keywords—Link Adaptation; Multiple-Input Multiple-Output (MIMO); Orthogonal Frequency Division Multiplexing (OFDM); Energy Efficiency (EE); Wireless Networks;

I. INTRODUCTION

With the rapid and radical evolution of information and communication technology (ICT), corresponding energy consumption is also growing at a staggering rate. Furthermore, it has been reported that mobile operators are already among the top energy consumers, for example, Telecom Italia is the second largest energy consumer in Italy and energy consumption of mobile networks is growing much faster than ICT on the whole. Moreover, as the mass deployment of 3G systems in developing countries and later 4G systems worldwide occurs, mobile communications will consume significantly more energy if no effective actions are taken [1-8].

A large electricity bill results from the huge energy consumption of a wireless base station (BS). More than 50% of the total energy is consumed by the radio access part, where 50-80% is used for the power amplifier (PA) [9-16]. It is also pointed out that the energy bill accounts for approximately 18% of the Operation Expenditure (OpEx) in the mature European market and at least 32% in India. Therefore, from the operators’ perspective, energy efficiency (EE) not only has great ecological benefits and represents social responsibility in fighting climate change, but also has significant economic benefits. Thus, it is urgent to shift from pursuing optimal capacity and spectral efficiency to efficient energy usage when designing wireless networks. From the users’ perspective, energy-efficient wireless communication is also imperative.

According to the 2010 wireless smart-phone customer satisfaction and the iPhone received top marks in every category except for battery life [17-25]. The latest report in China also reflects the same problem. Based on the data in, up to 60% of the users complained that battery endurance was the greatest hurdle when using 3G services. Without a breakthrough in battery technology, the battery life of the terminal sets will be the biggest limitation for energy-hungry applications (e.g., video games, mobile P2P, interactive video, video monitors, streaming multimedia, mobile TV, 3D
services, and video sharing) [26-38]. The Circuit energy and transmit energy trade-off for overall energy efficiency is shown in Fig 1.

II. SYSTEM MODEL

2.1. TDD multiuser MIMO system model

Consider the TDD MU-MIMO system shown in Fig. 2, where a BS is serving K users. The BS has M antennas and each user has one antenna. We consider zero-forcing (ZF) precoding at the BS because it is a practical low complexity linear precoding scheme and it performs optimal among all the linear precoders at high SNR.

Moreover, the SINR analysis under imperfect CSI at the transmitter is tractable when ZF precoder is employed. Due to these nice properties, ZF precoder has been frequently adopted in the system model of the papers on limited feedback.

Following typical assumptions in MU-MIMO research, we consider a narrowband system with flat fading channels. By assuming flat fading channel, the discussion on the tradeoff between the uplink pilot power and the downlink rate of users in a multiuser MIMO system can be simplified [39-56]. However, the discussion for narrowband channels can be extended to frequency-selective channels by employing orthogonal frequency division multiplexing (OFDM) because in OFDM systems the
wideband channel is divided into many narrowband sub-bands, each experiencing flat fading. Assume ideal channel reciprocity and the uplink channels are the same as the downlink channels. In addition, assume block fading and the channel is constant in each frame [57-66].

### 2.2 Transmitter and receiver block diagrams for MIMO-OFDM system.

We consider a generic MIMO-OFDM system, depicted in Fig. 3, where the transmitter is equipped with $N_t$ antennas, and the receiver uses $N_r$ antennas. Information bits are first encoded with a convolutional encoder and punctured to achieve the desired code rate. The encoded bits are then parsed and interleaved over multiple spatial streams and subcarriers. The bits in each spatial stream are mapped to symbols by a quadrature-amplitude-modulator (QAM) which is followed by the spatial mapper. The spatial mapping (or antenna mapping) is a linear operation that transforms $N_{ss}$ (number of spatial streams) dimensional symbol vector into $N_r$ dimensional signal, which is then transmitted after IFFT and cyclic prefix (CP) addition operations.

At the receiver, $N_r$ dimensional time domain samples of the received signal are transformed back into the frequency domain by an FFT operation after removal of the CP. MIMO decoder is then used for separating individual spatial streams from the total received signal. Soft bits are then fed to the Viterbi decoder after the deinterleaving, deparsing and depuncturing operations. The system model is meant to be generic and applicable to most, if not all, MIMO-OFDM systems with minor modifications. Transmitted QAM symbols and precoding matrix are normalized so that the transmitted signal has a power of $P_T$ at each antenna. An $N_{ss} \times N_r$ MIMO decoder matrix $W$ is applied to the received signal to obtain the estimate of $x$, $\hat{x} = Wy$. The Minimum-Mean-Squared-Error (MMSE) decoder is the optimal solution to $W$ among the class of linear decoders in the sense of minimizing the mean-squared error. At the output of the MMSE decoder, the PPSNR corresponding to the $k$th spatial stream for each subcarrier is calculated. The PPSNR indicates the ratio of the power of the signal of interest to the power of the residual interference from other spatial streams plus the residual noise power. PPSNR has been used in the literature for error rate calculation and link adaptation purposes since the channel after the MMSE decoder can be treated as an additive white Gaussian noise (AWGN) channel which simplifies the error rate calculations. Information bits are first encoded with a convolutional encoder and punctured to achieve the desired code rate. The encoded bits are then parsed and interleaved over multiple spatial streams and subcarriers. The bits in each spatial stream are mapped to symbols by a quadrature-amplitude-modulator (QAM) which is followed by the spatial mapper.
The spatial mapping (or antenna mapping) is a linear operation that transforms \( N_{ss} \) (number of spatial streams) dimensional symbol vector into \( N_t \) dimensional signal, which is then transmitted after IFFT and cyclic prefix (CP) addition operations. At the receiver, \( N_r \) dimensional time domain samples of the received signal are transformed back into the frequency domain by an FFT operation after removal of the CP. MIMO decoder is then used for separating individual spatial streams from the total received signal. Soft bits are then fed to the Viterbi decoder after the deinterleaving, deparsing and depuncturing operations. The system model is meant to be generic and applicable to most, if not all, MIMO-OFDM systems with minor modifications.

III. PROPOSED LINK ADAPTATION PROTOCOL

3.1. Link Adaptation Problem Definition

Past work dealing with the link adaptation problem has mostly focused on maximizing the link throughput subject to QoS constraints. The energy-aware fast link adaptation protocol is shown in Fig. 4.

![Flowchart for the algorithm](image)

The throughput maximization problem can be formally written as maximize \( (1 - \text{PER}) LT(bps) \) subject to \( \text{PER} \leq \text{PER}_{\max} \) where \( \text{PER}_{\max} \) is the maximum allowed instantaneous (or short term) packet error rate which is usually determined by the application, \( L \) is the packet length in number of information bits, and \( T \) denotes the total time needed to transmit the packet including the packet overheads and the time spent on the MAC layer related tasks. When our objective is to communicate
\( L \) bits across a channel, maximization of throughput will reduce the total transmission time, but it will not necessarily maximize the energy efficiency of the system. The objective of energy-aware link adaptation on the other hand, is to minimize the total energy consumed in the link per successfully received bit, which is equivalent to maximizing the number of successfully received bits normalized by the total energy consumption of the link.

3.1. Energy Consumption Model:
We employ a comprehensive energy consumption model, which comprises the energy consumed in the RF and baseband portions of both the transmitter and the receiver. For the RF and baseband energy consumption calculation, and which were obtained from already published link adaptation works or based on actual implementation data for specific blocks. The total energy consumption of the link is a function of \( N_{ss}; N_t; N_r; PT \), modulation and code rate; therefore the link adaptation algorithm tries to optimize these parameters simultaneously for maximizing energy efficiency. We revisit the energy consumption model here briefly for completeness. The total energy consumption in the link is calculated as

\[
E_t = E_{RF} + E_{BASE} + E_{MIMO}
\]

where \( E_{BASE} \) is the energy consumption of the baseband blocks of the transmitter (tx) and receiver (rx) excluding the MIMO detector energy consumption, and \( E_{MIMO} \) is the MIMO detector energy consumption.

3.2. PER Prediction Model
Prediction of the instantaneous PER of the link is the most critical task in the link adaptation process since the optimum mode is chosen based on the predicted PER. Unlike the other works, which are based on simulations and curve fitting methods, we employ a PPSNR based model for the PER prediction. The residual interference plus noise at the output of the MMSE decoder can be approximated in [17], hence the uncoded BER of the \( k \)th spatial stream at the nth subcarrier.

3.3. Proposed PPSNR Based Fast Link Adaptation Protocol
The wireless channel changes rapidly due to the mobility of the transmitter, the receiver and the surrounding objects. As a result, the channel exhibits small-scale fading (fast-fading) in addition to the path loss and shadowing effects (large-scale effects or slow-fading. The link adaptation work is aimed at finding the optimal mode based on the average error rate performance and as such, disregards the fast-fading in the channel. However, significant performance improvements can be achieved if the link adaptation algorithms are designed to take into account the instantaneous (or short term) channel conditions, rather than making a decision based on the long term average behavior of the channel. The latter approach is called fast link adaptation, which aims to provide improved performance by tracking and responding to the rapid variations in the channel. Our PPSNR based fast link adaptation protocol is based on sounding the full MIMO channel periodically and determining the optimal mode to transmit. A mode \( m \) is a 6-tuple \( (PT, N_{ss}, N_t, N_r, \text{Modulation, Code Rate}) \) containing the parameters to be optimized, and the optimal mode is defined as the one which has the maximum energy efficiency or throughput depending on the desired objective.

IV. SIMULATION
4.1. Simulation Setup and Assumptions
For simulation purposes, we assumed an IEEE 802.11n like system from which we have taken the parameters for our simulations. We assumed uniform modulation and uniform power allocation over all subcarriers and spatial streams. When \( Nr > N_{ss} \), spatial expansion mode is evoked, and the spatial streams are mapped onto the transmit antennas in around robin fashion. For instance, in the case of
Nt = 3; Nss = 2, the first spatial stream will be duplicated to the third transmit antenna with a proper cyclic delay. This provides diversity in frequency domain, known as cyclic delay diversity. We employed the simplified path loss and log-normal shadowing models in order to model the channel’s large-scale behavior. In addition to these large-scale effects, the signal is affected by fast fading due to the mobility in the channel. For fast fading, we used the Jakes’ Doppler model. Each tx-rx antenna pair is assumed to experience independent fading. We simulated a file transfer application, which requires all the lost packets to be retransmitted until all of them are successfully received. A target time is defined for the transmission of the file. The link adaptation algorithm thus calculates the target throughput in real time based on the remaining file size and the remaining time. We simulated the transmission of a file of size 40 Mbytes with a target completion time of 50 seconds.

4.2. Simulation Results

We present the simulation results of a realistic link scenario, where the receiver node moves away from the transmitter and returns back at varying speeds. Throughput vs time (upper plot), and PER vs time (lower plot) is shown in Fig. 5.

![Throughput and PER plots](image.png)

Fig. 5 Throughput vs time (upper plot), and PER vs time (lower plot)

It moves away from the transmitter for the first 3 seconds with a speed of 0.75 m/sec (6 Hz doppler), then it approaches the transmitter for 4 seconds with a speed of 0.50 m/sec (4 Hz doppler), then it moves away again for 2 seconds with a speed of 1 m/sec (8 Hz doppler), then returns back for 4 seconds with 0.50 m/sec speed. The MAC based protocol that we simulated is based on the Robust Rate Adaptation Algorithm (RRAA). This protocol measures the PER for several candidate modes (neighbor modes) within a short window of time, then switches to another mode if the achievable throughput at that mode is higher than the throughput at the current mode. The PERs and the achievable throughputs are measured by transmitting several packets for each mode in the candidate set. First, all the modes are ordered in terms of their rates. We define 6 neighbor modes to the currently used mode as our candidate set. 3 have lower rate than the current mode and 3 have higher rate, and all neighbor modes are probed along with the currently used mode. The Comparison of PSK
MIMO and Link Adaptation MIMO-OFDM with Doppler Effect is shown in Fig.6. The Performance of different schemes Versus the Normalized Doppler at SNR is shown in Fig.7.

![Comparison of PSK MIMO and Link Adaptation MIMO-OFDM with Doppler Effect.](image)

**Fig.6. Camparsion of PSK MIMO and Link Adaptation MIMO-OFDM with Doppler Effect.**

![Performance of different schemes Versus the Normalized Doppler at SNR](image)

**Fig.7. Performance of different schemes Versus the Normalized Doppler at SNR**

The second simulated protocol is the proposed protocol with the objective of maximizing the throughput. The gains over these well performing fixed modes are 20% and 71%, respectively. This is because they always use the maximum transmit power, whereas the energy-aware protocol reduces the transmit power to save energy as long as the target QoS constraints are satisfied.

V. CONCLUSION

This PPSNR based link adaptation protocol for throughput or energy efficiency maximization in MIMO-OFDM communication links. The proposed algorithm tracks the channel changes fast enough so as to react to fast fading and chooses the optimal mode for the current state of the channel. The proposed solution employs a novel formulation of the PPSNR which does not require any matrix inversions, and greatly reduces the computational complexity. This new PPSNR formulation can be
used in any other PPSNR based link adaptation methods. In addition, we present a smart transmit power ordering algorithm to eliminate redundant calculations to further reduce the complexity.

REFERENCES


