CROSS LAYER ENERGY-EFFICIENCY OPTIMIZATION FOR COGNITIVE RADIO TRANSCEIVERS

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ABSTRACT

Designing energy-efficient cognitive radio transceivers requires joint optimization of medium access control and the physical layer implementation. In this paper we show an energy efficiency optimization strategy for IEEE 802.11n compliant transceivers in terms of energy consumed by the receiver per successfully received bit. To this end, we propose and explore several modifications of a conventional physical layer implementation, all of which target energy proportional behavior. The proposed modifications intentionally include operation modes and algorithm choices that are suboptimal with respect to throughput and error-rate performance. Yet, we show how (under ideal conditions) the rate adaptation at the medium access control layer can exploit these modifications to achieve superior energy efficiency that is 44% below that of a rate adaptation targeting only maximum goodput.

Index Terms—Energy proportionality, cognitive radio, energy efficiency, IEEE 802.11n

1. INTRODUCTION

Until the year 2020 the estimated carbon dioxide emissions for mobile devices are expected to grow to 178 Mtons per year [1] rendering its minimization an important optimization target. Further, beside reducing the carbon footprint, energy-efficient, green computing techniques will also extended the battery lifetime of mobile devices. Therefore, energy-efficient computing is clearly one of the major research challenges for near future.

Today, most receiver implementation for IEEE 802.11n compliant wireless systems are optimized for performance, that either is expressed in terms of throughput or in terms of low error rate. Unfortunately, neither the optimization for high throughput nor the optimization for low error rate necessarily provides the best energy-efficiency of the receiver. Furthermore, the high data rates of modern wireless LAN (WLAN) systems is mostly used for short periods only, for example in streaming applications, where short data packets (typically 1.5k bytes) in fixed time intervals are regularly encountered.

While transmit power optimization has been well studied based on information-theoretic energy-efficiency metrics for complex scenarios, we focus in this paper on the overall energy consumed by the physical (PHY) layer hardware of the receiver. The combination of different transmission schemes and corresponding PHY layer configurations, which we call (system) modes, results in different performance characteristics in terms of throughput, error rate, and energy consumption per bit of the receiver. The medium access control (MAC) layer may intelligently choose between these different modes to optimize for one or multiple of these metrics. Usually the optimization targets are throughput or error rate, but could also be energy-efficiency. **Prior Work:** In [2] it is proposed to trade transmission rate with delay by adapting the utilized modulation scheme. The work in [3] applies the approach of [2] to develop a rate adaptation (RA) algorithm that is optimal in terms of transmit power based on information-theoretic criteria, clearly focusing on the transmitter and using a heavily simplified system model. For the receive side, [4] shows that the baseband processing of software-defined radios is most of the time underutilized and states that this underutilization can be used for power reduction (resulting in the desired energy proportional behavior). However, in terms of RA algorithms [5–8] current publications only show measurement results or results based on elaborate system models to optimize primarily for high throughput or low error rate which not necessarily result in the most energy-efficient operation or in energy-savings on the receiver side.

Contribution: The aim of this paper is to enable the development of wireless LAN receivers with good energy-efficiency. To this end we first propose several modifications of the physical layer. Further, we show how these modifications of the physical layer can be exploited by the medium access control layer to significantly enhance the energy-efficiency of the receiver with a energy consumption guided rate adaptation and validate the proposed optimization on a typical IEEE 802.11n scenario.

Outline: In Sec. 2 an IEEE 802.11n WLAN communication protocol, an IEEE 802.11n complaint MIMO-OFDM receiver, along with a corresponding energy model are described. In Sec. 3 we present modifications to enable further energy proportional operation on the PHY layer and in Sec. 4 we show how these modifications can be exploited by the MAC with proper RA to enhance the energy efficiency of the receiver. The proposed optimizations are applied to a typical IEEE 802.11n environment in Sec. 5 to point out the limits and scope of the potential gains and the paper is concluded in Sec. 6.

2. SYSTEM MODEL

In this section we first describe a typical IEEE 802.11n transmission, a corresponding PHY layer implementation, and an energy model later used for optimization.

2.1. Transmission Scenario

As shown in Fig. 1, the receiver sequence begins with a frame start waiting period. The duration of this phase depends on proper sleep time prediction based on the power save poll MAC protocol. The actual frame starts with a training sequence used for frame start detection, initial frequency offset estimation and channel estimation. This channel estimation is then used to detect the frame header, containing information about the subsequent data payload (e.g., the payload length in number of bits and the modulation and coding scheme



Fig. 1. Transmission protocol used in this paper.



Fig. 2. Simplified receiver block diagram with units using different processing rates highlighted.

(MCS) which together determine the frame length in number of symbols). The MCSs defined in IEEE 802.11n also specify the number of spatial streams (i.e., the number of concurrent data streams transmitted in the same frequency band using multiple-input multiple output (MIMO) technology) and thereby the minimum number of receive chains required to receive the corresponding frame. If the number of spatial streams differs between header and payload, an additional training sequence is required to enable the detection of the payload data. The final part of the received frame is the data payload itself. Within an inter frame spacing (IFS), the receiver has to decide if the frame was correctly decoded and has to start transmitting an acknowledgment (ACK). Having sent the ACK, the PHY layer goes into sleep mode until he is again triggered by the MAC for the next frame.

2.2. Receiver Architecture

We consider in this paper an architecture of a typical IEEE 802.11n WLAN receiver, shown in Fig. 2, combining MIMO and orthogonal frequency division multiplexing (OFDM). The signal from each of the N_R antennas is fed into a separate analog/RF frontend where the radio frequency signal is downconverted to baseband and digitized. After a parallel to serial converter, time multiplexing the receive chains, a digital frontend is responsible for frame start detection and for coarse-grain frequency synchronization. If a frame start is detected, the signal is forwarded to a time-multiplexed FFT. Training sequences are fed to a channel estimation and preprocessing unit, where the channel state information is estimated and all remaining computations are performed which only depend on the training sequence. The output of the channel estimation and preprocessing unit is fed into the subsequent MIMO detector together with the data payload baseband samples. After detection the bits (with or without reliability information) are forwarded to the channel decoding unit that comprises a deinterleaver and Viterbi decoder or an LDPC decoder.

In the transmission scenario described Sec. 2.1 the analog/RF frontend is always turned on (in receive or transmit mode) except during the sleep period. The highest work load of the subsequent digital frontend is during the frame start detection and the first training phase. The FFT is processing data during the training phases, the header phase, and the data payload phase. During the training phases also the channel estimation and preprocessing units are active. The subsequent (MIMO) detection and the channel decoding units process both header and data payload.

The processing rate of the different units is shown in Fig. 2.

Most units run at the symbol rate of the transmissions (related to the bandwidth). The channel estimation and preprocessing unit has to process data only during short periods and is otherwise idle. The channel decoding unit is processing at the coded bit rate of the transmission, that may vary in IEEE 802.11n compliant systems from 13 Mb/s to 720 Mb/s.

2.3. Receiver Energy Model

We define a set Ω by enumerating all meaningful system modes (i.e., all allowed MCSs together with potential receiver configurations such as number of antennas or algorithm choices for demodulation and decoding). Each of these modes $m \in \Omega$ is, for packets of a given length L, associated with a throughput $\Phi(m)$ and a packet-error¹ rate $P_e(m)$ which together provide the goodput as $(1 - P_e(m))\Phi(m)$ and the average number of successfully transmitted bits per packet as $(1 - P_e(m))L$.

We now consider the energy-efficiency of the receiver as our metric of main interest. To this end, we start by dividing the energy per received packet into three main contributions:

- A constant energy-overhead for synchronization, header processing, training, and channel-rate processing e_H(m) in Joules. This part depends partially on the choice of m since different MCSs and different antenna configurations change also the duration of the training and have different energy costs.
- The second contribution comprises the RF and the baseband processing which is characterized by the power consumption $p_{BB}(m)$ in Watts and the duration of the data phase. The latter is determined by the length L and the throughput $\Phi(m)$ so that the corresponding contribution to the energy-per-frame amounts to $e_{BB}(m) = p_{BB}(m) \frac{L}{\Phi(m)}$.
- The last contribution comprises mostly the channel coding which is typically carried out on a bit-by-bit basis and can be described by the energy-efficiency of the channel decoding $\eta_{CC}(m)$ and the length of the frame L as $e_{CC}(m) = L\eta_{CC}(m)$.

Combining the contributions above and normalizing with the average number of successfully transmitted bits per packet (thereby implicitly incorporating the error rate), we obtain

$$\eta(m) = \frac{\left(\frac{e_H(m)}{L} + \frac{p_{BB}(m)}{\Phi(m)} + \eta_{CC}(m)\right)}{1 - P_e(m)} \tag{1}$$

as our metric of interest for optimization.

2.4. Discussion of the Energy Model

Before proceeding with the optimization of (1) by properly choosing m, a brief discussion of the implications of this model and the dependency between its variables (through the choice of m) provides some insight into trends and ideas to simplify the estimation of the potential for energy savings.

As a starting point for our considerations, we note that in the rather generic expression in (1), $e_H(m)$, $p_{BB}(m)$, and $\eta_{CC}(m)$ all depend on m. However, in practice (at least for linear receivers), the amount of energy spent is often independent of the mode and even the variation of $e_H(m)/L$ with m is often insignificant compared to the remaining contributors. In that case, choosing m to maximize $\Phi(m)$ trivially minimizes the denominator of (1) with diminishing returns due to the bias terms. Unfortunately, $P_e(m)$ also approaches one as $\Phi(m)$ increases which ultimately limits goodput, but also the energy-gains. To eliminate the rather complex relationship between m and $P_e(m)$, we take advantage of the presence of a fast and conservative rate-adaptation. For each channel realization we can now

¹A packet is correct if all coded bits of the packet are decoded correctely.

divide the available modes into two groups: one that is able to get a packet across with very high probability $P_e(m) \approx 0$ and a second group of modes that will almost surely fail $P_e(m) \approx 1$. In that case, the choice of the highest-rate mode that is still reliable is clearly the most favorite strategy and little potential exists for further optimization for energy-efficiency.

3. MODIFICATION TO THE PHY LAYER

To enable further energy-efficiency improvements beyond that associated with the natural choice of the highest-rate mode, the physical layer implementation must be improved. The main idea is to first introduce a more energy-proportional behavior in a sense that $e_H(m)$, $p_{BB}(m)$, and $\eta_{CC}(m)$ take significant advantage of different processing requirements for different modes m not only in terms of complexity (i.e., energy consumption), but also in terms of throughput (i.e., rate). In a second step, such behavior then encourages the introduction of new modes which are not necessarily optimal in terms of their goodput, but may still provide an overall energy-efficiency advantage.

3.1. Energy Proportionality Through Suboptimal Detectors

A first modification to improve energy proportional behavior is to take advantage of the fact that in some situations different receiver algorithms with noticeable complexity difference exhibit a similar error-rate behavior. Hence, choosing the more complex algorithm may still not allow for a goodput improvement that out-weights the higher energy-cost.

A good example is the choice of the MIMO detector, where a solution with close to maximum likelihood (ML) performance can be combined with a low-complexity detector. The first detector provides good performance required for bad conditions, (e.g., low signal to noise ratio (SNR) or bad condition of the MIMO channel) while the low-complexity alternative uses less energy. For conditions where the occurrence of a frame error is independent of the detector (e.g., very high SNR, very low SNR), the low-complexity alternative has clearly better energy-efficiency.

3.2. Energy Proportionality Through DVFS

A well designed physical layer implementation already provides a certain degree of energy-proportionality in a sense that the energyconsumed depends more or less linearly on the number of operations. A good example is the channel coding, which contributes to (1) a constant energy per decoded bit. To further increase this desired behavior, we notice that in VLSI circuits the maximum working frequency of a digital circuit scales approximately linear with the supply voltage (within reasonable range). However, the power consumption of the circuit scales quadratic with the supply voltage. Therefore, we can also translate relaxed throughput requirements (in terms of operations per second) into further energy-savings per operation, an idea that is commonly referred to as (dynamic) voltagefrequency scaling (DVFS)².

Application of DVFS to channel decoding: A first, obvious opportunity to apply to a conventional receiver DVFS is the channel decoding. There, the rate varies significantly, while without DVFS the energy consumed per decoded bit remains roughly constant. With DVFS, this part of the receiver can take advantage of the reduced rate and provide an overall better energy-per-bit without negative impact on error rate performance.

²We note that the practical application of DVFS is clearly associated with many difficulties and with overhead (e.g., voltage regulators and alike) that are neglected here on purpose to explore the limits regardless of their technical issues on circuit level.

Application of DVFS to active antenna selection: A second opportunity to apply DVFS comes along with the consideration of reduced-complexity receiver configurations that are suboptimal in terms of error rate performance compared to modes that fully utilize all the available hardware capabilities. Since the corresponding reduced complexity modes will generally only allow for rates that are lower than provided by more complex modes, they can only be advantageous when savings in $e_H(m)$, $p_{BB}(m)$, and $\eta_{CC}(m)$ make up for the goodput loss. The most obvious target for such additional modes is the choice of the number of active antennas N_R at the receiver such that it is equal or greater than the number of spatial streams N_{ss} . Such adaptation allows to roughly linearly scale the power of the analog/RF frontend with N_R . The baseband processing takes advantage of the same linear scaling due to the reduced number of operations but also benefits from DVFS since fewer chains must be processed in a time-interleaved fashion and therefore more time is available per chain.

4. RATE ADAPTATION

The selection of the best transmission mode toward a given objective and under a given set of constraints is made by a fast (compared to the coherence time of the channel) RA which in our case is located at the receiver and provides regular feedback to the transmitter with the desired mode for the subsequent frames. To determine this mode, the corresponding algorithm collects side information that allows to reliably predict the error rate $P_e(m)$ for all available modes using for example detailed knowledge of the instantaneous SNR and the actual channel realization. In addition to the error rate performance estimate, further information on the implications of each mode such as its energy-efficiency (cf. (1)) are also available through lookup tables. In the following, we consider three main objective functions: a goodput-guided (GG) RA, a purely energy-guided (EG) RA, and a goodput-aware energy-guided (GE) RA which is a compromise between the first two.

Since the purpose of this paper is to explore the potential and the limits of energy-awareness we intentionally assume a genie-aided approach. This simplification avoids introducing uncertainties due to specific RA strategies and it simplifies the full explanation of the setup under consideration. The genie provides an upper bound on goodput and energy efficiency by perfectly predicting transmission failures by sending each packet in all modes for each channel and noise realization (not counting the associated massive overhead) which - of course - is only feasible in simulations. Hence, $P_e(m)$ is either one or zero which boils down to limiting the selection to the error-free modes.

Goodput-Guided (GG) RA: GG RA selects the system mode m_{GG} , which results in the highest goodput

$$m_{GG} = \operatorname*{arg\,max}_{m} \Big\{ \left(1 - P_e(m)\right) \Phi(m) \Big\}. \tag{2}$$

No attention is paid toward energy-efficiency and even the genie is constrained not to use any of the non Pareto-optimal (w.r.t. error rate vs. throughput) modes such as reduced number of receive antennas or detectors with inferior reliability. Yet the receiver can optionally still perform DVFS on block such as channel coding which have no impact on performance.

Energy-Guided (EG) RA: As opposed to the GG RA, the EG RA selects the transmission mode to minimizes the energy consumption of the receiver according to

$$m_{EG} = \arg\min_{m} \left\{ \eta(m) \right\}.$$
(3)

No attention is specifically paid toward the impact on goodput, except for the implicit dependency of $\eta(m)$ on $P_e(m)$ and $\Phi(m)$ in



Fig. 3. Energy consumption per successfully transmitted bit.

(1). This dependency still provides a small bias toward the higher rate modes, but also respects the availability of modes associated with lower rates for the benefit of energy-efficiency.

Goodput-Aware Energy-Guided (GE) RA: Finally, the GE RA seeks a compromise of the goodput achieved by the GG RA and the energy-efficiency provided by the EG RA by selecting the mode m_{GE} with the best goodput and an energy consumption that is not worse than k > 1 times the energy consumption of m_{EG} based on

$$n_{GE} = \operatorname*{arg\,max}_{m} \Big\{ \eta(m) : \phi(m) < k\phi(m_{EG}) \Big\}. \tag{4}$$

By selecting an appropriate value of k, the MAC is able to trade energy consumption versus throughput and therefore allows more elaborate tradeoffs.

5. SIMULATION SETUP AND RESULTS

In this section we explore the limits of the gains in energy-efficiency that can be achieved with the proposed modifications to the PHY combined with an appropriate genie-aided RA.

5.1. Transmission Scenario

We considered an IEEE 802.11n system with up to 4 spatial streams and up to 4 receive antennas using 40 MHz bandwidth. For channel coding we use only the convolutional code of the standard. The 32 mandatory MCS defined in the IEEE 802.11n have result in a variable frame duration for a fixed payload of 1500 Bytes transmitted over a flat Rayleigh block-fading channel.

Each MCS has been simulated with 4 receive antennas and with the minimum number of antennas required for the corresponding number of spatial streams. Furthermore, all schemes have been simulated with a hard-output lattice reduction aided linear detector [9] and a low-complexity soft-output MMSE detector, resulting in 112 different system modes comprising Ω .

5.2. Receiver Energy Model

The receiver energy model $\eta(m)$ is based on power numbers of the analog frontend in [10] and the PHY layer implementation presented in [11], ported to a 90 nm CMOS technology. We further assume that the PHY layer has employed all modifications proposed in Sec. 3.

5.3. Results

In Fig. 3 to Fig. 5 we compare the impact of the proposed modifications in conjunction with the RA strategies described in in Sec. 4 on absolute and relative energy-efficiency and on goodput.

We compare all curves to the reference curve given by a GG RA in conjunction with a PHY layer without the modifications proposed in Sec. 3. This baseline implementation has the worst energy consumption per successfully received bit as shown in Fig. 3 but has also highest goodput over the entire SNR range as shown in Fig. 5.



Fig. 4. Relative power consumption with respect to throughputdriven RA without DVFS.



Fig. 5. Throughput of the different schemes.

- Without influence on the goodput the energy efficiency of the above mentioned curve can be improved if DVFS is applied to channel decoding by 5% shown in Fig. 4.
- Combining DVFS on the channel decoding with EG RA improves the energy-efficiency up to 15% compared to the reference. The limited capability to perform energy proportional computing in the baseband and the limitation to 4 receive antennas limits the efficiency gains of this approach.
- Enabling active antenna selection together with DVFS combined with EG RA results in the best energy-efficiency achievable. Compared to the reference curve up to 44% of the energy consumed per bit can be saved. Unfortunately, this large saving also results in a severely reduced goodput.
- The two remaining curves show a PHY layer implementation with adaptive antenna selection and the TE RA with either 5% or 10% energy-efficiency margin. It can be seen in Fig. 4 that the efficiency for both implementations only have a minor efficiency loss compared to the best scheme, but the 97% of goodput of the TG RA is restored.

6. CONCLUSION

In this paper, we show that rate adaptation for energy efficiency rather than for goodput can lead to significant energy savings for the receiver in an IEEE 802.11n scenario. The key elements of the approach are additional PHY layer modes that are not necessarily optimal in terms of error-rate performance but provide energy reduction by exploiting voltage-frequency scaling and other methods for energy savings. Validation is based on numbers extracted from an actual PHY implementation, combined with a genie-aided rate adaptation to explore the limits of the idea.

7. REFERENCES

- R. Bolla, R. Bruschi, F. Davoli, and F. Cucchietti, "Energy efficiency in the future internet: A survey of existing approaches and trends in energy-aware fixed network infrastructures," *IEEE Communications Surveys Tutorials*, vol. 13, no. 2, pp. 223–244, 2011.
- [2] C. Schurgers, O. Aberthorne, and M. Srivastava, "Modulation scaling for energy aware communication systems," in *Proceedings of the 2001 international symposium on Low power electronics and design*, Huntington Beach, California, USA, Aug. 2001, pp. 96–99.
- [3] M. Lin and Y. Ganjali, "Power-efficient rate scheduling in wireless links using computational geometric algorithms," in *Proceedings of the 2006 international conference on Wireless communications and mobile computing*, Vancouver, British Columbia, Canada, July 2006, pp. 1253–1258.
- [4] N. Zompakis, A. Papanikolaou, P. Raghavan, D Soudris, and Catthoor F., "Enabling efficient system configurations for dynamic wireless applications using system scenarios," *International Journal of Wireless Information Networks*, pp. 140–156, June 2013.
- [5] T.L. Jensen, S. Kant, J. Wehinger, and B.H. Fleury, "Fast link adaptation for MIMO OFDM," *IEEE Transactions on Vehicular Technology*, pp. 3766–3778, Oct. 2010.
- [6] P. Tan, Y. Wu, and S. Sun, "Link adaptation based on adaptive modulation and coding for multiple-antenna OFDM system," *IEEE Journal on Selected Areas in Communications*, pp. 1599–1606, Oct. 2008.
- [7] G. Martorell, F. Riera-Palou, and G. Femenias, "Cross-layer fast link adaptation for MIMO-OFDM based WLANs," *Wireless Personal Communications*, pp. 599–609, Feb. 2011.
- [8] G. Judd, X. Wang, and P. Steenkiste, "Efficient channel-aware rate adaptation in dynamic environments," in *Proceedings of the 6th international conference on Mobile systems, applications, and services*, Breckenridge, CO, USA, June 2008, pp. 118–131.
- [9] L. Bruderer, C. Senning, and A. Burg, "Low-complexity Seysen's algorithm based lattice reduction-aided MIMO detection for hardware implementations," in *Proc. IEEE Asilomar*, Pacific Grove, CA, Nov. 2010, pp. 1468–1472.
- [10] R. Kumar, T. Krishnaswamy, G. Rajendran, D. Sahu, A. Sivadas, M. Nandigam, S. Ganeshan, S. Datla, A. Kudari, H. Bhasin, M. Agrawal, S. Narayan, Y. Dharwekar, R. Garg, V. Edayath, T. Suseela, V. Jayaram, S. Ram, V. Murugan, A. Kumar, S. Mukherjee, N. Dixit, E. Nussbaum, J. Dror, N. Ginzburg, A. EvenChen, A. Maruani, S. Sankaran, V. Srinivasan, and V. Rentala, "A fully integrated 2 × 2 b/g and 1 × 2 a-band MIMO WLAN SoC in 45nm CMOS for multi-radio IC," in *IEEE ISSCC*, San Francisco, CA, Feb. 2013, pp. 328–329.
- [11] A. Burg, S. Haene, M. Borgmann, D. Baum, T. Thaler, F. Carbognani, S. Zwicky, L. Barbero, C. Senning, P. Greisen, T. Peter, C. Foelmli, U. Schuster, P. Tejera, and A. Staudacher, "A 4-stream 802.11n baseband transceiver in 0.13 μm CMOS," in *Dig. Techn. Papers, Symp. on VLSI Circuits*, Kyoto, Japan, June 2009, pp. 282–283.