Energy-Efficient Link Adaptations in IEEE 802.11b Wireless LAN*

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ABSTRACT

The growing popularity of Wireless LAN-based connectivity has increased the use of IEEE 802.11b as an edge access technology. However, with the ability to support high data rates and a wide range of applications, data access in these networks poses a significant demand on limited energy resources of mobile devices. In addition to the application demand, energy consumption can be significantly affected by varying channel conditions.

In order to alleviate the energy constraint, in this paper we explore the potential for adaptations in the link layer, and present an energy-efficient IEEE 802.11b Data Link Layer. We specifically study the effect of three parameters: *fragmentation threshold*, *transmission power*, and *retry limit* on energy consumption. Based on the study, we design run-time adaptation policies that monitor current channel conditions to appropriately set the parameter values dynamically. We demonstrate that significant energy savings (17 - 44%) can be achieved by enabling dynamic adaptation in the IEEE 802.11b Data Link Layer.

KEY WORDS:Wireless LAN, IEEE 802.11, Energy Efficiency, Link Adaptations

1 Introduction

The increasing popularity of mobile connectivity coupled with the inexpensive access provided by Wireless LAN (WLAN) have sparked growing interest and usage of IEEE 802.11b as an edge access technology. In fact, the use of WLAN is predicted to increase dramatically from one million to twenty-one million users in the next five years [1]. However, there remain a few bottlenecks that need to be addressed in order to adequately satisfy user demands.

One of the primary bottlenecks for data access using WLAN is the limited energy resource available in mobile devices. Battery capacity is projected to increase at a much slower rate than the energy requirements needed to provide rich wireless access to the Internet [2]. To meet application demands in WLAN networks, energy consumption should be reduced in order to extend the device lifetime effectively.

In addition to application demand, varying channel conditions is another factor that significantly affects energy consumption. Channel interference caused by other devices operating in the same public radio spectrum (2.4 GHz) of the IEEE 802.11b network is a primary contributing factor to the channel variation. In addition, due to the typical indoor usage of WLAN, propagation loss and multipath effects are also heavily present in these networks.

With these challenges in mind, there has been a wide range of work that has focused on minimizing energy in WLAN networks. Previous work varies from power-saving methods [3], which controls the device's sleeping routine, to routing/scheduling techniques in ad-hoc networks [4] [5]. While the other schemes target minimizing energy consumption during idle periods, in this paper, we focus on minimizing the energy consumed during data transmission periods, and hence can be complimentary to other power-saving methods. In our approach, we focus on adapting parameters related to data transmission that have impact on energy consumption.

We target the Data Link Layer and identify parameters that can be adapted to minimize energy consumption. We focus on the Data Link Layer because of its ability to control access to the wireless medium and obtain information about current channel variations from the physical layer. As a first step, we identify and study the effects of dynamically adapting parameters available in the IEEE 802.11b protocol standard. In this paper, we study the following parameters: *fragmentation threshold*, *transmission power*, and *retry limit*. In our choice of these parameters, we looked for parameters that can be adapted without affecting the backward compatibility with the existing standard.

With the goal of reducing energy consumption, we design run-time adaptation policies that appropriately set the values of these parameters for energy minimization. For each of these policies, we select a technique to monitor channel conditions, determine when to invoke the adaptation, and use feedback mechanisms to further improve the policies. Additionally, we investigate the issues in combining multiple policies and develop multi-parameter adaptation policies. Using an *OPNET*-based simulation framework, we demonstrate that significant savings can be achieved by enabling energy-efficient adaptations at the IEEE 802.11b Data Link Layer. Note that the proposed techniques can be applied to other IEEE 802.11-based standards, including IEEE 802.11a and 802.11g, as the link layer functionality is the same.

While there has been previous work in adapting a few

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of these parameters, our work improves upon these techniques by enabling dynamic adaptations using alternative channel estimation techniques, as well as passive channel feedback. For example, although the fragmentation threshold parameter was investigated in [6], [7], and [8], the older work focuses only on a static setting of this parameter and the more recent work is limited to using downlink measurements to estimate the uplink channel conditions. In addition to proposing a closed-loop formula to find the optimal fragmentation threshold, we design a policy that uses the experienced retransmission in the uplink direction as a feedback mechanism to optimally set the fragmentation threshold.

Similarly, with respects to transmission power, there has been recent work done on determining the appropriate power level setting for wireless networks [9], [10], [11], [12]. The above efforts range from power control loops using a signaling system in ad-hoc networks to the use of inter-packet power level fluctuations. In this paper, we present a simple adaptation policy that sets the transmission power level per packet.

Finally, in terms of the retry limit, work has been done to evaluate the effects of different link level error control mechanisms such as ARQ in terms of energy and throughput [13]. However, to the best of our knowledge, there are no adaptation policies that use retry limit to minimize energy consumption in IEEE 802.11b networks.

The rest of the paper is organized as follows. We present our proposed adaptation policies in Section 2. For each of the parameters, we first present an analysis of the effects on energy consumption, and follow with a description of our adaptation policies. Experimental results follow next in Section 3, demonstrating the effectiveness of our adaptation methodology. Finally, in Section 4, we conclude and describe future directions.

2 Adaptable Parameters and Effects

In this section, we present different adaptable parameters and describe their effects on energy constraints. The parameters we target are *fragmentation threshold*, *transmission power*, and *retry limit*. For each parameter, we present a discussion on how the parameter affects energy consumption and present an adaptation policy to reduce energy consumption by finding the appropriate value of these parameters considering the current channel conditions.

2.1 Fragmentation Threshold

IEEE 802.11b defines a mechanism to partition network level data packets into smaller units. Using packet size as a criterion, packets larger than a specified *fragmentation threshold* are partitioned in order to respond to dynamic erroneous channel conditions. Fragmentation improves the packet transmission reliability since the probability of a successful transmission increases with the decrease in packet size. However, partitioning of large data packets into smaller fragments can lead to additional data transmission overhead. Once a packet is partitioned, each fragment is augmented with headers, sent as an independent transmission, and acknowledged individually. Hence, under good channel conditions, fragmentation can lead to suboptimal performance. Having described the fragmentation threshold, we next analyze the effect on energy consumption.

2.1.1 Analysis

In order to understand the effects of fragmentation, we present an analysis of the energy consumed given a specified fragmentation threshold under current channel conditions. Given that n_{frag} is the number of fragments after a packet has been partitioned, a_{req} is the average number of attempts before a successful fragment transmission, and e_{frag} is the energy consumed for each fragment, the total energy (E) consumed by transmitting a packet can be written as

$$E = n_{frag} * a_{req} * e_{frag} \tag{1}$$

Given a fragmentation threshold of *F* (bits), the probability of a fragment not in error is given by $p = (1 - BER)^F$, where *BER* is the bit error probability. Note that a packet is considered erroneous in this analysis when one or more bits are in error. With this probability, we calculate the expected number of attempts required a_{req} to be $1/(1-BER)^F$, assuming that there is no limit on the number of retransmissions.

Given that *X* represents the upper layer packet size in bits, we can replace the number of fragments with n_{frag} = *X/F*. Furthermore, the energy consumed by each fragment can be expressed as $e_{frag} = (P_T * (F + H))/R$, with P_T as transmission power (W), R as data rate (bits/sec), and H as header size (bits). Hence, total energy consumption to send a packet of size X can be expressed as

$$E = \frac{X}{F} * \frac{1}{(1 - BER)^F} * \frac{P_T}{R} * (F + H) \tag{2}$$

In order to find the optimum fragmentation threshold, we compute the gradient (dE/dF) and equate it to zero. For very small values of BER, the optimum fragmentation threshold can be approximated to the following expression.

$$F_{opt\_energy} = -\frac{H}{2} + \sqrt{\frac{H}{BER}} \tag{3}$$

2.1.2 Adaptation Policies

Having presented the optimum fragmentation threshold value given the current BER, we present two fragmentation threshold adaptation policies: *Dynamically Varied Open Loop (DVOL)* and *Dynamically Varied Closed Loop (DVCL)*.

DVOL uses downlink channel measurements to estimate uplink channel conditions. It measures the signal strength, and estimates the BER of the received traffic from the access point. It uses the BER information to set the fragmentation threshold for the uplink traffic. We call this policy *Open Loop* since the decisions are made based on the observed signal strength, and do not use any form of active feedback on the uplink. Note that, the measured BER information is used to estimate the channel conditions in the uplink assuming that the communication channels are symmetric in IEEE 802.11b based networks. The success of the policy is dependent on the availability of downlink traffic, which may not be the case in particular applications. Additionally, it assumes that both the receiver and transmitter experience the same channel and interference conditions.

To counteract the heavy dependence on downlink traffic, as well as consider a possible difference in experienced interference at the receiver and the access point, *DVCL* uses packet retransmission information to estimate the uplink channel condition. Using the relationship between the packet error probability and the BER value, we estimate the current BER with the following Equation 4. We use the measured retransmission ratio as an indication of packet error probability. In this equation, fragment and header sizes are represented by F and H respectively. We call this policy *Closed Loop* as it uses both measured information and retransmission information in the uplink channel as an active feedback.

$$BER_{est} = \frac{Retransmission\ Ratio}{(F+H)} \tag{4}$$

The detailed flowcharts of DVOL and DVCL adaptation policies are shown in Figure 1 and Figure 2 respectively. In the DVOL policy, with every received packet, the average BER of the channel is updated. A basic counter is used to control the frequency of the fragmentation adaptation. Given that the BER is averaged for a sufficient number of packets, the fragmentation threshold is set to a final value, as given by Equation 3, as explained earlier.

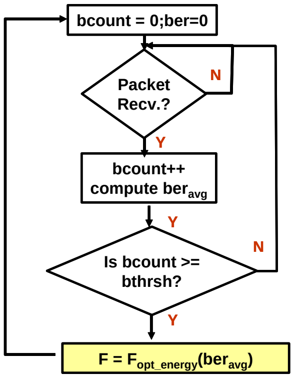

Figure 1. Fragmentation Adaptation Policies : Dynamically Varied Open Loop (DVOL)

For the DVCL adaptation, the main goal is to use retransmission information to determine the current channel condition. If the downlink measurements of the retransmission ratio are insufficient, the DVCL policy defaults to DVOL and uses the averaged BER value to determine the fragmentation threshold. If the uplink information is sufficient, DVCL estimates the current BER of the channel using the retransmission ratio with Equation 4, and then uses this value of BER in Equation 3 to determine the fragmentation threshold. Next, we present the effect of another parameter that can be controlled by the link layer, *i.e. transmission power*

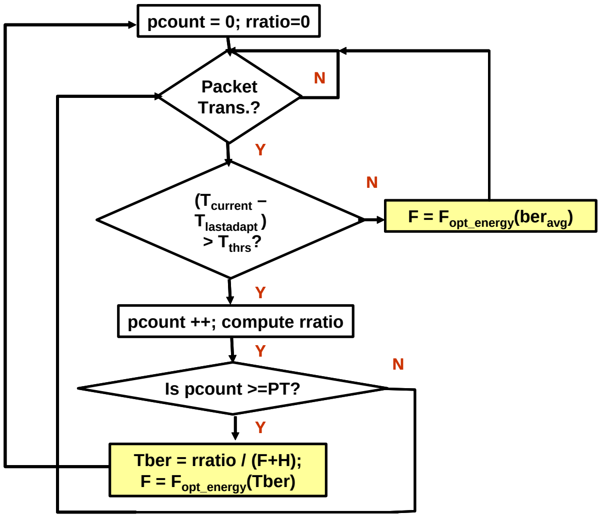

Figure 2. Fragmentation Adaptation Policies : Dynamically Varied Closed Loop (DVCL)

2.2 Transmission Power

In addition to selecting the appropriate packet size, another parameter that can affect the probability of successful transmission of packets is the *transmission power*. We next present a brief description on the effect of transmission power on energy consumption.

2.2.1 Analysis

The experienced BER value at the receiver end provides information about the channel conditions and can be used in energy saving techniques at the MAC level. The BER heavily depends on the signal strength at the receiver, which can be influenced by many factors including the transmission power level, propagation loss, antenna gain, and processing gain. Since the received signal strength is directly proportional to the current transmission power level, the transmission power level can be adjusted to change the signal strength and hence the BER at the receiver.

In terms of energy consumption, the effect of transmission power on energy consumption has been measured and modeled in previous work. In [14], the results indicate a strong dependence between the energy consumption and transmission power, and this relationship can be described using a linear model.

With the above mentioned effects, a trade-off can be seen between the BER experienced and energy consumption depending on the transmission power level selection. Under good channel conditions, the transmission power level can be reduced to save energy consumption. However, under bad channel conditions, in addition to fragmentation, an increase in transmission power will reduce the percentage of retransmission and dropped packets, thus improving energy per goodput.

2.2.2 Adaptation Policies

With an understanding of the transmission power level parameter, we design an adaptation policy that responds to very extreme channel conditions. The transmission power adaptation algorithm increases the transmission power when the channel conditions are poor, as indicated by a significant amount of dropped packets or high BER. On the other hand, when the channel conditions are good, the transmission power is decreased to conserve energy.

One possible concern in adapting the transmission power level is that it may lead to an increase in hidden node scenarios when nodes using different power levels may be unable to hear each other properly. In our adaptation policy, we address the concern by using high transmission power levels for control packets, such as RTS, CTS, and ACK, to minimize the chances of hidden nodes.

2.3 Retry Limit

In addition to fragmentation threshold and transmission power, the IEEE 802.11b Data Link Layer uses an automatic repeat-request (ARQ) based error recovery mechanism in order to tolerate interference and collisions. This generally involves the retransmission of frames after a timeout period if no acknowledgment is received from the destination station. To regulate the number of retransmissions, the Data Link Layer defines a parameter named *retry limit*, the maximum number of retransmissions allowed before a station discards the frame.

It is important to note that the number of retransmissions needed to successfully send a packet depends on current channel conditions and application requirements. Although an increase in the allowable number of retransmissions can increase the probability of a successful transmission in bad channel conditions, such an increase leads to a greater energy consumption. Additionally, the retry limit can be used to control the average number of packets dropped. Under bad channel conditions, this parameter can be useful when applications are able to tolerate a certain percentage of dropped packets.

2.3.1 Analysis

In this section, we present the effect of the *retry limit* on energy consumption and packet drop rate given current channel conditions. The probability of a packet of size P being received correctly when experiencing the bit error rate of BER is $(1 - BER)^P$. Let us denote the probability of successful packet transmission as p and the probability of erroneous transmission as $q = 1 - p$. Assuming the maximum retransmissions allowed is RL, the drop packet probability (dp_{prob}) after RL attempts is given by

$$dp_{prob} = q^{RL} \tag{5}$$

If the target packet drop rate is P_{drop}, we would want to insure that $q^{RL} \leq P_{drop}$. Given this P_{drop} and the current BER, we calculate the expected number of retransmissions, R_{exp}, with the following expression.

$$R_{exp} = \frac{log(P_{drop})}{log(1 - (1 - BER)^P)} \tag{6}$$

In terms of energy consumption, if the expected number of retransmissions, R_{exp}, is greater than the current retry limit for a specific packet, we can expect the packet to be dropped. The retransmissions of this packet contribute to wasteful energy consumption without increasing the goodput of the system. Hence, under drastic channel conditions which require a large amount of retransmissions, packets can be dropped early to conserve energy.

2.3.2 Adaptation Policy

Based on the above observations, we develop an adaptation policy to select the appropriate *retry limit* (RL) value depending on current conditions and requirements. In this policy, the expected number of retransmissions, R_{exp} is calculated using Equation 6 and compared to the current retry limit. If it is clear that the packet will be dropped by this estimate, we set the retry limit to a small value in order to avoid excess retransmissions. If this is not the case, we set the retry limit to either the default value or the expected number of retransmissions calculated at the earlier step, depending on which has the smaller value.

3 Experimental Results

In this section, we present the experimental evaluation of our adaptation policies. We first briefly describe the experimental setup. Next, we describe the effects of our adaptation polices on the Data Link Layer as described in the earlier sections. Finally, we present the performance of combining multiple policies on energy consumption.

3.1 Setup and System Configuration

For our experiments, we use the *OPNET* [15] simulation environment, which provides models of the Distributed Coordination Function (DCF) Data Link Layer and Direct Sequence Spread Spectrum (DSSS) physical layer of the IEEE 802.11b standard. The *OPNET* tool uses a pipeline model to determine channel variation and evaluates characteristics such as propagation loss and interference. For our experiments, we consider an IEEE 802.11b infrastructure-based network and evaluate a number of test cases with varying number of nodes and mobility patterns. We constructed a network scenario where the wireless clients connect to the remote data server through a IP backbone infrastructure. For estimating energy consumption, we used the energy models proposed in [16] and [17] that were developed through measurements of IEEE 802.11b interfaces with different transmission power.

3.2 Adaptation Policies

We now discuss the results of running the adaptation policies described in earlier sections and describe the effects of the following parameters: *fragmentation threshold*, *transmission power*, and *retry limit*. For these sets of experiments, we created and simulated a network with nodes running the *FTP* application.

Fragmentation Threshold

To determine the effects of the different fragmentation adaptation policies on energy and throughput, we implemented both the DVOL and DVCL policies presented in Section 2.1 and integrated these mechanisms in the *OPNET* model. Due to sensitivity of the fragmentation threshold policy to channel variations, the simulation considered three different channel models: *fixed*, *Gilbert-Elliot Model*, and the *OPNET Generated*.

For the *fixed* cases (FIX1 & FIX2), the channel models were set to the values representative of bad and good conditions, i.e. BER values set to 10^{-6} and $5{*}10^{-4}$ respectively. Using the *Gilbert-Elliot* model, we simulated four test cases (GE1 to GE4). The Gilbert-Elliot model, as described in [18] and [19], generates BER based on a two state Markov chain model. We varied the transition probabilities of the model, similar to the values presented in [18], using combinations of 0.99 and 0.95. These probabilities alter the percentage of time spent at each state and the frequency of transition. The probabilities values selected for the models are as follows : GE1 (Pgg=0.99, Pbb=0.99), GE2 (0.95, 0.99), GE3 (0.99, 0.95), and GE4 (0.95, 0.95). Finally, we evaluated a single mobile node experiencing the channel variation as given by the *OPNET* pipeline model (MOB) and a case with multiple nodes (MUL).

The criteria used for comparing these scenarios was *Energy per Goodput*, which is the total energy consumed for every bit successfully sent. For each of the above test cases, we compared the fragmentation adaptation policies, DVOL and DVCL, with a test case using a static fragmentation threshold of 800 bytes, as suggested by [6]. Table 1 presents the results of the evaluation comparison.

Table 1. Effect of Fragmentation Adaptation Policies on Energy per Goodput

	Energy per Goodput (mAs/bit)				
	Static	**DVOL**	**% Savings**	**DVCL**	**% Savings**
FIX1	3.65E-05	3.42E-05	6.30%	3.41E-05	6.58%
FIX2	1.20E-03	1.10E-04	90.83%	1.40E-04	88.33%
GE1	5.90E-05	5.76E-05	2.37%	5.75E-05	2.54%
GE2	8.80E-05	7.81E-05	11.25%	7.90E-05	10.23%
GE3	4.11E-05	4.05E-05	1.46%	4.04E-05	1.70%
GE4	5.38E-05	5.20E-05	3.35%	5.08E-05	5.58%
MOB	4.83E-05	4.06E-05	15.94%	4.02E-05	16.77%
MUL1	1.13E-05	1.06E-05	5.60%	9.10E-06	19.11%

The percentage savings recorded in the table indicate the percentage improvement between the adaptive policies and the static case. The results indicate that the adaptation policies of DVOL and DVCL can improve energy. On average, we see an average savings of 17% for DVOL and 19% for DVCL in terms of Energy per Goodput. We note that the improvement is more significant in the situations when the channel is experiencing high BER, such as in FIX2, GE2, and MOB. In addition, the results indicate the DVCL policy fairs better than DVOL when there are frequent transitions of the channel or downlink prediction is inaccurate, such as in GE4 and MUL.

Transmission Power

In addition to the fragmentation policy, we also evaluated the effects of our transmission power adaptation. Using the *OPNET* pipeline model, we considered multiple test cases with varying fragment sizes (128 - None) and number of nodes in the network (1-4). Due to space constraints, we present six of the testcases and summarize our simulation results in Table 2. We see that we can improve Energy per Goodput by 17-49%.

Table 2. Effect of Transmission Power Adaptation

Description		Energy per Goodput (mAs/bit)		
# Nodes	**FragThresh**	**w/o adapt**	**w/adapt**	**% savings**
4	512	6.64E-05	8.488E-05	21.82%
	none	5.71E-05	9.54E-05	40.16%
2	512	5.49E-05	7.04E-05	22.02%
	none	4.55E-05	8.93E-05	49.10%
1	512	3.90E-05	4.75E-05	17.89%
	none	3.80E-05	5.10E-05	25.49%

Retry Limit

For the retry limit, we implemented our adaptation algorithm in order to determine the effect on Energy per Goodput and throughput. Our initial experiment was to determine whether the expected number of retransmissions, R_{exp}, as given by Equation 6, was accurate in comparison to the actual retransmissions required. We considered a case without fragmentation and found that the expected number of retransmissions given by our formula is 80-90% accurate. Next, we created a scenario using FTP traffic with UDP as the transport layer (so as to allow for packet drops at the transport layer) and consisting of three different nodes experiencing varying BER. The target P_{drop} for this experiment was assumed to be 10%. We simulated with and without adaptation and obtained the results summarized in Table 3.

Table 3. Effect of Retry Limit Adaptation

		Energy per Goodput (mA/s)			Drop %			Retx %		
Node	**Average BER**	**w/o Adapt**	**w/ Adapt**	**% Savings**	**w/o Adapt**	**w/ Adapt**	**% Inc**	**w/o Adapt**	**w/ Adapt**	**% Dec**
1	3.00E-04	2.32E-04	1.59E-04	31.47%	20	21.00	1.00	33	25	8
2	1.00E-05	4.79E-04	3.68E-04	23.17%	7.5	11.00	3.50	25	18	7
3	7.50E-06	1.16E-05	1.10E-05	5.17%	1	4.00	3.00	7	9	-2

As seen in this table, the adaptation leads to a 31% improvement in Energy per Goodput for Node 1 with only an increase of 1% dropped packets. With Node 2 and 3, we obtain an improvement of 23% and 5%, respectively, but suffer from a slight increase in dropped packets. This increase may be tolerable depending on the application.

3.3 Multiple Policies

Having looked at the individual parameters and their adaptations, we evaluated the effects of using multiple policies. In addition to activating multiple policies at once, we also considered the dependencies and coordination needed between the policies. For example, if both the fragmentation and retransmission policy were activated, the fragmentation policy was scheduled to run first due to the retransmission policy's dependence on fragment length. In addition, when the transmission power and fragmentation policy were activated, the use of the transmission power policy was only activated when the fragmentation policy was exhausted and could not improve the situation.

In order to understand the effects of these policies, we evaluated the effect of different combination of adaptation policies on a network of four nodes in terms of Energy per Goodput. Table 4 summarizes the results averaged over the nodes. It can be seen from the table that the fragmentation adaptation policy is more effective compared to any other individual policy. Also, it is clear that energy savings can be improved by combining policies.

Table 4. Effects of Multiple Policies

Policies	Energy per Goodput (mAs/bit)	% Savings
none	1.09E-04	0.00%
frag	6.91E-05	36.75%
retry	9.08E-05	16.93%
tx	7.80E-05	28.60%
frag-tx	6.17E-05	43.52%
frag-retry	6.58E-05	39.77%
tx-retry	7.79E-05	28.72%
all	6.13E-05	43.89%

4 Conclusion and Future Work

In this paper, we presented the effects of different adaptable parameters in the IEEE 802.11b Data Link Layer on energy consumption. We introduced a number of runtime adaptation policies and showed that it can be beneficial in terms of energy savings. We discussed the challenges of combining the policies and showed that with the appropriate selection of policies, we were able to further improve our energy savings. Though our experimental results are based on an IEEE 802.11b model, we believe the presented techniques would be valid for other IEEE 802.11-based standards, including IEEE 802.11a and 802.11g, as well. Having demonstrated that significant savings can be achieved by enabling adaptation at the IEEE 802.11b Data Link Layer, our future directions include further investigations of parameters available in IEEE 802.11b, and exploration in the effects and implications of adaptation in an ad-hoc network.

References

[1] "Public wireless lan access : Us market forecasts 2002-2007." `http://www.analysys.com`, Jan. 2002.

[2] I. Buchmann, "Batteries in a Portable World." On-line book, available at `http://www.cadex.com`.

[3] R. Krashinsky and H. Balakrishnan, "Minimizing energy for wireless web access with bounded slowdown," in *mobicomm*, (Atlanta, GA), September 2002.

[4] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: An energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks," *ACM Wireless Networks*, vol. 8, September 2002.

[5] V. Kanodia, C. Li, A. Sabharwal, B. Sadeghi, and E. Knightly, "Distributed priority scheduling and medium access in ad hoc networks," *Wireless Networks*, vol. 8, no. 5, pp. 455–466, 2002.

[6] B. P. Crow, I. Widjaja, J. G. Kim, and P. Sakai, "Investigation of the IEEE 802.11 medium access control (mac) sublayer functions," in *Proceedings of IEEE INFOCOM*, (Kobe, Japan), pp. 126–33, Apr. 1997.

[7] P. Lettieri and M. B. Srivastava, "Adaptive frame length control for improving wireless link throughput, range, and energy efficiency," in *Proceedings of IEEE INFOCOM*, (San Francisco, CA), pp. 564–571, Apr. 1998.

[8] D. Qiao and S. Choi, "Goodput enhancement of IEEE 802.11a wireless lan via link adaptation," in *Proceedings of IEEE ICC*, (Helsinki, Finland), pp. 1995–2000, June 2001.

[9] S. Agarwal, R. H. Katz, S. V. Krishnamurthy, and S. K. Dao, "Distributed power control in ad-hoc wireless networks," in *Proceedings of IEEE PIMRC*, (San Diego), pp. F59–66, Sept. 2001.

[10] J. P. Ebert and A. Wolisz, "Combined tuning of rf power and medium access control for wlans," *ACM Mobile Networks and Applications*, vol. 6, no. 5, pp. 417–26, 2001.

[11] N. Poojary, S. V. Krishnamurthy, and D. Son, "Medium access control in a network of ad hoc mobile nodes with heterogeneous power capabilities," in *Proceedings of IEEE ICC*, (Helsinki, Finland), pp. 872–7, June 2001.

[12] E. S. Jung and N. Vaidya, "A power control mac protocol for ad hoc networks," in *Proceedings of ACM MobiCom*, (Atlanta, Georgia), Sept. 2002.

[13] M. Zorzi and R. Rao, "Arq error control for delay-constrained communications on short-range burst-error channels," in *Proceedings of IEEE VTC*, (Pheonix, AZ), pp. 1528–1532, May 1997.

[14] J. P. Ebert, B. Burns, and A. Wolisz, "A trace-based approach for determining the energy consumption of a wlan network interface," in *Proceedings of European Wireless*, (Florence, Italy), pp. 230–236, Feb. 2002.

[15] "Opnet simulation framework." `http://www.opnet.com`.

[16] J.-P. Ebert, S. Aier, G. Kofahl, A. Becker, B. Burns, and A. Wolisz, "Measurement and simulation of the energy consumption of a wlan interface," tech. rep., Telecommunication Networks Group, Technische Universitt Berlin, 2002.

[17] L. M. Feeney and M. Nilsson, "Investigating the energy consumption of a wireless network interface in an ad hoc networking environment," in *Proceedings of IEEE INFOCOM*, (Anchorage, AK), pp. 1548–57, Apr. 2001.

[18] J.-P. Ebert and A. Willig, "A gilbert-elliot bit error model and the efficient use in packet level simulation," tech. rep., Telecommunication Networks Group, Technische Universitt Berlin, Mar. 1999.

[19] A. Willig, M. Kubisch, and A. Wolisz, "Measurements and stochastic modeling of a wireless link in an industrial environment," tech. rep., Telecommunication Networks Group, Technische Universitt Berlin, Mar. 2001.