

White Paper

**Power Consumption and Energy
Efficiency Comparisons of WLAN
Products**

Power Consumption and Energy Efficiency Comparisons of WLAN Products

Executive Summary

This paper examines the power consumption of various wireless local area network (WLAN) cards, spanning the major 802.11 standards. An accurate measure of the battery life impact from each WLAN card is made by measuring the power consumption of the complete laptop platform, and measuring how much the platform power changes when the WLAN card is used in various modes.

An important observation in this paper is that the power consumption increase due to WLAN operation comes not only from the WLAN card itself, but also from the additional main CPU activity and other parts of the laptop platform required to operate the WLAN interface. In some cases, the extra power consumed by the rest of the platform is several times higher than the power consumed by the WLAN card itself.

In order to readily compare different WLAN and PC configurations, this paper uses an energy consumption metric that balances a combination of idle time and periods of sending and receiving data. The energy consumption metric reflects the energy consumption of the wireless network connection, measured in units of energy (Joules) per megabyte of data transferred. The most efficient WLAN cards have the least energy consumption per megabyte of data transferred, thereby providing the lowest battery drain.

The results in this paper show a difference of more than a factor of 15 between the best and worst energy consumption of the different WLAN and laptop configurations tested. The differences are due to the following factors:

- WLAN protocol: While incurring similar power consumption as 802.11b, high-rate protocols such as 802.11a and 802.11g enable the WLAN radio to be actively transmitting and receiving for a much shorter time because the data rate is much higher. Compared to 802.11b, 802.11a and 802.11g consume much less energy for a given workload, and thus contribute to the longevity of the battery.
- WLAN implementation: Different architectures, and hardware and software designs produce big differences in WLAN energy consumption. For example, on a Sony VAIO PCG Z1-AP1 laptop employing the new Pentium M processor, the Atheros multi-mode Mini PCI solution in 802.11b is more than twice as energy efficient as Intel's Centrino Mini PCI solution in 802.11b mode.
- Host CPU: Power-efficient processors such as the Transmeta Crusoe or Intel's Pentium M incur much smaller penalties for WLAN operation than do relatively power-hungry processors such as the Pentium 4.

The results are summarized in [Figure 1-1](#).

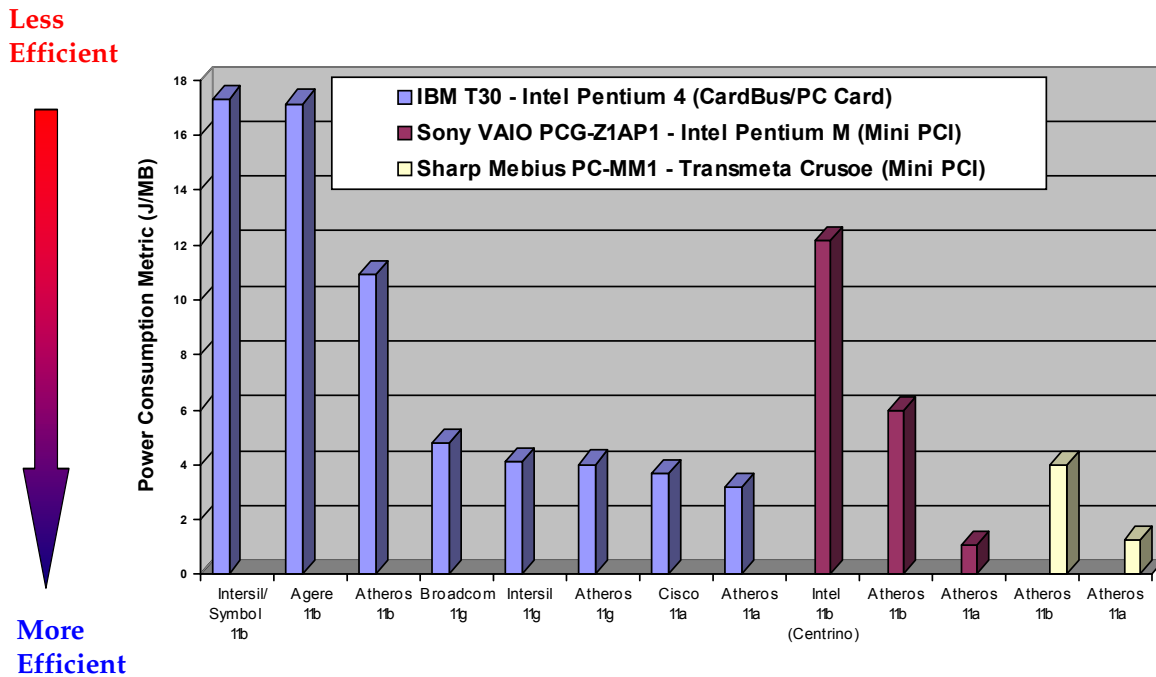


Figure 1-1. Comparison of Platform Energy Efficiency Among Various 802.11 WLAN Products

From [Figure 1-1](#), one can see that the most energy efficient 802.11b laptop is based on a Transmeta Crusoe CPU with an Atheros 802.11b solution. It is 3 times more energy efficient than the Intel Centrino 802.11b solution using a Pentium M processor. The Atheros multi-mode solution in 802.11b mode is twice as energy efficient as Intel Centrino 802.11b on the same Pentium M platform.

The most energy efficient WLAN solution is a Pentium M based laptop paired with an Atheros 802.11a solution, with Atheros 802.11a on Transmeta Crusoe a close second. On that very same laptop, the Atheros 802.11a solution is 11 times more energy efficient than the

Intel Centrino 802.11b solution and 16 times more energy efficient than an Intersil/Symbol 802.11b card on a Pentium 4 platform.¹

This paper describes the factors that affect WLAN platform power consumption and identifies the scenarios under which power consumption should be considered. Then, it provides a detailed methodology for measuring platform power consumption. It then proceeds to unify platform power consumption measurements and real-world usage scenarios to create an overall measure of energy efficiency. Finally, this paper summarizes the power consumption and energy efficiency of a variety of 802.11-enabled laptops.

Understanding Platform Power Consumption

A WLAN generally consists of one or more access points (APs) that connect to a wired network and remote client devices that connect to the AP through wireless links. These devices are usually laptop PCs with WLAN cards² installed. Since remote devices are usually mobile and often use battery power, while an AP is stationary and uses AC power, the topic of power consumption is focused on investigating the energy efficiency of a WLAN remote device.

The power consumption of the entire laptop PC platform is what ultimately determines battery life. Platform power consumption is the sum of a host of factors, including the power consumption of the CPU, memory, display, hard disk drive, I/O bus, and other peripherals.

When a WLAN card is added to the laptop, platform power consumption increases for two reasons:

1. The additional power consumed by the WLAN card itself.
2. The additional power consumed by the rest of the platform in supporting the WLAN card and the WLAN connection.

The first item is typically documented by the WLAN card manufacturer as the maximum power consumption of the card when it is receiving and transmitting. However, these numbers do not reflect typical usage (since the card is often idle or asleep). Moreover, the second item often represents more significant power consumption than the first.

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 2. A WLAN card is a Network Interface Card (NIC) that provides WLAN functionality. A WLAN card can come in various form factors, for example, PC Card or Mini PCI.

The goal of this paper is to consider the effect of the WLAN connection on the total power consumption of the laptop. This can be measured by comparing the difference (“delta”) between the total power consumption of the laptop without the WLAN card or connection (“baseline”) and the total power consumption of the laptop with the WLAN card and connection in various modes, such as idle or actively sending/receiving data.

Factors That Determine Platform Power Consumption

The following are factors that contribute to the platform power consumption due to WLAN operation:

1. **WLAN Card Design** - The physical design and specifications of the WLAN card, including board layout, chip design, transmit output power, voltage regulation efficiency and component selection, affect the power drawn by it. Even the form factor affects the design target for the power consumption of a WLAN card. For instance, the power consumption for the Mini PCI form factor must be less than 2 W. Thus, there will be a wide variation among WLAN implementations due to different chipsets, power amplifiers, voltage regulators, etc.
2. **Hardware (NIC/CPU) Interactions** - Besides the on-board power consumption from the WLAN card, power usage from interacting with the rest of the laptop platform hardware such as the host CPU, busses and memory must also be considered.

A WLAN card communicates with the host CPU by exchanging data on an interface bus. Architectures such as 16-bit PC Card use CPU driven I/O to send and receive data. That is, the host CPU must manually transfer each word of data to or from the WLAN card. This is CPU intensive and wasteful of energy since the CPU is usually much faster than the bus. Newer architectures such as CardBus PC Card support a scheme known as DMA (Direct Memory Access). DMA offloads memory transfer tasks to a separate controller, which allows the CPU to sleep during data transfer. This can dramatically reduce platform power.

3. **Software and Protocol Design** - Software implementation of the driver for the WLAN card is critical to conserving platform power. The following issues must be considered when determining the energy efficiency of the WLAN software:
 - **Power Management** - Since a wireless network is idle most of the time, it is not necessary to keep the WLAN card fully powered all the time. Software intelligence can be added to put the WLAN card hardware into a low-power “sleep” mode whenever possible while maintaining high data transfer performance.

To sustain network connectivity, the WLAN card must have power to listen for traffic, including beacons, periodically. However, the circuitry responsible for sending and receiving packets can be turned off or set to “sleep” when there is no traffic to send or receive. This can lead to considerable power savings. In fact, this is how power saving works in current WLAN cards. When power save is enabled, the WLAN card will follow a periodic “sleep-awake-sleep-awake” pattern to minimize the power drawn by the card.

When the WLAN card is sleeping, incoming packets will be buffered at the AP. Periodically, the card wakes up to listen to beacons from the AP, which the AP uses to tell the card if incoming traffic is queued. Once the card notices incoming traffic is available, it tells the AP to deliver the traffic. After that, the card goes to sleep again. The penalty for saving power via sleep is greater latency on the delivery of new incoming packets. Moreover, depending upon the implementation, if only a few packets are delivered before the card goes to sleep again, the data rates will be significantly reduced.

Thus, it is necessary to seek a balanced implementation that optimizes for both power efficiency and throughput performance.

- **Driver/CPU Interactions** - How the WLAN driver interacts with the PC operating system affects how much power the host CPU expends on WLAN-related activities. The power used by the host CPU in processing software events can aggregate to more than the power drawn by the actual WLAN card itself.

Registering the WLAN card with the underlying operating system and configuring the WLAN card are examples of one-time software events that occur during a user's WLAN session. Since these events are infrequent, they account for a negligible percentage of the final platform power consumption.

Before packets are transmitted and after packets are received by a WLAN device, they are processed by the host CPU running the driver software. This processing consumes additional platform power. Depending upon the implementation, encryption may be done in software. This requires substantial CPU computation, and thus additional power consumption, on every data packet. Hardware-based encryption implementations will be considerably more power efficient.

In addition, certain parts of the driver run at regular intervals to perform 802.11 tasks. It is in this case that optimized driver software can greatly reduce platform power consumption. Here are some of the software tasks that draw CPU power at regular intervals (depending upon the implementation, these might be done by the main CPU or an embedded CPU on the WLAN card itself):

- Physical Layer Management - Because the WLAN device is mobile, its physical surroundings will change from time to time. To maintain optimal performance at all times, the driver needs to periodically update various 802.11 PHY parameters to adapt to a changing environment. An example of one of these parameters is transmission data rate.
- Connection Services - To maintain association with an AP while being aware of the APs in the vicinity, the WLAN card performs regular, periodic beacon searches. Since the CPU must process the received data from the search, additional battery power is consumed periodically.
- Power Save Polling - Either the CPU tells the WLAN card to wake up periodically to listen for beacons and traffic or the WLAN card wakes up autonomously without involving the CPU. By using dedicated logic and low frequency clock counters, the latter implementation will be more platform-power efficient. When there is new outgoing traffic, the CPU will be involved to tell the WLAN card to wake up.

Figure 1-2 shows an example of the contributions to total platform power from various components mentioned above.

Composition of Total Platform Power

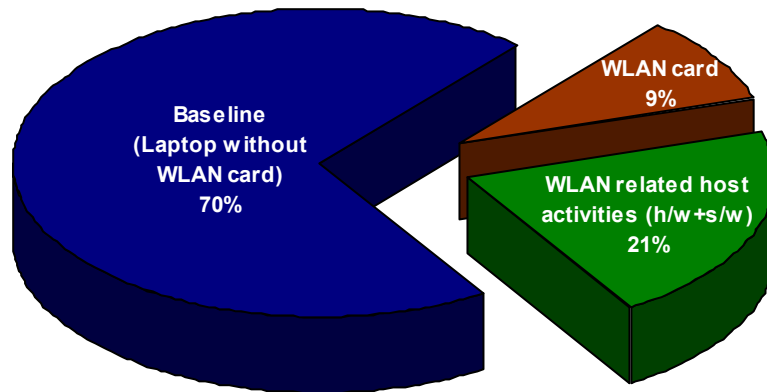


Figure 1-2. Total Platform Power - Typical Example

Measuring Platform Power Consumption

There are five physical states that the WLAN card can be in:

1. **Off.** The device is completely powered off.
2. **Sleep.** A majority of the circuitry is turned off, except for certain critical parts.
3. **Listen.** The radio is listening for traffic but is not passing any data to the host.
4. **Receive.** The WLAN card is detecting, demodulating and passing packets to the host.
5. **Transmit.** The WLAN card is modulating and sending packets onto the air.

Although the five physical states of the WLAN card are useful, conceptual tools, their individual power consumptions will not actually be measured. Instead, the focus should be on the actual usage scenarios, which abstract many of the lower-level details and are more relevant to the end user.

Actual usage scenarios are linear combinations (weighted averages) of the above physical states. That is, in the normal course of WLAN operation, the user will put the system into all of the above states at various times. The basic usage scenarios are:

- **Baseline:** there is no WLAN peripheral attached to the laptop. This is the same as the WLAN card always being **Off**. There should be no active computations or peripheral accesses in progress. The Windows³ Task Manager or similar utility can be used to monitor any unusual application or background task activity. Once it is determined that the laptop is in a steady state, the power consumption can be recorded.
- **Searching/Roaming:** the laptop is searching for an available network. The laptop is in this state if the WLAN card is enabled but cannot associate with an access point. After the initial failure to associate, the device actively scans the channels of all the supported bands once every preset interval. In this usage scenario, the card is not only in the **Listen** and **Receive** states on a periodic basis, but is also in the **Sleep** state some of the time.
- **Associated and Idle:** the laptop is associated with the access point but is not passing data. This is an important test scenario because laptops are in this state the majority of the time. There are two sub-categories to test:
 - *Power Save Off.* The WLAN card never enters **Sleep**. It is always in **Listen** unless it is actively receiving or transmitting.
 - *Power Save On*⁴. The WLAN card enters **Sleep** after a certain elapsed period of inactivity. It wakes up after a preset interval to check for traffic queued for it at the access point. It is thus briefly in the **Listen** and **Receive** states on a periodic basis, but is in the **Sleep** state the vast majority of the time.
- **TCP Uplink:** the laptop is actively transmitting data. The device is thus in **Transmit** most of the time. However, according to the 802.11 standard, it must listen for an acknowledgement packet (physical layer ACK) and listen to sense if the channel is busy immediately after sending each packet. This is true even when it is sending consecutive packets. Thus, the device might be in the **Transmit** state perhaps 60% of the time and in **Listen** and **Receive** the rest of the time.
- **TCP Downlink:** the laptop is actively receiving data. The device is thus in **Receive** most of the time. However, according to the 802.11 standard, it must transmit a physical layer ACK, listen to sense if the channel is busy immediately after receiving a packet, and also transmit TCP ACKs and receive their physical-layer ACKs. Thus the station will be mostly in the **Receive** and **Listen** states, and briefly be in the **Transmit** state.

Here is an example of the composition of the power consumption in the TCP Uplink scenario in terms of the WLAN physical states:

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3. Windows is a registered trademark of Microsoft Corporation.
 4. WLAN cards from different manufacturers have different definitions of "Power Save." Some cards even have multiple levels of power-save configurations. To ensure fair comparisons, for each WLAN card, its "Power Save ON" mode is defined as the configuration that achieves maximum power saving without degradation of throughput performance. In other words, this is the configuration that uses the least amount of energy per data transferred (Joules/MByte).

Given the following WLAN physical power consumption: Transmit = 2 W, Receive = 0.9 W, Listen = 0.8 W, Sleep = 40 mW,

$$\begin{aligned} &\text{TCP Uplink Power Consumption} \\ &= 0.6 \times \text{Transmit} + 0.2 \times \text{Listen} + 0.2 \times \text{Receive} + 0 \times \text{Sleep} \\ &= 0.6(2 \text{ W}) + 0.2(0.8 \text{ W}) + 0.2(0.9 \text{ W}) \\ &= 1.54 \text{ W} \end{aligned}$$

As shown in [Figure 1-2](#), the platform power consumption of the above usage scenarios includes not only the WLAN power consumption, but also the power consumption from the laptop (that is, Baseline scenario and WLAN related host activities). Thus, an example of platform power consumption for the TCP Uplink scenario is:

Given Baseline power consumption is 15 W and power consumption due to software and hardware activities related to the WLAN TCP Uplink operation is 2.85 W,

$$\begin{aligned} &\text{Platform Power Consumption} \\ &= \text{TCP Uplink Power Consumption} + \text{Baseline} + \text{Host Activities Power Consumption} \\ &= 1.54 \text{ W} + 15 \text{ W} + 2.85 \text{ W} \\ &= 19.4 \text{ W} \end{aligned}$$

Test Methodology

Power consumption is of concern to the users only when the laptop is battery powered. This performance measure becomes irrelevant for AC-powered systems. Since the underlying OS reports to the system how it is powered, the laptop's CPU and peripherals such as WLAN cards behave differently under different power conditions. Thus, to truly reflect WLAN platform power consumption when this performance measure is of relevance, the laptop under test must be powered by battery.

To record the instantaneous current draw of the laptop, the battery pack is physically removed from the system and wires are used to extend the electrical connections from the battery to the laptop. By monitoring the battery's voltage and recording the instantaneous current draw of the laptop, an instantaneous power consumption figure can be calculated. To log the current readings for post processing, a fast analog to digital converter is used to measure the voltage across a small series resistor. For these tests, a National Instruments PCI-6110E3 DAQ card was used with a precision metal-wound 0.1 Ohm series resistor. The resistor is connected in series with the ground (negative) side of the battery supply to reduce the common-mode signal measured by the DAQ card. The LabView environment was used to collect the data and write it to disk for post processing.⁵

5. National Instruments and LabView are trademarks of National Instruments Corporation.

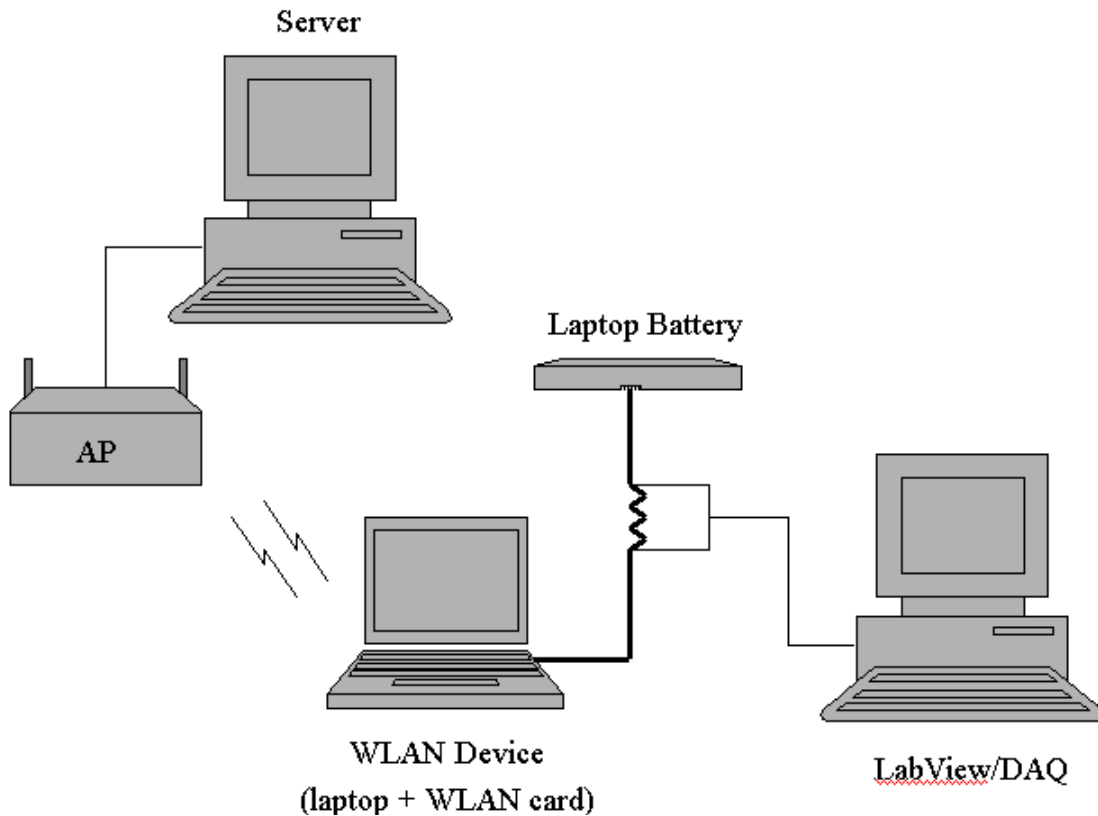


Figure 1-3. DAQ Setup with Differential Voltage Probe and LabView Data Collection Interface

The setup for testing platform power consumption of WLAN cards is depicted in [Figure 1-3](#). For each WLAN card the following steps are repeated:

1. Run one of the following basic usage scenarios for 60 seconds:

- Baseline
- Searching
- Associated and Idle

- Power Save OFF

- Power Save ON (repeat for each power saving mode)

- TCP Uplink
- TCP Downlink

The TCP Uplink and Downlink scenarios are run with Power Save ON.

2. Wait 30 seconds to up to a few minutes for startup transients to die out and for the laptop to reach steady state.

- Record data for 60 seconds, a period long enough that the average power of that period represents the average or typical usage. For example, when the WLAN module is associated and idle with power saving on, it goes through cycles of active and sleep. Consequently, the instantaneous power consumption shows periodic peaks, corresponding to the active period, as shown in Figure 1-4. The measurement should be done over a few complete cycles to get a more accurate average power consumption measurement.

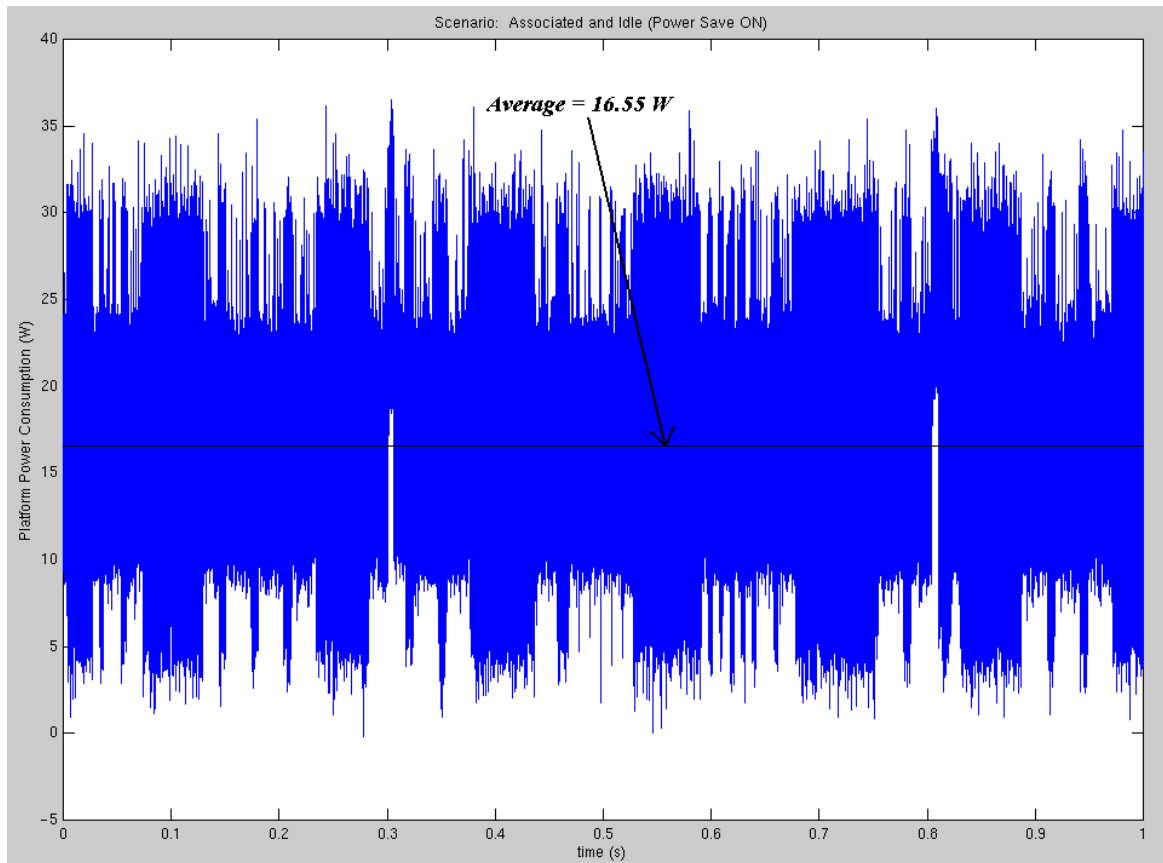


Figure 1-4. Example of Instantaneous Power Consumption Over a One Second Period

- Repeat steps 2-3 two more times to obtain a total of 3 sets of data for each state. The results of the 3 data sets are averaged.

Energy Consumption

The raw data should be imported into a program such as Excel or MATLAB, where measures such as the mean and standard deviation can be computed across the data sets. The result should be in a matrix⁶ such as this:

6. These are actual data based on the platform power consumption of IBM T30 + Atheros CardBus in 802.11a mode.

Table 1-1. Example Test Results Matrix

	Baseline	Searching	Associated and Idle (Power Save Off)	Associated and Idle (Power Save On)	TCP Downlink	TCP Uplink
Platform Power Consumption (Watts)	13.64	13.76	15.61	14.39	21.09	20.83
Delta Power Consumption Relative to Baseline (Watts)	—	0.13	1.97	0.75	7.45	7.19
TCP Throughput (Mbps)	—	—	—	—	23.04	23.28

The energy consumption performance metric should measure how energy efficient the WLAN system is at transferring data. That is, it measures how much of the battery is discharged to send a given amount of data. The unit of the metric is W/MByte/sec, or equivalently, Joules/MByte. The lower the metric, the more energy efficient the system is, and the longer the expected battery life is. It should also take into account the fact that a typical application usage scenario like Web surfing is a mix of the basic usage scenarios (idle most of the time, more downlink TCP traffic than uplink). Thus, the metric should be a weighted average of the power consumption when the system is idle and when the system is transferring data. An average scenario of 70% idle, 20% downlink TCP data and 10% uplink TCP data is assumed. Specifically, the metric is:

Performance Metric

$$= \frac{\text{Total Power Consumption}}{\text{Data Rate}}$$

$$= \frac{0.7 \times \text{Associated \& Idle Power} + 0.2 \times \text{TCP Downlink Power} + 0.1 \times \text{TCP Uplink Power}}{0.2 \times \text{TCP Downlink Throughput} + 0.1 \times \text{TCP Uplink Throughput}} \times \frac{8 \text{ bits}}{\text{byte}}$$

For the above system, the performance metric is:

$$\frac{0.7 \times 0.755 \text{ W} + 0.2 \times 7.454 \text{ W} + 0.1 \times 7.190 \text{ W}}{0.2 \times 23.04 \text{ Mbps} + 0.1 \times 23.28 \text{ Mbps}} \times \frac{8 \text{ bits}}{\text{byte}}$$

$$= 3.16 \text{ J/MB}$$

Test Setup

The Atheros AR5001X+ 802.11a/g/b chipset was used as a benchmark, to compare the energy efficiency of various 802.11a, 802.11g, and 802.11b products. Three sets of tests were performed, each on a different laptop platform. In test #1, an IBM T30 with 1.8 GHz Intel Pentium 4 processor running Windows XP was used as the platform. The following matrix of WLAN card/AP combinations were then tested for platform power consumption:

Table 1-2. Devices Under Test for Test #1

Mode	802.11a		
Access Point	Atheros Dual-Band Access Point		
WLAN Card	Atheros AR5001X+ CardBus Card	Cisco Aironet ⁷ 5 GHz CardBus Card	
Mode	802.11b		
Access Point	Atheros Dual-Band Access Point		
WLAN Card	Atheros AR5001X+ CardBus Card	Intersil/Symbol PC Card	Agere PC Card
Mode	Draft 802.11g		
Access Point	Atheros AR5001X+ Access Point	Broadcom Access Point	Intersil Access Point
WLAN Card	Atheros AR5001X+ CardBus Card	Broadcom PC Card	Intersil PC Card

For the 802.11a and 802.11b tests, an Atheros dual-band Access Point (AP) was used. This AP has been certified for interoperability by the Wi-Fi Alliance. Because the 802.11g standard has not been finalized, the 802.11g tests used APs and cards from the same vendor to avoid interoperability-related issues.

7. Aironet is a registered trademark of Cisco System, Inc. and/or its affiliates in the US and other countries.

In test #2, the Sony VAIO PCG-Z1AP1 with Intel Centrino technology (1.3 GHz Pentium M processor and Intel PRO/Wireless 802.11b Mini PCI card) running Windows XP was tested for its platform power consumption. The Intel Mini PCI card was then replaced with the Atheros AR5001X+ 802.11a/b/g Mini PCI card and its platform power consumption was measured.

In test #3, the Sharp Mebius PC-MM1 with a 1 GHz Transmeta Crusoe processor running Windows XP was used to test the platform power consumption of the Atheros AR5001X+ 802.11a/b/g Mini PCI card.

Results

The detailed test results are shown in Appendix A and are summarized in [Figure 1-5](#).

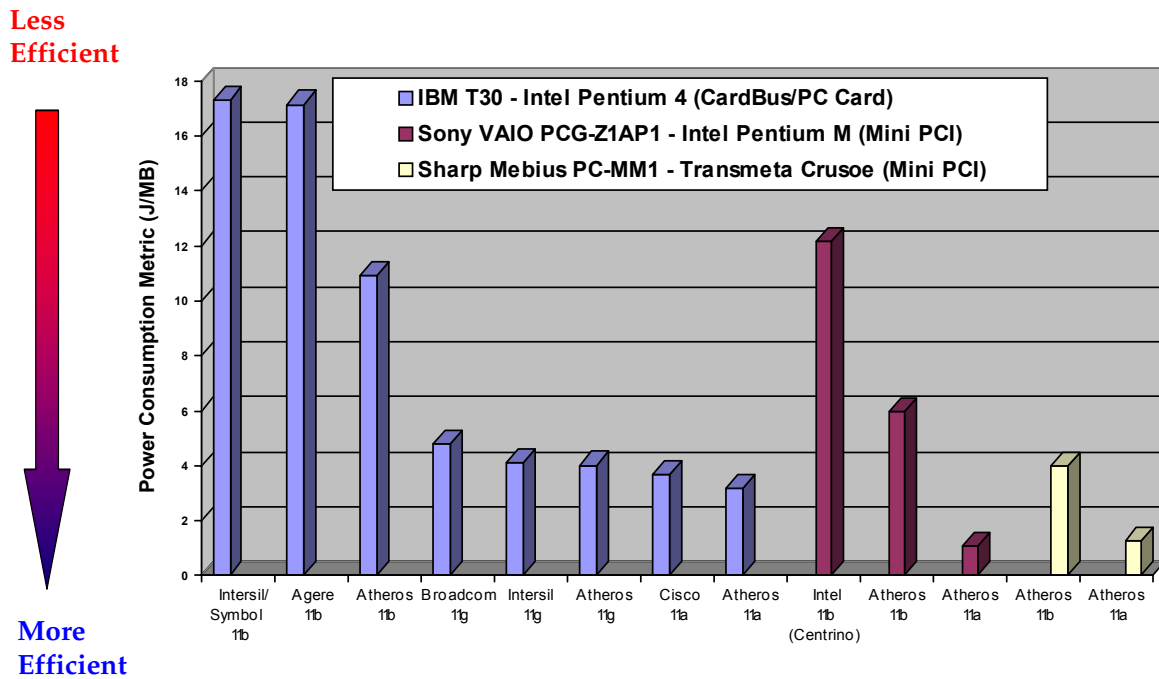


Figure 1-5. Comparison of Platform Energy Efficiency Among Various 802.11 WLAN Products (copy of Figure 1-1)

Architectural, algorithmic, and implementation decisions all affect system power consumption characteristics. Achieving good overall energy consumption metrics requires addressing power management at all these levels in the wireless LAN card design. Even when operating in the same mode, various cards differ in terms of energy efficiency by up to a factor of 2.2! This arises from several design factors, including the partition of responsibility between the WLAN card and its host CPU, the choice of memory interface, the design of radio and baseband digital signal processing and the implementation of sleep protocols. For instance, in 802.11b mode, since Atheros' WLAN card uses DMA, it is more than twice as energy efficient as cards that use CPU driven I/O. Another example is the

Sony VAIIO test case. The Intel Centrino (Pentium M and PRO/Wireless 2100) combination required more than twice the energy to transfer the same amount of data than the Intel Pentium M and Atheros 802.11b combination did.

The comparison between 802.11a, 802.11b, and 802.11g mode shows that a higher-performance wireless interface actually consumes the least amount of energy to transfer the same amount of data. The most energy efficient 802.11a CardBus PC Card is from Atheros and it is 5.5 times more efficient than the least energy efficient 802.11b card. 802.11a's inherent energy efficiency is even more pronounced on a platform using the low-power Crusoe or Pentium M processor. When operating in 802.11a mode, the Atheros AR5001X+ Mini PCI card can be as much as 11 times more efficient than the less energy efficient Centrino Intel PRO/Wireless 2100 802.11b Mini PCI card.

The 802.11g tests were done in 802.11g only mode, with no 802.11b devices present. Therefore the throughputs were similar to 802.11a. However, in most cases 802.11g devices will be used in networks with 802.11b devices, meaning 802.11g must use CTS or RTS/CTS protection. This reduces the maximum throughput to 14.4 Mbps (CTS protection) or 11.8 Mbps (RTS/CTS protection). This reduces the energy efficiency of 802.11g compared to 802.11a because the total power consumption is similar, but the throughput is lower. (See the paper "802.11 Wireless LAN Performance" at <http://www.atheros.com/pt/papers.html> for more details.)

Although the WLAN card platform power consumption due to "Searching" is not considered in the performance metric, it is still important to compare this quantity between WLAN cards (see "Appendix: Test Data" on page 16). "Searching" can be a significant component when the WLAN user is in a new environment, looking for access points to connect to. Once again, the results show that Atheros' WLAN card consumes very low platform power compared to the other retail cards. This is especially true when the card is operating in the high data rate 11a and 11g modes.

Conclusion

Power consumption is an important factor in evaluating WLAN products because of its impact on the battery life of a laptop. More important than isolating the physical power consumption of the WLAN device is quantifying the effect of WLAN operation upon the power consumption of the entire laptop platform. That measure captures the effect that WLAN operation has on the CPU, memory subsystem, and I/O bus power consumption and is therefore the true measure of the impact WLAN operation has on energy efficiency and thus battery life.

The results in this paper show more than a factor of 15 difference between the best and worst energy consumption of the different WLAN and laptop configurations tested. The differences are due to these main factors:

- WLAN protocol: While incurring similar power consumption as 802.11b, high-rate protocols such as 802.11a and 802.11g enable the WLAN radio to be actively transmitting and receiving for a much shorter time because the data rate is much higher. Compared to 802.11b, 802.11a and 802.11g consume much less energy for a given workload, and thus contribute to the longevity of the battery.

- WLAN implementation: Different architectures, and hardware and software designs produce big differences in WLAN energy consumption. For example, on a Sony VAIO PCG Z1-AP1 laptop employing the new Pentium M processor, the Atheros 802.11b solution is more than twice as energy efficient as Intel's Centrino 802.11b solution.
- Host CPU: Power-efficient processors such as the Transmeta Crusoe or Pentium M incur much smaller penalties for WLAN operation than do power-hungry processors such as the Pentium 4.

WLAN solutions based upon the Atheros AR5001 chipset family yield industry-leading energy efficiencies. In fact, in a head-to-head 802.11b comparison on a Pentium M laptop, the Atheros solution was more than twice as energy efficient as the Intel Centrino solution. On that same laptop, the Atheros multi-mode solution in 802.11a mode was more than 11 times more energy efficient than the Intel Centrino 802.11b solution.

For more information on the comparison between Atheros WLAN solutions and those based upon the Intel Centrino family of chips, visit the Atheros website at <http://www.atheros.com/pt/papers.html>, where the whitepaper entitled, "Centrino vs. Pentium M: The Battle for Wireless Notebooks" is posted.

Appendix: Test Data

This appendix contains the raw measurement data.

Test #1: IBM T30 (Intel Pentium 4) + Various PC WLAN Cards

Table 1-3, Table 1-4, and Table 1-5 show measurements for various PC WLAN cards in 802.11a, 802.11b, and 802.11g modes, running on a Pentium 4 laptop.

Table 1-3. PC WLAN Cards on a Pentium 4 Laptop in 802.11a Mode

	Atheros AR5001X+	Cisco Aironet 5 GHz
Baseline	14.00 W	
Searching		
Delta Power Consumption relative to Baseline	0.13 W	0.45 W
Associated and Idle		
Power Save Off: Delta Power Consumption relative to Baseline	1.97 W	1.59 W
Power Save On: Delta Power Consumption relative to Baseline	0.75 W	1.04 W
TCP Downlink		
Delta Power Consumption relative to Baseline	7.48 W	7.28 W
Throughput	23.0 Mbps	20.0 Mbps
TCP Uplink		
Delta Power Consumption relative to Baseline	7.19 W	6.96 W
Throughput	23.3 Mbps	22.3 Mbps
Performance Metric	3.16 J/MB	3.69 J/MB

Table 1-4. PC WLAN Cards on a Pentium 4 Laptop in 802.11b Mode

	Atheros AR5001X+	Agere	Intersil/Symbol
Baseline	14.00 W		
Searching			
Delta Power Consumption relative to Baseline	0.24 W	0.42 W	0.54 W
Associated and Idle			

Table 1-4. PC WLAN Cards on a Pentium 4 Laptop in 802.11b Mode (continued)

	Atheros AR5001X+	Agere	Intersil/Symbol
Power Save Off: Delta Power Consumption relative to Baseline	2.59 W	0.98 W	1.95 W
Power Save On: Delta Power Consumption relative to Baseline	0.87 W	0.14 W	0.46 W
TCP Downlink			
Delta Power Consumption relative to Baseline	5.85 W	10.58 W	8.84 W
Throughput	5.9 Mbps	4.9 Mbps	3.6 Mbps
TCP Uplink			
Delta Power Consumption relative to Baseline	6.15 W	9.37 W	7.42 W
Throughput	5.9 Mbps	4.9 Mbps	3.6 Mbps
Performance Metric	10.84 J/MB	17.14 J/MB	17.28 J/MB

Table 1-5. PC WLAN Cards on a Pentium 4 Laptop in 802.11g-Only Mode

	Atheros AR5001X+	Intersil	Broadcom
Baseline	14.00 W		
Searching			
Delta Power Consumption relative to Baseline	0.33 W	1.29 W	2.63 W
Associated and Idle			
Power Save Off: Delta Power Consumption relative to Baseline	2.56 W	2.02 W	1.81 W
Power Save On: Delta Power Consumption relative to Baseline	0.92 W	1.32 W	1.78 W
TCP Downlink			
Delta Power Consumption relative to Baseline	8.45 W	7.15 W	7.46 W
Throughput	21.0 Mbps	19.0 Mbps	18.4 Mbps
TCP Uplink			
Delta Power Consumption relative to Baseline	8.36 W	6.01 W	6.75 W

Table 1-5. PC WLAN Cards on a Pentium 4 Laptop in 802.11g-Only Mode (continued)

	Atheros AR5001X+	Intersil	Broadcom
Throughput	21.0 Mbps	19.3 Mbps	20.2 Mbps
Performance Metric	4.02 J/MB	4.12 J/MB	4.79 J/MB

Test #2: Sony VAIO PCG-Z1AP1 (Intel Pentium M) + Various Mini PCI WLAN Cards

Table 1-6 shows measurements for various Mini PCI WLAN cards in 802.11a and 802.11b modes, running on a Pentium M laptop.

Table 1-6. Mini PCI WLAN Cards on a Pentium M Laptop

	Atheros AR5001X+ 802.11a	Atheros AR5001X+ 802.11b	Intel PRO/Wireless 2100 (Centrino) 802.11b
Baseline	9.01 W		
Searching			
Delta Power Consumption relative to Baseline	0.44 W	1.24 W	0.78 W
Associated and Idle			
Power Save Off: Delta Power Consumption relative to Baseline	1.14 W	1.72 W	1.82 W
Power Save On: Delta Power Consumption relative to Baseline	0.19 W	0.71 W	0.91 W
TCP Downlink			
Delta Power Consumption relative to Baseline	2.60 W	2.77 W	3.50 W
Throughput	22.0 Mbps	5.8 Mbps	4.3 Mbps
TCP Uplink			
Delta Power Consumption relative to Baseline	2.61 W	2.45 W	3.35 W
Throughput	22.7 Mbps	5.9 Mbps	4.7 Mbps
Performance Metric	1.09 J/MB	5.97 J/MB	12.18 J/MB

Test #3: Sharp Mebius PC-MM1 (Transmeta Crusoe) + Atheros Multi-mode Mini PCI WLAN Card

Table 1-7 shows measurements for various Mini PCI WLAN cards in 802.11a and 802.11b modes, running on a Transmeta Crusoe laptop.

Table 1-7. Mini PCI WLAN Cards on a Transmeta Crusoe Laptop

	Atheros AR5001X+ 802.11a	Atheros AR5001X+ 802.11b
Baseline	8.72 W	
Searching		
Delta Power Consumption relative to Baseline	0.19 W	0.28 W
Associated and Idle		
Power Save Off: Delta Power Consumption relative to Baseline	1.55 W	1.50 W
Power Save On: Delta Power Consumption relative to Baseline	0.41 W	0.39 W
TCP Downlink		
Delta Power Consumption relative to Baseline	2.48 W	1.98 W
Throughput	22.4 Mbps	5.9 Mbps
TCP Uplink		
Delta Power Consumption relative to Baseline	2.66 W	2.07 W
Throughput	23.0 Mbps	5.9 Mbps
Performance Metric	1.24 J/MB	3.98 J/MB

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