

# Power Consumption and Conservation in WiFi Based Phones: A Measurement-Based Study

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**Abstract**— WiFi based phones are becoming increasingly popular due to the ubiquitous presence of wireless LANs and the use of unlicensed spectrum. These phones use VoIP techniques over wireless LANs. In addition to the spectral efficiency and security issues, power consumption is a vital issue in making the usage of these phones widespread. Efforts are underway in improving power conservation in these phones and thus increasing the duration between recharging the battery. This paper provides a detailed anatomy of the power consumption by various components of WiFi-based phones. Through a measurement-based study of WiFi-based phones, we have analyzed the power consumption for various workloads at various components. The impacts of scan operations and related issues in the power consumption on WiFi phones are quantified through actual measurements. Several inferences and derived guidelines are provided for improving the power conservation approaches in WiFi-based phones from the first of its kind experimental study.

**Index Terms**— Power Consumption, Power Conservation, Voice over IP (VoIP), Voice over WiFi (VoWiFi), WiFi Phones.

## I. INTRODUCTION

WiFi is designed to support mobility and hence is used extensively in cellular, laptop and handheld devices like PDAs. Recently WiFi has been integrated with VoIP phone technology in the form of WiFi based phones. The phone converts the dialed number into data packets that are transmitted over radio waves to a wireless access point or other such wireless receivers, as shown in Fig. 1. Voice is transmitted as data packets like in Voice over Internet Protocol (VoIP) schemes. The specific protocols are usually variants of the Session Initiation Protocol (SIP). VoIP refers to a system of protocols, software and hardware that enable the transmission of voice traffic over packet switched data network instead of circuit switched public switched telephone network (PSTN).

SIP or other proprietary variants are used for signaling the creation, maintenance, and tear down process of a call session. Real Time Protocol (RTP) is used for voice traffic and the RTP packets are sent over UDP. The main characteristics of VoIP applications can thus be summarized as:

- VoIP applications do not require high throughput but cannot tolerate jitter. They are very sensitive to delays that can directly affect the voice quality.
- Voice requires quality of service in terms of low latency and jitter, low packet loss and high availability. On the other hand, most of the power save mechanisms trade off with the latency and availability.
- VoIP wireless phones require support for seamless roaming capabilities to enable user mobility.
- Security in terms of prevention of denial of service attacks and eavesdropping is a must for the wireless media. Power consumption depends on the complexity of the algorithms.
- VoIP is an isochronous traffic stream with a packetization rate of 20ms (G.711 codec).

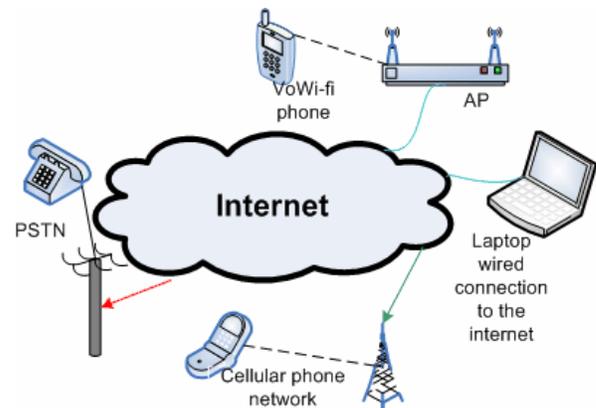


Figure 1: Voice over Internet Protocol

WiFi phones are showing a promising trend. However, with the deployment and use of these devices several issues have surfaced that have to be addressed in order to sustain growth of these devices in the market. The primary issues include capacity, security, quality, and power. The purpose of this paper is to study the power consumption characteristics of various aspects and components of WiFi phones. Phones with low battery life defeat the mobility functionality. Hence it is important to minimize the power consumption while still maintaining the required quality of service.

The measurement-based study presented here provides a detailed anatomy of power consumption in WiFi phones that can be exploited in designing schemes for extending the lifetime (between recharges) of these phones. Experimental evaluation using real VoIP WiFi phones are used for validating our study and the proposed enhancements. To the best of our knowledge, this is the first such study reported in the literature.

The rest of the paper is organized as follows. Basics of VoIP phones are outlined in Section II. In Section III, power conservation issues in WiFi phones are detailed. The measurement results are discussed in Section IV, followed by inferences in Section V. The related works and the concluding remarks are presented in Sections VI and VII, respectively.

## II. VOIP PHONES

VoIP application can be implemented over WiFi (IEEE802.11) and WiMax (IEEE 802.16) networks in infrastructure mode or multihop mesh mode. A WiFi VoIP (VoWiFi) phone is similar in structure to a cell phone and consists of the following basic components: processor, speaker, microphone, numeric keypad and function keys, lithium ion battery, screen (LCD), antenna and memory. The WiFi VoIP phones use a different radio frequency than the cell phone.

The chief advantages of these phones are:

- **Low Cost:** The network is less expensive to install and maintain. Calls can be placed across the world practically free as compared to usual landline or cell phone services.
- At the enterprise level, the person need not be tied to the desk to receive calls. Allows the flexibility to roam while maintaining the low cost. This is especially useful in the enterprise environments like the healthcare industry where the doctors and caregivers are constantly on the move in the hospital.
- VoIP offers more convergence with existing data centric technologies.
- Provides coverage where there may be poor or unavailable cell coverage.

Many VoWiFi phones meant for use at the home environment use a specific WiFi service or network. For example, UTStarcom makes a WiFi phone for Vonage service. To use such phones one must have an account with that provider. Other phones work with a protocol rather than a particular network or provider. For example ZyXel makes WiFi phones that use Session Initiation Protocol (SIP) which is an open source protocol. It is also used by VoIP providers that maintain a closed network.

At the enterprise level, the phones are deployed in companies and places where there is dense coverage of wireless access points, for example health care, university campus, organizations etc. WiFi phones may also be implemented as softphones on a handheld device. Some of the existing softphones are by Skype, MyJabber, EyeBean and FreePP. There exist a multitude of WiFi VoIP phones: F1000, F1000G, F3000 by UTSTARCOM, Hitachi-Cable Wireless IPC-5000 WiFi SIP VoIP 802.11b phone, Prestige 2000W 802.11b phone by ZyXel, CWP100 802.11b WIFI WLAN SIP Phone by ClipComm, BV3100 by FreePP, Linksys, Spectralink and GemTek WiFi phones. Most of these phones are meant for the home environment. The power efficiencies of these phones are listed in terms of talk/standby time per recharge in Table I.

Table I: Power efficiency in hours.

Phone	Prestige 2000W	Wireless IPC- 5000	CWP100 802.11b	BV3100	F3000
Talk Time	4	3	4	3	3
Standby/ Idle time	24	55	30	40	75

## III. POWER CONSERVATION ISSUES IN WIFI PHONES

WiFi phones are required to be of small form factor for portability thus limiting the battery size. Further, battery technology is not improving at the same pace as the power requirements of the devices. Hence the devices have to be power efficient to increase their operational lifetime. With phones, availability is an almost mandatory feature. Hence the phone must have talk and standby times comparable to cell phones. In the soft phones, when the WiFi capability is turned on, the battery only lasts for approximately 1.5 hours. Battery lifetimes are higher for WiFi phones, and are shown in Table I.

The standby times advertised are usually measured in optimal conditions of practically no-noise environment, with good signal strength and no roaming or scanning. In reality there is movement causing roaming and high noise inherent with wireless technology. Intra-WLAN roaming from AP (Access Point)-to-AP is responsible for poor battery life. Much of the battery-life problem is related to how clients roam in today's WLANs. Point to point roaming puts a heavy burden on the client, since it's up to the client to scan the network and determine where to go next, consuming a lot of power.

Various hardware and software techniques have been proposed to reduce power consumption of mobile wireless devices [6]. Hardware solutions have focused on the development of high capacity batteries, low power CPUs and power modulation techniques. Software solutions, on the other hand, have been used

for low power displays (using BIOS or screen savers), spinning down the hard disk or stopping the CPU depending on the work load.

Our research explores the various energy conserving techniques used for making wireless communications power efficient across the physical, MAC, network, transport and application layers.

### A. Elements of Power Consumption

The power consumed by a communicating device can be factored into following elements [8], [15], [16]:

*Transmission*: This accounts for the energy spent in data packet transmission.

*Reception*: This accounts for the energy spent by a node in data reception.

*Idle listening*: Refers to the power consumed when the radio of the node is waiting to receive potential packets but the media is idle.

*Overhearing*: Refers to the power used by a node when it is receiving packets on the media meant for another destination.

*Control Overhead*: This factor accounts for the power used to send and receive control packets.

*Reliability [8]*: This element pertains to energy consumed in meeting the protocol reliability requirement, i.e., data retransmissions because of lossy media, collisions and mobility.

*Turnaround time [16]*: This is the time required to switch modes from transmit to receive and vice versa.

Different power saving techniques strive to minimize the energy consumed by combinations of these factors.

### B. Power Saving Techniques

#### 1) Transmission Power Control [3]

Transmission power has a strong impact on the capacity, connectivity, bit error rate and inter-radio interference. High transmission power increases the network connectivity. It decreases the signaling overhead needed for route maintenance in high mobility. High power transmission, however, generates interference on the shared radio media that reduces network capacity by limiting transmissions from other potential operators. On the other hand low power transmission reduces interference but generates high signaling overhead. Transmission power control is most useful in dense networks for efficient media usage while minimizing interference.

-*Physical Layer*: At the physical layer, transmission power control (TPC) is achieved by:

- Using directional antennas [19],
- Tuning for low power transmission [4].

- Adaptively modifying the bit rate per frame in Code Division Multiple access (CDMA) based devices depending on the load in the frame [11].
- Using antenna diversity.
- *MAC layer*: TPC in the MAC layer is achieved by:
  - Controlling the frame length (rate change),
  - Reducing the number of retransmissions by choosing a different channel/link.
  - Varying the transmission power based on the distance required to the destination instead of using the maximum power level [10] [2].
- *Network Layer*: Network layer uses topology control [17], allowing each wireless device to adjust its transmission range and select its appropriate neighbor. Every node can shrink its transmission range sufficiently while maintaining connectivity with its farthest selected neighbor..
- *Application Layer*: Application layer can reduce the number and size of transmissions by using data compression and aggregation techniques [5].

#### 2) Reduced Control Overhead

Reducing the number of control messages without incurring substantial loss in link quality or accessibility can improve power efficiency. The number of control messages can be reduced both by reducing the control signaling for one handshake and the control packet flooding/partial flooding in the network.

*MAC Layer*: Control overhead can be reduced at the MAC layer by using the following schemes:

- Using a Time Division Multiple Access (TDMA) scheme would reduce the signaling to a minimal. However TDMA is not an optimal approach for highly mobile devices.
- MARCH [20] reduces the control overhead by using one RTS and multiple CTS messages, instead of multiple RTS and CTS messages.

*Network Layer*: At the Network layer, the number of control messages transmitted can be reduced by using direction-aware or location-aware routing.

#### 3) Sleep Awake Mechanism

An 802.11 WaveLAN card consumes 1.65W, 1.4W, 1.15W and 0.045W in transmit, receive, idle and sleep states respectively [1]. Hence maximum power is saved when a device is in sleep mode. It is, therefore, desirable that a wireless device, when not actively communicating, remains in sleep mode also called the Power Save (PS) mode. The challenge lies in estimating when the other devices may have data to send to it and waking up at the right time. If the estimate is poor then it will cause delay, jitter, buffer overflows and loss of power on other devices continuously trying to reach it.

- *Physical Layer*: The ideal way to implement a wakeup mechanism would be to allow any remote device to wake up the node if it wants to send data to the node. This can be implemented using a special circuit called Remote Activated Switch. Chiasserini et al in [4] describe how a device may go to sleep in stages with varying amount of time spent in each stage depending on the delay requirements.

- *MAC Layer*: The power save mode is implemented in the MAC layer and hence this is the prime target to optimize the mode.

- HIPERLAN allows nodes called p-savers to sleep for any length of time. They inform other nodes called p-supporters of this period of time so that p-supporters can buffer packets destined for them. A p-saver can be associated with more than one p-supporter[7]. The p-supporters are assumed to have more power at their disposal, much like base stations.
- 802.11 supports power save mode though only in single hop scenarios. The different modes that 802.11 standard uses for power save are PS bit (Legacy 6), PS Poll (Legacy 5) [23] and WMM Power Save (WiFi Multimedia)/UPSD (Unscheduled Power Save Delivery) [22].
- Tseng et al in [3] describe three different 802.11 based schemes depending upon mobility level: dominating awake, periodically-fully awake and quorum based.
- PAMAS [18] uses two channels; one for data and the other for control. Nodes that hear RTS/CTS in the neighborhood cannot initiate any transmission or receive any packets and switch to power save mode. This protocol is applicable in low load highly connected networks where otherwise nodes would spend a lot of time in idle listening and/or overhearing.

- *Network Layer*: One example of sleep-awake mechanism in network layer is the pulse protocol [9]. A reservation message is sent to the base station, reserving all the nodes on the path to the base station during the periodic pulse period by the nodes that want to transmit. The reserved nodes remain awake for the duration of time the transmission has to take place, while other nodes can go to sleep. Two protocols, the Basic Energy-Conserving Algorithm (BECA) and the Adaptive Fidelity Energy-Conserving Algorithm (AFECA), use an "adaptation" strategy [14] for optimizing sleep cycles in ad hoc networks. BECA keeps the radios of the nodes asleep unless they are required for transmitting or forwarding data. AFECA balances the load on the network adaptively using the information on the density of the network in order to fine tune the sleep cycle.

*Application Layer*: Kravets et al in [5] demonstrate that an application/application mix can send power save information to the MAC layer asking it to power down the communication device for a specified amount of time as it does not expect to receive any communication in that time. In this approach the base station is treated as a slave and the node is the master. The base station buffers packets for the node until the node wakes up and asks for it.

#### IV. ANATOMY AND MEASUREMENTS

As discussed in section III, power save mode or doze state is the most effective way to save power. It is thus desirable that the VoWiFi phone stays in this state as long as possible without degradation in its functionality and quality of service. The time spent in doze state can be increased by minimizing the frequency of the wakeups and reducing the wake up period. In the following subsections we study the characteristics of a representative set of VoWiFi devices and vary parameters that affect the frequency of wakeups and the wakeup period.

##### A. Scanning and Roaming

1) *Discovery and Pre-emptive Scans*: In VoWiFi devices, apart from the data transmission and the signaling overhead of call control, scanning, roaming and authentication contribute to a significant percentage of the total device power consumption. Channel scanning is performed to enable seamless roaming from one AP to another to enable user mobility or adapt to changing network conditions. Roaming can be performed at layer 2 or layer 3 of the OSI model depending on whether the client roams from an AP to another one within the same IP subnet or to a different IP subnet. In this paper, we focus on roaming within the same IP subnet, that is, layer 2 roaming. Layer 3 roaming can be implemented using Mobile IP or incorporated in SIP. Roaming occurs when the phone disassociates with the current AP and associates with another one. This could happen because of user movement, high noise, AP malfunction or other network conditions. A roaming decision can then be made based on the configurable criteria (a) missed beacons, (b) low signal strength (RSSI), (c) high load (d) packet loss and (e) loss of connectivity. To enable seamless roaming a VoIP device periodically scans to find other candidate APs on the same or other channels in the network that meet the user security and SSID criteria. Two types of scanning are generally described:

- *Active Scanning*: Send a probe request and receive probe response from APs on that channel.

- *Passive Scanning*: Wait on a channel to receive the beacon(s) from the AP(s).

Passive scanning causes the device to be awake longer as it waits on the channel for receiving the beacon which is sent out typically 10 times a second. This aspect adds to the receiver overhead and dissipates energy. On the other hand active scanning requires the transmission of probe requests and adds to the transmit overhead which uses more power than reception. Real time application like VoIP, require that latency and delay be minimized and typically perform active scanning. Scanning is a significant source of power consumption in these mobile devices.

Another way in which scanning is categorized is *immediate scans* for network discovery and *pre-emptive periodic scans* for maintenance. Discovery scan is a series of scans on all channels to discover all enabled APs in the network. When the phone first boots up it would typically perform a discovery scan, to enumerate all the APs and select the best one to connect to. Alternatively, it could also associate to the first suitable AP it finds and subsequently roam to better ones as they are discovered. This approach could incur lower latency in getting the phone on the network but higher power consumption if the number of roams is high. Pre-emptive periodic scans are single channel scans performed in anticipation of connection loss. The scan process could take up to 50ms depending on the radio and other hardware and software characteristics. If the device scans all channels on disconnection for a qualified AP to connect to, it could take a long time. Hence most VoIP handsets perform pre-emptive periodic scanning. These devices periodically scan and keep updated lists of available APs to roam to.

As a scan requires the device to tune to a different channel, it could result in data loss from the AP it is associated to. This situation is resolved by taking advantage of the power save schemes. The device signals to the AP that it is switching to power save mode, but it actually scans a different channel while the AP buffers packets for it. This means that the device is actually using power and hence optimization algorithms for scanning are required to decrease this overhead without sacrificing user experience.

2) *Adaptive Scanning Algorithm*: We developed an adaptive scanning algorithm that minimizes the scanning requirement without significantly affecting the delay in network discovery and the roaming process. The adaptive scanning algorithm reduces scanning frequency based on network availability and the amount of time the device remains in the disconnected or idle state. We determine when the device is in inactive state and depending on how long the it has been in this state,

adaptively increase the scanning period to a preconfigured threshold that should ideally be determined by usability studies. The amount of time that a device remains in a particular state can be monitored using counters. At increasing counter values, the scan periodicity is decreased. Time is measured in multiples of TIM periods (beacon period). This duration and frequency of sleep period increases if there is no communication activity until the wake up period reaches a configurable specified time.

For our experiment we used a development platform with baseband PRISM2 chipset and a proprietary MAC. This is an 802.11b device that provides voice communications. The network topology used is shown in Fig 2. The device is associated to an AP that is connected to a switch. The switch is connected to the call processor, DHCP server, other APs and a wireline VoIP phone. The set up could also include an Access Control Server (ACS). However, we use open authentication mode for simplicity.

Similar to most VoWiFi devices, this device also operates in infrastructure mode and uses a lithium ion battery. Typically the Lithium ion battery has a very good shelf life, is lighter than alkaline battery and performs well under heavy loads. The battery comes in different capacities ranging from 1300mAh to 2400mAh. We used 1560mAh for testing the algorithm. During the sleep period the AP continues to buffer packets for the sleeping client.

We distinguished the idle condition from the out of network condition. A device is in idle state if it is associated to an AP and connected to the network but not making or receiving any calls. A device is in out of network state if it has no network connectivity and hence would be unable to make or receive any calls. We implemented the adaptive scanning algorithm in the out of network mode since that has the least impact on its usability.

We determined the loss of connectivity by lack of response to a probe sent on all channels within a time out period. After waiting for another minute the device is assumed to be in the out of network state. Given the lossy nature of the wireless media we allow another full scan of all the channels in that band (b/g). Once the scan completes without finding an AP to connect to the device will issue scans in an arithmetic progression. We start with two second scans. One channel will be scanned every two seconds. When all the channels in the band have been scanned we change the scan periodicity to every 4 seconds and then 6 seconds up to a threshold limit beyond which user experience of network discovery could suffer. For experimental purposes we used a threshold of 10 seconds. The time taken to reach the 10 seconds threshold in the b/g band is 220 seconds.

An exponential algorithm would have been faster (154s) and fewer scans. However, a slower algorithm was chosen to address corner cases when there is transient loss in connectivity.

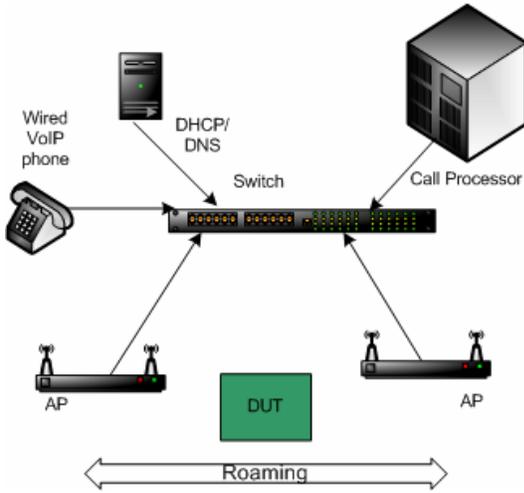


Figure 2. VoWiFi Test Setup

On gaining connectivity or on user action, the algorithm reverts back to the base periodicity. Earlier the out of range battery time was 11 hours. Our algorithm increased it 17-18 hours depending on the battery variance. This is on an average more than 60% improvement. The idle time was about 15 hours and we got about 20% improvements there. We found that if we turned off scanning altogether we got a battery life of about 19 hours. Hence this algorithm is close to optimal. This algorithm would require fine tuning of the back off factor based on the device it is to be implemented on. The idea, though, is generic and can be applied to any wireless VoIP device. Note that currently there are better chipsets than the PRISM2 and the algorithm may have a better result with those. The current drawn in the idle state was measured to be 84.5 mA and in the out of range state was 73.6 mA, which would translate to a battery life of 18 and 21 hours, respectively. For this device during a scan the current drawn is approximately 335 mA. We also determined that most of the other tasks were in low power mode when the device was in idle state using a logic analyzer. This required checking that the DSP, CODEC, USB, keypad and serial drivers were in low power state in idle mode and the LCD refresh rate was minimal. In fact, lowering the clock of the serial device helped us get 5% more power savings on the base power consumption of the device. The contribution of these tasks to the overall power consumption is minimal.

For the following measurements (subsections B-G) we used a different device. We used a TI chipset on the development platform. We did not have access to the

proprietary code, however we could measure certain parameters as described.

### B. Beacon Receive Period

We varied the value of the time that the phone wakes up before an expected beacon. We obtained the current drawn values using an Agilent 66321D power meter. The test setup is shown in Fig 3.

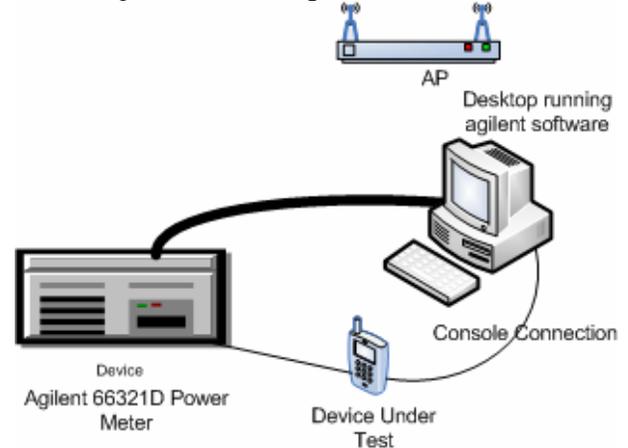


Figure 3. Test setup to measure power consumption

We connected the device to the power meter that is also connected to the laptop. We use a software application to control the power meter settings such as voltage, current, sampling rate. The sample rate is set to 10 ms and the voltage to the maximum capacity on the battery. The current drawn values are averaged over 10 minutes. This newer chipset supports both b and g modes. The signal strength is high and dynamic transmit power control is enabled. The device is set up to use PS Poll, and is connected to the network but not making or receiving a call.

The measured results of this study are depicted in Fig 4. Note that this is the power consumed by the device as a whole including the other processes that may be running, although the LCD is kept off since that consumes about 65mA. This is similar to most cell phones behavior in which the display is turned off after a time out period when the phone is idle. Here, we are more concerned with the comparison of the numbers. If the period is too small then the power consumption is much higher since the device misses many beacons and thus stays awake to receive the next one. The power consumption then goes down as the period increases as the device misses fewer beacons. It again rises since the phone remains awake for longer than necessary.

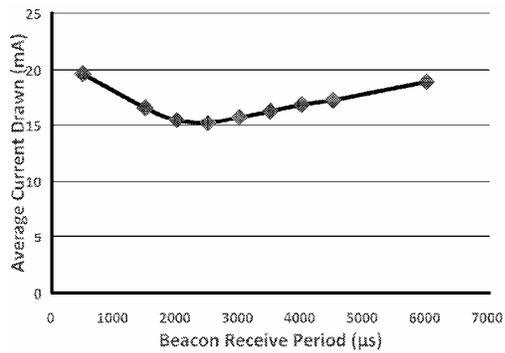


Figure 4. Power Consumption at varying beacon receive period

### C. Out of Network Scan periodicity

When the phone detects it is in out of network state, it is energy efficient to scale out the scan periodicity. We tried different scan periods in this state in b/g mode. The measurements results are illustrated in Fig. 5. The current drawn decreases with the increase in the scan period and the gains stabilize after a certain period.

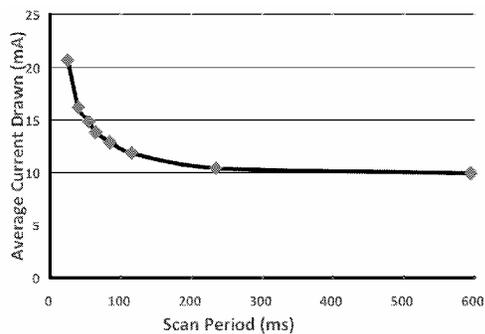


Figure 5. Power Consumption with varying scan period.

### D. Varying the DTIM period on the AP

A VoWiFi device would wake up at every DTIM (Delivery Traffic Indication Map) period (multiple of beacon period; usually 100ms) to check for any broadcast or multicast traffic. We varied the DTIM period and studied its effect on the power consumption. The device was in standby state, i.e., connected to the network but not making a call. The signal strength was high with an RSSI of about -35 dBm. The AP and the device were transmitting at 20mW with dynamic transmit power control enabled. The LCD was off and the device was configured for b/g with PsPoll enabled.

The results are depicted in Fig. 6. Increasing the DTIM reduces the power consumed but the gains diminish as the period increases. In this case we observe that the maximum savings can be achieved with a DTIM of 10. More traffic is buffered at the AP causing higher contention and making the device stay awake for longer period of time to download all the packets. We believe at higher traffic the gains will taper off at a higher rate and

may infact be reversed at some point. It would be useful to find the cut off in high, moderate and low traffic scenarios and determine an appropriate DTIM period to use. For our study (Subsections B-F) we have used a DTIM of 2 and have carried out the experiments in an environment of negligible interference. At DTIM intervals we saw the power consumption of the device shoot to 237mA.

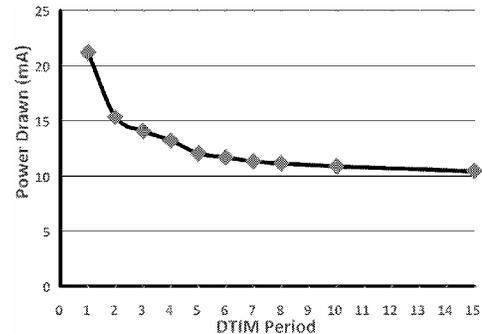


Figure 6. Power Consumption at varying DTIM

### E. Changing device state and battery discharge.

We varied the device state to the *On Call*, *Standby* and *Out of network* mode and measured the power consumption at 4.2V and 3.7V. We also varied the signal strength. The device was in b/g mode using PSpoll, DTIM was set to 2 and dynamic power transmit control was enabled. The LCD on the device was turned off and there was only one AP that the device could associate to and it was on channel 1(2.412 GHz). The results we obtained are shown in Table 2.

As expected the power consumption is very high on call compared to that in standby mode. The numbers are lower in out of network stat as the scan period is decreased. At lower RSSI values the trend is the same but the numbers are much higher than at high signal strength. This behavior is attributed primarily to the increased retransmissions and secondly to the probability that the device is looking more aggressively to find a better AP to roam to. The power consumption is always higher at 3.7 V than at 4.2 V probably because the battery check operation is executed more frequently at this stage to be able to shut down the phone gracefully before the battery discharges.

A similar test in 802.11a (Table 3) was carried out with parallel results. However if we compare the numbers between 802.11a and 802.11b modes we find that the power drawn is slightly higher in 802.11b/g. This is not always reproducible and only happened in the tightly controlled environment when 802.11b data rates were being used. We attribute this to the difference in the preamble lengths of b and a/g modulation scheme. In 802.11b, the short preamble is 96 microseconds and long preamble is 192 microseconds. In 802.11a/g modulation

technique the preamble length is 20 microsecond. Hence the time a device remains awake for transmitting or receiving a packet in 802.11b mode is longer than 802.11a/g mode. The out of network numbers for a mode is higher than that of b/g mode since the number of channels to be scanned in a mode is much higher.

Table 2. Avg current drawn in different states (b/g).

802.11b/g	# of APs	Current Drawn on Call (mA)		Current Drawn in Standby (mA)		Current Drawn Out of Network (mA)	
Voltage		4.2V	3.7V	4.2V	3.7V	4.2V	3.7V
High RSSI (-35dBm to -50 dBm)	1	119.0	133.8	18.4	21.2	12.1	14.1
	2	116.3	128.7	18.4	20.9	11.2	14.1
Low Signal Strength (-65 to -77 dBm)	1	128.4	143.1	20.5	25.1	12.4	14.2
	2	123.5	136.8	18.9	23.4	11.7	13.0

Table 3. Avg. current drawn in different states (a).

802.11a	# of APs	Current Drawn on Call (mA)		Current Drawn in Standby (mA)		Current Drawn Out of Network (mA)	
Voltage		4.2V	3.7V	4.2V	3.7V	4.2V	3.7V
High RSSI (-35dBm to -50dBm)	1	117.4	129.9	16.2	18.6	12.4	16.1
	2	115.5	126.1	16.1	18.2	12.4	18.1
Low Signal Strength (-65 to -77 dBm)	1	119.3	132.0	24.0	26.7	12.4	16.1
	2	114.2	126.1	21.0	24.5	12.3	18.1

#### F. Increasing number of APs

We added one more AP to the setup in Fig. 3. In b-g mode the first AP to which the device was associated to was on channel 1 (2.412GHz) and in a mode it was on channel 44 (5.220Ghz). The second AP used channels 11(2.462Ghz) and 64(5.320Ghz) in b-g and a modes respectively. In both 802.11b/g and 802.11a modes, we observed that at low signal strengths or when the device was on call, if the second AP was turned on, the power consumption of the device decreased a little (Table 3 & Table 4). However, in standby mode at high signal strength there was no change in the power consumption. On further study we discovered that the gain is not always reproducible. The device at low signal strength or on call is constantly scanning channels to discover an alternate better AP to connect. In this scanning mode when the phone sends a probe request it receives a reply sooner when an AP was present and subsequently returns to doze state sooner as compared to the time it remains in active mode waiting for a reply before timing out when no other AP is present. At high signal strength (-30 dBm) and standby mode the device is probably not scanning and hence addition of another AP in the network does not make a difference. This behavior was observed in the sanitized environment of negligible interference. However, in a higher noise environment,

the probe response could be delayed or even lost so that the power gains would be reversed. Hence the dwell time during a scan could be further fine-tuned.

Table 4. Current draw comparison at different power save modes (b/g)

Mode	No Power save	PsPoll	UAPSD
Average Current Drawn (mA)	274	119	115.6
Estimated Hours of battery life	4.37	10.08	10.38

#### G. Active-PsPoll-UAPSD.

We compared the power consumption for the device on call in active mode, PsPoll mode and UAPSD mode. By active mode we mean that none of the power save modes are enabled. The device was configured to be in b-g mode and test was setup so that the device saw high signal strength. Our results are shown in Table 4. The number of hours of battery life is estimated assuming a 1400mAh battery. While PsPoll shows a substantial improvement over active mode, UAPSD has only an incremental improvement over PsPoll. However PsPoll can cause high latency and degradation in service when there is large data traffic or high number of active users as the contention at APs would increase causing the associated to devices to wait longer. This would also result in higher power consumption.

The approximate current drawn at lower RSSI (-70dBm) values with PsPoll enabled rose to 125mA while there was negligible impact when the phone was in active mode at lower RSSI values. We attribute this to higher retransmissions causing greater contention and hence the device staying up longer. We also compared the standby time power consumption for a phone in active mode and Ps-Poll modes to be able to quantify some base power consumption of the device with no power saving features at the wireless level. The average current drawn when the device is in standby mode with no power savings enabled was measured to be 214.6mA, while with PS-Poll enabled it was 18.5mA. This observation only serves to underline the importance of power saving modes. In 802.11a mode the device exhibits similar behavior.

Please note that the precise numbers are often not reproducible. Though the general trend remains the same but the actual figures can vary a little bit. This could be because of a temperature difference that affects the meter or the environmental interferences. Most of our tests for a particular subsection were performed on the same day under the same environment and test-bed in a shielded room with minimal radio interference, which was verified with a sniffer.

## V. INFERENCES

From our observations we determined that scanning algorithms have significant impact on the battery life of VoWiFi devices. Ideally, we believe that scan operation should not consume more than ten percent of the total power expenditure of the device. For the PRISM2 device we achieved close to 5% for the scanning at 10 seconds interval scan. However, the worst case for network discovery was on the higher side. Once the scanning algorithm cost is reduced to the 10 percent value it no longer remains a major factor in total power consumed. We would recommend adaptively increasing the scanning period in out of network as well as standby mode depending on the length of time the phone has been idle. Infact ideally the adaptive increase should be a function of the length of time the phone has been idle, residual battery and user behavior and priorities. Other possibilities pertaining to power save options are:

- *-Power save levels:* At increasing levels the device sleeps for longer amount of time and scans with decreased frequency. A maximum threshold could be specified based on usability study. A device switches back to an upper level if it detects gain in power.
- *-User priorities:* A user can specify priorities for each level in terms of aggressiveness in power saving versus higher availability. User input could be obtained at device configuration time or every time a new battery level is hit.
- *-User dependent Adaptive and Predictive:* Kravets et al in [5] mention that the “Effectiveness of power management strategy is dependent on usage pattern of the target of such strategies”. Hence the device can adaptively change its sleep period depending on the predicted and current communication activity on the device. We note that the probability that a device may be in use depends on the user schedule and pattern.

Most 802.11b deployments use the non-overlapping channels of 1, 6 and 11, often enabled in their network infrastructure. Hence a device may get onto the network faster if those channels are scanned at a higher priority than the others.

Although UAPSD did not provide much in power savings over PSpoll, it would decrease traffic on the APs and cause less contention thereby increasing the capacity. Verifying this would require extensive resources and is beyond the scope of this paper. However, we recommend enabling UAPSD in any enterprise level deployment of VoWiFi. As seen from our results enabling PSpoll can make a huge impact on battery performance of VoWiFi devices. However we

did not have the resources to study the effect of PSpoll in large user environment. There would probably be degradation in capacity and power efficiency if the number of active users is high or if data traffic is huge because of high contention.

## VI. RELATED WORK

The authors of [13] discuss power save mode in conjunction with 802.11 QoS for integration of 802.11e capabilities in mobile wireless devices for applications like VoIP. They mostly discuss power save using ps poll mechanism. The station can sleep for a multiple number of beacon periods wake up during the listen interval when it communicates with the AP. During the listen interval the station polls for data if it is buffered at the AP. This indication of data present is received from the TIM (Traffic Indication Map). The QoS and power saving are affected depending on the length of the beacon period and the number of beacons that the station sleeps for. Their results show that QoS are affected by PSM mode and beyond a certain number of stations associated to the same AP, PSM could result in high contention.

Banginwar and Gorbatov discuss an application aware power management scheme called Gibraltar for IEEE 802.11 [12]. They limit the delay introduced by the 802.11 PSM mode to achieve optimal power consumption. Gibraltar uses a prediction strategy based on the application mix and history of network accesses. Their results are however based on asynchronous data activities like e-mail and web browsing in laptops and PDAs and not fine-tuned to VoIP which is isochronous and jitter sensitive.

Jensen et al in [6] propose to use a motion detector in wireless mobile devices to determine movement and enable scanning. This would allow the device to stop scanning if there is no motion. However this approach does not take into account that there could be other causes for loss of connectivity apart from motion, like increased traffic on the AP as other users move towards it and associate or increased noise in the network. Another proposed approach is to have a radio hierarchy, such as using a Bluetooth radio which has low power consumption to do the scanning in idle mode when the WiFi radio can be completely turned off. Our proposed scheme is orthogonal to this as it optimizes the scanning algorithm and could be applied to the Bluetooth radio as well to save more power.

Vahdat et al [21] discuss a technique that obtains energy savings for multimedia applications by using a proxy server to shape the traffic. The authors also discuss possibility of dynamically changing the TIM period to reduce packet delay. Our approach is for real time voice traffic that is isochronous, cannot suffer high

delays of over 150 ms and does not consume high bandwidth.

## VII. CONCLUSION

The popularity of VoWiFi devices is increasing exponentially, primarily because of the low cost of deployment and use while providing flexibility and integration with existing data technologies. Battery life of these devices is a major hurdle in their mass adoption. We performed a measurement based study on power consumption characteristics of two such devices at the wireless MAC level. We explore various methods of increasing the time the device spends in this state without significantly affecting its functionality. This can be done by increasing doze time and decreasing the frequency of wakeups. In particular we recommend an adaptive scanning algorithm, a simplistic version of which resulted in considerable power savings. We also recommend prioritizing the scanning of different channels to further save on power consumption.

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