3. Approach

This document provides an in-depth analysis of design alternatives of various WiRAD subsystems. Selection amongst the presented hardware and software approaches was based upon consideration of the WiRAD design constraints, as well as WiRAD's goal of providing easy and affordable wireless access to streaming Internet radio.

3.1 Functional Overview

WiRAD is a portable audio device equipped with a wireless module that allows users to listen to Internet radio stations over WiFi. After connecting to a station, the WiFi module streams MP3 data to the microcontroller (MCU), where it is decoded and set to a digital-to-analog converter (DAC) and, finally, to an audio jack. A battery powers all hardware.

The selection of Internet radio stations can be programmed as presets via Universal Serial Bus (USB). In the field, the user can navigate up and down the list of presets in increments of one and ten, as well as increase and decrease the volume. There is also a button that resets the WiFi connection in order to force reevaluation of the strongest nearby WiFi network. Every user key-press results in an audio cue being played from an external electrically erasable programmable read-only memory (EEPROM). This functionality is illustrated in Fig. 1.

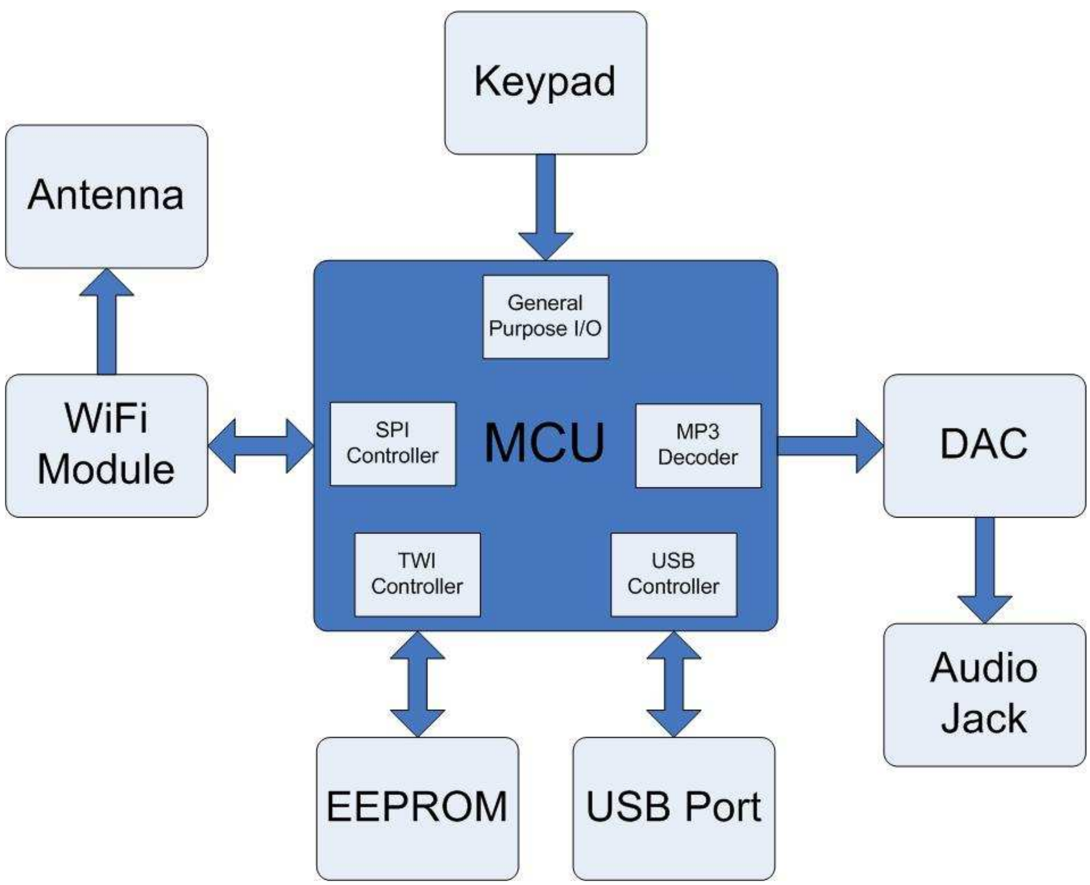

Fig. 1. Functional overview diagram

3.2 Hardware Design

3.2.1 Microcontroller

3.2.1.1 Microcontroller Approaches

The central processing requirement of this project is to interface the various system components. Such interfacing involves data movement, not intense computation. Consequently, an MCU was chosen for this task, rather than a full-fledged microprocessor. Additionally, the low cost and simplicity of an MCU solution contributes to the economic and manufacturability practical design constraints [3].

The chief factors involved in MCU choice were cost, clock speed, program memory, random access memory (RAM), and on-chip capabilities. Initial efforts focused on Microchip's PIC series of MCUs. While these MCUs exhibit adequate clock speeds at low cost, very few contain on-chip USB controllers and none contained on-chip MP3 hardware decoders. If a PIC-based design had been pursued, these functions would almost certainly have been delegated off-chip. The additional cost, complexity, and component count of this design precluded the use of PIC MCUs.

The search for greater on-chip functionality yielded the Atmel AT89C51SND1C. This MCU is intended for use in portable consumer electronics devices and includes an on-chip USB controller and MP3 hardware decoder. The Atmel device also contained more program memory and RAM when compared to the PIC. Table I contains a summarized comparison.

Table I: MCU Comparison [1,2]

	PIC18F45J10	**Atmel AT89C51SND1C**
Maximum clock speed	40 MHz	20 MHz
Program memory	32 KB	64 KB
RAM	1 KB	2 KB
Price	$4.25	$9.00
Integrated USB	No	Yes
Integrated MP3 decoder	No	Yes

As a result of superior on-chip functionality and increased memory, the Atmel AT89C51SND1C was chosen for this design.

3.2.1.2 Atmel AT89C51SND1C Overview

The Atmel AT89C51SND1C is an 8-bit 8051 architecture MCU available in an 80-pin surface-mount package. It includes 2304 bytes of internal RAM, 64KB of program memory, and 4KB of boot flash memory. In addition to the on-chip USB controller and MP3 hardware decoder, the AT89C51SND1C also contains specialized hardware for serial peripheral interface (SPI), two-wire interface (TWI), multimedia card (MMC) interface, and a full duplex universal asynchronous receiver and transmitter (UART) [1]. Fig. 2 presents a functional diagram of the AT89C51SND1C.

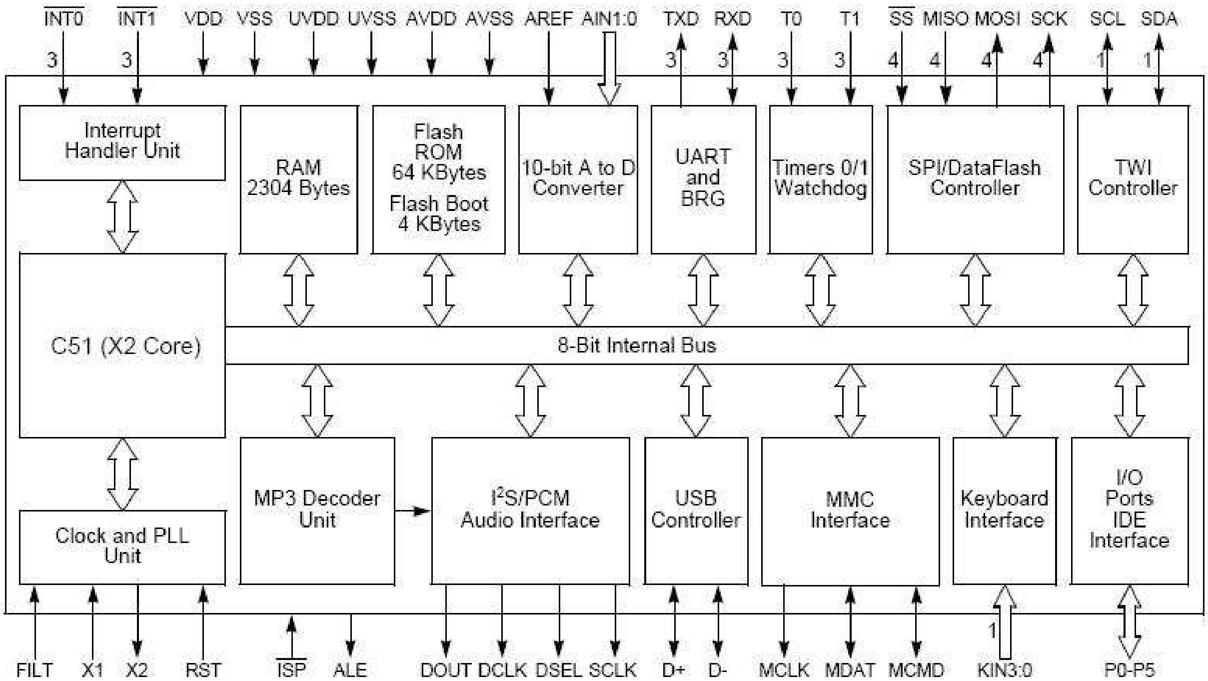

Fig. 2. Functional overview of AT89C51SND1C [1]

The AT89C51SND1C satisfies all related design constraints. The on-chip MP3 decoder is capable of decoding 128kbit/s audio streams as outlined by constraint 2.1.1. The hardware decoder also satisfies constraint 2.2.2, which dictates that appropriate MP3 licensing fees be paid, by including MP3 licensing fees in the MCU cost. Additionally, this MCU contributes to the USB compatibility constraint in 2.2.3 by providing an on-chip USB controller [3].

3.2.2 WiFi

3.2.2.1 WiFi Approaches

WiRAD's WiFi aspect is its most significant innovation when compared to conventional media players. In an effort to ensure manufacturability, speed, and processor independence, three approaches to achieving WiFi connectivity were explored.

The first method explored was to utilize a radio frequency (RF) transceiver and a software TCP/IP stack implemented on the MCU. While the manufacturability of such a design is high due to simple component circuitry, this method exhibits no independence from the MCU, which would necessarily be involved in the movement of each bit. Speed would also be severely limited with this design due to processor dependence.

The second approach for achieving WiFi connectivity studied was the use of a commercial USB to WiFi adapter. While this method exhibits slightly more processor independence than the first approach due to the ability of such adapters to buffer data, it still requires that a TCP/IP stack be implemented on the MCU. In addition to this dependence, a design utilizing this method would not be manufacturable due to the nature of commercial adapters.

The final studied WiFi approach was the use of a WiFi module with an embedded application processor. Such devices run a real-time operating system (RTOS) implementing a TCP/IP stack and allowing the

WiFi module to operate independently of an external MCU. Additionally, the speed of such modules is comparable to equivalent commercial adapter solutions, and their manufacturability is high.

As a result of its processor independence, competitive speed, and superior manufacturability, the final solution of a WiFi module with an embedded application processor was chosen.

3.2.2.2 Airborne WLNB-AN-DP100 Details

The particular WiFi module chosen was the Airborne WLNB-AN-DP100. This module includes an on-board 16-bit 120 MHz RISC application processor with 128KB static RAM (SRAM) running a RTOS with web server, TCP/IP stack, command interface, and an 802.1x supplicant. Interfacing with an embedded application, in this case the Atmel AT89C51SND1C, is accomplished via SPI [4]. Fig. 3 presents a functional diagram of the WLNB-AN-DP100.

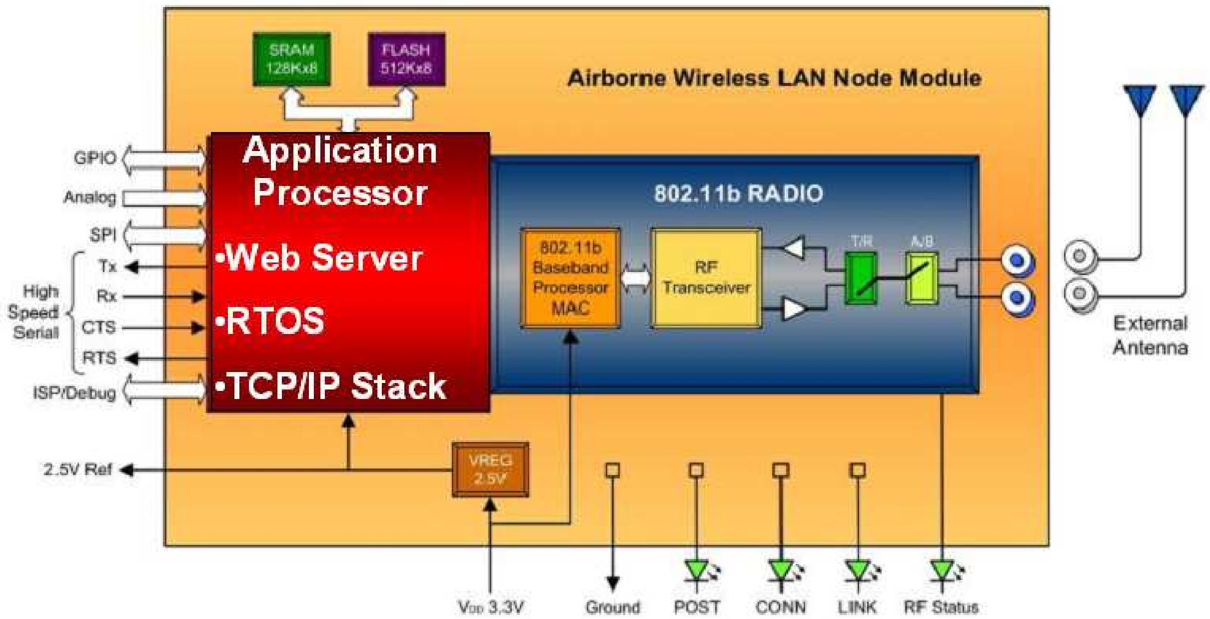

Fig. 3. Functional overview of WLNB-AN-DP100 [4]

The WLNB-AN-DP100 satisfies all related design constraints. The raw data rate of this module is 11Mbit/s, well above the 128kbit/s rate dictated by constraint 2.1.2. Additionally, this module satisfies the manufacturability constraint of 2.2.4, in that it is easily integrated into embedded applications, such as WiRAD, for mass production [3].

3.2.3 Antenna

3.2.3.1 Antenna Approaches

Antennas come in a variety of shapes and sizes suitable for sundry applications. The chief factors in antenna selection include directionality and weight. Table II compares the three major portable antenna technologies.

Table II. Antenna technologies

	Wire	**Aperture**	**Microstrip**
Omnidirectional	No	Yes	No
Lightweight	Yes	Yes	Yes
Common applications	Mobile phones	Microwave	Aircraft, Spacecraft

Wire antennas come in various shapes such as a dipole, loop, and helix. Wire antennas, and helix wire antennas in particular, are commonly used for broadband applications and exhibit omnidirectional performance.

Aperture antennas are lightweight directional antennas. The most common forms of aperture antennas are horn and rectangular waveguide.

Microstrip antennas consist of a metallic patch on a grounded substrate. The metallic patch can take many different configurations; however, the rectangular and circular patches are the most popular because of ease of analysis and fabrication. These small, durable antennas are simple and inexpensive to fabricate using modern printed-circuit technology. Microstrip antennas are low efficiency, low power, and have a narrow bandwidth.

Of these, aperture antennas were immediately eliminated because of their highly directional nature; WiRAD must receive information regardless of the direction it is facing. This left the wire and microstrip antennas. Table III compares two commercial antennas we considered.

Table III. Comparison of commercial wire and microstrip antennas [5, 6]

	2.4 GHz 5.5dBi HyperGain HG2405RD-NM	**2.4 GHz 8dBi HyperGain HGV-2409P**
Technology	Helix Wire	Microstrip
Frequency	2400-2500 MHz	2400-2500 MHz
Gain	5.5dBi	8dBi
Impedance	50Ω	50Ω
Weight	20g	180g
Dimensions	221 (L) x 13 (D) mm	114 (L) x 114 (W) x 23 (H) mm
Polarization	Vertical	Vertical or Horizontal
Cost	$10.00	$23.99

While the helix wire antenna is superior in cost and weight, the microstrip antenna offers a greater gain, more versatile polarization, and dimensions more suitable for the WiRAD form factor. Additionally, microstrip antennas can be easily designed and manufactured, as opposed to more complicated helix wire antennas. This property offsets the price advantage of helix wire antennas by reducing production costs for microstrips to $.50. Consequently, it was decided that a microstrip antenna would be designed and manufactured.

3.2.3.3 Microstrip Antenna Details

The microstrip antenna consists of a patch antenna as illustrated in Fig. 4 and a ground plate separated by a dielectric as illustrated in Fig. 5.

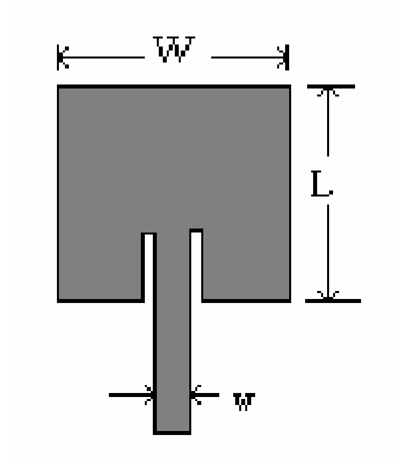

Fig. 4. Square patch antenna

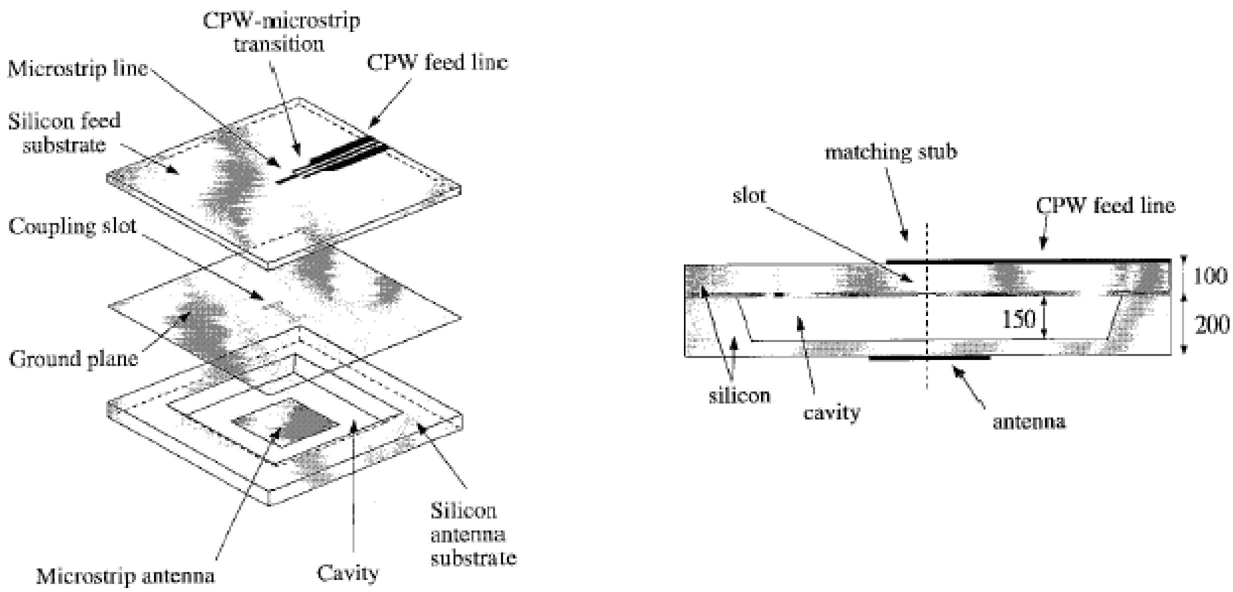

Fig. 5. Microstrip antenna [7]

For a patch antenna, several dimensions are needed to construct the design. With a dielectric constant of the substrate ε_r = 4.4, a substrate height (distance between patch antenna and ground plate) of 1.5cm, and a resonant frequency of 2.4 GHz, the length (L) and width (W) of the patch antenna were derived in the following equations.

The wavelength of the resonant frequency was found by the following equation.

$$\lambda_o = \frac{\text{Speed of Light}}{\text{Resonant Frequency}} = \frac{V_o}{f_r} = \frac{3x10^8\, m/s}{2.4x10^9\, Hz} = 0.125m$$

Using the wavelength found above, the width of the actual patch antenna needed was:

$$W = \frac{\lambda_o}{2} * (\frac{\varepsilon_r + 1}{2})^{-\frac{1}{2}} = \frac{0.125}{2} * (\frac{4.4+1}{2})^{-\frac{1}{2}} = 3.80cm$$

The effective dielectric constant of the patch was then found by the following equation.

$$\varepsilon_{eff} = \frac{(\varepsilon_r + 1)}{2} * \frac{(\varepsilon_r - 1)}{2} \frac{1}{\left(1 + 12\frac{W}{h}\right)^{\frac{1}{2}}} = \frac{(4.4+1)}{2} * \frac{(4.4-1)}{2} \frac{1}{\left(1 + 12\frac{3.80cm}{0.15cm}\right)^{\frac{1}{2}}} = 2.7973$$

An area of dielectric material must surround the patch antenna. The extended incremental length of the patch, ΔL , was found by the following equation.

$$\Delta L = 0.412h \frac{(\varepsilon_{eff} + 0.3)}{(\varepsilon_{eff} - 0.258)} * \frac{\left(\frac{W}{h} + 0.264\right)}{\left(\frac{W}{h} + 0.8\right)} = 0.412 * 0.15cm \frac{(2.7973 + 0.3)}{(2.7973 - 0.258)} * \frac{\left(\frac{3.80cm}{.15cm} + 0.264\right)}{\left(\frac{3.80cm}{.15cm} + 0.8\right)}$$

$$\Delta L = 0.0674cm$$

The actual length of the patch was found by the following equation.

$$L = \frac{1}{\left(2 f_r \sqrt{\varepsilon_{eff}} \sqrt{u_o \varepsilon_o}\right)} - 2\Delta L = \frac{V_o}{2 f_r \sqrt{\varepsilon_{eff}}} - 2\Delta L = \frac{3x10^9}{\left(2 * 2.4x10^9 \sqrt{2.7973}\right)} * 2 * 0.0674cm$$

$$L = 2.39cm$$

An effective antenna operates at a power return loss of less than -10dB [8]. After the construction of the antenna, test results were obtained through a simulation in HFSS to verify that the antenna operated effectively at the broadband frequency of 2.4 GHz.

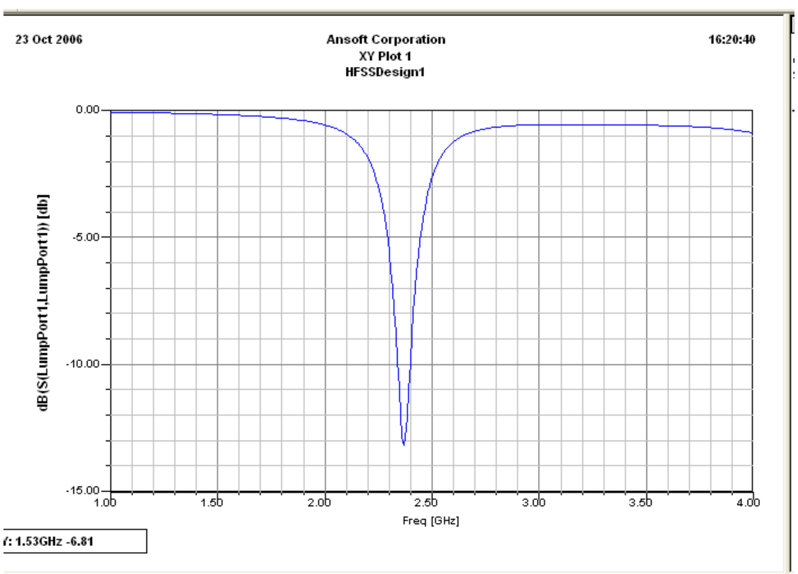

Fig. 6. Return loss (dB) simulation of microstrip antenna

This antenna satisfies the related design constraint of portability, in that the size of the antenna is within the volume limitations outline in 2.1.4. The antenna's low cost also contributes to satisfaction of the economic constraint in 2.2.5. As shown in Fig. 6, the antenna's compatibility with the 802.11b standard (2.4 GHz) satisfies the compatibility constraint in 2.2.3 [3].

3.2.4 Power System

3.2.4.1 Battery Approaches

The WiRAD technical design constraint in 2.1.3 dictates that WiRAD's battery provide three hours of continuous usage before recharging [3]. To establish the battery rating necessary to support such usage, the current draws of the main system components were considered in Table IV.

Table IV. Major component current draws

	Max current draw
WiFi module (3.3V)	450mA
Atmel microprocessor (3.3V)	35mA
Protection circuit (3.7V)	5mA
LEDs (3.3V)	10mA
Total	500mA

With these current draws, three hours of battery life would require a 1500mA battery. A 100% error margin was built into this estimate, and batteries in the 3000mA range were evaluated. The three battery technologies considered were nickel cadmium (NiCd), nickel metal-hydride (NiMH), and lithium ion polymer (LiPo). These technologies are compared in Table V.

Table V. Battery comparisons [9]

	NiMH	**NiCd**	**LiPo**
mAH	3000	3000	2700
Weight	260g	215g	70g
Charge cycles	400	800	500
Cost	$10.99	$6.27	$12.19

While all considered batteries had comparable mAH ratings, the NiCd battery was found to be superior in cost and charge cycles. Despite these advantages, the lighter LiPo battery was chosen in order to satisfy WiRAD's portability constraints [3].

3.2.4.2 Charging Approaches

The two considered charging approaches were wall transformer and USB. Since a USB connector was going to be included to facilitate device configuration regardless of charging method, the USB charging method was chosen to help satisfy WiRAD's portability constraints by minimizing external connectors.

Another charging consideration was the possibility of overcharging. Overcharging is a safety risk in that it can cause battery overheating or explosion. Consequently, a protection circuit was required to keep the battery from overcharging. While a customized analog circuit could have been designed to meet this need, an integrated circuit solution was chosen for small package size and affordability.

3.3 Software Design

3.3.1 Development Approach

Establishing a development environment was the first major obstacle associated with the decision to use the Atmel MCU. While the support structure for the PIC MCUs includes free use of a C compiler, multiple device programmers, and a large hobbyist community, development choices for the AT89C51SND1C consist of high-price development suites and open source tools of questionable usability.

Furthermore, differences between the major compilers ensured porting difficulty and occluded the possibility of changing compilers after an initial decision was made. These differences primarily consisted of syntax for language extensions. Language extensions are special compiler directives that convey items such as data pointer size, heap location, total program memory, special function register (SFR) locations, and interrupt vectors. Each compiler has its own syntax that must be followed if the environment is to understand a microcontroller's sub-architecture. Consequently, much consideration was given to the three major 8051 architecture compilers.

The first considered compiler for the 8051 architecture was the Small Device C Compiler (SDCC). SDCC is a small, command-line, open source compiler maintained and originally written by Sandeep Dutta. While this compiler would have functioned for WiRAD purposes, it was difficult to install and configure.

The next considered compiler was Keil uVision3. Keil, unlike the SDCC, is a Windows compatible graphical development suite. It has the additional advantage of being the environment in which the demo source code for the AT89C51SND1C is written. While this seems like the obvious choice for a development environment, economic concerns played a large role in the decision not to use the Keil environment; a single Keil license costs $2,000.

The IAR Embedded Workbench (IAR) was the final 8051 architecture compiler explored. Like Keil, IAR is also a graphical development environment that enjoys all of the same advantages over SDCC. However, Mississippi State University (MSU) was able to provide the WiRAD team with an on-site license for development efforts. While IAR is unsupported by the sample software and source code associated with the AT89C51SND1C, extensive porting efforts yielded equivalent routines under this compiler. Consequently, IAR was chosen for the WiRAD development environment.

3.3.2 Flowchart

The flowchart of Fig. 7 illustrates the WiRAD's states and state transitions.

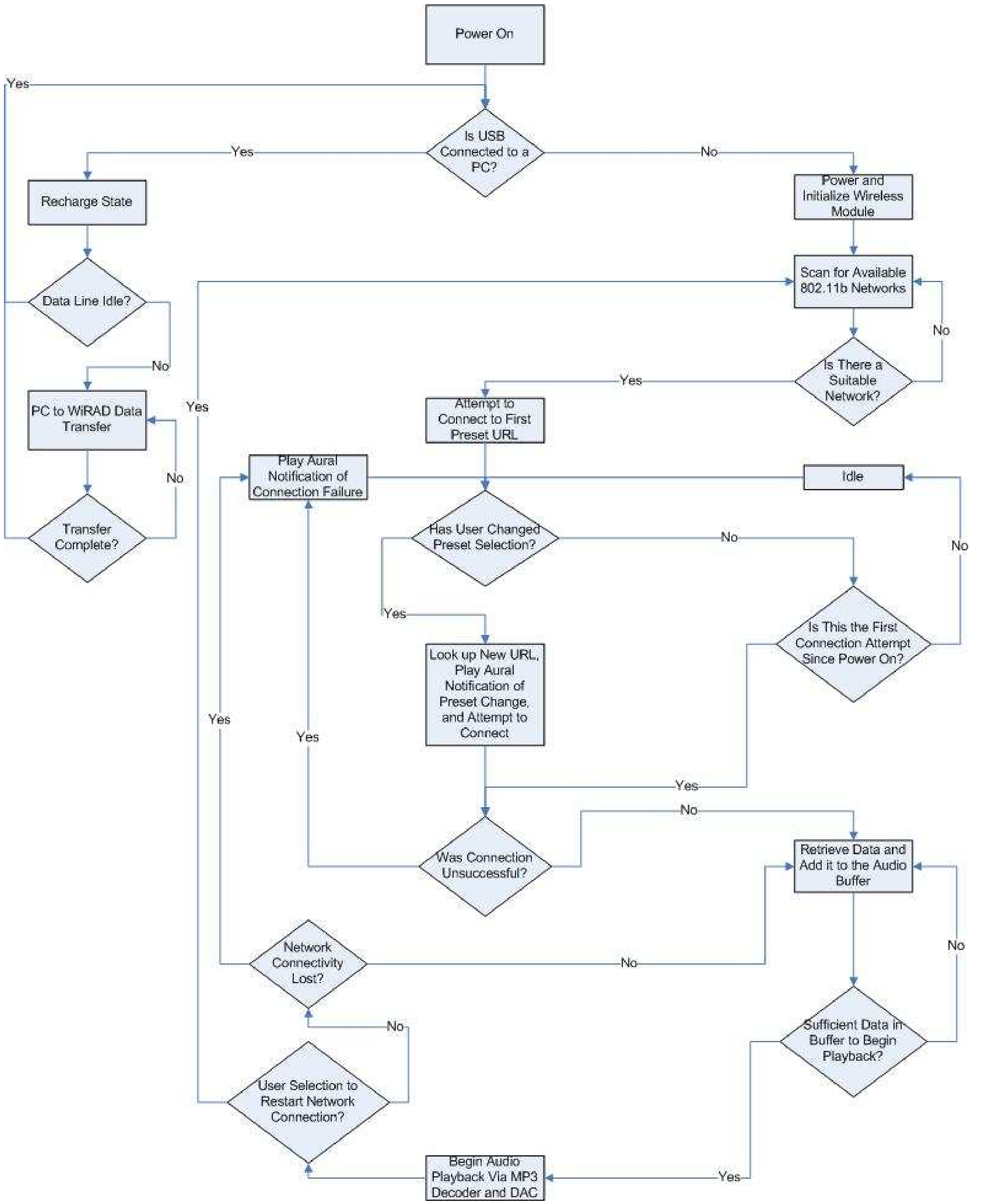

Fig. 7. State flowchart

3.3.3 Use Cases

As an aid to the software design process, possible WiRAD use cases were brainstormed and proper system response was formulated. Some of these use cases illustrate best-case operating conditions; these are termed "sunny-day" use cases. Others illustrate worst-case operating conditions; these are termed "rainy-day" use cases.

3.3.3.1 Sunny-Day Use Cases

The use case in Fig. 8 illustrates normal WiRAD operation; *i.e.*, the device is powered on and begins streaming a station.

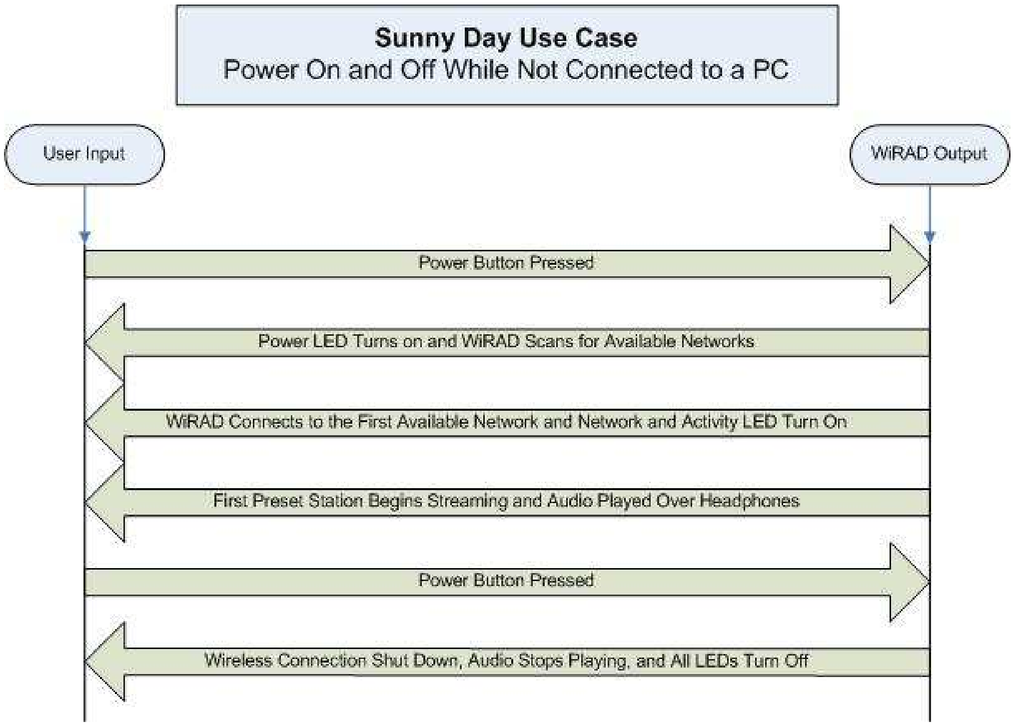

Fig. 8. Sunny Day - Power on and off while not connect to a PC

Fig. 9 illustrates WiRAD operation upon the changing of a station.

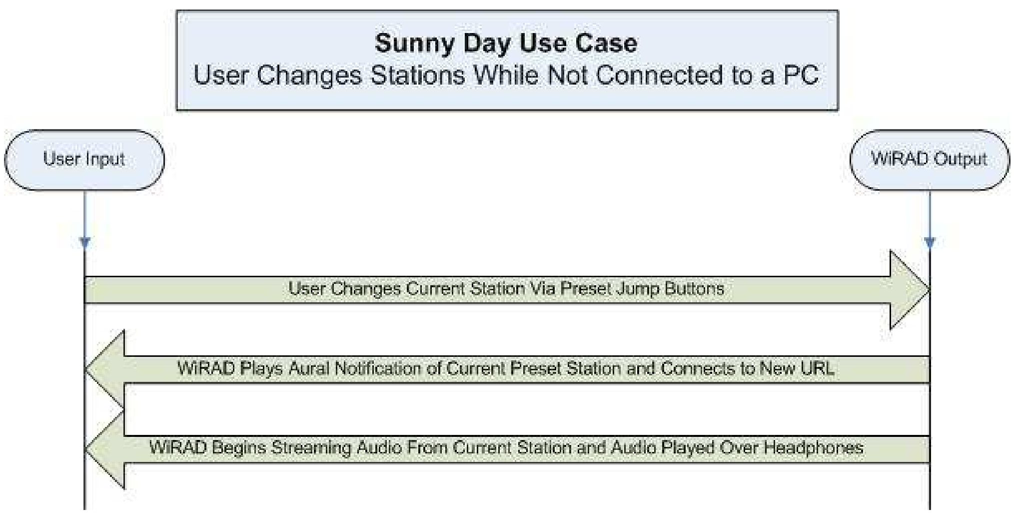

Fig. 9. Sunny Day - User changes stations while not connected to a PC

Fig. 10 illustrates WiRAD operation when connected to a PC for charging and configuration.

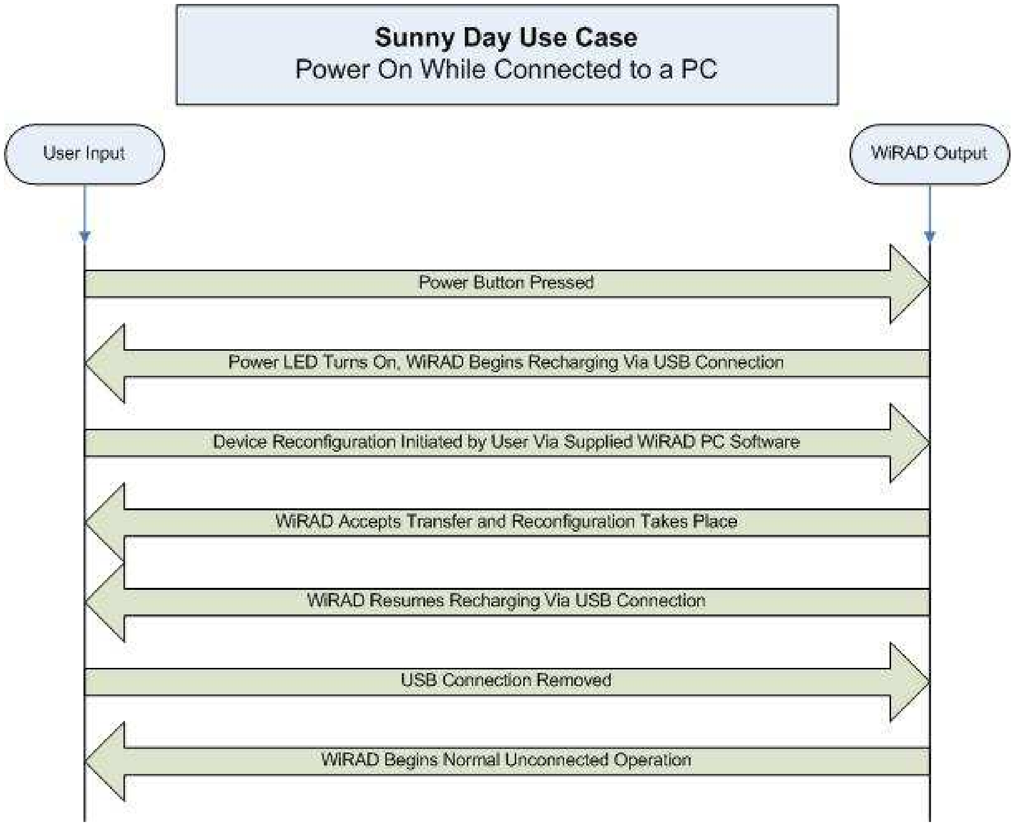

Fig. 10. Sunny Day - Power on while connected to a PC

3.3.3.2 Rainy-Day Use Cases

The use case in Fig. 11 illustrates WiRAD operation when a preset station cannot be contacted.

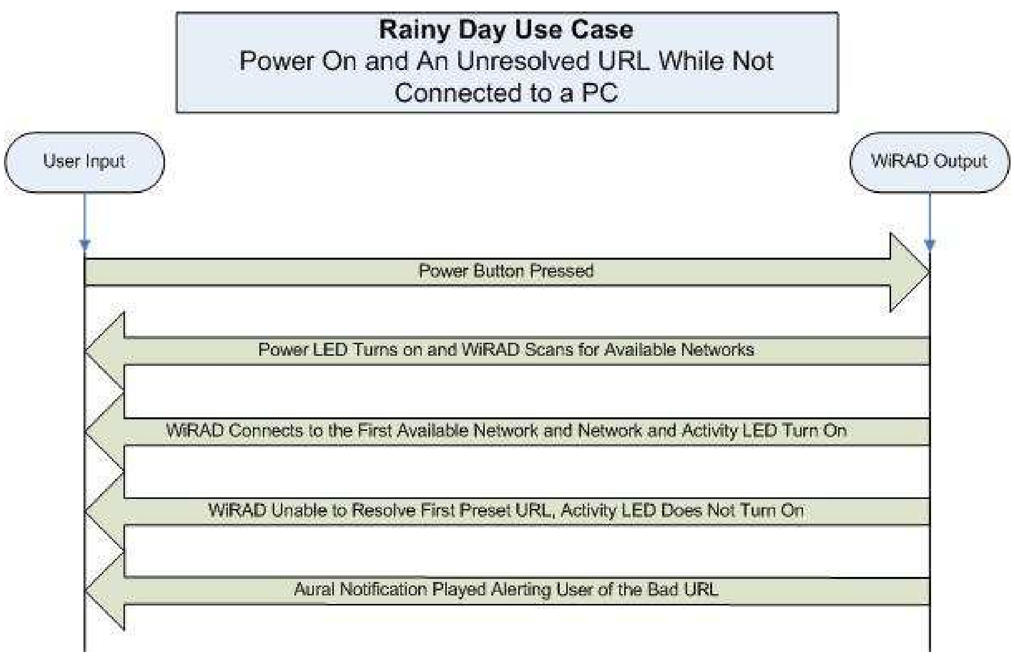

Fig. 11. Rainy Day - Power on with unresolved URL while not connected to a PC

Fig. 12 illustrates WiRAD operation when power runs out.

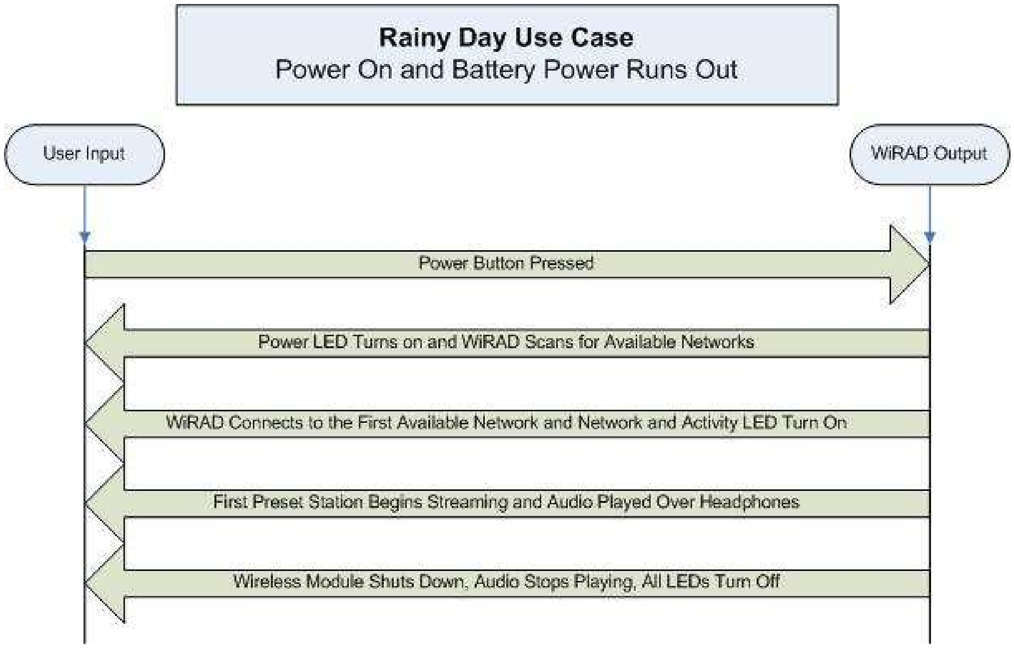

Fig. 12. Rainy Day - Power on and battery power runs out

Fig 13. illustrates WiRAD operation when the device is powered on but no presets are programmed.

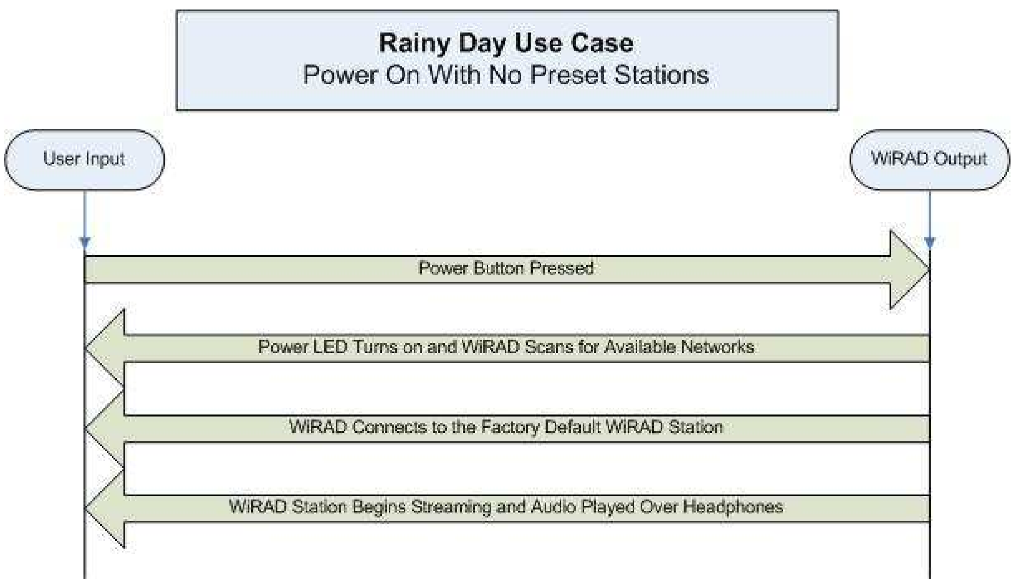

Fig. 13. Rainy Day - Power on with no preset stations

3.4 References

[1] Atmel Inc., "Features," in *AT89C51SND1C Databook*, pp. 1-2.

[2] Microchip Inc., "Special Microcontroller Features," in *PIC18F45J10 Family*, pp. 3.

[3] W. Holland, K. Strong, A. Taheri, E. Tramel, *Design Constraints*, Senior Design document, Dept. Elect. and Comp. Eng., Mississippi State Univ., Starkville, MS, 2006.

[4] DPAC Technologies, "Specifications," in *Airborne Wireless LAN Node Module Databook*, pp. 8-9.

[5] Hyperlink Technologies. (2006, Oct. 25). "2.4 GHz 5.5 dBi N-Male Rubber Duck 802.11b 802.11g Wireless LAN and Bluetooth Compatible WiFi," *Hyperlink Technologies New Products*. [Online]. Available: http://www.hyperlinktech.com/web/hg2405rd_nm.php

[6] Hyperlink Technologies. (2006, Oct. 25). "2.4 GHz 8 dBi 802.11b 802.11g Wireless LAN and Bluetooth Compatible Mini Flat Patch WiFi Ant," *Hyperlink Technologies New Products*. [Online]. Available: http://www.hyperlinktech.com/web/hg2409p.php

[7] M. Aziz, M. Rahim, and A. Asyrokin. (2006, Oct. 20). "Broadband Microstrip Antenna Design for Broadband WLAN Application." [online]. Available: http://fist2.mmu.edu.my/~m2usic/proceedings05/TS05/06-356

[8] E. Topsakal, Electrical and Computer Engineering, Mississippi State University, MS, private communication, October 2006.

[9] Tenergy. (2006, Oct. 25). "All-Battery.com - Rechargeable batteries and chargers." [online]. Available: www.all-battery.com