

# Dynamic Current Profiling

## Application Note

### Introduction

If you are designing with embedded systems, you face various power optimization and power characterization hurdles throughout your design process. You know what you want to output, simulate, and measure, — but you need a whole “toolbox” of instruments and hardware to do the job. Not only is this toolbox costly, but properly configuring the hardware and software into an accurate, dependable solution can be time consuming.

The power challenges that embedded system designer’s face can be broken into three categories: properly powering on and off multiple power inputs, characterizing power needs under dynamic load conditions, and simulating real-world power conditions. This application note focuses on characterizing the power needs of an embedded design under dynamic load conditions. We will explore why it is critical to fully characterize a dynamic load for minimizing power usage and increasing battery life. Then we will introduce you to a single, easy-to-use instrument that can supply and characterize the dynamic power needs of your embedded design.

Rapid advances in semiconductor technology and portable device technology have led to an explosion in the development of low-power embedded systems that conserve battery life. In battery-powered devices, power is limited, which leaves you at the mercy of available power when you try to decide what features to include, what size your device should be, and at what speed it should operate. Because of the power challenges battery-powered devices present, it is becoming critical that you optimize the hardware and software of your design for minimum power usage.

To conserve power, many embedded applications have turned to dynamic power usage models. Dynamic power usage models have an ever-changing current profile, which is caused by the various power-saving steps that are being taken dynamically during the embedded system’s operation. These power-saving steps may include putting components in sleep or idle mode when they are not being used, slowing the system clock during certain stages of operation and trying various hardware and firmware methods to optimize a task for power efficiency. As the designer, you need to figure out the most accurate and fastest way to characterize and analyze an embedded design’s current profile so you can optimize your design to achieve lower power consumption and longer battery life.



*This is the second in a series of application notes that addresses power optimization, characterization, and simulation challenges in embedded designs.*



# The Growing Need for Dynamic Current Profiling

Capturing the dynamic current profile of your embedded design requires a power source and some type of digitizing instrument that can capture the output of the power source over the full dynamic range of the design. Such a setup is typically expensive and requires you to invest significant time to configure it. But capturing the dynamic current profile, versus just capturing average current, gives a more complete view of a device's current needs.

Three ways current profiling helps you design embedded systems for maximizing battery life:

## 1. Capturing areas of high current consumption

Areas of high current consumption in some embedded designs include time periods when the various systems on the integrated circuit are active, thus the highest power draw occurs to power these various processes. With so many tasks going on concurrently, there are typically a number of different ways these tasks can be performed from a hardware and software standpoint. Of course, with every change in how a task is carried out, there are always a number of tradeoffs. One of those tradeoffs is often power consumption.

Capturing the dynamic current profile of your embedded design allows you to first identify these areas of large current consumption with a high degree of resolution. This allows you to run multiple iterations of the same task and get an accurate picture of the effect on the power needs of the design. Also, details in the current profile of embedded designs often allow you to spot when different tasks begin and end. This type of insight into the power profile allows you make performance adjustments such as varying the clock speed and scheduling operations. Digitizing the dynamic current profiles also allows you to spot current anomalies, such as sudden spikes of current that averaged measurements would not allow you to see.

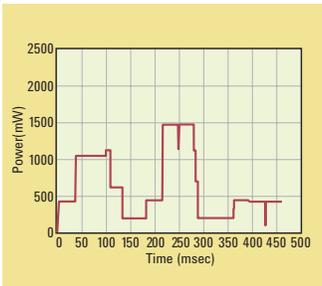
## 2. Capturing areas of low current consumption

In embedded system designs, there are often periods of inactivity where CPUs and other semiconductor components are turned off or put in sleep mode or idle mode. During these low-power states, most of the current that is consumed is in the form of a small leakage current that can be less than 10  $\mu\text{A}$ . At such low current values it is hard to find a digitizing instrument that can accurately capture the current profile. Low-level current profiles are important to characterize because they can tell you if the various integrated circuits on your embedded design are properly configured for the lowest power consumption in their inactive state. For example, for a microcontroller to achieve its lowest current levels while in sleep mode, its data sheet typically specifies that you must set all the pins as inputs and ensure certain registers are in default states. With everything internally on the microcontroller set for low power consumption, current levels below 10  $\mu\text{A}$  are easily achievable, but without the proper settings you could see current levels somewhere around 1 mA. For designs that go through long periods of inactivity, ensuring the design is at the lowest current consumption possible can lead to significant increases in battery life.

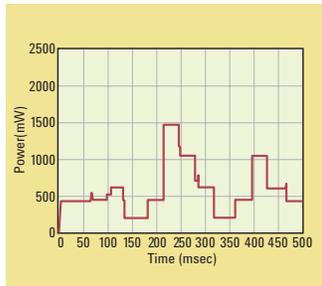
## 3. Stochastic battery modeling

There are several different battery modeling techniques you can use to predict a device's battery life based on its power consumption. Stochastic battery modeling is ideal for embedded system designs that have a dynamic current profile, such as a design that goes in and out of sleep/idle modes or a device that has sudden current pulses, like a power amplifier. This type of battery modeling accounts for the non-linear effects on battery drain during high-current phases of a dynamic current profile, and it accounts for periods of low current flow when charge recovery can take place in the battery. For a brief description of why the battery exhibits the behavior described above, refer to the paper, "*Battery-Driven System Design: A New Frontier in Low Power Design*".<sup>[1]</sup> The following section provides an example of the benefits of using a stochastic modeling approach with an embedded design. For more information on stochastic battery models, see the papers, "*Importance of a Pulsed Battery Discharge in Portable Radio Devices*,"<sup>[3]</sup> and "*Battery Life Estimation for Mobile Embedded Systems*".<sup>[4]</sup>

Stochastic modeling was used on an IEEE 802.11 media access control (MAC) processor-based embedded system design. Besides the MAC processor, our example employs multiple integrated circuits for carrying out various tasks. Figure 1 shows the power profile of our example embedded system running through various stages of a communication protocol. The difference between the current profile in 1a and the one in 1b is caused by a change in the ordering and method in which certain tasks were carried out. See "*Efficient Power Profiling for Battery-Driven Embedded System Design*." [2]



**Figure 1a:**  
*HW and SW Configuration 1*



**Figure 1b:**  
*HW and SW Configuration 2*

For the power profile in **Figure 1a**, the average power over the 500 ms is 596.2 mW, and for the power profile in **Figure 1b** the average power is 590.7 mW. In this outcome, the average power of Figure 1b is less than 1% better than the average power in Figure 1a. But calculating the battery life of these two examples using a stochastic battery model yields a much larger difference between the two configurations. The battery life for the configuration in Figure 1a is 3,673 s and the battery life for the configuration in Figure 1b is 4,783 s, which is a 30% battery life improvement [2]. The increased battery life for the configuration in Figure 1b is due to a better mix of short-duration high current levels and ample time periods of low current levels that allow charge recovery to occur within the battery. If we had employed a battery modeling technique based on averaging the power consumption of the load, such as the analytical modeling technique [1], that 30% improvement in battery life would have been hidden from us. To perform stochastic modeling you need to be able to simulate and capture the dynamic current profile of the design.

## Traditional Methods of Capturing Dynamic Current Profiles

In the previous section we discussed the advantages of capturing a detailed picture of the current profile of an embedded design compared to making averaged current measurements. The downside to employing tools to characterize the dynamic current needs of an embedded design is the added cost and the additional configuration time required. First and foremost, you will need some type of digitizing device like a scope with a current probe or shunt. Since the lower range of an oscilloscope current probe is typically limited to the milliampere range, it cannot capture the low current levels that are typical when a device is in sleep mode. Using some type of shunt is effective for small current ranges, but large dynamic ranges present the problem of varying measurement accuracies because you are using a fixed shunt. Also, at high current levels, the voltage drop across the shunt will affect the design's performance.

There are some specialized power supplies with built-in digitization capability to capture dynamic current, but you will need some type of software tool and a computer to analyze the data, which adds to test configuration time and complexity. The majority of embedded designs require multiple power inputs, so any scope or digitizing power supply solution would require multiple channels or you would need to take the time to move the dynamic current capture solution to each channel and rerun the test.

## Overcoming Embedded-Design Challenges

The dynamic current profile characterization challenges embedded design engineers face can be overcome with the Agilent N6705A DC Power Analyzer. The N6705A combines the functionality of four power supplies, an oscilloscope, a data logger, a voltmeter, an ammeter, and a power arbitrary waveform generator into a single bench-top instrument. The N6705A's power supply modules employ digitizers that capture the output current profile or the output voltage profile – or both – from its outputs. You can log the digitized data in non-volatile memory and view it on the N6705A's scope-like display.

The N6705A provides up to four power supply outputs in a single mainframe, and each output is defined by a plug-in module. There are 21 different modules available, which vary in power range, measurement capabilities and speed. Table 1 on page 8 provides a list of modules that are a great fit for embedded design testing and shows their key specifications.

For measuring low-level sleep and leakage currents, the N6705A offers plug-in modules with a 200- $\mu$ A measurement range that allows you to capture current levels accurately down to microamp levels. Other features on the N6705A that are valuable for embedded design testing:

- An oscilloscope-like display shows voltage, current, and power versus time on multiple channels. This feature allows you to view in real time the voltage, current, and power events of your designs.
- A built-in data logger continuously logs time-stamped data to a large color display and to a file. You can log data on all four outputs at the same time. You can save data log files to internal memory or to an external USB memory drive.
- Built-in waveform functions and arbitrary waveform capability let you modulate DC outputs. An arbitrary waveform can be defined with up to 64k points.
- Power on/off sequencing with slew rate control

The scope and data logging functions of the N6705A allow you to capture and analyze dynamic current models without writing a single line of code or putting together complicated hardware setups. Because all the functionality of the instrument can be accessed through its front panel, setup is quick and easy. You can view and measure the logged data from the built-in data logger from the N6705A's large display or export the data from the N6705A in a .csv file (no special software needed) for post processing, such as for performing stochastic battery modeling.

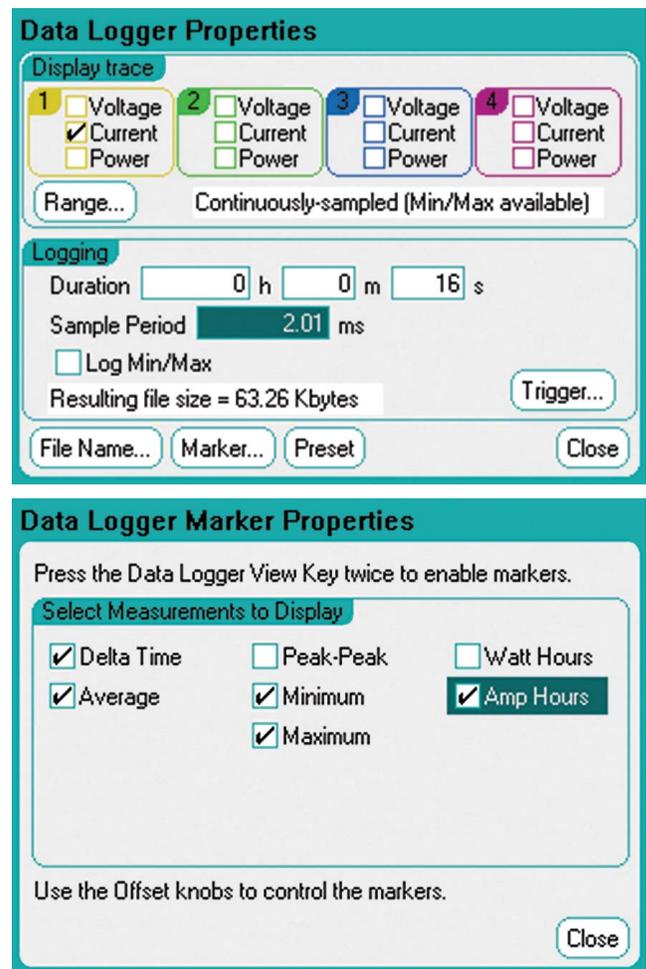
## Using the N6705A to capture the current profile of an embedded design

To demonstrate the current profiling capabilities of the N6705A using the data logger feature, a simple embedded design is set up using a 24-bit microcontroller. The microcontroller-based design also employs four LEDs and an EEPROM memory chip. The microcontroller requires a 3.3-V input supply. The 3.3 V supply is being provided by channel 1 of the N6705A using the N6762A precision power module (see specs for modules in Table 1).

When the microcontroller is powered on, it attempts to communicate with the EEPROM memory chip. The EEPROM chip indicates that it is currently busy and the microcontroller goes into a power save mode that includes setting all of the IO ports as high impedance inputs to prevent leakage current, setting up a wake-up timer, and finally going to sleep. At wake up, the microcontroller reconfigures its IO pins, checks the memory chips status (which is no longer busy), and begins transferring data to the EEPROM chip. While data is being transferred, the four LEDs are lit up to signal a data transfer. The LEDs are cycled at a rate that, to the human eye, gives them the appearance of continued illumination. The N6705A data logger feature was set up to capture 16 s of the output current profile of channel 1.

**Figure 2** shows the data logger setup screen and the measurement marker setup screen. As shown in Figure 2, setting up the N6705A can be done quickly and easily via the front panel. Changing your data capture or measurement settings is as easy as pushing a button.

We performed two 16 s data logs on the microcontroller circuit, each with a different sample period (see Figure 2 for setting the sample period). The internal digitizer performing the current measurement on channel 1 of the N6705A is sampling at a rate of 100 kS/s. The sampling period returns the average value of samples that occur in the sampling period. The first data log returned the average value of samples over a 2 ms sample period, and the other returned the average value of samples over a 40  $\mu$ s sample period, giving us increased resolution.



**Figure 2.** Datalogger setup screen and measurement marker setup screen

In **Figures 3a, 3b, and 3c** you will see three screen captures of the N6705A scope-like display showing the current profile of the microcontroller using the 2-ms sample period. The N6705A allows you to analyze all the logged data by zooming in or out and by performing quick measurements using the built-in measurement markers. Figure 3a displays the whole 16-s data log. Figure 3b shows a more zoomed-in view of the current when the microcontroller powers on, checks the status of the EEPROM chip, and then goes into sleep mode. Figure 3c shows a zoomed-in view of the microcontroller after it wakes up from sleep mode, reconfigures itself, and starts transferring data to the EEPROM chip and driving the LEDs. Notice in this screen shot the markers are being used to perform measurements.



Figure 3a. Entire 16 s data log

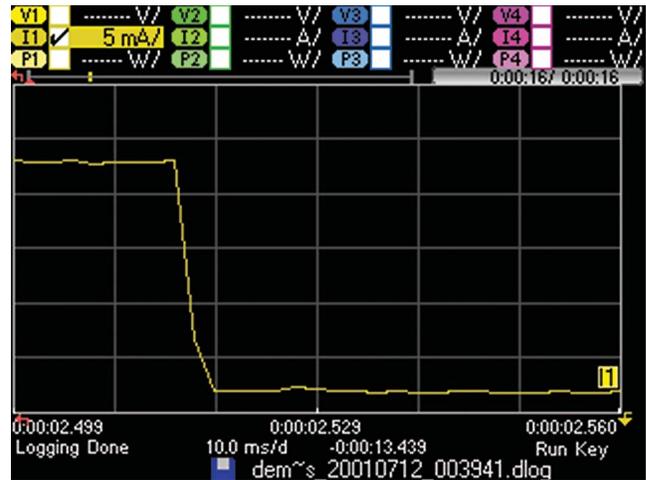


Figure 3b. Dynamic current switching into sleep mode

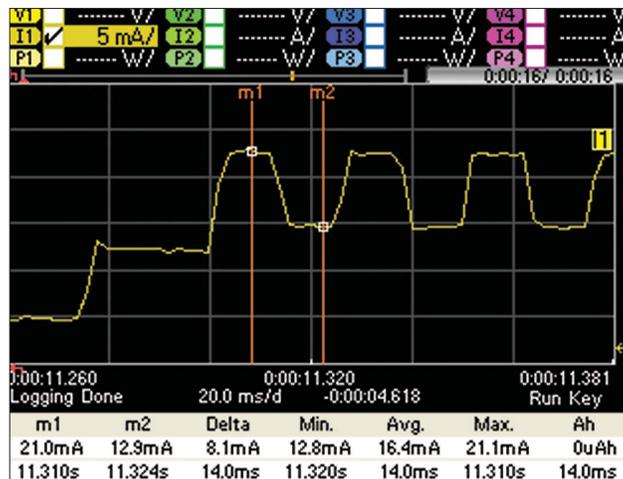


Figure 3c. Dynamic current measurements with built-in markers

Figures 4a and 4b show two screen captures of the data log being performed with a 40- $\mu$ s sample period. Figure 4a shows all of the 16-s logged data and Figure 4b shows a zoomed-in view of the current profile of the microcontroller after it wakes up from sleep mode, reconfigures itself, and starts retrieving data from the EEPROM chip and driving the LEDs.

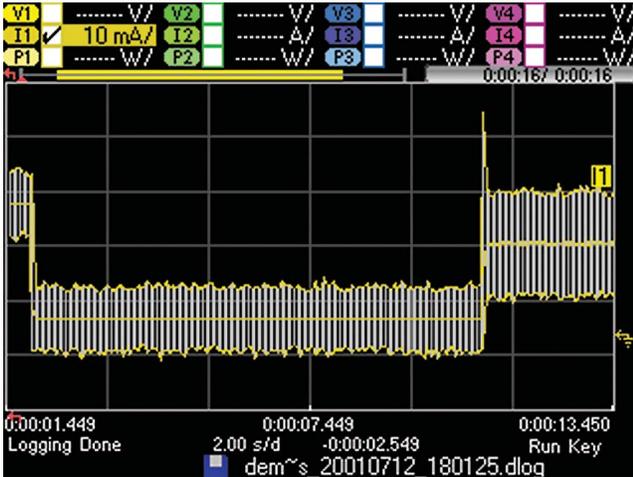


Figure 4a. Entire 16 s data log

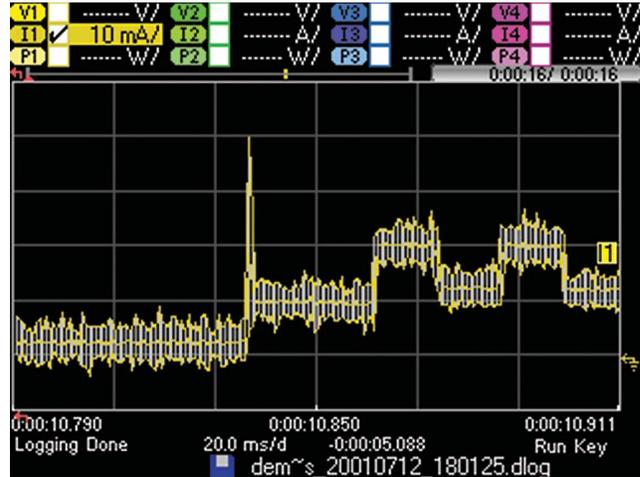


Figure 4b. Dynamic current coming out of sleep mode

Using a sample period like 2 ms cancels out most of the random noise to give you an easy-to-read visual picture of an embedded design’s current profile. It is also handy during post processing for calculating a power use model. A short sample period like 40  $\mu$ s is useful when you are trying to capture any short-duration anomalies in your current profile. For example, in Figure 4b we can see a sudden sharp spike of high current when the microcontroller comes out of sleep mode and begins reconfiguring itself. This short-duration spike of current was caused by low impedance paths to ground that were briefly created at two IO pins on the microcontroller during reconfiguration. In Figure 3c, in the 2-ms sample period example, the current anomaly does not really show up, and this simple error in the design may have gone unnoticed. Figure 5 shows a close up of the current spike from the 40- $\mu$ s sample period data log using the measurement markers. The measurement marker gives us an easy, quick way to get the peak current value and the time stamp of the current spike to help easily identify the point where the event took place.

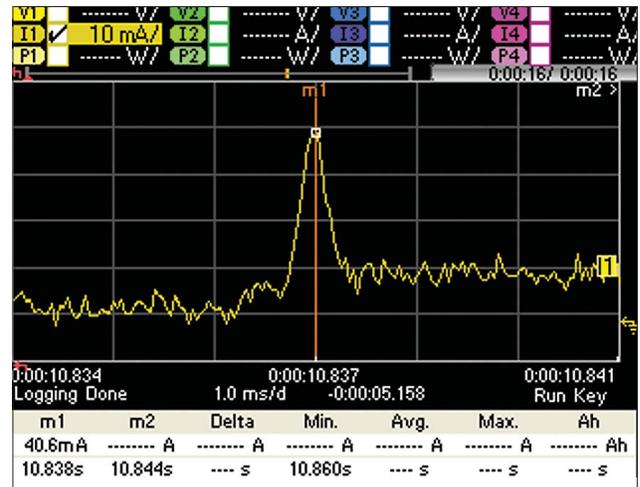


Figure 5. Current spike captured using a 40- $\mu$ s sample period

It is important to pick up these current anomalies during the design process to prevent early component failure in the device from high current values and to cut down on the device’s power cost, since periods of high current cut down on battery efficiency.

## Conclusion

In embedded system designs where power is expensive, engineers devote significant effort to minimizing the power needs of their designs. For embedded designers, this means adopting a dynamic power usage model. During the design process, you need a way to accurately capture the current profile of your embedded system's dynamic power model to test and analyze various power optimization techniques and understand their tradeoffs. In the past, a solution consisted of multiple hardware pieces and software that required significant configuration time. The N6705A DC Power Analyzer overcomes those obstacles by providing a single solution that can accurately capture and display a dynamic current profile without requiring you to write any code or use special software.

The N6705A is a bench-top instrument that combines the functionality of a four-output power supply, a data logger, oscilloscope, voltmeter, ammeter and high-power arbitrary waveform generator. In this application note we showed how the N6705A data logger function allows you to quickly and easily capture the current profile of your embedded design to non-volatile memory. The N6705A data logger can be easily reconfigured to run multiple tests using varying measurement time interval periods so you can get an easy-to-read overall picture of the current profile or a detailed view that will reveal short-duration current anomalies. You can then analyze the data on the N6705A via the large front-panel scope-like display and built-in measurement capabilities. Retrieving the logged data out of the N6705A's memory for post processing, such as performing stochastic battery modeling, can be easily done through the front-panel USB port or via the Web interface, which you can access with a LAN connection and a Web browser.

Table 1 provides a list of N6705A modules that are a good fit for embedded design along with some of their key specifications.



**Table 1: N6705A modules**

		N6751A/52A	N6754A	N6761A/62A
<b>DC output ratings</b>	Voltage	50 V	60 V	50 V
	Current	5 A / 10 A	20 A	1.5 A / 3 A
	Power	50 W / 100 W	300 W	50 W / 100 W
<b>Max up-programming time with full R load</b> (Time from 10% to 90% of total voltage)	Voltage change	0 to 10 V	0 to 15V	0 to 10 V
	Time	0.2 ms	0.35 ms	0.6 ms
	Voltage change	0 to 50 V	0 to 60 V	0 to 50 V
	Time	1.5 ms	2.0 ms	2.2 ms
<b>Voltmeter/ammeter measurement accuracy</b> (at 23°C ± 5°C) voltage	Voltage high range	0.05% + 20 mV	0.05% + 25 mV	0.016% + 6 mV
	Voltage low range (5.5 V)	N/A	N/A	0.016% + 1.5 mV
	Current high range	0.1% + 4 mA	0.10% + 8 mA	0.04% + 160 µA
	Current low range ( <sup>±</sup> 100 mA, at 0 - 7 V)	N/A	N/A	0.03% + 15 µA
	( <sup>±</sup> 100 mA, at 0 - 50 V)	N/A	N/A	0.03% + 55 µA
	(≤200 µA)	N/A	N/A	0.5% + 100 NA (Option 2UA)

## References

1. Kanishka Lahiri, Anand Raghunathan, Sujit Dey, Debashis Panigrahi, "Battery-Driven System Design: A New Frontier in Low Power Design" <http://esdat.ucsd.edu/~klahiri/papers/vlsi02.pdf>. 2002.
2. Kanishka Lahiri, Anand Raghunathan, Sujit Dey, "Efficient Power Profiling for Battery-Driven Embedded System Design" <http://esdat.ucsd.edu/~klahiri/papers/tcad-04-3.pdf>. 2004.
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