

■ BY FRED EADY

RIDING AN RF ENERGY HARVESTER

What do you get when you mix three watts of 915 MHz RF with some special silicon attached to an antenna and a capacitor? The answer is obvious. You get 3.3 volts DC. This month, I'll explain how a three watt 915 MHz Powercaster transmitter coupled with a Powercast P2110 Powerharvester receiver can be used to power a PIC24F series microcontroller, an MRF24J40MA 802.15.4 2.4 GHz radio, and a gaggle of sensors. It all begins with the 915 MHz transmitter.

A WIRELESS POWER SOURCE

The power needed to drive our PIC, MRF24J40MA 2.4 GHz radio, and sensors is derived from a Powercast 915 MHz Powercaster transmitter. In addition to the electrical energy, the transmitter also periodically transmits eight bits of encoded data within the RF power stream. The data is in the form of a standard RS-232 frame and contains the transmitter ID. The transmitter ID can be used to identify the power source of mobile sensor

modules that move between multiple 915 MHz Powercaster transmitter domains. I superimposed the tag attached to the rear of our 915 MHz transmitter to the frontal shot of it in **Photo 1**. As you can see, our transmitter ID is 130 decimal. The transmitter ID is encoded in a nine-bit RS-232 frame clocked at 16660 bps.

The 915 MHz transmitter is factory aligned and its radio configuration and power output cannot be altered. A pair of wall wart jacks on the bottom and rear allows it to be wall mounted or sit upright on a flat surface. A built-in antenna with 8 dBi of gain is housed under the covers. A five volt DC power source is all that may be externally attached. There are no knobs or electronically accessible configuration options. A lone LED displays the status. Green is good. Red is bad. To install the transmitter, just mount it in an eight foot or higher unobstructed line-of-site view of the nodes it is to power and plug it in. The transmitter's radiation pattern is 60° high by 60° wide and is vertically polarized.

WHERE THERE'S RF, THERE'S PROBABLY AN ANTENNA

The Powercast Lifetime Power Energy development kit for wireless sensors includes the pair of antennae shown in **Photo 2**. The smaller printed circuit board (PCB)

■ **PHOTO 1.** No, it is not the monolith the apes danced around in *2001: A Space Odyssey*. The Powercast 915 MHz Powercaster transmitter has no knobs or configuration options that can be accessed in the field. It is what it is — a five volt powered, wall mountable, three watt 915 MHz transmitter. The power output and transmitter ID can be seen on the superimposed rear tag.



■ PHOTO 2. The dipole antenna is intended for short range power production. The larger twin-bladed patch antenna has a defined radiation pattern and offers almost 4x signal gain over the dipole.

antenna is configured as a dipole. It is omnidirectional and is intended to operate as a vertically polarized element. The linear gain of the dipole antenna is 1.25.

The larger patch antenna's RF connector is hidden from view on the back side of the larger of the antenna plates. Unlike the omnidirectional dipole, the directional patch antenna has an energy pattern and a substantial amount of gain. The vertically polarized patch antenna has a linear gain of 4.1.

So far, we've established an RF energy source and a means in which to capture that energy. We need to convert the captured RF energy to power we can use to drive our PIC, radio, and sensors.

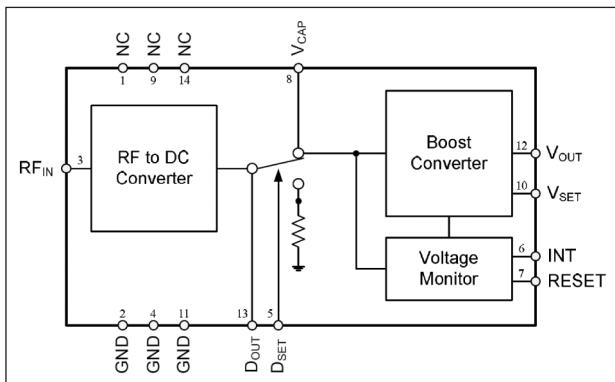


AN RF ENERGY HARVESTER

I'm sure that by now you know that the word "battery" will only be used to describe the absence thereof. The P2110 Powerharvester receiver is an SMD module that converts RF to DC for micro-power devices used in battery-free applications. When it comes to help with RF energy harvesting, the P2110 receiver captured by the Canon in **Photo 3** only requires an antenna and a capacitor to squeeze 3.3 VDC out of the incoming RF. A voltage adjust resistor placed between the V_{SET} and V_{OUT} pins can be added to the receiver circuitry to raise the harvested voltage to a maximum of 5.25 volts, or lower the voltage to a minimum of 1.8 volts.

Take a look at **Figure 1**. The receiver sucks the harvested RF energy in from the antenna into its internal RF to DC converter. The converted DC is stored in a capacitor. The value and quality of the storage capacitor determines how much energy can be siphoned from the receiver's V_{OUT} pin. Lower value capacitors will yield shorter operation cycles. Larger value storage capacitors

■ FIGURE 1. The P2110 Powerharvester receiver operation is logical. Basically, the harvested RF energy is stored in a capacitor and boosted for use by the micro-power device. The default output voltage of the receiver is 3.3 volts.



provide longer operation cycles.

Fred Eady's First Rule of Embedded Computing states that nothing is free. The tradeoff between a larger and smaller valued storage capacitor is the time that the storage capacitor takes to charge. Larger value storage capacitors provide longer operation cycles but take longer to charge. Consider this storage capacitor value equation:

$$C = 15V_{OUT}I_{OUT}t_{ON}$$

Where:

C = Estimated storage capacitor value

V_{OUT} = Output voltage of the P2110

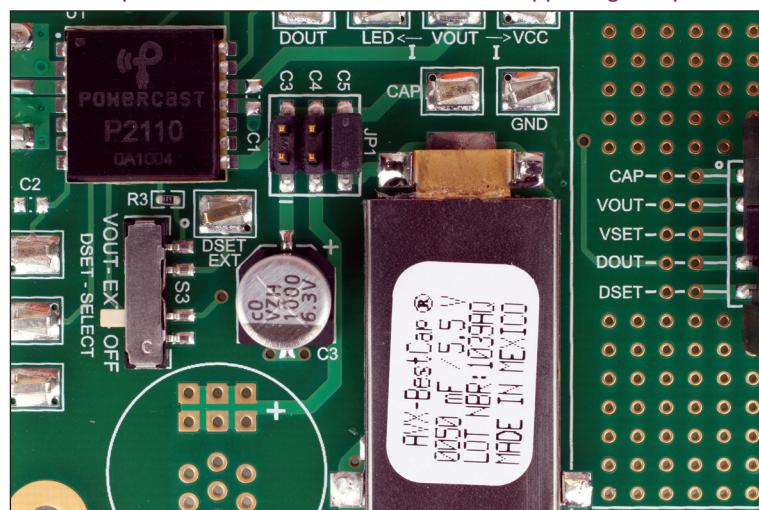
I_{OUT} = Average output current from the P2110

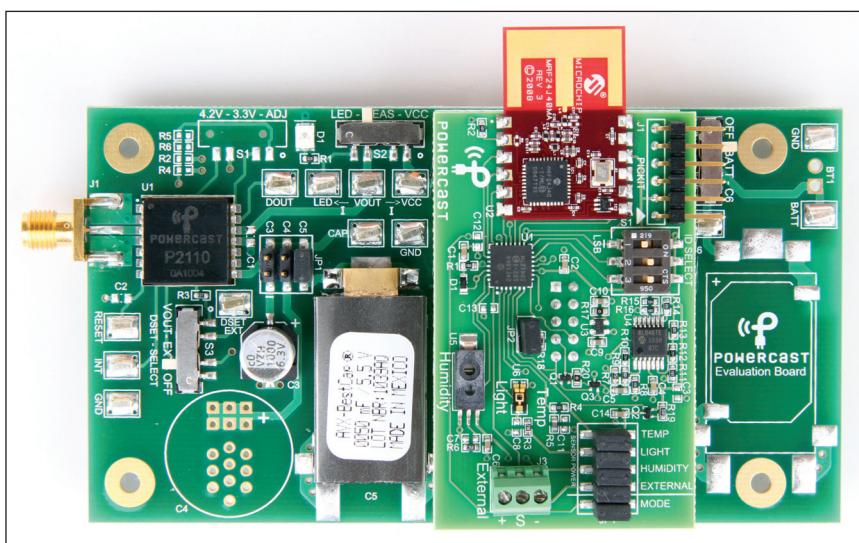
t_{ON} = On-time of the output voltage

If we hold V_{OUT} at a constant value, it's easy to see that as on-time increases, the value of the storage capacitor must increase. The same holds true for I_{OUT} . The storage capacitor value must increase as current output demand increases. I_{OUT} and t_{ON} are also inversely proportional as the more I_{OUT} you require, the less t_{ON} you get and vice versa.

When the capacitor charge threshold is reached, the boost converter comes into play and boosts the storage capacitor voltage to a preset level. The boosted voltage is presented to the load on the receiver's V_{OUT} pin. If the receiver's V_{SET} pin is not hosting an

■ PHOTO 3. The high quality 50 mF capacitor stores the converted RF energy. The capacitor to its left (C3) is a test capacitor. Note the absence of receiver supporting components.





output voltage adjust resistor, the boosted voltage on the V_{OUT} pin will be +3.3 VDC. The receiver can source up to 50 mA of current. When the capacitor is discharged to its low voltage threshold, voltage to the V_{OUT} pin is turned off. Thus, the receiver supplies an intermittent stream of regulated power. The energy delivered in a power cycle is dependent upon the required load current and the power cycle on-time. Typically, a 15 mS power cycle is sufficient to drive a low power RF-equipped sensor node.

Let's revisit **Figure 1** and talk about the rest of the receiver's pins. Some of the pin functions are obvious. So, let's begin with the analog output pin D_{OUT} which provides an analog voltage level that corresponds to the harvested power. Remember the transmitter ID that is encoded in the RF power stream? Well, with the help of some basic analog circuitry, the D_{OUT} pin also plays an important part in capturing the transmitter ID frame.

The active-high D_{SET} digital input redirects the harvested DC power to an internal sense resistor. As you can see in **Figure 1**, the harvested power is diverted from the V_{CAP} pin and the storage capacitor is not charged while D_{SET} is logically high. The sampled receive signal

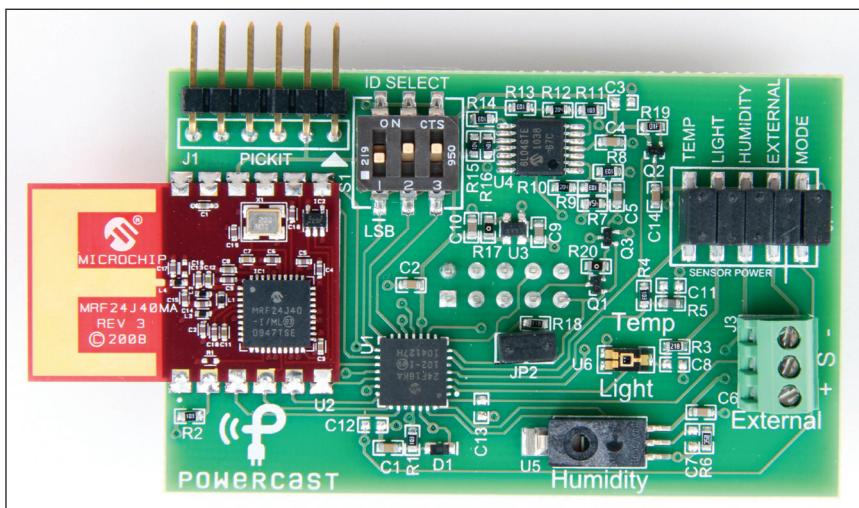


PHOTO 4. The P2110 Powerharvester receiver evaluation board has lots of hooks and is designed to be probed heavily. I took advantage of the hooks to grab a digital view of how the receiver behaves under the influence of the PIC24F16KA102 on the piggy-backed sensor module.

voltage is routed to D_{OUT} . Thus, an RSSI (Received Signal Strength Indicator) function is enabled in this way with the D_{SET}/D_{OUT} pin pair.

The P2110 receiver contains a voltage monitor subsystem that allows the voltage at the V_{OUT} pin to be turned off by applying a logical high to the RESET pin. Use of the RESET function allows the load voltage at V_{OUT} to be terminated before the storage capacitor reaches its low voltage threshold. Energy is conserved as the microcontroller

can use the RESET pin to cut power immediately upon the completion of its task. In our case, the task is reading and transmitting the sensor data. In that the storage capacitor is not allowed to reach its low voltage threshold, the recharge time to our maximum charge threshold is shortened. Using the RESET pin has its advantages in that a larger value storage capacitor can be used to supply more energy to the load without impeding operational recharge time.

The voltage monitor's INT pin is a digital output that goes logically high when voltage is present at the V_{OUT} pin. The logically high level of the INT pin falls between the V_{CAP} maximum and minimum voltage levels which are 1.25 and 1.02, respectively. If the amount of harvested energy increases to a point as to drive the V_{CAP} voltage level above 1.25 volts, the receiver will clamp the V_{CAP} voltage to less than 2.3 volts. Clamping the V_{CAP} voltage protects low voltage supercaps that are used as storage capacitors.

The receiver and the storage capacitor share real estate on the P2110 Powerharvester Receiver Evaluation Board which is acting as a motherboard for our sensor module in **Photo 4**.

WHERE THERE'S A PROBE, THERE'S PROBABLY A SIGNAL

The full brunt of the RF energy that is harvested by the P2110 receiver is aimed at the wireless sensor board you see in **Photo 5**. From left to right, the wireless sensor board is made up of a MRF24J40MA 2.4 GHz radio, a nanoWatt PIC24F16KA102

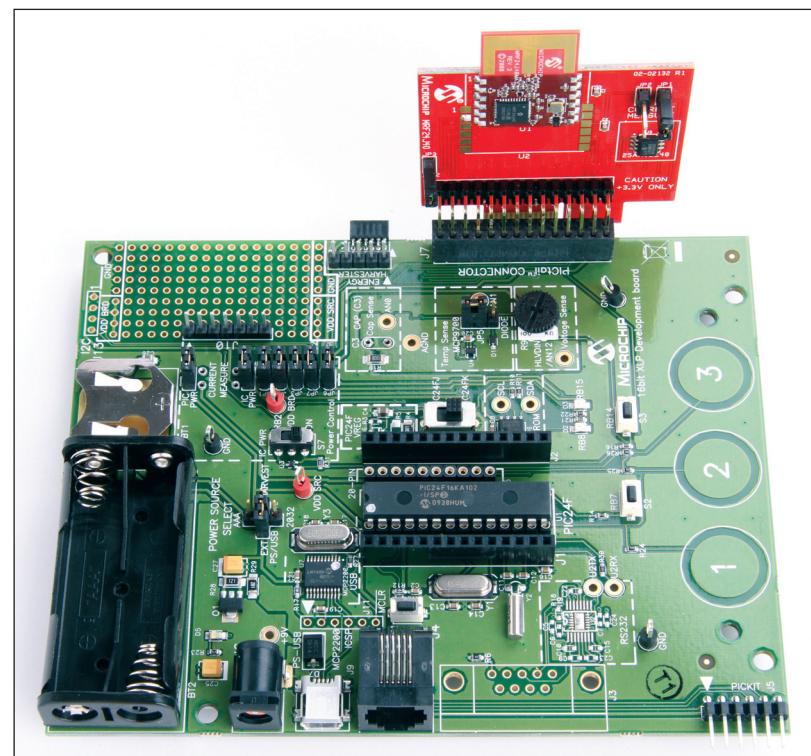
PHOTO 5. This is the typical rig a P2110 Powerharvester receiver would be assigned to. Every active component on this wireless sensor board has the ability — one way or another — to fall into a power-saving sleep mode. Note the PICkit connector.

■ PHOTO 6. This is the access point whose sole purpose in this application is to gather the sensor data from wireless sensor boards and present it to humans via HyperTerminal.

microcontroller, a 3.0 volt LDO voltage regulator, an MCP6L04 operational amplifier, and a trio of sensors. There's also a PICkit programmer portal for those that want to roll their own code.

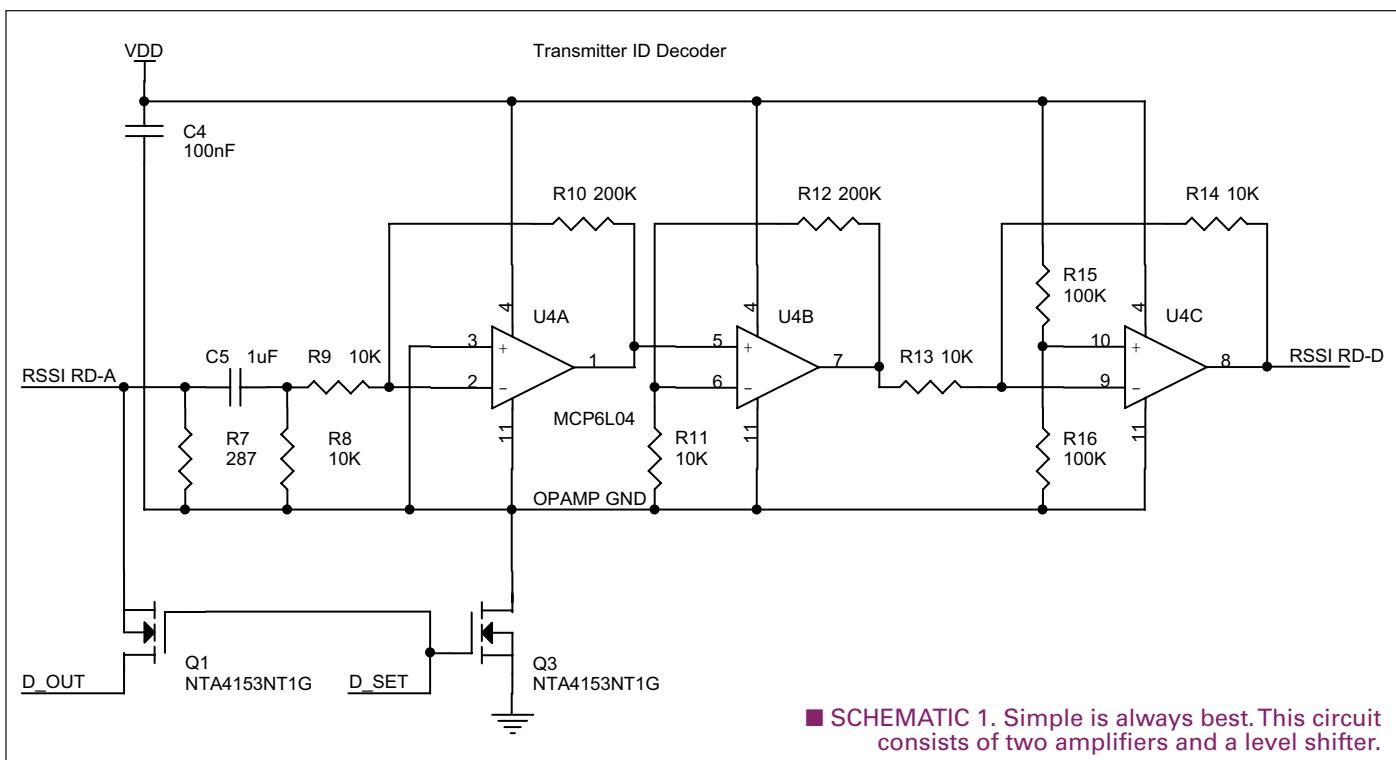
The MRF24J40MA mounted on the wireless sensor board is used by the PIC24F16KA102 to transmit the sensor data to an access point. Our access point — which is actually a Microchip XLP 16-bit development board — is under the lights in **Photo 6**. Basically, the access point is an MRF24J40MA coupled to a PIC24F16KA102 that supports an MCP2200 USB portal. The PIC24F16KA102's task is to collect and process the incoming sensor data and prepare it for display via a HyperTerminal session.

Recall that the 915 MHz Powercaster transmitter encodes its transmitter ID into the RF energy stream. The access point's application expects to see the transmitter ID in the wireless sensor board's sensor data stream. That means that the wireless sensor board must contain circuitry to decode the transmitter ID. The RF portion of the transmitter ID decode task is taken care of by the receiver. The transmitter modulates the transmitter ID using ASK (Amplitude Shift Keying). The receiver provides the demodulated transmitter ID logic levels at its D_{OUT} pin. The D_{OUT} logic levels — which are in RS-232 frame format — must be boosted to 3.0 volt logic levels before feeding them to the PIC24F16KA102's UART. That's



where the MCP6L04 shines. The MCP6L04 is a quad rail-to-rail op-amp that only requires 85 μ A of current for normal operation.

Let's walk the transmitter ID signal through it decoder circuit outlined in **Schematic 1**. The assigned PIC I/O pin drives D_SET logically high. At this point, the wireless sensor board application awaits the transmitter ID frame. Driving D_SET logically high turns on MOSFETs Q1 and



■ SCHEMATIC 1. Simple is always best. This circuit consists of two amplifiers and a level shifter.



■ SCREENSHOT 1. This CleverScope capture freezes the transmitter ID bit stream. Thanks to the MCP6L04, the bits presented to the PIC24F16KA102's UART transition are between 0 and +3.0 volts.

very beginning.

The 915 MHz transmitter is correctly positioned and powered up. A power stream of 915 MHz RF energy begins to emanate from the transmitter's integral antenna. Wireless sensor board antennae in the range of the transmitter soak up the RF energy and begin to feed it to the receiver. Each wireless sensor board is addressable via a three-position DIP switch. So, for the purposes of this discussion, let's concentrate on the wireless sensor board with a node

address of 5 which is within range of the transmitter with an ID of 130.

At this point, the receiver is busy charging Node 5's 50 mF storage capacitor. Once the storage capacitor reaches its charge threshold, +3.3 volts appears on the receiver's V_{OUT} pin. The rising edge of V_{OUT} triggers the Saleae logic analyzer capture as power is applied to the number 5 wireless sensor board.

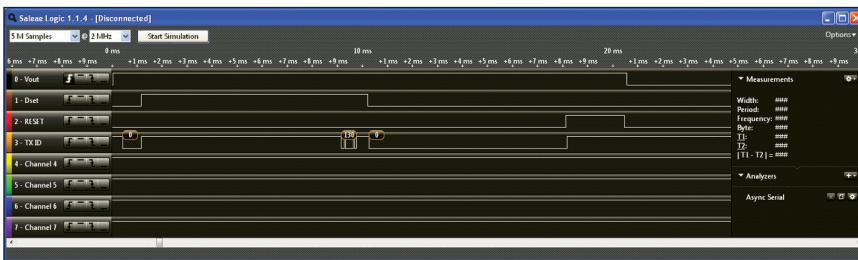
With power applied, the PIC24F16KA102 performs a POR (Power On Reset) and the sensor application is kicked off. Before the sensors are powered up, the wireless sensor board application attempts to retrieve a valid transmitter ID. According to the Saleae logic capture in **Screenshot 2**, 1.149 ms after power appears at V_{OUT} , the PIC24F16KA102 initializes the wireless sensor board, obtains the board's node address, sets the receiver D_{SET} pin, enables the UART, and waits for the UART to fish out a valid RS-232 frame:

```
// Initialize the system
BoardInit();
GetBoardID();
// Turn on circuit to read TX ID,
// and enable reading of RSSI later
PC_DSET = 1;
// Clear UART1 read buffer
U1RXREG;
U1RXREG;
U1RXREG;
U1RXREG;
// Clear RX buffer ready flag
IFS0bits.U1RXIF = 0;
// Enable UART1, used to read in TX ID
U1MODEbits.UARTEN = 1;
// Wait for UART1 to see a valid TXID
while(!IFS0bits.U1RXIF);
```

Pay particular attention to the comment "and enable reading of RSSI later." Let's revisit **Schematic 1** (the transmitter ID

THE DIGITAL VIEW

Pulling the transmitter ID out of the air is just one piece of the total power cycle. **Screenshot 2** is a Saleae logic analyzer view of a typical P2110 receiver power cycle. The Saleae logic analyzer sequence is triggered on the rising edge of the V_{OUT} pin, which corresponds with the initial application of power to the wireless sensor board. Let's walk through a receiver power cycle from the



■ SCREENSHOT 2. This is a digital capture of an actual Powercast P2110 Powerharvester receiver power cycle under the control of the PIC24F16KA102-equipped Powercast wireless sensor board you see in Photo 5.

decoder). When D_SET is driven logically high, MOSFET Q1 opens a signal path from the receiver's D_{OUT} pin to RSSI RD-A (RSSI READ Analog) which is the input of the transmitter ID decoder hardware module. What you don't see in **Schematic 1** is that the analog signal at RSSI RD-A is also routed to an analog-to-digital input on the PIC24F16KA102. So, while D_SET is logically high, an RSSI measurement is taken at RSSI RD-A during the sensor read task.

When a valid transmitter ID byte is received, it is saved for transmission by the MRF24J40MA in the 2.4 GHz sensor data stream and the analog-to-digital sensor read task is invoked. If a valid transmission ID is not received, the TXID value is set to 0xFFFF which indicates a transmitter ID receive error and the sensor read task is invoked. The termination of the sensor read task is indicated by forcing D_SET logically low. The Saleae logic digital capture in **Screenshot 2** tells us that the D_{SET} logical high duration for this power cycle was 9.031 ms.

The Saleae logic analyzer can be configured to capture and decode asynchronous serial data streams. So, I assigned an async serial analyzer to the Saleae logic analyzer's TXID input. As you can see in the capture, the transmitter ID was detected 7.9685 mS into the logically high D_{SET} period and decoded as 130 decimal (0x82 hexadecimal). Since all of the sensor read activity ended at the falling edge of D_{SET}, the sensor read task was completed in 0.4575 mS. Here's how the code fell into place during the remaining moments of the D_{SET} interval:

```
IFS0bits.U1RXIF = 0;      // clear UART1 ready flag
TXID = U1RXREG;           // read UART1 buffer
TXID_Check = TXID & 0x0100; // used to check for
                           // valid ID

// If an error occurred while reading the TXID,
// wait for another one
if (U1STAbits.FERR == 1 || TXID_Check != 0)
{
    while(!IFS0bits.U1RXIF);

    IFS0bits.U1RXIF = 0;
    TXID = U1RXREG;
    TXID_Check = TXID & 0x0100;

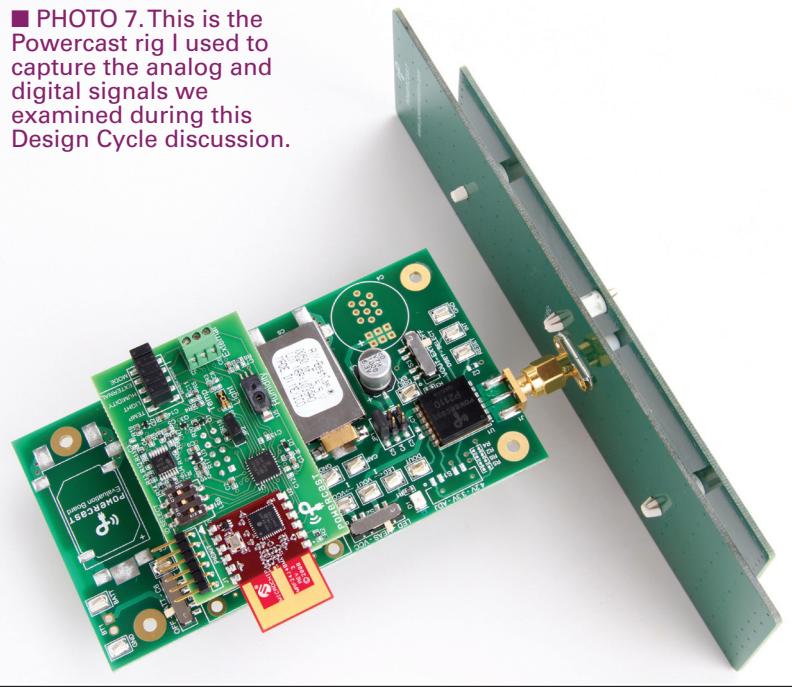
    // This time, if an error occurred
    // transmit the error code
    if (U1STAbits.FERR == 1 || TXID_Check != 0)
    {
        TXID = 0xFFFF;
    }
}

// Disable UART1
U1MODEbits.UARTEN = 0;

// Get all sensor data
AdcRun();
// Turn off TX ID receiver
// circuit, and disable RSSI
PC_DSET = 0;
```

The quest for a valid transmitter ID involves a total of

■ PHOTO 7. This is the Powercast rig I used to capture the analog and digital signals we examined during this Design Cycle discussion.



two tries before the UART is deactivated. The sensors are powered up and read along with the RSSI voltage in the AdcRun() function. Once all of the sensor data and RSSI data are captured, the D_{SET} pin is forced logically low by the PIC24F16KA102 and the sensor task ends.

The remainder of the receiver power cycle (7.931 mS) is used to assemble and transmit the sensor data to the access point. Upon completion of the transmit cycle, the PIC asserts the RESET signal and terminates the voltage at the receiver's V_{OUT} pin. At this point, the power cycle is complete and the charging of the storage capacitor commences. The good news is that the assertion of the RESET signal does not allow the storage capacitor to reach its low voltage threshold. Thus, the storage capacitor recharge time is dramatically decreased.

The actual receiver power cycle time is 18.11 mS. The additional 2.4195 mS of power at V_{OUT} captured after the rising edge of the RESET signal is not being emitted by the receiver V_{OUT} pin.

At worst case, if there's enough energy available, the PIC falls into SLEEP mode after forcing the receiver's RESET line logically high:

```
MiApp_BroadcastPacket(FALSE); // Send packet
PHY_RESETn = 0;
PC_Reset = 1;               //force P2110 Power
                           //harvester Receiver HIGH
Sleep();
while(1);
```

When the PIC24F16KA102 drives RESET logically high, the wireless sensor board sensors are not being powered. If the PIC managed to execute the SLEEP instruction, it is drawing minimal current. The receiver's V_{OUT} pin is driving the input of the 3.0 volt LDO voltage regulator and a 1.0 μ F voltage regulator input capacitor. The charge held in the 1.0 μ F voltage regulator input

```

powercast - HyperTerminal
File Edit View Call Transfer Help
Packet #15585 | Node 5 | TX ID 130 | Temp 76.1 F | Light ---- 1x
Time 03:51:15 | dT 00:00 | RSSI 4.66mW | Humidity 46 % | Extrnl 0 mV
Packet #15586 | Node 5 | TX ID 130 | Temp 76.1 F | Light ---- 1x
Time 03:51:17 | dT 00:02 | RSSI 4.31mW | Humidity 46 % | Extrnl 0 mV
Packet #15587 | Node 5 | TX ID 130 | Temp 76.1 F | Light ---- 1x
Time 03:51:17 | dT 00:00 | RSSI 4.66mW | Humidity 46 % | Extrnl 0 mV
Packet #15588 | Node 5 | TX ID 130 | Temp 76.1 F | Light ---- 1x
Time 03:51:18 | dT 00:01 | RSSI 4.46mW | Humidity 46 % | Extrnl 0 mV
Packet #15589 | Node 5 | TX ID 130 | Temp 76.2 F | Light ---- 1x
Time 03:51:19 | dT 00:01 | RSSI 4.14mW | Humidity 46 % | Extrnl 0 mV
Packet #15590 | Node 5 | TX ID 130 | Temp 76.2 F | Light ---- 1x
Time 03:51:20 | dT 00:01 | RSSI 4.66mW | Humidity 46 % | Extrnl 0 mV
Packet #15591 | Node 5 | TX ID 130 | Temp 76.3 F | Light ---- 1x
Time 03:51:21 | dT 00:01 | RSSI 4.46mW | Humidity 46 % | Extrnl 0 mV
Packet #15592 | Node 5 | TX ID 130 | Temp 76.2 F | Light ---- 1x
Time 03:51:22 |

```

Connected 3:04:15 Auto detect 19200 8-N-1 SCROLL CAPS NUM Capture Print echo

■ **SCREENSHOT 3.** The access point application provides the packet number, time, and delta time. The raw data for the node, TX ID, RSSI, temp, humidity, light, and external display entries originated at the wireless sensor board.

capacitor is the only power source that is active. As shown in the Saleae logic capture, it takes 2.4195 mS for the charge on the voltage regulator input capacitor to dissipate.

POINTY HATS AND FEATHERS

Well, it looks like those guys and gals that wear those funny looking pointy hats adorned with moons and stars have done it again. Powering a PIC and a 2.4 GHz radio from radio waves is indeed a feather in their pointy caps.

THE REST OF THE STORY

Screenshot 3 represents the HyperTerminal output supplied by the access point application. The raw data used to produce the data in **Screenshot 3** originated in the Powercast equipment shown in **Photo 7**.

Every bit of Powercast code and every electrical connection we've discussed can be yours for a download from the Powercast website. The only thing you can't get from the website is the Saleae logic capture which is available from the Nuts & Volts site. Download the Saleae logic software if you want to use my session capture to double-check my timings.

The folks at Powercast figured you'd want to add their transmitter and receiver to your Design Cycle. So, they included a Microchip PICkit3 in the standard equipment included with the Powercast Lifetime Power Energy Harvesting development kit for wireless sensors. **NV**

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SOURCES

Powercast Corporation

Powercast P2110 Powerharvester Receiver
Powercast 915 MHz Powercaster Transmitter
Powercast Wireless Sensor Board
Powercast Lifetime Power Energy Harvesting Development Kit for Wireless Sensors
www.powercastco.com

Microchip

XLP 16-bit Development Board (Access Point)
MRF24J40MA PICtail Daughter Card
PICkit 3 Programmer
www.microchip.com

Saelig Company

CleverScope
www.saelig.com

Saleae

Logic Analyzer
www.saleae.com