Integrated ZigBee Radio Implementation and Testing

APPLICATION NOTE

When designing embedded ZigBee (or other IEEE 802.15.4 based protocol) radio solutions, there are several trade-offs in the level of integration into the end-product that are available.

The challenge is to balance the level of integration and development costs base against the performance requirements of the end use application. As low cost radio technologies proliferate through many electronic product applications, streamlining validation and verification of ZigBee module performance is important. This application note demonstrates the utility and simplicity of the Tektronix MDO4000 Series Oscilloscope to validate and verify ZigBee radio module integration.

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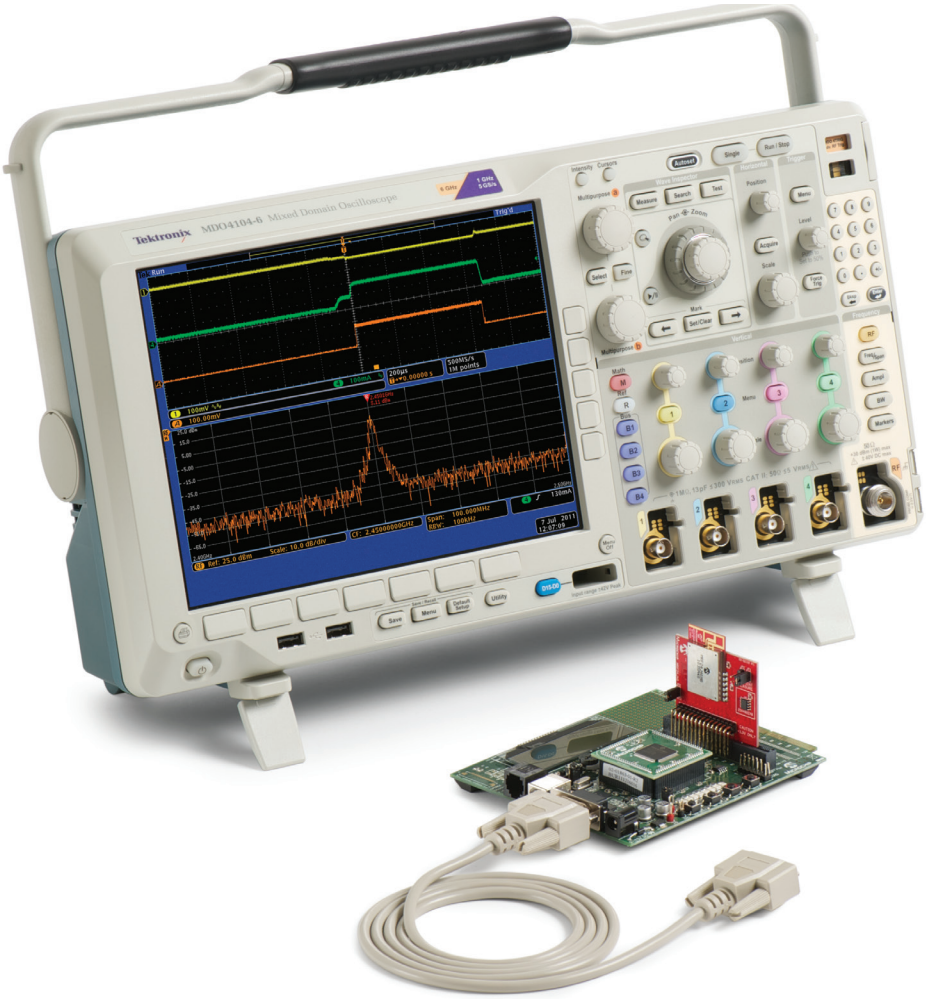

Figure 1. Tektronix MDO4000 Series Mixed Domain Oscilloscope and Microchip Radio Test Board Module.

Embedded Integrated ZigBee Modules

The IEEE 802.15.4 physical layer radio has proven very popular for a wide range of short range control and data communications applications. The ZigBee protocol provides a mesh network of devices so that large areas and hundreds or even thousands of devices can communicate. At least in theory, ZigBee compliant devices from different sources can communicate with each other. There are a variety of vendors of IEEE 802.15.4 protocols that typically offer fewer features and simpler software that might work in a specific application with limited or specific functionality.

Applications for these radio systems include home and commercial building automation, energy monitoring and control, security systems, medical monitors, and a wide variety of commercial and industrial products.

A rich support structure has developed around this set of communications standards at both bare integrated circuit level and modules which typically come complete with the antenna and FCC or other regional agency approval. There are two further options for each of integrated circuits (ICs) and modules. Embedded products are available with just the radio circuitry with the IEEE 802.15.4 lower level protocol requiring a separate microcontroller or microprocessor to handle the ZigBee or other higher level software as well as the application. Alternatively, there are ICs as well as modules that have a microcontroller built in to run the ZigBee or other protocol software. Many of these ICs and modules have uncommitted I/O pins so that a complete product may need little more than the module and sensors and/ or actuators and an enclosure. In addition, modules are available with power amplifiers and receiver low noise preamplifiers (LNA). The power amplifier and LNA can substantially increase the radio range, though at higher cost and power consumption.

For any of these choices, a printed circuit test board will be needed to support the IC or module. A power supply with sufficient peak power and freedom from noise will also be needed. If a chip level radio is selected, the appropriate antenna interface circuits will also be needed.

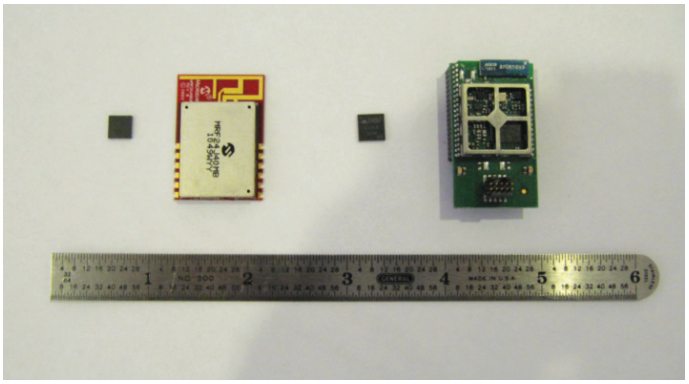

Figure 2. Examples of typical ZigBee radio options from different vendors can be supplied with different levels of integration, from radio IC to fully integrated module with microcontroller, power amplifier, antenna, and LNA.

Figure 2 shows from left to right a radio only IC (the Microchip Technologies MRF24J40), a radio only module with a 100 mW power amplifier and LNA (Microchip MRF24J40MB), a radio and microcontroller IC (Ember EM357), and a radio module with microcontroller and external power amplifier and LNA (Ember EM357-MOD).

ZigBee Design Considerations

While there are a variety of end-use applications and thousands of products that use ZigBee technologies, there are also a number of trade-offs in selecting from among the types of radio systems for any one application. These include:

1. **Cost –** There is a substantial trade-off of material cost vs. the cost of engineering and agency approval for modules compared to ICs. Modules cost substantially more that the radio ICs with their support components and assembly labor even in large quantities. Part of the extra cost lies in the duplicated printed circuit board material, but most of it is in offsetting the engineering cost of the module and in providing a return to the module manufacturer. However, engineering the radio circuitry and gaining agency approval has substantial cost. For IC based designs, ZigBee Alliance testing and approval adds to the cost if this protocol is to be used. Experience suggests that the cost breakeven between integrating ICs vs. modules is typically around 10,000 to 25,000 units.
2. **Development Time –** Pre-certified modules can be marketed as soon as the product is ready. Agency approvals for IC level designs can take as little as a month, but often much longer than that. Generally this time is added to the development process because the product needs to be in close to final form and the software also needs to be essentially complete before the approval testing can begin.
3. **Form Factor –** Designing a custom radio from the IC level provides flexibility in the configuration of the radio circuitry. With a custom design, the radio can use spaces that no module can fit into given the overall configuration of the product. Generally the available modules have all of their parts on one side of the printed circuit board so that the module can be soldered to the main board. In a custom design, parts can be placed in any configuration and on both sides of the board.
4. **Protocol Flexibility –** Many manufacturers of modules and of ICs with an embedded microcontroller do not provide access to the source code of the ZigBee or other communications software. This means that if there is a desire or need for custom features there is little recourse if the vendor does not provide this feature.
5. **Special Requirements –** For some applications, there may be a need for hardware capabilities beyond what is available in modules or ICs that have the radio and microcontroller integrated. While it is always an option to add a second microcontroller, the total cost can be increased beyond what is needed. In other cases, it may be desired to provide capabilities not commercially available. For example, the US regulations allow up to 1 Watt of radio output power, but there are few, if any, modules with this capability.
6. **Antenna Type and Placement –** There are modules available with antennas on the printed circuit board either as a printed pattern like on the Microchip module or a “chip” antenna like on the Ember module, with an external antenna. An antenna on the module can have impaired performance if the antenna is inside of a shielding enclosure or if it is located too close to other components in the end package design. There are modules available with connectors for external antennas. However, it is only legal to use antennas that have been certified with the module. If there is a reason, such as the need for higher gain, to use an antenna not supported by the module vendor, agency approval with its accompanying cost and time are required.

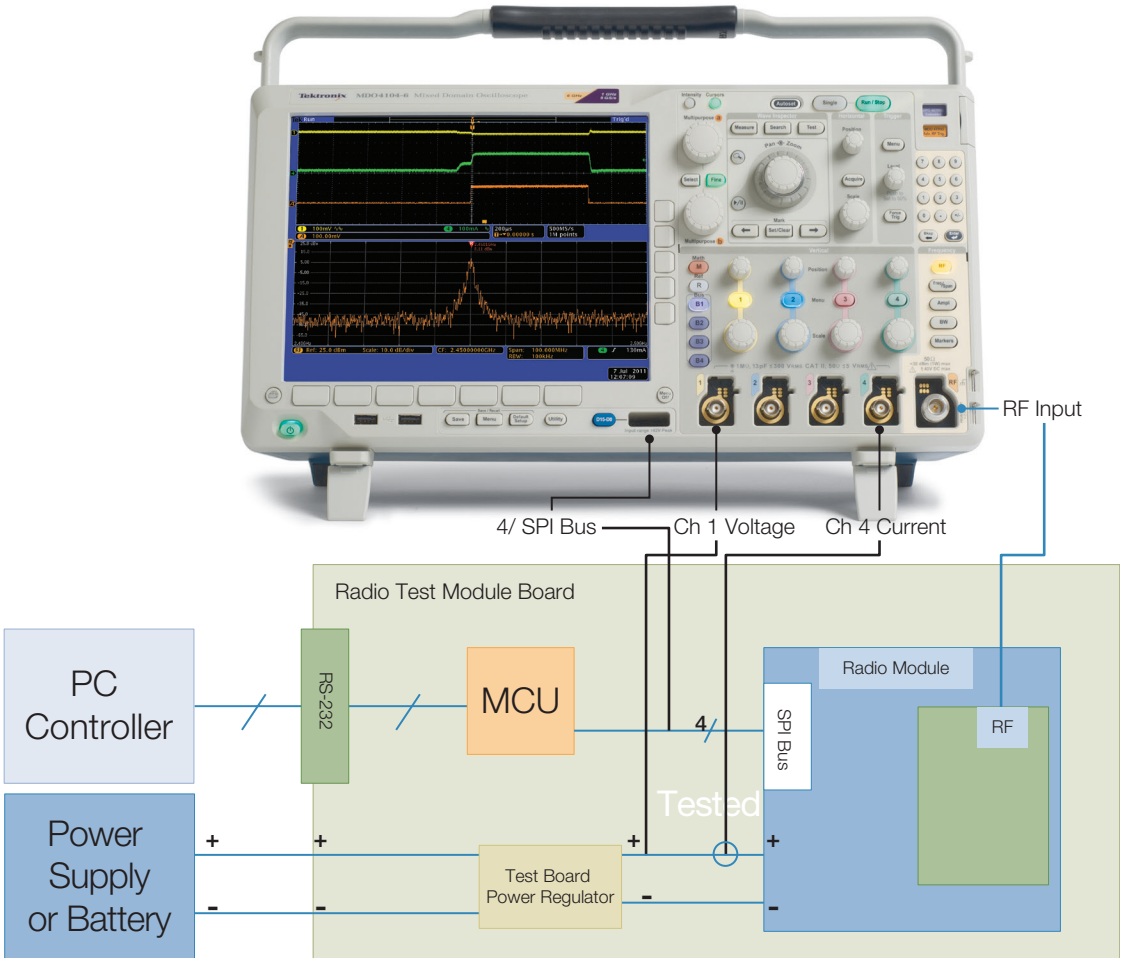

Figure 3. Test connection between the (Microchip Technologies MRF24J40MB and Explorer 16 demonstration board) ZigBee radio module/test board and the MDO4000 Series Mixed Domain Oscilloscope.

Test Validation of the integrated radio

Once the approach to the radio implementation is selected, the appropriate printed circuit board laid out, and any necessary software written, there are a number of tests to be performed to assure good communications:

For many applications, there will be serial communications between the radio system and other parts of the product. For example, the Microchip IC and modules use a four wire SPI connection to control the radio IC and any related components such as a power amplifier. SPI commands are needed to set internal registers for the selection of the frequency channel, the output power level, and many other operating parameters. SPI is also used to control general purpose port pins for control of a power amplifier, or other devices. SPI is also used to send the data packet to the IC or module and sends the command to transmit the packet. Received data is returned through the SPI bus as well.

Software in the microcontroller (whether integrated or separate) needs to provide the higher levels of the protocol (ZigBee or other) as well as control the power to the radio, and run other aspects of the product. In many applications timing of the radio transmission is critical so that the radio is not transmitting while some other power consuming part of the product is running and draining the power supply voltage below acceptable levels.

To illustrate some of the tests that should be carried out to verify radio operation, a Microchip Technologies IEEE 802.15.4 amplified radio module (MRF24J40MB) is used with an Explorer 16 demonstration board. The screen shots are taken with the Tektronix MDO4000 Series Multi Domain Oscilloscope which allows simultaneous time correlated viewing of RF, analog, and digital signals. Setup and data commands are sent from a PC to allow manual control. Figure 3 shows the test setup. Note that a direct connection to the radio is used to facilitate power and other measurements. A calibrated antenna could equally have been used to take the RF measurements.

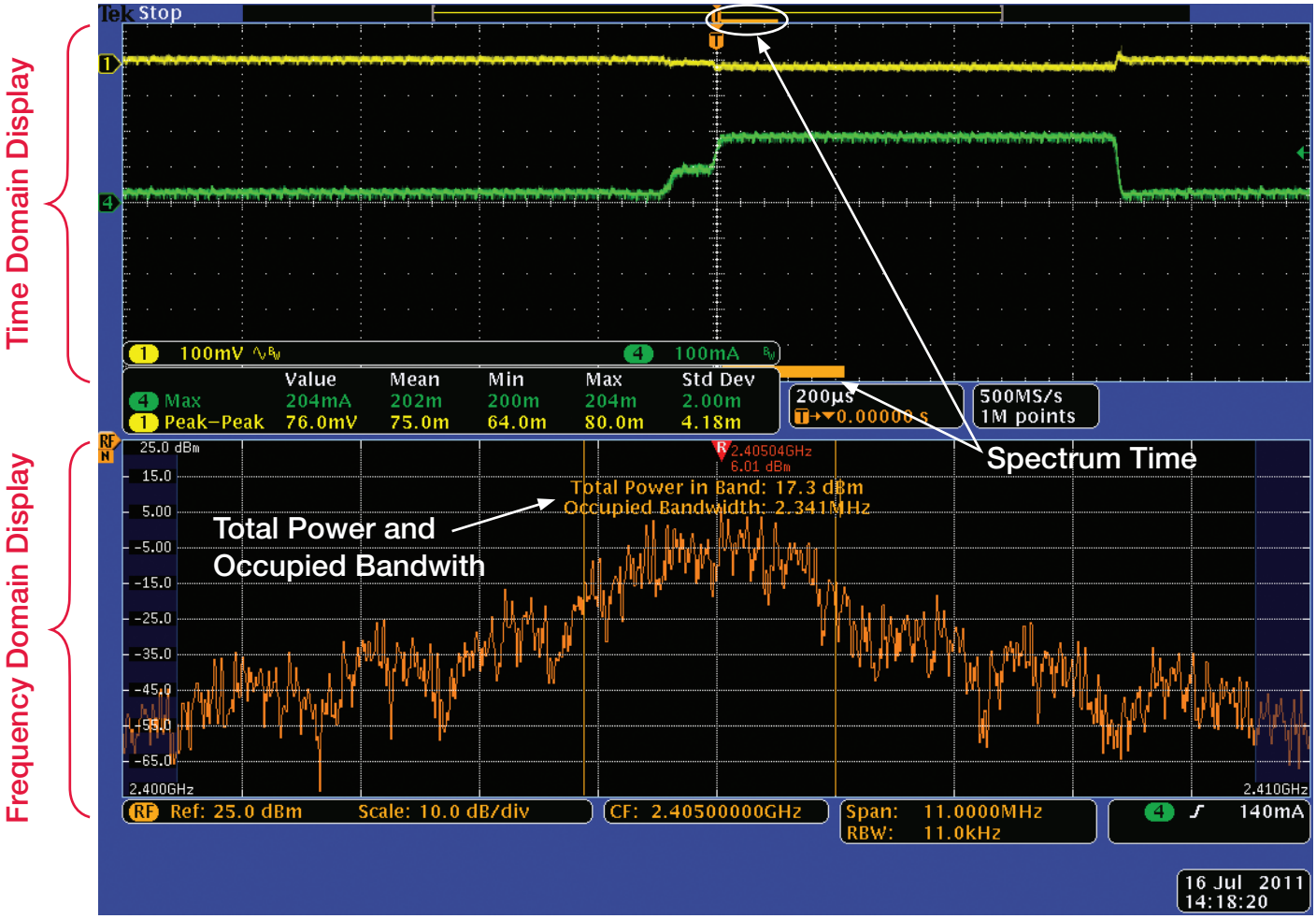

Figure 4. Time Domain and Frequency Domain displays. Orange Bar represents the spectrum time of the frequency domain display relative to the time domain measurements.

Some of the critical tests to verify radio operation are:

RF and Power Supply Measurements – The Tektronix MDO4000 Series Mixed Domain Oscilloscope is unique in that it allows simultaneous viewing of the radio spectrum and the power supply as shown in Figure 4.

The channel spacing for IEEE 802.15.4 (including ZigBee) is 5 MHz. The 20 dB channel bandwidth should be significantly less than the channel spacing. The measured occupied bandwidth of 2.3 MHz shown in the Figure is well within the specification. The output power is expected to be in the range of 20 dBm. The screen shows the output spectrum in the lower part of the screen and direct measurements of bandwidth and power. The test cable drop is about 2 dB in this frequency range, so the power measurement is in the range of what is expected.

The Orange Bar at the bottom of the top half of the screen indicates the time period in which the spectrum trace is displayed. The spectrum time is defined as the Window Shaping Factor divided by the resolution bandwidth. In this example, using the default Kaiser FFT function (Shaping Factor 2.23) and the RBW of 11 kHz, the spectrum time is approximately 200 us. Moving the spectrum bar across the time domain window allows the spectrum and measurements to be taken at any time during the packet transmission. This acquisition correlates just after turn-on of a radio packet transmission.

The Tektronix MDO4000 Series Oscilloscope RF acquisition can perform Power and Occupied Bandwidth measurements of the RF signal. Because it also acquires a time record of the RF acquisition, a digital downconversion process can be used to produce the I (Real) and Q (Imaginary) data. Each I & Q data sample represents the instantaneous deviation of the RF input from the current Center Frequency. With this analysis, the RF Amplitude versus Time can be computed from the recorded data.

Figure 5. Measurements of power and occupied bandwidth, with correlated RF amplitude vs time, and measurements of the power supply current and drain voltage.

Figure 5 shows the added trace of the RF Amplitude versus time added to the display of Figure 4. This demonstrates that the events of the current and voltage measurements shown in Figure 5 correlate to the turn-on of the RF transmission.

The Green Trace (Trace 4) shows the current drawn by the module. During packet transmission, the current draw is almost 200 mA (note the direct measurement of 174 mA), so the power supply must be designed to support this load. The Yellow Trace (Trace 1) shows the effect of this current draw on the supply voltage. The drop is only about 70 mV which should be fine (note the direct peak to peak measurement of 72 mV).

The Orange Trace (Trace *A*) in the upper part of the screen shows the RF signal amplitude versus time. The input current rises in two steps. In the first step, the radio IC is turned on. There is then a delay to allow the frequency synthesizer to stabilize before the power amplifier is turned on. The rise of RF power coincides with the second part of the current step. The turn-on period appears to be approximately 100 us.

Figure 6. Spectrum and measurements with resistance in series with the module power source to study low power performance behavior.

In Figure 6, a 1.5 Ohm resistor is placed in series with the module to simulate the effect of a depleted battery. The current drawn by the module is only a few milliamps lower, but the voltage drop is about 230 millivolts. Note that the output power is reduced by 1 dB as measured by the RF power measurement and there is a slight increase in the adjacent channel noise can be seen in the spectrum display. The lower output can also be seen on the amplitude versus time (Trace *A*). It is often necessary to understand the performance of radio transmitters during low battery conditions or conditions when the power supply becomes current limited to understand the margins of radio compliant performance.

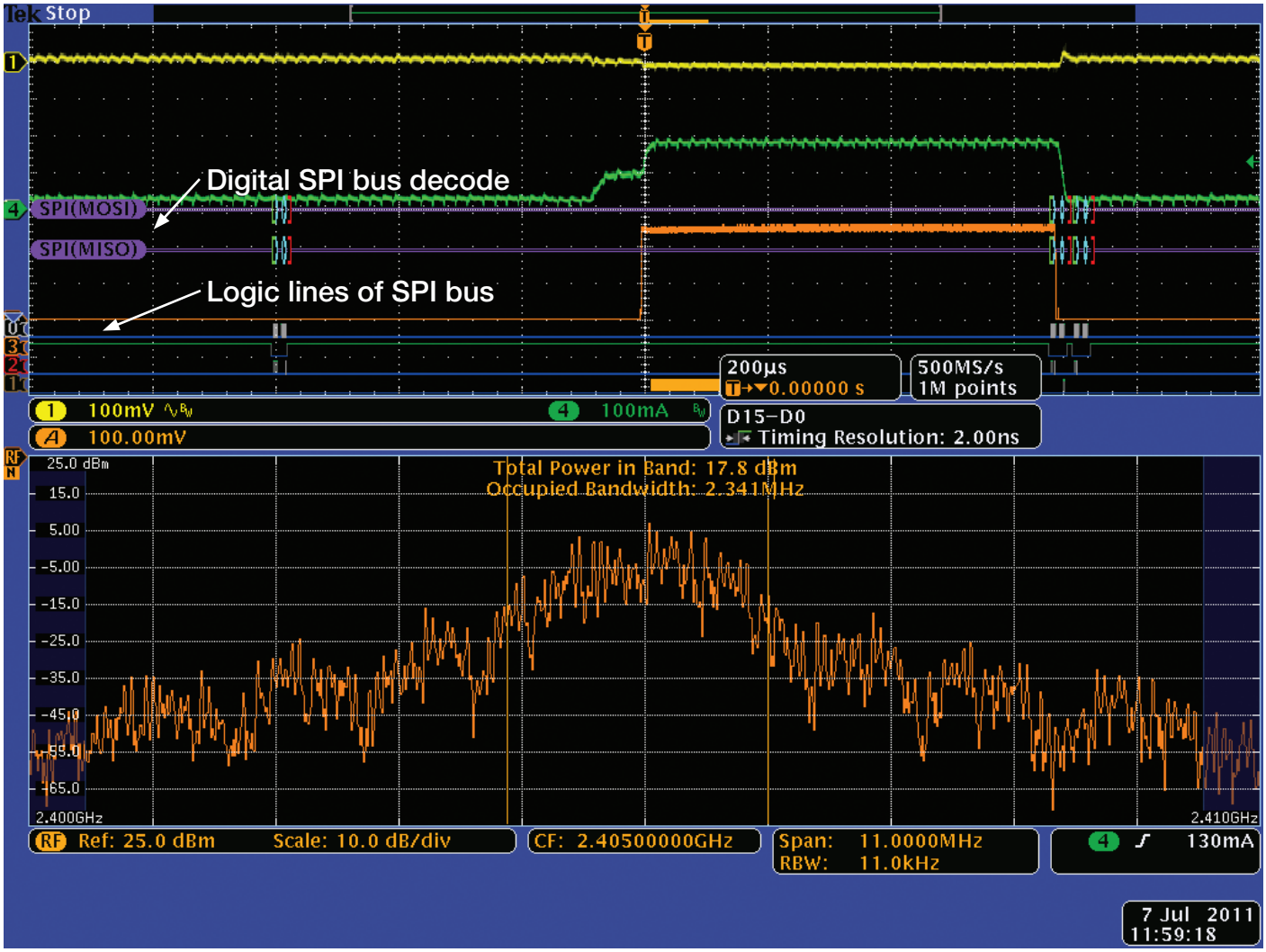

Figure 7. Packet decode of SPI Digital signals (SPI - MOSI and MISO) added to display.

Digital Commands – Radio ICs and modules will need to be set up to meet the operating requirements of the specific application and any protocol specific setups. The MDO allows decode of the SPI commands to the ZigBee module. Figure 7 shows the digital capture of the SPI commands in the same time frame as Figure 4. Decode is enabled, but is not readable in this time scale.

In Figure 7, the analog, digital, and RF acquisitions have been set trigger on the drain current of Trace 4 occurring above 130 mA level. All the time domain measurements in the upper display left of center show the events that occur prior to the current exceeding this level at RF turning on. This includes digital decode, analog (voltage and current), and RF vs time. From this information, it is easy to see that a digital command occurs roughly 600 microseconds before the RF event turn-on.

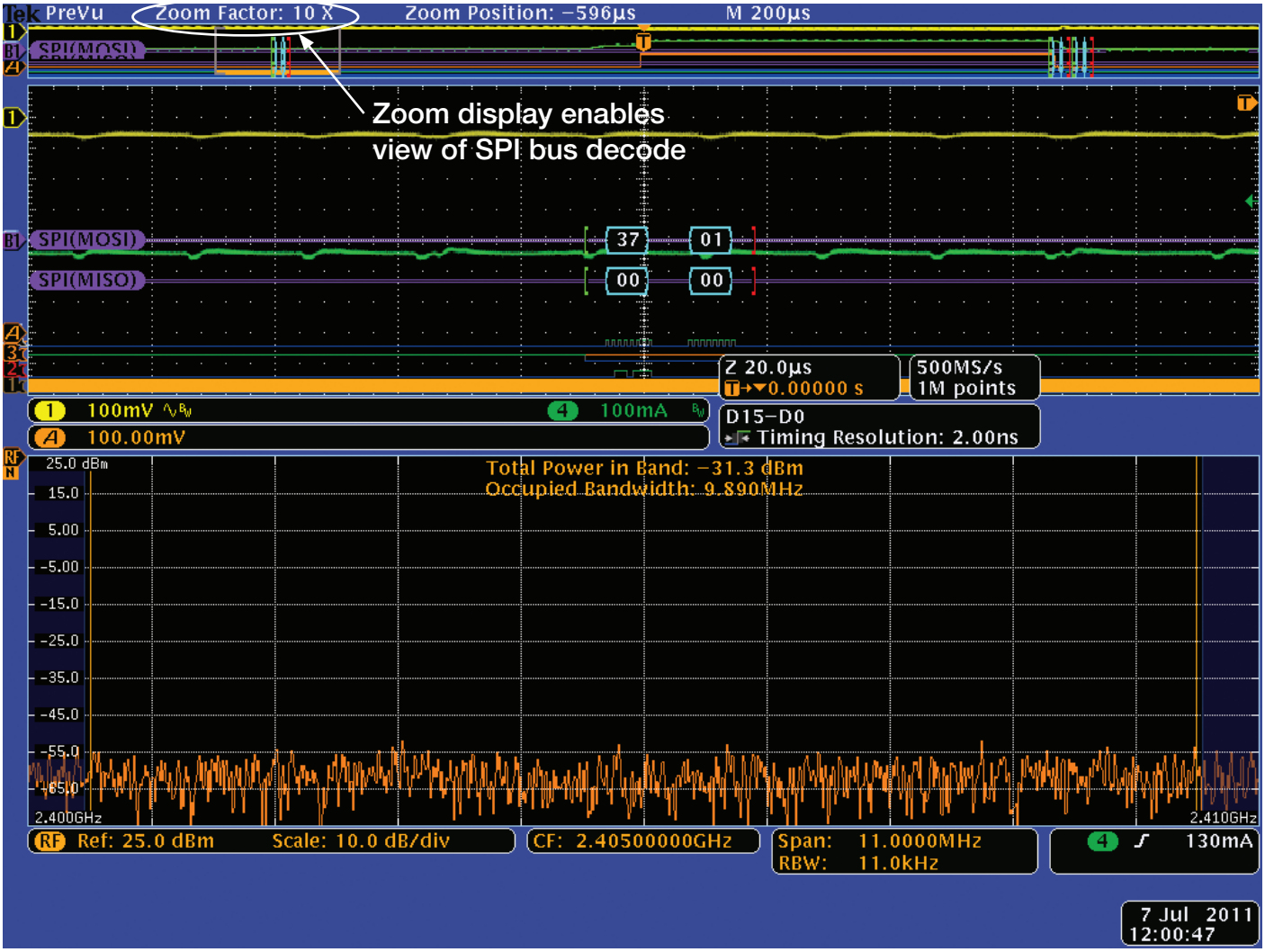

Figure 8. Magnified view of digital trace and decode. Notice the spectrum time is now viewing the RF Spectrum before the transmission is turned on.

The traces in purple show where the decoded data is in the time domain. In Figure 8, the MDO Wave Inspector pan and zoom functions are used to allow reading of the digital waveforms and the decoded data.

The SPI(MOSI) trace shows the commands to the module in hex format. In this case the command {37} is the command to the Transmit trigger (TXNMTRIG) register and the argument {01} tells the module to send the packet in the transmitter FIFO which has been determined to occur about 600 microseconds later. The digital waveforms are shown, but the automatic decode is much easier to read than the digital signals.

Other commands and data read back on SPI(MISO) can be read or triggered to confirm correct commands and verify operation of the radio.

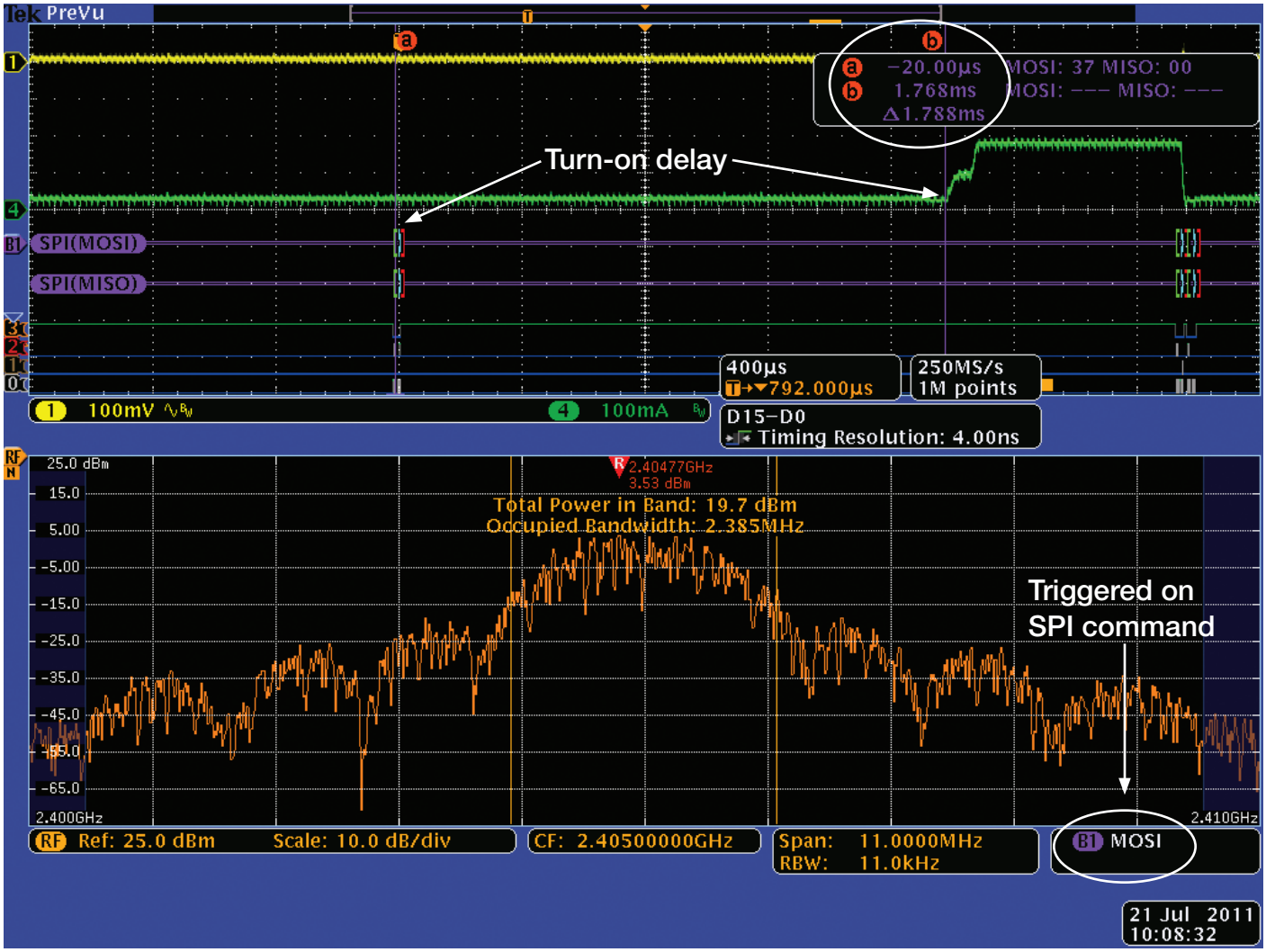

Figure 9. Subsequent acquisition triggered on SPI command shows delay between command and radio turn-on.

The unique architecture of the Tektronix MDO Series Mixed Domain Osciiloscope allows simplified measurements between SPI command triggering and correlated RF events. In Figure 9, the trigger event is now changed to the SPI command {37}, the radio Transmit trigger command. Markers on the Time Domain display show the SPI command to current draw (at the beginning of the RF Tx turn-on) is now 1.768 ms.

In the previous example from Figure 7, the command delay to turn-on was about 600 us. The actual event in Figure 9 is almost three times longer. This demonstrates the behaviour of the ZigBee radio is actually complying to one of the PHY layer performance requirements of IEEE 802.15.4. The ZigBee radio uses a pseudo-random delay between command and turn-on event to enable the radio to listen for other ZigBee radio trasnmitters or other radio interference channels.

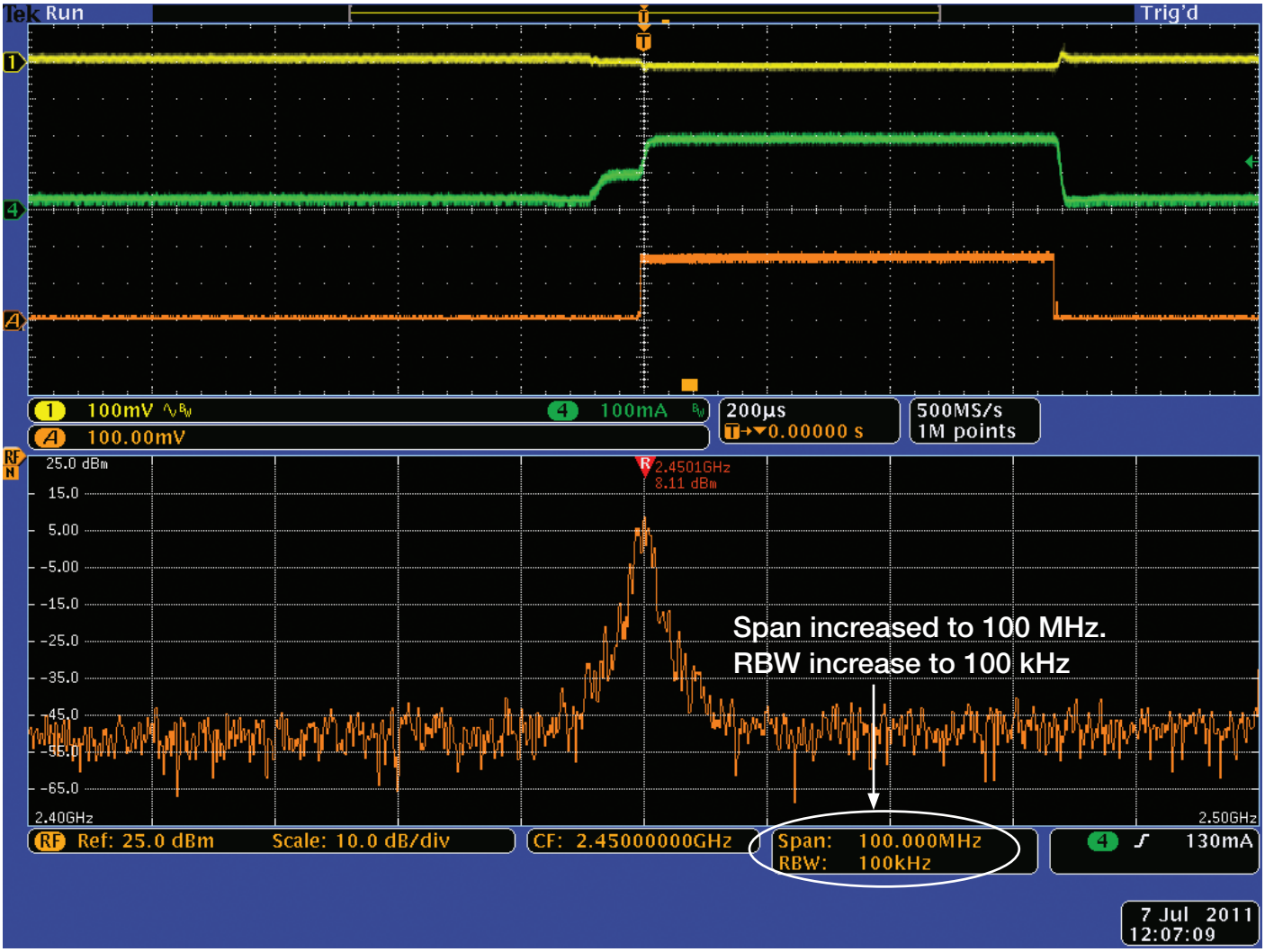

Figure 10. Wide scan of 2.45 GHz spectrum enables a signal view of the entire ISM-band.

Spurious Signals – It is critical in confirming operation of a radio to be sure that there are no spurious signals that could cause interference. Figure 10 shows that there are no significant spurious signals in the band in which ZigBee operates. Note that the module is set to transmit in the center of the 2.45 GHz band for this Figure. Here the marker function is used to measure the peak signal. With the Resolution Bandwidth now set to 100 kHz, the Spectrum Time is now reduced to just over 20 microseconds.

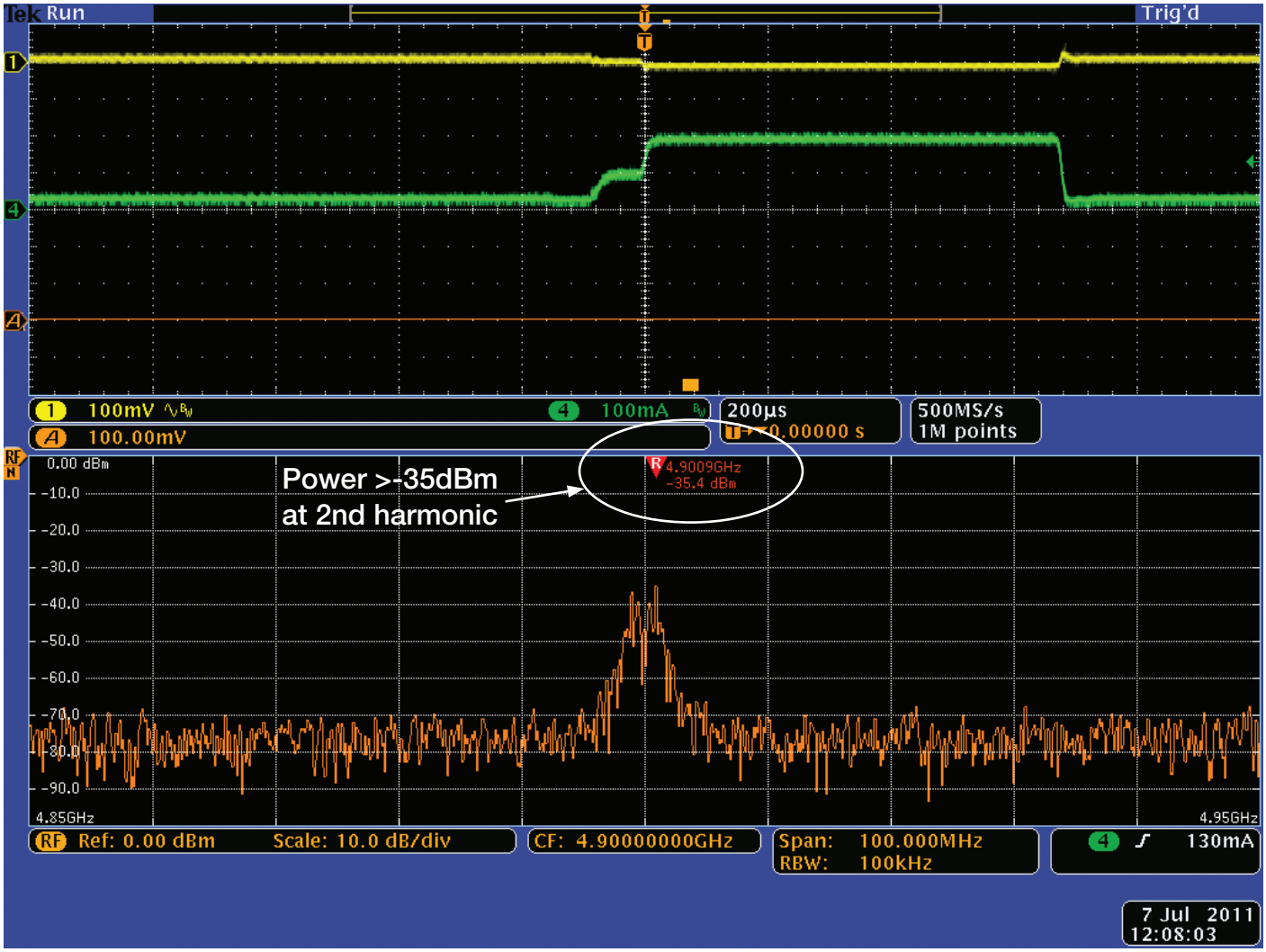

Figure 11. A time-correlated sweep at 4.9 MHz of the second harmonic triggered during the same turn-on conditions of the previous examples.

It is also important to look for signals in other parts of the spectrum. Figure 11 shows the frequency range of the second harmonic of the transmitted signal that is still correlated to the triggered level of the current draw during the RF transmission turn-on. Note that there is only a small signal at the second harmonic, and nothing significant at other frequencies. The second harmonic signal at the marker is about 35 dB lower than the fundamental which is well within the FCC rules applicable to this type of radio transmitter. The spectrum analyzer of the MDO allows rapid scanning of a wide range of frequencies to help assure that there are no unwanted spurious signals. For radio certification and compliance, a full scan for agency compliance will require a higher frequency spectrum analyzer, but many of the potentially most troublesome spurious signals can be found with the MDO, thus reducing risk for radio compliance testing.

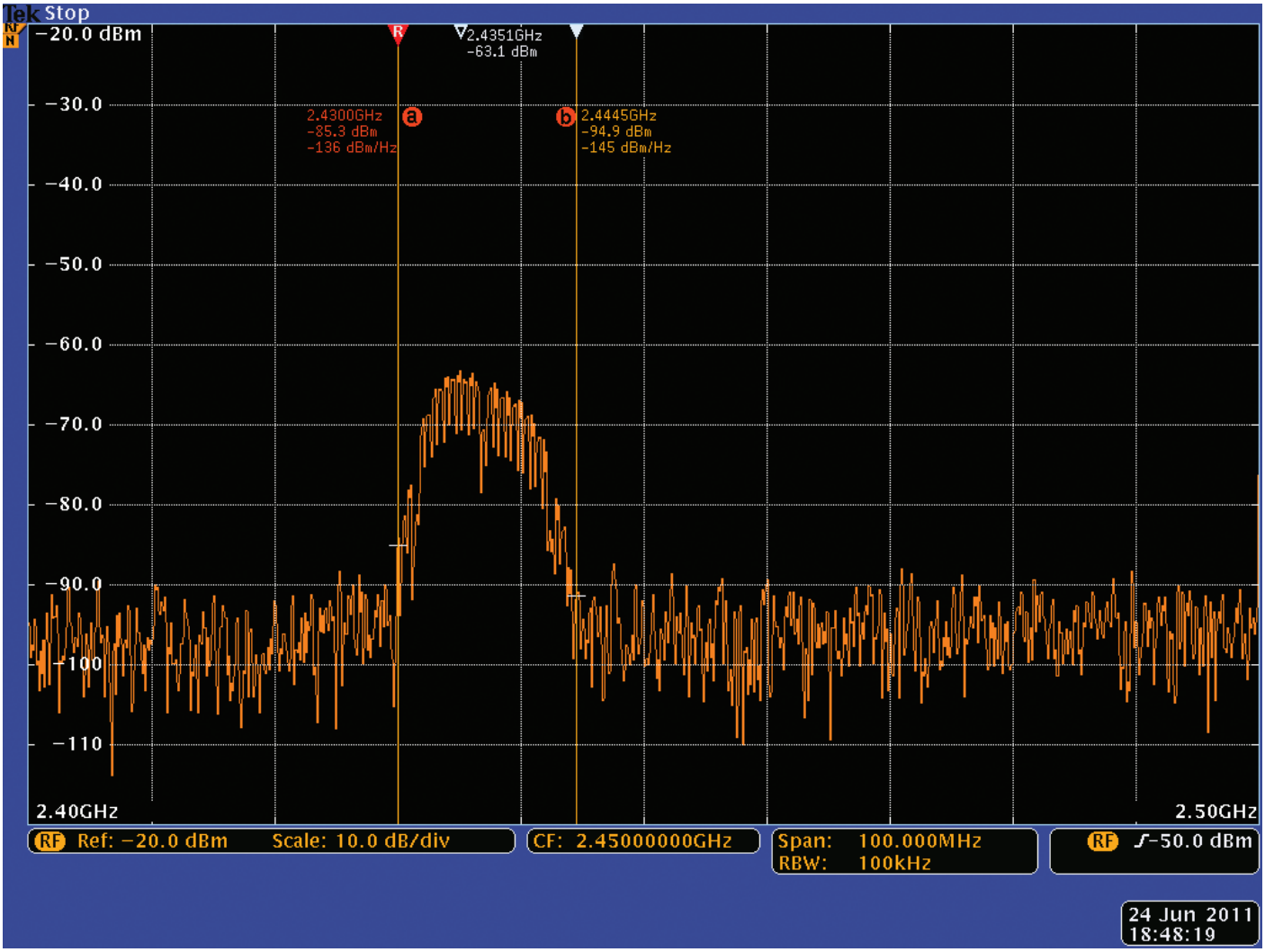

Figure 12. Wireless LAN interfering signal shown to assess impact during interoperability testing.

Interference – The MDO can also be used with an antenna to check for other radio sources that might cause interference to the radio being developed. In Figure 12, a reference antenna is used to look for possible interfering radio sources. Note the presence of a wide band signal centered at approximately 2.46 MHz. This is the Wi-Fi radio in the same building. This covers a number of channels that the ZigBee radio could use. In an application for this radio module, it would be wise to avoid using the channels around this frequency since the range of the ZigBee radio would be impaired or the radio blocked completely. The MDO offers a fast way to look for these signals. In this case, only the spectrum analyzer is used. The RF trigger capability of the MDO is used to allow rapidly capturing of any signal in the band of interest. The main reference marker shows that this is a rather strong signal. The manual markers (a) and (b) give a readout of the range of frequencies of the interfering source. The frequency range and power of this interference would make ZigBee channels 17 to 19 unusable. Of course, most protocols, including ZigBee, will scan for interference like this and move operation to a clear channel. Less sophisticated protocols may need to be manually adjusted for operating channel.

Summary

There are many options for implementing ZigBee or other IEEE 802.15.4 radios. The selection of the best approach depends on many factors including development time, the unit cost vs. engineering and approval cost, and special requirements such as space available, form factor, and special electrical requirements for the radio. Regardless of the approach selected there are a number of measurements needed to assure that the radio system is working correctly. RF measurements include checking the RF output frequency, output amplitude, occupied bandwidth and spurious outputs. Confirmation of packet timing, current consumption and any power supply noise are important as well. In addition, it is valuable to confirm that the correct digital configuration information is being set to the radio and correct data is being received.

The Tektronix MDO4000 Series Mixed Domain Oscilloscope can be used to monitor and verify operation in RF at up to 6 GHz frequencies, four analog channels up to 1 GHz bandwidth, and 16 digital channels; all time correlated. One investment supports all of the integration options including multiple serial protocols including SPI and RS232. The ability to time correlate all of these signals is especially valuable and can save time in troubleshooting.

The Tektronix MDO is compact and portable for any field tests. It provides a consistent and easy to learn interface even for complex tests of multiple types of signals.

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