Experimental Method for Evaluating Wireless Coexistence of Wi-Fi Medical Devices

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Medical device manufacturers are incorporating wireless communication into medical devices, and healthcare facilities are adopting wireless technology at an increasing rate. A large percentage of facilities are implementing Wi-Fi, which resides in the 2.4- and 5-GHz industrial, scientific, and medical (ISM) unlicensed frequency bands. These frequency bands are shared, where medical devices do not have exclusive use, raising the problematic issue of wireless coexistence. Although the Wi-Fi infrastructure of a healthcare facility is planned, personal hotspots and neighboring wireless networks can create potential problems, creating Wi-Fi–to–Wi-Fi interference. Additionally, for home-use medical devices, Wi-Fi network coverage is usually not planned, raising the potential for Wi-Fi–to–Wi-Fi interference.

The Food and Drug Administration’s (FDA’s) guidance, Radio Frequency Wireless Technology in Medical Devices—Guidance for Industry and FDA Staff, recommends addressing considerations that may affect the safe and effective use of medical devices that incorporate radio frequency (RF) wireless technology, including the wireless coexistence of a wireless medical device. The FDA defines wireless coexistence as "the ability of one wireless system to perform a task in a given shared environment where other systems (in that environment) have an ability to perform their tasks and might or might not be using the same set of rules."

When manufacturers implement wireless communication into a medical device, they are faced with the challenge of testing the coexistence of their wireless functionality. Additionally, healthcare technology management (HTM) professionals are faced with the challenge of maintaining wireless medical devices in healthcare facilities and debugging wireless problems, such as wireless coexistence. Joint work between the Wireless Working Group (SM-WG06) of the Association for the Advancement of Medical Instrumentation (AAMI) and Subcommittee 7 of ANSI ASC C63 (American National Standards Institute accredited standards committee) is underway to develop a technical information report that addresses the risk management of RF coexistence for medical devices and a standardized process to assess wireless coexistence. This article presents the experimental results of Wi-Fi–to–Wi-Fi coexistence testing that was done to support the development of the AAMI and C63 documents. Additionally, we have developed a method to evaluate a Wi-Fi medical device operating in the 2.4- and 5-GHz ISM bands based on those experiments. Our wireless coexistence test method is applicable for Institute of Electrical and Electronics Engineers (IEEE) 802.11a/b/g/n/ac Wi-Fi and can be applied to in-lab testing and in situ testing in healthcare facilities. The general process can serve as a foundation for coexistence testing for other wireless technologies in other spectrum bands.
bands, such as Bluetooth. The experimental results presented in this article can offer insights to HTM professionals to increase the likelihood of coexistence in healthcare facilities when managing Wi-Fi–enabled medical devices.

Pretest Preparations
The following pretest steps can help create a clear use-case scenario to test for wireless coexistence of a wireless medical device under test (DUT) that uses Wi-Fi.

1. Identify the wireless technology used in the medical device. For example, a medical device might be able to use IEEE 802.11b/g/n in the 2.4-GHz band and/or IEEE 802.11a/n/ac in the 5-GHz band.

2. Identify the wireless functions of the medical device. For example, a wireless function could be the transmission of a patient's physiological waveforms via Wi-Fi to a central monitoring station.

3. Define acceptable performance criteria for each wireless function based on the risks to the patient. When assessing the risk of the wireless function, consider the case of communication delay or failure and if appropriate feedback mechanisms and redundancies are in place. Monitor the wireless functions of the DUT for indications of communication delay or failure. One way to monitor the wireless functions could be through custom test software on the DUT. For example, the manufacturer might decide that the performance criteria monitored during testing are network latency and the accuracy of physiological waveforms sent to the central monitoring station. An HTM professional could determine initial acceptable performance requirements by referring to the medical device user manual.

4. Determine the signal-to-noise ratio (SNR) needed at the DUT for acceptable performance of wireless functions, based on the acceptable performance criteria in step 3. To reduce the number of test runs, select the minimum SNR and then experimentally verify the SNR during coexistence testing. The SNR at the DUT is inversely proportional to the operational range between the DUT and the companion DUT (Figure 1). That is, as the operational range increases, the SNR decreases.

5. Identify the intended use electromagnetic environment of the DUT. Specifically, try to identify other RF transmitters in the co-channel and adjacent frequency bands that could be possible sources of interference to the DUT. The identified RF transmitters are used during coexistence testing. Possible sources of RF transmissions in the 2.4-GHz band are Wi-Fi, Bluetooth, ZigBee, RFID (radio frequency identification), and microwave ovens. Possible sources of RF transmission in the 5-GHz band are Wi-Fi and the forthcoming LTE-U/LAA (Long-Term Evolution—Unlicensed/License Assisted Access).

Coexistence Test Setup
Two wireless devices are defined as coexisting if they can be brought near one another without significant degradation in their performance. The terms “significant” and “near” are open to interpretation, but the idea is conveyed in Figure 1, with the DUT and the companion DUT communicating over their operational range. For Wi-Fi, the companion DUT could be a Wi-Fi access point or another Wi-Fi device communicating in peer-to-peer mode. The separation distance is the distance between the DUT and the interfering network. In our setup, the monitoring device is a vector signal analyzer that monitors the electromagnetic environment and measures the power and channel utilization received from the companion DUT and the interfering network.

Figure 1. General wireless coexistence test setup. Abbreviation used: DUT, device under test.
Coexistence among wireless devices depends upon more than just the separation distance. Coexistence depends on three main factors:

1. **Frequency.** The probability of coexistence increases as the frequency separation of channels increases between wireless networks.
2. **Space.** The probability of coexistence increases as the signal-to-interference ratio (SIR) increases.
3. **Time.** The probability of successful coexistence increases as the overall channel occupancy of the two wireless networks decreases.

Wireless coexistence testing can be performed using the following steps:

1. Determine a suitable electromagnetic test environment
2. Baseline the wireless functions of the DUT in the test setup
3. Determine and baseline the interfering network in the test setup
4. Test the wireless functions of the DUT in the presence of the interfering network

**Step 1: Determine a Suitable Test Environment**

First, the electromagnetic environment is considered when choosing a test setup. Wireless coexistence test setups can be generalized into two groups: radiated and conducted. For the radiated test setup, testing can be performed in an open environment or anechoic chamber. When testing in a radiated open environment test setup, the electromagnetic environment should not affect testing. This can be verified by monitoring the spectrum during testing. Radiated testing in an anechoic chamber can further help manage the unwanted effects of the electromagnetic environment on testing. The same principles apply for the conducted test setup; the electromagnetic environment should not couple into the test setup.

In our test setup, a monitoring device (vector signal analyzer) was used to measure the electromagnetic environment before, during, and after testing. Testing was performed in an anechoic chamber. The radiated test setup we used is shown in Figure 2. The DUT, companion DUT, and interfering network were placed on nonconductive tables with a height of 1 m. In this test setup, the operational range between the DUT and the companion DUT determines the SNR at the DUT receiver. The separation distance between the interfering transmitter and the DUT determines the interfering power. Together, these two parameters determine the SIR at the DUT. For our test setup, five identical omnidirectional antennas (Figure 3) were used for the DUT, companion DUT, monitoring device, interfering transmitter, and the interfering receiver. Additionally, 20 dB of attenuation was used at each receiving antenna to reduce the voltage standing wave ratio (VSWR) and to compare the radiated and conducted test setup. For our experimental tests, data were sent one way from the interfering transmitter to the interfering receiver. The interfering receiver sent acknowledgment packets, but the effect of the acknowledgment packets on the DUT was found to be negligible. For other interfering networks where there is two-way communication, the interfering transmitter and receiver should have the same separation distance from the DUT.
The conducted test setup (Figure 4) is set up to replicate the path loss of the radiated test setup. Each wireless device is connected to a four-way, 0° power splitter/coupler (Mini-Circuits ZN4PD1-63+; Mini-Circuits, Brooklyn, NY). Attenuators were placed between the wireless devices and the splitter/coupler to decrease the VSWR. The five splitter/couplers were connected to one another with SMA cables. The attenuation between each wireless network was measured to verify similar attenuation values. Tests between the radiated and conducted test setups show similar results.

**Step 2: Baseline the Wireless Functions of the DUT in the Test Setup**

Next, baseline the wireless functions of the DUT in the test setup with no interfering network. To reduce the number of test runs, set the SNR at the DUT to the minimum value where the wireless function can achieve acceptable performance. In the radiated test setup, the operational distance is increased between the DUT and the companion DUT to decrease the SNR. In the conducted test setup, the variable attenuator #1 (Figure 4) is increased. Then, experimentally verify the SNR during testing. An iterative process may be needed to determine the minimum SNR, adjusting the SNR and verifying the wireless function can achieve the defined acceptable performance criteria. The DUT and the companion DUT should be positioned as they would be in the intended use environment.

**Step 3: Determine and Baseline the Interfering Networks**

Based upon the transmission frequency of the DUT and the intended use environment, determine the interfering networks that will be used during testing. Then, determine the baseline performance of the interfering network in the test setup while the DUT is not operating. One way to do this is to use network performance/protocol test tools to generate test data and to analyze the performance of the wireless network. Ixia (www.ixiacom.com) or Wireshark (www.wireshark.org) are just two examples of network performance software. The network performance of the interfering network can be measured in several ways, including throughput, latency (one-way delay), jitter (latency variation), and packet error rate.

To emulate a conservative worst case scenario, operate the interfering networks at their maximum transmission power and maximum channel utilization.

**Step 4: Test the Wireless Functions of the DUT**

Next, test the wireless functions of the DUT in the presence of the interfering network. After the DUT, companion DUT, and interfering network have been positioned, turn on the

![Figure 4. Conducted test setup. Abbreviation used: DUT, device under test.](image-url)
interfering network, transmitting at the maximum power and throughput. Then start the wireless function of the DUT. Through an iterative process, find the minimum separation distance between the DUT and the interfering network where the wireless functions can pass the acceptance criteria. A starting minimum separation distance is 0.5 m, based on C63.18.¹

In the conducted test setup, adjusting the value of attenuation #2 changes the SIR at the DUT (Figure 4). The impact of the DUT to the interfering network can also be recorded. Table 1 shows data for each test run.

Table 1. Example of coexistence test data collected for a test run. DUT=device under test; RSS=received signal strength.

<table>
<thead>
<tr>
<th>Wireless Technology Under Test</th>
<th>Wi-Fi (802.11n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless medical device: wireless channel</td>
<td>Channel 6 (2.437 GHz)</td>
</tr>
<tr>
<td>2.4-GHz noise level</td>
<td>&lt; –100 dBm</td>
</tr>
<tr>
<td>Operational range between DUT and companion DUT</td>
<td>10 m</td>
</tr>
<tr>
<td>RSS at DUT</td>
<td>–81 dBm</td>
</tr>
<tr>
<td>Interfering network</td>
<td>802.11n</td>
</tr>
<tr>
<td>Interfering channel</td>
<td>Channel 6 (2.437 GHz)</td>
</tr>
<tr>
<td>Transmit power of interfering network</td>
<td>16 dBm</td>
</tr>
<tr>
<td>Average throughput of interfering network (baseline)</td>
<td>55.3 Mb/s</td>
</tr>
<tr>
<td>Average throughput of interfering network (during test)</td>
<td>34.5 Mb/s</td>
</tr>
<tr>
<td>Separation distance between DUT and the interfering network</td>
<td>1 m</td>
</tr>
<tr>
<td>SIR at DUT</td>
<td>–20 dB</td>
</tr>
<tr>
<td>DUT function tested</td>
<td>Function 1</td>
</tr>
<tr>
<td>Outcome</td>
<td>Pass/fail</td>
</tr>
</tbody>
</table>

Figure 5. Received signal strength (RSS) versus throughput of a wireless medical (DUT) with no interfering network. The black circle represents DUT throughput at –81 dBm.

Results

In this section, we follow the wireless coexistence methodology and explore the three different variables of coexistence: frequency, space, and time.

MikroTik 802.11n development boards were used for both the DUT and interfering network. Radiated tests (Figure 2) were performed in an anechoic chamber. The noise level and 2.4-GHz spectrum were measured by the monitoring device using a National Instruments (NI) PXIe-1075 chassis equipped with a PXIe-5663 vector signal analyzer. The vector signal analyzer made continuous spectrum measurements before, during, and after each test to ensure that the electromagnetic background noise did not affect the coexistence testing (step 1).

Since the 802.11n development boards lack a specific wireless function on the application layer (like a medical device), the test setup was set at the minimum SNR in which the DUT can transmit data at its maximum throughput (~55 Mb/s). This was verified experimentally in the test setup (step 2). The experimental results demonstrate that throughput increases as the SNR increases (Figure 5). This is due to the adaptive modulation scheme of 802.11n. As the SNR ratio increases between the DUT and the companion DUT, the 802.11n transmitter utilizes higher throughput modulation schemes (from QPSK [quadrature phase shift keying] to 16 quadrature amplitude modulation [QAM] to 64 QAM). The minimum received signal strength (RSS) was measured to be –81 dBm. This was verified by the vector signal analyzer. The RSS at the DUT is –81 dBm for all of the following experimental tests.

To generalize the results of the example, the throughput of the DUT is reported to provide
insight into the behavior of Wi-Fi–to–Wi-Fi coexistence. It’s important to define a clear, acceptable performance criterion for each wireless function of the DUT. For our experimental results, we can arbitrarily set the acceptable performance criterion of the DUT, stating that the wireless function of the DUT fails when it transmits at less than 10 Mb/s.

Next, the interfering network is positioned near the DUT (step 3). For each test run, the DUT attempts to transmit at its maximum throughput (55 Mb/s) with the interfering network turned off. This is shown in Figures 6–9 by the blue empty square (DUT Baseline). The DUT transmits data for one minute. Then, the interfering network starts to transmit data at its maximum data rate. Co-transmission occurs for both the DUT and the interfering network for one minute. This is shown in each figure by the solid blue square (DUT Co-Transmission) and the solid red triangle (Interfering Network Co-Transmission). The DUT then stops transmitting data while the interfering network continues to transmit data, shown by the red triangle (Interfering Network Baseline). Individual co-transmission results are plotted as small filled-in circles. Each experimental test was repeated 10 times.

Figure 6 shows the change in throughput of the DUT as the SIR changes. The DUT and interfering network are both operating on Wi-Fi channel 6 (2.437 GHz) and set to try and achieve maximum throughput. As expected, the DUT and interfering network share the channel in a relatively equal share over an SIR range of –35 dB to –5 dB. The arbitrary performance criteria we have set for the DUT is acceptable for all tests in Figure 7.

Next, Figure 7 shows the effect of the interfering network’s throughput (5–55 Mb/s at 5 Mb/s steps) on the DUT. The RSS of the DUT is kept at –81 dBm, the SIR is –34 dBm (Figure 6, black circle), and the throughput of the interfering network is set to its maximum. The black circle in Figure 7 is equivalent to Figure 6 black circle. The Figure 7 x-axis is the Wi-Fi channel of the interfering network (1–11). The DUT is on Wi-Fi channel 6. As the interfering network approaches Wi-Fi channels 1 and 11,
the throughput of the interfering network increases and the DUT approaches 0 Mb/s. The arbitrary performance criteria set for the DUT are 1) acceptable when the interfering network is operating on Wi-Fi channels 3–9; 2) dependent upon the test run when the interfering network is operating on Wi-Fi channels 2 and 10; and 3) unacceptable when the interfering network is operating on Wi-Fi channels 1 and 11.

This occurs because the DUT detects the side lobes of the interfering network that occupies channel 6 (when the interfering network is on channel 1 or 11). The side lobes of the interfering network are above the carrier sense multiple access collision avoidance threshold because there is a ~34 dBm difference between the signals (SIR), causing the DUT to back off. Additionally, when the interfering network is on channel 1 or 11, the interfering network cannot sense the DUT’s side lobes because of the SIR difference. The interfering network continues to transmit near its maximum throughput.

Figure 9 shows the effect on the DUT as the SIR changes, with the DUT operating on Wi-Fi channel 6 and the interfering network operating on Wi-Fi channel 1 (Figure 8, black circle). The RSS at the DUT is ~81 dBm. For adjacent channel Wi-Fi networks (channels 1 and 6), the throughput of the DUT decreases as the SIR decreases, unlike in Figure 6, where the two Wi-Fi networks share the channel over a large range of SIRs. In the SIR region where the DUT has a throughput of 0 Mb/s, the DUT is able to sense the side lobes of the interfering network in channel 6, and the interfering network is unable to sense the DUT’s transmission. The arbitrary performance criteria we have set for the DUT is acceptable when the SIR is greater than ~23 dB and unacceptable when the SIR is less than ~25 dB.

Figure 10 overlays the experimental results of the performance of the DUT from Figure 6 (co-channel coexistence) and Figure 9 (adjacent channel coexistence) as the SIR changes. The DUT is operating on Wi-Fi channel 6. The RSS at the DUT is ~81 dBm. The crossover point is at ~20 dB (SIR), where the effect of adjacent channel interference is less than the effect of co-channel interference to the DUT.

To illustrate these two scenarios in Figure 10 (co-channel and adjacent channel), consider a Wi-Fi medical device connected to a healthcare information technology (IT) network on Wi-Fi channel 6 with adequate SNR (>~80 dBm) to transmit and receive data at its highest modulation rate (55 Mb/s). An example is a vital sign patient monitor that transmits electronic medical records wirelessly over the healthcare IT network. Then a second Wi-Fi network, such as a personal hotspot or another Wi-Fi medical

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**Figure 8.** Device under test (DUT) throughput versus interfering network channels 1–11.

**Figure 9.** Device under test (DUT) throughput (channel 6) versus interfering network channel 1 (changing signal-to-interference ratio [SIR]).
system operating in ad hoc mode, is brought within 1 m of the Wi-Fi patient monitor. In this scenario, the SIR at the patient monitor could be −20 dB to −40 dB. In this case, the wireless performance of the patient monitor is dependent upon the operating channel and throughput of the second incoming Wi-Fi network.

If the second network is operating on channel 1, the patient monitor will detect energy in channel 6 and back off and delay transmission. This sensed energy is actually the side lobe energy of the second network’s transmission from channel 1. Depending upon the SIR at the patient monitor, this can cause the effective throughput of the patient monitor to approach 0 Mb/s (Figure 9), while the second network continues to operate. In this case, wireless interference can be diminished if an adequate separation distance is maintained between the patient monitor and the second Wi-Fi network.

If the second network is operating on the same channel as the patient monitor (channel 6), the two wireless networks sense the transmission of each other and share the channel (Figure 6). However, the presence of the second network can cut the achievable throughput of both Wi-Fi networks in half. This affects network performance of all Wi-Fi devices connected to the healthcare Wi-Fi access point to which the patient monitor is connected.

The experimental results of the Wi-Fi–to–Wi-Fi coexistence testing provide wireless medical device manufacturers and HTM professionals possible scenarios to consider when testing for wireless coexistence:
• Frequency: co-channel versus adjacent-channel interference
• Space: SIR at DUT
• Time: channel utilization (throughput) of the interfering network

**Conclusion**

We have presented a coexistence test method designed to evaluate Wi-Fi medical devices operating in the 2.4- and 5-GHz ISM bands. Experimental results were provided to show different scenarios to consider when testing for wireless coexistence. Emphasis is placed on testing the wireless function of the medical device with clear acceptance criteria and interfering networks that operate in the intended environment of the DUT. In some cases, the frequency and channel utilization of interfering networks in the intended environments of the DUT cannot be controlled. In these instances, the primary deliverable from wireless coexistence testing is to determine the minimum separation distance (or SIR) for the DUT to have acceptable performance of its wireless functions.

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**Disclosure**

The mention of commercial products, their sources, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products by the Department of Health & Human Services.

**References**


**Figure 10.** DUT throughput (channel 6) vs co-channel (6) and adjacent channel (1) with a changing signal-to-interference ratio (SIR)