Test Methods for RF-Based Electronic Safety Equipment: Part 2 –Development of Laboratory-Based Tests

Kate A. Remley and William F. Young, National Institute of Standards and Technology

kate.remley@nist.gov, wfy@boulder.nist.gov

Abstract: We describe the development of free-field test methods for wireless electronic safety equipment that replicate field-test conditions in a laboratory environment. The test methods can be used to verify the performance of wireless devices, such as those used by emergency responders, in the presence of known attenuation and under RF interference conditions. The test methods presented here were developed to support the National Fire Protection Association (NFPA) in the revision of NFPA 1982: Standard on Personal Alert Safety Systems (PASS), but would be applicable to other types of RF-based equipment as well. In Part 1, we illustrated methods for extracting performance metrics from a series of field tests conducted by NIST researchers. In Part 2, we replicate the key field test conditions in the laboratory and verify device performance under those conditions.

I. Testing RF-Based Emergency Equipment

The U.S. Department of Homeland Security (DHS) Science and Technology Directorate's Standards Branch is supporting research at the National Institute of Standards and Technology (NIST) to provide technical support for the development of consensus standards for new wireless products used by the public-safety community. In this two-part article, we describe the development of laboratory-based test methods that have been designed to support the National Fire Protection Association (NFPA) in the revision of NFPA 1982: Standard on Personal Alert Safety Systems (PASS) [1] to include RF-based PASS. Even though the test methods discussed here were developed for NFPA 1982, we have designed them to be as general as possible, so that they may be applied to RF-based electronic safety equipment and other wireless devices having a variety of form factors.

A PASS is essentially a "firefighter-down" beacon that emits a loud audible alarm when the wearer is motionless for 30 seconds. Some PASS manufacturers are now including an RF transceiver in the portable, body-worn PASS device to alert the incident command station when the motion alarm is activated. The transceiver is also capable of receiving, among other things, an evacuation alarm signal from the incident command station.

In Part 1 of this article [2], we described a series of field tests carried out by NIST researchers in "difficult" radio environments representative of those encountered by firefighters including those with high attenuation and/or multipath. From the measurements, we extracted values of key performance metrics for use in the test methods. In Part 2 of this article, we develop the laboratory-based test methods and illustrate their application to a set of RF PASS devices.

The Low Attenuation Test and In-Band RF Interference Test to be described here represent two fundamental test methods in a suite of tests intended to comprehensively assess the RF side of PASS systems. Additional test methods will be developed to assess the effects of higher levels of attenuation, high-power out-of-band interference, and multipath.

II. Laboratory-Based Test Methods

In Part 1, we introduced a simple classification scheme for the development of the RF PASS attenuation test methods. We wished to keep the categories very broad to minimize the number of required tests, and, consequently, settled on the three main classifications described in Table 1. The "Low" attenuation classification in Table 1 indicates that RF PASS systems consisting of a single base station and a single portable device should be able to operate successfully in the presence of 100 dB of attenuation. For higher values of attenuation, repeaters may need to be incorporated into the system. Based on The National Institute for Occupational Safety and Health (NIOSH) statistics, the vast majority of firefighter deaths occur in low attenuation environments (small buildings) [3]. This served as motivation for developing this test method first.

Table 1: Classification of structures in terms of attenuation arising from building signal penetration.

Classification	Attenuation (dB)	Typical structures	Current PASS
Low	Less than 100	Houses, small buildings with exterior-facing rooms	Single unit
Medium	100 to 150	Moderate-sized and tall structures with some interior rooms	With repeater
High	Over 150	Very large structures and those with subterranean floors	Multiple repeaters

The second test method described below concerns the operation of RF PASS systems in the presence of external RF interference. For this test method, we have focused on interference generated by equipment that operates in the same RF band as the RF PASS, with approximately the same output power and, generally, the same transmission format. For example, RF PASS systems that operate in the unlicensed industrial, scientific, and medical (ISM) frequency bands from 902 MHz—928 MHz must coexist with other wireless devices such as RFID readers used in warehouses, cordless phones used in homes and offices, and some types of two-way radios. The "In-Band RF Interference Test" uses the same test environment as the attenuation test, along with the introduction of an external RF interference signal into one of the test chambers.

In Part 1 of this article, we presented measured data on the RMS delay spread in several environments. We showed that the effects of path loss and RF interference on success or failure of RF PASS transmissions was more significant than was the effect of multipath. Consequently, we have prioritized the development of the Attenuation Test and the RF Interference Test presented here. However, the RMS delay spread data will be used to develop a laboratory-based multipath test in future work.

A. The Point-to-Point RF Attenuation Test

The Point-to-Point RF Attenuation Test verifies the performance of RF PASS systems operating under conditions where a significant level of attenuation is encountered, such as inside a building or other structure. A combination of two shielded anechoic chambers, antennas, cables, and an adjustable attenuator are used to create a repeatable RF propagation environment where a specified level of attenuation can be inserted between a portable RF PASS device and its base station. The portable unit and the base station are rotated relative to the measurement antennas within the chambers to capture the most significant radiation-pattern-related effects.

This test method is designed to allow free-field testing of a complete RF PASS system under non-line-of-sight conditions without the use of conducted measurements in which the antennas are removed. Conducted measurements, where a coaxial cable connects the output of the base station to an anechoic chamber containing the portable unit, are often used for typical EMC tests. However, free-field testing allows the system to be characterized with its antenna radiation pattern intact. This is important because the antennas on some RF PASS devices are integrated into the firefighter's self-contained breathing apparatus (SCBA), an arrangement that can impact the radiation pattern of the antenna.

Two alarms are tested in the Point-to-Point RF Attenuation Test. First, the reception of the "firefighter down" alarm by the base station is tested when the distress alarm on the portable RF PASS device is activated. Second, reception of an "evacuation alarm" by the portable device is tested when initiated by the base station.

The Point-to-Point RF Attenuation Test is designed to replicate the Low Attenuation classification, corresponding to houses, small buildings, and buildings with exterior-facing rooms, such as multi-story apartment buildings where each unit faces the outside of the building. The target attenuation value of 100 dB represents the path loss between the transmit and receive antennas, as described in previous sections.

i. The Test Environment

Figure 1 shows the Point-to-Point RF Attenuation Test setup. Two anechoic chambers provide shielding between the portable unit and the base station. The use of two chambers is necessary to replicate the non-line-of-sight propagation environment where RF PASS is typically used. The path loss (or gain) associated with each of the various fixed elements in the test environment is given in Figure 1. The combined "target" path loss is designed to simulate the path loss experienced by personnel carrying the RF PASS within a building or structure when the base station is located outside. The value of the external attenuator is adjusted in a calibration step described below to set the target attenuation.

The chambers are shielded so that the user-worn RF PASS and base station are isolated from each other. In this case, the only signal path from the portable unit to the base station is controllable, making the test method repeatable. The anechoic material in the chamber simulates a reflection-free environment. Multipath reflections will be tested with a separate test method. The mechanical and electrical characteristics of the chambers that we use for testing RF PASS systems are described in the sidebar "Shielded Anechoic Chambers." These may need to be modified if other equipment is tested.

Directional patch antennas are mounted in the top of each chamber to receive the signal emitted by the device under test and couple it to the exterior of the chamber. The total system attenuation includes the gain of these antennas, the free space "channel" path loss between the device under test and these antennas, the cables connecting the chambers, and external attenuators that are added to achieve the desired amount of path loss. The test method requires that the RF PASS system is able to send and receive alarms when the sum of these components of attenuation corresponds to that specified in the standard, in our case 100 dB.

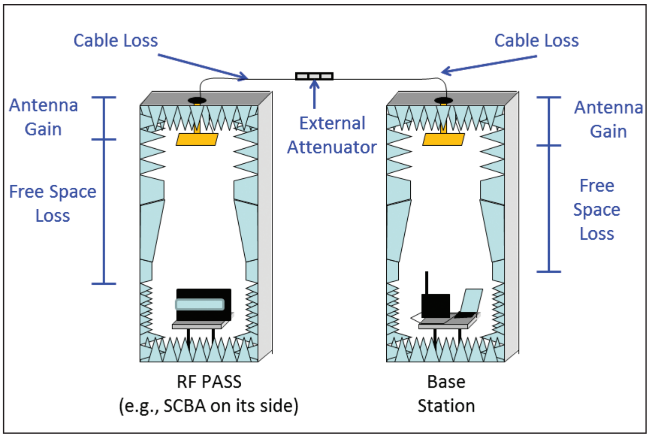


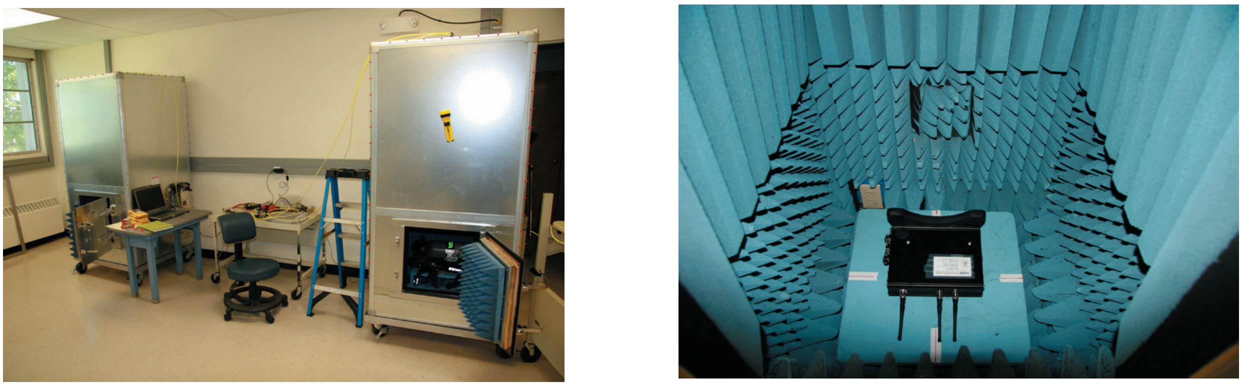
***Figure 1:** Test setup for the Point-to-Point RF Attenuation Test. Two shielded anechoic chambers are connected together by coaxial cables, and a specified target level of attenuation is inserted between the portable RF PASS device and its base station. A calibration step is used to determine the attenuator setting needed to achieve the target attenuation. Sources of fixed attenuation (and gain) in the test environment are labeled in the figure.*

Shielded Anechoic Chambers

Shielded anechoic chambers are used to isolate the base station and portable RF PASS device while providing, to first order, a reflection-free propagation environment. The minimum specifications for the chambers in terms of shielding and minimum physical dimensions are, therefore, critical. These specifications are spelled out below. Photographs of the chambers in the NIST laboratories are shown in Figure 2.

The chambers include non-conducting, non-reflective tables capable of supporting an SCBA containing an integrated PASS. The doors in the chambers must be large enough to insert an SCBA. The top of the table must be positioned above the RF-absorbing material covering the interior walls of the chamber. For RF PASS systems operating in the 900 MHz and 2.4 GHz unlicensed frequency bands, the test chambers must meet the following minimum specifications:

- The width and depth of the chambers must be large enough to allow insertion, placement and rotation of complete SCBAs. Usable space must be a minimum of 61 cm (24 inches) width × 61 cm (24 inches) depth × 30.5 cm (10 inches) height at the height of the table. Usable interior width and depth may be smaller at other heights within the chamber (for example, see the use of tapered wedge absorber in Figure 1).
- The height of the chamber should be maximized to reduce antenna near-field effects, yet low enough to fit under a standard laboratory ceiling height to reduce costs. Overall usable interior height should be no less than 102 cm (40 inches) between the antenna and table top or 140 cm (55 inches) total. Note that 1.0 m = 3 wavelengths at 900 MHz.
- The portable device and base station must be RF-isolated from each other, with each chamber providing at least 100 dB of shielding over the range from 900 MHz to 3 GHz when the bulkhead ports specified below are in place. Measurements verifying the shielding performance may be provided by manufacturer.
- The chambers are intended to replicate a reflection-free environment, with a minimum RF attenuation of 25 dB provided by RF absorbing material at normal incidence, from 900 MHz to 3 GHz. Measurements verifying absorber performance may be provided by the manufacturer.
- Because several repeat measurements must be carried out for the Attenuation Test, the chamber must have a hinged door, not a hatch, with no more than two latches that must be operated to open the door, preferably operated with a single handle. The minimum door size should be approximately 46 cm (18 inches) × 30.5 cm (12 inches).
- A top access panel must be provided to mount antennas, with minimum panel size 30.5 cm (12 inches) × 30.5 cm (12 inches).
- A non-conducting table top must be provided, with surface dimension of approximately 30.5 cm (12 inches) square. The height of the table, approximately 38 cm (15 inches), should clear the RF-absorbing cones on the bottom of the chamber.
- The chambers should include at least two Type N precision or SMA bulkhead ports on the side and top antenna access doors.
- Because the chambers must be positioned near to each other, they should have roll-around capability with wheels or casters.



(a) (b)

Figure 2: Hardware set up for the Point-to-Point RF Attenuation Test showing (a) the two shielded anechoic chambers, and (b) an RF PASS base station lying on its side (direction of maximum radiation) on the tabletop within one of the shielded anechoic chambers.

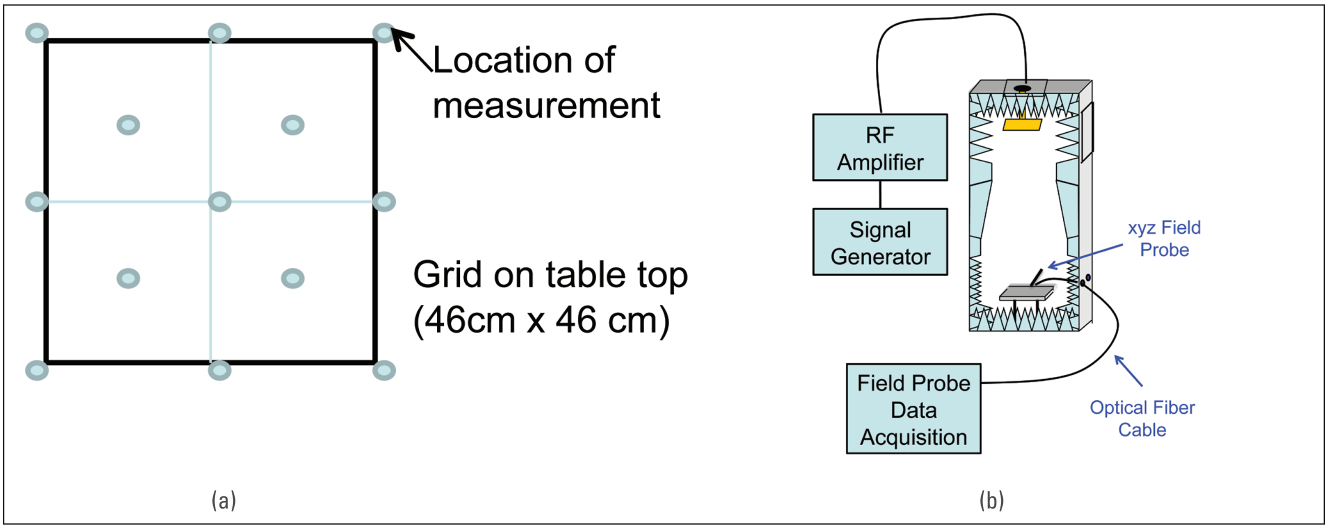


Figure 3: To calibrate for field uniformity, the total electric field is measured at a minimum of 13 locations on the tabletop within the chamber, as shown in (a). An electric field probe capable of measuring all three field components is connected, through a fiber-optic cable running through the bulkhead, to acquisition hardware outside the chamber, as shown in (b). The antenna at the top of the chamber must be the same one used in the test method.

ii. System Calibration: Field Uniformity

Before the RF PASS system components are tested for their ability to operate under the specified attenuation conditions, the test environment itself must be characterized. The antennas at the top of the chambers are selected to illuminate the table as uniformly as possible. However, nonidealities such as antenna near-field effects, and reflections off the walls due to imperfect RF absorber, antenna pattern, polarization, and beamwidth will cause deviations from uniform illumination. This will, in turn, affect the uniformity of the field on the table where the device under test is placed. The field uniformity must be measured for each frequency band for which RF PASS testing will occur. The same measurement antenna (located at the top of the chamber) to be used at that frequency must be in place.

Field-uniformity tests are carried out by placing a three-axis field probe at a minimum of 13 different locations covering the surface of the tabletop, as shown in Figure 3(a). A signal generator is connected to the top input port of the chamber, then the signal is fed through the bulkhead to the patch antenna at the top of the chamber, and the three components of the electric field are measured, as shown in Figure 3(b). Use of an amplifier may be necessary if there is insufficient field level at the field probe. The absolute field level at the tabletop is not critical because we are concerned with the change in field level across the surface of the table.

Figure 4 illustrates the results of a sample test of field uniformity (a) a circularly polarized patch antenna and (b) a broadband dual-ridge-guide (DRG) antenna. In these figures, contour plots were generated by taking the logarithmic values of the total measured field and interpolating to the nearest decibel. We see the linear polarization of the DRG antenna in the difference in received field strength between the vertical and horizontal directions.

The variation in field strength over the center portion of the table-

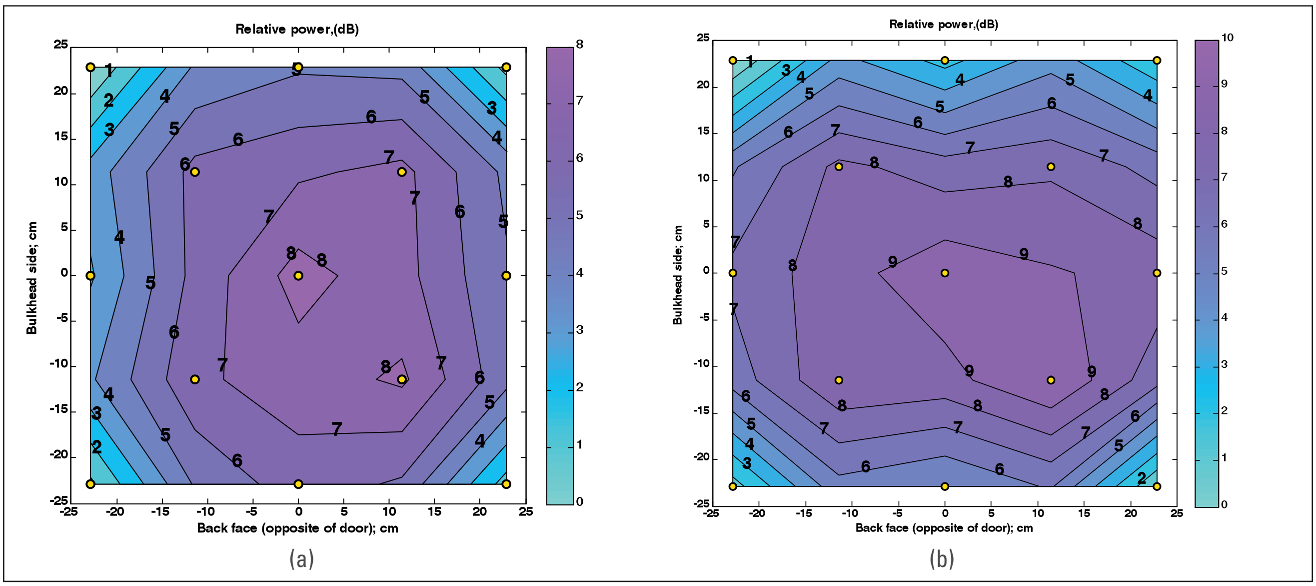


Figure 4: (a) 900 MHz circularly polarized patch antenna; (b) broadband dual-ridge-guide antenna. The polarization of the dual-ridge-guide antenna is evident from the asymmetry in the field uniformity pattern in (b). The maximum variation over the center 30 cm (12 inches) of the table is 2 dB +/-0.5 dB for the patch antenna and 2 dB +/-0.75 dB for the DRG.

top is accounted for in the attenuation test by increasing the total target attenuation. For example, if the target attenuation is 100 dB, and the field uniformity over the center portion of the tabletop is 2 dB, we would increase the target attenuation to 102 dB to account for the possibility that the device under test has inadvertently been placed in a field minimum on the tabletop.

III. System Calibration: Target Path Loss

As described above, the goal of the Point-to-Point RF Attenuation Test is to verify that an alarm can be reliably transmitted from the portable RF PASS unit to the base station when the propagation channel includes a specified target path loss (for example, 100 dB). To replicate the target path loss in the laboratory test method, the total path loss between the two tabletops on which the RF PASS and base station are placed (see Figure 1) must equal the target value.

We first add together (in decibels) the losses (or gains) of the fixed elements in the test-chamber environment when the external, adjustable attenuator is set to zero. Then, to obtain the target path loss, the fixed test chamber loss is augmented by an external attenuator or group of attenuators. The correct setting for the attenuator is found in a calibration step requiring the use of two additional antennas and a spectrum analyzer.

The two calibration antennas are first inserted into the test chambers on the same tabletops where the RF PASS components are placed during the attenuation test, as shown in Figure 5. For this calibration step, the use of circularly polarized patch antennas is preferred, because they provide highly uniform illumination of the tabletop and are insensitive to polarization, as described above. The gain of these antennas should be known beforehand, and may be obtained from the manufacturer's specifications or by use of a more sophisticated technique, such as a three-antenna method. As an example, the manufacturer-specified gain was 9 dBi for the 900 MHz antennas that we used in the example that follows.

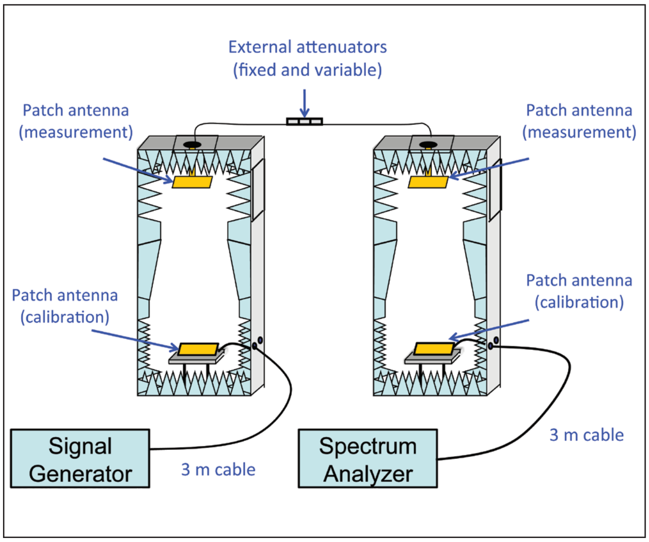


Figure 5: The system calibration set up to provide the target path loss. The target path loss of 100 dB consists of the summation (in decibels) of the various fixed elements in the propagation path, plus the external attenuator. The external attenuator is adjusted so that the target path loss is obtained.

The calibration antennas are connected to a signal generator and to a spectrum analyzer through bulkhead adapters in the sides of the test chambers. The cables connecting the antennas to the bulkhead adapters should be as short as possible to minimize reradiation and reflections. A block of RF absorber should be placed over them within the chamber. The loss due to the cables connecting the signal generator and spectrum analyzer to the external bulkhead adapters is determined by first connecting them directly between the signal generator and spectrum analyzer.

A spectrum-analyzer measurement in this configuration corresponds to the cascade of the elements in the RF propagation path shown in Figure 1 plus the calibration antennas and connecting cables. To identify the attenuator setting, we first define a variable $P_{System,0dB}$ that represents the combination of all of the fixed elements in the path loss except the attenuator. Our goal is to set the attenuator value such that $P_{System,0dB} + P_{Attn,dB} = P_{Target,dB}$, where $P_{Attn,dB}$ corresponds to the path loss introduced by the attenuator, and $P_{Target,dB}$ is the target path loss (in our example, 100 dB).

To find $P_{System,0dB}$ from the spectrum analyzer measurement $P_{Meas,0dB}$, we must calibrate out the gain of the calibration antennas and the loss in the cables that connect the signal generator and spectrum analyzer to the chambers:

$$P_{System,0dB} = P_{Meas,0dB} + P_{CalAnt1,dB} + P_{CalAnt2,dB} - P_{Cable1,dB} - P_{Cable1,dB}. \quad (1)$$

Note that we denote $P_{Meas,0dB}$ as a "loss," so its value will be positive; that is, a measurement of –30 dB on the spectrum analyzer would give $P_{Meas,0dB} = 30$ dB. Likewise, because the gains of the calibration antennas artificially reduce the system path loss, their gains are added to the measured path loss to increase its value. This may seem counterintuitive at first.

Knowing $P_{Meas,0dB}$, the gain of the two calibration antennas, and the loss in the two connecting cables, we can then find the attenuator value required to obtain the target path loss as

$$\begin{aligned} P_{Attn,dB} &= P_{Target,dB} - P_{System,0dB} \\ &= P_{Target,dB} - P_{Meas,0dB} - P_{CalAnt1,dB} - P_{CalAnt2,dB} + P_{Cable1,dB} + P_{Cable1,dB}. \end{aligned} \quad (2)$$

$P_{Attn,dB}$ corresponds to the required path loss introduced by the attenuator given the other path-loss mechanisms in the propagation path. As an example, suppose the target path loss is 100 dB, the manufacturer-specified gain of the calibration antennas is 9 dBi, the measured cable loss is 1 dB for each connecting cable, and the measured value of $P_{Meas,0dB}$ is 30 dB at the frequency of operation. Then,

$$\begin{aligned} P_{Attn,dB} &= 100\text{dB} - 30\text{dB} - 9\text{dB} - 9\text{dB} + 1\text{dB} + 1\text{ dB} \\ &= 54\text{ dB}. \end{aligned} \quad (3)$$

The external attenuator should be set to 54 dB in this case. If we include the 2 dB calculated from the field uniformity tests above, the external attenuator would be set to 56 dB.

IV. Performing the Attenuation Test

With the attenuator setting determined from $P_{Attn,dB}$ in the last step, the portable RF PASS is placed in Chamber 1 and the base station is placed in Chamber 2, as shown in Figure 1. If the base station utilizes a portable computer, this should be placed in Chamber 2 as well, because leakage through the chamber wall on a power cord will affect the test results. Most power-line filters do not provide the level of shielding required because the test method examines the ability of the wireless device to receive extremely weak signals. Note that this requires that the RF PASS, base station, and portable computer all be battery-operated.

Testing is conducted with the RF PASS in two orientations: vertical (standing upright on the table) and horizontal (lying flat on the table) so that the directionality of the RF PASS antennas is less critical. The base station should be tested with its antenna lying horizontally on the table. This may require placing the base station on its back or side. This orientation is designed to maximize the signal level received at the antenna at the top of the chamber, which is presumably how the base station will be deployed in the field (oriented for maximum signal level).

The test method is conducted as follows: A wireless link is established between the base station and portable RF PASS device before the chambers' doors are closed. The doors are then closed. For testing of the RF PASS motion alarm, the test administrator simply waits 30 seconds until the motion alarm automatically triggers. The test is passed if the base station receives the alarm within 30 seconds, as determined by an audible alarm emitted from the base station.

Testing the evacuation alarm can be more involved because often a mouse click on a computer initiates the evacuation alarm, and the computer must be located within the test chamber. For this case, a computer program is used that enacts a mouse click at a specified location on the computer screen after a specified delay. The computer program, instead of the operator, then initiates the evacuation alarm. As a second complication, once the doors are closed, the operator must physically move the portable unit at least once every 20 seconds to prevent the motion pre-alarm from activating. This can be done by placing a wooden dowel through a small bulkhead opening and jostling the portable unit. Under these conditions, successful reception of the evacuation alarm within 30 seconds of its transmission constitutes passing the test.

The four graphs in Figure 6 show measurements conducted in the test environment on an RF PASS system. The portable unit was placed in four different orientations on the tabletop: two vertical and two horizontal. The base station was placed horizontally in the other chamber, as shown in Figure 2(b). The total attenuation was varied around the failure point of the system (providing, essentially, a variable value of P_{Target}) to study the limits of reliable operation for this system. For each measurement sample reported, the portable unit was moved and repositioned on the tabletop to additionally study the reproducibility of the measurements.

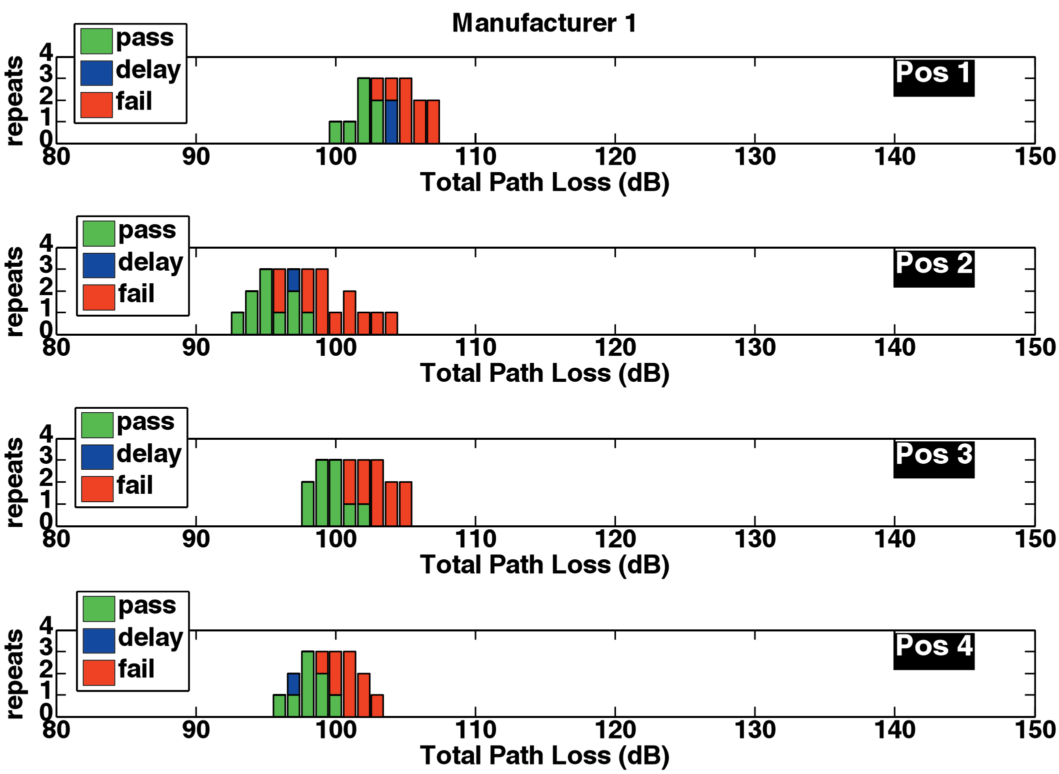


Figure 6: Example results from RF PASS motion-alarm measurements made in the test chamber environment developed for the Point-to-Point RF Attenuation Test. The portable unit was placed in two horizontal and two vertical orientations on the tabletop. The base station orientation was held fixed. The differences in the attenuation value required to cause the alarm transmission to fail results from a nonuniform radiation pattern in the portable system.

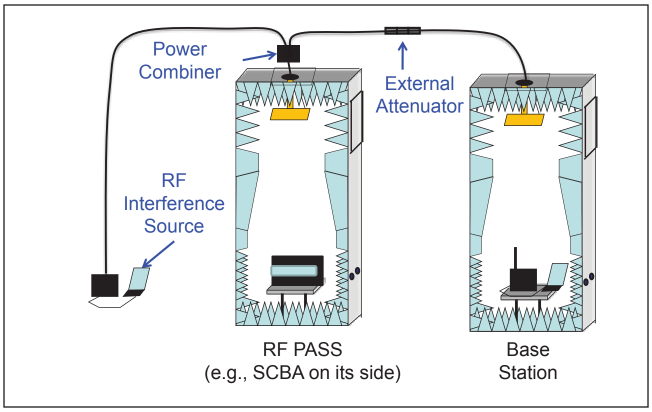


Figure 7. A typical RF Interference Test set up for RF PASS. The RF interference source is connected via a power combiner to the antenna located at the top of the chamber containing the RF PASS portable unit.

The four graphs in Figure 6 show that the success or failure of the motion alarm transmission depends on the position of the portable unit on the table top. For the orientations of the portable RF PASS unit in the first, second, and fourth graphs, the unit would just pass the test method with a 100 dB target level of attenuation. For the orientation shown in the third graphs, the attenuation must be less than 100 dB, which would constitute a failure of the test. The dependence on orientation indicates that this portable unit has a non-uniform radiation pattern. This is to be expected, because the antenna for this unit is integrated into the SCBA. For certain orientations, it is apparent that the SCBA blocks the RF PASS antenna from the measurement antenna.

The graphs of Figure 6 also show that a delay typically occurs for attenuation values near the failure point of the RF PASS motion alarm transmission. This delay corresponds to the random success of one of the multiple retransmissions of the alarm. Graphs such as these can help manufacturers develop improved RF PASS systems for firefighter use.

A. Interference Test Results

The RF Interference Test is designed to introduce into the RF propagation channel the types of interference that may be found in environments where firefighters are deployed. This test focuses on replicating conditions for large building structures such as office buildings, factories, convention centers, and apartment buildings. Certain wireless transmissions that may cause interference are commonly found within these structures. For example, in offices and apartment buildings, the use of wireless local-area networks (WLAN) or wireless personal-area networks (WPAN) is common. In warehouses and factories, the use of RFID technology is common.

Wireless systems such as WPAN and RFID operate in the unlicensed ISM frequency bands, with frequencies and power levels specified by the FCC. Because many RF PASS units also operate within these unlicensed frequency bands, in-band interference is possible. Consequently, the RF Interference Test is designed to test systems that operate in similar frequency bands by use of commonly encountered transmission protocols.

The interfering source in this test method will operate at approximately the same output power as the RF PASS—that is, at the maximum power allowed by the FCC. Higher-power signals that are transmitted either within the same band as the RF PASS (for example, signals that operate in the 900 MHz frequency band that are licensed for land-mobile radio operations) or at frequencies other than the RF PASS system (for example, broadcast radio or cellular telephone operations) are not considered in this test method.

As shown in Figure 7, the interfering signal is introduced into the test chamber that contains the user-worn RF PASS. This configuration is tested to simulate the condition where a firefighter is indoors in the presence of some other radio system. Because we expect that the firefighter will typically be some distance from the RF interfering source, in this test method, the output power of the interferer is reduced by the free-space path loss corresponding to a 1.25 m distance. This distance was chosen as the closest expected proximity between a firefighter and another wireless device. Note that this distance falls within the range of distances proposed in similar work on medical device RF interference testing discussed in [4] [5].

As with the Point-to-Point Attenuation Test, this test method is designed to allow free-field testing of a complete RF PASS system without the use of conducted measurements or removing the antennas. Free-field testing allows the system to be characterized with any unusual antenna radiation pattern intact.

Finally, we point out that interference testing has been reported in prior literature: for the 900 MHz ISM band, see [3][4]; and for the 2.4 GHz ISM band, see [5][6][7]. In addition, [7] performed laboratory-based coexistence testing in the 2.4 GHz ISM band for medical applications. All of the aforementioned work utilized several elements similar to those of the test method we describe here, such as the use of an anechoic chamber to control the test environment and the use of commercial wireless devices as representative interference sources. In the future, it may be possible to merge some of the testing concepts, such as the channel occupancy (discussed here) and the transaction "breakdown" (discussed in [7]).

i. The Target Value of Interference

The interference tests described below focus on two primary frequency bands and transmission formats. These target values of interference are detailed in Table 2. The transmission formats used in this test (including power level, modulation and encoding schemes, and signal bandwidth) have been designed to replicate those of commonly found wireless devices. As designed, the interference source is active 50 percent of the time in either the frequency band (e.g., over the 902 MHz—928 MHz band), or the initial channel of operation (e.g., over one of the six IEEE 802.11b/g 20 MHz channels, numbered 1, 3, 5, 7, 9, 11).

Because the anticipated channel usage by the interferer in an actual deployment will vary from instant to instant, we statistically verify the target value of interference used in testing. We define 50 percent channel usage such that a spectrum analyzer measurement over a 30-second period will detect the presence of the interference source 50 percent of the time, with the remaining samples measuring a clear or interference-free RF channel. In addition, over any five-second interval, the interference should be active between 25 and 75 percent of the time. Figure 8 shows an example based on the specified criteria for a 2.4 GHz interference source.

Table 2: Interference sources for RF PASS testing in the 900 MHz and 2.4 GHz ISM bands.

Frequency Range	Transmission Format or Modulation Scheme	Subcarrier or Channel Bandwidth	Output power and FCC part
902-928 MHz	Frequency Hopping Spread Spectrum (FHSS)	100 kHz subcarrier	1 W peak power (30 dBm) into antenna (w/ max 6 dBi gain), FCC Part 15.247 [8]
2.4-2.472 GHz	Direct Sequence Spread Spectrum (DSSS)	20 MHz (IEEE 802.11 channels)	63 mW peak power (18 dBm) into antenna, FCC Part 15 (See example 2 [8] for determination of correction factor.)

The channel usage percentage is measured with a spectrum analyzer and data acquisition software that samples the spectrum at the rate described above. In our case, the spectrum analyzer sweeps across the frequency band of interest in less than 3 ms; the data acquisition software captures the spectrum with a sampling rate of 225 ms ± 50 ms, and searches for the maximum value within the captured spectrum. Only the interference source is active when determining the interference channel usage; that is, there is no RF PASS communication activity. To arrive at the statistics for the target interference, a minimum of 500 samples are collected over approximately two minutes of data acquisition. The ratio of interference signal samples to the noise samples provides the channel usage percentage. As discussed above, the channel usage percentage may vary in any five-second interval between 25 and 75 percent. The test configuration for the RF interference source based on the use of standard commercial wireless products is included in the measurement description that follows.

ii. Measurement System

Figure 9 shows a typical RF Interference Test set up. Two anechoic chambers provide shielding between the portable unit and the base station. The total path loss (or gain) associated with the environmental elements (shown in Figure 1) simulates the path loss experienced by personnel carrying RF PASS within a building or structure when the base station is located outside. The value of the external attenuator is adjusted in a calibration step described in the section entitled "System Calibration: Target Path Loss." For the example results shown below, a 100 dB total path loss was inserted between the base station and portable RF PASS. Note that the attenuation path now includes the power combiner, and so the external attenuator value must be changed from that used in the Point-to-Point Attenuation Test.

The interferer is connected to the test chamber containing the user-worn device through a coaxial cable connected to the power combiner. The loss due to the coaxial cable and power combiner must be added to the nominal output power specified in Table 2, above.

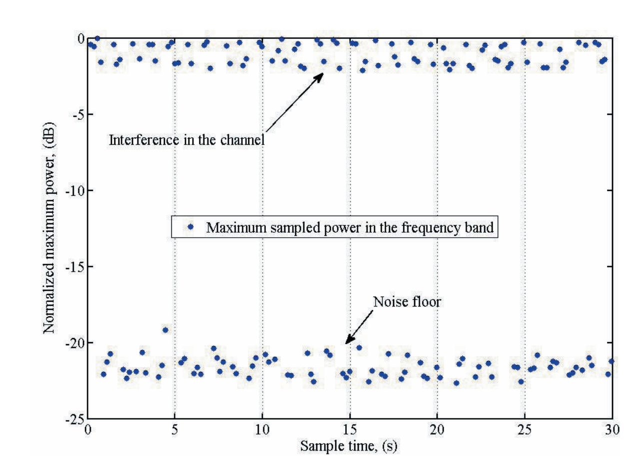


Figure 8. An example measurement showing 50 percent channel usage over a 30-second interval. The sampling rate was approximately 190 ms, and the 5-second intervals delineated by the dashed lines indicate active interference between 40 and 60 percent of the time within the interval. The measurement of a "noise" value means that the channel is clear of interference.

iii. Specific Interference Test Configurations for 900 MHz and 2.4 GHz Systems

This section provides specifics on setting up the interference sources used in testing the RF PASS devices. Note that in both the 900 MHz frequency-hopping, spread-spectrum (FHSS) and 2.4 GHz direct-sequence, spread-spectrum (DSSS) interference tests, the RF data rates are intentionally low in order to create high usage of the RF wireless channel by the interfering device. Most wireless systems are designed to maximize data throughput while minimizing the usage of the wireless channel to the greatest extent possible. This optimization is achieved, in part, by choosing a modulation format that allows the system to transmit the most data for the detected signal-to-noise ratio. The lower the signal-to-noise ratio, the lower the data throughput. If a lower-throughput modulation format is chosen, the transmission will require more time, and thus occupy the channel longer while transmitting the same amount of data. Here, we are intentionally inefficient in our usage of the RF wireless channel in order to mimic high-usage conditions. The amount of wireless-channel activity in terms of RF transmission power levels and duration is important here, not the amount of data transferred over the wireless link.

Table 3 provides specifics for the 900 MHz frequency-hopping interference test. The interference source is a wireless development board that utilizes industrial wireless transceivers, and is intended to represent a typical interference source that may be encountered during the deployment of an RF PASS system. As shown in Table 3, the key parameter for varying the interference duty cycle is the hop duration. A 19 ms hop duration creates the 50 percent channel usage with the statistical behavior described above. The 900 MHz interference source used here is a DNT900 series wireless development board from RF Monolithics, Inc. previously employed as an RF interference source in [4]. [1]

[1] Disclaimer: Mention of any company names serves only for identification, and does not constitute or imply endorsement of such a company or of its products by NIST. Other products may work as well or better.

Table 3. Parameters for the 900 MHz interference source.

Fixed Parameters	Hop Duration (ms)	Interferer Channel Usage (percent of time)
RF channel bandwidth = 100 kHz	16	57
RF data rate = 38.4 kb/s	18	53
Serial data rate = 38.4 kb/s	19	50
Power level = 30 dBm	20	47
	22	45
	24	39

The 2.4 GHz DSSS interference set up differs slightly from the set up shown in Figure 7. In this case, the interference source is established by connecting two wireless access points and then passing data between the two devices. The combined output power constitutes the RF interference source, which is connected to the chamber containing the portable RF PASS device in the same manner as in the previous configuration. Figure 9 shows the interference test set up that utilizes two access points.

In these tests, the access points were devices that can operate in multiple IEEE 802.11 configurations. The devices are set up in a bridging mode to allow "ping" packets between the two access points. Use of two access points in bridging mode and at equal distances from the RF PASS allows the maximum testing range (up to near 100 percent channel usage), and thus supports testing of the RF PASS to failure, if so desired. This also allows testing for lower channel-usage values, such as the proposed 50 percent, which simulates the channel usage of multiple wireless devices connected to a single wireless access point on the same channel.

The devices are given unique IP addresses on the same subnet, and the security filters are set to allow the connection between the two devices. The computer is connected via an Ethernet port to one of the access points, which then repeatedly "pings" the other access point with the "continuous ping" option set. The ping packet size is adjusted to achieve the desired channel usage with the packet size option in the ping protocol. Table 4 lists the parameter settings for various interference channel usage values. A ping packet size of 28 kb/s corresponds to the 50 percent channel usage described above. The results provided here are based on D-Link® DAP-2553 access points [9].

V. Measurement Procedure for Interference Testing

The previous section provided details on how to configure commercial wireless devices to create the desired RF interference behavior. Testing of the RF PASS system is carried out in almost the same manner as the Point-to-Point Attenuation Tests, but with the addition of the appropriate interference source.

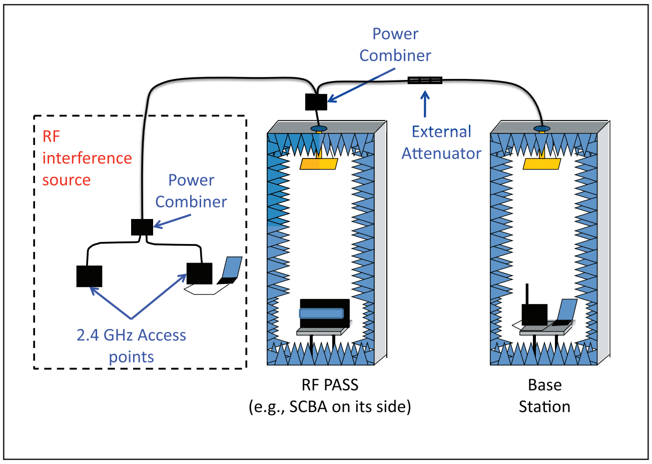


Figure 9. RF interference testing set up for the 2.4 GHz frequency band. Two access points are connected together through a power combiner. The combined signal is then connected to the power combiner that feeds the chamber containing the portable RF PASS unit.

Table 4. Parameters for the 2.4 GHz interference tests using two access points.

Access Point Settings	Ping Packet Size (kb/s)	Interferer Channel Usage (percent of time)
Mode = Wireless Distribution System/Bridging (WDS)	20	35
Physical layer = IEEE 802.11b/g	22	38
RF Channel = 1 Mb/s	24	42
Power level = 18 dBm	26	45
	28	50
	30	53

The test is conducted for any of the four Attenuation Test positions of the portable RF PASS device under the assumption that the system has successfully passed the Attenuation Test. The base station is again positioned with its antenna lying horizontally on the table. This orientation is designed to maximize the signal level received at the antenna at the top of the chamber.

The test method is conducted as follows: A wireless link is established between the base station and portable RF PASS device before the chambers' doors are closed. The doors are then closed and the interfering source is turned on. The test administrator simply waits 30 seconds until the motion alarm automatically triggers. The test is passed if the base station receives the alarm within 30 seconds, during which the interference source is active, as determined by an audible alarm emitted from the base station.

A. Interference Test Results

Interference testing was performed on products from three different RF PASS manufacturers. One system operated in the

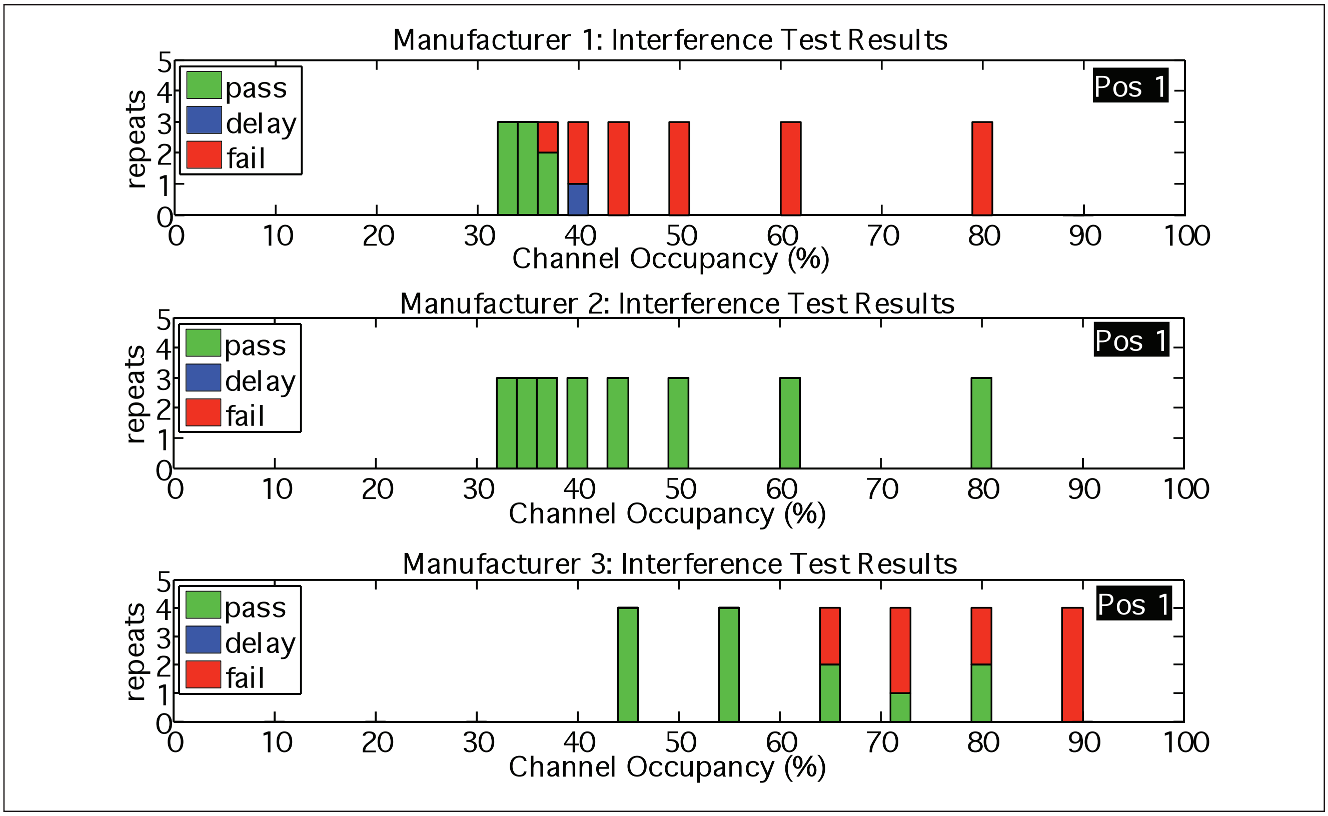


Figure 10. RF Interference Test results based on the channel usage (occupancy) criteria. RF PASS manufacturers 1 and 2 both operate in the 900 MHz band with a frequency-hopping, spread-spectrum modulation format; RF PASS manufacturer 3 operates in the 2.4 GHz band with a direct-sequence, spread-spectrum modulation format.

2.4 GHz ISM band with a DSSS modulation approach; the other two systems used FHSS modulation in the 900 MHz ISM band. The 50 percent channel usage of each interference source allows a basic comparison of the systems.

In Figure 10, the first two RF PASS manufacturers use FHSS in the 900 MHz band. The top graph indicates that the first manufacturer consistently fails to successfully transmit the PASS motion alarm when the interference source is active more than 40 percent of the time. However, as shown in the middle graph, the second manufacturer successfully transmits the motion alarm with active interference present 80 percent of the time. As shown in the bottom graph, the third manufacturer, who uses DSSS in the 2.4 GHz band, successfully transmits PASS motion alarms with interference channel usage up to approximately 60 percent. This system experiences intermittent failures with between 65 and 80 percent channel usage, and it experiences complete failure when the channel usage is 90 percent or more of the time.

The test results clearly indicate that (1) successfully transmitting RF PASS motion alarms under the specified interference conditions is possible; (2) the RF Interference Test provides a quantifiable measure of performance for systems that use different modulation schemes and frequency bands; and (3) the test can determine whether manufacturers may need to change their designs for more effective alarm communication in the presence of RF interference.

VI. Conclusion

We described the development of test methods designed to aid standards bodies with the evaluation of wireless technology used in firefighter, public-safety, and other applications where point-to-point communication is utilized. The test methods described here were designed to be as cost-effective as possible so that, not only test laboratories, but manufacturers and even end users can reproduce them for design, test, and evaluation purposes.

NIST's methodology for categorizing path loss according to various RF-propagation environments was described. These categories enable the development of laboratory-based test methods that are appropriate for types of wireless technology that will be deployed in various environments. The NIST classifications were based on field-test data collected in several large public structures, representative of those that may be encountered by emergency responders. Two test methods, designed to evaluate device performance in the presence of RF-propagation-channel attenuation less than 100 dB and in the presence of in-band RF interference, were discussed in detail.

We anticipate that, as more and more wireless electronic-safety equipment becomes available, the test methods described here will be used for testing those systems as well. These test methods would also be appropriate for testing any point-to-point wireless technology, such as that used in medical applications.

References

[1] National Fire Protection Association, NFPA 1982: Standard on Personal Alert Safety Systems (PASS), document scope available at http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=1982 , accessed Nov. 4, 2011.

[2] K.A. Remley and W.F. Young, "Test methods for RF-Based Safety Equipment: Part 1 - From field tests to performance metrics," IEEE EMC Mag., vol. 1, no. 4, pp. 53-60, 2012

[3] National Institute for Occupational Safety and Health, "Fire fighter fatality investigation and prevention program," http://www.cdc.gov/niosh/fire/, accessed Jan. 2012.

[4] "American National Standard Recommended Practice for an On-Site, Ad Hoc Test Method for Estimating Radiated Electromagnetic Immunity of Medical Devices to Specific Radio- Frequency Transmitters," ANSI C63.18-1997, Piscataway, NJ: IEEE, 1997.

[5] N. J. LaSorte, H. H. Refai, D. M. Witters Jr., S. J. Seidman, J. L. Silberberg, "Wireless medical device coexistence," Medical Electronics Design, Aug. 2011.

[6] T. Keller, J. Modelski, "Experimental results of testing interferences in 2.4 GHz ISM band," 33rd European Microwave Conference, pp. 1043-1046, Oct. 2003.

[7] S. Seidman, W. Kainz, P. Ruggera, and G. Mendoza, "Wireless coexistence and EMC of Bluetooth and 802.11b devices in controlled laboratory settings," Open Biomed. Eng. J.," 2011, vol. 5, pp. 74-82.

[8] http://transition.fee.gov/oet/info/rules

[9] ftp://ftp10.dlink.com/pdfs/products/DAP-2553/DAP-2553_ds.pdf

Biographies

***Kate A. Remley** (S'92-M'99-SM'06-F'13) was born in Ann Arbor, MI. She received the Ph.D. degree in Electrical and Computer Engineering from Oregon State University, Corvallis, in 1999.*

From 1983 to 1992, she was a Broadcast Engineer in Eugene, OR, serving as Chief Engineer of an AM/FM broadcast station from 1989-1991. In 1999, she joined the Electromagnetics Division of the National Institute of Standards and Technology (NIST), Boulder, CO, as an Electronics Engineer. Her research activities at NIST include metrology for wireless systems, characterizing the link between nonlinear circuits and system performance, and developing standardized test methods for the public-safety community.

Dr. Remley was the recipient of the Department of Commerce Bronze and Silver Medals, an ARFTG Best Paper Award, and is a member of the Oregon State University Academy of Distinguished Engineers. She was the Editor-in-Chief of IEEE Microwave Magazine from 2009 - 2011 and was the Chair of the MTT-11 Technical Committee on Microwave Measurements from 2008 - 2010.

***William F. Young** (M'06-SM'05) was born in Kolonia, Pohnpei. He earned a M.S. from Washington State University and a Ph.D. from the University of Colorado, both in electrical engineering. He worked at Sandia National Laboratories from 1998 to 2010, and collaborated with the National Institute of Standards and Technology (NIST) on wireless systems and measurements since 2003. He joined the Electromagnetics Division at NIST in 2010. He has coauthored over twenty-five technical reports, conference, and journal articles covering various aspects of wireless systems, electromagnetic propagation and MIMO technology. He has co-instructed short courses for audiences at the Defence Science Organisation in Singapore and the U.S. Water Works Association.*

Dr. William Young's fourteen years of experience in wireless communication systems, includes diversity antenna design, radio frequency propagation measurements, MIMO system applications, electromagnetic interference testing, and wireless network security analysis. He is currently focused on developing reverberation chamber and other laboratory measurement techniques to evaluate the performance of wireless systems, with a particular emphasis on MIMO technologies. He is also actively involved with the Working Group on ANSI C63.27, which is developing standards for wireless coexistence in the unlicensed frequency spectrum.

Call for Papers: Assessing Susceptibility

Due 1 August 2013

"*Monitor the EUT for degradation of performance. If susceptibility is noted …*", these instructions from MIL-STD-461F susceptibility test procedures and similar directives written in other susceptibility/immunity test procedures can be some of the most daunting tasks facing the EMC design and test engineer struggling with equipment EMC qualification. Albeit equipment under test (EUT) with only a few functions or modes can be straightforward to assess susceptibility, but what about multiprocessor computers, networks, multimode wideband sensors and complex suites of equipment? How do you specify allowable bit error rates or other baseline parameters that are used to define degradation? How do the criteria for operational critical systems differ from those for entertainment systems? How do you determine the subset of functional modes to test - especially, for reasons of efficiency, you may only have a few seconds per frequency step to assess the immunity? These questions and many more confront design and test engineers. We are looking for papers that will address these types of questions and describe practical approaches for assessing susceptibility/immunity/degradation. Papers will be reviewed and those accepted will be published in a future issue of the IEEE Electromagnetic Compatibility Magazine. Please send your papers by 1 August 2013 to: Amy Pinchuk, InField Scientific Inc., email: a.pinchuk@ieee.org. For questions or more information, phone: 514-695-2677.