Test Methods for RF-Based Electronic Safety Equipment: Part 1 – From Field Tests to Performance Metrics

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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 illustrate 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. Background: The Need for Representative Test Methods

Emergency responders count on reliable radio communications between mobile personnel, who are often inside a structure, and the incident command station outside. New wireless technology is being developed that can further increase responders’ safety and efficiency by remotely monitoring their position, physiological status, and situational awareness, among other things. The public safety community would like to take advantage of this technology. However, because lives may depend on its performance, this community requires that wireless devices are rigorously tested under representative radio-frequency propagation channel conditions before they are certified. Even though standards currently exist for commercial wireless devices such as cell phones, wireless local area networks, and handheld radios, few standards presently exist specifically for public-safety-sector applications.

In this article, we describe the development of laboratory-based test methods that are intended to support standards development for RF-based electronic safety equipment. NIST has been working with the National Fire Protection Association (NFPA) on the revision of NFPA 1982: Standard on Personal Alert Safety Systems (PASS) [1] to include RF-based PASS. PASS devices are described in the sidebar. This work provides an interesting example of test method development from the initial assessment of the radio propagation environment to final device testing in the laboratory.

Even though the test methods discussed here were developed for the NFPA, we have designed them to be as general as possible, so that they may be used to evaluate other types of wireless devices for which it is desirable to test under freefield conditions with the device antenna left intact. Such devices include those with integrated antennas, such as some medical devices, or “machine-to-machine” systems, such as ATMs and parking kiosks. The procedures described here—from the extraction of relevant channel parameters to laboratory-based test—can be tailored to other wireless applications as needed.

In Part 1 of this article, we describe a series of field tests carried out by NIST researchers in “difficult” radio environments, that is, those with high attenuation and/or multipath. From the measurements, we extract representative values of key channel parameters 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 two test methods described here are the first in a suite of several tests that will evaluate wireless device...
performance in a free-field environment in the presence of common channel impairments such as attenuation (path loss), multipath (self-interference due to reflections) and RF interference. The test methods described here focus on attenuation levels less than 100 dB and in-band RF interference.

This work is funded by the U.S. Department of Homeland Security (DHS) Science and Technology Directorate’s Standards Branch, which is supporting research at the National Institute of Standards and Technology (NIST) to provide technical support for the development of consensus standards [2-6].

II. NIST’s Technical Strategy

For consensus standards involving wireless equipment, laboratory-based test methods are often desirable, allowing device testing that is both repeatable and efficient. It is possible to carefully control the test environment and conditions in a laboratory while covering a wide range of propagation-channel parameters. NIST’s goal, therefore, has been to develop laboratory-based test methods that expose the system under test to representative levels of attenuation, multipath, and interference, reproducibly and with known uncertainty. We also wish to minimize the cost of the test methods so that manufacturers, or other interested parties, could reproduce them in their own laboratories for product design and verification.

Our technical strategy involved several steps. We first needed to determine “representative” values of key wireless-propagation channel parameters for use in the test methods. We analyzed data from an extensive set of NIST field tests in representative emergency responder locations, including high-rise buildings, urban canyons, tunnels, apartment buildings, office buildings and other large structures where radio communication problems are sometimes encountered [7-10].

It was necessary for NIST to perform the measurements because most prior published data were acquired to support commercial applications such as cellular telephones and wireless local-area networks. In these applications, a base station provides coverage to multiple nodes within a given area. For public-safety applications, direct, point-to-point communications between a pedestrian-height base station and a mobile unit are often encountered. For more information on the extensive set of studies that NIST has carried out, see the sidebar “NIST RF Propagation Channel Studies.”

To develop the test methods, we also collected data on RF PASS performance in several of these environments, placing the portable RF PASS device and its base station in approximately the same locations as the transmit and receive antennas for the channel measurements. From these measurements, we were able to directly study the effects of attenuation, multipath, and interference on the performance of the RF PASS devices. We then derived representative values of these impairments to use in the laboratory-based test methods. We have prioritized development of the attenuation and interference test methods reported here. This is because the digital modulation formats incorporated into commercially available RF PASS have been designed for use in environments where a moderate amount of multipath exists, such as indoor offices and warehouses. As a result, multipath is a less-frequently observed cause of failure than attenuation and interference. Our analysis supports this conclusion, as will be shown later. Multipath test methods will be the focus of future research at NIST.

Having extracted key channel parameters, the next step in the development of the test methods consisted of replicating the representative channel conditions in a laboratory environment. We required that the test environment be able to simulate the range of attenuation values found in the field tests, while also allowing the introduction of RF interference. Further, the test environment had to allow the wireless device to operate in its standard, off-the-shelf form. Two shielded anechoic chambers form the crux of the
NIST RF Propagation Studies

Most of the propagation-channel data analyzed here were collected in support of projects funded by NIST’s Public Safety Communications Research Laboratory, in the NIST Office of Law Enforcement Standards (see refs. [7-10] and the NIST Technical Notes referenced therein). In these studies, NIST researchers focused on acquiring and publishing open-literature data on point-to-point propagation-channel conditions that may be encountered by emergency responders. The NIST work focuses primarily on channels that simulate a fixed-location incident command station outside a structure communicating with mobile personnel inside.

In one type of study, researchers carried continuous-wave (CW) transmitters operating at frequencies near common emergency response bands to as many locations as possible within a structure. Receivers outside the structure continuously recorded the received signal level. These data provide statistics on the expected path loss within various structures.

A second type of study involved the use of a measurement system based on a vector network analyzer (VNA), such as described here. In this type of study, measurements were made of the outdoor-to-indoor channel at several fixed locations within the structure. These data, collected over a wide frequency band, could then be transformed to the time domain to study the reflective, multipath behavior of a certain structure. The VNA data could also be used to provide a calibrated estimate of the received power at specific locations, as described in this article.

Taken in tandem, these data offer representative samples of the RF propagation channel in environments where emergency responders may have difficulty with wireless communications. The data are proving valuable in the development of standards (as discussed here), as well as in improved design of wireless devices used by the emergency response community, and in development of improved deployment methods.
III. Propagation-Channel Measurements in Emergency-Responder Environments

Reducing the complex, highly variable radio-propagation environment to a laboratory environment is extremely challenging. The approach taken here is typical of those reported in the literature [11-14], where data are collected in several representative environments and then processed to extract the values of key parameters relevant to the specific end use of the wireless device. In our case, the key parameters are attenuation (path loss), multipath (self-interference due to reflections), and RF interference from sources operating with transmission formats and power levels similar to those used by the RF PASS systems (“in-band” interference).

A. Measurement Strategy

Our propagation-channel measurements were designed to allow selection of representative values of attenuation and multipath (see sidebar). Interference levels were inferred from FCC requirements and anticipated usage of an interferer in public environments, rather than from direct measurement (more on this in the section “Interference Test”). NIST is currently developing measurements to better quantify expected levels of interference.

To characterize the levels of attenuation and multipath in a given propagation environment, we measured the wideband frequency response and time-delay characteristics of the outside-to-inside RF propagation channel with a measurement system based on a vector network analyzer (VNA). We expect the inside-to-outside channel to have similar, although not identical, characteristics because of the interaction of the transmit and receive antennas with their respective local environments.

The VNA-based system, described in more detail in [8], lets us measure the complex transfer function of the radio-propagation channel as a function of frequency. The field-test data presented in references [9, 10] and used in this study were based on measurements covering the frequency band 725 MHz to 800 MHz.

To average out the effects of small-scale fading, we estimated the attenuation as the average of the magnitude-squared of the received transfer function, with the average taken across all frequency points in the band (75 MHz). The large-scale path loss was relatively constant over this band for the environments of interest [9, 10]. The attenuation was found with respect to a 4 m reference; that is, antenna gains are also removed. From the Fourier transform of the measured transfer function over the measured 75 MHz band, the power delay profile (the received power as a function of time) and RMS delay spread of the channel were found in post processing. A frequency resolution 1 MHz enabled calculation of a 1 μs maximum delay.

The expected difference between the measured values of attenuation in this “750 MHz band” and the attenuation experienced by the RF PASS signals at other frequencies of operation are discussed in the sidebar “Uncertainty in Relating Attenuation to RF PASS Performance.” Other sources of uncertainty in our estimates of attenuation are also discussed there.

We carried out side-by-side measurements of the propagation channel and the RF PASS systems in several representative emergency responder environments. These environments include a multistory high-rise office building; a 12-story apartment building with corridors flanked by apartments having exterior windows; a single-level office building with corridors flanked by offices having windows; a small office building with subterranean floors; a stor-
Attenuation and Multipath

Knowledge of attenuation is essential because the path loss, or reduction in signal strength, experienced by a signal as it penetrates and travels through a structure will directly impact the ability of an emergency responder’s wireless device to receive a signal from the incident command post, and vice versa.

Multipath is important because, in reflective environments, signals may travel from the transmitter to the receiver along multiple paths by way of signal bounces off reflective surfaces. As a result, multiple copies of the signal at the receiver may arrive over a range of times. For digitally modulated signals in particular, the self-interference arising from the multiple delayed copies of a signal can degrade the ability of the receiver to demodulate the received signal properly. The effects of multipath are often described with a metric called root-mean-square (RMS) delay spread, which is proportional to the time period for reflections to decay below a certain threshold of received-signal power.

age building with a tunnel; a convention center; and an outdoor “urban canyon,” consisting of city streets surrounded by tall buildings. In this article, we minimize the detailed analysis of the individual environments so that we may focus on the development of the test methods. The complete analysis of the data measured in these environments is presented in [15]. Figure 1 shows examples of test locations where propagation-channel characteristics and RF PASS systems were conducted.

Figure 2 shows examples of the measurement results from the two environments shown in Figure 1. We plot the RMS delay spread vs. attenuation measured at several test points within each structure. The different types of symbols indicate the success (circles), delay less than one minute (diamonds), or failure (x’s) of the RF PASS transmission measured at approximately the same location that the channel characteristics were measured. A delay of one minute was selected to define alarm failure because this was deemed the upper limit for a firefighter in distress. Note that, with the relatively low data rate required for RF PASS systems, one minute provides adequate time period for several retransmission attempts. Failure to receive the alarm in that period indicates that the signal reception has truly been lost.

By plotting RMS delay spread vs. attenuation for all of the points within each environment where the RF PASS systems were tested, we obtain several key pieces of information such as (1) whether attenuation, multipath, or interference is the primary cause of RF PASS failure within a given environment; (2) the typical range of attenuation values within that environment; and (3) the typical range of RMS delay spread values within that test configuration. Again, note that these results hold for our specific test configuration, which was designed to mimic that of an emergency response event.
In Figure 2(a), we plot the RMS delay spread vs. attenuation measured at the locations shown in Figure 1(a) in a high-rise office building. The measured attenuation between the base station just outside the lobby door and various locations on the first 10 floors of the building varies from approximately 69 dB to 113 dB, while the RMS delay spread ranges from 40 ns to around 400 ns depending on the proximity to the receiver. We see that the RF PASS fails for attenuation values of approximately 100 dB or higher for any value of RMS delay spread. This indicates that attenuation, rather than multipath, is causing the RF PASS to fail in this high-rise building environment.

In Figure 2(b), we plot the RMS delay spread vs. attenuation measured at a 12-story apartment building having a much smaller footprint than the
high-rise office building. The attenuation values range from approximately 69 dB to 90 dB. The thick concrete walls and reduced number of windows in the apartment building yield attenuation values that are on the same order as for the high rise. However, the RMS delay spread, ranging from approximately 25 ns to 80 ns, is typically shorter than in the high-rise because the apartment building is physically much smaller. However, the large number of delays (denoted by diamonds), even for low values of attenuation and multipath, indicates that some other effect is disrupting the RF PASS transmission. A cellphone tower located on floor 12 of this apartment building is likely the cause of the disruption. The graphs in Figures 2(a) and (b), and many more like them (see [15]), were used to both prioritize the development of the attenuation and interference tests, as well as to ascertain representative values of path loss and multipath for the laboratory-based test methods.

Figure 3 summarizes, in histogram form, the measured path-loss and multipath data for all seven of the sites where we conducted side-by-side testing. A total of 95 measurements are included, divided into 50 bins. In Figure 3(a), we see that a large number of attenuation values lie between approximately 80 dB and 120 dB. Another group of attenuation values lie between 130 dB and 140 dB (the upper limit of 140 dB corresponds to the noise floor of our VNA measurement system). These ranges of values were used to develop simple classifications of attenuation for use in the laboratory-based test methods, as discussed below in the section “Classification of Attenuation Values.”

In Figure 3(b), we show the RMS delay spread for 78 of the 95 side-by-side measurements that we analyzed. Low signal level prevented our calculation of RMS delay spread for all 95 measurements. The RMS delay spread is less than 100 ns for the majority of sites, indicating only a small amount of multipath for channels corresponding to building penetration. Because most digitally modulated signal formats have been designed to operate in the presence of small amounts of multipath, the data presented in Figures 3(a) and (b) again indicate that attenuation will have a more significant effect than will multipath on the success or failure of an RF PASS transmission.

B. Classification of Attenuation Values

Just as a fire company uses different configurations of hoses, trucks, and personnel to fight fires in various environments, the configuration of an RF PASS system will vary with the type of environment encountered at the incident. In particular, structures presenting high levels of attenuation may require the use of repeaters to receive and retransmit the signal. Repeaters can significantly extend the range of the RF PASS system, but their use also increases the complexity of the RF PASS system. For example, they must be designed to reliably form an ad hoc network and monitor the status of multiple nodes without significantly increasing the delay through the system. To aid in the development of test methods that are appropriate for various RF PASS system configurations, we developed rough classifications of attenuation values, as discussed below.

Most of the environments we tested exhibited at least 80 dB of attenuation (see Figure 3(a)), created by the penetration of signals from outside to inside a structure (or vice versa) plus the distance between transmit and receive antennas. As well, only the outdoor urban canyon environment and the shallow, 12-story apartment building had maximum attenuation values less than 100 dB. We expect that typical house structures, small commercial buildings (such as small stores in strip malls and office buildings with exterior-facing offices) and small-to-moderate-sized apartment buildings (in which all apartments have an exterior wall) would provide an environment where the total signal attenuation is less than 100 dB. We classify this type of structure as “Low” attenuation.

A second group of environments studied had maximum attenuation values between 120 dB and 140 dB. We expect that moderate-sized structures
such as small hospitals, and moderate-sized and tall commercial, office, and apartment buildings would provide an environment with attenuation values in this range. Thus, we classify “Medium” attenuation as that between 100 dB and 150 dB. Buildings with window treatments that block sunlight (and, often, RF signals) may also fit into this class. The use of a single repeater can often overcome this level of attenuation.

Very large structures and those with subterranean floors, even for buildings of small size, can be expected to provide attenuation greater than 150 dB, which we classify as “High” attenuation. Multiple repeaters would need to be used in such environments, with current (2012) RF PASS technology.

We used the simple classification scheme presented in Table 1 in 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 above. As an example, the “Low” attenuation classification in Table 1 indicates that every RF PASS system

![Figure 2: Measured RMS delay spread vs. path loss for (a) the first 10 stories of a high-rise office building and (b) the seventh floor of a 12-story apartment building. The symbols represent success (circles), delay (diamonds) or failure (x’s) of an RF PASS operating without a repeater.](image)

![Figure 3: Histograms of 95 path-loss and 78 corresponding RMS-delay-spread measurements made by NIST researchers. The data were collected in a variety of radio-propagation environments with a VNA-based measurement system. In some cases, a low received-signal level precluded calculation of the RMS delay spread.](image)

**Table 1:** Classification of structures in terms of attenuation arising from building signal penetration.
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. The Point-to-Point Attenuation Test described in Part 2 is based on the “Low” attenuation classification. Additional attenuation tests for higher levels of attenuation are in process at NIST.

In Part 2 of this article, we will describe the development of laboratory-based tests for both attenuation and in-band RF interference. We will develop methods to test “attenuation” separately from “attenuation plus interference.” RF PASS systems are tested separately under both of these conditions so that these performance impairments can be assessed individually, enabling manufacturers to improve performance in one area or the other as necessary. EMC

**References**


Uncertainty in Relating Attenuation to RF PASS Performance

As discussed above, we approximated the path loss corresponding to the success or failure of an RF PASS alarm using path-loss data acquired in the 750 MHz frequency band (ranging from 725 MHz to 800 MHz). However, the RF PASS systems that we studied operate in the 450 MHz (ranging from 400 MHz to 500 MHz) or 900 MHz (ranging from 902 MHz to 928 MHz) frequency bands. The error in relating attenuation at 750 MHz to RF PASS performance at other frequencies is given by $u_{750\text{MHz}}$ in Table 2, along with the other expected contributions to measurement uncertainty. Additional detail may be found in [15].

The combined uncertainty in our estimates of path loss used to assess RF PASS devices operating at 450 MHz and 900 MHz is:

$$u_{\text{combined}} = \sqrt{u_{\text{fading}}^2 + u_{\text{repeat}}^2 + u_{750\text{MHz}}^2 + u_{\text{ref}}^2 + u_{\text{drift}}^2 + u_{\text{fiber}}^2}$$

(1)

where the error mechanisms are combined with a root-sum-of-squares on the linear (as opposed to logarithmic) values, and then converted back to decibels.

Based on 95 measurements made in seven environments, our expected value of $u_{\text{combined}}$ is 7.0 dB. This uncertainty is high when compared against many laboratory measurements. However, it is acceptable for our application, because the goal of this work is to provide broad classifications of environments whose measured path-loss values range from a few tens of decibels to well over 150 dB.

Table 2: Uncertainties in estimated attenuation values that are used to assess RF PASS performance at 450 MHz and 900 MHz.

<table>
<thead>
<tr>
<th>Uncertainty Name and Type</th>
<th>Uncertainty Description</th>
<th>Method of Estimate</th>
<th>Value (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{\text{fading}}$ Type A</td>
<td>Small-scale fading (&quot;channel variability&quot;) derived from multiple path-loss estimates.</td>
<td>Mean of the standard deviation from 36 independent path loss estimates. Each standard deviation found from 75 frequencies, nine antenna positions, and two repeats.</td>
<td>5.7</td>
</tr>
<tr>
<td>$u_{\text{repeat}}$ Type A</td>
<td>Measurement system repeatability.</td>
<td>Standard deviation from eight independent reference measurements at NIST OATS. Derived from complete system measurements, including VNA, fiber optic link, and antennas.</td>
<td>0.3</td>
</tr>
<tr>
<td>$u_{750\text{MHz}}$ Type B</td>
<td>Use of 750 MHz path loss measurements to estimate path loss at 450 MHz and 900 MHz.</td>
<td>Average measured difference between 50 % CDF probability at 750 MHz and other frequencies in two representative environments and free space.</td>
<td>4.6</td>
</tr>
<tr>
<td>$u_{\text{ref}}$ Type B</td>
<td>Use of reference measurement made in controlled environment on field test data.</td>
<td>Difference in path loss estimate for representative environment calculated with both types of reference data.</td>
<td>–</td>
</tr>
<tr>
<td>$u_{\text{drift}}$ Type B</td>
<td>Drift in VNA measurements over time</td>
<td>Observed VNA drift over three days.</td>
<td>0.1</td>
</tr>
<tr>
<td>$u_{\text{fiber}}$ Type B</td>
<td>Impact of temperature on fiber optic cable</td>
<td>Observation in controlled experiment over three days.</td>
<td>0.1</td>
</tr>
</tbody>
</table>


Biographies

Kate A. Remley (S’92-M’99-SM’06) 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 an 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.
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Test Methods for RF-Based Electronic Safety Equipment:
Part 2 – Development of Laboratory-Based Tests

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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.

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

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 multistory 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.
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.
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 dualridge-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 tabletop 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.

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

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.
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 \( P_{\text{System},0\text{dB}} \) 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 \( P_{\text{System},0\text{dB}} + P_{\text{Attn},\text{dB}} = P_{\text{Target},\text{dB}} \), where \( P_{\text{Attn},\text{dB}} \) corresponds to the path loss introduced by the attenuator, and \( P_{\text{Target},\text{dB}} \) is the target path loss (in our example, 100 dB).

To find \( P_{\text{System},0\text{dB}} \) from the spectrum analyzer measurement \( P_{\text{Meas},0\text{dB}} \), 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:

\[
P_{\text{System},0\text{dB}} = P_{\text{Meas},0\text{dB}} + P_{\text{CalAnt1},\text{dB}} + P_{\text{CalAnt2},\text{dB}} - P_{\text{Cable1},\text{dB}} - P_{\text{Cable2},\text{dB}}.
\]  
(1)

Note that we denote \( P_{\text{Meas},0\text{dB}} \) as a “loss,” so its value will be positive; that is, a measurement of –30 dB on the spectrum analyzer would give \( P_{\text{Meas},0\text{dB}} = 30 \text{ dB} \). 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 \( P_{\text{Meas},0\text{dB}} \), 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

\[
P_{\text{Attn},\text{dB}} = P_{\text{Target},\text{dB}} - P_{\text{System},0\text{dB}} = P_{\text{Target},\text{dB}} - P_{\text{Meas},0\text{dB}} - P_{\text{CalAnt1},\text{dB}} - P_{\text{CalAnt2},\text{dB}} + P_{\text{Cable1},\text{dB}} + P_{\text{Cable2},\text{dB}}.
\]  
(2)

\( P_{\text{Attn},\text{dB}} \) 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 \( P_{\text{Meas},0\text{dB}} \) is 30 dB at the frequency of operation. Then,

\[
P_{\text{Attn},\text{dB}} = 100\text{dB} - 30\text{dB} - 9\text{dB} - 9\text{dB} + 1\text{dB} + 1\text{dB} = 54 \text{ dB}.
\]  
(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 \( P_{\text{Attn},\text{dB}} \) 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 $P_{\text{Target}}$) 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.
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.

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

Figure 8. An example measurement showing 50 percent channel usage over a 30-second interval. The sampling rate was...
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.

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 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.
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].

Table 3. Parameters for the 900 MHz interference source.

<table>
<thead>
<tr>
<th>Fixed Parameters</th>
<th>Hop Duration (ms)</th>
<th>Interferer Channel Usage (percent of time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF channel bandwidth = 100 kHz</td>
<td>16</td>
<td>57</td>
</tr>
<tr>
<td>RF data rate = 38.4 kb/s</td>
<td>18</td>
<td>53</td>
</tr>
<tr>
<td>Serial data rate = 38.4 kb/s</td>
<td>19</td>
<td>50</td>
</tr>
<tr>
<td>Power level = 30 dBm</td>
<td>20</td>
<td>47</td>
</tr>
</tbody>
</table>

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

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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.
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.

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

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

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.
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


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.

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