

## **Radio Communications for Emergency Responders in Large Public Buildings: Comparing Analog and Digital Modulation\***

Kate A. Remley<sup>1</sup>, Marc Rüttschlin, Dylan F. Williams,  
Robert T. Johnk, Galen Koepke, Christopher L. Holloway  
National Institute of Standards and Technology; 325 Broadway; Boulder, CO 80305  
1. Corresponding author: ph. (303) 497 3652, email: remley@boulder.nist.gov

Mike Worrell, Phoenix Fire Department; Phoenix, AZ  
Andy MacFarlane, Medaire, Inc.; Phoenix, AZ

*To assess in-building radio coverage, in 2004 the City of Phoenix Fire Department carried out extensive testing of their radio systems. They deployed firefighters in standard configurations in a variety of buildings, and rated on a scale of 1 to 5 the audio quality of the received signals. To provide a link between the qualitative ratings and absolute field strength, NIST staff later carried out a series of measurements side-by-side with the Phoenix firefighters. The calibrated data from the NIST tests enables translation of the larger set of Phoenix Fire Department data into transferable values useful to industry, standards organizations, and other public-safety groups. We report here on a subset of these tests that compare analog and digitally modulated signals at 800 MHz.*

### **1. Introduction**

Reliable communication between emergency responders operating in hazardous situations is critical to both the safety of personnel and the success of their mission. Their radio communications equipment must be extremely reliable, and the communications functions provided must be predictable. To assess their in-building radio communications under field conditions, the Phoenix Fire Department (PFD) conducted extensive testing of new and existing radio systems deployed in configurations common to the department [1].

Testing focused on the ability of firefighters deployed in a building interior to be able to communicate with a command position on the exterior of the building. An analysis of fire-ground communications was performed for each building studied. All responses were based on the Phoenix Fire Department Standard Operating Procedures (SOPs) for the various National Fire Protection Association (NFPA) building types (see Appendix).

During the testing process, the National Institute of Standards and Technology (NIST) became aware of the Phoenix Fire Department testing. NIST developed measurement techniques to determine the absolute received signal strength at locations near PFD personnel during a set of tests. A team from NIST spent a week measuring radio signal levels. The NIST measurements were later calibrated in a post-processing step to find the electric field strength.

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Comparing these field strengths to the qualitative ratings provided by Phoenix Fire personnel allowed us to “translate” the larger set of Phoenix Fire Department tests into approximate quantitative values that are transferable to other locations and enables technical evaluation or comparison of different radio systems.

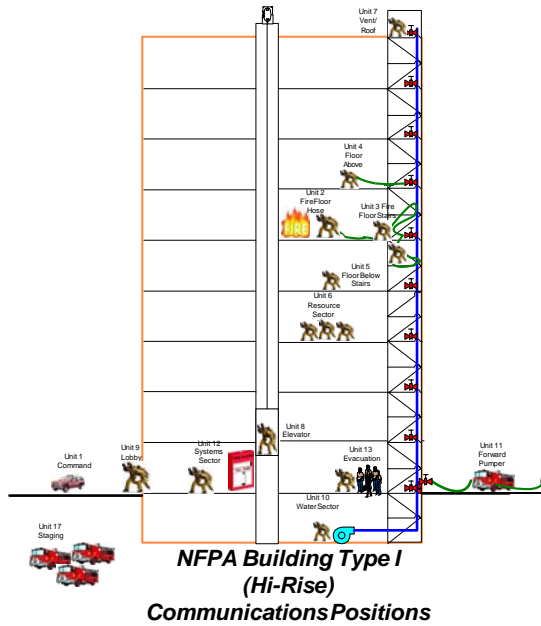
Among the tests carried out were those using point-to-point 700/800 MHz analog simplex and 700/800 MHz digital simplex. These tests provided an opportunity to compare radio reception when both digital and analog modulation were used. We report on these tests below.

### **2. The Phoenix Fire Department Tests**

The Phoenix Fire Department tests were performed over an eight-week period. The tests were conducted in 30 buildings that consisted of the five different NFPA construction types (see Appendix). Approximately 1,500 talk paths were tested. The same test participants were used throughout the testing to provide test consistency in the grading process.

A command structure was developed for each response. Analyzing the command structure and determining the logical fire ground communications paths led to the development of the talk matrix. A test script was developed for each unique communications path identified in the talk matrix. Each communications path was categorized as either fire ground communications or wide-area communications, with the majority of the paths being fire ground. A typical layout is shown in Fig. 1.

Each building was pre-planned for the test session. Personnel were placed in the buildings to represent fire companies on an incident response. The personnel

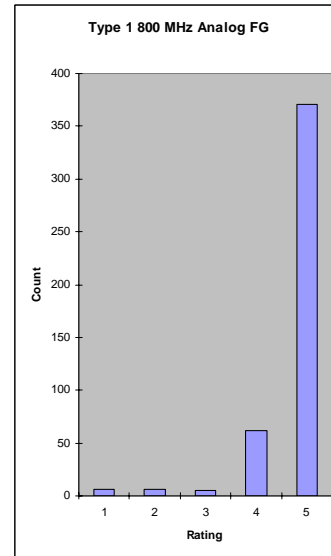


**Figure 1:** Typical firefighter deployment in a high-rise building. Radio links between all deployed positions were tested by PFD.

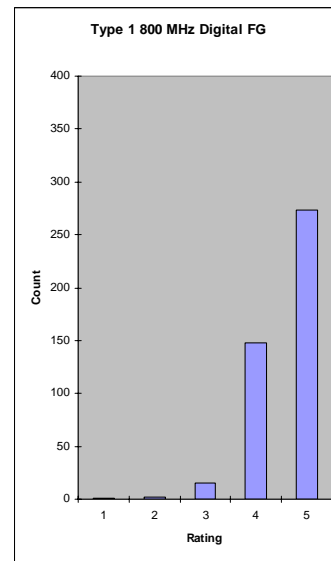
followed the test plan and graded each communication path. Each path was graded on a 1-5 scale with 1 representing poor communications and 5 being the best audio quality. Participants also determined whether the communications were useable on the fire ground on a pass/fail basis.

Upon completion of testing each day, the building's test results were entered into a spreadsheet containing the bidirectional grades for each communications path. Using the spreadsheet data, histograms were created for each building type and path category. NFPA Type 1 (concrete and steel) buildings were found to have the most variability in the histograms, and are also the buildings with the highest-risk environments, most complex interiors and largest operational structure. The histograms in the following are for fire-ground operations in Type 1 buildings.

Test results showed that the 700/800 MHz analog simplex channels provided clear, consistent communications in most test situations. This is shown in Fig. 2 by the high number of "5" ratings in the histogram. The test participants preferred this mode of operation over all others. Before testing commenced we expected that there would be differences in penetration capabilities between the 450 MHz and 700/800 MHz RF frequency bands. However, the penetration differences between the RF bands were negligible for the buildings we tested.



**Figure 2:** PFD test results: Analog simplex signals received in the local fireground (FG) over the course of all tests. A rating of 5 represents the clearest audio transmission.



**Figure 3:** PFD Test Results: Digital simplex signals received in the local fireground (FG) over the course of all tests. A rating of 5 represents the clearest audio transmission.

The 700/800 MHz digital simplex channels (see Fig. 3) provided consistent communications. Test participants did note that the majority of transmissions had some level of digital distortion as reflected by the large number of "4" ratings and an increase in "3" ratings. The typical level of distortion did not render the communications unusable. However, users did encounter more situations where a repeat broadcast was needed to interpret the message.

Digital modulation did outperform analog modulation in many low signal-level situations. The digital mode would



**Figure 4:** NIST calibrated measurements were taken in close proximity to Phoenix Fire personnel using the system shown on the left side of the photo.

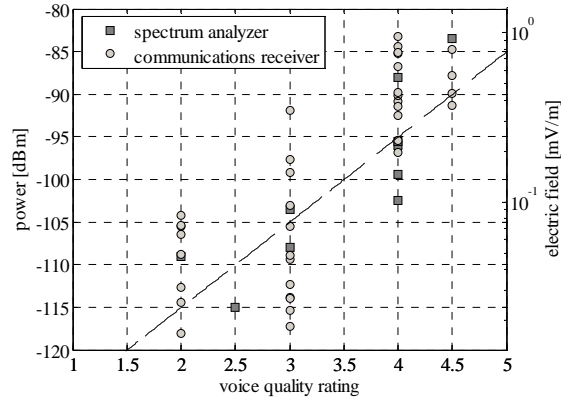
provide understandable communication when the same analog path would be scratchy and barely readable.

### 3. The NIST Tests

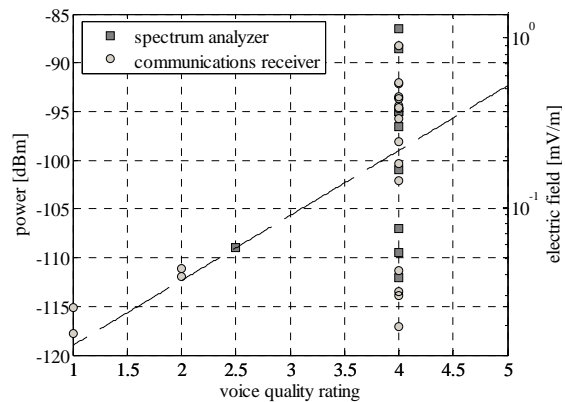
The goal of the NIST collaboration with the Phoenix Fire Department was to assign measured power and absolute electric field strength levels to the various qualitative ratings. While rating schemes such as the one described above are common, they suffer limitations inherent to “subjective” scales: they do not enable technical evaluation or comparison of different radio systems and it is difficult to compare ratings carried out by other groups in similar experiments.

The NIST measurement system consisted of a communications receiver, antenna system, and laptop computer. This system was developed to detect very weak signals in a cost effective way. The calibrations involved in these tests are described in [2,3]. The receiver system was used to collect data on the ground floor of an eight-story commercial building in Phoenix. The transmitter – a portable radio identical to those used by the Fire Department – was carried up and down a staircase on the opposite side of the building.

To ensure that the NIST experiments covered the entire range of voice quality ratings described in the Phoenix tests, we carried the transmitters to places with good and bad radio reception. At various locations in the building, an audio and silent test count were performed to allow nearly simultaneous PFD evaluation of the voice quality and NIST measurement of the power in the modulated carrier. The quality of the audio transmission was evaluated by a firefighter located at the listening station; both test counts were recorded using the communications



**Figure 5:** Measured average power and field strengths corresponding to voice quality evaluations for 860 MHz analog transmissions. The dashed line is a linear fit of all the data.



**Figure 6:** Measured average power and field strengths corresponding to voice quality evaluations for 860 MHz digital transmissions. The dashed line is a linear fit of all the data.

receiver system for later calibration and evaluation. The silent test counts were also monitored with a spectrum analyzer. This allowed us to have a backup set of measurements should one system fail, and also provided an independent verification of the communications receiver measurements. Among other tests carried out, analog and digital transmissions at 860 MHz were investigated and are the ones reported on here.

Scatter plots of the measured field strengths corresponding to voice quality evaluations are shown in Figures 5 and 6 for the 860 MHz analog and 860 MHz digital transmission respectively. The linear fit to the data in each graph may be used to estimate the field strength required for a particular quality of transmission. For example, in Fig. 5 all of the analog transmissions rated 3 correspond to received power levels below -90 dBm.

Unlike the analog case, the digital signal scatter plot in Fig. 6 shows that the majority of transmissions were given a voice quality level of 4, even for quite weak measured signal levels. This is the “digital shelf” effect noted by the PFD earlier. Note that all the quality ratings of 3 or worse were for signals with power levels of lower than -105 dBm.

The number of ratings of lower audio quality in the NIST tests is greater than that for the Phoenix Fire Department tests shown in Figs. 2 and 3. The NIST-led experiment was designed to intentionally cover the entire range of audio quality levels, whereas the Phoenix Fire tests reflected more realistic communications scenarios.

Factors such as multipath, the approximate one-meter difference in position between firefighters and the receiver system, repeatability of transmitter position, and the subjective nature of the audio quality assessments likely contribute to the spread of data for a given audio quality rating in Figs. 5 and 6. The graphs shown here are thus an estimate of the range of signal strengths that would result in a certain voice quality being received in the same room.

#### 4. Summary

Tests that compared audio quality of received signals from analog and digitally modulated radio systems were part of an extensive study carried out by the Phoenix Fire Department. The purpose of this study was to assess effectiveness and deployment of various firefighter radio systems in the field. Results showed that both analog- and digitally-modulated systems work in a majority of situations in an NFPA Type 1 building (concrete and steel). However, digitally modulated signals were discernable at lower signal levels than those for their analog counterparts. When both types of signals could be received, the firefighters preferred the audio quality of the analog signals.

To investigate the link between the subjective ratings used in the Phoenix Fire Department tests and received signal strength levels, NIST carried out measurements of absolute field strength in an eight-story building in Phoenix in which poor signal transmission quality had been observed in previous tests. Audio quality ratings were provided by

members of the Phoenix Fire Department who had participated in the earlier tests. Plotting the received signal levels vs. audio quality ratings provided a link between quantitative and the qualitative results. This link allows for comparison of the Phoenix Fire Department test data with data collected by other groups. Furthermore, having absolute signal strengths enables the data to be used in the technical evaluation of different radio systems, which may be of use to industry, standards organizations, and other public-safety groups.

#### Appendix—NFPA Building Types

Type 1: Fire-Resistive Construction

Reinforced concrete and structural steel

Type 2: Non-Combustible/Limited Combustible Construction.

- a) Metal-Frame covered by metal exterior walls
- b) Metal frame enclosed by concrete block, non-bearing exterior walls
- c) Concrete block bearing walls supporting a metal roof

Type 3: Ordinary Construction/Brick and Joint Construction

Type 4: Heavy Timber Construction

Type 5: Wood Frame Construction

#### Acknowledgement

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