Radio Communications for Emergency Responders in High-Multipath Outdoor Environments*

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We present measurement data to support development of technology and standards for broadband, digitally modulated radio communications used by emergency responders. Measurements were conducted at an oil refinery having extensive outdoor piping and other metal components. This structure represents a class of high-multipath, outdoor propagation environments that includes electrical generation facilities, chemical plants, and other outdoor, heavy industrial environments where reliable emergency responder communications is critical. The measurement results presented here quantify the extent of the multipath, loss, and other propagation effects in such high-multipath outdoor environments.

Keywords: emergency responder; excess path loss; multipath; propagation; radio wireless system.

1. Introduction

We report on measurements of parameters relevant to broadband, modulated-signal radio communication for the public-safety sector. Our tests were carried out at an oil refinery near Denver, Colorado in March, 2007. We performed three types of tests in these experiments: (1) received power at key public-safety frequencies; (2) excess path loss; and (3) waveform measurements of complex digitally modulated, broadband signals. Studying the issues related to radiowave propagation from these three perspectives gives us insight into the sources and significance of impairments for outdoor, high-multipath environments such as oil refineries, utility plants, chemical plants, and other heavy industrial environments.

Wireless communication using wideband, digitally modulated signals transmitted into and out of large structures is complicated by several factors. These include the strong attenuation of radio signals caused by losses in the building materials, scattering from structural features (multipath), and the waveguide effects of corridors and tunnels. Understanding the losses and their variability, decay times for reflected signals, the frequency-selective behavior of the channel, and the combined effect that these factors have on broadband digitally modulated signals can help system designers assess various technologies. This information also can help in designing and verifying network simulations, and ultimately will help with standards development.

The collection of data presented here shows a number of propagation effects relevant to transmission of broadband modulated signals in a high-multipath environment that may be encountered by public-safety and emergency-responder practitioners. We will show that transmitted signals experience intense frequency-selective distortion and multipath across the signal's modulation bandwidth in the oil refinery. This can be a challenge when deploying robust wireless communications. We anticipate that this collection of data allow for development of methods to improve performance in this difficult propagation environment.

2. Current Research in Emergency Responder Communications

To aid in the development of standards that support reliable wireless communications for emergency responders, the Department of Justice, through the Community-Oriented Policing Services (COPS) program is supporting the National Institute of Standards and Technology (NIST) in the acquisition of data describing radiowave propagation in key emergency responder and public-safety environments. In past work by NIST [1-3], measurements were collected in buildings scheduled for implosion to simulate collapsed-building environments. The focus of current work is to study radiowave penetration into large buildings and structures where inadequate radio reception is often encountered. Four large structures were studied: a 12-story apartment building, an office corridor, a subterranean tunnel, and an oil refinery [4, 5]. Here we focus on the results from the oil refinery, representing the most difficult propagation environment for digitally modulated signals.

Many publications have described measurement characterization of the propagation environment with respect to loss, delay spread, bit error rate, and/or other wireless system figures of merit. Most of these publications (e.g., [6] and references cited therein) describe measurements intended to simulate communications via cellular telephone or other wireless systems. These systems consist of a fixed base station whose antenna is positioned high above the ground and a mobile user located at ground height. Few publications describe measurements that simulate point-to-point radio-communication scenarios (e.g., [7] and the references cited therein), such as those required in many emergency-responder scenarios.

In addition to supplying standards-development organizations with real-world data available in the open literature, one of the goals of this program is to provide data for verification of network simulations of emergency responder radio links. The oil refinery was chosen because it is an environment that is similar to the chemical plant explosion scenario described in the SAFECOM Statement of Requirements (SoR), 2nd revision [8]. We anticipate that these data may also be used directly by system designers and researchers, and by end users, including public-safety practitioners.

3. Overview of Oil Refinery Measurements

The Suncor oil refinery* is an outdoor facility covering many hectares with several intricate, multi-story metallic piping systems, as shown in Fig. 1(a) and (b). The complex is several hundred meters long. The tower in Fig. 1(a) is nine stories high. In certain areas, the dense overhead piping forms a tunnel-like structure, Fig. 1(c), that can impede radio communications.

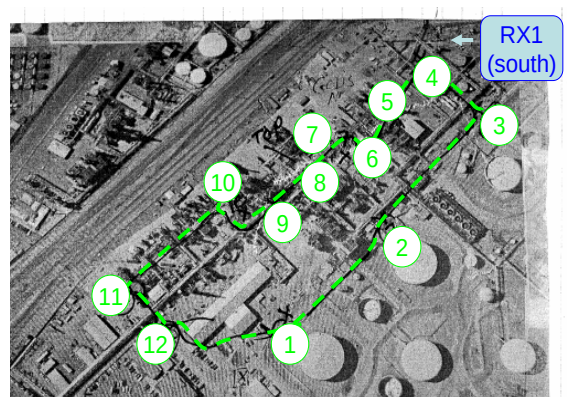
We carried out three types of radio transmission tests in this environment: (1) narrowband received-power measurements by use of a calibrated communications receiver, (2) wideband excess-path-loss measurements by use of a synthetic-pulse system based on a vector network analyzer, and (3) modulated-signal measurements of the spectrum using a vector signal analyzer. A more detailed account of these measurements can be found in [5].

3.1 Narrowband received-power measurements: We collected single-frequency (unmodulated, carrier only) received-power data at frequencies near public-safety and cell-phone bands as well as in the unlicensed Industrial, Scientific, and Medical (ISM) and wireless local-area network (WLAN) bands (approximately 50 MHz, 150 MHz, 225 MHz 450 MHz, 900 MHz, and 1.8 GHz).

The radios were similar to those of first responders, except they were placed in ruggedized cases and were modified to transmit continuously. An example can be seen in Fig. 1(c) in the left hand of the NIST researcher on the left.

We carried the radio transmitters throughout the oil refinery, along the path shown in Fig. 1(b), while recording the received signal at a fixed receiver site located approximately 30 m from the piping structure (labeled RX1). The receiving equipment was placed in a van (Fig. 2) made available for NIST use by the Institute for Telecommunication Sciences (ITS), a sister Department of Commerce organization at the Boulder Laboratories Site. Omnidirectional discone receiving antennas were mounted on masts on top of the van, as shown in the figure.

(a)



(b)

(c)

Figure 1: Oil refinery near Denver, Colorado. (a) Overview of the site. (b) Aerial view of the facility including the path taken for the received-power measurements. (c) Dense piping makes a tunnel-like propagation environment in certain areas.

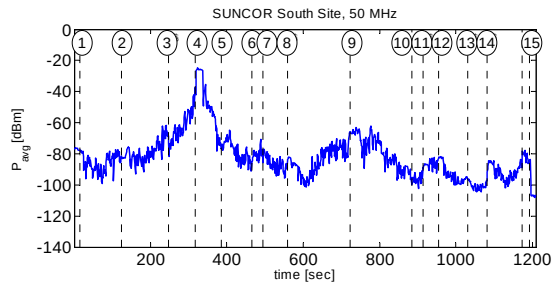
* This company is identified solely for completeness of description, and such identification constitutes no endorsement by the National Institute of Standards and Technology.

We used a narrowband communications receiver. This instrument, when combined with NIST-developed post-processing techniques [9], provides a high-dynamic-range measurement system that is affordable for most public safety organizations. Part of our intent was to demonstrate a user-friendly system that could be utilized by public-safety organizations to assess their own unique propagation environments.

Figure 2: The receiver was located inside a van with antennas top-mounted on a mast approximately 7.5 m (25 feet) above the ground.

The dashed line in Fig. 1(b) represents the path where the transmitters were carried by foot through the refinery. The path wound through the center of the processing section. In many places we encountered dense piping both to the side and overhead. Tunnel-like corridors through the piping are approximately five meters in width. As mentioned above, in most cases the piping extended several stories into the air. Fig. 1(c) shows NIST personnel carrying a portable transmitter through such a corridor.

Fig. 3 shows three representative sets of received data gathered while the transmitters were carried by foot through the facility. The numbered points on the graph correspond to those labeled in Fig. 1(b), with the exception of point 13 – 15, which were located below the lower edge of the photo. For a 50 MHz carrier frequency, we see in Fig. 3(a) that the received signal levels decrease rapidly as the transmitter moves from a nearby, line-of-sight location (position 4) to a location having line-of-sight but deep inside the piping structure (for example, position 8). This rapid attenuation is due to a waveguide-below-cutoff effect described in [5] and the references therein. The received power for the 448 MHz carrier frequency (Fig. 3(b)) has, on average, a slightly higher level than the 1830 MHz carrier frequency (Fig. 3(c)), but the rapidity of the changes are very similar with position (or time).



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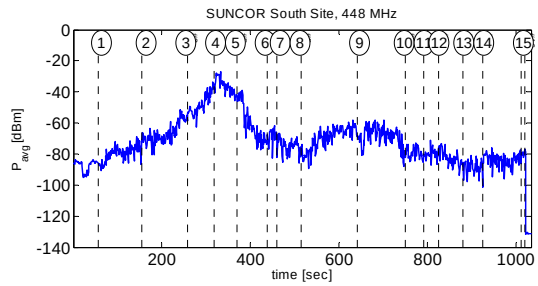

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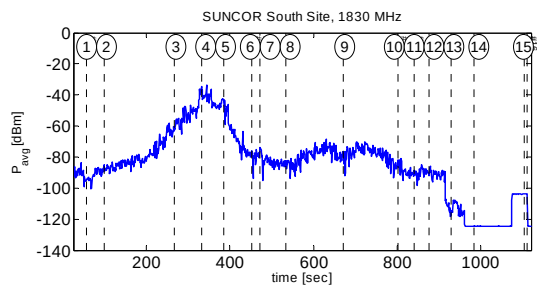


(c)

Figure 3: Received-power measurements collected as transmitters were carried by foot throughout an oil refinery complex for carrier frequencies of (a) 50 MHz, (b) 448 MHz, and (c) 1830 MHz. The highest received signal level is nearest to the receiver. The second-highest level is located at the top of a tall tower.

3.2 Excess-path-loss measurements: We studied excess path loss over a wide frequency band at specific locations within the oil refinery. These locations were confined to the path between points 7 and 9 in Fig. 1(b) for logistical reasons. The excess-path-loss measurements provide the received signal strength relative to a direct-path signal over a frequency band from 25 MHz to 18 GHz for the system we used.

Our synthetic-pulse, ultrawideband system is based on a vector network analyzer (VNA). The post-processing and calibration routines associated with it were developed at NIST [10]. In the synthetic-pulse system, the VNA acts as both transmitter and receiver. The transmitting section of the VNA sweeps over a wide range of frequencies, a

single frequency at a time. The transmitted signal is amplified and fed to a transmitting antenna. We used directional horn-type transmitting and receiving antennas at frequencies between 1 GHz and 18 GHz.

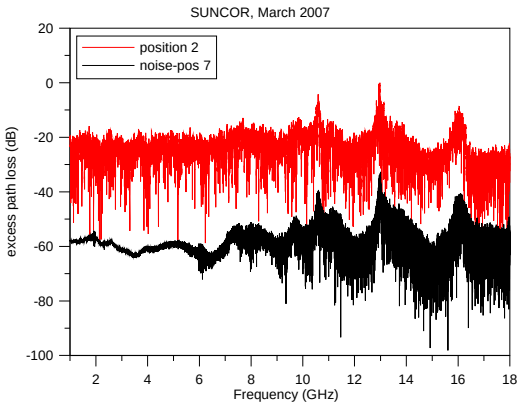
The received signal is picked up over the air by the receiving antenna and sent back to the VNA via a fiber-optic cable. The fiber-optic cable phase locks the received signal to the transmitted signal enabling reconstruction of the time-domain waveform associated with the received signal in post processing. Because the wideband transmitted signal corresponds to a short-duration pulse in the time domain, this system allows us to quantify the effects of the propagation environment, including losses and multipath reflections.

We carried out measurements at 13 positions (a subset of the receiver positions) in the oil refinery that were located in an area of very dense piping. We rolled the receiving antenna along the path on a mobile cart. The VNA was located in the ITS mobile test van. The vertically polarized transmitting antenna was located on top of this van.

Figure 4 shows excess path loss for frequencies between 1 GHz and 18 GHz at various positions in the oil refinery. The top curve represents the received power levels relative to the reference value, and the bottom curve represents the noise floor of the measurement system.

At a line-of-sight position shown in Fig. 4(a), the spectrum is quite flat with frequency. The peaks in the spectrum correspond to peaks in the instrumentation noise floor. Once the transmitting antenna is within the piping corridor, the spectrum starts to show significant frequency dependence, caused by strong reflections, as shown by the nulls and peaks in Fig. 4(b). Then, as the transmitting antenna turns the corner and proceeds even further down the piping corridor, the signal drops off rapidly and is almost lost in the noise, Fig. 4(c). The higher frequency bands show greater attenuation with distance than do the lower frequency bands. The complete set of UWB excess-path-loss data is given in [5].

3.3 Modulated-signal spectra: We also conducted measurements of representative broadband digitally modulated signals at carrier frequencies of 2.4 GHz and 4.95 GHz. We used a vector signal analyzer (VSA) to measure the signals. The VSA maintains the relative phase of the measured frequency components and enables laboratory-grade measurements of distortion in digitally modulated signals. The transmitter consisted of a vector signal generator, power amplifier, and omnidirectional antenna mounted on a cart. The VSA receiver was located in the ITS van.



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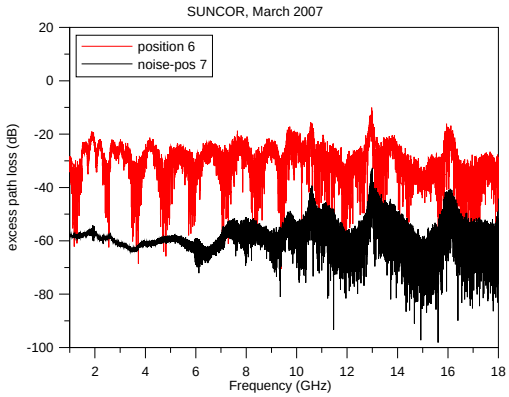

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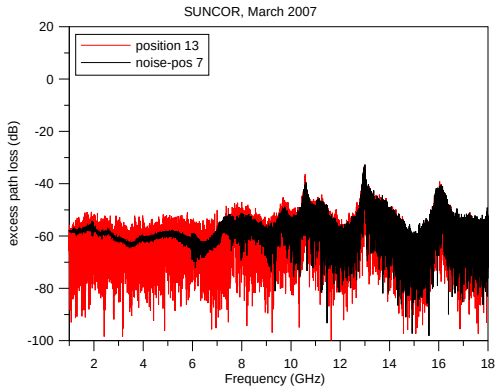

(c)

Figure 4: Excess-path-loss measurements at an oil refinery for (a) line-of-sight, (b) down piping corridor, and (c) non-line-of-sight positions for frequencies from 1 GHz to 18 GHz. The path was located outdoors but under dense piping several stories high, at 13 positions between points 7 and 9 shown in Fig. 1(b).

The modulated signal used as excitation was based on the orthogonal frequency-division multiplexing (OFDM) multiple access scheme, as specified by the

IEEE 802.11a™-1999 standard [11-12]. OFDM is used in wireless local-area networks (WLANs), in dedicated short-range communication (DSRC) systems for tracking and observing loads in commercial vehicles, and in the public-safety band at 4.95 GHz. In the latter, OFDM signals are often transmitted in a 10 MHz wide channel using the 802.11j standard, instead of the 20 MHz wide channel utilized in 802.11a. The demodulator that we used was able to measure only the 802.11a standard, as reported below.

We also made measurements of multisine signals designed to simulate the statistical properties of digitally modulated signals [13]. Multisines are collections of simultaneously generated sine waves whose amplitudes and relative phases are engineered to transmit a waveform having properties similar to the digitally modulated signal, but in a more efficient and easier-to-characterize fashion.

We made measurements at the same positions where the synthetic-pulse VNA measurements were made. Figs. 5(a)–5(c) show measured bandpass spectra for a digitally modulated quadrature-phase-shift-keyed (QPSK) signal and for a multisine signal designed to simulate it. Fig. 5(a) shows a measurement where the transmitter and receiver were located approximately three meters from each other in a low-multipath environment. This undistorted signal may be used for comparison to the distorted signals described below.

In Fig. 5(b), the transmitter has just entered into the metallic piping structure and there is still a good line of sight between the transmitter and receiver. Still, the figure shows much frequency-selective distortion, indicated by the deep nulls across the modulation band of the signal. This could impair accurate decoding of the signal. The 2.41 GHz carrier signal is more strongly affected than the 4.95 GHz carrier one. We suspect this is due to the physical dimensions of objects within the piping structure.

In Fig. 5(c), the transmitter has proceeded down the piping corridor to the same location shown in Fig. 4(b). The signals at both carrier frequencies are attenuated and again, significant frequency-selective wideband fading is seen. We were unable to receive the digitally modulated signal in the non-line-of-sight location due to the limited dynamic range of the VSA system we used.

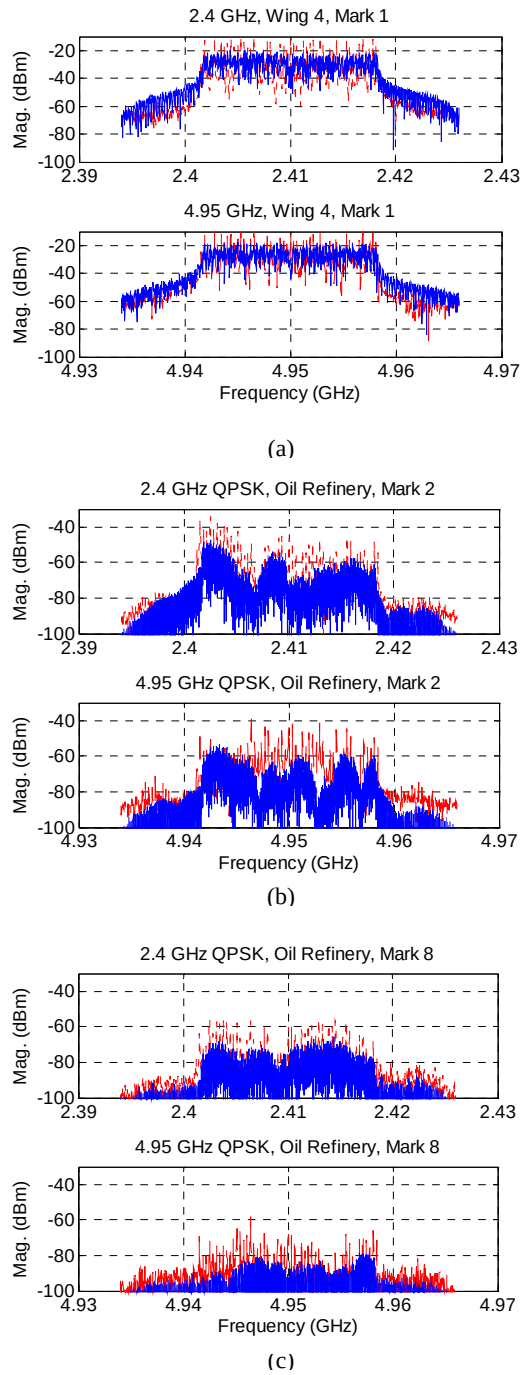

Figure 5: Bandpass spectra measured using the vector signal analyzer showing received QPSK digitally modulated OFDM signals at carrier frequencies of 2.41 GHz (top graphs) and 4.95 GHz (bottom graphs). The dashed lines correspond to multisine signals designed to simulate the modulated signals. (a) Undistorted received signals. (b) Line-of-sight path between transmitter and receiver in the oil refinery. (c) Down the piping corridor, still line of sight.

4. Conclusion

We have presented a variety of measured data collected in a high-multipath, outdoor environment. The intent of this work is to improve radio communications for emergency responders when they transmit wideband, digitally modulated signals.

Results showed waveguide-below-cutoff attenuation effects at the lower carrier frequency of 50 MHz. We saw frequency-dependent behavior in the channel due to strong multipath reflections and attenuation within the piping structures. In non-line-of-sight conditions, we saw classic Rayleigh noise-like signals. In digitally modulated signals, significant distortion occurred in the bandwidth of the signal. This indicates significant wideband fading that may impair wireless transmissions. It is hoped that these data will prove useful in standards development, as well as improved technology and system design for the emergency-responder community.

Acknowledgement

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