Industrial Equipment

Radio Frequency Noise Measurements and Models for Indoor Wireless Communications at 918 MHz, 2.44 GHz, and 4.0 GHz

A Presentation of the Measurement Techniques and Statistical Analyses of Average and Impulsive Noise in Several Common Work-Place Environments

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Development of radio-frequency communications equipment for wireless indoor networks is an active field. A thorough understanding of the channel characteristics is needed to develop reliable system design guidelines and installation techniques for future indoor wireless systems. These systems will be used for reconfigurable voice, data, and video networks that link portable computers, vision systems, cash registers, and telephones in stores, offices, and factories.

Researchers have given considerable attention to the investigation and modeling of indoor radio wave propagation in recent years [1-4]. However, it appears that little scientific work has been done to determine the significance of indoor radio-frequency (RF) noise and its impact on system performance. Noise models for indoor channels and specific noise sources are important for determining irreducible error rates and coding requirements for indoor communication systems. Further, if specific devices are known to be noise sources, this knowledge can be used to assist in the successful deployment of indoor wireless networks.

This article describes the experiment design, measurement procedures, and statistical results of average and impulsive noise measurements made in a suburban grocery store (denoted as Site A), a department store located in a suburban area near a busy 4-lane highway (Site B), two large open-plan office buildings located in a metropolitan district (Site C and Site D), and in a closed-plan office building (Site E) located in a rural area. The measurements were performed at 918 MHz, 2.44 GHz, and 4.0 GHz. Models and statistical characterizations of the noise data, as a function of location, frequency, and noise source, are presented in the form of average noise level.

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Figure 1. Block diagram of the three-band noise measurement system.

Figure 2. Typical receiver calibration curves. This figure illustrates the receiver baseband response to an applied CW signal at the receiver antenna terminal.
distributions, amplitude probability distributions, pulse duration distributions, and pulse spacing (interarrival time) distributions.

**Measurement System**

The three-band noise measurement system consisted of a superheterodyne noise receiver, omni-directional and directional antennas, a spectrum analyzer, a digitizing oscilloscope, and a personal computer. The block diagram of the noise measurement system is shown in Figure 1.

The noise receiver incorporated a bank of microstrip band pass filters, wide band low noise amplifiers, and a logarithmic video detector which provided over 70 dB of dynamic range. The noise receiver had a 3-dB RF bandwidth of 40 MHz centered around the 918 MHz and 4.0 GHz bands, and 30 MHz centered about the 2.44 GHz band.

A broadband omni-directional discone antenna measured noise from all azimuth directions. Three directional helical antennas, with gains of approximately 12 dB, measured RF noise characteristics of individual sources. Detailed descriptions of discone and helical antenna designs can be found in [5] and [6].

A spectrum analyzer allowed the system...
Experimental Procedures

In most buildings, six three-minute measurement runs were performed over a period of an hour in each frequency band at each measurement location. This procedure is recommended in [7]. In each building, measurements were made at several locations deemed likely for future indoor communication systems (for example, near a computer's hard disk). Before each measurement run, the noise receiver was calibrated to allow antenna output power levels to be determined from oscilloscope vertical deflection. The power level of an applied CW signal was varied over a 75 dB range above the receiver noise floor, and the time-average DC signal level at the output of the log detector was measured and stored in the computer. A typical calibration curve is given in Figure 2. The system’s bandpass response in each band was also calibrated using a white-noise generator and the spectrum analyzer. The amplitude and bandpass responses in each band were consistently flat throughout the measurement campaign.

**Receiver Calibration.** Before all measurement runs, the noise receiver was calibrated to allow antenna output power levels to be determined from oscilloscope vertical deflection. The power level of an applied CW signal was varied over a 75 dB range above the receiver noise floor, and the time-average DC signal level at the output of the log detector was measured and stored in the computer. A typical calibration curve is given in Figure 2. The system’s bandpass response in each band was also calibrated using a white-noise generator and the spectrum analyzer. The amplitude and bandpass responses in each band were consistently flat throughout the measurement campaign.

**Average and Impulsive Noise Measurements.** Before each measurement run, a 50 Ohm “dummy” load was placed at the receiver antenna terminal. The time-average DC signal out of the log-detector was then recorded. This DC level corresponded to the average thermal noise floor of the receiver at that location, and was a function of the noise figure of the receiver. This value was stored for future data processing and varied by less than 1 dB throughout the measurement campaign.

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**IMPULSIVE NOISE PSD**

Typical Cases — Site A (All Locations)

\[ \tau_b = 40 \text{ ns} \]

- 918 MHz
- 2.44 GHz
- 4.0 GHz

**Figure 6(a).** Pulse spacing distributions (PSDs) of impulsive noise measured at all sites with sweep speeds of 1 s/div.

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**IMPULSIVE NOISE PSD**

All Measurements

\[ \tau_b = 400 \mu \text{ s} \]

- 918 MHz
- 2.44 GHz
- 4.0 GHz

**Figure 6(b).** Pulse spacing distributions (PSDs) of impulsive noise measured at all sites with sweep speeds of 100 s/div.

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**IMPULSIVE NOISE PSD**

All Measurements

\[ \tau_b = 400 \mu \text{ s} \]

- 918 MHz
- 2.44 GHz
- 4.0 GHz

**Figure 6(c).** Pulse spacing distributions (PSDs) of impulsive noise measured at all sites with sweep speeds of 100 ms/div.
This calibration showed the nominal noise figure of the receiver was 10 dB.

The dummy load was then replaced with the discone antenna. In order to find the average environmental noise floor at each location, the system logged noise waveforms for 3 minutes in a continuous fashion. The oscilloscope provided a running average DC voltage that was referenced to the dummy load measurement at the same location. In this manner, it was possible to obtain the exact average channel noise factor of the particular indoor location, relative to the receiver noise floor. The channel noise factor, \( F_a \), is defined as the ratio of the noise power at an antenna to the thermal noise power produced by a room temperature source over the same bandwidth. That is, the noise power into the receiver (directly out of the antenna) can be expressed as

\[
P_a = F_a kT_b B
\]  
(1)

where \( k = \text{Boltzmann's constant} = 1.38 \times 10^{-23} \text{ J/K} \), \( T_0 = 290 \text{ K (room temperature)} \), and \( B \) is the bandwidth of the receiver.

The oscilloscope trigger level was then adjusted to a level above the average noise floor so that the scope would not trigger on thermal noise but rather on impulsive noise bursts. Every time a noise burst exceeded the trigger threshold, a waveform was acquired and quantized into 512 equal time bins. The oscilloscope sweep speed determined the duration of each bin. The horizontal sweep rate was set at one of the three following rates, which corresponded to the specified time resolution per bin:

1 s/div, 40 ns/bin
100 s/div, 4 s/bin
10 ms/div, 400 s/bin

Measurements were made at each of these sweep rates to ensure that successive noise bursts that occurred within nanoseconds or within milliseconds of each other could be detected and recorded depending on the sweep rate.

Six 3-minute runs at each of the three frequency bands were performed with the omni-directional antenna and with antenna height varying from 1.75 to 2.25 meters above the floor in order to average out any multipath effects.

Directional antennas were used to measure specific noise sources. Three 3-minute measurement runs in each frequency band were made with an antenna height of 2.0 meters using the three horizontal sweep speeds.

Snapshots of typical measured waveforms are shown in Figures 3(a)-(c). These waveforms were recorded at Site A during three different 3-minute measurement runs near an operating cash register. The waveforms shown in Figure 3(a)-(c) were measured in the 918 MHz band using 1 s/div, 100 s/div, 10 ms/div sweep speeds, respectively. The number of waveforms measured during a measurement run depended on the number of impulsive events that occurred above the oscilloscope's trigger level. For example, Figure 3(c) is one of 465 snapshots recorded during a 3-minute measurement run.
Characterizations of Specific Noise Sources

In order to investigate the noise signatures of particular noise sources, three measurements, one at each horizontal sweep speed, were made over 1-minute intervals during the continuous operation of several specific noise sources. The directional helical antennas were used to receive RF noise from each source. The noise sources measured were a pay-per-copy photocopier, an elevator switch and door opener, and a microwave oven. Typical noise signatures are given in the section titled Statistical Models for Specific Noise Sources.

Statistical Models of Impulsive Noise Inside Buildings

This section presents all results obtained from the processed impulsive noise data recorded at Sites A-D. Results are presented in the form of amplitude probability distributions (APDs), pulse duration distributions (PDDs), pulse spacing distributions (PSDs), and noise factor distributions. Results of the specific noise source measurements at Site E are presented in the section titled Statistical Models for Specific Noise Sources.

Amplitude Probability Distributions. Typical amplitude probability distributions (APDs) of the data measured in each frequency band with the discone antenna are shown in Figure 4. This figure indicates that impulsive noise amplitude levels were significantly greater in the 918 MHz band than in the other measured bands. The tails (0.001 percent levels) of the APDs shown in Figure 4 indicate that the amplitude levels measured in the 918 MHz band were 10 dB and 15 dB higher than those measured in the 2.44 GHz band and 4.0 GHz band, respectively. This phenomenon may be explained by higher path losses at the two higher frequency bands. That is, if an impulsive noise source has a flat energy density throughout the microwave region, then equal gain antennas will receive less energy at higher frequencies. The following equation (derived from Friis free space transmission formula) relates the difference, in dB, between path losses $L_{p_1}$ and $L_{p_2}$ to the frequency ratio $\frac{f_1}{f_2}$ for the case of an equal energy source at $f_1$ and $f_2$:

$$L_{p_2} - L_{p_1} = 20 \log_{10} \left( \frac{f_1}{f_2} \right) \text{ dB} \tag{2}$$

The free space path losses, calculated using (2), for frequencies of 2.44 GHz and 4.0 GHz are 8.5 dB and 12.8 dB, respectively, higher than free space path loss at 918 MHz. These path loss differences are very close (within the 1 dB accuracy of the noise receiver) to the differences in the tails of the APDs shown in Figure 4. This suggests the power radiated by impulsive noise sources in retail stores and office buildings is constant over a wide bandwidth, and that
impulsive noise sources can be approximated as point sources.

**Pulse Duration Distributions.** Typical pulse duration distributions (PDDs), determined using a threshold level equal to the average peak power level of each measured waveform for data measured in each frequency band are shown in Figure 5. The PDDs of data collected at all other sites are very similar to those shown in Figure 5, which suggests that pulse duration characteristics of the impulsive noise measured were not dependent upon measurement location. The PDDs shown in Figure 5 indicate the pulse durations of impulsive noise bursts measured in all three frequency bands were comparable. Note, however, that pulse durations in the 2.44 GHz band were slightly longer than in the 918 MHz and 4.0 GHz bands. This was due to the smaller RF bandwidth (30 MHz) of the receiver in the 2.44 GHz band.

The PDDs shown in Figure 5 were compiled from the data measured with a 1 s/div sweep speed (40 ns bin duration). The bin widths of the other two sweep speeds, 100 s/div and 10 ms/div, are wider than the minimum time resolution of the duration of a noise burst detected with a 40 MHz RF bandwidth is 50 ns). It is possible that as many as 8,000 individual noise bursts could have occurred within each 400 s bin. Therefore, accurate small scale pulse duration statistics cannot be determined from the data measured with the two slower sweep speeds.

**Pulse Spacing Distributions.** Figures 6(a)-(c) are pulse spacing distributions (PSDs) of the data measured at all sites in each frequency band with each of the three horizontal sweep speeds. These PSDs may be used to determine the likelihood of bursts occurring in succession and to determine suitable block-code lengths for given bit error requirements in digital communication links. These PSDs were determined using a threshold level equal to the average peak power and are typical of all the PSDs calculated (with a threshold level equal to the average peak power) from the data collected at each measurement site.

Figure 6(a) suggests distributions of spacing between consecutive noise bursts were closer in the 918 MHz band than in the 2.44 GHz and 4.0 GHz bands when a 1 s/div sweep speed was used in the measurements. For example, 50% of the time, consecutive bursts were 180 ns apart at 918 MHz and 200 ns apart at 2.44 GHz. Figure 6(b) indicates pulse spacings measured in the 2.44 GHz were farther apart than in the 918 MHz and 4.0 GHz bands when a 100 s/div sweep speed was used. However, Figure 6(c) indicates pulse spacings measured in the 918 MHz were farther apart than those measured in the 2.44 GHz and 4.0 GHz bands.

**Noise Factor Distributions.** Typical case noise factor distributions are shown in Figure 7(a). The typical noise factor distributions indicate the noise factors measured in the 918 MHz band were consistently higher than those in the other two bands. Figure 7(b) shows the worst case noise

![Figure 7(a). Noise factor distributions for typical measurements in each frequency band.](image1)

![Figure 7(b). Noise factor distributions for worst case measurements in each frequency band.](image2)

![Figure 7(c). Noise factor distributions for data measured at all sites in the 918 MHz band.](image3)
factor distributions in each measured band. The worst measured noise factor distribution occurred in the 918 MHz band at Site C. The high measured noise factors at Site C were caused by adjacent and co-channel interference in the 918 MHz band. Site C is located in a metropolitan area with a large amount of cellular telephone traffic. The skirts of the 918 MHz bandpass filters could not adequately suppress these cellular telephone signals. Figure 7(c), which is the noise factor CDFs of the data measured in all locations in the 918 MHz band, further illustrates this point. This figure signifies the impact of adjacent channel cellular telephone signals on measured noise factor distributions. Cellular telephone signals were detected, using the receiver spectrum analyzer, between 860 MHz and 890 MHz in Sites A, C, and D. Cellular telephone signals were not detected at Site B. At the time measurements were made at Site B (summer 1990), there was no cellular telephone service in the Blacksburg, VA area. During the time between measurements at Site B and Site A (measurements were made at Site A in January 1991), a cellular telephone service was installed in Blacksburg. The significance of the cellular telephone signals on the measured noise factors in the 918 MHz band can be seen by comparing Site A and Site B noise factor distributions in Figure 7(c). The 12 dB difference in measured noise factors at Sites A and B suggest that cellular telephone signals were the major reason for high noise factors in the 918 MHz band. This means that tight front-end filters are needed for commercial radio LAN products in the 902-928 MHz band.

Statistical Models for Specific Noise Sources

This section presents results obtained from the processed impulsive noise data recorded at Site E. Three noise sources were examined: a pay-per-copy photocopier, an elevator, and a microwave oven.

Amplitude Probability Distributions. Figures 8(a)-(c) show the APDs of impulsive noise produced by the photocopier, elevator, and microwave oven. A snapshot of the noise produced by an operating microwave oven at Site B. The noise waveform was measured in the 2.44 GHz band. The microwave oven and receiver were 15 meters apart and separated by a drywall partition.
impulsive noise power, produced by the photocopier and elevator switches indicate pulse durations are similar in all bands. However, the pulse duration distributions of the photocopier impulsive noise suggest somewhat longer durations than those for the elevator door opening switches.

The PDD of the measured microwave oven noise indicates pulse durations of 8 ms. This was also observed during the measurements. The noise waveforms produced by the microwave oven had a period of 16 milliseconds due to the 60 Hz switching power supply used to drive the magnetron, and a duty cycle of approximately 50 percent.

Pulse Snaking Distributions. The pulse spacing statistics computed from the data measured at Site E suggest impulsive noise produced by the photocopier and elevator switches are similar in all bands. The PSD of the microwave oven noise data indicate a 16 millisecond spacing between consecutive noise bursts generated by the microwave oven which was caused by 60 Hz switching.

Other Results
Analysis of the data and log sheets recorded at all measurement locations indicate that the most significant sources of impulsive noise in office and retail environments are microwave ovens, copiers, printers (cash register receipt printers and line-feed printers), elevators door switches, and gas-powered engines with spark-gap ignition systems.

Noise generated by a microwave oven (located 15 meters from the receiver and behind a drywall partition) was detected at Site B in the 2.44 GHz band. Figure 9 is one snapshot of the impulsive noise produced by the microwave oven. The maximum peak power received at the discone antenna was approximately -50 dBm. The spectrum of the noise generated by the microwave oven was also noted on log sheets. The recorded spectrum contained spectral lines separated by less than 200 Hz and had a bandwidth greater than 30 MHz. The noise bursts produced by the microwave oven had a period of 16 milliseconds due to 60 Hz AC, and duty cycle of approximately 50 percent (as indicated in Figure 9). Most microwave ovens operate at a nominal frequency of 2.45 GHz. Therefore, noise produced by the microwave oven can be modeled as a 2.45 GHz carrier modulated by a 60 Hz square-wave pulse train. Noise from an operating microwave oven was also detected in Site A. The microwave oven and receiver were 50 meters apart and separated by a Cinder-block wall and several rows of metal stock shelves. Peak power levels of -68 dBm were measured with the omni-directional discone antenna.

Acknowledgements
The authors would like to thank Scott Seidel and Mike Keitz for their assistance in the development of the measurement system and data collection during the measurement campaign. The authors also gratefully acknowledge NCR Corporation for sponsoring this research and permitting us to publish this work.

References