Proc. Intl. Symp. Advanced Radio Technology, ISART 2005, Boulder, CO, March 2005, pp. 199-204.
Poster Presentation by Marc Rutschlin.

Measurement of Weak Signals Using a Communications Receiver System*

Marc Rütschlin[1], Kate A. Remley, Robert T. Johnk, Dylan F. Williams, Galen Koepke, Chris Holloway
NIST Electromagnetics Division 818; 325 Broadway; Boulder, CO 80305
1. Corresponding author: ph. (303) 497 4674, email: rutschln@boulder.nist.gov

Andy MacFarlane, Mike Worrell
Phoenix Fire Department; Phoenix, AZ

We develop and characterize an inexpensive, reliable system for use in weak-signal detection. The system is implemented using widely available components, including a communications receiver and a computer sound card. Our characterization procedure allows the conversion of signals measured with the receiver system to electric field values. This enables comparison of measurements carried out on different receiver systems. The receiver system allows detection of signals up to several orders of magnitude weaker than is possible using handheld radio transceivers. This is of great use to the public safety community.

1. Introduction

A well-known problem facing first responders who rely on radio communications is the loss of signal in complex propagation environments such as large buildings, tunnels, basements, and collapsed structures. Reduced signal strength due to attenuation through building materials can significantly hamper communication. In the case of a dire emergency such as a collapsed building, the ability to detect a radio signal from a survivor may enable searchers to focus their efforts and may let the survivor communicate his or her status.

Here we describe a method that can be used to improve detection of weak signals by up to several orders of magnitude. The technique, sometimes known as joint time-frequency analysis [1,2], is particularly suitable for the detection of weak sinusoidal signals with time-varying frequency content such as those typically encountered in handheld radio communications. It has been used for years by ham radio enthusiasts, as well as in deep-space and other sciences that rely on weak-signal detection. Here we adapt the method to the unique needs of the public safety community where systems must be reliable, straightforward to implement, and easy to use in emergency scenarios. The system described here meets these objectives. Additionally, it is inexpensive and does not preclude the use of existing radio systems. At present, the method is limited to the detection of narrowband signals, meaning that its primary use is to determine only whether a radio signal is present and the strength of that signal rather than for voice communications.

A focus of this paper is the development of a characterization procedure that allows the calculation of the absolute electric field strength of received signals measured with the communications receiver system. This provides additional information on signal level for the operator, enables comparison of measurements that have been made on different systems, and makes it suitable for studying propagation in complex environments. Note that the procedure we discuss here does not increase the range of measurable signals; it merely allows us to calculate the absolute field strength.

Our approach in this paper will be to first describe the receiver-based measurement system, then to focus on the characterization procedure, which is divided into two steps: the quantification of the communication receiver's gain, and the measurement of the antenna factor. Finally, a case study implementing the system in the measurement of signal transmissions in a building will be described.

2. The Measurement System

The measurement system is shown in block diagram form in Fig. 1. It is based on a common communications receiver, which is used to downconvert a narrow band of radio frequencies, and a personal computer (PC) sound card, which is used to digitize this band of frequencies. The digitized frequency band is then amplified and/or graphically displayed, letting the operator know whether a radio signal is present and what the level of that signal is.

As shown in Fig. 1, the electric field corresponding to the signal is received by the antenna (labeled “handset” in the figure) and fed as P_{rec} to the RF input of a communications receiver (CR). The receiver is operated in its upper sideband (USB) mode at a frequency slightly below that of the transmitted signal (it is assumed that we have knowledge of that frequency).

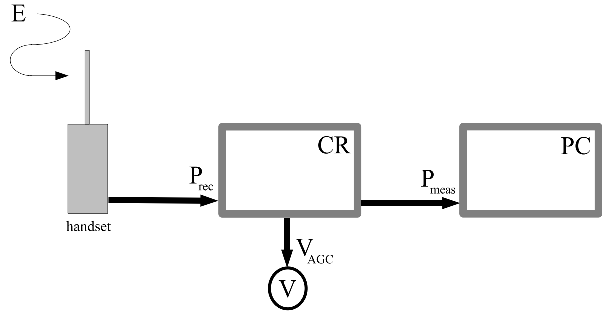

Figure 1: Block diagram of the measurement system. The electric field detected by the antenna (labeled "handset" in the figure) is related to the RMS voltage associated with the received power by an antenna factor: $E = AV_{rec}$, where $V_{rec} = (P_{rec}R)^{1/2}$; the power measured with the PC's sound-card input is related to P_{rec} by a V_{AGC}-dependent power gain: $P_{meas} = G_pP_{rec}$, where $G_p = f(V_{AGC})$ and AGC is the automatic gain control of receiver.

In this way, the receiver operates as a simple frequency converter, down-converting an entire block of frequencies simultaneously. By setting the receiver's frequency somewhat lower than the center frequency of the transmitted signal, the modulated received signal is converted down to the audio band. We may observe the upper and lower sidebands of the down-converted signal by setting the receiver's center frequency to approximately the middle of its passband. For example, a 100 MHz signal may be measured by a receiver with a 3 kHz passband by tuning the receiver to 99.9985 MHz. In this case, the receiver will display the 100 MHz signal at 1.5 kHz.

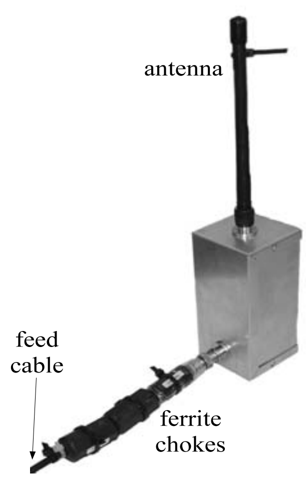

Figure 2: Photograph of the handset simulator used to develop the characterization. The receive antenna is of the helical type typically used with portable radio handsets. The effect of the feed cable is reduced through the use of ferrite chokes.

The received signal may consist of the unmodulated FM carrier or a frequency-modulated audio transmission. For public safety and other networked applications, the modulation may also correspond to a squelch tone. This sort of continuous tone is produced by many two-way radio handsets when the 'push-to-talk' button is depressed.

The down-converted signal is sampled by a sound-card connected to a PC running audio recording software. The communications receiver has an automatic gain control (AGC) circuit whose function is to control the receiver gain to produce a constant output signal regardless of the input power. In practice, the AGC is active only for signals within a certain power range, and does not modify weak signals (on the order of $P_{rec} < -90$ dBm). We monitor the level of feedback of the AGC, which is directly related to the input power, by measuring the voltage at the AGC jack on the back panel of the receiver at one-second intervals by use of a digital multimeter with a recording feature.

For the purpose of representing the signals measured by our system in terms of electric field strength, we developed a handset simulator, shown in Fig. 2, whose electrical properties emulate a typical handheld transceiver but is easier to characterize. A description of its construction is aided by the photograph shown in Fig. 2. It consists of an antenna attached to a metal box, fed through the box by a coaxial cable. Magnetic ferrite 'chokes' are placed near the point where the coaxial feed attaches to the box, disrupting common mode current flow and allowing the box to act as the second element of an asymmetric dipole, as it would in an isolated radio handset. The success of these chokes in removing the effect of the feed cable, at least at relatively low frequencies, has been demonstrated previously [3] and confirmed in our own tests. At higher frequencies, a narrow-band sleeve balun of the type proposed by Icheln *et al.* may also be used [4].

3. Receiver Characterization Procedure

Two steps are involved in the characterization procedure: first, apply a gain factor to convert the perceived power measured by the PC sound-card to the actual power at the RF input of the communications receiver; and second, use an antenna factor to convert this actual power to the electric field level present at the antenna.

The characterization procedure is carried out as follows:

1. Record the sound card input as a '.wav' file using commercially available audio recording software at the same time as the AGC voltage. The two measurements must be synchronized during post-processing. For long recordings such as field mapping in buildings, record time stamps corresponding to important events. For example, one might record the time of departure from a certain room. A sequence of this sort of time stamp allows for easier deciphering of the final recording.

2. Convert the signal to the frequency domain using successive *N*-point Fast Fourier Transforms (FFTs). Each FFT is carried out on a segment of the signal centered on a time that corresponds to when V_{AGC} was measured. The length of the FFT should be a power of two for greatest efficiency. A longer FFT will increase the frequency resolution of the results but will decrease the temporal resolution, which may cause loss of detail in a rapidly changing input.

3. Calculate the average power, P_{rec}, in the period chosen for the FFT by squaring and summing the magnitude of the frequency components over the frequency band of interest, as

$$P_{rec} = \frac{1}{G_p R} \sum_{i=\omega_1}^{\omega_2} \left| V_i(\omega) \right|^2 , \qquad (1)$$

where $V_i(\omega)$ is the root mean square (RMS) voltage of the *i*th spectral component, ω_1 and ω_2 are the lower and upper band-limiting frequencies, and *R* is the characteristic impedance of the system. The frequency band in (1) is chosen to incorporate as many transmitted signal components as possible. It will be limited by the communications receiver's IF filter bandwidth. The power gain, G_p, may be determined by the method described in Section 3.1. It is defined as

$$G_p = P_{meas} / P_{rec} = G_v^2 \qquad (2)$$

$$G_v = V_{meas} / V_{rec} , \qquad (3)$$

where G_v is the voltage gain that describes the ratio of the signal measured with the soundcard to the signal entering the communications receiver. Each voltage in (2) and (3) is an RMS quantity associated with the relevant average power:

$$V_{rec} = (P_{rec} R)^{1/2}, \quad V_{meas} = (P_{meas} R)^{1/2} . \ (4)$$

4. Obtain the electric field by multiplying V_{rec} by the antenna factor, *A*, derived in Section 3.2:

$$E = A V_{rec} . \qquad (5)$$

Using (3), the electric field can be written simply as

$$E = A \frac{V_{meas}}{G_v} , \qquad (6)$$

where V_{meas} is the voltage measured at the PC sound card port. The determination of the gain function G_v is described in Section 3.1, while the characterization of the antenna in a TEM cell with a characteristic impedance of 50 Ω is described in Section 3.2.

3.1. Gain Determination

The relation between the power measured with the sound card, P_{meas}, and that entering the communications receiver, P_{rec}, will be determined in this section. The setup of Fig. 1 is used, with the handset replaced by a signal generator that supplies a known signal. The V_{AGC}-dependent gain may be determined as follows:

1. Use a signal generator, or in our case a vector signal generator (VSG), to excite single-frequency signals over a desired range of power levels. This range is representative of the signal levels likely to be encountered in transmission scenarios where the set-up will be used. The minimum power level of the signal generator may be decreased by the use of attenuators.

2. The communications receiver output, operated as described above, provides the input to the sound card. After the signal generator output has been allowed to stabilize, the signal is recorded. Its spectrum is found using an FFT, and its average power, P_{meas}, is calculated from this spectrum. At the same time the AGC voltage is monitored and recorded.

3. The ratio of measured voltage to input voltage, G_v, defined in (3), is plotted versus V_{AGC} to obtain a gain curve.

During a field measurement, the actual gain may be extracted by interpolating the curve based on the measured AGC voltage. We show gain curves at three frequencies in Fig. 3 for the particular receiver system that we characterized. Note how the gain increases fairly linearly with rising V_{AGC}, then flattens off when the voltage approaches its maximum of about 2.42 V. This maximum voltage is reached when the AGC is no longer active due to an insufficient strength of input signal.

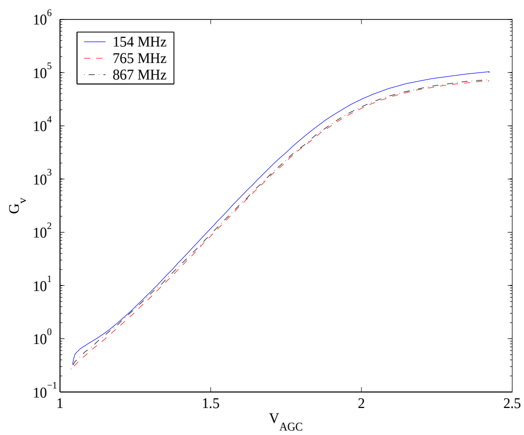

Figure 3: V_{AGC}-dependent voltage gain curves for the receiver system we characterized at three frequencies.

3.2. Antenna Characterization

A relatively simple way of characterizing the antenna is to determine its response to a known electric field. Such a field may be created to a good degree of accuracy–locally for physically small antennas such as ours–in a transverse electromagnetic (TEM) cell [5]. We used a broadband flared gigahertz TEM (GTEM) cell with a 50 Ω characteristic impedance. In similar cells, measurements of small antennas' gain factors have previously compared favorably to anechoic chamber measurements [6].

It is a simple matter to establish a specific potential difference between the conductors. Placing the antenna at the position where the plate spacing is x meters results in its exposure to an electric field of $1/x$ V/m if the potential difference between the plates is 1 V. The configuration we used is sketched in Fig. 4. A vector signal analyzer (or spectrum analyzer) is used to measure the received signal as V_{VSA}, the RMS voltage corresponding to the measured power (equivalent to P_{rec} in Fig. 1). The antenna factor is thus defined as

$$A = \frac{E_{cal}}{V_{VSA}}, \qquad (7)$$

where E_{cal} is the known electric field applied to the antenna.

Certain precautions are necessary when placing the antenna in the TEM cell so as to minimize impact on the field distribution in the immediate vicinity of the antenna. For example, we attach the feed cable to the antenna from 'behind', i.e. from the direction opposite to the TEM cell feed point, effectively 'hiding' it by attaching it to the lower conducting plate with adhesive conducting tape.

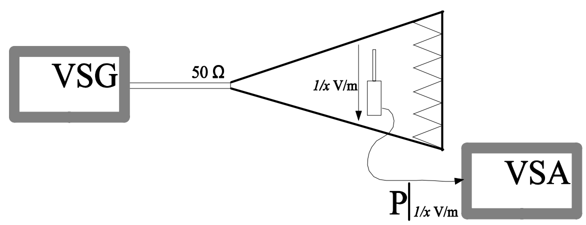

Figure 4: A block diagram view of the TEM cell antenna characterization. The TEM cell's input is supplied by the VSG. The antenna, positioned such that it is exposed to a $1/x$ V/m field, has its output measured by a vector signal analyzer or similar instrument.

4. A Case Study

Our receiver-based measurement technique described above was utilized in conjunction with an independent study conducted by the Phoenix Fire Department [7]. Their aim was to compare the voice quality of radio transmissions at different frequencies and with different modulation schemes (e.g., analog, digital) in various typical building environments. The result is a subjective evaluation of the different schemes: individual communications between positions at which firefighters would typically be positioned are rated according to the criteria shown in Table 1. Our goal is to assign absolute field strength values to these subjective ratings.

Our aim was to attempt to match electric field strengths to the ratings (1-5) given in Table 1. The difficulty in comparing an objective quantity (the field strength) to a subjective rating will require additional study involving the firefighters who carried out the ratings. However as a first cut, we can denote levels three, four, and five as "acceptable" communications, while levels zero, one and two will result in "unacceptable" communications. This division is borne out by the data shown in Fig. 5. These data, collected over a number of months by the Phoenix Fire Department, describes the perceived quality of voice transmissions over a wide spectrum of building types, at different frequencies and for different modulation schemes. There is a clear division between the ratings of 3-5, where a significant number of evaluations were made, and the ratings of 0-2, where very few were made.

Table 1: The criteria for the subjective evaluation of voice signal quality used by the Phoenix Fire Department in its study (from [7]).

Rating	Definition
0	No speech heard.
1	Unusable, speech present but unreadable.
2	Understandable with considerable effort. Frequent repetition due to noise or distortion.
3	Speech understandable with slight effort. Occasional repetition required due to noise or distortion.
4	Speech easily understood. Occasional noise or distortion.
5	Speech easily understood.

To investigate the link between these subjective ratings and absolute electric field strength, we first developed a map of signal strength in an eight-story building in Phoenix in which poor signal transmission quality had been observed in previous tests. A listening station–an implementation of the measurement set-up described in Fig. 1–was placed on the fifth floor of this building. Hand-held radios were set to transmit continually while being carried on a circuitous path through the building. At the same time, the radio bearers were regularly in voice communication with the listening station, allowing the quality of transmission to be judged and compared to the ratings from Table 1. Separate walks were done for transmissions at about 154, 765 and 867 MHz. Detailed notes were kept of the whereabouts of the transmitter as well as the signal quality, allowing the analysis shown below.

Since all results displayed the same trends, only the case for 867 MHz is discussed in detail here as a representative example. The measured electric field is shown in Fig. 6, plotted versus an 'absolute time' measured from the beginning of the walk. The vertical marker lines and comments are based on the notes taken during the walk. Of particular interest are the comments regarding degraded signal quality: all occur when the measured electric field is below about 1×10^{-4} V/m, shown in Fig. 6 by the horizontal marker line. We assign this level to the "unacceptable" (levels 0-3) given in Table 1. This choice is somewhat arbitrary, since it is based on limited observations.

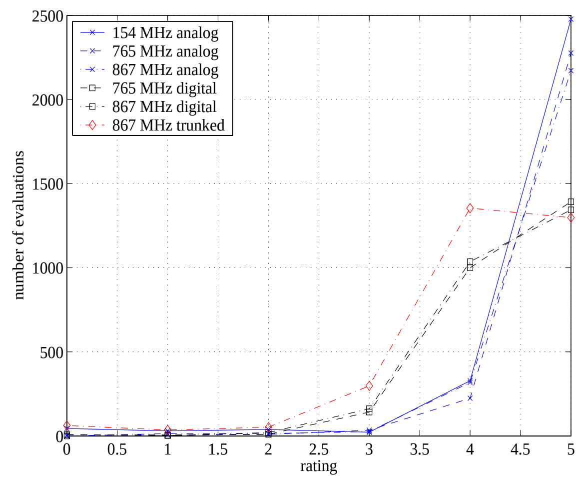

Figure 5: Sum of evaluations of radio transmission quality based on the rating descriptions in Table 1, reported for measurements of different modulation schemes at various frequencies in a wide range of buildings undertaken by the Phoenix Fire Department (based on data in [7]).

The route of the walk is roughly described by the comments along the top of the graph, e.g., 'stair ascent' refers to the transmitter being carried from the ground floor past the receiver position on the fifth floor to the roof. Note the correspondingly strong measured field just after the 300 second mark for this case. Access to the roof was not possible, so a brief circuit was walked on each floor before the sublevels were visited. As shown by the comments in Fig. 6, the measured field strengths were lowest when the transmitter was in the roof access hatch just above the eighth floor (at about the 600 second mark), and when it was in the parking garage sublevels ('SL1' and 'SL2'). At these points the received audio quality was also worst, deserving ratings lower than 2 according to Table 1. A further aspect of the use of our receiver-based method for the detection of weak signals, indicated by the comments in Fig. 6, is that the carrier was visible even when the voice quality was very poor. This would appear to hold promise for alternative means of communication when voice transmission is difficult.

5. Conclusion

We have described a method, developed for the public safety sector, for detecting weak signals based on commercially available equipment. A focus of this paper was to calculate the absolute electric field strength from the measured signal. Use of electric field values allows the comparison of measurements made using different systems and makes the technique suitable for mapping signal propagation in complex environments. We applied the measurement technique to develop such a field-strength map in a large public building. Based on an assessment of audio quality, we assigned a field strength value below which communications were considered "unacceptable."

6. References

[1] S. Qian, D. Chen, "Joint Time-Frequency Analysis," *IEEE Sig. Proc. Mag.*, pp. 52-67, March 1999.

[2] R. Johnk, G. Koepke, D. Novotny, K. Remley, C. Grosvenor, M. Rutschlin, D. Williams, "Propagation measurements using computer soundcard methods," *NIST Technical Note*, in process.

[3] J. Demarinis, "The Antenna Cable as a Source of Error in EMI Measurements," in *Proc. 1988 IEEE Symp. on EMC*. IEEE, pp. 9–14, 1988.

[4] C. Icheln, J. Ollikainen, and P. Vainikainen, "Reducing the Influence of Feed Cables on Small Antenna Measurements," *Electron. Lett.*, Vol. 35, No. 15, pp. 1212–1214, July 1999.

[5] M. L. Crawford, "Generation of Standard EM Fields Using TEM Transmission Cells," *IEEE Trans. EMC,* Vol. 16, No. 4, pp. 189–195, Nov. 1974.

[6] P. Hui, "Small Antenna measurements Using a GTEM Cell," in *Antennas and Propagation Society International Symposium*, 2003. IEEE, Vol. 4, pp. 715–718, June 2003.

[7] Mike Worrell and Andy MacFarlane, "Phoenix Fire Department Radio System Safety Project," *Final Report*, Oct. 2004.

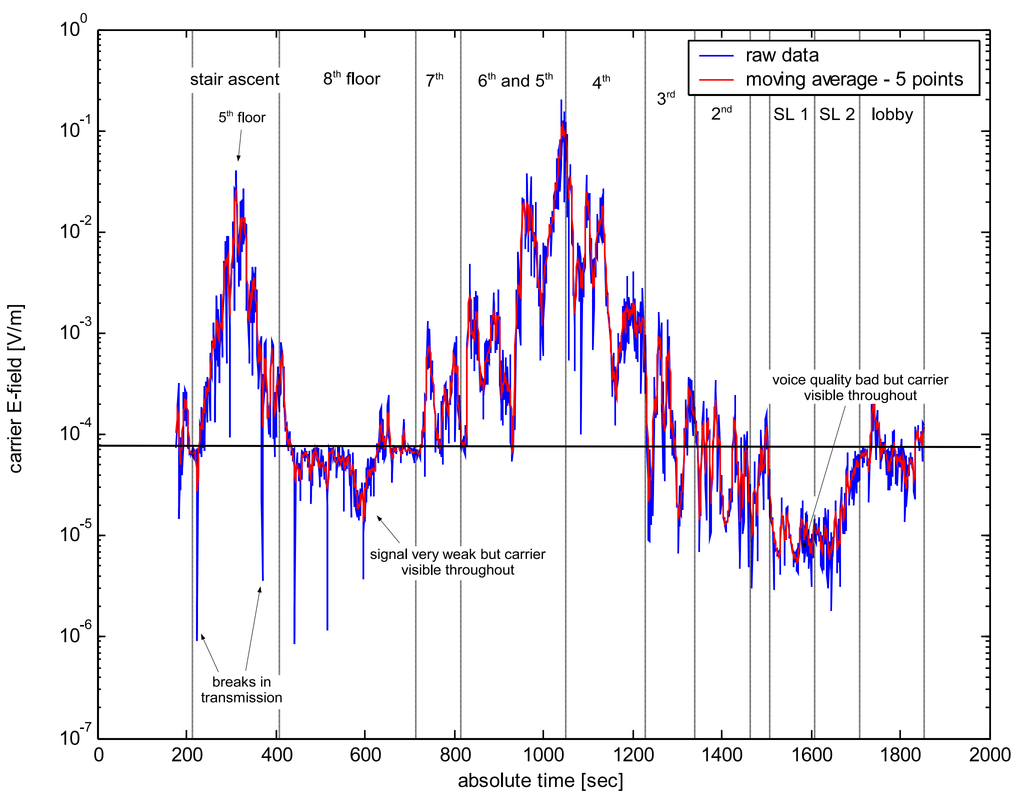

Figure 6: Electric field strengths measured during the 867 MHz building walk-through. The vertical marker lines represent boundaries in time between different sections of the walk. The horizontal marker at 1×10^{-4} V/m is the threshold below which poor signal quality, corresponding to ratings of 1 or 2 in Table 1, was observed. The lighter curve is a five-point moving average of the raw measured data shown by the darker curve.