TRANSMITTING SITE EVALUATION USING A MOBILE SPECTRUM MEASUREMENT SYSTEM

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ABSTRACT

This technical paper describes general development and application of a mobile coverage data collection system, employing an RF spectrum analyzer, a Global Positioning System (GPS) receiver, and a custom digital signal processor interface. The paper also describes how the system was used to gather coverage data on an existing lower power FM facility already operating from the potential relocation site of a client FM station. That data was then appropriately scaled and studied using powerful coverage analysis and mapping tools, resulting in the development of a relocation profile for the client station.

Other system applications include comparative analysis of station coverages in a particular home market, an adjacent market, or in weak signal areas, and evaluation of FM booster transmitter performance. Gathered field strength data can be linked with similar data predicted by popular terrain-sensitive computer algorithms, providing a "predicted-to-actual" performance comparison. This ability additionally allows easier troubleshooting of transmitting installations that provide coverage perceived to be poorer than expected.

INTRODUCTION

The need to better understand the physical nature of signal propagation has driven development efforts to produce improved computer modeling and measurement verification tools. These tools have been used to predict and verify the coverage of broadcast facilities, especially that of TV and FM stations.

With respect to field verification, mobile field strength data gathering systems for coverage analysis are becoming increasingly common. Typically, these systems are based on single-channel or scanning receivers. These receivers obtain signal level information for only one channel at time and, unless multiple receivers are employed in parallel, some settling time must be allowed after a frequency change. When multiple channels are being measured, this requirement often restricts the data sampling interval on each channel. Typical receivers also have difficulty in providing accurate signal level information in the presence of strong adjacent-channel signals, and they are also subject to receiver-induced intermodulation effects; both of these factors can contaminate measurement data. Also, some receivers have a limited dynamic range for use in conducting mobile field strength measurements, and the inclusion or removal of external filters, attenuators and/or preamplifiers must be constantly addressed by a trained operator or an automated process to avoid the possibility of signal loss or receiver saturation.

A broadband spectrum analyzer is a signal measurement instrument that overcomes many of these limitations. With proper selection of the frequency span, multiple signals can be measured nearly simultaneously, and proper choice of resolution bandwidth can yield accurate results, even in a crowded signal environment. Further, the considerable viewable dynamic range available on most spectrum analyzers allows simultaneous measurement of weak signals in the presence of strong signals. The spectrum analyzer is still a swept measurement instrument, so data for multiple signals is not truly available simultaneously, but no settling time is required to yield usable data. However, a spectrum analyzer is traditionally a "bench" instrument. The goal of the present effort was to develop a recording system that could utilize the advantageous measurement capabilities of a spectrum analyzer in a mobile data collection system.

SYSTEM DESIGN

The system is designed around a low cost Tektronix Model 2710 spectrum analyzer. The key component in the system is an interface module between the spectrum analyzer and a portable computer. The module uses a digital signal processor (DSP) circuit to digitize the analog sweep output signal from the analyzer, perform signal processing, and convert each display sweep into a

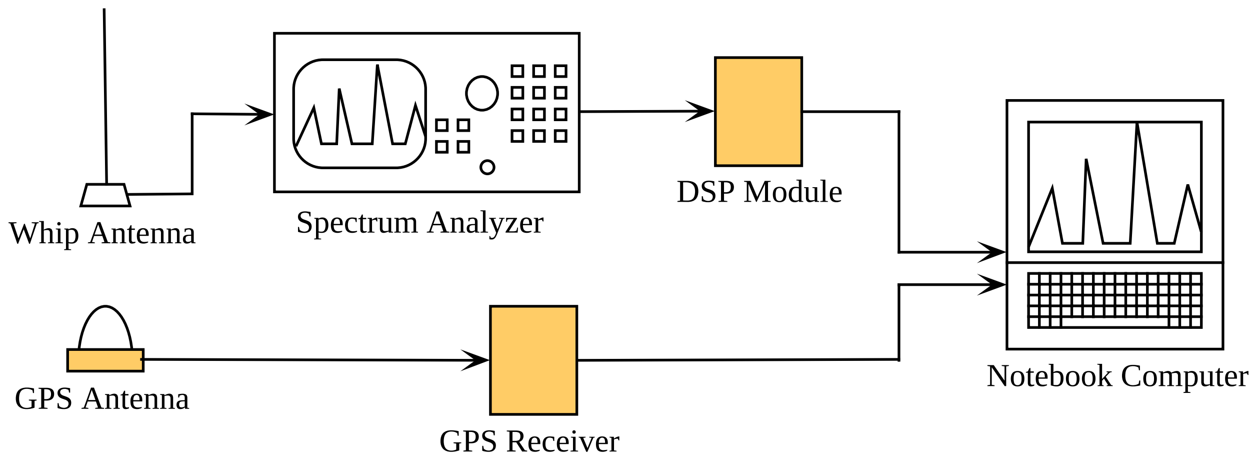

Figure 1. Block diagram of spectrum analyzer recording system.

packet of data that is then transmitted to the computer. The system also includes a GPS satellite receiver to provide position data. Custom software running on the computer controls the system and records the data. Figure 1 shows a block diagram of the data gathering portion of the system.

Receiving antenna. A quarter-wave vertical whip antenna was selected for use with the system, because it is most representative of antennas commonly installed on automobiles for FM reception. While other types of nondirectional mobile antennas could be employed, the vertical whip antenna is easy to use and to mathematically characterize. It is adjusted by setting its length to correspond with the wavelength of a desired signal being measured or to the center frequency of the selected spectrum analyzer span. The metal roof or body of the vehicle on which it is mounted provides the required counterpoise. Magnetic mount versions of whip antennas are easily transported, for use on rented vehicles.

Spectrum analyzer. The selected spectrum analyzer covers a frequency range of 100 kHz to 1.8 GHz with 70 to 80 decibels (dB) of usable dynamic range [1]. Through careful selection of sweep span and resolution bandwidth parameters, the sweep time can be relatively short, in the 0.25 to 0.5 second range for a full sweep, making it well suited for mobile measurement applications where signals are changing rapidly. The spectrum analyzer provides output signals suitable for processing and recording, including an analog sweep trace signal and a digital sweep gate signal.

DSP module. The DSP module contains a Texas Instruments TMS320C50 DSP chip and a TLC32040 analog interface circuit (AIC). The DSP chip [2] is an advanced 32-bit processor running at a clock rate of 20 MHz. The AIC [3] contains an analog-to-digital converter with 14-bit resolution capable of sampling at rates of up to 20,000 samples per second. The output signals from the spectrum analyzer are fed to the DSP module, with the sweep trace signal connected to the AIC and the sweep gate signal connected to processor interrupt lines. The DSP code receives interrupts at both the start and end of the sweep gate. The DSP module digitizes the sweep trace signal only during the active portion of the sweep. Digitized data for each sweep is delivered to the control computer in a single data packet through a full-duplex asynchronous serial interface. The DSP has sufficient processing power to perform serial transmit-and-receive signal processing as well as other functions; no separate serial interface hardware is needed.

The sweep trace signal is digitized at a sampling rate of 19,200 samples per second. This rate was chosen because it allows serial data transmission to be driven by the analog sampling interval, simplifying the code design. Depending on the spectrum analyzer sweep parameter settings, the duty cycle of the sweep gate can be as high as 90%. Consequently, the DSP module cannot store the sweep data for transmission during the inactive portion of the sweep gate, so serial transmission to the computer is synchronized with data sampling. The DSP performs peak-hold processing on the digitized signal to reduce the sampling rate for transmission. Serial transmission limits the data size to 8 bits per sample, so the signal is clipped and scaled from the 14-bit signed output of the AIC to an 8-bit unsigned signal for transmission to the computer.

The operational code for the DSP is downloaded from the computer when the system is initialized. This feature simplified and accelerated the development process, allowing the code to be revised quickly and easily and greatly shortening the debugging cycle.

GPS receiver. The GPS receiver employed in the measurement system is a Magellan five-channel module, which requires an external controlling device communicating through an asynchronous serial interface. Software on the control computer provides a status display and user interface for the GPS receiver. The receiver provides position updates to the computer at one-second intervals.

Computer and recording software. The computer must initialize and control the DSP module and the GPS receiver. A multi-tasking operating system is used on the computer so the software applications controlling each device can be entirely separate. This scheme greatly simplified and accelerated the development process. The operating system used is Linux, a popular public-domain operating system developed by a collaboration of programmers on the global Internet. While there was some trepidation at using non-commercial software, Linux met or exceeded every expectation, and proved to be extremely reliable.

The spectrum analyzer software application initializes and controls the DSP module and provides a real-time graphical display of the digitized sweep data from the analyzer. The system operator can visually compare the corresponding screen displays on the analyzer and computer to confirm that the system is functioning properly. The software records each analyzer sweep, along with a time stamp and control information, to a file on the computer hard disk drive. The operator may manually enter reference markers in the data stream to note significant events or locations during recording. The GPS software application controls the GPS receiver and records position reports to a disk file. Time stamps are included, and since they are referenced to the same clock being used by the spectrum analyzer recording software, the separate data streams are correlated. The operator may switch between the two applications on the computer screen whenever desired without interrupting the execution of either.

The first use of the system was with a notebook computer containing a 386SX processor running at 16 MHz, with 4 megabytes of memory and a 60 megabyte hard disk drive. This modest platform was perfectly adequate to the task, although the small disk drive limited the total recording time; the spectrum analyzer recording software generates data at the rate of 3 to 4 megabytes per hour. The computer has since been upgraded to another notebook employing a 486DX2 processor running at 66 MHz, with 8 megabytes of memory and a 500 megabyte disk drive. The more powerful computer increases total recording time, and it also facilitates data post-processing and analysis in the field. Separate post-processing and analysis software, discussed later, requires a considerably more powerful computer platform than does the recording software.

SYSTEM IMPLEMENTATION

The system is designed to be installed in a vehicle; it can be set up in less than 30 minutes. The spectrum analyzer requires 120 VAC power, so the remainder of the system was designed to operate from a 120 VAC source. The system is typically installed in a modified GMC "Safari" field measurement van, which is equipped with interior bench space and a high capacity AC power system. Antennas for GPS and RF reception are permanently installed on this vehicle. The total power requirement of the system is a relatively modest 175 W, so if the system must be used in a different vehicle, power can be supplied by a portable DC inverter. Portable magnetic-base GPS and vertical whip antennas would be used in the latter configuration. The only inconvenience encountered with the portable DC inverter is the need to run power cables directly to the vehicle battery to accommodate a current drain greater than the capability of common cigarette lighter jacks.

The most significant installation problem encountered was radio-frequency interference (RFI) from the recording system hardware. The spectrum analyzer itself is very well shielded and not a direct source of RFI. The DSP module and GPS receiver are both constructed in shielded enclosures and were found to be minimal contributors. It was expected that the largest RFI source would be the computer itself, but surprisingly, it too was found to be only a minimal source of interference. Conducted energy on the power and control cables, however, was significant. Extensive use of shielded cabling and ferrite cores reduced the problem to a tolerable level, sacrificing less than 5 dB of the measurable dynamic range. Depending on the frequency band being measured, an additional significant source of RFI can be vehicle engine ignition systems. This interference can originate not only from the measurement vehicle itself, but from nearby and passing vehicles on the road. Thus, shielding the measurement system from such interference or eliminating it at the source is impossible. Fortunately, the appearance of this interference in the recorded spectrum data has a unique signature that allows it to be eliminated through virtual filtering in the post-processing software, as discussed later. Figure 2 is a photo of the system installed in the Hammett & Edison measurement van.

Figure 2. System installed inside measurement vehicle.

SYSTEM OPERATION

During actual data gathering, the system requires relatively little operator intervention. It can be used in an unattended manner, with a single individual used both to operate the system and drive the vehicle. The operator starts the system and initiates data recording, then proceeds to drive the measurement route without the need for any further attention to the recording system. When used in a moving vehicle, the GPS system is prone to brief outages, during which position reports are either inaccurate or not available. They occur due to localized obstructions interfering with one or more of the GPS satellite signals, or due to the need for the receiver to periodically change the specific satellites being tracked. Outages are usually insignificant, and the analysis software can interpolate between periods of valid position data to reconstruct the route. GPS data may not even be required if an operator is available to record accurate position markers.

DATA ANALYSIS

The recording system gathers volumes of raw data, which must be processed into usable signal level versus location information. The analysis process occurs in two steps. First, the raw sweep-trace data from the spectrum analyzer is processed and converted to produce signal level versus time data. Then, separate applications correlate this data with the GPS position data or manual position markers to produce the final results.

RF system calibration. Before the raw spectrum analyzer sweep data can be processed, a correlation of the recorded digital values to the screen graticule of the analyzer is needed. This produces a data mapping of the raw digital values from the recording system to equivalent relative positions on the analyzer screen. This data was obtained several times over a period of months, and correlation was found to be highly stable; the correlation data remains constant as long as the analyzer itself does not undergo a factory recalibration. Overall accuracy ultimately depends on the calibration of the analyzer instrument itself, so frequent factory recalibration of the analyzer is important.

With correlation data available, the operator of the analysis software need only provide the range and sweep parameters used during a particular recording session. These parameters include the amplitude reference level, the sweep center frequency, and the sweep range per division. The analysis software can then translate any point in the recorded data to a signal level at a known frequency.

The signal level value obtained by this process represents receiver terminal voltage at the analyzer input. To equate it to actual field strength, the receiving antenna and interconnecting cables used also must be considered. For the vertical whip antenna, the following formula, derived from antenna theory, can be used to convert the voltage at the antenna terminals to a corresponding electric field value:

$$E = V + 14.65 - 20 \log (\lambda) + L,$$

where E is the electric field in dBuV/m (or dBu), V is the voltage measured at the antenna terminals in dBuV, λ is the wavelength in meters, and L is the loss of the antenna lead in dB for a given wavelength. The equation assumes an antenna gain of 5.15 dBi [4] and a system load impedance of 50 ohms. Practical use of this equation assumes that the antenna/vehicle combination performs as a theoretical quarter-wave antenna over a perfect ground plane.

When highly accurate field strength data is desired, supplementary measurements are taken using a calibrated reference receiver and antenna to determine field strength at specific locations, and then they are compared to the indicated results at the same locations with the measurement antenna. In general, though, most applications of the system are not intended to determine absolute field strengths at specific locations. Rather, they are intended to produce relative levels and field strength trends that can be correlated to results predicted by terrain-weighted computer propagation analysis, such as that produced by the Terrain-Integrated Rough Earth Model (TIREM) algorithms [5]. Experience with the system has shown that measurements in the broadcast FM band, using a measured-length vertical whip antenna on the roof of a metal-bodied vehicle, can yield field strength figures that correlate well with critical measurements and with the results of computer propagation studies.

Spectrum data analysis. Once adequate calibration data is obtained, the operator uses an additional software application to study the recorded spectrum analyzer data and produce signal level versus time data. The analysis software provides the operator with a graphical display that mimics the screen of the spectrum analyzer. The software can replay the recorded sweep data in real or accelerated time, or allow the operator to single-step through the recorded sweeps. Many sweep and display features available at the spectrum analyzer front panel can be emulated by the software, such as a peak-hold display. The major focus of the software, though, is to produce amplitude data for the signals being studied. To accomplish this task, the operator can define one or more channel windows, entered as a center frequency and frequency span. When displaying each recorded sweep, the software will determine the peak signal observed in each of these channel windows. The software can convert the measured signal level values to various units, including a field strength based on calculated or measured antenna parameters. The values are displayed on the computer screen, and on user command they can be recorded to a disk file for use in a second stage of analysis. The output data indicates the time at which a particular sweep was recorded along with the signal values for all defined channels.

Several problems that can exist in the recorded sweep data may require additional data processing features in the analysis software. As mentioned earlier, the recording system is inherently and unavoidably prone to RFI from vehicle engine ignition systems. The interference appears in the sweep data as a series of extremely narrow signal spikes as the periodic short-interval broad-band noise bursts from ignition firing occur. The data analysis software eliminates much of this ignition-spike noise by passing the recorded sweep data through a simple magnitude-comparison routine, discarding small groups of data samples that greatly exceed their neighbors in magnitude. This approach is effective as long as the spectrum analyzer sweep parameters are chosen so the resolution bandwidth is much smaller than the expected occupied bandwidth of the signals being measured, resulting in short-interval spikes in the data that are never desired information.

Even after the ignition-spike noise is reduced or eliminated, recorded data still can be very rough, due to the effects caused by signal modulation. Using a single peak recorded value in a channel window to determine signal strength produced data with a high level of random variation. A method was needed to eliminate as much of this spurious information as possible. An approach was chosen to treat the recorded sweep data as a simple time-varying signal and apply low-pass filtering to eliminate noise. After filtering of the ignition spikes as described above, the analysis software uses digital finite impulse response (FIR) filtering, with variable parameters, to smooth the data for a recorded sweep. The software can then take the single peak value from the filtered data in each channel window and convert it to a signal level having a much lower degree of random variation due to modulation effects and measurement artifacts, with any variation remaining likely to be significant data. Figures 3 and 4 show a single recorded sweep before and after these filtering steps are applied.

Signal analysis. The final stage of data analysis is to convert the signal level versus time data, from the spectrum analysis, to signal level versus location data. Additional software routines correlate the recorded GPS position data to the signal level data based on time. The GPS data often requires some additional processing to eliminate spurious position reports due to localized disruptions in GPS signal reception. The analysis software filters the recorded position data by applying limits on the apparent velocity of the vehicle. When two position reports are farther apart than could be possible given the time interval between them, both are discarded.

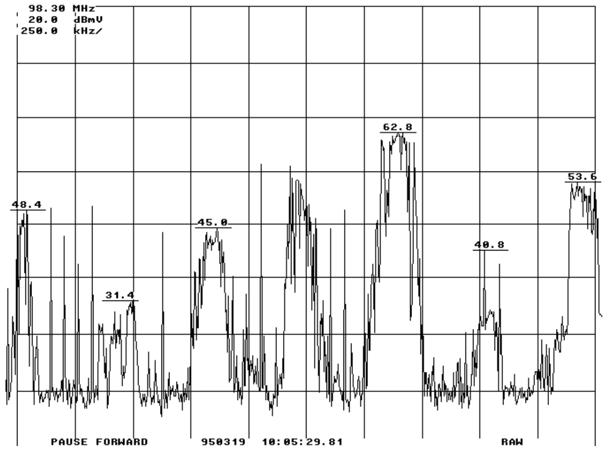

Figure 3. Raw recorded spectrum sweep data.

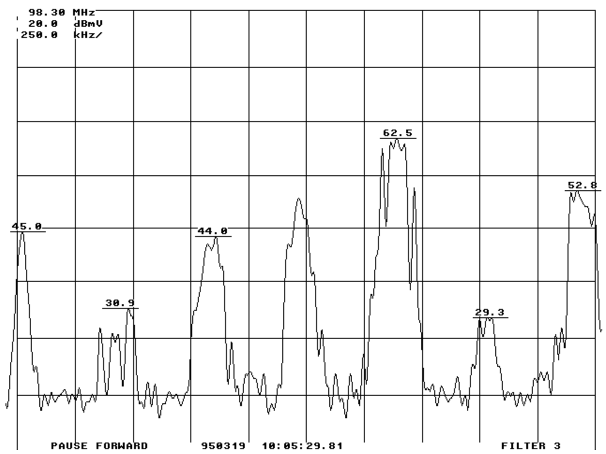

Figure 4. Spectrum sweep data after filtering.

Once the position data has been filtered, an interpolated position for each recorded signal level value is determined based on the time stamps in the data. The software does have the ability to supplement the GPS position data with location markers recorded by the system operator during the measurement process, so signal data can be used even when GPS is not available, as long as accurate and sufficiently frequent markers are recorded.

The final result of the analysis process is a set of geographical locations and signal level readings at those locations. These data can be presented on a map, or further processed to produce signal level contours or to determine information such as desired-to-undesired (D/U) signal ratios.

SYSTEM APPLICATION EXAMPLES

Having presented information on how the system was designed and how it operates, the real proof of its value lies in the results that it can provide with respect to actual project applications. To date, some of the more interesting system applications have involved evaluation of FM transmission systems with regard to transmitting site selection, booster performance verification, and comparative signal level determination.

Transmitting site evaluation. The developed system actually has its roots in a project to evaluate a prospective transmitter site for a client FM broadcast station, and to determine if operation from that site would provide improved coverage in desired market areas over the station's existing transmitting facilities. While the prospective transmitter site provided greatly improved height, its location was considerably father from the desired coverage areas than the existing site. Therefore, a proper selection was not intuitive.

Traditional analysis involving FCC methods was not useful to determine the better site, because terrain obstructions in the signal propagation paths from each of the sites could not be adequately modeled using "average terrain" data. Terrain-weighted computer propagation studies were conducted, but the collected data yielded inconclusive results when a possible statistical error of several dB was considered. It was determined that objective signal level measurements, taken simultaneously from both transmitting sites, would provide the most useful comparative information. The proposed site already supported another FM facility, albeit operating at much lower power than could the client station at that site. However, signal level measurements taken on the lower power facility could be appropriately scaled to provide valid data for the proposed facility.

Field measurement studies were conducted in several populated areas within the desired station listening area. The spectrum analyzer was set up to display both the station's existing signal and the signal of the proxy station. To be sure that the collected data would be valid at the center of the measurement area, each area was traversed in different intersecting perpendicular directions (north-to-south, then east-to-west, for example), in paths that exceeded at least several city blocks, so that collected data could be correlated.

In the analysis phase, a mean signal level was calculated for each station using a one-minute data sample centered at the intersection location, using approximately 240 total measurement points. It was found that data processed in this manner for the intersecting paths yielded excellent correlation, with only a 1 to 2 dB difference at most measurement locations. With regard to the determination of the better site, the analysis showed that the proposed transmitter site would provide greater signal level in 72 percent of measurement locations, the existing site would provide greater signal level in 14 percent of the locations, and that the signals would be essentially equal (± 3 dB) at the remaining locations. Thus, the proposed site was clearly shown as superior, provided that signal losses in the 14 percent of areas served better by the existing facility would be acceptable.

FM booster performance verification. Another project involved field verification of synchronous FM booster transmitter performance, and determination whether the booster would cause significant interference to the signal of the station's main transmitter in populated locations.

Previous laboratory and field work has yielded data on the key performance traits of FM booster transmitters, and how they interact with their host FM stations [6]. In summary, interference between main and booster facilities, which operate on the same FM channel, was noted when the associated signal levels were found to be within about 15 dB of each other. As expected, terrain shielding between the transmitting sites and coverage areas of the main and booster stations provided the least interference between the facilities and, hence, the best performance. Though optimum separation of transmitting sites is not often possible, carrier and modulation synchronization of the facilities, utilizing an adjustable time delay [7], may be used to "steer" predicted interference zones into unpopulated areas, while maintaining a good transition between main and booster facility signals in desired coverage areas.

The measured client station operates a main transmitting facility that is situated on the north-facing slope of a mountain. While most of the desired population covered by the station also lies to the north, recent population growth in the area south of the mountain yielded a significant number of persons without adequate service from the station, even though that population was inside the "protected" FCC contour of the station. Thus, construction of a booster transmitter was initiated. The actual booster facility was constructed on the southern slope of the same mountain, employing a directional antenna oriented to the south. Calculations were made to set adjustable system delays, such that the main and booster signals would be time synchronized at a populated location along a major highway where both signals were predicted, using the TIREM terrain-weighted computer propagation analysis algorithm, to be equal in strength.

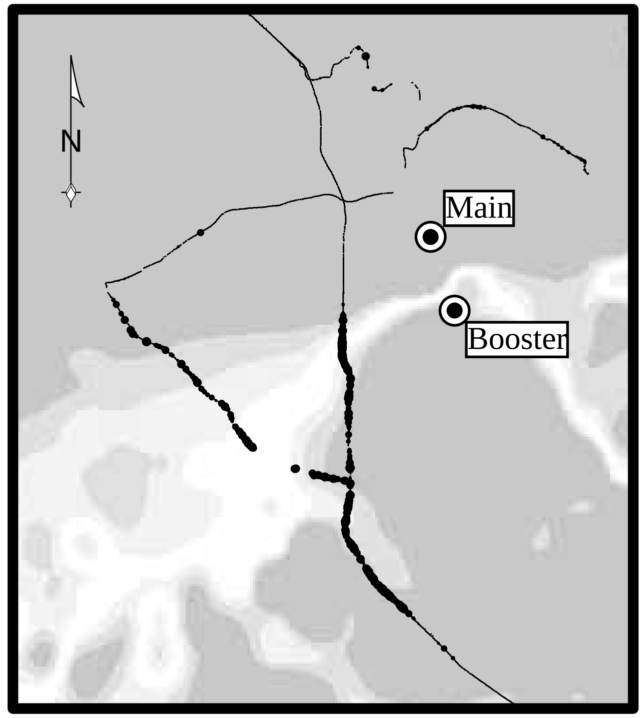

Figure 5. Calculated and measured D/U ratios for example FM booster installation.

Field verification of the booster system design involved separate measurement of the main and booster transmitting facilities, one at a time, along identical measurement routes. (Only the facility being measured was activated during measurement.) The collected data was then synchronized for position so the facilities could be compared and D/U ratios could be determined. Figure 5 shows the results of the study. The thin lines show the routes traveled, as derived directly from GPS data; discontinuities in the lines are due to interruptions in GPS data caused by localized terrain features or changes in GPS satellite geometry. A thickening of the lines indicates a reduction in D/U ratio for measured signals within 15 dB of each other, with the lowest relative D/U ratios at the thickest parts of the lines. The map is overlaid onto a calculated TIREM plot of the areas predicted to have reduced D/U ratios; the darkly shaded areas are predicted to have D/U ratios greater than 15 dB, while the next two lighter shaded areas depict D/U ratios of 10 to 15 dB and 5 to 10 dB, respectively. White areas are predicted to have D/U ratios of 5 dB or less. Thus, for the routes measured, good correlation was found between TIREM predictions and actual D/U level measurement.

Figure 6 is a graph of overlaid relative main/booster signal levels versus distance, showing the proper location for transmitter time synchronization. It was found that the measured synchronization point precisely matched the point that had been previously calculated using TIREM data. Thus, the booster system was already properly adjusted for best performance in the transition area.

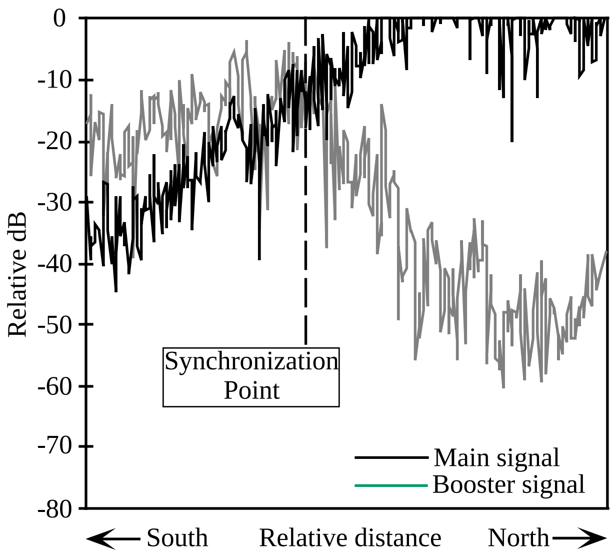

Figure 6. Measured signal levels of main and booster stations near area of lowest D/U ratio.

Other applications. In probably the simplest and most straightforward application, the system has been used to measure the relative signal levels of multiple FM stations in a market, allowing direct comparison of the strengths and weaknesses of various facilities. Other specific applications include interference analysis between FM stations in distant markets and analysis of cellular telephone base station performance. In general, the RF signal levels of almost any communications system used in the mobile environment can be characterized and, as required, compared to similar facilities.

CONCLUSION

Valuable information can be obtained by using a low cost spectrum analyzer for RF signal level measurements in a mobile environment, especially when it is tied to appropriate data sampling and logging apparatus. The developed system overcomes many of the drawbacks associated with the use of fixed-tuned receivers in similar field applications, and it allows critical data to be post-processed in a form that preserves multiple variables, allowing thorough and concise post-measurement analysis.

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