New Technologies in Single Frequency Networks

A Case Study—WSUN (FM) Tampa/St. Petersburg, Fla.

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Abstract: *FM Single Frequency Networks (SFNs) and FM on-channel boosters have been around for many years but have often had serious problems with self (or simulcast) interference.During the past several years, Geo-Broadcast Solutions (GBS) has committed significant research and development to improve the technology to greatly reduce and in some cases, completely eliminate, the simulcast interference issues. The commercialization of this technology is called MaxxCasting.The advances in the technology were, under a consulting contract, verified by NPR Labs. Further testing to determine acceptable listener interference thresholds was performed at Towson (Md.) University under Dr. Ellyn Sheffield's supervision. Sheffield has conducted numerous listening test studies with focus groups in the past for National Public Radio (NPR) and iBiquity Digital Corp. The results form a core of formulae, along with some highly intelligent software program, to predict coverage and minimize interference to present a far improved implementation of an SFN, whether it contains two or more nodes.*

INTRODUCTION

The MaxxCasting system deploys "zones" within a defined service area of a primary (main) FM broadcast transmitter. These zones can contain one-to-n number of on-channel, same frequency booster transmitters that broadcast in a simulcast (synchronized) manner. The design of the zone is such that the synchronized booster transmitter(s) comprising the zone create a signal (and RF field density) over the intended coverage area for that zone which is significantly higher than the main transmitter signal. This results in a FM "capture" effect occurring at the receiver, a phenomenon widely known with FM reception in which only the stronger of multiple signals at, or near, the same frequency will be demodulated. This effect also provides an improvement in performance of the audio output from the receiver in terms of quality.[1]

In a typical broadcast transmitter implementation, transmission sites are often chosen that provide the largest amount of RF coverage and to reduce implementation costs. It is well known that transmitter antennas with higher radiation centers (above local terrain) have lower RF path loss slopes, resulting in a larger geographical coverage area to a receiver. However, in a simulcast situation involving multiple transmitters on the same frequency (often referred to as a single frequency network, or SFN) this approach creates a larger interference area where the main and the booster signals are close in power level, but arrive at the receiver at larger than acceptable differential time delays, creating unacceptable audio impairment.[2] This interference area is proportional to the square of the radius of the transmitters' coverage area.

By deploying multiple synchronized transmitters in the desired coverage zone with lower antenna radiation heights, the coverage radius of each booster is reduced, thereby decreasing the interference area with the main transmitter. In addition, by deploying the booster transmitter antenna radiation centers at lower heights, the path loss slope of the booster is generally greater than the main transmitter.[3,4] The main transmitter is typically deployed at the highest level above the local terrain that is allowed by regulations, so that the largest coverage area can be achieved. Because the path loss slope of the synchronized booster transmitters in the zone have greater path loss slopes than the main transmitter, the signal from the synchronized booster transmitters tends to decrease more rapidly as a function of distance from the transmitting antenna. This has the effect of reducing the geographical area where the signal from the booster transmitter is close in field strength to the main transmitter.

It is also well understood that the time differential between two signals and the RF signal power ratio of the signals determine the amount of distortion that ends up in the audio signal presented to the listener. Distortion of FM audio increases as a function of the time separating two indistinguishable signals. Similarly, distortion decreases as the RF ratio grows.

Therefore, another benefit of deploying multiple synchronized transmitters in the desired coverage zone with lower antenna radiation heights, [is that] the time of arrival of the sign from the main transmitter can be more closely synchronized with the booster transmitter signal over the geographical area of interest. This area of interest occurs when the RF ratios from the main transmitter and the booster transmitter are of similar levels (i.e., 0 to 18 dB for monophonic transmission, and 0 to 24 dB for stereophonic transmission, for example). By controlling the time of arrival delays of the signals in these areas, the amount of distortion can also be controlled to an acceptable level to the listener. As this report indicates, this has been well studied and documented under laboratory and listening tests.

Typically, SFN systems are employed in the United States as a "patch" where terrain blockage restricts FM coverage, and the more severe the blockage, the better the performance provided. The converse is also true where there is "leakage" from the booster(s) back to the main signal—interference is difficult to eliminate. Regardless, an SFN provides a very compelling argument for both spectrum efficiency and transparency to listeners who do not need to change broadcast frequencies as would be required for alternate frequency usage.

MaxxCasting Development

SFN technology as applied to FM analog broadcasting has been discussed for decades, even as far back as 1940, before FM was even popular. W. H. Doherty, in a 1940 article, discusses the issues of carrier frequency stability (which he refers to as "average," given it is instantaneously changing), and also other components which must synchronize[5].

Despite early thoughts of SFNs, the challenges of mitigating self-interference where "leakage" around terrain exists have plagued the technology from the start. Excellent terrain blockage has made possible a number of successful installations. It is where there is less than perfect elimination of overlapping signal from the main transmitter and the booster transmitters that problems traditionally occur. The research of Geo-Broadcast Solutions and the verification of the technologies utilized by NPR Labs was further aided by the studies at Towson (Md.) University with over 20,000 samples of audio listened to and rated.[6]

Lack of Standards

The Federal Communications Commission Rules & Regulations fail to offer SFN standards for simulcast interference. While they fully authorize boosters under CFR 74, it is totally "caveat emptor." Even the ITU (International Telecommunication Union) fails to fully address the matter, especially in the sense that they were tested with stationary roof-top antennas under a 50 dB signal-to-noise ratio, quite different than how most FM radio is listened to today.[7] This issue is much more easily solved in digital broadcasting than for analog for both FM radio and television. Further, differences in audio processing density and musical genres versus talk formats yield different results, given the same level of signal interference. Add in the difference in performance between monaural or stereophonic broadcasting, and another variable is introduced. Geo-Broadcast set out to quantify much of this.

The key for GBS to achieve this goal resided in two main areas: development of simulated audio and focus group testing. The development of lab-generated audio simulations is generally regarded as superior to in-the-field measurements, because simulation results are generally very accurate and this provides the ability to evaluate hundreds of different environmental scenarios, which would be cost-prohibitive if performed in-the-field, not to mention the amount of unknown variables. The microchip industry evaluates new chip technologies in this manner quite commonly.

Focus Group Testing

Through collaboration with NPR Labs, GBS design parameters were optimized following listening tests held at Towson University in two small, 7 x 8-foot internal rooms, set up to simulate a home listening environment and an automobile cabin. Forty participants (20 males and 20 females) between the ages of 18 and 65 were recruited for this consumer test, and each participant was required to listen to 533 samples of audio. The largest takeaway were the thresholds of listener acceptance or rejection of audio samples recorded at various interference levels and using various genres of music and talk formats including voice over plus mono and stereo reception. Among other things, the variables included time of arrival and RF ratios of the signals.

The information was first compiled into tables and then to surface sharts such as the one shown in Figure 1.

Over 20,000 data points were taken by Dr. Ellyn Sheffield, an individual quite renowned in this area of work and having done such prior testing for the iBiquity HD Radio codec, for the IAAIS for audio reading services for the blind for SCA and digital listening, and many others. The goal was to determine at what level of interference at least 90 percent of the group would remain with the station rather than wanting to turn it off. This is referred to as the 90 percent keep-on score. However, the resulting data provides the capability to generate a model for a variety of keep-on percentages which may be desired.

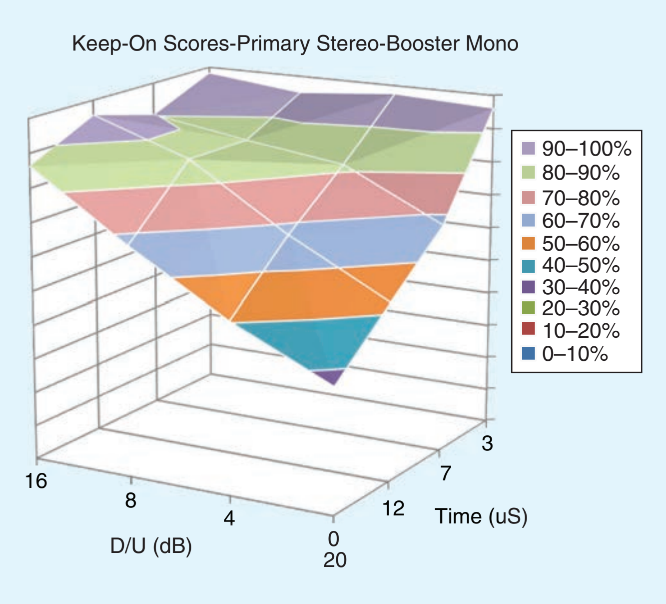

Figure 1. Sample "keep-on" score chart.

With the interference thresholds clearly identified and the modeling software finalized, it was possible to create accurate predictions of station coverage with and without booster nodes as well as to predict interference areas which are those below the 90 percent keep-on score (or as otherwise programmed). With further tuning of the model it is possible to mitigate interference significantly as well as in some cases to simply move it to areas of little concern (low population, no highways, etc.).

The WSUN Project

Cox Radio developed an interest in the MaxxCasting concept and engaged Geo-Broadcast to install a system in St. Petersburg, Fla. area. The first node is located on the company-owned studio-to-transmitter link (STL) tower behind the studio building in northeast St. Petersburg.

The Cox organization admitted that they chose this station for two reasons. First, they wanted a look at how the technology worked, and Roz Clark, the Cox head of engineering for the Tampa/St. Petersburg market was curious as to how this could

Table 1: WSUN Transmission Parameters
WSUN-FM Channel: 246C2 97.1 MHz
Holiday, Fla.
Fac. Service: FM Analog & Digital
Site Location: 28-10-56.0 N; 82-46-06.0 W (**NAD 27**)
Site Location: 28-10-57.0 N; 82-46-05.4 W (**NAD 83**)
Effective Radiated Power: 11.5 kW
Transmitter Output Power: 7.6 kW
Antenna Center HAAT: 224 meters
Antenna Center AMSL: 226 meters
Antenna Center HAG: 223 meters

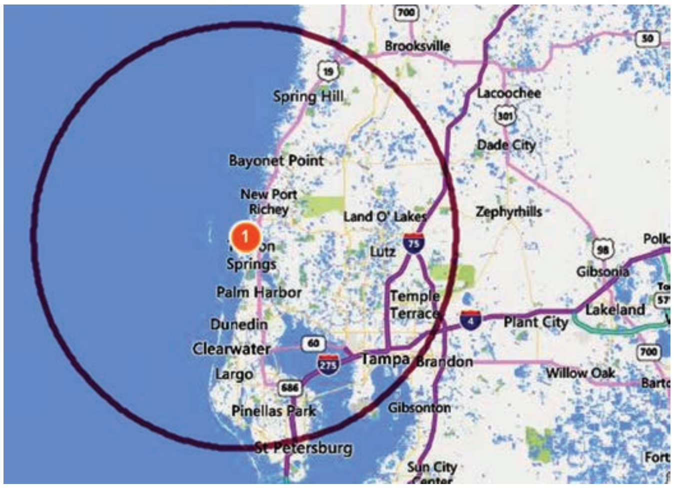

Figure 2. WSUN 60 dBu contour

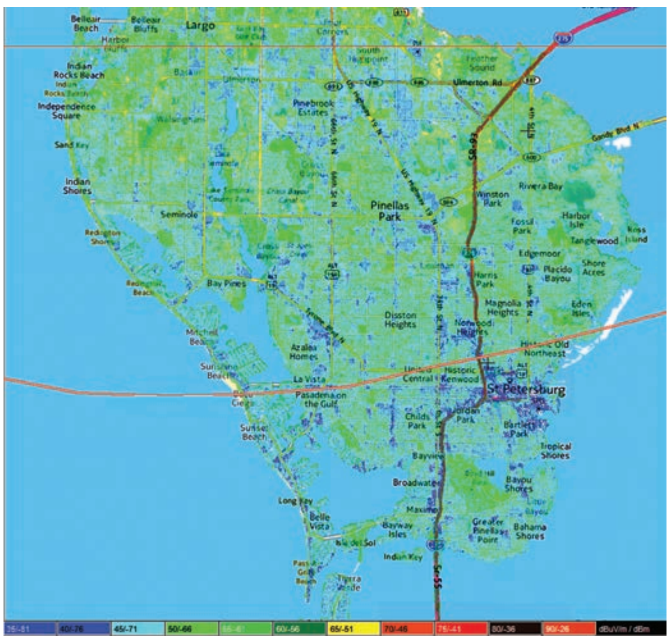

Figure 3. Pre-tuned model predicted coverage

work in a "worst case scenario." By that it is meant a situation where there is no terrain shielding and an even distribution of listener population, thus greatly exacerbating the problem with simulcast interference. Although the main WSUN broadcast transmitter was found to have a typical 24 dB/decade path loss slope and the WSUN-FM1 booster was found to have a steeper 33 dB/decade path loss slope, there were significant areas where the signals were within ±6 dB, as will be discussed.

The WSUN transmitter site is located approximately 23 miles northwest of the studio, placing it further from downtown St. Petersburg and Tampa, definitely classified as a "rimshot" station [See Figure 2]. Signal levels downtown and in the residential areas are not adequate for good building penetration. In fact, the signal at the studio site does not penetrate the building sufficiently for off-air reception on table radios. The location of the booster at the studio, while not optimum, was expeditious (Cox owned the tower and readily had IP connectivity at the site to the main transmitter). With the single node operational, the signal was excellent in the studio building and south towards the downtown area.

Geo-Broadcast uses computer based prediction tools to model the physical event of RF propagation using terrain and clutter data [See Figure 3]. The accuracy of coverage estimation }using these tools depends on the accuracy and resolution of the available data. The common practice in designing cellular and two-way coverage is to measure the signal strength for a test transmitter in the service area and to tune the propagation model using the measured data. Using this technique, coverage can be more accurately and reliably estimated.

The coverage model was generated using the ITU-525 standard with Deygout '94 diffraction geometry and Standard-RM subpath calculations (similar to ITU-R P.526-13 Subpath diffraction losses). [9]

Once the computer model is created, field strength readings were taken to verify the prediction using an FCC calibrated receiver and antenna (See Figure 4). Should the initial predictions be off by more than a few tenths of a dB

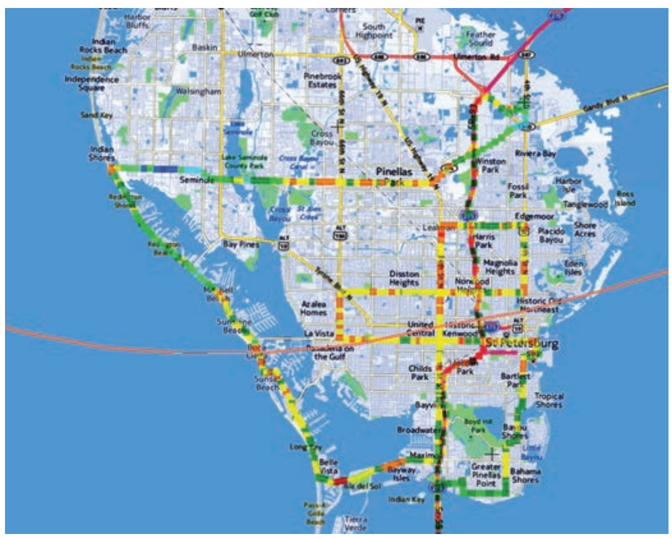

Figure 4. Sample RF signal collection route

(average error), or have a standard deviation greater than 3 dB the model is "tuned" using the empirical data collected. This tuning process involves alternation of the clutter absorption loss, the clutter heights, and/or the diffraction losses, as an example.

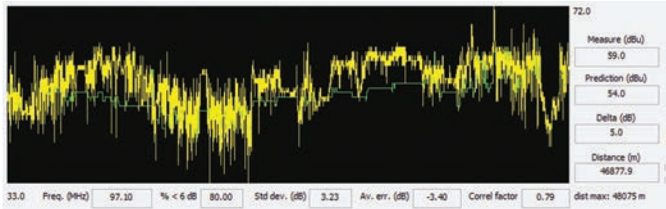

Figure 5. Pre-model tuning correlation

As indicated in the Figure 5, the collected RF signal values had a correlation factor of 0.79, with a predicted minus measured average value of −3.40 dB, indicating that the model was conservative. After several iterations of adjusting clutter losses (diffraction and absorption losses), the model was tuned to have a correlation of 0.96 with a −0.28 dB average error, as shown in Figure 6.

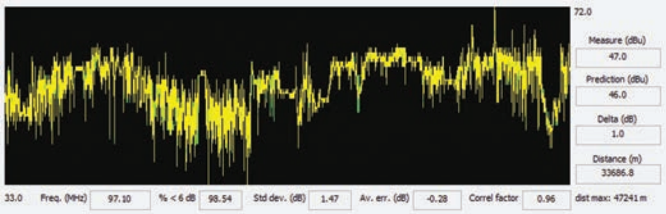

Figure 6. Post-model tuning correlation

The tuned coverage model is shown in Figure 7.

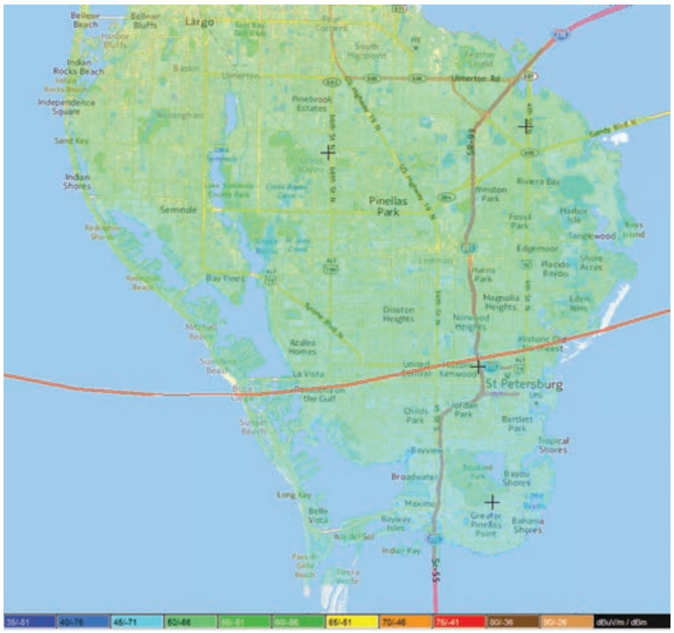

Figure 7. Tuned model predicted coverage

WSUN-FM1 Booster Node Phase One

The node located at the Cox St. Petersburg Studio location consisted of a pair of log-periodic antennas mounted horizontally with a 30-degree slant (See Figure 8).

Table 2. WSUN-FM1 Transmission Parameters
WSUN-FM1 Booster Node Phase One
WSUN-FM1 Channel: 246D 97.1 MHz
St. Petersburg, Fla.
Site Location: 27-52-26.0; N 82-38-22.0 W (**NAD 27**)
Site Location: 27-52-27.1; N 82-38-21.4 W (Converted to **NAD 83**)
Effective Radiated Power: 0.266 kW horiz.; 0.8 kW vert.
Antenna Center HAAT: 0 meters
Antenna Center AMSL: 26 meters
Antenna Center HAG: 24 meters

Figure 8. Dual-log node installation

The same procedure was performed for the booster node WSUN-FM1 where the main signal was turned off for a period of time while RF measurements were made. Figure 9 shows the composite coverage of both the Main WSUN and WSUN-FM1 coverage, as well as predicted interference as defined as "below" the 90 percent keep-on score.

As indicated in Figure 9, a significant improvement in RF signal level is found in the area south of the node WSUN-FM1. Areas that are calculated to have less than a 90 percent keep-on score are indicated in magenta, and are found to the west and northwest of the node. Listening tests in these areas were found to have some noticeable sound interference, but more than acceptable for commercial operation. In addition to the predicted areas of interference, areas that had signal levels within ±6 dB were analyzed for the amount of interference that could exist. Figure 10 illustrates this concept. Shown in red is where the main WSUN signal is dominant, shown in orange indicates where the WSUN-FM1 node is dominant, and the white are shows where the signals are within ±6 dB. These areas are where much of the testing and optimization of the timing, modulation levels, etc. were performed.

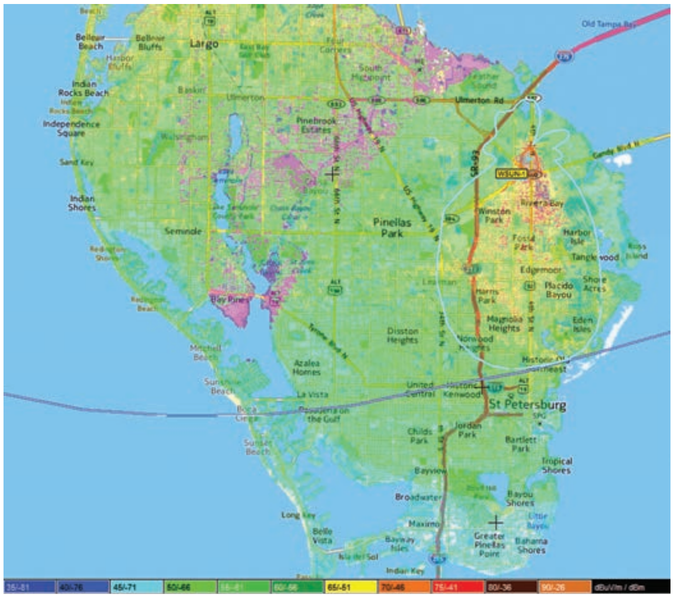

Figure 9. Tuned model predicted composite coverage plus interference

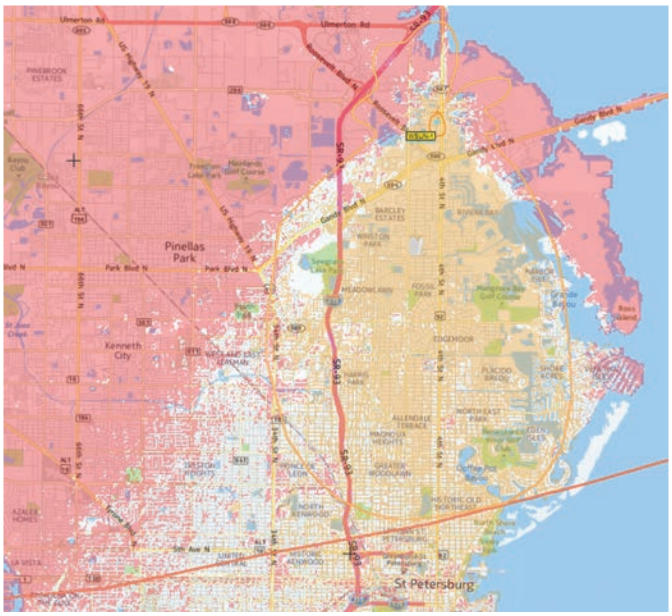

Figure 10: WSUM-FM1 best server plot ±6 dB

Table 3: WSUN-2 Transmission Parameters
WSUN-2 Channel: 246D 97.1 MHz
Pinellas Park, Fla.
Site Location: 27-52-11.0 N; 82-41-54.0 W (**NAD 27**)
Site Location: 27-52-12.1 N; 82-41-53.4 W (**NAD 83**)
Effective Radiated Power: 0 kW horiz.; 0.8 kW vert.
Antenna Center HAAT: 0 m
Antenna Center AMSL: 0 m horiz.; 28 m vert.
Antenna Center HAG: 0 m horiz.; 23 m vert.

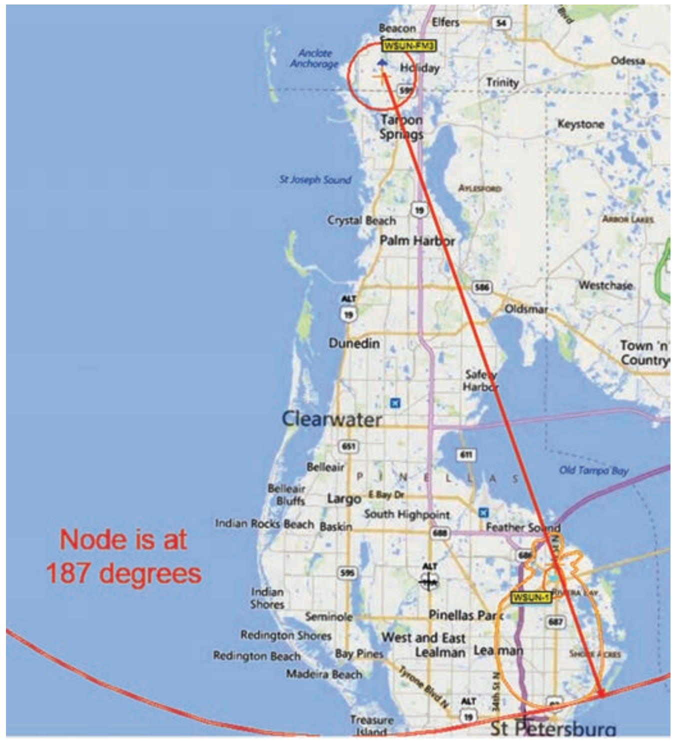

Figure 11: Node is at 187-degrees; angle of propagation is at 160-degrees

WSUN-FM1 and Booster Node Phase Two

After the WSUN-FM1 node in phase one was optimized and audio found acceptable in both the predicted SFN interferences areas and the ±6 dB overlap areas, the design evolved to a phase two approach where the WSUN-FM1 node was adjusted (from 187 to 160-degrees azimuth) to accommodate an additional node (WSUN-2) which would extend coverage and building penetration (See Figure 11). At the time of this writing the second node is in the construction phase.

The WSUN-2 node coverage and interference prediction is shown in Figure 12. As indicated, the coverage density is predicted to be considerably improved.

Setting Up the System

Traditional mathematical calculation brings us to a first setting of the timing between the transmitter and the booster site(s) The formula for this is approximately 3.33 microseconds/kilometer. However, additional latencies often must be added such as delays through the delivery system or individual components. Even different exciters from the same manufacturer can have different delays. For instance, GatesAir indicates the FAX series is 11.878 millisecond fixed delayed, as compared to the FlexStar HDx exciter, in addition to the approximate 160 microsecond air delay. For the distribution network, multiple IP-Link200s were deployed across a wireless IP Service provider's network. Given variable delays in this type of service, an additional 500 millisecond delay was added to improve IP link performance.

However, "real world" conditions require "driving the signal," careful listening, measurements and tweaking a dozen or so microseconds either way to determine best performance in the desired transition zones, such as those found in the ±6 dB overlap areas. Multiple zones require timing considerations to both the main transmitter signal and, if applicable, adjacent nodes when overlap occurs or nearly occurs, and alteration of the timing can be used to move an interference zone from the original design model. Further compensation (in milliseconds) would be needed to properly time signals when disparate exciters are used. Also, latency in the IP links between the sites must be taken into account. Additional delay on the main transmitter is necessary to make sure that there is always sufficient delay available through the network, even using an automated delay compensation system such as Synchrocast. An additional 500 milliseconds of buffering was added to the system insuring nearly perfect performance whereas they were experiencing some dropped packets at low latency settings. Since the station operates in the HD Radio mode, adding the additional one-half second of delay made no difference as the studio announcer cannot monitor off-the-air in any event (See Figure 13).

The connections in this manner permit WSUN to use any of its three methods of audio transfer from studio to main transmitter and this change will have no impact on the operation of the booster. The connection between the studio node and the main transmitter is by IP and provided by Rapid Systems, a local ISP based in Tampa. The service provided does not traverse the public Internet at any point in the interconnection between the two sites; it is all within the Rapid Systems private network. The connectivity bandwidth between the sites is approximately 6 mbps, which is significantly more than needed. The connection is uncompressed/linear and uses no audio data compression. However, this system is now capable of using Opus or AAC and other variants of AAC where the bandwidth is limited.

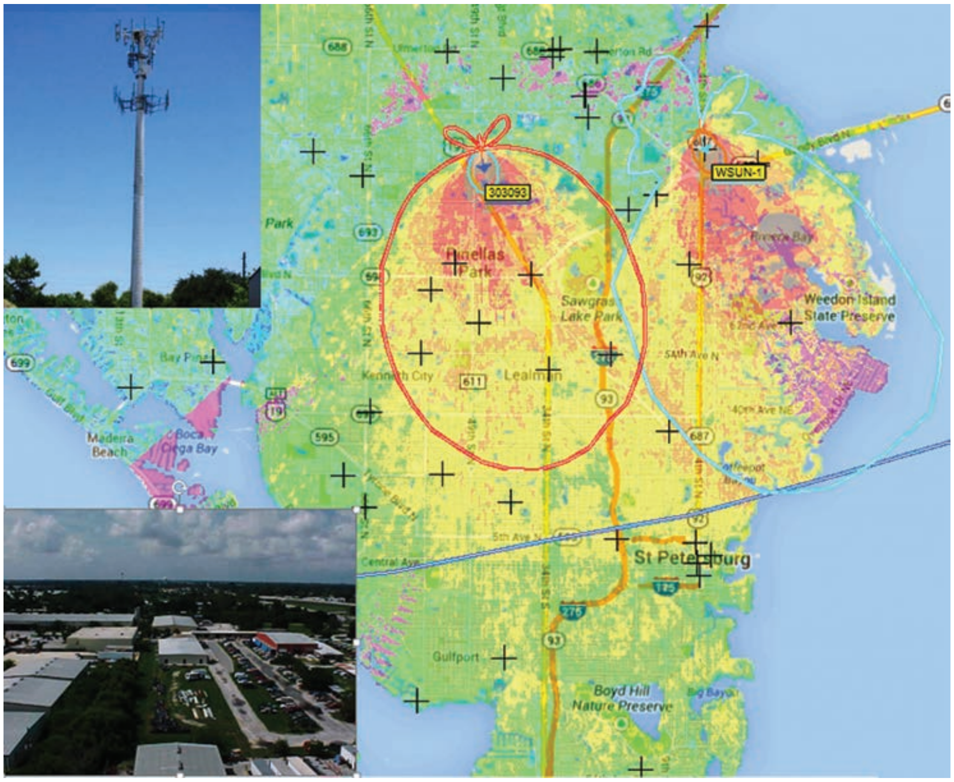

Figure 12: Two-node configuration

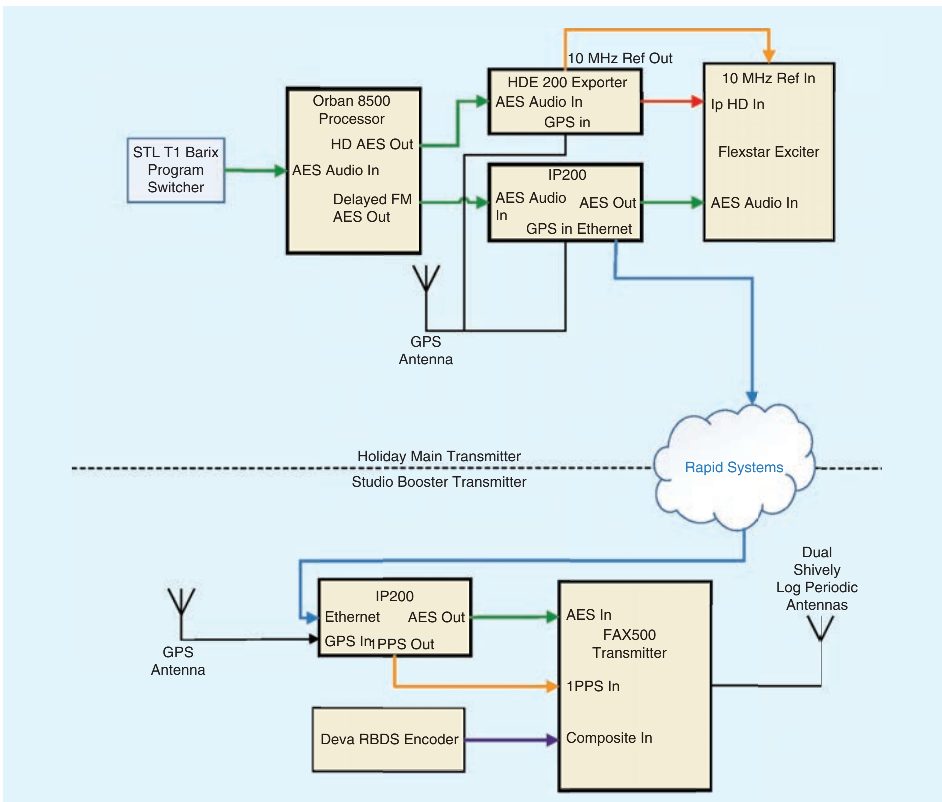

Figure 13: WSUN block diagram

Initial Observations

All single frequency networks must be synchronized, with time and frequency references (1 PPS and 10 MHz) common and identical, in all respects, to all transmitters in the network (including audio and modulation levels). The easiest and cheapest way to obtain these references is based on GPS receivers.

When the equipment was first set up and powered up using the initial timing there were a number of problems. First there were packets being dropped which was resolved by increasing the buffer to 500 milliseconds as mentioned earlier as well as adding dual stream splicing to the IP Link 200 system. Also there were issues with the equipment. The IP Link 200 and the FAX transmitters were both new products. It turned out that some internal issues were discovered that kept them from synchronizing properly. Support from GatesAir rectified these matters, and with proper operating equipment it was now possible to correctly align the system and tune for proper synchronization. Transition in the northwesterly direction (leaving the booster, heading directly towards the main transmitter) yielded virtually transparent transition zones as the booster signal strength rapidly declined and the main transmitter's signal quickly increased creating a very narrow transition area. Traveling to the south, away from the booster as well as the main transmitter there were some minor areas of slightly increased multipath as both signals remained relatively even for longer periods of time. However, fine tuning of the system produced results that were well within the 90 percent "keep-on" score and increased signal density was noted.

Conclusions

Through collaboration with NPR Labs, GBS design parameters were optimized following listening tests held at Towson University. The resulting findings included the thresholds of listener acceptance or rejection of audio samples recorded at various interference levels and using various genres of music and talk formats including voice over plus mono and stereo reception. These parameters, including acceptable time delay versus power ratios, are used in computer simulations to predict SFN performance.

Before accurate computer simulations are created, field strength readings are taken to verify coverage. Should the initial predictions be off by more than a few tenths of a dB (average error), or have a standard deviation greater than 3 dB the model is "tuned" using the empirical data collected.

By deploying multiple synchronized transmitters in the desired coverage zone with lower antenna radiation heights, the coverage radius of each booster is reduced, thereby decreasing the interference area with the main transmitter. In addition, by deploying the booster transmitter antenna radiation centers at lower heights, the path loss slope of the booster is generally greater than the main transmitter, also reducing the potential interference area.

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Ed Allen, chief engineer, Cox Radio, Inc., St. Petersburg, Fla.

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Hal Kneller *is global vice president of sales and business development at GeoBroadcast Solutions, LLC. He has also held positions with Nautel Ltd, iBiquity Digital Corp. and Harris Broadcast, and has served on the DRM (Digital Radio Mondiale) steering and executive boards. He holds degrees from Emerson College and also Society of Broadcast Engineers PBE and CBNE certifications.*

Bill Hieatt

Bill Hieatt *is the chief technology officer of GeoBroadcast Solutions, with responsibilities in the areas of system architecture definition, RF propagation, SFN modeling, network infrastructure design, construction, intellectual property creation and patent applications. He holds degrees from the University of Texas, Florida International University and the Keller Graduate School. He has also been awarded several U.S. and international patents in broadcasting and telecommunications. He is a member of the IEEE and the Society of Broadcast Engineers.*

[Hal Kneller presented this paper on FM SFN deployment at the 2015 Orlando BTS Broadcast Symposium.]

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