Single Frequency Networks for HD Radio

Philipp Schmid
Nautel Ltd
Hacketts Cove, Nova Scotia
pschmid@nautel.com

Abstract - *FM single frequency networks (SFNs) are recognized by the FCC as fill-in booster stations and are in common use for FM operation today. With fewer frequencies available for FM translators, building out on-channel coverage is often the best option and enhances a station's frequency branding. Today, many broadcasters are desiring to extend both their FM and HD Radio coverage.*

The planning parameters required for a hybrid FM+IBOC booster installation that minimizes on-channel interference are detailed. Tight time synchronization is required between all nodes of the SFN for both FM and IBOC. We detail a method to achieve precise input to output time synchronization for In-Band-On-Channel (IBOC) signal transmission across multiple HD Radio transmitters. Lab results of the signal operating synchronously demonstrate seamless handoff from one transmitter to the next. A real-world installation at KUSC, Los Angeles CA, is shown including the equipment used, drive test results and overall system performance.

SFN Application Areas

Radio broadcasting is all about reaching listeners with the best possible signal in the most cost effective way. Typically, this is best achieved by maximizing the effective radiated power (ERP) via transmitter power output (TPO) and antenna gain within the station's class and established allocation rules [1]. There are, however, cases where this approach is neither practical nor possible for a station to extend its coverage and listenership. Creating a single frequency network (SFN) of multiple transmitters on the same channel can address these cases but must be carefully engineered to mitigate potential interference. This interference will always degrade the analog FM audio quality and can at best be minimized. Digital radio transmission, on the other hand, maintains good audio quality unless the signal is lost entirely. The forward error correction (FEC) inherent to digital radio can correct interference induced bit errors. We can achieve seamless hand-off from one transmitter to the next provided the engineering guidelines shown in this paper are observed.

Digital radio transmission in the form of In-Band On-Channel (IBOC) or other orthogonal frequency division multiplexing (OFDM) standards are ideally suited for the following application areas.

I. *Fill-in FM Booster Stations*

Terrain obstruction through mountain ranges is the most common application area of SFNs and are considered by the Federal Communications Commission (FCC) as fill-in booster stations that are treated as translator stations on the same frequency as the main station [1]. Figure 1 shows a class C3 station at 25 kW ERP at a height of 100 m. Such a station has a 60 dBu F(50,50) protected contour at a radius of 39.1 km, but often listeners will tune to the station in the 40 dBu range depending on the level of local interference. This brings a station's effective contour to over 60 km, which also means significant interfering energy is present a long way from the station.

Per the current rules [1] a FM booster station's 60 dBu contour must be entirely contained within the primary station's protected contour. This allows for areas shadowed through terrain obstruction to be covered as shown in Figure 1; a 250 W booster can cover up to 12.9 km at a HAAT of 100 m. This example represents a typical use case for FM booster stations today.

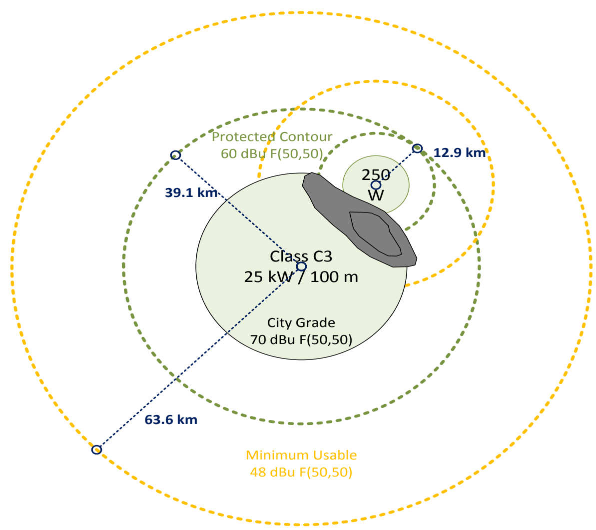

Figure. 1: Fill-in Booster Station Example.

Later in this document it is shown that SFNs not only effectively fill in the coverage area but under the existing allocation rules can also be used to extend the station's 70 dBu city grade coverage, as well as, extend its HD Radio[1]

[1]XPERI's HD Radio™ Technology is a proprietary trademark of iBiquity Digital Corporation. The author is not affiliated with and this text is not endorsed by XPERI.

coverage beyond its protected contour. Beside terrain shielding, fill-in boosters can also mitigate blanketing effects from strong adjacent channel stations in areas of a weak main signal, particularly for rim shot transmissions.

II. Micro Boosters

FM coverage can be minimal or non-existent in roadway tunnels or underground structures, such as parking garages or subway lines. It is often desirable to provide emergency broadcast services to motorists or passengers underground. Underground signal shielding is often so perfect that for analog FM transmission, no real SFN planning is necessary; a motorist may simply experience a momentary audio interruption when entering or exiting a tunnel. While this is tolerable for FM transmission, it is desirable for digital transmission to maintain signal lock for uninterrupted service. Therefore, time and modulation synchronization must be achieved in the transition areas, otherwise digital receivers may take an excessive amount of time re-locking to an unsynchronized signal, delivering no service to the listener in the process.

FM service is often impaired through excessive multipath in downtown cores. Low power micro-boosters may be used to provide a dominant signal path to the receiver while keeping interference to a minimum. Sport stadiums may be covered in this way to ensure superior coverage within a defined geographic area. Micro booster can be fed directly from the off-air feed and rebroadcast on frequency with echo cancelling.

III. Roadway Coverage

Population centers are not typically found to neatly match the coverage area of your broadcast from your broadcast site. Directional antennas can be used to tailor the intended coverage area; however, a single transmission will always pose a limitation in shaping the effective coverage area. Perhaps the best example is providing service to motorists along an extended roadway. This application area can be partially addressed using the alternate frequency (AF) function of the Radio Broadcast Data System (RBDS). For example, 11 transmitters of the Canadian Broadcasting Corporation (CBC) cover highway 401 from Windsor to Cornwall and the Ottawa Region with Radio One programming [2]; a driving distance of over 800 km. Only receivers equipped with the AF function will tune to the strongest signal as motorists transition from one coverage area to the next.

SFNs are superior to AF based implementations, as receivers always stay on frequency and do not require RDBS. From a network planning perspective, this also means we can cover the roadway with more lower power transmitters with an optimized coverage area for the roadway in question. Interference areas are well defined on roadways and can be planned for to provide seamless coverage for digital transmission. IBOC is ideally suited for this application as motorists can be served with multiple audio services in the same transmission. While current FCC rules require the entire broadcast to be identical, from a technical point of view, not all logical channels within the IBOC broadcast must necessarily be part of the SFN. Localism can be injected in the extended P3 partition on separate IBOC carriers, while the P1 partition maintains the common program service. This way motorists can be warned of hazards and road conditions immediately ahead of them; nearby gas and service stations can advertise their services and prices.

IV. Wide Area Coverage

Covering large geographic areas with the same program material beyond the coverage area of a single transmitter is best done using SFNs; only a single FM channel needs to be allocated for this purpose rather than a set of alternate frequency translator channels. Overall, this represents the best use of available spectrum, since transmitters can be closely spaced and, with careful SFN interference planning, do not have to consider the interfering contour of adjacent SFN nodes in the distance planning. Figure 2 demonstrates this concept by looking at covering a large area using class C1 stations at 50 kW ERP and 299 m height. The protected 60 dBu F(50,50) contour is at a distance of 65.3 km and the co-channel interfering 40 dBu F(50,10) contour is at 154.7 km [4]. Using an alternate frequency implementation requires at least a 3-frequency reuse pattern as shown in the figure below. To ensure quality service, no interfering contour must intersect the protected contour of the same color.

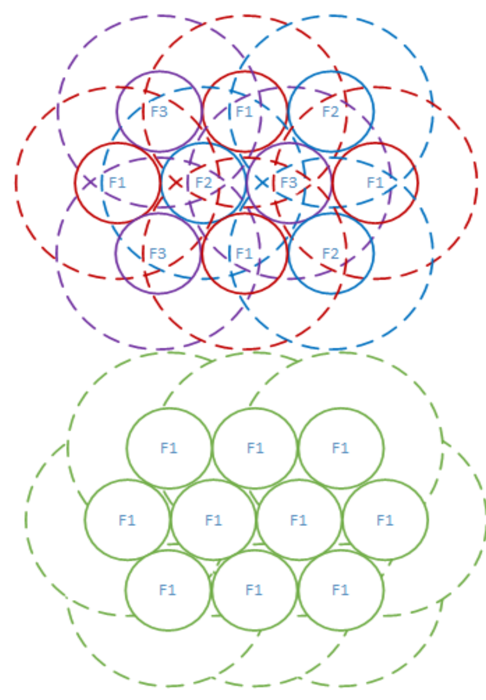

FIGURE. 2: NEAR SFN (TOP) VERSUS TRUE SFN (BOTTOM).

Provided we can address the SFN interference regions this example shows that an SFN can be at least 3 times more spectrally efficient. Only co-channel protection is considered in this simple example. Once first and second adjacent protection is also considered, more than the 3 channel allocations in the near SFN example are affected; anyone installing a network of translator networks today is aware of this fact.

The gains in spectral efficiency stems from minimizing the effects of interference between protected (or core) contours and their respective interfering contours. This is only possible when we understand the requirements for establishing a SFN.

V. All Digital HD Radio SFN

While HD Radio is broadcast in hybrid FM+IBOC mode, the application for SFNs will be limited by the FM SFN requirements established below. The HD Multiplex concept [3], as shown in Figure 3 was demonstrated by the author at the 2015 NAB show on a Nautel VS and GV transmitter producing up to 15 audio services. HD Multiplex eliminates the FM carrier and combines frequency shifted IBOC sidebands to fill in the new white space. Since the concept is based on today's definition of IBOC, HD Multiplex can draw on the critical mass of HD Radio receivers in the field today allowing for accelerated transition to all digital broadcasting.

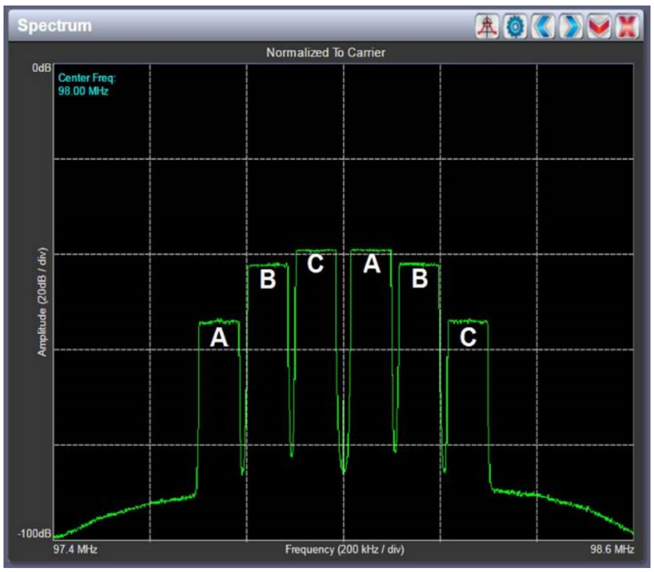

FIGURE. 3: ALL DIGITAL HD MULTIPLEX SPECTRUM [3]

HD Multiplex can combine many IBOC transmissions to form flexible multiplex configurations that are akin to Digital Audio Broadcasting (DAB) or DAB+ networks deployed in Europe and across the world. Except that HD Multiplex is in-band and aligns with existing broadcasters transmitting FM or hybrid FM+IBOC. Just like DAB, HD Multiplex is based on OFDM and, thus, can make optimal use of SFN technology. This all digital transmission method may be of interest to national broadcasters with a mandate to serve the entire population with a number of program services through SFN nodes across many communities. What is unique to HD Multiplex is that not all sets of IBOC sidebands must be part of the SFN, allowing for localism on dedicated sets of sidebands.

SFN REQUIREMENTS

VI. FM SFN Protection Ratios

In order to minimize the impact of interference between coverage regions and plan SFN networks, one must understand FM protection ratios with synchronized SFN modulation. Fortunately, the International Telecommunications Union (ITU) has studied the subject matter in recommendation BS.412[5] from which table 1 is taken. As can be seen from the table, it is a two-dimensional problem dependent on the relative received signal power from the two transmissions and their relative time delay. For example, any point on the coverage map where the two stereo FM signal sources are offset in time by 5 µs, we require one signal to be 10 dB stronger than the other to obtain a grade 3 signal impairment; defined as fair quality with slightly annoying impairment [7]. This compares to commonly accepted co-channel protection ratios of 20 dB for stereo FM service and shows the benefit of synchronizing the FM. Since 5 µs only represents 1.5 km of signal flight time we must carefully consider both the relative signal strength and timing at a granular level across the potential interference region.

Time Delay		Monophonic Mode		Stereophonic Mode	
Impairment Grade		3	4	3	4
2 µs	600 m	<1 dB	1 dB	4 dB	6 dB
5 µs	1.5 km	1 dB	2 dB	10 dB	12 dB
10 µs	3 km	1 dB	3 dB	14 dB	16 dB
20 µs	6 km	-	11 dB	-	-
40 µs	12 km	-	20 dB	-	-

TABLE. 1: FM SFN PROTECTION RATIOS [5]

The author also performed stereo FM protection tests [6] and arrived at very similar results as shown in Figure 4. The noticeable impairment curve on the figure was found by increasing the relative signal levels while keeping a fixed time delay offset until the impairment was just noticeable. Despite the subjective nature of the test, these independently measured results are remarkably close to the results in table 1. The high-quality curve was recorded when the measured noise floor in the received composite spectrum subsided to unimpaired levels as one signal was increased.

Table 1 and Figure 4 provide the planning requirements for a SFN network. Time deltas of 10 µs should ensure at least 14 dB signal ratios, 5 µs require 10 dB and where signals are closely aligned, we can tolerate 4 dB signal ratios. Mono FM transmission is remarkably more resilient to SFN interference requiring only 3 dB signal ratios at 10 µs time differential.

These results were found with professional grade modulation monitor receivers; the author suspects that commercial automotive FM receivers with multipath mitigation will perform better. Hence, these guidelines can be considered a conservative planning guideline for hybrid IBOC installations.

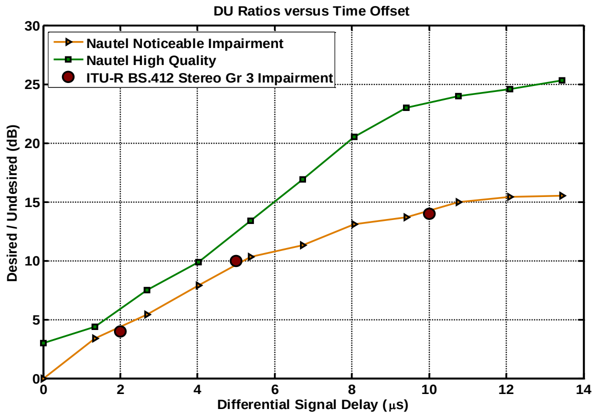

FIGURE. 4: STEREO FM SFN AUDIO IMPAIRMENT TESTS [6].

VII. IBOC SFN Protection Ratios

The IBOC signal promises better protection ratios compared to the FM broadcast due to two factors:

1. Better timing margins of up to 75 μs of delay
2. Better unsynchronized protection ratios of 4 dB

The author tested these parameters with the results shown in Figure 5 [6]. The raw or uncoded bit error rate is what the impairment grade is to FM transmission; the difference is that unlike the gradual audio degradation in analog transmission, digital transmission can recover the raw bit errors through FEC delivering pristine audio to the listener until the FEC breaks down as marked by the IBOC reception limit in Figure 5. This limit was found by the author by injecting average white Gaussian noise (AWGN) to an IBOC signal until standard IBOC receivers would no longer produce solid audio. The raw bit error rate was then measured under the same test conditions and was found to be around 9 10^{-2} or about 1 in 11 bits being in error. At the reception limit a receiver typically maintains HD Radio lock, but the audio may drop out momentarily. Receivers can also conceal short interruptions in the audio waveform. HD Radio lock is typically maintained until a bit error rate of almost 1 in 3 bits being in error; where 1 in 2 bits in error is a statistically random signal.

Replacing the AWGN interferer with a time delayed copy of the IBOC signal, we could vary the relative signal levels and measure the bit error rate after accumulating at least 10^8 bits or about 15 minutes of audio for critical data points. Even with the two signals in near perfect alignment (blue curve), we measured bit errors as the two signal levels approached equal levels. This is explained by the fact that while we have perfect modulation alignment, the RF carrier frequency generation is not in perfect alignment causing a beating effect between the two signals that can be observed as a slow flat fading effect on a spectrum analyzer. We intentionally did not perfectly lock the RF carriers as in a real mobile environment the relative phasing of the two signals would be constantly changing at a wavelength of around 3 m. Even with this realistic effect, the bit error rates were well below the IBOC reception limit, demonstrating that it is possible to create conditions of seamless receiver “hand-off” from one transmitter to the next and seamlessly join coverage areas.

The bit error rate nudges up as the time differential between the two signal sources is increased. At 40 μs we can operate just below the reception limit for all signal levels. But at 75 μs we require at least 2 dB of protection ratio for IBOC reception. At 2 ms delay offset we essentially have an uncorrelated signal requiring a 4 dB protection ratio. These tests were performed in a static, non-fading environment. In a Rayleigh fading environment we would be wise to add an additional 3 dB fading margin as shown by John Kean [8].

We recommend that the potential interference zone for IBOC be defined as any coverage region with signal ratios of 7 dB or less and 40 μs of time differential or more compared to 10 μs and 14 dB for stereo FM transmission. It is

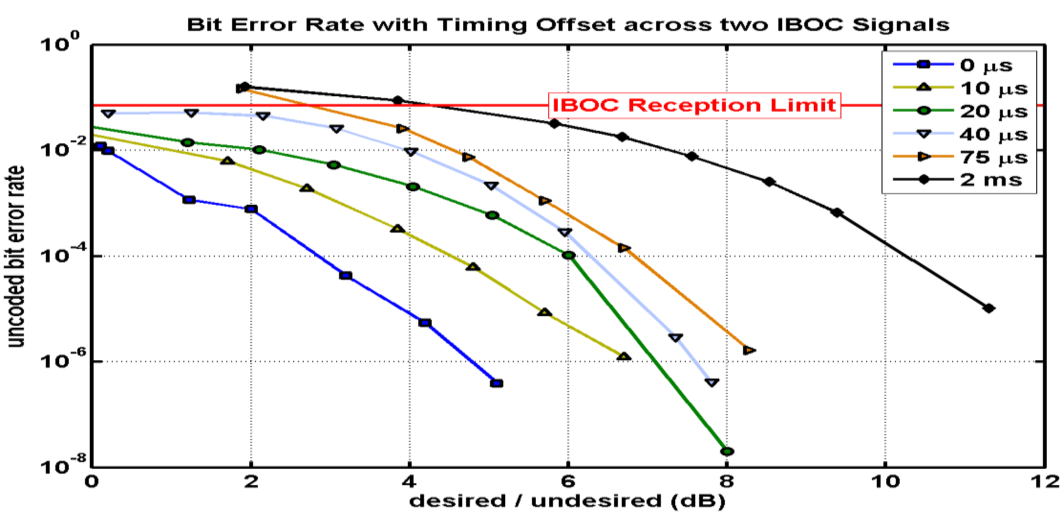

FIGURE. 5: STEREO FM SFN AUDIO IMPAIRMENT TESTS SERVICE MODE MP1 [6].

important to note that these results only apply to the P1 logical channel of the MP1 service mode. Audio and data services delivered in other logical channels, such as P3, or other service modes, such as MP6, will have different forward error correction applied. The raw bit error rates shown here would still apply, but the effective reception limit for these services would be higher or lower. The author has tested the MP6 mode and found IBOC reception can be maintained with ratios as low as 1.5 dB [3] for unsynchronized signals, indicating that all-digital IBOC SFNs will work even better than what is presented here.

The results in Figure 5 highlight that even with perfect time synchronization bit errors are introduced. A necessary conclusion then is that IBOC SFN overlap should be planned for regions with sufficient signal power such that this effect is the only contribution to the overall bit error rate. Further research is required to correlate the presented results with typical receiver sensitivity. Perhaps planning for interference regions to be at least in the 40 to 50 dBu region may be prudent.

VIII. Time Alignment

RF signal ratios are terrain dependent, do not follow nicely established patterns and are best obtained using RF coverage simulations. Signal arrival times, however, are deterministic and can be solved using basic geometry. Figure 6 shows a main and booster transmitter with a 26 km separation representing the distance of the main and booster in Figure 1.

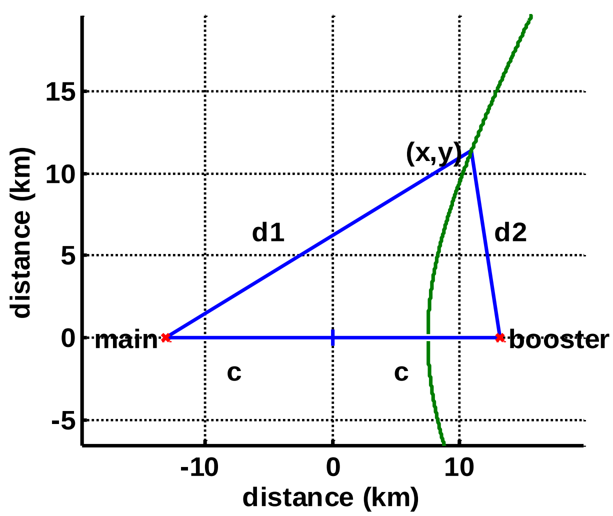

FIGURE. 6: TRIANGULATING EQUAL DELAY LINES.

Assuming the booster transmitter emits a signal 50 µs after the main transmitter, then the main wave front will have travelled distance d_1 and the booster wave front will have travelled the lesser distance of d_2. We can now solve for all co-ordinates where the signals meet for any given time t greater than the flight time to the midpoint (44 µs in this example) plus half the booster time offset (25 µs in this example).

We can describe the problem with the following equations 1-4 based on both the geometry and travel time of the signal. These contain four unknowns for a given point in time: d_1, d_2, $x(t)$, and $y(t)$.

$$d_1 = v_c t \quad (1)$$
$$d_2 = v_c(t - \Delta t) \quad (2)$$
$${d_1}^2 = (c + x(t))^2 + y(t)^2 \quad (3)$$
$${d_2}^2 = (c - x(t))^2 + y(t)^2 \quad (4)$$

where v_c is the speed of light and Δt is the configurable booster time offset.

Now we can solve for $x(t)$ and $y(t)$ and arrive at:

$$x(t) = \frac{{d_1}^2 - {d_2}^2}{4c} \quad (5)$$
$$y(t) = \pm\sqrt{{d_1}^2 - (c + x(t))^2} \quad (6)$$
$$\forall t \geq \frac{c}{v_c} + \frac{\Delta t}{2} \text{ and } 0 \leq \Delta t \leq \frac{2c}{v_c}$$

With equations 5 and 6, we can now plot the constant delay lines for various booster time offsets as shown in Figure 7. In this example, it takes 87 µs for the main wave front to reach the booster. With a 60 µs booster time offset, the booster wave front will first meet the main wave front 14 µs later as both race towards each other splitting the 27 µs difference. Figure 7 shows the two wave fronts meeting at the 81 µs mark; the wave fronts will stay time synchronized along the entire curve indefinitely. The constant delay lines on the main transmitter side are, of course, a reflection of the situation.

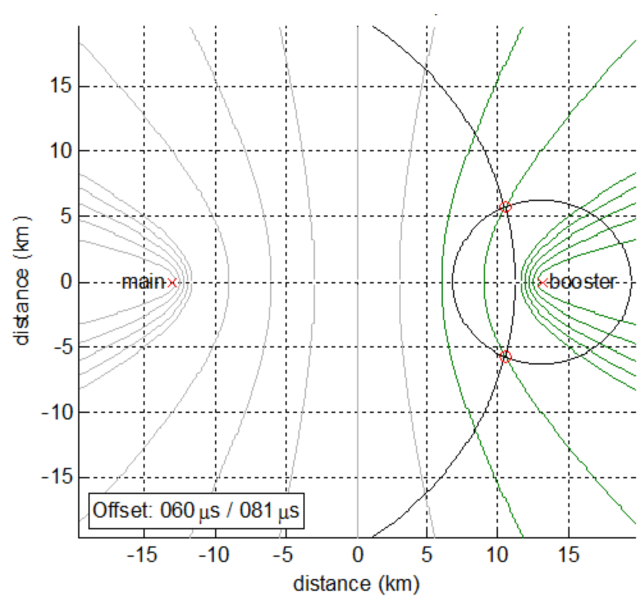

FIGURE. 7: CONSTANT DELAY LINES WITH 60 µS BOOSTER DELAY.

We can now take our knowledge of time alignment required and see how well we can match the relative signal levels to the constant delay lines and stay within the established requirements for IBOC and FM transmission.

SFN Simulations

The following simulations assume a flat world without any terrain obstructions. In reality, RF coverage studies should be performed taking the terrain into consideration. However, for better clarity and to show a worst-case scenario a flat world model is used. The simulations are based on standard FCC F(50,50) curves and scaled to the station example shown in Figure 1 with a main ERP of 25 kW and a booster ERP of 250 W. The 70 dBu city grade contour is shown as the inner purple lines and the 60 dBu contour is the outer purple line.

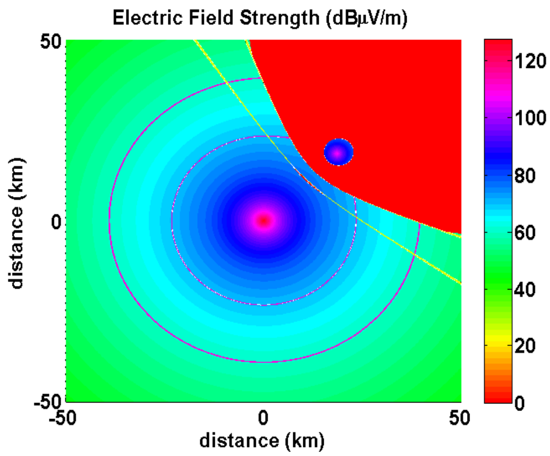

Figure. 8: Stereo FM Potential Interference Areas.

Figure 8 shows the potential interference areas created in this setup taking into consideration the 14 dB desired versus undesired ratio (D/U) established in earlier sections for stereo FM transmission. Of course, this is a simplification as this simulation does not consider the gradient impact on the received audio. The area bounded by the yellow lines is the area that we can improve through time aligning the two wave fronts to within a 10 μs differential. The booster is delayed by 27 μs from the main which means the booster emits its wave front 60 μs in advance of the main wave front reaching the booster site. The two wave fronts will meet after 30 μs as they race towards each other; this is 9 km from the booster. The large potential interference region makes seamless coverage a challenge for stereo FM transmission. The booster transmission requires terrain shielding from the main transmitter and could benefit from a directional antenna not considered in this simulation. It is often more beneficial to keep stereo FM booster ERP low in order to control the coverage area better.

As established earlier, the SFN requirements for mono FM transmission is greatly relaxed requiring a D/U ratio of 3 dB only. The impact is clearly visible in Figure 9. The time differential remains the same for mono and stereo transmission at 10 μs. However, now that there is a smaller interference region to worry about, we can adjust the booster delay to shape the interference free region to better match our intended coverage. If the transmission is held off by 67 μs, the wave fronts meet 3 km out from the booster and the constant delay region creates a curve that more effectively addresses the interference region, but it does have the potential of creating interference between the two transmitters.

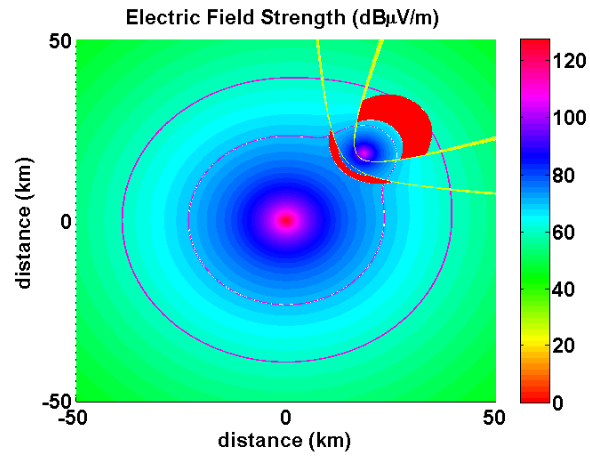

Figure. 9: Mono FM Potential Interference Areas.

This demonstration shows that mono FM transmission can be employed much more effectively than stereo transmission. Perhaps in the not too distant future, FM transmission will truly become a fall back to IBOC and broadcasters may be willing to opt for mono FM in order to leverage the SFN benefits of IBOC transmission.

Figure 10 shows that with the 40 μs timing margin for IBOC transmission we can easily address a 7 dB D/U ratio and provide seamless coverage across the entire coverage region. The delay has been set to 40 μs in advance of the incoming main wave front clearing the entire area ahead of the booster transmitter. A small region of potential interference was left for demonstration in behind the booster transmitter. However, this region can easily be addressed by setting the delay to just under 40 μs. The combined effect to the 70 dB contour is now apparent providing city grade IBOC coverage to a much greater coverage area. Due to the current allocation rules of containing the 60 dBu contour of the booster within the main, the combined 60 dBu is minimally impacted.

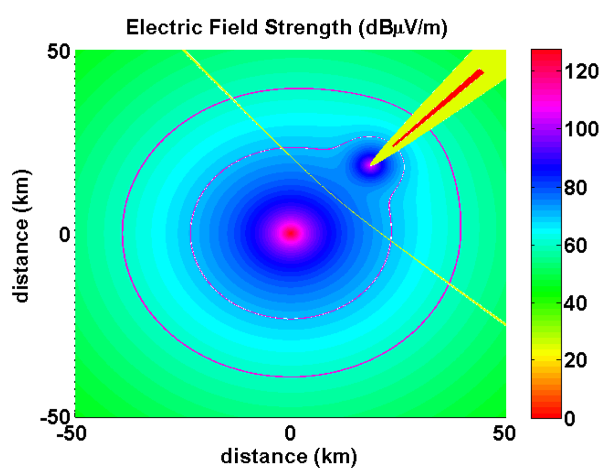

Figure. 10: IBOC Potential Interference Areas.

These results are based on an IBOC injection ratio of -10 dBc on both the main and the booster with 2.5 kW of IBOC from the main and 25 W from the booster. What if we could increase the IBOC power further to 250 W, or 0 dBc injection while keeping the FM power at the same level to comply with the allocation rules? Those results are shown in Figure 11 with the addition of two other boosters.

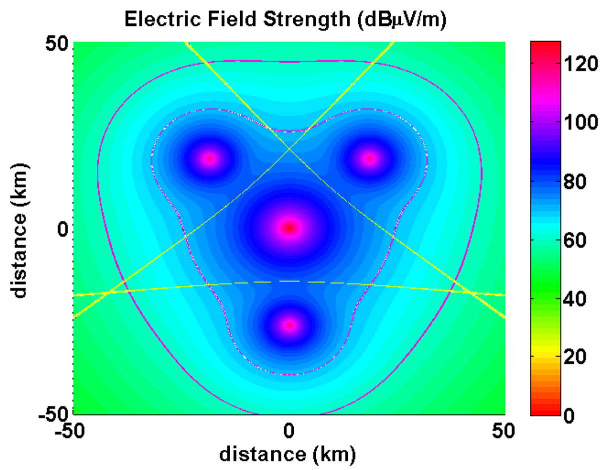

FIGURE. 11: INCREASED COVERAGE AREA WITH 3 IBOC BOOSTERS.

Now the station's IBOC equivalent 60 dBu and 70 dBu contours are significantly expanded. Note that both Figures 9 and 10 show these contours in an FM equivalent way. In reality, the IBOC signal strength at these locations is 10 dB lower, but we are working with the assumption that 10% IBOC power provides roughly the same coverage compared to 100% FM power. The contours are drawn at an FM referenced level as many readers will be more familiar with FM performance levels.

The point of this exercise is to show that the IBOC SFN parameters are well suited for typical station applications and can provide seamless coverage between adjacent transmitters. Should a station experience trouble containing the interference zones created in stereo FM transmission, the station may opt to go mono on the FM transmission while maintaining high quality stereo on the digital simulcast. Under today's rules, a station can increase their on-channel coverage and enforce their frequency branding. Experimental authority or a slight rule change allowing boosters with higher injection ratios will allow a significant increase in IBOC coverage.

One may question whether we should keep the FM carrier in the booster at all and only broadcast the IBOC. The answer lies in the fact that IBOC only booster risk drowning out the FM for non-IBOC receivers. Good FM ceramic filters have a 20 dB bandwidth of ±150 kHz [9] capturing only a small portion of the IBOC signal. Typical FM ceramic filters have a 20 dB bandwidth of well over ±200 kHz [9] capturing all the IBOC carriers attenuated up to 20 dB. At established IBOC injection ratios between -20 dBc and -10 dBc the captured IBOC power is typically acceptable [10]. However, a receiver close to an IBOC only booster will capture far more IBOC RF power compared to the residual FM transmission from the main. SFN tests conducted on WKLB, Boston, by iBiquity Digital Radio suggest that a low level FM carrier injected into the booster may suffice for many FM receivers, but further study is required. Perhaps, a 0 dB injection ratio with the FM equal to the IBOC power may be a good compromise.

SYNCHRONIZING THE IBOC SIGNAL

The challenge with synchronizing the IBOC signal is that we must feed geographically separated transmitters with the same content from a single common node typically originating at the studio to the time accuracy defined in earlier sections. Figure 12 shows the key IBOC system components and how they can be modified to ensure synchronized signal transmission.

Typically, the common node in a station setup is the FM+HD audio processor that takes the main audio feed and

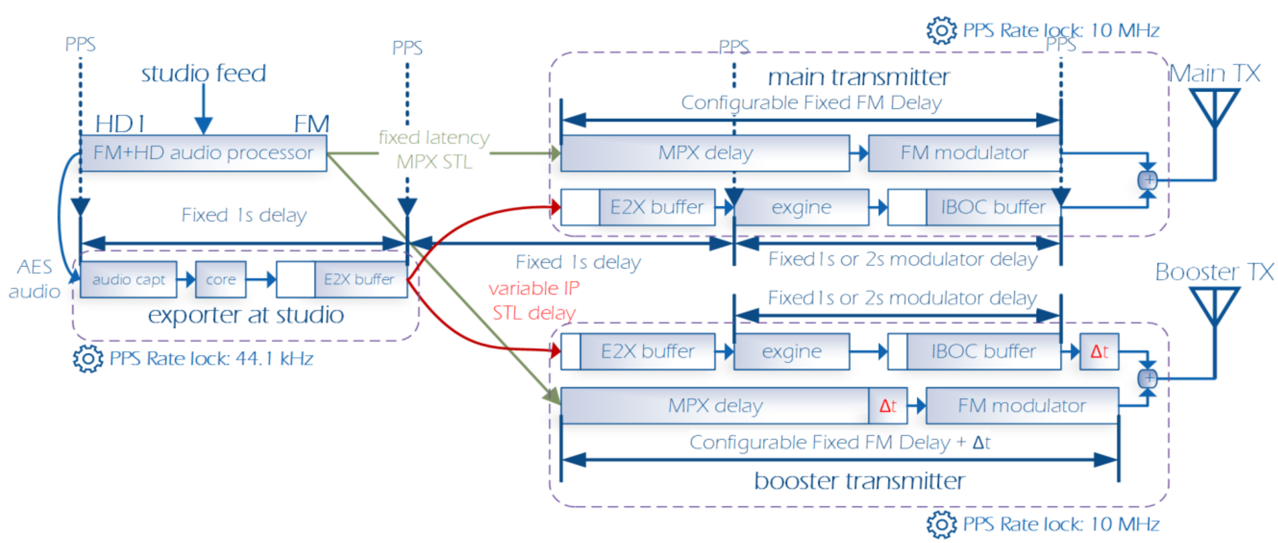

FIGURE. 12: SYNCHRONIZED IBOC SYSTEM ARCHITECTURE

produces the processed audio for FM and HD1. While FM and HD1 are simulcasts, the applied processing to the audio is typically different so two audio outputs must be maintained. The audio processor produces an AES audio feed for the HD1 and, ideally, a digitized MPX signal either over IP or AES for the FM audio. The MPX signal must be delivered from the audio processor to all remote exciters with a fixed latency better than the accuracy required for SFN synchronization; off-the-shelf solutions exist delivering the MPX to within ±1 µs to all end destinations.

The exciter and transmitters used for the FM broadcast must be able to support configurable fixed FM delay from MPX input to RF output. The delay buffer must be configurable to under ±1 µs accuracy. Often it is not easy to determine the throughput delay of an FM exciter and can vary by exciter and transmitter model, input mode (stereo audio versus MPX), applied signal filtering, software and hardware versions, temperature and reference clock accuracy. Consult the transmitter manufacturer to obtain this information. Note that all FM modulators must be configured for identical modulation depth and frequency deviation direction. Using a test signal and an HD modulation monitor both can be verified; the HD1 signal can be used to ensure correct polarity of the FM broadcast on all SFN nodes. It is not sufficient to simply invert audio, therefore, Nautel's transmitters allow the configuration of the FM deviation direction so we can match all nodes in the network.

Unlike the FM synchronization that assumes fixed delays across multiple independent system components, the IBOC synchronization proposed by Nautel is a time tagging solution that aims to close the signal transport timing loop from HD1 audio capture at the exporter to RF output at the transmitter. Variable delays in between processing steps are absorbed through flexible buffers at each stage. The proposed method only requires a pulse per second (PPS) for intermediate stages to stay in-sync and does not require knowledge of absolute time, which is not always available in today's transmitters with sufficient accuracy.

When HD1 audio is sampled at the exporter at the studio, the audio is sample rate converted to 44.1 kHz based on a GPS disciplined 10 MHz oscillator. This means every second interval produces precisely 44100 audio samples, so we can count samples from 0 to 44099 and reset the count on every PPS pulse. Audio samples are grouped into 4096 sample groups that are sent to the exporter core that applies the HD codec to the audio samples and packages all IBOC data into a data packet every 92.9 ms; the same rate 4096 audio samples are produced. Each group of audio samples is tagged with the audio sample count of the first sample in the group. The sample count is maintained through the transformation of audio to IBOC data within the exporter core. Before sending the IBOC data across the exporter-to-exgine (E2X) link, the packets are buffered. Each packet is sent over the IP network one second after the corresponding audio has been captured at the input based on the tagged sample count.

The transmission across an arbitrary IP network to two or more destinations may introduce variable delays that can also change over time. The same method to synchronize the internal exporter handling is also employed across the IP network and can observe up to one second of variable delay. Since E2X packets are not sent into the IP network until after the last PPS, the exgine will buffer E2X packets until the next PPS and the packet's sample count has elapsed.

Different exgine modulator implementations may have varying processing delays. An E2X packet is transformed into 32 IBOC symbols taking up 92.9 ms just as the originally captured 4096 audio samples did. The sample count that was initially obtained is again maintained through the processing stages. This allows IBOC symbols to be passed to the digital upconverter in the exciter after an elapsed PPS plus sample count. Typically, digital upconverters can be built with low latency variations of within one IBOC sample period of 1.3 µs. Nautel found that requiring the exgine modulator to complete its tasks within a one second time slot was too tight and so expanded the time slot to two seconds. The implementation can handle this amount of variation internally and ensure a fixed two second throughput delay. Provided all exgine modulators in the system agree on either a one or two second interval, the system will stay in sync. In the case of the booster transmitter a configurable sample delay achieves the configurable time delay required for optimal SFN implementation.

Our timing budget is now composed of one second in the exporter, one across the IP link and two across the exciter. Note that these are transport and processing delays. Within the various processing steps there are delays, such as modulator interleaving and filter delays, that impose a delay within the described transport mechanism. In total the overall IBOC delay from input to output is around 8.5 seconds.

Since the entire system is rate locked based on PPS, derived from GPS or precision time protocols, the described time synchronization only requires to be run at startup. The interlocking gears of rate locking will maintain time alignment long term to within the specifications of the time references and control loops.

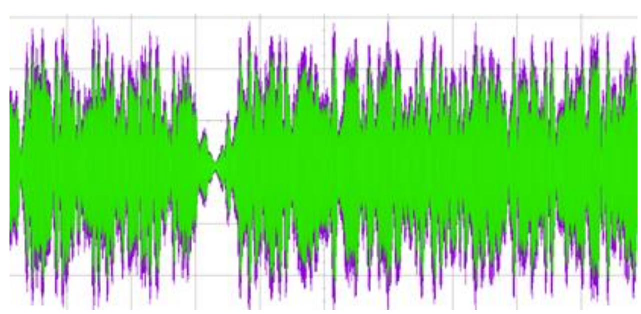

FIGURE. 13: SYNCHRONIZED IBOC WAVEFORMS (NO FM CARRIER)

Figure 13 shows the resulting aligned IBOC waveforms from two transmitters superimposed on two oscilloscope traces. The guard interval of the two IBOC symbols represented by the drop in power is clearly aligned between the two signals. Using this test setup a clean hand-off from one IBOC transmitter to the other can be demonstrated without the HD Radio receiver losing HD Radio lock or skipping a beat.

Lab tests have also confirmed that the HD-1 audio delay also remains consistent to within ±2 µs. This is well within the 68 µs diversity delay alignment specification of NRSC-5C. Therefore, the proposed architecture can very well solve the industry's diversity delay issues for non SFN stations, as well, provided the FM audio throughput delay stays constant.

KUSC Field Trials

In 2016 Nautel implemented the proposed architecture with the intent of trialing IBOC SFNs on-air. University of Southern California's KUSC was in the middle of upgrading their existing FM only on-channel booster serving the community of Santa Clarita, 30 miles north-west of downtown Los Angeles when Nautel proposed to turn the new booster installation into a hybrid FM+IBOC booster. Santa Clarita is largely shielded from KUSC's 39 kW directional transmission from Mount Harvard; Figure 14 shows the two transmissions with the equal delay lines superimposed. Despite terrain shielding, overlap regions still exist that require synchronizing the IBOC signal. Particularly, motorists traveling on I-5 could be impacted when crossing between the two coverage regions and experience extended IBOC outages as the HD Radio receiver would struggle to re-acquire the IBOC signal from the other transmission.

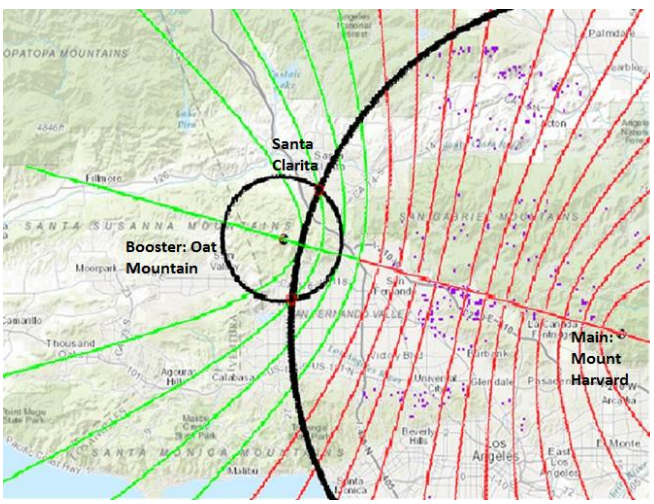

FIGURE. 14: KUSC FIELD TRIALS, SANTA CLARITA AND LOS ANGELES

The 200 W booster is located on Oat Mountain with a directional antenna pointed at Santa Clarita and serves the community with a good signal. Both the main and the booster are transmitting IBOC at an injection of -20 dBc or 390 W and 2 W respectively. The primary Nautel NV transmitter and exgine software was updated to allow for time synchronization from the co-located Nautel exporterPlus at Mount Harvard, which represents the common IBOC signal source for this installation. The integrated GPS receiver in the exporterPlus provides the PPS timing signal for the primary transmitter as they are co-located. The E2X link at Mount Harvard is simply the local network. Two intraplex links from Mount Harvard first to the KUSC studio and then on to Oat Mountain form the E2X link to the booster. Together the two links imposed over 30 ms of latency and showed some packet loss. Reliable HD Transport [11] was used to address packet loss across the two links. Note this 30 ms link difference is inherently handled in the detailed SFN architecture and does not need to be accounted for or measured accurately. The PPS timing at the booster site was provided by an ESE-101 GPS based master clock generator feeding the VSHD exciter with a PPS signal.

The signal flight time from main to booster is 176 µs, so the booster offset was set to 136 µs creating a large area of time synchronization in the field. KUSC could advance the booster further and push the equal delay contours further toward Mount Harvard thereby reducing potential interference in the LA direction. Potential interference zones would appear in behind the booster and fall over the Santa Susanna Mountains, which could be acceptable in this situation. However, at present IBOC power levels this was not deemed necessary.

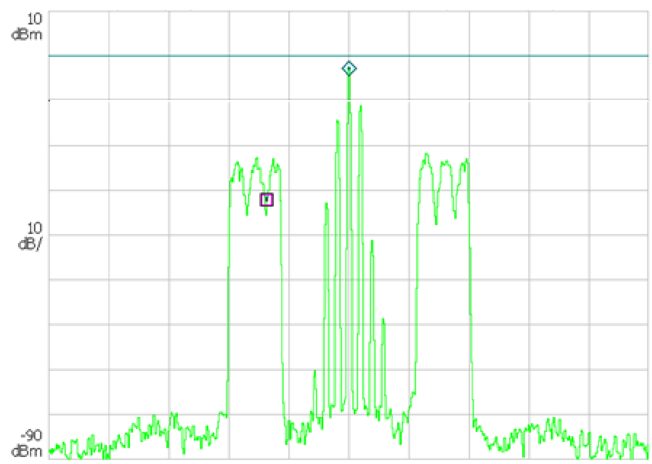

FIGURE. 15: FREQUENCY SELECTIVE FADING AT 33 US TIME DIFFERENTIAL

There is a practical way to ensure the IBOC delays are dialed in correctly. When coupling two delayed copies of the IBOC signal, the RF spectrum exhibits notches with frequency spacing related to the IBOC signal delay as shown in figure 15 captured with a 33µs signal differential in the lab. Any IBOC carrier delayed by itself will cancel in the frequency domain if it is delayed by 1/2 its period, 3/2 its period, 5/2 its period and so on provided both signal sources have the same RF carrier phase. The exact frequencies measured in the field, hence, depend on the location where the spectrum was taken with respect to the incoming 3 m wavelengths. The frequencies may also wander with slight RF carrier variations. However, the reciprocal of the frequency spacing between nulls should remain constant and represents the delay that has been applied to one of the signals plus the flight delays. The minimum delay one can measure using this method is about 15 µs with both notches on the outside of the IBOC carriers. Delays below that should appear more and more as flat fades across one or both IBOC carriers. In the interference zone with equal receive signal levels (RSL) one should be able to move the receive antenna across the 3 m wavelength and observe a flat fade on the IBOC carriers if the delay has been set correctly.

We were able to observe this effect at the Oat Mountain booster site with an off-air spectrum capture on the far side of Oat Mountain providing shielding from the booster transmission in order to better match the RSL from both transmissions. This may not always be possible, but one can mute the booster by running it into a dummy load and coupling the RF monitor port through a switched attenuator with an off-air signal capture. Measurements in the interference zone may benefit from a directional receive antenna to match RSLs.

Verifying the FM is aligned correctly is a bit more challenging as the FM does not provide a nice flat top spectrum like the IBOC carriers and the two FM transmissions may not be 100% identical with minute differences in modulation depth and other FM generation parameters. But having the IBOC verified allows us to use diversity delay monitors with delay measurement capability to use the IBOC as a reference to verify the FM is at least synchronized to within one audio sample of 22.7 µs. This is a sanity check, not a precision measurement. Perhaps future modulation monitor models may provide sub-sample accuracy suitable for this application. The modulation monitor will also ensure the correct FM audio polarity with respect to the IBOC signal with identical polarity across all SFN nodes. This method was used at KUSC to align the FM audio. The lack of precision was deemed sufficient for the FM due to the significant terrain shielding in Santa Clarita.

With the main and booster configured with the correct delays drive tests were conducted to observe the SFN operation. The 200 W of FM and 2 W of IBOC from Oat Mountain provides solid coverage in the Santa Clarita valley. The canyon lands around Santa Clarita can provide wild variations in RSL from either transmitter, including complete absence of either transmission. It was noted that even in areas with heavy FM interference, solid HD lock with perfect HD1 audio was observed. When the HD was dropped, it would typically come back momentarily, showing that the two signal sources were time aligned and the receiver did not have to re-lock to a new signal source. RF coverage simulations predicted potential interference regions in the Sylmar region toward the main transmission on the LA side of the terrain obstruction with shadowing from both transmissions. This area, too, only showed momentary HD drops only with specific shadowing through buildings and underpasses.

CONCLUSIONS

Nautel has successfully demonstrated an IBOC SFN implementation at KUSC, Los Angeles, that showed that IBOC coverage extension is possible even in difficult mountainous terrain. The IBOC signal is well suited for SFN operation, allowing for seamless coverage fill-in using on-channel signal boosters under today's allocation rules. A station can use IBOC signal boosters to extend coverage especially with elevated IBOC power levels on the booster. While hybrid FM+IBOC transmission on the main transmitter is maintained, SFN performance will be limited by the FM SFN parameters as the booster must also remain hybrid. Reduced FM power levels and elevated IBOC power levels at the booster allow a station to minimize FM interference while maximizing IBOC coverage. A mono FM signal, better suited for SFN operation, may serve as a fall back signal until conversion to all-digital broadcasting is achieved. All-digital solutions, such as HD Multiplex, combined with SFN operation will lead to new application areas such as national or state-wide, single frequency roadway coverage or micro SFN repeaters.

ACKNOWLEDGEMENTS

The author would like to thank Ron Thompson and Tom King of KUSC for the help with the presented tests and John Kean of Kean Consulting for the KUSC RF coverage analysis, as well as, my colleagues at Nautel that made this paper possible.

REFERENCES

[1] FCC Audio Division, "FM Translators and Boosters" https://www.fcc.gov/media/radio/fm-translators-and-boosters Accessed Jan 16 2017

[2] Aubé, P, "Radio Broadcast Data System" http://www.cbc.radio-canada.ca/en/reporting-to-canadians/sync/sync-issue-2-2012/radio-broadcast-data-system/, Accessed Jan 12, 2017

[3] Schmid, P. "Interleaving IBOC Signals for a Digital HD Radio Multiplex", 2015 IEEE BTS Symposium

[4] "FM and TV Propagation Curves" https://www.fcc.gov/media/radio/fm-and-tv-propagation-curves

[5] ITU-R BS.412-9 Annex 3: "Protection ratio for FM sound broadcasting in the case of the same programme and synchronized signals."

[6] Schmid, P., "FM+IBOC Broadcast Systems Architecture Considerations for Single Frequency Networks" 2009 NAB Broadcast Engineering Conference Proceedings

[7] ITU-R BS.1284-1 "General methods for the subjective assessment of sound quality"

[8] Kean, J., "An Improved Coverage Prediction Method for HD Radio", 2008 NAB Broadcast Engineering Conference Proceedings

[9] Carter, B "The FM Ceramic Filter Page" http://earmark.net/gesr/cf.htm Accessed Jan 22, 2017

[10] Vernier, D., The Looming Danger of Digital Host Interference Radio World, March 2009

[11] iBiquity Digital Radio, "HD Radio Single Frequency Network Field Test Results – WD2XAB Baltimore & WKLB Boston", NAB Fastroad Project

[12] Schmid, P., "E2X Bandwidth and Bit Error Requirements for Ethernet Synchronization" 2007 NAB Broadcast Engineering Conference Proceedings