FM Boosters
Single Frequency Networks

The "Synchronize Everything" Approach

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Introduction

With recent advances in technology and the resultant improved understanding of the issues that affect their performance, FM synchronous boosters and single frequency networks (SFN) can now be a much more effective way to solve problems that have long plagued broadcasters due to the characteristics of FM propagation. With limited frequency availability in many developed markets, and populations expanding into areas not previously served by a particular FM signal, expanding coverage by using a single existing frequency can solve these problems. The philosophy of accurately aligning <u>all</u> aspects of the FM signal significantly improves the listener's experience in the overlap or interference zone, which is the key to good system performance. The result: RF sites that were marginal before because of interference issues now become viable options for extending programming into new population corridors or to fill-in areas underserved by a main FM signal.

Why a SFN or booster?

Single frequency networks and related boosters are defined as two or more broadcasts at different locations that share a common frequency. The application ranges from a network of low-powered FMs covering a region, province or state, to a booster signal transmitting into an area overshadowed by a mountain or tall building.

FM transmitters synchronized to broadcast the same programming on the same frequency can serve many purposes. Synchronous FM broadcasts can provide station and program continuity along a highway, across a large region or as a fill-in "booster" to a main signal within a particular area previously un-served or under served due to population expansion or relocation.

Through synchronized broadcasts spaced at geographic intervals, commuters can continue to receive a program while driving along an extended stretch of highway, and without changing the dial position on their radios. Similarly, a network of synchronized FMs enables broadcasters to expand program coverage across a larger region not possible with just one broadcast tower. In addition, a booster signal synchronized to the main signal is an increasingly popular option for reaching populations within a station's 1mVm contour but otherwise unreachable by the main signal due to mountains or buildings shielding the signal.

Potential applications

- Scenario 1: Fill in "dead" spots within a licensed geographic contour unreachable by a main signal
- Scenario 2: Cover a major highway from one end to the other with one frequency
- Scenario 3: Expand broadcast across a large geographic area to establish a true regional station
- Scenario 4: Possible alternative to raising HD Radio output power, to improve building penetration of HD Radio signals. Note: This scenario is not within the scope of this paper.

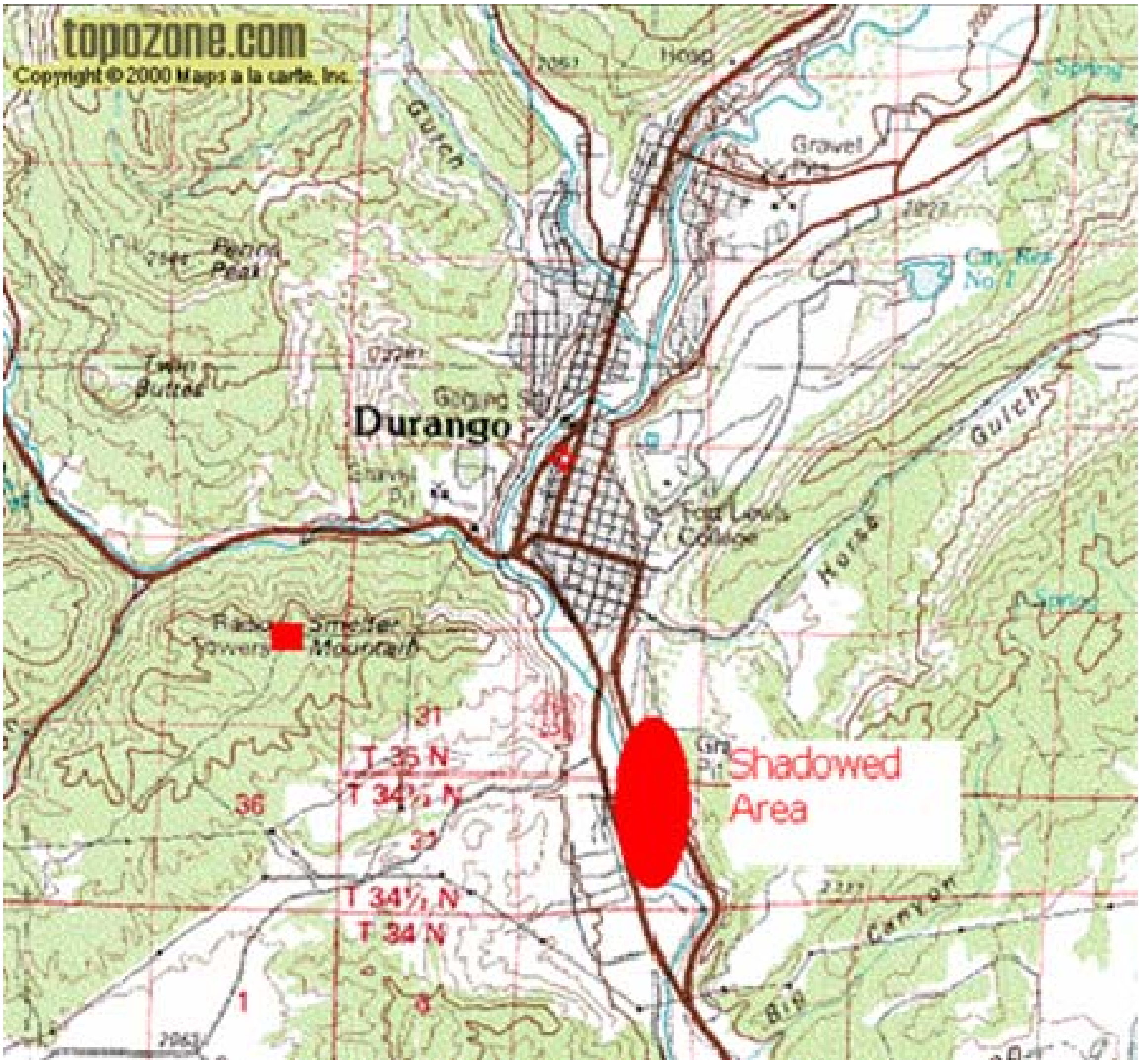
Frequency preservation, cost savings and continuity of service are main advantages of SFN and booster applications

Allocating one frequency for a network of synchronized FMs is more band efficient than broadcasting on a succession of frequencies, especially if a single frequency has been established already in a mature market and the remaining frequencies available present a possibility of adjacent channel interference. Costs across the board, from capital expenditure to operating expenses, also may be comparatively less for SFN or booster applications, depending on the extent and location of broadcasts.

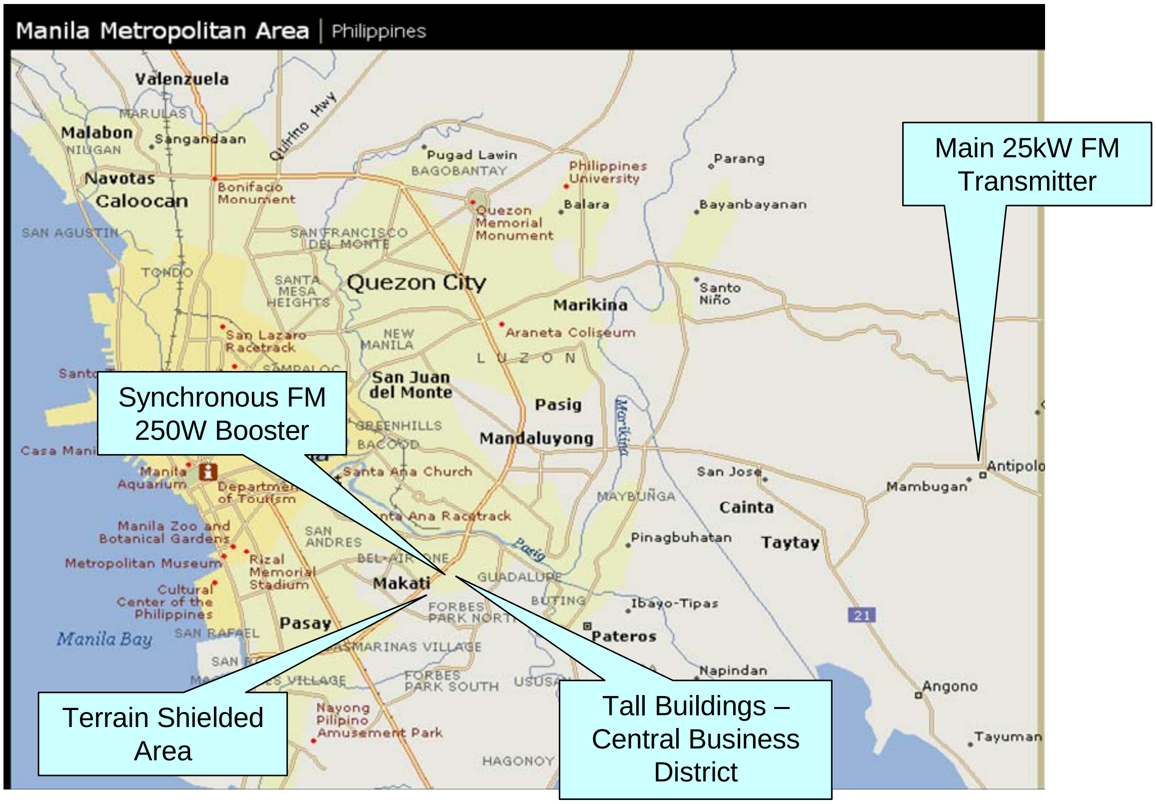
Just as important, the SFN and booster application is largely seamless to the listener; he or she can continue to listen to the same broadcast over a wider region without changing frequencies. For many broadcasters, this application offers a way to extend and expand programming coverage without listener loss.

Example installations

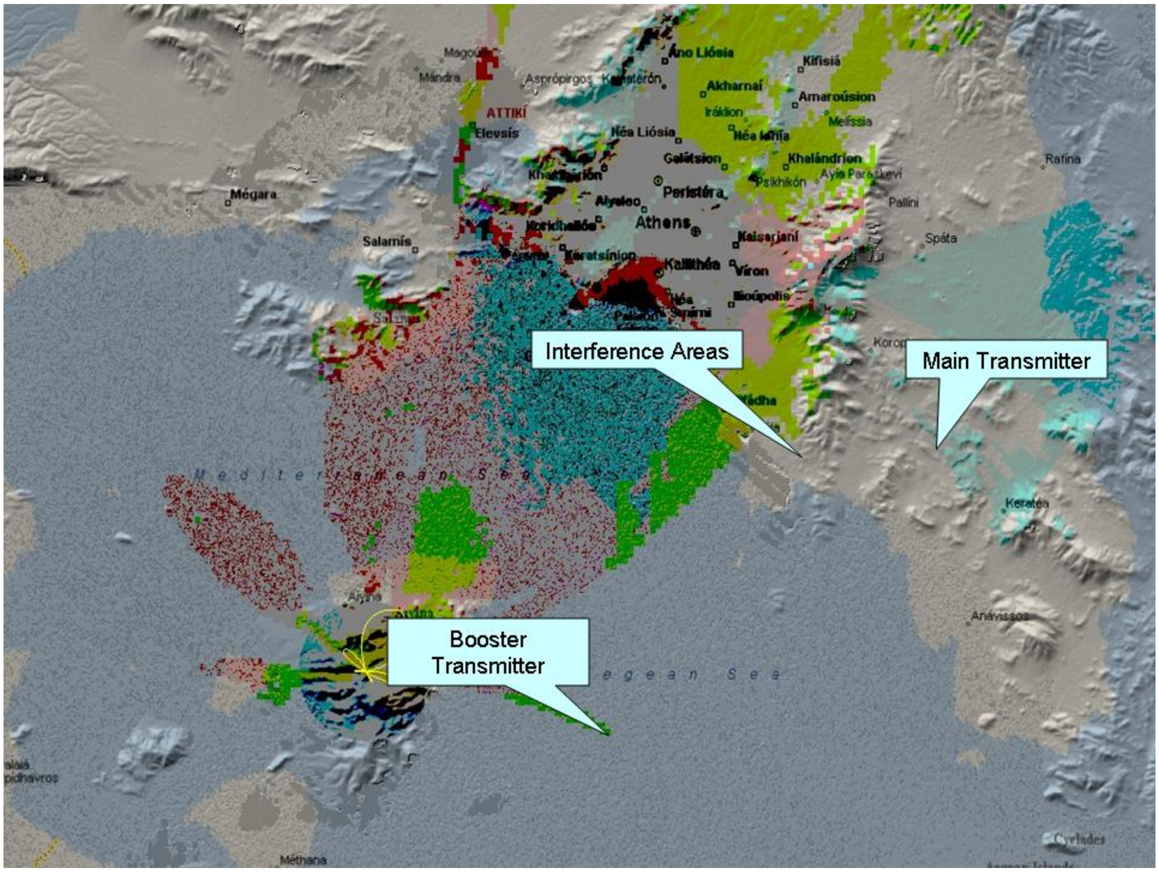
The following are just a few examples of the dozens of synchronous FM applications BE has been involved in over the years.



This topographic map illustrates a booster installation successfully completed near Durango, Colorado. The shaded areas shown are representative of the dead spots within the primary coverage area that are out of the line-of-sight of the main broadcast signal and filled in by a booster signal. A properly conducted and executed engineering study identified the ideal location for the booster site in order to maximize population penetration and minimize interference to the listener.

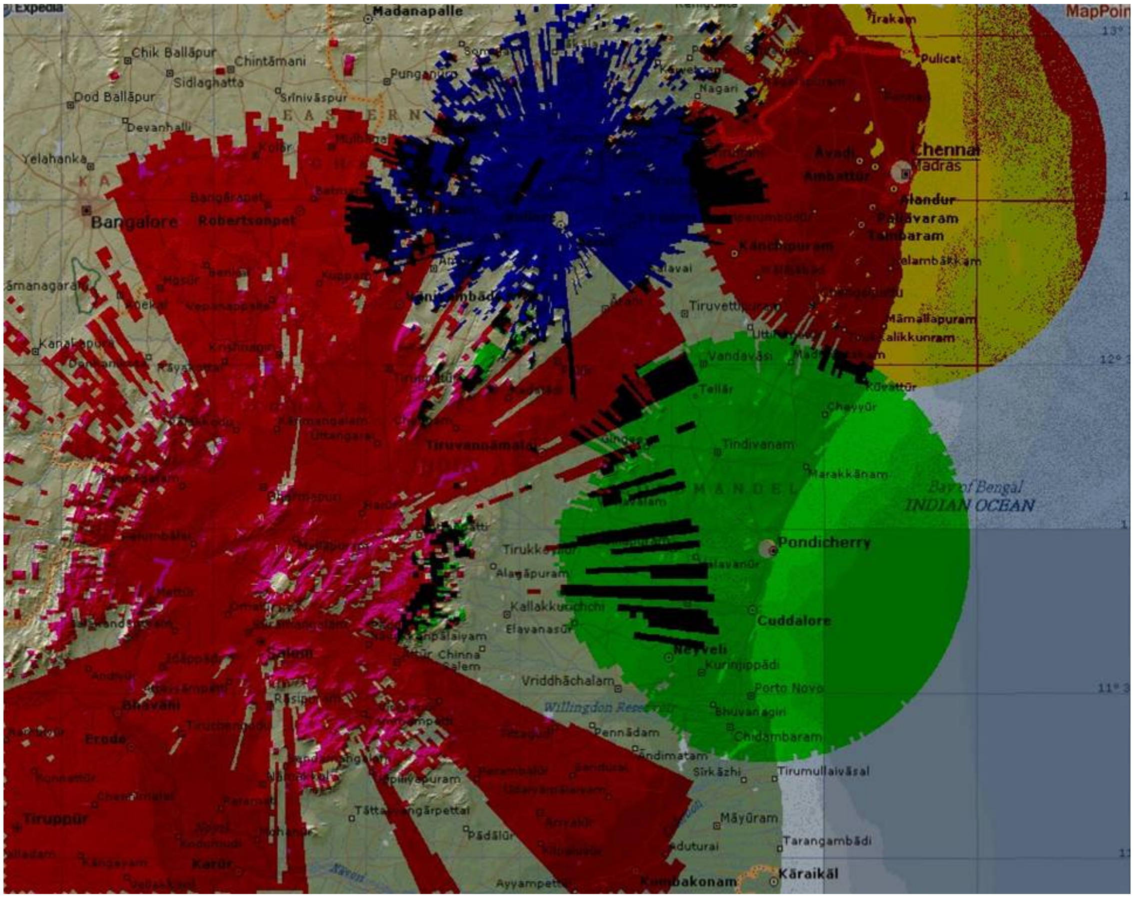


Natural terrain as well as large buildings in the central downtown business district shielded the main 25kW broadcast originating some distance from downtown Quezon City, Manila. A 250W booster signal supplied by BE and synchronized to the main FM filled in the listenership gaps in this downtown area.



This topographical map shows a single-frequency network along with a booster application implemented near Athens, Greece, by Broadcast Electronics engineers. Initially broadcasting on two separate frequencies in the region, the broadcaster synchronized both its stations to cover the same regional area using one frequency, and returned one frequency to the communication authority for reallocation to other public services. Also, notice the blue shaded area along the Mediterranean sea. A booster tower was installed on the adjacent island with the signal aimed at the city so listeners could continue to receive the broadcast uninterrupted as they drove along the highway below the bluff overlooking the sea.

Long, well-traveled highways are good candidates for low-powered synchronized FM networks, as shown here in this representation of a SFN in Malaysia. The circles in red are representative of the coverage patterns of 12 low-powered transmitters making up a single-frequency network synchronized to provide unbroken service from one end of the highway to the other.



Several high-powered stations synchronized on one broadcast frequency efficiently cover a large area while preserving the frequency band in that region or country. This is one example of how BE's "synchronize everything" approach enabled this India broadcaster to air programming to a large region using one frequency, instead of four, five or more frequencies.

Interference zones

In theory, the SFN and booster application provides new and rich opportunities for reaching out to new listeners. In practice, however, the application has seen limited success because of "interference" zones, where overlapping signals of equal strength from two broadcasts on the same frequency can cause audible distortion and dramatically increased noise.

Interference happens when two signals broadcasting on the same frequency arrive at the receiver within 3dB of each other in signal strength. These interference zones are the areas where one transmitter hands off coverage to another. If one signal is weaker by roughly 3dB, the receiver captures the stronger signal and completely ignores the weaker one, resulting in adequate reception. The problem arises when both signals are of near equal signal strength and are combined within the receiver.

If both signals are coming into the receiver at the same signal strength, the receiver cannot separate one from the other and it reproduces the resulting difference as noise. As the receiver detects signals coming from both, the resulting audible distortion and noise sound similar to multipath.

Issues affecting interference

Several key issues affect the degree and severity of noise and distortion in the overlap zone:

- If the RF carriers are not frequency synchronized, significant distortion and noise will result.

- If the audio levels are not exactly the same, within approximately .1dB, the noise floor increases dramatically with a "white noise" which varies with the level of the audio.

- If the pilots are not synchronized, in both frequency and phase, the pilot detector in the receiver will switch back and forth and this will be audible in the stereo signal.

- If the audio phase is not synchronized, distortion results.

- If everything – audio, pilot and carrier – is synchronized, the signal will be optimized within the targeted portion of the overlap zone.

Early field experiments proved that it's not enough to align carrier frequencies. Audio level differences from both broadcasts potentially increase the noise floor, causing varying degrees of white noise. In addition, audio arriving at the interference zone at different intervals results in an out of phase condition, causing even more noise.

What's more, if the two stereo pilots are out of phase, noise will show up in the stereo signal as the receiver switches between the two pilots trying to lock onto a signal.

What is needed is a way to precisely lock the carrier and the pilot in frequency and in phase, and to synchronize audio levels as well as delay the audio at one of the transmitters so that it arrives at the interference zone exactly at the same time as the audio coming from the other transmitter.

Audio levels and phase affect reception in the interference zone

As mentioned earlier, we have been able to mitigate some distortion in the interference zone by synchronizing the RF carrier frequencies of both transmissions. As early as 1988, BE began aligning the carrier frequencies by synchronizing the booster exciter to a reference frequency generated in the main exciter. This lessened the disparity between the two signals coming into the receiver, and reduced the affect of one cause of distortion.

The advent of GPS technology along with BE's introduction of the FXi exciter in 2002, which was the first to employ direct-to-channel carrier synthesis based on the GPS external 10MHz reference, was used to generate not only the carrier but the pilot as well. This allowed the next step to be taken in improving overall booster performance. In addition, with the use of a pilot sync option and the external 1 pulse per second capability of later GPS receivers, the phase of the pilot signal could also be locked to a common reference. The use of an extremely accurate modulation adjustment of the AES/EBU input also helped align the resultant modulation levels of multiple exciters.

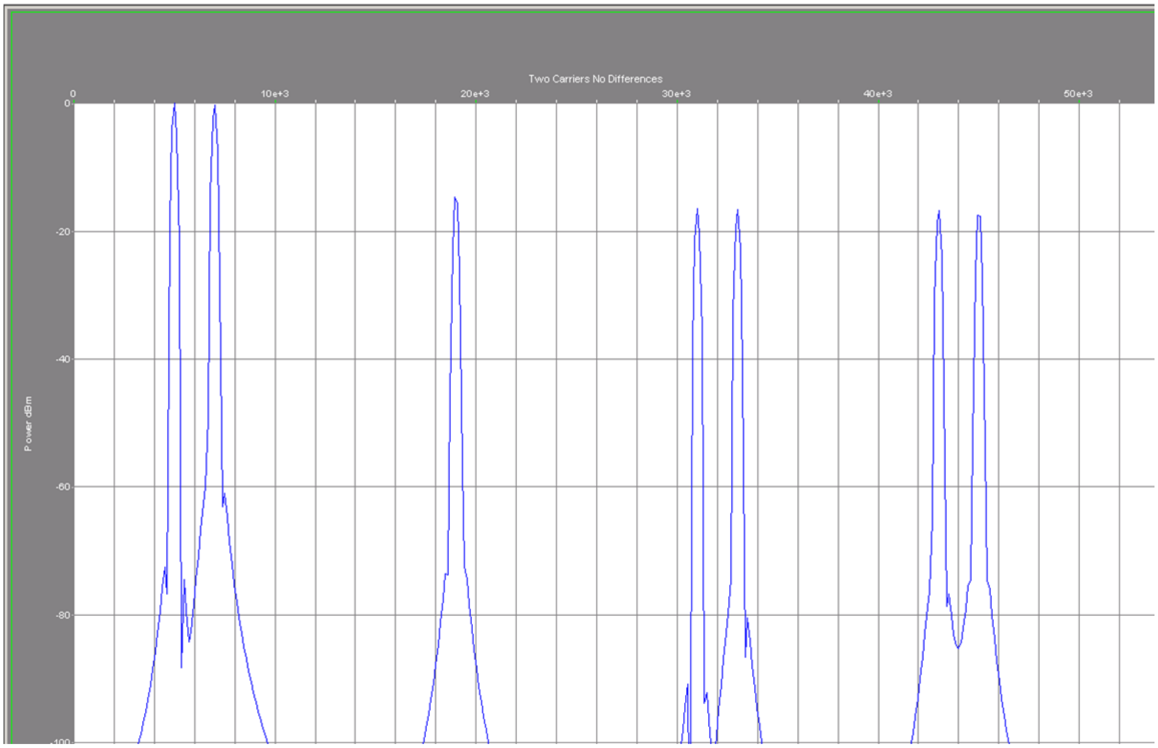
BE has since refined the application of synchronous technology with the introduction of its next-generation FXi 60/250esp digital FM exciter in April, 2008, which now includes built-in synchronous features ideal for this application.

BE's approach is to synchronize everything

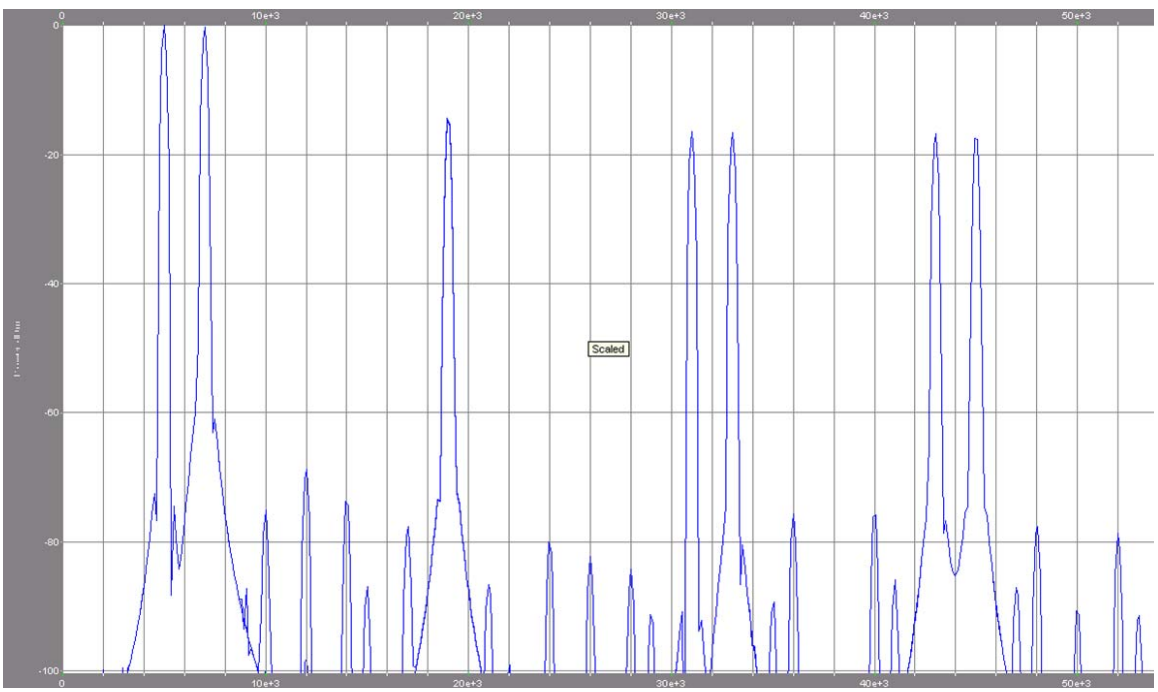
- An uncompressed digital AES/EBU studio-to-transmitter link is recommended. This makes it possible to synchronize audio accurately using the exciter's AES/EBU input; BE's FXi exciter has the ability to adjust input levels to within 0.1 dB.
- GPS receivers are needed to synchronize carrier and pilot, both in frequency and phase. BE's FXi 60/250 exciter has a GPS receiver built-in, saving the additional cost of acquiring rack-mount GPS units; all that is required is an external antenna.
- A delay function is needed to accurately synchronize programming in the selected region of the interference zone. Internal delay in the BE FXi exciter accurately adjusts the delay with a resolution of 1 microsecond along with the capability to adjust the minimum delay to approximately 1 microsecond; another cost savings. This is essential when the difference in distances between the two sites and the interference zones is small and a small amount of delay is required.

What happens when audio levels from separate sites differ?

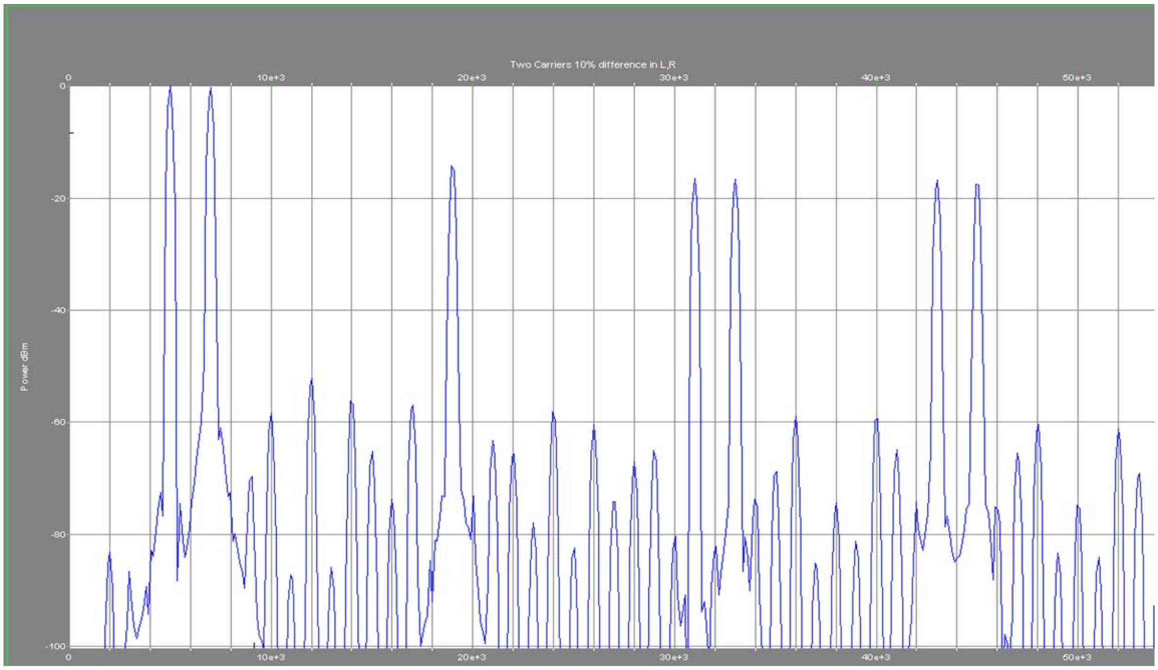
The following graphs show what happens when variations in audio modulation levels take place between two transmitters, similar to what happens in the interference zone as programming coming from two separate broadcasts on the same frequency conflict with each other in the receiver. These plots were created by feeding the two signals into a combiner and viewing the resultant output.



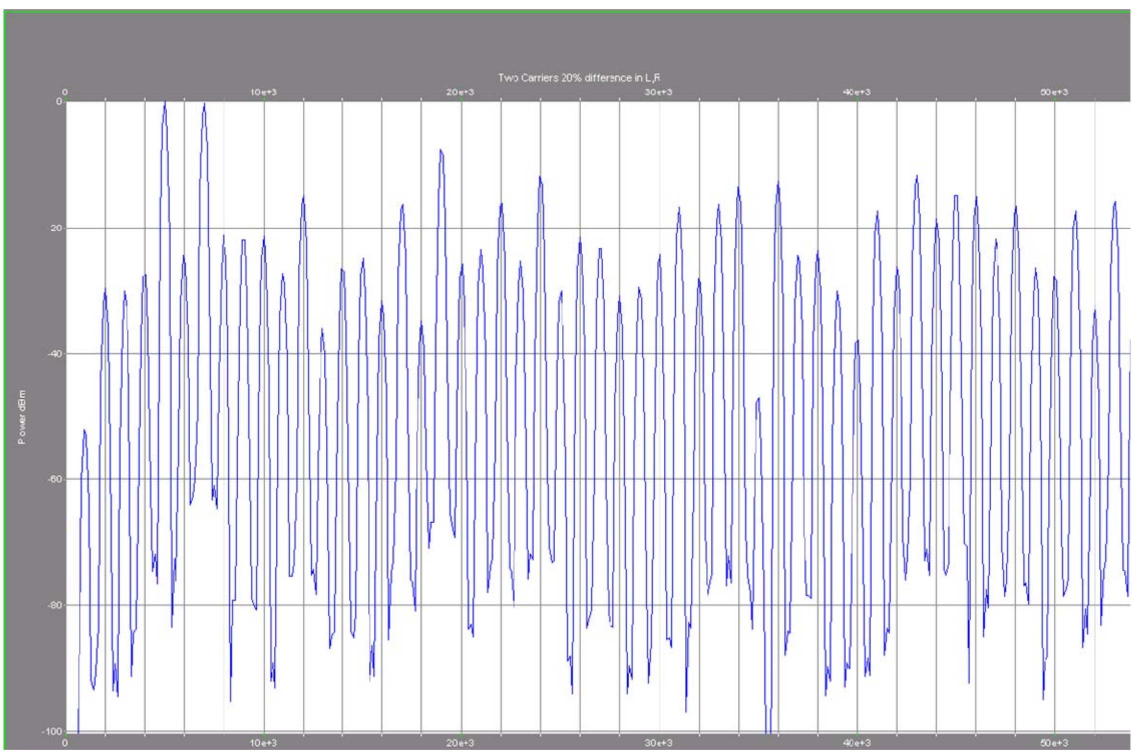
Two carriers in phase. *Here we are looking at the composite baseband of two carriers in alignment. Notice the relative absence of noise.*



Two carriers - ¼ dB deviation difference*. Small variations in modulation levels can affect reception quality. Above is a quarter of a decibel variation in modulation between the two broadcasts, resulting in an increased noise floor from -90 dB to -70 dB.*



Two carriers – ½ dB deviation difference. *If we increase the modulation variation, the noise floor is even more pronounced. Shown here is a modulation deviation of a half a decibel, resulting in a rising noise floor approaching -50 dB.*

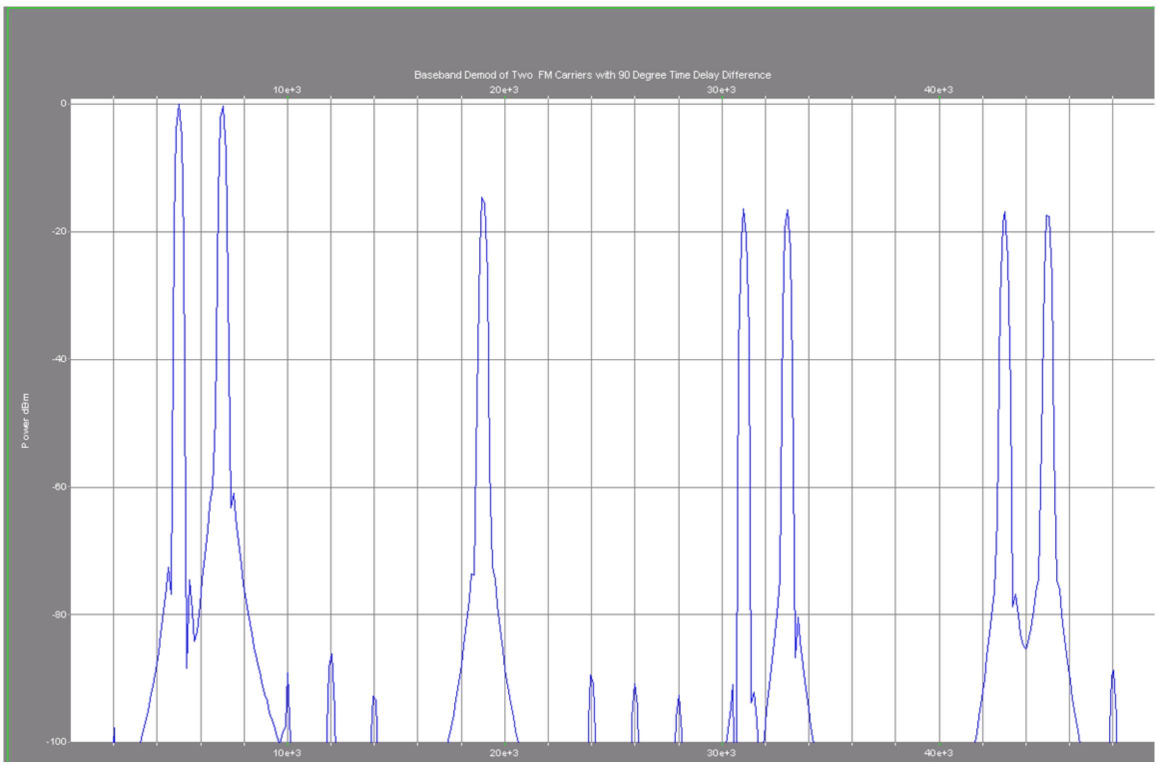


Two carriers – 1 dB deviation difference. *Finally, if we increase the modulation variation between the two signals to a full decibel, the signal becomes largely unlistenable.*

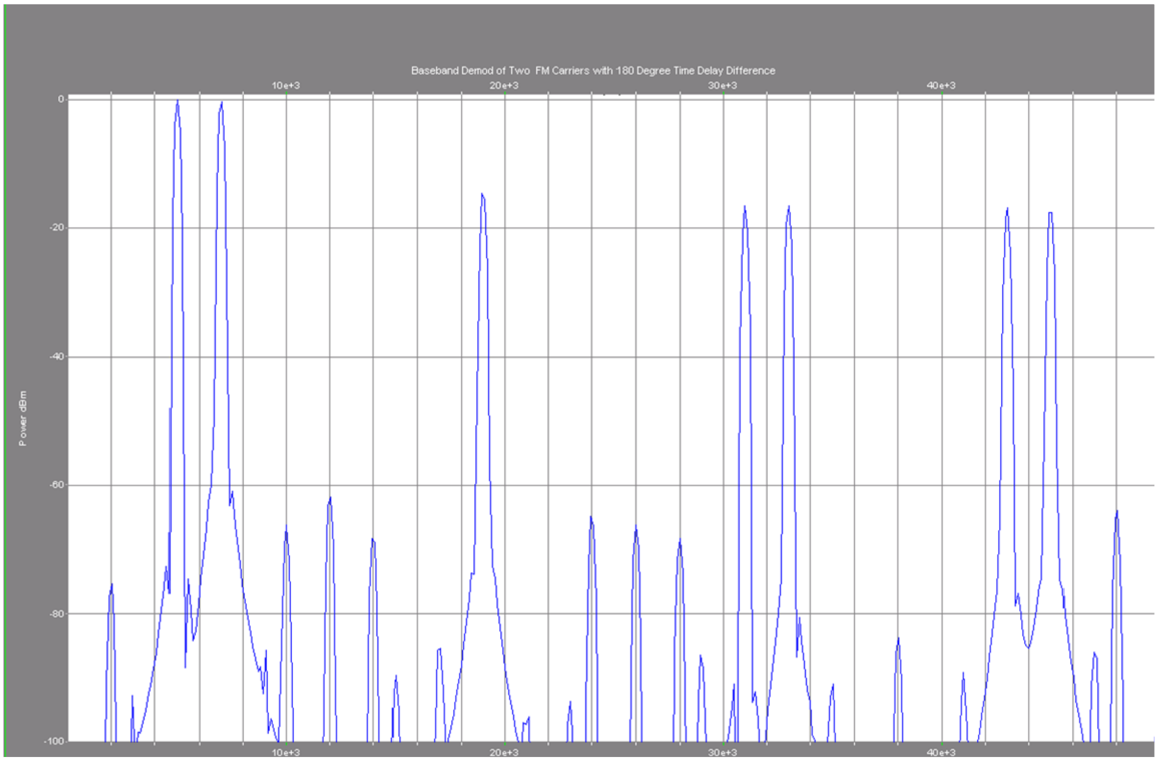
A little later in this paper, we'll address the critical role audio modulation alignment plays in the single-frequency network and booster application and why BE's FXi 60/250esp exciter has an input level adjustment with 0.1 dB resolution to accurately calibrate modulation levels of both broadcasts.

What happens when signals transmitted from separate sites arrive at the overlap zone at different intervals?

The following plots show what happens when signals from each transmitter arrive at the receiver at different time intervals, where one signal is delayed or out of phase with the other. These plots were created by feeding the two signals into a combiner and viewing the resultant output.



Two carriers 90 degree time delay. *Shown here is the resulting noise when signals from two sources are shifted 90 degrees out of phase. Note the noise in the -80 to -100 dB range as a result of one signal arriving at a 90 degree time delay.*



Two carriers 180 degree time delay. *Here is the resulting noise, between -60 and -80 dB, when the two signals are shifted 180 degrees out of phase.*

A little later in this paper, we'll address the critical role timing plays in the single-frequency network and booster application and why BE's FXi 60/250esp exciter includes internal audio phase alignment dynamically adjustable from zero to 1 millisecond.

Building blocks to the "synchronize everything" approach

In the late '80s and the early '90s, we focused primarily on syncing the carrier and pilot frequencies in an attempt to reduce the interference in the overlap zones. And, to some extent, we were successful. We found that by setting up a secondary booster exciter as a slave to the main exciter, we could reduce the interference noise to a level much lower than is possible without this synchronization.

Figure 1 is a typical block diagram of the master/slave synchronous configuration:

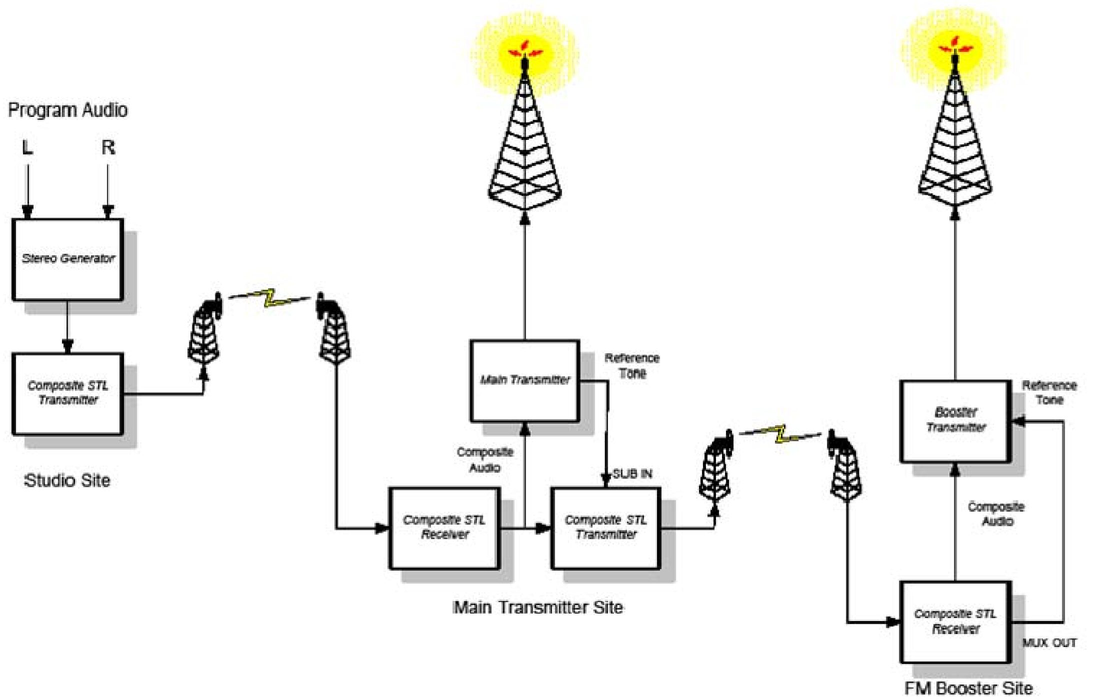


Figure 1: PREVIOUS SYSTEM BLOCK DIAGRAM

As GPS devices became available, we moved away from the master/slave configuration and started adding GPS receivers at each transmitter site as a more accurate common reference for synchronizing the carrier and pilot frequencies, as well as the phase of the pilot. We designed our first-generation FXi exciter to accept an external digital carrier reference, which enabled two FXi exciters to be synchronized to a common carrier frequency as referenced to 10MHz GPS outputs. Then, as time went on and we recognized the importance of synchronizing the phase of the pilot as well, we added a 1 pulse-per-second (PPS) reference from the GPS to our next-generation FXi 60/250esp exciter to create a reference to which each pilot frequency can be phase locked.

By doing so, we virtually eliminated the noise created when the receiver switches between the pilots of the two carriers.

Yet, we continually ran into program timing problems that caused another source of noise in the overlap zones. Audio arriving from each tower at different intervals resulted in audio phase issues; the more the two audio sources were out of phase with one another, the more distortion showed up in the interference zone.

As our previous plot graphs indicate, two signals shifted at 180 degrees out of phase can create distortion on the order of -70dB.

To correct for this, an extremely accurate delay unit, with a very low minimum delay, is required. The resolution of the delay unit is of critical importance in order to precisely correct for any phase variation between the two broadcasts.

This type of unit was difficult to find and quite expensive, plus it represented an additional level of complexity that could be avoided by including the delay in the exciter.

In Figure 2, the delay unit is eliminated from the configuration block diagram because this function is designed into the FXi 60/250esp digital FM exciter.

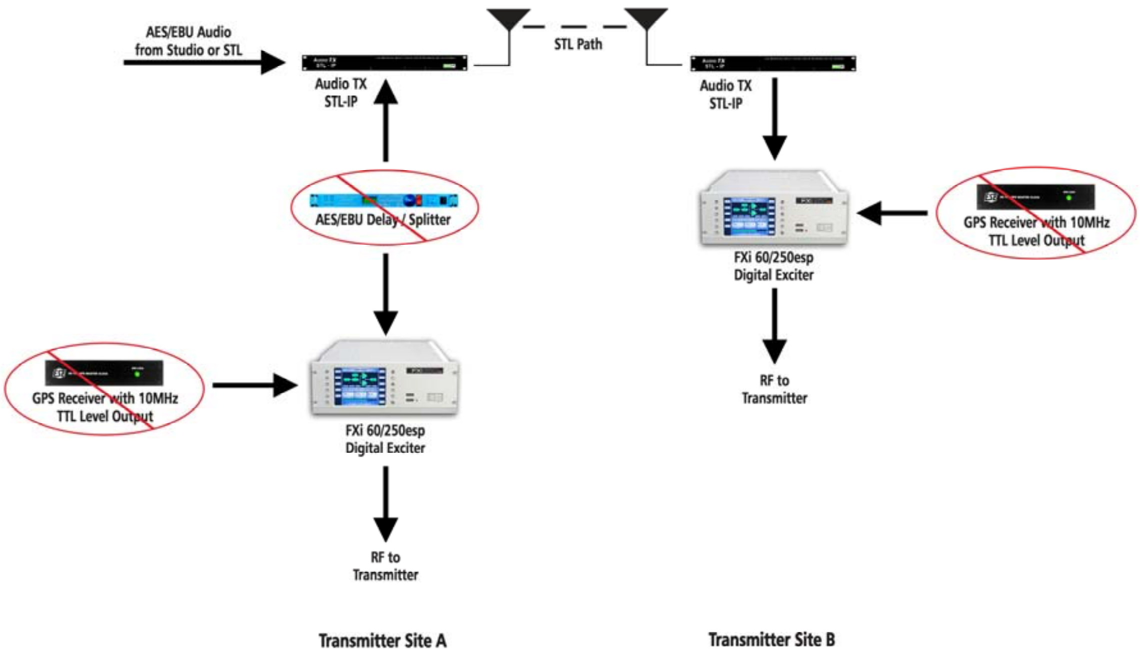


Figure 2: CURRENT SYSTEM BLOCK DIAGRAM

Setting delay in the unit can be done in 1 microsecond increments, starting at zero and going up to several seconds' delay in order to cover any parameters that might be needed in the field.

In addition to delay functions, the FXi 60/250esp has fine calibration of the AES/EBU inputs to align the modulation levels of two or more exciters within 0.1 dB deviation accuracy. As mentioned earlier, if modulation levels from two exciters are not exactly the same, the resulting affect is noise in the interference zone. Even level differences of 0.3 to 0.5 dB can result in poor audio reception.

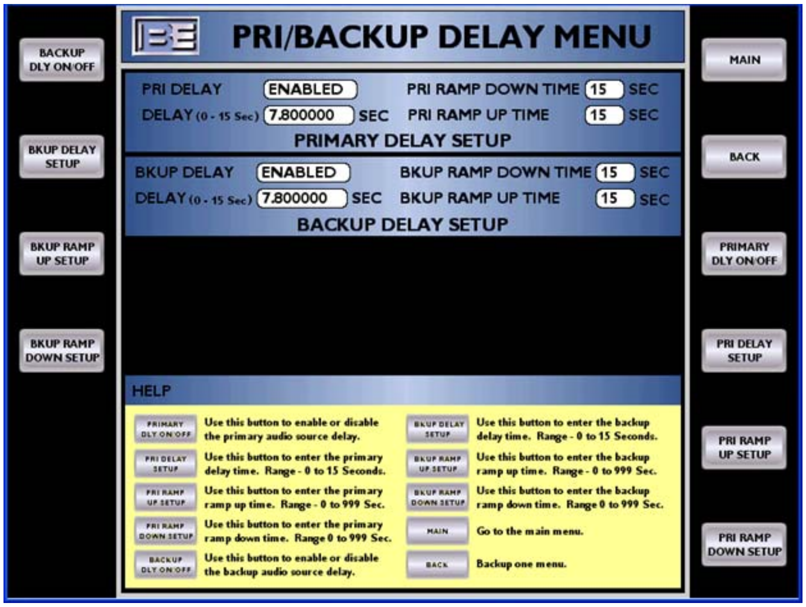


Figure 4: Shown, the delay setup menu in the FXi 60/250esp digital FM exciter, which replaces a standalone delay/splitter unit.

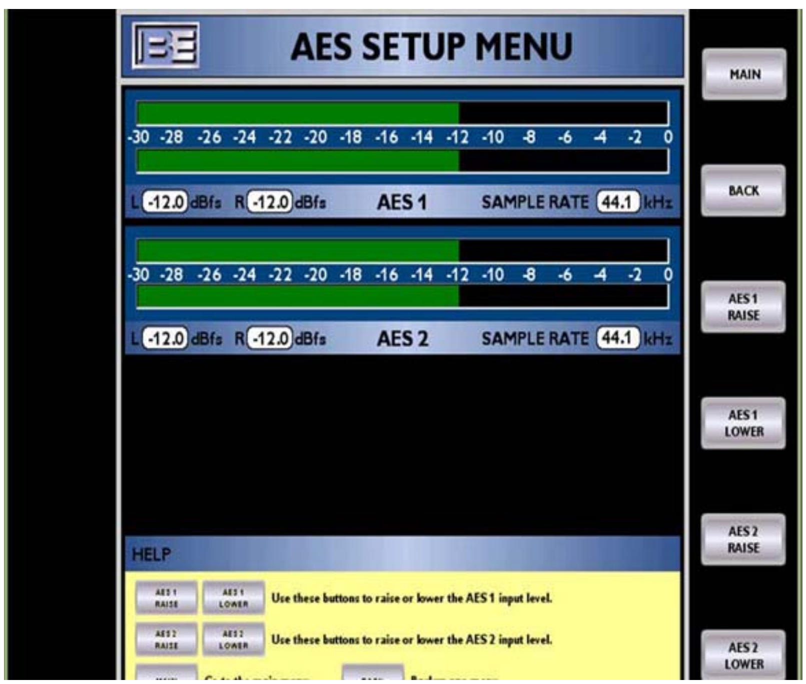


Figure 5: Shown, the AES input setup menu in the FXi 60/250esp digital FM exciter for setting modulation levels within 0.1 dB deviation accuracy.

Also absent from Figure 2 are the two rack-mount GPS receivers previously needed. This is because this function is now built into our new FM digital exciter. We included an internal GPS receiver into the FXi 60/250esp digital FM exciter, so an external GPS receiver is no longer needed to create the 10MHz output reference needed for locking the pilot and carrier frequencies to a shared frequency. The internal GPS, which is fed by an antenna connection on the rear panel of the FXi 60/250 exciter, also supplies the 1 PPS reference for aligning the pilots in phase. The 1 PPS triggers the pilot every second, effectively re-aligning the pilots in proper phase with each other.

BE's FXi 60/250esp is the first exciter to come standard with these synchronous features, saving broadcasters the cost of an external audio delay unit and GPS receiver at up to US$5,000 per site.

In addition to synchronous technology, the FXi 60/250esp includes an instrument grade spectrum analyzer, digital adaptive correction, dual RF outputs to drive two transmitters, Ethernet connectivity and IP control, more than 45 flexible I/O configurations, and more.

The instrument grade spectrum analyzer saves an additional US$6,000 to US$20,000.

Engineering considerations

Antenna patterns and site locations are outside the scope of this paper, except to say that we cannot stress enough the importance of an accurate and comprehensive engineering study before attempting the SFN or booster application.

A comprehensive engineering study by a qualified engineer will identify the most ideal transmitter location(s), taking advantage of natural terrain when possible to isolate the booster signal from the main signal, for example. One important issue that must be considered when starting this study is the size of the interference zone. The interference zone should be as small as possible while still accomplishing the coverage expansion required. It is simply not possible to effectively align the two signals over a large area. It may be possible to have the interference zone occur in a location that is not a critical part of your desired coverage area. In this case, the alignment may not be as critical over a larger area. This, and many other issues, will need to be addressed by a comprehensive engineering study by a qualified engineer.

Conclusion

BE's "synchronize everything" approach is by no means the final word on SFN and booster applications. But for the properly designed and implemented system, this approach can solve many of the interference issues and significantly improve the success and viability of a marginal site for extending programming into new population growth areas or for reaching areas underserved by a main FM signal.

References

Anthony, Edward, *Implementation of a Reliable Synchronous FM Booster*
Kelly, Charles, *Synchronous FM: A New Approach*
Salek, Stanley*, Opportunities and Challenges of FM Boosters*

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