ANALYSIS OF FM BOOSTER SYSTEM CONFIGURATIONS

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Abstract

There has been little documentation of the performance of FM booster transmitters using different forms of synchronization with the signal of the main FM station. This paper describes laboratory measurements conducted to study booster systems without synchronization, with carrier synchronization, and with combined carrier and modulation synchronization. The study also examines the beneficial (and possibly detrimental) effects of adding carrier delay to reduce interference in the areas where overlap of the main and booster signals is present.

INTRODUCTION

FM booster stations are a special class of FM translators that receive the signals of a full-service FM station and retransmit those signals to areas that would otherwise not receive satisfactory service from the main signal, due to intervening terrain or other factors. FM boosters operate on the same carrier frequency as their primary full-service station. Among other requirements defined in Federal Communications Commission Rules, a booster's coverage may not extend beyond the predicted class contour of its primary station [1].

In August 1987, the Federal Communications Commission released a Report and Order that amended its rules with respect to FM and TV boosters [2]. For FM, the amended rules allow alternative signal delivery methods and increased power. Until that time, FM boosters were limited to using direct off-air reception and retransmission methods, with a maximum output power of 10 watts. The rule changes allow, with few exceptions, the use of virtually any signal delivery method, as well as power levels of up to 20 percent of the maximum permissible effective radiated power of the full-service station they rebroadcast.

Since the rule changes were implemented, many FM stations have installed booster systems to improve coverage. Unfortunately, as has been discovered in practice, boosters can also diminish usable coverage in locations where their signals substantially overlap coverage areas of the main facility. Increased perceptions of audio distortion and signal disruption are commonly reported, because the two unequally delayed signals can create significant amplitude modulation artifacts (self-generated multipath distortion) in the overlap area.

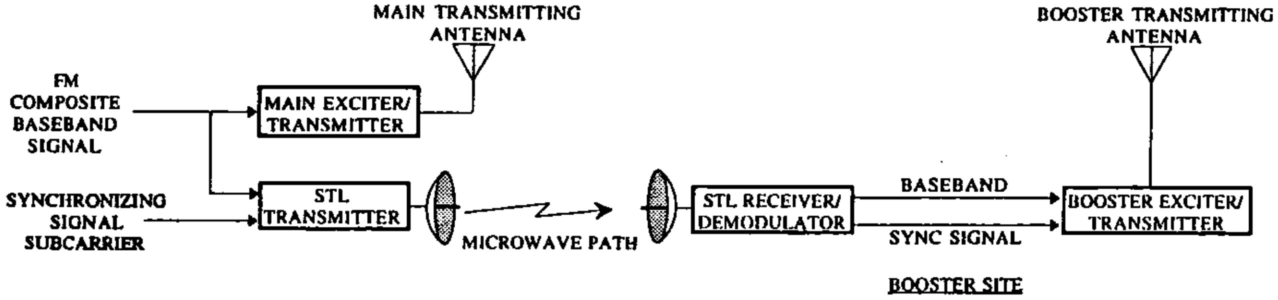
SYNCHRONIZING MAIN AND BOOSTER SIGNALS

Synchronization Methods

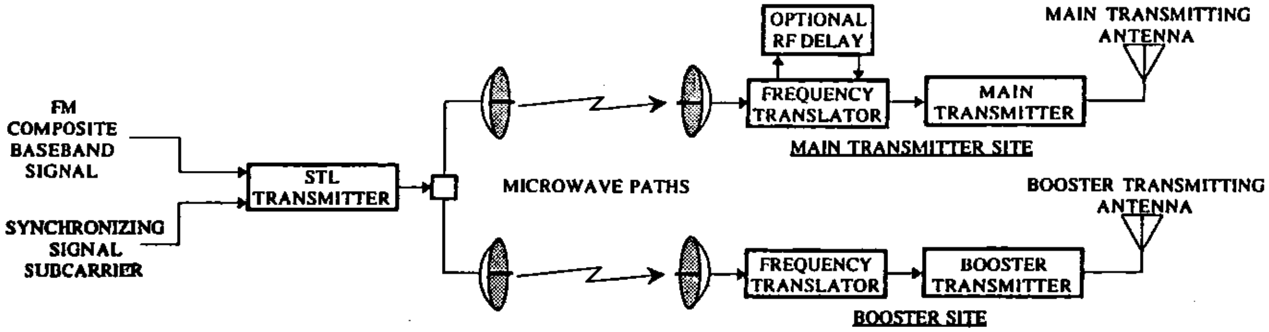
To combat these effects, some attention has been paid to synchronization of the main and booster signals, as well as to careful selection of the booster transmitter location [3]. Synchronization generally involves frequency locking the carriers of the main and booster transmitters, while adjusting the booster composite baseband modulation level to match the main as closely as possible.

Carrier synchronization. An example of carrier synchronization is shown in Figure 1a. In addition to the composite stereo signal, a microwave studio-to-transmitter link (STL) transmitter is fed with a synchronizing subcarrier. One method that has been used to generate the synchronizing signal involves dividing the FM RF carrier signal of the main transmitter by 1000 to produce a subcarrier near 100 kHz, which is extracted at the booster location and used to frequency lock the exciter carrier. Another method uses a high-stability timebase to derive the 19 kHz stereo pilot (as well as the other stereo subcarrier components), which is used at the booster exciter in a similar frequency locking scheme. The STL transmitter feeding the booster link can be located at the studio or the transmitter site of the main station, or at any other site where a stable RF sample of the main signal can be found.

Carrier and modulation synchronization. Both methods described above employ a technique that demodulates the composite baseband signal before it is used to remodulate the booster exciter. Field experience has shown that mismatch of the RF modulation components generated by the main and booster



(a) Carrier synchronization



(b) Carrier and modulation synchronization

Figure 1. Booster synchronization schemes.

transmitters (due to poor level matching, differences in equipment performance, composite overshoot, seasonal drifting, or other factors) may worsen areas of interference created by the implementation of the booster transmitter.

To minimize this effect, a system that uses a single modulator can be employed, as shown in Figure 1b. The modulator in the STL transmitter is used as the only FM modulator in the signal path, feeding both the main transmitter and booster sites. Instead of demodulating the microwave signal at the transmitter sites, it is translated, within the RF domain, to the licensed FM broadcast carrier frequency. The synchronizing signal is used to frequency lock each translator, producing transmitted RF signals that are frequency and modulation coherent.

Carrier delay. Carefully synchronizing the RF signals of the main and booster transmitters does not, however, entirely solve the problems of interference caused when the two signals are received simultaneously. Depending on terrain conditions, there could be a number of locations that receive strong signals from the two sites, but due to unequal signal propagation times and poor summation, a region of interference is still created. Adding RF delay to the main or booster transmitter signal path has been found useful to time equalize the two signals at a particular location, significantly reducing received interference.

LABORATORY STUDY DEVELOPMENT

Study Goals

Even though the described synchronizing methods have been known to improve booster system performance, engineers have relied on heuristics to select a booster site and to calculate interference zones. To provide better guidance, a laboratory study was designed with the following goals: (1) to determine the overall ability of each synchronizing method to reduce self-generated multipath (excessive amplitude components) and receiver distortion, (2) to determine the range of signal levels required to create interference zones, and (3) to determine the useful area of signal improvement when additional delay is added to time synchronize the two signals at a particular location.

Model development

The design of the booster study model assumed a hypothetical flat terrain condition. This selection yielded a simpler analysis than the assumption of arbitrary terrain

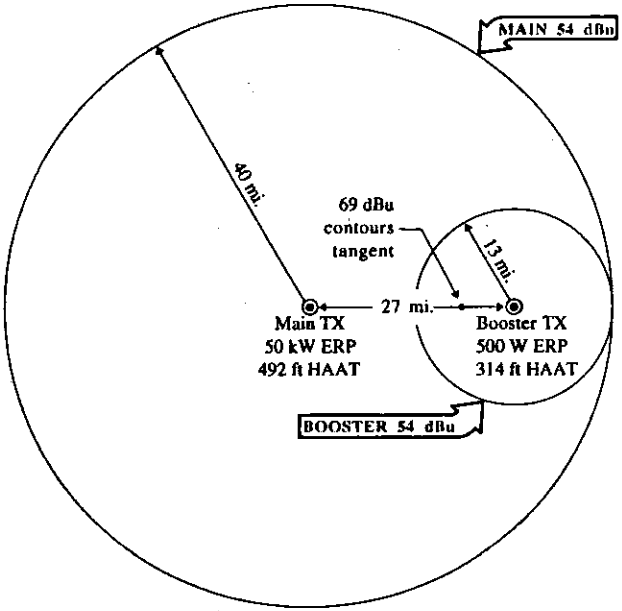


Figure 2. Booster study model.

conditions, and also produced the largest interference zones.

The defined model is shown in Figure 2. The main station was modeled as an omnidirectional Class B facility, having an effective radiated power (ERP) of 50 kilowatts and a height above average terrain (HAAT) of 492 feet (150 meters). Under the assumed flat terrain conditions, the theoretical radius of the 54 dBu class contour of this station (using FCC F(50,50) methods) extended approximately 40 miles (64 kilometers). An omnidirectional booster site was located at two-thirds of this distance, having a power of 500 watts ERP at 314 feet (95.7 meters) HAAT. The radius of the booster's 54 dBu contour extended about 13 miles (21 kilometers), so the two contours were tangent at one point and the class contour of the main station was not extended.

From this model, it was calculated that, between the two sites, the 69 dBu contours of the facilities were tangent to each other, defining the signal level at a point of presumed maximum interference. Considering that most automobiles use a receiving antenna of approximately one-quarter wavelength at FM broadcast frequencies, the following formula was derived from antenna theory to convert the electric field to a voltage:

$$V = E - 36.8 + 10\log(R) + 20\log(\lambda) + G - L, \qquad (1)$$

where V is the voltage at the antenna terminals in dBuV, E is the electric field in dBu, R is the load resistance across the terminals in ohms, λ is the wavelength in meters, G is the gain of the antenna above an isotropic radiator, and L is the loss of the antenna lead. For this case, a 50 ohm load was assumed, along with a wavelength of 3 meters (100 MHz), an antenna gain of 5.15 dB [4], and no line loss, yielding 64 dBuV or 1.6 millivolts at the antenna terminals for an ambient filed strength of 69 dBu.

Equipment interconnection. The equipment interconnection is shown in Figure 3. A low-distortion audio generator fed the left channel of an FM stereo generator with a 1 kHz tone, while the right channel input was terminated. The stereo generator produced a 100 percent left channel-only composite waveform, containing frequency components at 1, 37, and 39 kHz, in addition to the 19 kHz pilot signal. A high-stability clock source was used to lock the stereo generator timebase to within ±2 parts per million; the 19 kHz stereo pilot frequency served as the system synchronizing signal [5].

The composite baseband output of the stereo generator was split and fed through two attenuators, one of which was used to vary the signal level in the lower transmission path by ±1.5 dB for level mismatch analysis. The two composite signals fed identical microwave STL transmitters, both of which generated FM-modulated RF carriers (±37.5 kHz peak deviation) at 953 MHz.

After being attenuated to appropriate levels, the microwave signals were connected to an option jumper arrangement, which modified the equipment configuration as required to select the synchronization mode being tested. Option 1 independently connected each STL RF signal to the remainder of the test setup, for analysis of unsynchronized and carrier synchronized cases. Option 2 employed only one STL signal, which drove an RF power divider, for the carrier and modulation synchronized case.

The two STL RF signals were connected to the inputs of frequency translators, which converted the STL RF signals to appropriate FM broadcast signals at 100.7 MHz. In the process, the STL carrier signal deviations were converted to ±75 kHz using an intermediate frequency doubling method. The translator also contained the circuitry needed to lock to the pilot synchronization signal (or to its own internal reference if the stereo pilot was switched off) [6].

Digital time delay units were connected to each translator unit through a 2.5 MHz intermediate frequency loop-through point [7]. Translator B delay was fixed at 150 microseconds, which represented an arbitrary (but reasonable) time period for the signal to travel to the booster transmission site and back out to the 69 dBu interference zone. (At the speed of light, radio signals travel one mile in 5.37 microseconds.) Translator A delay was adjustable to time periods less than or greater than the Translator B time delay; its setting was used as a test variable.

The translator RF outputs, both of which were fixed at +23 dBm (after bypassing the final power amplifiers),

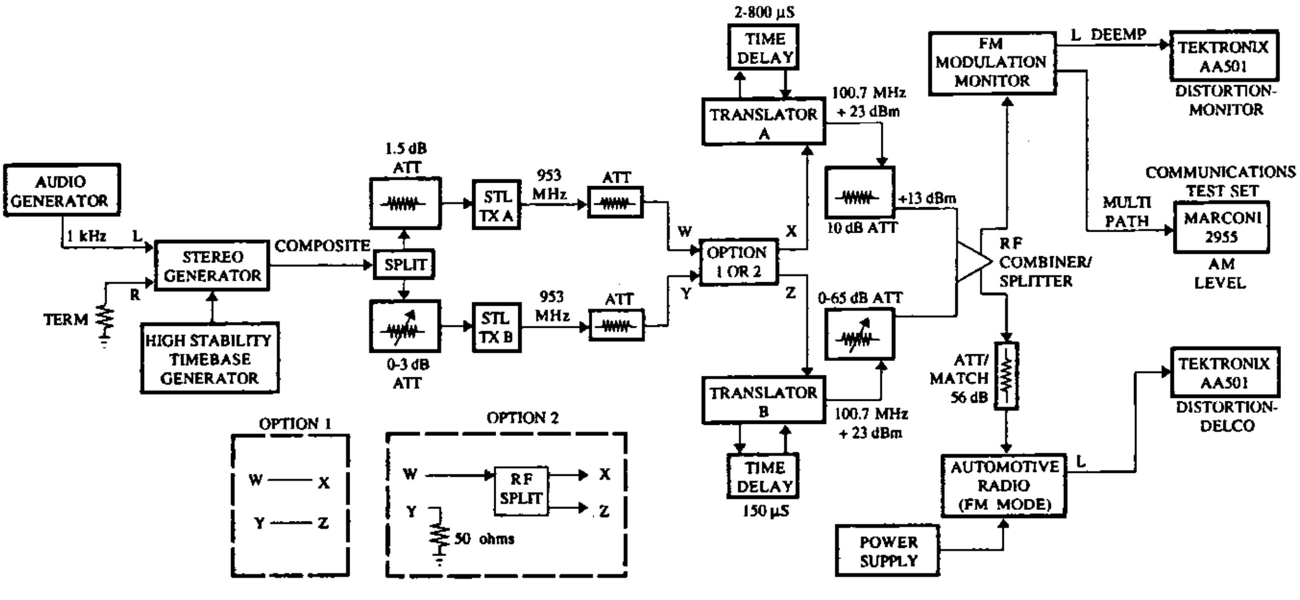


Figure 3. Equipment interconnection.

were each fed to attenuator networks. Translator A, which represented the main transmitter, was attenuated to +13 dBm by a fixed 10 dB pad. Translator B, which represented the booster, fed a 0–65 dB variable attenuator. This allowed the ratio of the two sources to be adjusted over a wide range.

The outputs of the two attenuators were summed and then split to feed a typical FM modulation/stereo monitor and a popular domestic automotive radio receiver, both of which were tuned to the 100.7 MHz carrier frequency. The 56 dB matching pad used with the automotive radio attenuated the combined main and booster signals to about 1.6 millivolts, which corresponded to the antenna terminal voltage calculated earlier.

Measured parameters. Two parameters, audio distortion and amplitude modulation content, were measured for varying system composite level matching, time delay matching, and main/booster signal level ratios. Separate harmonic distortion test sets were connected to the left channel deemphasized audio output ports of the monitor and receiver. A 30 kHz measurement bandwidth was selected. Even though audio artifacts not related to harmonic signals were likely to be present during data collection, they were included in the measurements to produce overall distortion figures.

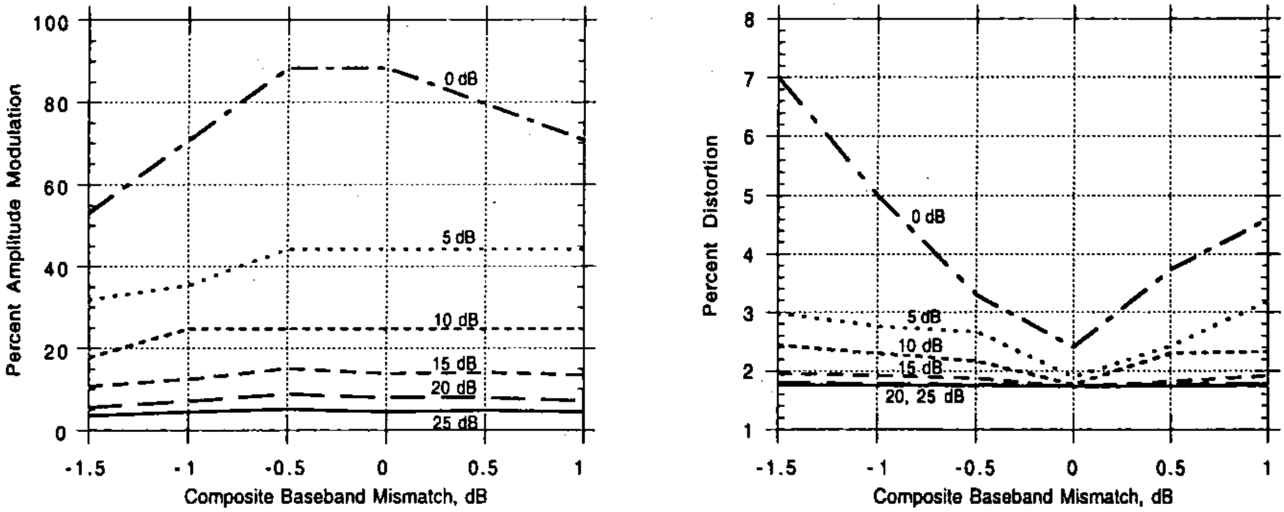
AM content, the other monitored parameter, was defined as the detected amplitude component created by the interaction of the main and booster signals. It was measured using an envelope detector circuit contained in the modulation monitor, which is normally metered to provide a relative multipath indication for receiving antenna adjustment [8,9]. The selection of this detector was based on a review of international studies of automatic deemphasis (multipath distortion masking) circuits employed in automotive receivers [10]. A storage oscilloscope, contained in a separate communications test set, was used to average the monitored amplitude component over several seconds per measurement.

DATA MEASUREMENT AND RESULTS

Data Collection

Study data were collected in three phases. During the first two phases, both STL transmitters were operated independently (using Option 1 shown in Figure 3). The third phase employed only one STL transmitter (using Option 2). For all three phases, AM level and distortion readings were taken as a function of main and booster signal level ratios, and as a function of the other parameters noted below. Because there was excellent correlation between distortion readings taken from the monitor and the automotive receiver, only the receiver distortion data are shown in the accompanying graphs.

Phase I: unsynchronized operation. The first phase measured the system in an unsynchronized mode, with the translators using their own separate internal reference oscillators instead of being locked to the pilot reference (the carrier frequencies were manually matched to within a few Hertz of each other). In this mode of operation, the time delay units were unused. Data were taken as a function of composite level mismatch, over a −1.5 to +1 dB range in 0.5 dB increments. The line graphs of Figures 4a and 4b illustrate the results.



(a) AM content versus composite level mismatch

(b) Distortion versus composite level mismatch

Figure 4. Data taken for unsynchronized operation over 0–25 dB carrier signal ratios.

Figure 4a shows the measured amplitude modulation component for six selected RF signal level ratios versus composite baseband level mismatch. While the baseline AM generation was found to be about 2.5 percent for either of the main or booster systems operating independently, no significant worsening was noted until the RF signals were set to within 20 dB of each other. As the signal level ratio further decreased, the AM component rapidly increased, climbing above 50 percent when the signal levels fell within 5 dB of each other. Careful adjustment of composite level matching produced no significant improvement.

Figure 4b shows measured audio distortion for the same test conditions. No significant worsening of the receiver's inherent audio distortion (about 1.5 percent) was measured until the signal ratio fell below 10 dB, with the ultimate measured distortion reaching seven percent. Also, lower distortion was measured when the composite levels were closely matched.

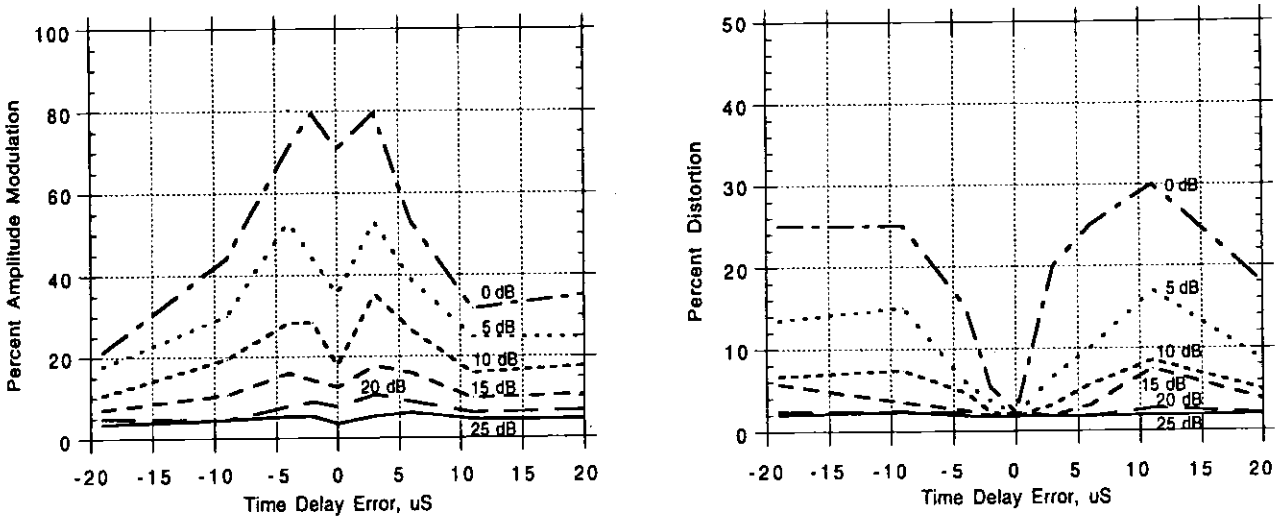
Another test was run with the carrier frequencies of the main and booster transmitters separated by 500 Hz. No worsening of the measured distortion was noted, but the AM level increased more rapidly, exceeding 50 percent at signal level ratios less than 15 dB.

Phase II: carrier synchronization. The second phase of the study measured the system in a carrier-synchronized mode, with both translators frequency locked to the 19 kHz stereo pilot reference. The variable delay unit connected to Translator A was set for nine individual delay times between 131 and 171 microseconds for each RF signal level ratio measured, which was equivalent to a relative time shift between the main and booster signals of –19 to +21 microseconds. Data were taken as a function of the relative time alignment of the main and booster transmitters, as well as the setting of the composite level matching attenuator at the input of STL transmitter A. The graphs of Figures 5a and 5b illustrate the measurement results for equal composite level matching. Figure 5a shows the AM component steadily increasing as the RF signal level ratio decreased, reaching almost 80 percent at 0 dB. Highest levels were found when the signals were nearly time aligned, with somewhat lower levels measured at at perfect time correlation, as well as when the signals were removed in time by more than 10 microseconds.

Measured distortion under the same test conditions is shown in Figure 5b. Almost no distortion increase was measured when the main and booster RF signals were perfectly time aligned, but a rapid degradation was noted at low signal level ratios when the time alignment was shifted by more than five microseconds.

The importance of composite level matching when using this synchronization method was also discovered. A 1 dB mismatch worsened and broadened the area of the measured AM component and distortion to a point about the same as was found for unsynchronized operation. For a mismatch greater than 1 dB, no substantial benefit was gained from time aligning the main and booster RF signals; the AM component uniformly exceeded 50 percent for a signal level ratio of less than 10 dB.

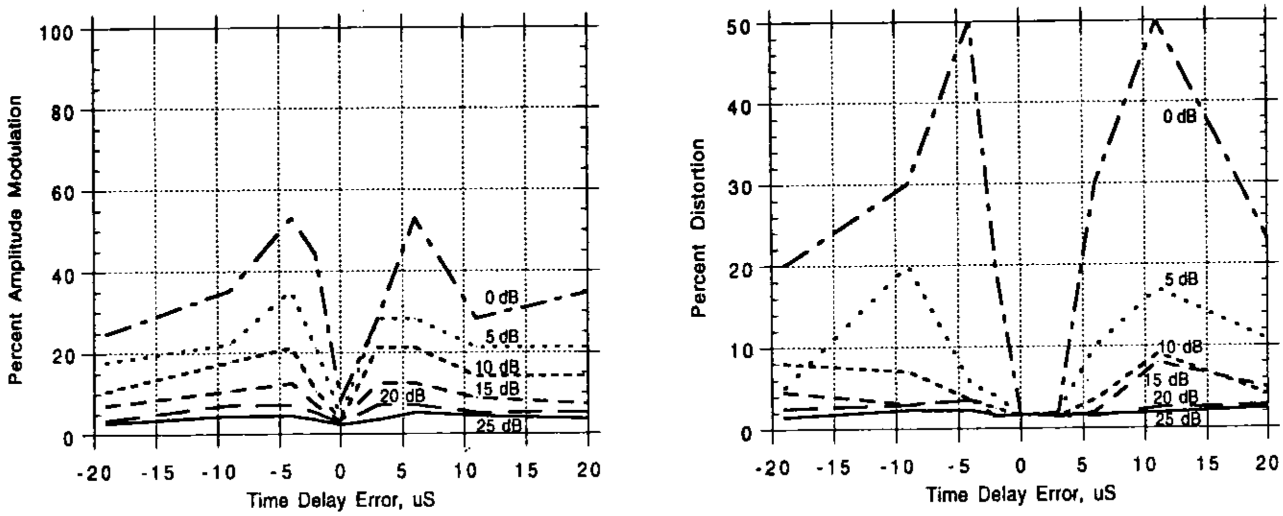
Phase III: carrier and modulation synchronization. The final measurement phase evaluated system performance using a single STL transmitter feeding both translators. Once again, the 19 kHz pilot signal was used to frequency lock the translators. Data were taken as a function of the relative



(a) AM content versus time delay matching

(b) Distortion versus time delay matching

Figure 5. Data taken for carrier-synchronized operation.



(a) AM content versus time delay matching

(b) Distortion versus time delay matching

Figure 6. Data taken for carrier and modulation synchronization operation.

time alignment of the main and booster transmitters, over the same range as the carrier synchronization-only measurements. The measurement results are shown in the graphs of Figures 6a and 6b.

Figure 6a shows the ability of this synchronization mode to reduce the generation of the incidental AM signal. The AM component found at zero time alignment error is virtually non-existent, with generally smaller peaks than were measured in the other test phases.

The range of low measured distortion also was improved using this synchronization scheme. Figure 6b shows that for an RF signal level ratio greater than 5 dB, more than a 10 microsecond region (corresponding to about 2 miles at 5.37 microseconds per mile) was reduced below 10 percent distortion, with higher distortion readings found only at a nearly equal RF signal ratio for relative time delays of five to ten microseconds.

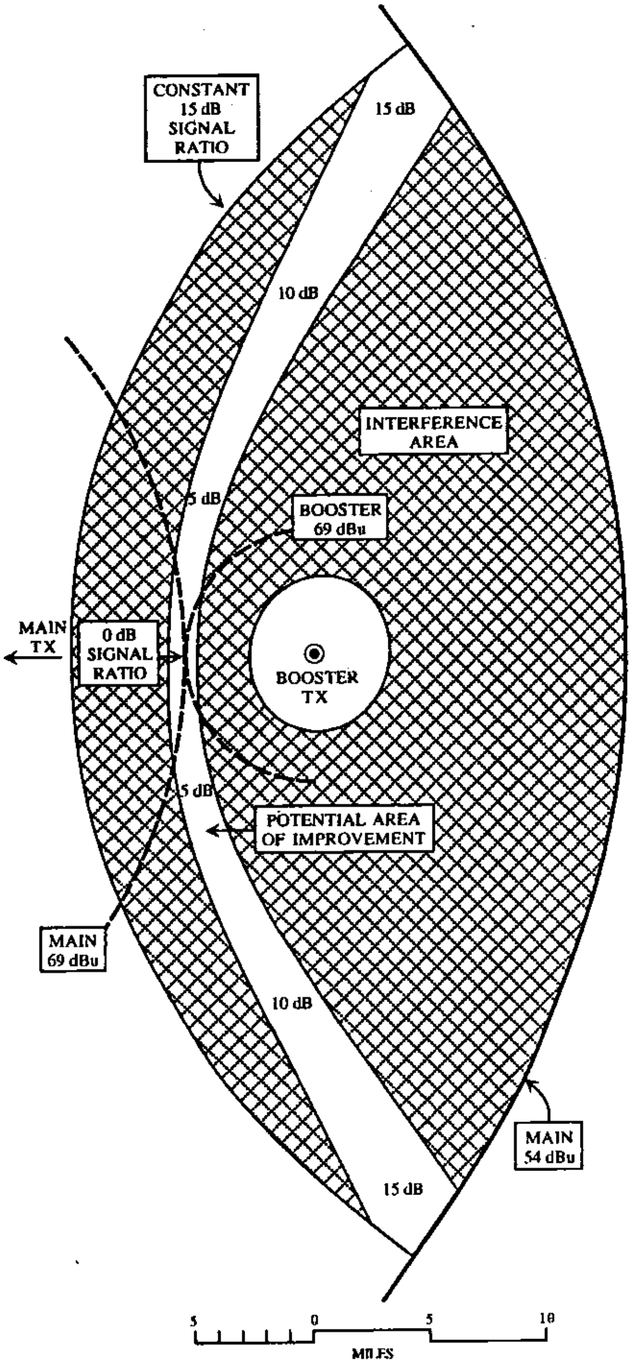


Figure 7. Study model showing interference zone and potential area of improvement.

ANALYSIS AND CONCLUSIONS

Discussion

The measurements taken of the unsynchronized mode configuration were somewhat surprising, in that the measured distortion levels remained low in all cases, regardless of the composite baseband level matching. However, the enormous AM levels found for RF signal level ratios less than 10 dB are almost certainly a dominant factor in creating the multipath-like interference zones that would be quite evident in a moving vehicle.

The carrier synchronization method reduced AM generation and improved distortion performance over unsynchronized operation, as long as the main and booster composite input signal levels and transmission chains were well matched. In practice, however, the AM component may be difficult to minimize in a predictable fashion. As with unsynchronized operation, signal level ratios greater than about 15 dB produced negligible degradation to the received signal, regardless of the relative time delay.

Carrier and modulation synchronization provided the best balance, by greatly reducing the incidental AM component and distortion when the signals were closely time aligned. From interpretation of the improved areas shown in the graphs of Figures 6a and 6b, it was determined that selective time alignment could improve a hyperbolic-shaped area. Once again, if the signal level ratio exceeded 15 dB, incident AM and distortion levels remained low when other parameters were varied.

Figure 7 illustrates an enlarged part of the study model, showing the interference zone and a potential area of improvement when time alignment methods are employed. The interference zone is defined by the shaded region between the boundaries of the main and booster contours that differ by 15 dB, out to the 54 dBu contour of the main station.

The unshaded band shows an example of the area that may be improved by time synchronizing the arrival of the main and booster RF signals. It is narrowest, about 1 mile across, when the signal ratio is 0 dB, increasing to above 2 miles for a 5 dB signal ratio and 3 miles for a 10 dB ratio. By adjusting the time delay, the improved area can be moved to any location within the interference region. In this worst-case example, the potential improvement area is relatively small compared to the total interference area. In real situations that include hills, mountains, or other high terrain between the sites, most of the interference zone likely would be located in unpopulated areas.

Booster Implementation Guidelines

Interpretation of the data indicates that booster transmitters constructed using any of the synchronization methods, including no synchronization at all, can operate without significant disruption in areas where the RF signal level ratio remains above 15 dB. In coverage areas that are well shielded by terrain obstacles, a simple unsynchronized booster may work quite well.

However, when signal overlap with ratios less than 15 dB is predicted in important coverage areas, synchronization methods can provide some improvement within the overlap region. Using both modulation and carrier synchronization provides the potential added benefit of improving system performance over time, because the demodulation and remodulation steps, prone to system drift and aging, are not needed. Additionally, the ability to "steer" reception improvement into critical areas of the interference zone, using precision time delay matching, may prove useful in many implementation situations.

Based on the study results, the following FM booster system design steps are indicated:

1. Identify the approximate boundaries of the coverage problem area from listener reports and informal drive-through reception surveys.
2. Conduct field strength surveys or use a terrain-sensitive computer analysis method to verify the location(s) and severity of the coverage loss.
3. Identify potential booster transmitter sites and antenna coverage patterns.
4. Using terrain-sensitive computer analysis techniques, determine the optimum booster site and antenna system to maximize interference-free coverage of the affected area. Use a 15 dB signal level ratio as the basis to identify interference zones.
5. If all interference zones are shown to be in unpopulated areas, synchronization of the main and booster RF signals may not be necessary. Otherwise, identify candidate location(s) that may be improved using RF time synchronization. (Typical examples of important locations include major access roads or areas of significant population.) Calculate the time delay required (at 5.37 microseconds per mile) to time align the signals in the chosen area.

It is understood that real world conditions, including multipath distortion and other factors unrelated to the booster system, can degrade the ultimate improvements suggested by this laboratory study. Future field study experience should provide additional guidance in confirming the validity of the data presented.

ACKNOWLEDGEMENT

Funding for the measurement portion of this study was provided by TFT Inc. The author would like to thank Joseph Wu, Darryl Parker, and Terry Peterson of TFT for providing laboratory space, equipment, and guidance in developing the tests.

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