Design Parameters for Analog FM Signal Repeaters Based on Listener Testing

Ellyn Sheffield,
Melinda Hines
Towson University
Towson, MD

John Kean
NPR Labs
Washington, DC

Abstract - *This paper describes listener-based testing of optimal design criteria for networks of synchronized analog FM signal repeaters (boosters). Such criteria are necessary to avoid harmful multipath distortion effects caused by signal overlap. Listener-based tests using laboratory simulations of overlapping analog FM signals produced comprehensive data on the allowable signal ratios and modulation timing offsets. The paper also covers further development of a computer mapping system to geographically analyze multiple repeaters in a geographically-contiguous mesh. A paper prepared for last year's NAB Broadcast Engineering Conference presented a different type of repeater that delayed signals by at least 41 microseconds, which imposes some limitations on the size of the booster area. This paper deals with multipath effects from 0 to 20 microseconds, pertinent to a multi-node mesh of repeaters which, potentially, have no limit on area (save for the service contour of the primary FM transmitter).*

BACKGROUND

The implementation of analog FM signal repeaters is receiving increased attention from broadcasters to fill in coverage in weak-signal areas. However, accurate design parameters for optimal systems, based on signal time differentials and RF ratios, have been lacking. This has resulted in some signal repeater systems with unpredictable "mush zones" that annoy listeners. An original study was required to determine the planning factors that are pertinent to practical synchronous repeater networks (for simplicity, referred to below as boosters). The study was funded by Geo-Broadcast Solutions LLC, which is developing a "MaxxCasting" repeater network for analog FM stations.

FM multipath is affected principally by two parameters: the time differential between two signals and the RF ratio of the signals. It is well-known that distortion of FM audio increases as a function of the time separating two otherwise-identical signals, while distortion decreases as the RF ratio grows. However, data in this area to guide a booster system designer is limited, and do not provide all the parameters relevant to current analog FM service. The chart in Figure 1 shows how audio distortion changes as a function of the time difference between two analog FM stereo signals (actually, time shifted versions of the same analog FM stereo signal, also referred to below as "two path") [1]. Using objective measurements and calculations, this seminal study illustrated the important effect of multipath. However, audio distortion as one parameter does not determine how multipath distortion affects listeners' decisions to listen to or turn off a radio receiver.

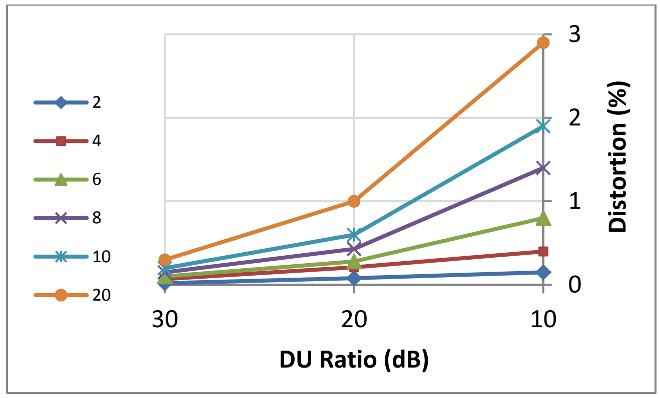

Figure 1 - Audio distortion with 1kHz FM versus DU ratio for various time differences (from 2 to 20 microseconds)

In its analog FM planning factors document, the ITU provides some guidance on multipath interference vis-a-vis listener measurements [2]. Figure 2 is derived from data showing how listener scores are affected by time difference and RF ratio. This data provides valuable information for fixed reception conditions, but not mobile reception, which is an important part of today's FM broadcasting service. It is likely the temporal effects of independent fading from the primary and booster signals in mobile reception situations affect listeners' satisfaction differently than with fixed reception.

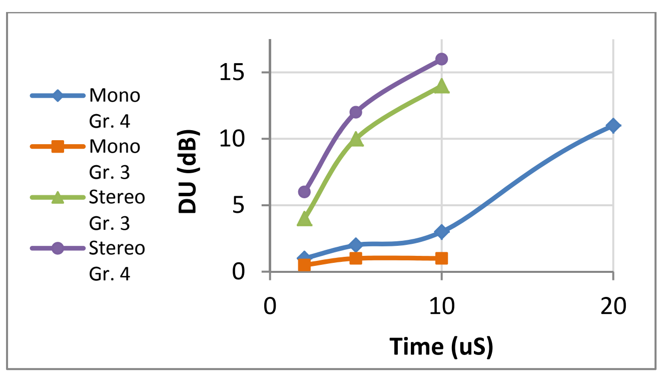

Figure 2 - Mean Opinion Scores for "two-path" analog FM as a function of DU ratio versus time difference

To determine the performance of a synchronized repeater system under a variety of reception conditions, a simulation of fixed and mobile reception was prepared and the resulting audio recordings were evaluated by a large panel of consumers in controlled listening tests. The tests considered monophonic and stereophonic reception and included a variety of program material types. Table 1 shows the combinations of tests for fixed and mobile reception. Reception to a mobile receiver from a primary transmitter was expected to involve large distances, whereas distances from boosters, because of their relatively low power, were expected to be small – probably two kilometers or less. To model the fading more appropriately, a Rayleigh fading profile was used for the primary transmitter signal, while a milder Rician fading profile, with a K factor of 5, was used for the booster path.

Table 1 - Matrix of tests for FM signals showing fixed-multipath and mobile-fading scenario

Fixed Reception	**Booster**	**Booster**
	Stereo	*Stereo*
	Stereo	*Mono*
	Mono	*Mono*
Mobile Reception 1	**Primary (Rayleigh Fading)**	**Booster (Rician Fading)**
	Stereo	*Stereo*
	Stereo	*Mono*
	Mono	*Mono*
Mobile Reception 2	**Booster (Rician Fading)**	**Booster (Rician Fading)**
	Stereo	*Stereo*
	Mono	*Mono*

PREPARATION OF AUDIO TEST MATERIAL

NPR Labs' RF Test Bed was configured as shown in Figure 3 to generate the audio samples for listener testing. Audio stored on a computer was streamed through an E-MU 0404 audio interface to an Omnia 6EX+HD audio processor and stereo generator, connected to the composite analog input of a Harris Flexstar exciter. The low-level (-10 dBm) RF output was split to provide the primary transmitter and booster FM signals. The audio material passed through the RF Test Bed is discussed in the listener test section, below.

Two RF channel simulators were configured to represent the signal received from the primary station and the booster using an urban 50 km/hr model [3]. The simulator can be set for fixed or Rayleigh fading with delays from zero to 20µS (microseconds) with 1 ns resolution. The outputs from the two channel simulators were connected through separate RF attenuators and combined before connection to the FM receiver.

One booster was presented to the receiver at a level of -50 dBm to the receiver, representing a medium-strength signal of approximately 70 dBµ. This may be higher than would be experienced in the booster's expected multipath areas, but as the stereo blending in car radios is governed by signal level, this level would keep the receiver in stereo more of the time – a conservative measure to make multipath effects more audible. An Additive White Gaussian Noise generator shown was used only for test verification and was turned off during the audio recordings.

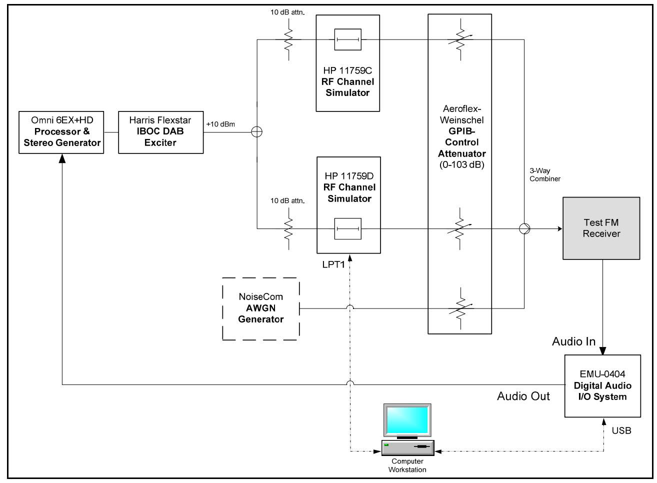

Figure 3 - RF Test Best for audio sample preparation

Fixed reception was accomplished using a Sony STR-DE197 home stereo receiver. Mobile reception was accomplished using a JVC KS-FX490 after-market car radio. Line-level audio output from each receiver was connected to the input of the E-MU 0404 interface, which provided 16-bit analog-to-digital conversion, which was stored on the lab PC as WAV files for listener testing.

CRITERIA BASED ON LISTENER TESTING

The purpose of the listener test was to determine how consumers rated audio samples with various levels of multipath impairment and specifically to understand the conditions under which consumers would keep on or turn off the radio. Results from the listening test determined the threshold signal ratios for degraded FM stereo reception under two scenarios: (a) compatibility of reception with signals from the primary station and booster ("Mobile Reception 1" in Table 1), and (b) compatibility of reception with signals arriving from two boosters ("Fixed Reception " and "Mobile Reception 2" in Table 1).

For each condition, 3 audio samples were included: (a) speech without background sounds, (b) commercial with moderate background sounds (e.g., light music); (c) commercial with heavy background sounds (e.g., aggressive music, sound effects). Speech samples were taken from NPR news programming, and included both male and female voices. Commercials were taken from Public Service Announcements, chosen to simulate the wide array of commercials found on commercial and public radio programming.

PARTICIPANTS

Forty participants (20 males and 20 females) between the ages of 18 and 65 were recruited for this consumer test from Towson University staff and administration via a posting on the University's daily announcement forum. Participants had no connection to either the radio or audio industries, and could be considered a "typical listener" in terms of demographics and occupation.

TEST ENVIRONMENT

Testing was held at Towson University in two small, 7'x8' internal rooms, set up to simulate a home listening environment and an automobile cabin. The side and rear walls of both rooms were draped with 7 lb. sound absorbing blankets to minimize reverberation effects. For the fixed reception listening tests, a Dell Optiplex 760 computer was used to run custom testing software to administer the test. A Creative Sound Blaster Audigy LS sound card converted the wave files to analog audio, which were sent to the stereo pair of Mackie HR 824 self-amplified professional monitor speakers that provided the audio stimulus for the test.

TEST METHODOLOGY

Participants were required to listen to 533 samples to complete all conditions in the test. In order to minimize listener fatigue, participants were tested individually in two sessions. In the first session participants listened to half of the recordings from the variety of conditions shown in Table 2 to Table 8. In the second session, they listened to the other half of the recordings. Within each session, audio selections were played in random order. Listening sessions were counterbalanced, such that half of the participants listened to the first session first, while the other half listened to the second session first.

During the first session, participants were greeted and asked to sign a consent form informing them about the purpose of the study and their rights as participants. After signing, they were brought back to the testing room. Participants were told that they would need to listen to a number of audio samples, focusing on the quality of the audio. Participants were encouraged to set the volume on the first trial of each of the sessions, after which the volume remained constant. Participants were presented with audio clips, one at a time, and were asked 3 questions:

(a) on a scale of 1-5 (1=bad, 2=poor, 3=fair, 4=good, 5=excellent), rate the audio quality of the sample;

(b) on a yes/no basis, were you satisfied with the audio quality; and

(c) would you keep listening to the radio or turn it off, given the audio quality of the sample.

Participants were told that they could take short breaks at any time, and that they would be given an opportunity for a longer break halfway through the study. When participants returned for the second session, they were informed the session would run identically as the prior session. When they completed the session, they received $100 and signed a receipt saying that they had received the money.

RESULTS - PRIMARY STATION TO BOOSTER

As can be seen from Table 2, when the primary station and booster was transmitting in stereo, an overwhelming majority of listeners claimed that they would keep the radio on when time differentials were short (0 and 3 us). However, at 9 uS, this dropped precipitously, particularly at lower RF ratios, and at 20 uS the majority of listeners were claiming they would turn the radio off below an RF ratio of 5dB.

Table 2 – Mobile stereo primary station to stereo booster station listener keep-on scores

RF Ratio (dB)	Time (us)			
	0	3	9	20
0	98%	93%	64%	36%
5	97%	97%	70%	28%
18	97%	96%	85%	69%
24	97%	97%	93%	87%
30	97%	97%	97%	93%

-All cells with gray shading interpolated from adjacent values

When the primary station was transmitting in stereo but the booster was in mono, listeners again claimed that they would continue to listen at shorter time differentials. However, listenership dropped off with longer time intervals (i.e., greater than 7 uS), particularly in lower RF ratios (below 8dB) (see Table 3)

Table 3 – Mobile stereo primary station to mono booster station listener keep-on scores

RF Ratio (dB)	Time (us)			
	3	7	12	20
0	96%	68%	52%	37%
4	97%	82%	68%	50%
8	95%	86%	86%	67%
16	98%	90%	96%	86%

When the primary station and booster were both transmitted in mono, the overwhelming majority of listeners claimed they would continue to listen to the radio (see Table 4).

Table 4 – Mobile mono primary station to mono booster station listener keep-on scores

RF Ratio (dB)	Time (us)			
	0	3	9	20
0	97%	95%	94%	87%
5	99%	94%	95%	88%
11	98%	95%	96%	96%
18	98%	96%	98%	97%

RESULTS – BOOSTER TO BOOSTER

As can be seen from Table 5 and Table 6, when boosters were in stereo for fixed listening, the overwhelming majority of listeners claimed they would keep listening at time intervals of 7 uS and below. At higher than 12 uS, listenership dropped considerably, particularly in lower RF ratios (below 4 dB). However, when boosters were in stereo for mobile listening, listeners were not as willing to continue to listen, particularly at greater time differentials and lower RF ratios.

Table 5 – Fixed stereo booster station to stereo booster station listener keep-on scores

RF Ratio (dB)	Time (us)				
	0	3	7	12	20
0	98%	95%	84%	63%	24%
4	99%	97%	90%	87%	68%
8	99%	98%	97%	91%	86%
16	99%	98%	97%	97%	96%
24	99%	97%	97%	98%	98%

Table 6 - Mobile stereo booster station to stereo booster station listener keep-on scores

RF Ratio (dB)	Time (us)				
	0	3	7	12	20
0	93%	84%	58%	32%	23%
4	94%	88%	70%	43%	32%
8	94%	88%	88%	58%	91%
16	94%	89%	89%	91%	97%
24	94%	92%	93%	93%	90%

As Table 7 and Table 8 show, when boosters were in mono for fixed conditions, an overwhelming majority of listeners claimed they would keep the radio on, but when boosters were in mono for mobile conditions, listeners again claimed they would turn the radio off at higher time differentials.

Table 7 – Fixed mono booster station to mono booster station listener keep-on scores

RF Ratio (dB)	Time (us)				
	0	3	7	12	20
0	99%	100%	98%	94%	96%
4	99%	98%	98%	97%	97%
8	99%	98%	98%	98%	94%
16	99%	99%	99%	100%	97%

Table 8 - Mobile mono booster station to mono booster station listener keep-on scores

RF Ratio (dB)	Time (us)				
	0	3	7	12	20
0	98%	95%	84%	63%	24%
4	99%	97%	90%	87%	68%
8	99%	98%	97%	91%	86%
16	99%	98%	97%	97%	96%

IBOC DIGITAL RECEPTION PERFORMANCE

In-Band On-Channel ("HD Radio™") digital radio employs OFDM (Orthogonal Frequency Division Multiplexing) signaling, which is popular for its ability to withstand multipath effects over a wide range of delay spread. This resistance to multipath would make it better-suited to repeater systems than analog FM. At the present time, however, the IBOC system lacks data packet tagging that would permit packet synchronization at multiple transmitters. This feature is expected in a future generation of Exporter software and hardware, thus, we did not consider IBOC coverage compatibility in this report.

DEVELOPMENT OF GIS TOOLS

To visualize the results of the listener testing, we employed the *Communications Systems Planning Tool* (CSPT), developed by the Institute for Telecommunications, part of the U.S. Dept. of Commerce NTIA, at Boulder, Colorado. CSPT is a large software extension to the ESRI ArcMap™ GIS platform, and provides extensive pathloss, computation and mapping capability. For the studies shown below, we used the TIREM (Terrain Integrated Rough Earth Model) pathloss model at a receive height of 2 meters above ground.

We anticipated that operation of lower-power, lower-height boosters in a network, or "mesh", could manage coverage and multipath interference better than the single higher-power and height boosters that have been traditionally built. However, with multiple boosters the prediction tool must consider the arrival of signals from each booster at every point in the study area. Figure 4 shows a simple example which considers signals from four boosters, as well as the primary transmitter. In the prediction tool, each signal has its own time-offset and terrain-related pathloss. We added new programming code to CSPT to process multiple signal arrivals to all geographic points on the map area.

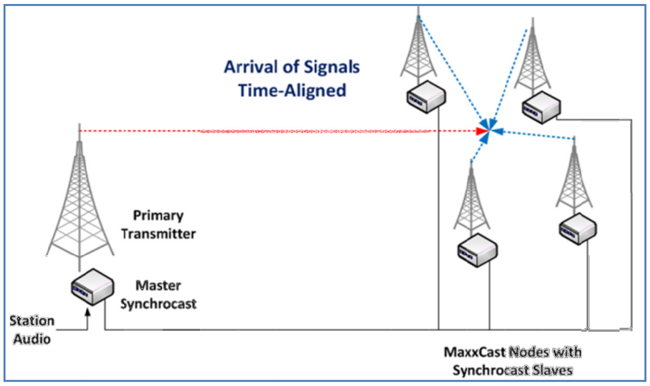

Figure 4 - Illustration of a multi-node network

Figure 4 shows a synchronization network between the primary transmitter and the booster nodes. This can be accomplished with the Harris Broadcast Synchrocast™ system, which employs GPS time-referenced units that are interconnected by a data network. AES digital audio (left and right stereo) and synchronization signals are transported from the master unit at the primary transmitter or studio, to a slave unit at each node. Adjustment of modulation timing synchronization is possible with a resolution of 1uS. FM carrier frequency of the primary transmitter and the nodes are controlled by GPS frequency reference.

Evaluation of Booster Performance

To illustrate the design technique, a case study was prepared for FM station KPRI, Encinitas, California, a Class B station on 102.1 MHz, serving the San Diego area. The map of Figure 5 shows the terrain-limited coverage at 2 m AGL, along with the FCC F(50,50) 54 dBµ service contour. Shadings of brown, green and yellow-green indicate the predicted minimum-quality service for mobile, indoor and portable reception, respectively. Relative population density is shown with blue squares that increase in size and darkness.

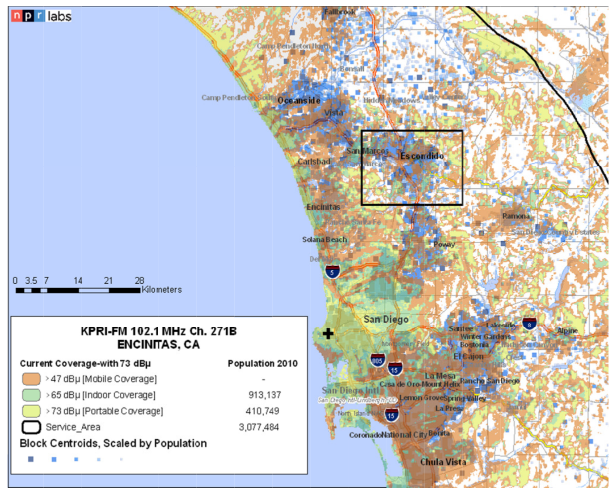

Figure 5 - Map showing terrain-limited coverage of KPRI; inset box shows study area for Escondido

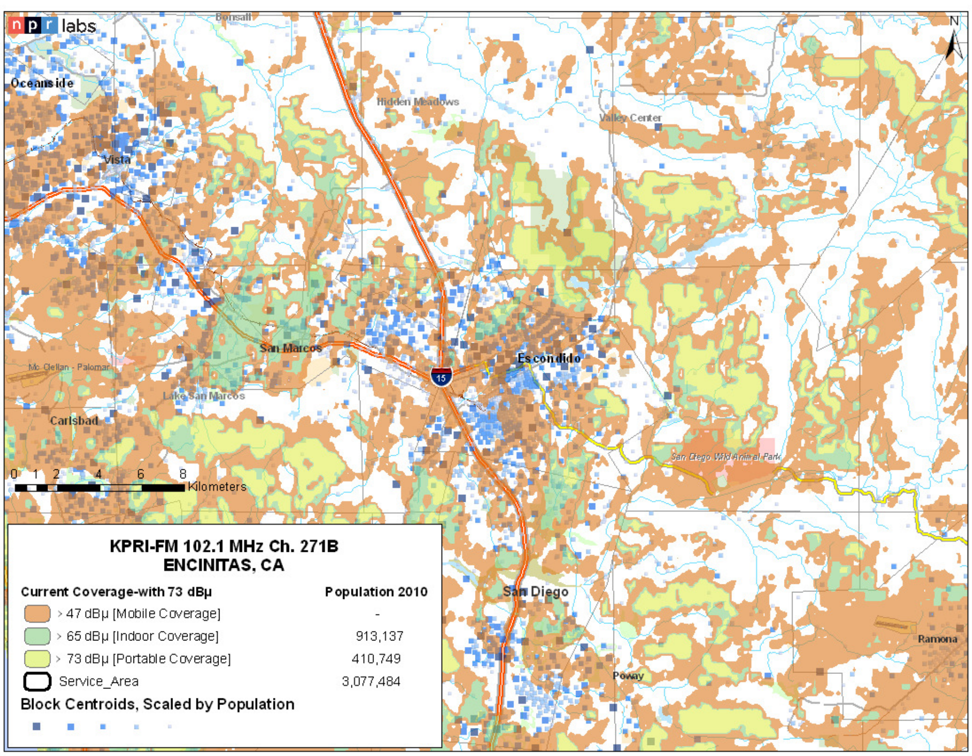

Figure 6 - Smaller scale map showing coverage in Escondido

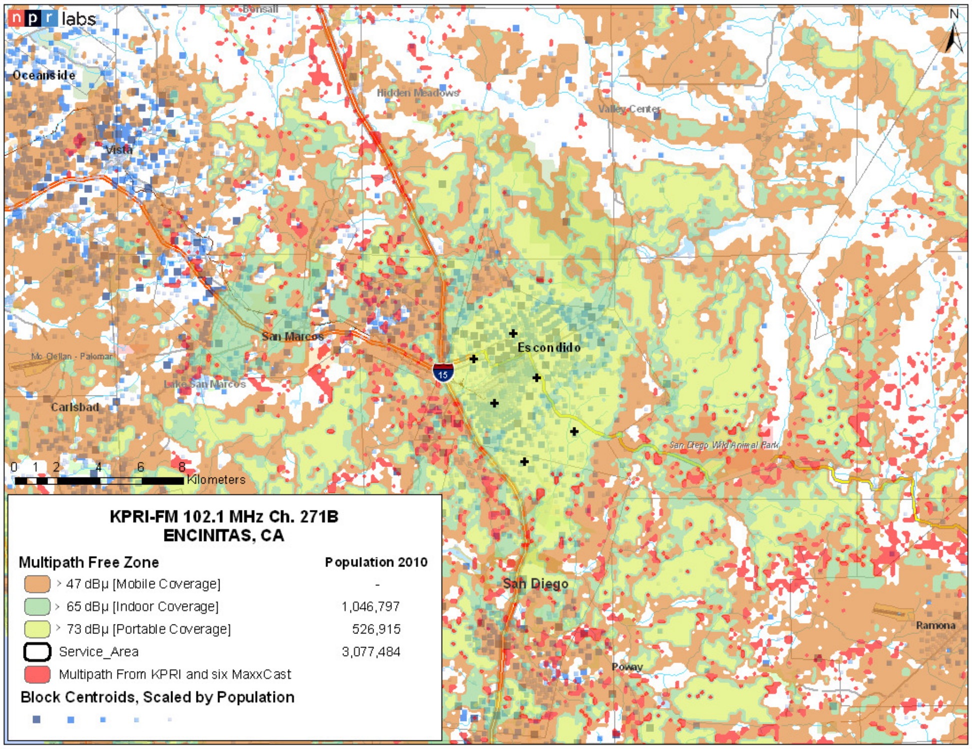

Figure 7 - Coverage for KPRI with 6-node mesh, showing predicted multipath in red

From the enlargement in Figure 6 it is apparent that the town of Escondido is an area of relatively high population density that is an area of high population density having no indoor and portable service and only fragmented mobile service. This area was chosen for a case study of the mesh network.

Figure 7 shows the predicted signal levels in the same area after the addition of six monophonic synchronous transmitter nodes, marked with "+" signs. Each operates with 1.5 kW ERP (directional, oriented northeast) at 32 m above ground. Multipath interference, as determined from the listener test parameters, is shown in red.

Table 9 - Potential coverage change with 6-node mesh network in Escondido

	Indoor Service	Portable Service
Current Operation	913,197	410,749
With Mesh	1,046,797	526,915
Change	133,600 (15%)	116,166 (28%)

The population change predicted for the case study is summarized in Table 9. All population counts are net of interference, that is, any population receiving interference as a result of the mesh was subtracted from the total. Even so, the case study shows a potential 15% gain in the station's indoor population and 28% in portable population. These changes are almost entirely first-service opportunities in Escondido.

This study determined the planning parameters for synchronous analog FM repeater systems, and applied the parameters to a station cast study with a multiple-node mesh. The data indicate that with the proper planning, this type of system can provide substantial opportunity for service population that is not reached by a single broadcast transmitter.

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