Areas of Cochannel Interference and Multipath Created by 8-VSB Modulated Distributed Transmitters in Flat Terrain

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***Abstract*— Presentation is made of the methodology for defining the area in which the signal from an auxiliary on-channel transmitter appears to the receiver as multipath, and the area where the signal from an auxiliary on-channel transmitter appears as new cochannel interference. The size and location of these areas depends on how well the contour of the receiver equalizer window can be made to overlap the cochannel interference contour. The optimum overlap requires a specific adjustment to the height, power and delay of the auxiliary transmitter.**

***Index Terms*—Cochannel interference, multipath, propagation loss, equalizer window, on-channel auxiliary transmitters, interference-free service area, added delay.**

I. INTRODUCTION

Previously published documents[1,23] stopped short of providing a methodology for explicit definitions of the cochannel interference and of the multipath areas created by distributed on-channel transmitters and of the dependence of the multipath areas on the adjustable time delay inserted in the retransmitted signal. For example, in flat terrain the area of newly created cochannel interference may far exceed the area over which the latest generation receiver can interpret the interference as multipath.

The objective of this paper is to demonstrate how the received signal levels and equalizer window contours can be made to overlap so as to create a service area in which cochannel interference can be processed as coherent multipath by the receiver. The remainder area is subject to cochannel interference and that interference must be kept well below the known threshold of visibility.

The method of analysis is presented by way of an example where a low-power auxiliary transmitter augments a high-power main transmitter. The auxiliary is located 64 kilometers away near the radio horizon of the main transmitter. The purpose of the auxiliary transmitter is to provide a strong signal to an important community far from the city of license. At the same time, the cochannel interference contour of the auxiliary transmitter should remain well inside that of the main transmitter so as to avoid interfering with another cochannel in an adjacent market.

The specific propagation algorithms applied to the analysis of the subject example, F(50,90) for coverage and F(50,10) for interference, may not apply in all cases and may not apply at all if the transmitters are in close proximity to each other.

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The analysis applies to the flat earth terrain model that is shown in Figure A1 of Appendix A. The methodology described here can be expanded with the aid of computer modeling without loss of generality to more complex terrain and other propagation algorithms.

Section II defines the *maximum area*, the area in which the signals from the main and auxiliary transmitters overlap and this area is thus subject to the analysis of potential elimination of cochannel interference. Section III is devoted to the development of the signal ratio contours of the main and auxiliary transmitters. The signal ratio contours delineate the area subject to cochannel interference, part or all of which could be converted from cochannel interference into coherent multipath.

Section IV covers the development of the contours within which the receiver equalizer could process the auxiliary signal as a coherent multipath of the main, or vice versa. The ratio of new service area to new interference area is developed in Section V.

II. STUDY AREA

Figure 1 shows the *study area* (shaded) bounded by the radio horizons of the main and auxiliary transmitters. The center of radiation of the main transmitter is at 305 meters and that of the auxiliary is at 46 meters above ground. Reliable reception is not possible beyond the radio horizon in the UHF band and only a few miles beyond the radio horizon in the VHF band.

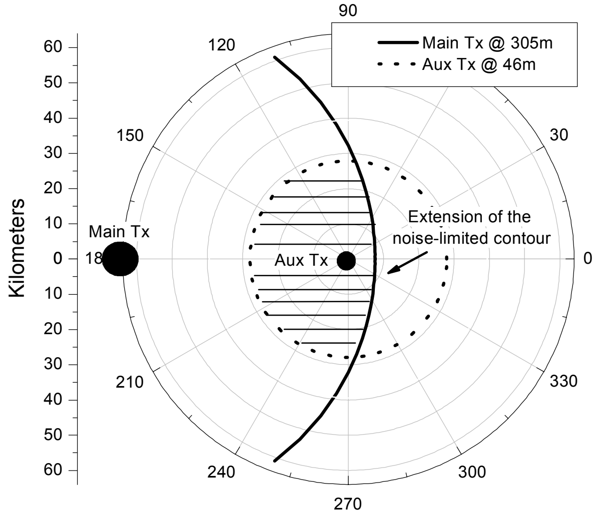

Figure 1: Intersection of the Radio Horizons
Main-Aux Separation=64 kilometers

The area bounded by the two radio horizons can be adjusted by changing the height of the center of radiation of either transmitter above ground. Decreasing the height limits the overlapped area, the size of which is key to a successful implementation of interference elimination through transmitter synchronization.

Note that in a flat terrain, positioning an omnidirectional auxiliary transmitter too near to the radio horizon may result in an effective extension of the noise-limited contour, potentially causing cochannel interference to another station.

Within the *study area*, the signal from each transmitter must be above the threshold of visibility of the receiver, which for 8-VSB modulation and an ideal receiver is assumed to be 41 dBu in the UHF band. For practical receivers a more realistic level would be 51 dBu[4].

Table 1 shows the Effective Radiated Power (ERP) required to provide 41 dBu to a receiver with an outdoor antenna 2m or 10m above ground at the two radio horizons of Figure 1.

Center of Radiation (meters above ground)	**Radio Horizon (kilometers)**	**ERP for 41 dBu for Rx 10/2 meters above ground per F(50,90) (kW)**
305	72	19.4 / 940
91	39	0.9 / 44
46	28	0.2 / 10

Table 1: ERP to deliver 41 dBu at the Radio Horizon, 10/2 meters above ground

As shown in Table 1, there is a vast difference, 18.6 dB in the UHF band, between the transmitter power required to deliver 41 dBu to a receiver 2m above ground compared with the power required for a receiver 10m above ground. Regulatory agencies estimate the field strength at 10m above ground for assessing interference to other stations.

If the auxiliary transmitter were located beyond the radio horizon of the main transmitter and the height of its transmitting antenna were sufficiently low, it would be essentially terrain shielded from the main transmitter. In the latter case, synchronization of the transmitters would not be necessary and the auxiliary transmitter could operate as a non-synchronized on-channel repeater.

III. AUXILIARY/MAIN SIGNAL RATIO CONTOURS

At the threshold of visibility of cochannel DTTV into DTTV interference the Desired to Undesired signal ratio[4] is +15 dB when the SNR ≥ 28 dB, and it rises to 21 dB when the SNR = 16 dB, the threshold SNR for decoding 8-VSB modulation.

Coincidentally, the receiver's equalizer requires that the multipath level exceed -20 dB relative to the desired signal. Therefore, the same 21dB contour would apply to the threshold of interference visibility and to the threshold of equalizer action. We must then establish the D/U = 21dB interference contours for the main and auxiliary transmitters, taking into account the gain of the receiving antenna for each path.

To facilitate the plotting of the relative signal levels at the receiver, the path loss and the Effective Radiated Power (ERP) in the direction of the receiver must first be determined.

Appendix B provides the formulas for the Egli and COST-Hata propagation models and a sample calculation of path loss between a transmitter 183m above ground and a receiver 2m above ground at a frequency of 600 MHz. The calculated path loss, up to the radio horizon, is plotted in Figure B1 as is the path loss based on the FCC F(50,50) curves. The COST-Hata algorithm was developed for mobile communications and will be used to compute the path loss between the Auxiliary transmitter with maximum height of 215m and a receiver at a height of 2m above ground. The Egli algorithm applies to center of radiation higher than 215m and will be used to compute the path loss between the Main transmitter and a receiver at a height of 2m above ground.

The ERP in the direction of the receiver will be based on two elevation patterns. The "Hi-gain Antenna" model for the Main transmitter and the "Lo-gain Antenna" model for the Auxiliary transmitter.

The two relative field elevation patterns are shown in Figure 2 and are given by:

$$E(\theta)=1 \;\; for \;\; 0\le\theta\le\theta_0$$

$$E(\theta)=\frac{Cos^n(90-\theta_0)}{Cos^n(90-\theta)} \quad for \;\; \theta\ge\theta_0 \qquad (1)$$

where θ is the depression angle below the horizontal and toward the receiver and θ_0 is the beam tilt of the antenna. The beam tilt is set at 1^0 for the antenna of the main transmitter and 3^0 for the antenna of the auxiliary transmitter. The exponent n is .7 for the main antenna and 1 for the auxiliary antenna.

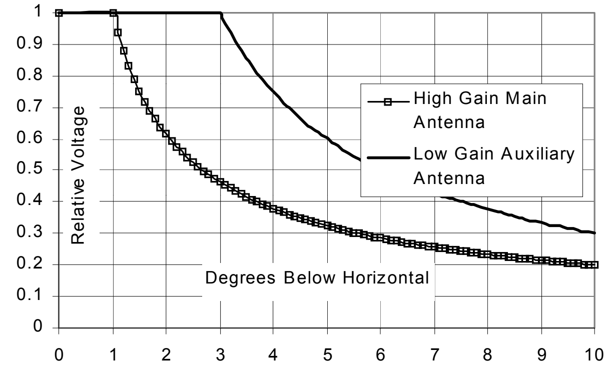

Figure 2: Elevation Patterns

Figures 3a and 3b show, respectively, the –21 dB, 0 dB and +21 dB auxiliary/main signal ratio contours generated by a 1,000 kW main transmitter, 305m above ground, and by a 100 kW auxiliary transmitter, 46m above ground. The relative position of the transmitters is shown in Figure 1 and the operating frequency was set at 600 MHz.

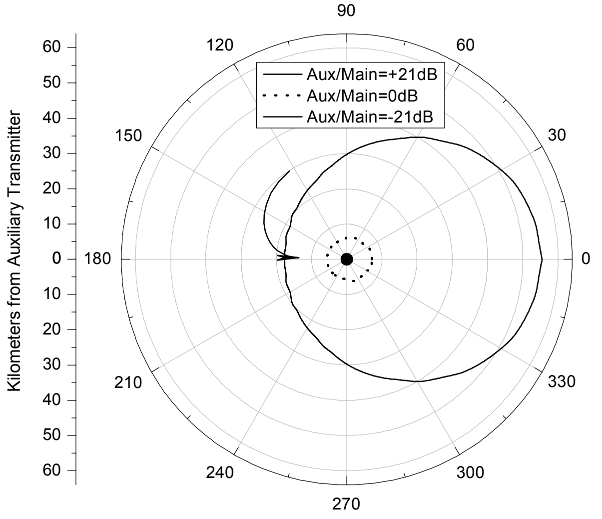

Figure 3a: Receiver at 2 meters Above Ground

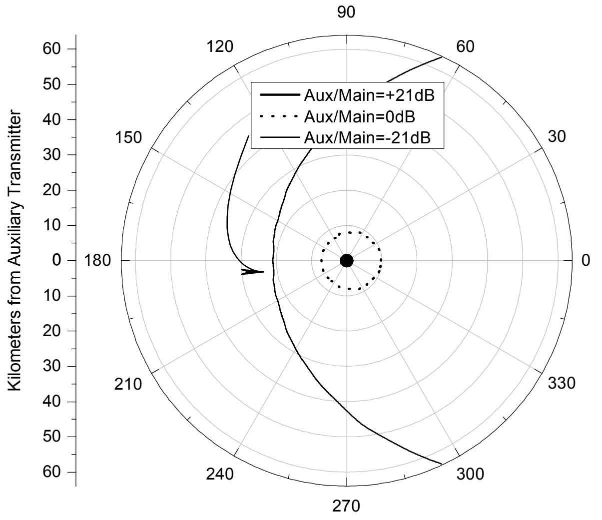

Figure 3b: Receiver at 10 meters Above Ground

The 0-dB contour, the contour at which equal signal levels from the main and auxiliary transmitters are received is shown as a dashed line. The +21 dB contour, the contour at which the signal level of the auxiliary transmitter exceeds by 21 dB that from the main transmitter, is shown as a black circle with a nominal radius of 1.6 km. The –21 dB contour is the outer contour at which the signal level of the main transmitter exceeds that of the auxiliary transmitter by 21 dB.

The area bounded by the –21 dB and +21 dB contours represents the *maximum area* in which the cochannel interference could be converted into coherent multipath provided the range of the receiver's equalizer window is sufficiently wide. The *maximum area* must be inside *the study area*, which, as is shown in Figure 1, is bounded by the radio horizons of the two transmitters.

Figures 4a and 4b show how the *maximum area*, the area that is subject to conversion from cochannel interference into coherent multipath, is constrained by the *study area* and by the ± 21 dB contours. It is clear that the *maximum area* depends strongly on the receiver height, propagation algorithm, and the height and power of each transmitter.

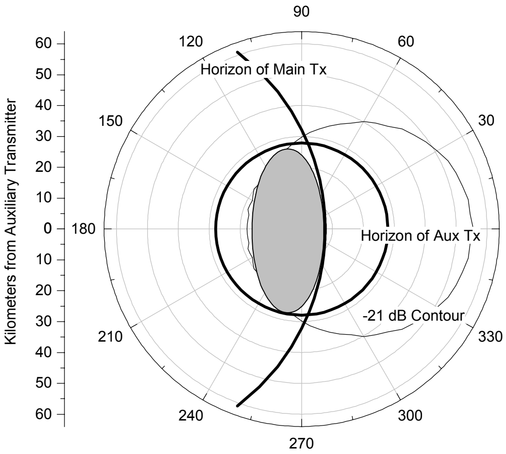

Figure 4a: Overlap of Study Area and Maximu Area (shaded) for Receiver 2m Above Ground
Shaded area subject to conversion of cochannel interference into multipath.

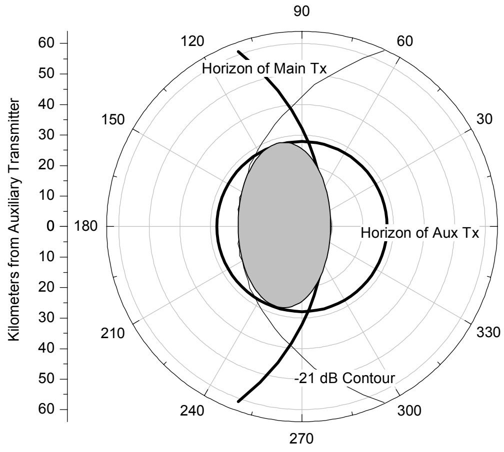

Figure 4b: Overlap of Study Area and Maximu Area (shaded) for Receiver 10m Above Ground
Shaded area subject to conversion of cochannel interference into multipath.

For the case of flat terrain and omnidirectional auxiliary antenna the *maximum area* has a shape of an ellipsoid whose minor width depends on the height of the receive antenna. In Figure

4a, the width is 25 km when the antenna is 2m above ground and 28 km when the antenna is 10m above ground. In Appendix A it is shown that, with the latest generation receivers, the minimum width of the multipath area is limited to 15 km, somewhat short of the 24-29 km that would be desired for the examples shown in Figures 4a and 4b.

A validated propagation algorithm, essential for practical system design, is unavailable at this time. It has been shown[5,6] that the two FCC methods for predicting coverage, Longley-Rice and F(50,90), fall short of the accuracy desired for the design of on-channel distributed transmission. For this reason, two other algorithms, one for the higher above-ground main transmitter and another for the lower above-ground auxiliary transmitter were used. A full discussion of these algorithms is presented in Appendix B.

IV. EQUALIZER WINDOW CONTOURS

The shaded area in Figure 4 is the *maximum area*, the area subject to conversion from cochannel interference to coherent multipath, provided that the equalizer window of the receiver is sufficiently wide. The latest generation of receivers for decoding 8-VSB modulation, the so-called fifth generation, have an equalizer window, which is approximately ±50μsec wide. With the speed of light being .3km/μsec, the equalizer window at its narrowest is 15km.

When the receiver's antenna is 2m above ground, the minor width of the ellipsoid in Figure 4a is 25km. Thus, the equalizer window is not quite wide enough to cover the *maximum area* in its entirety. Figure 5a shows the overlap of the *maximum area* with that of the equalizer's window when a delay of 100μsec is inserted at the auxiliary transmitter. Figure 5b shows the overlap of the *maximum area* with that of the equalizer's window when a delay of 150μsec is inserted at the auxiliary transmitter. It is clear that with a 150μsec delay inserted at the auxiliary transmitter, most of the cochannel interference within the *maximum area* will be treated by the receiver as coherent multipath.

V. RATIO OF COCHANNEL INTERFERENCE AND MULTIPATH AREAS

In Sections II-IV it was shown that an on-channel auxiliary transmitter could be designed to provide a strong, interference-free signal over a limited geographical area for receivers with sufficiently wide equalizer windows.

In designing distributed transmitters systems two areas should be delineated: the area of permanent cochannel interference and the multipath area. Naturally, the design objective would be to maximize the multipath area and minimize the area of permanent and unavoidable cochannel interference.

Figure 6 shows the F(50,10) interference contours of the main and auxiliary transmitters for the example analyzed in this paper. It can be seen that the interference contour of the auxiliary transmitter is well within that of the main transmitter. Thus, the interference into adjacent markets becomes negligible.

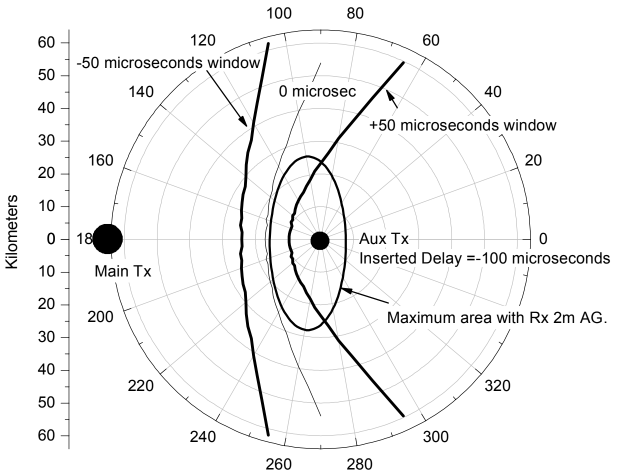

Figure 5a: Maximum Area Bounded by the Receiver Equalizer Window
Aux delay=-100 microseconds

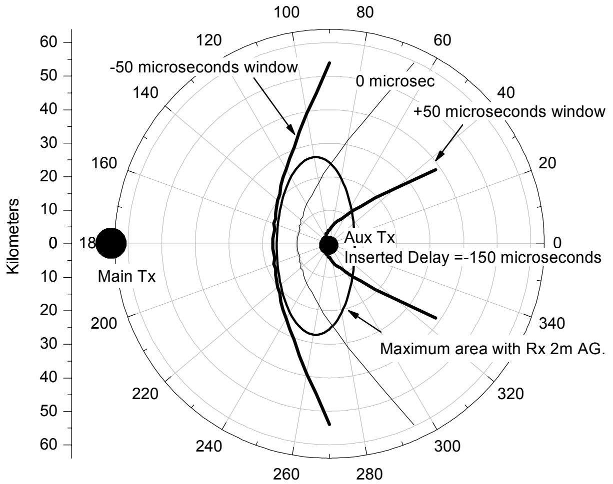

Figure 5b: Maximum Area Bounded by the Receiver Equalizer Window
Aux delay=-150 microseconds

Figure 6 also shows the intersection of the F(50,10) interference contour of the auxiliary transmitter with the contours describing the radio horizon and the F(50,90) coverage contour of the main transmitter, which is at the center of the polar plot.

Inside the radio horizon of the main transmitter, the cochannel interference area, depicted by vertical lines, is approximately 13,675 square kilometers. Inside the F(50,90) coverage contour of the main transmitter, the cochannel interference area depicted by vertical and horizontal lines is approximately 26,547 square kilometers. The area of the ellipsoid (assuming that the equalizer window covers it) is approximately 1,036 square kilometers.

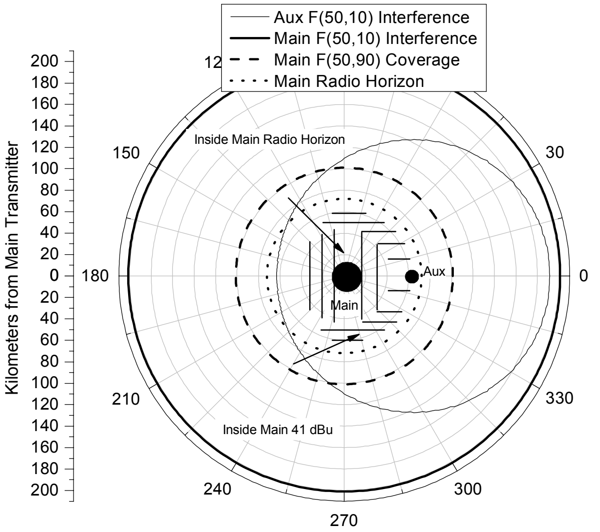

Figure 6: New Interference from Aux to Main

Therefore, inside the radio horizon of the main transmitter, an area of 13,675-1,36=12,639 square kilometers would be subject to new cochannel interference that could not be processed as multipath by the latest generation of receivers.

Unless the newly created area of cochannel interference is essentially unpopulated, the broadcaster must weigh the business issue of favoring some of the viewers with robust service at the expense of degrading the reception to other viewers.

VI. INTERFERENCE MITIGATION

Reducing the ERP of the auxiliary transmitter can significantly minimize the cochannel interference. Using the F(50,90) and F(50,10) propagation curves, a UHF omnidirectional antenna at a height of 30m above ground and radiating at an ERP=50 Watts, would provide the minimum required[7] 49 dBu up to a radius of 9km (41 dBu up to 13km). At the same time, the cochannel interference contour would be limited to 14km. Using a directional azimuth pattern would further reduce the cochannel interference within a specified arc.

We have already established that the width of the equalizer window of the latest generation of receivers is such that 15km of coherent cochannel interference could be converted into multipath. Therefore, a system of auxiliary transmitters, each with ERP ≤ 50 Watts and a directional antenna ≤ 30m above ground, would add little cochannel interference.

A system of auxiliary antennas, separated by 16km from each other, may pose a zoning objection in some communities, but the objection to new facilities may be alleviated if each antenna is masked as a flagpole or a tree.

Assigning another channel to the auxiliary transmitter(s) would eliminate the cochannel interference. In effect, creating a system of on-channel distributed translators. In major markets where channels are scarce, the auxiliary transmitter(s) will have to operate at a very low ERP. Such a system, covering an area of approximately 2 square kilometers, has been demonstrated[8] in downtown Ottawa.

VII. TDE or FDE

Clearly, Time Domain Equalization (TDE), especially when and where the channel impulse response is long, severely limits the practicality of distributed on-channel repeaters using 8-VSB modulation. Even if TDE could be implemented, such that the cochannel interference area would be negligible, the resulting large number of equalizer taps would make quick carrier recovery and synchronization impossible under dynamic conditions. Also, TDE of long channel impulse may significantly raise the noise power level.

Replacing TDE with Frequency Domain Equalization (FDE) has been suggested as a possible solution to the implementation of on-channel, distributed repeaters, in single-carrier systems[9]. Later, some of the original assumptions and conclusions were challenged[10]. It is true that TDE and FDE are mathematically equivalent. However, the practical implementation of the two operations is quite different. The implementation of FDE prior to the demodulation of the 8-VSB signal would necessitate additional time-frequency domain transformations. Possibly a combination of TDE with a few taps followed by FDE might provide the optimum solution for quick and cost effective equalization of channels with long impulse response. In any case, the optimum combination of FDE and TDE, in particular for on-channel repeaters, is still open.

VIII. CONCLUSIONS

This paper has shown that for 8-VSB modulated distributed transmitters in flat terrain, the receiver has limited ability to treat the cochannel interference that is generated by the auxiliary transmitter as coherent multipath. Further, the location and size of the *maximum area,* the area that is subject to conversion from cochannel interference into multipath, may not be entirely under the control of the system designer.

The cochannel interference area that cannot be processed as multipath by the receiver may be significant. In the example of this paper, the maximum area that was converted into multipath amounted to about 8% of the newly generated cochannel interference area.

The maximum allowable exposure to interference from adjacent markets is presently limited to a maximum of 2% of the population. There is no comparable limit on intra-market interference generated by distributed on-channel transmitters.

In UHF, a system of auxiliary transmitters with ERP ≤ 50 Watts and directional antennas ≤ 30m above ground, would not cause

undue interference because the F(50,10) interference contour could be inside the 15km width of the window of the equalizer. Each auxiliary transmitter would then provide service up to 8km radius.
In some markets, the existence of adjacent channels presents an additional complication[11]. To minimize the adjacent channel interference, all adjacent channels should be multiplexed on the main and auxiliary antennas and preferably radiate with equal power from the main antenna and equal albeit different power from the auxiliary antenna. Adding a programmable attenuator at the front-end of the receiver would prevent overload when the receiver is within very strong signals that emanate from adjacent channels.

Commercially available validated software that allows for system analysis of multiple transmitters in mountainous terrain and in the presence of adjacent channels is highly desirable.

IX. APPENDICES

A. Differential Arrival Time

Referring to Figure A1, the arrival time at the receiver of the direct signal from the main transmitter minus that from the auxiliary transmitters is:

$$\Delta t = \frac{1}{v}\left[\sqrt{D^2 + R^2 + 2RD\cos\theta} - R\right] \pm \tau \quad \text{(A1)}$$

Where υ is the speed of light=.3km/μsec and τ is the delay inserted at the auxiliary transmitter.

The model shown in Figure A1 is two-dimensional, which is applicable because the separation between the main and auxiliary transmitters is much larger than their heights.

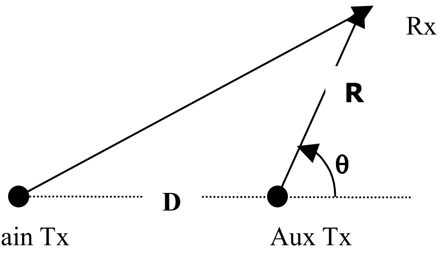

Figure A1: Geometry used for equation (A1)

Figure A2 shows the Δt=±50μsec contours for D=64km and τ=0, i.e. no delay inserted at the auxiliary transmitter. At the Δt = +50μsec contour, the arrival time of the signal from the Main Tx is 50 μsec behind the signal from the Aux Tx. At the Δt = -50μsec contour, the arrival time of the signal from the Aux Tx is 50 μsec behind signal from the Main Tx. The Δt=±50μsec contours are hyperbolas whereas for equal time of arrival (0 μsec) the contour line is straight and midway between the two transmitters.

At its narrowest, on the line bisecting the hyperbola, the distance between the ±50μsec curves is 15km, which is equivalent to half the width (50μsec) of the receiver's equalizer window. The latter relationship can be derived by solving equation (A1) for Δt=±50μsec.

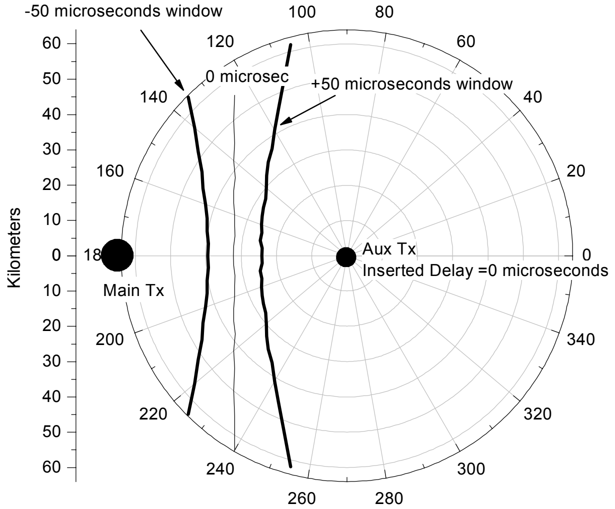

Figure A2: Service Area Bounded by the Receiver Equalizer Window
Main-Aux Separation = 64 kilometers

In Section IV it was shown that when a finite time delay τ is inserted at the auxiliary transmitter the equalizer window curves shift their positions relative to the two transmitters, and also change their shapes from hyperbolic to parabolic. When the auxiliary transmitter is delayed relative to the main transmitter, the window curves shift toward the auxiliary transmitter and when the auxiliary transmitter is advanced relative to the main transmitter, the window curves shift away from auxiliary transmitter.

B. Mean Propagation Path Loss

1. Main Transmitter

The Egli empirical model[12], based on data collected in various parts of the USA is not limited by the transmitter height.

The path loss between the main transmitter and the receiver is:

$$L_M(dB) = 112.6 + 40Log_{10}Z_{MR} + 20Log_{10}f$$
$$-20Log_{10}(H_M H_R) \quad \text{(B1)}$$

Where $Z_{MR}=(D^2+R^2+2RD\cos\theta)^{1/2}$ is the path length in miles between the main transmitter and the receiver, f is the frequency in MHz and H_M and H_R are, respectively, the heights in feet of the main and receiver antennas above ground.

2. Auxiliary Transmitter

For the auxiliary transmitter the more representative COST 231-Hata model[13], developed specifically for mobile communications is applicable.

In urban areas, the path loss between the main transmitter and the receiver is:

$$L_A(dB) = K + 69.55 + 26.16Log_{10}f - 13.82Log_{10}H_A$$
$$+ (44.9 - 6.55Log_{10}H_A)Log_{10}Z_{AR}$$

where

$$K = (.7 - 1.1Log_{10}f)H_R - (.8 - 1.56Log_{10}f) \qquad \text{(B2)}$$

Z_{AR} is the path length in kilometers between the auxiliary transmitter and the receiver, f is the frequency in MHz and H_A and H_R are, respectively, the heights in meters of the main and receiver antennas above ground. H_A is restricted to between 30m and 210m, which is the range expected for the auxiliary transmitter.

The comparative path loss for the Egli and COST-Hata models is shown in Figure B1. The FCC(50,50) path loss for two receivers, one at 2m above ground and one at 10m above ground, are also shown in Figure B1. The FCC path loss for a receiver at a height H lower than 10m above ground increases by[14]:

$$Loss(dB) = (4/3)*20Log(H/30) \qquad \text{(B3)}$$

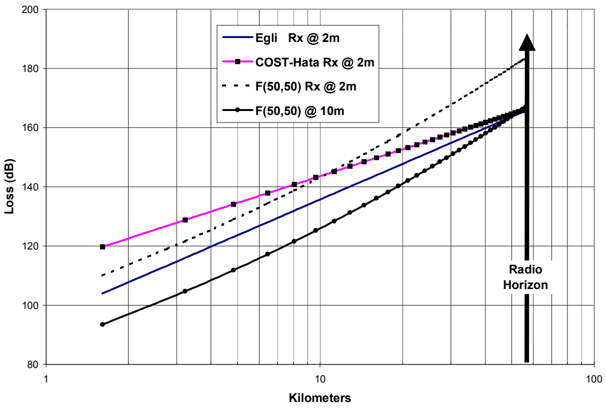

Figure B1: Comparative Path Loss @ 600 MHz
Antenna Height = 183 meters

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