FM RECEIVERS IN AUTOMOBILES: A CASE FOR DIVERSITY RECEPTION

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INTRODUCTION

The inconsistent quality of FM reception in automobiles is a major impediment to the well-deserved growth of this important medium. Although FM inherently has the potential for high-fidelity performance and has become a significant competitor to AM broadcasting to the home, it cannot hope to achieve full parity with AM until it can also successfully reach the automobile audience. This is not likely to happen as long as FM reception in autos is handicapped by the phenomenon of multipath distortion.

The multipath effect is characterized by severe signal dropouts experienced as a vehicle travels. At high vehicle speeds, these dropouts appear as short staccato-like bursts of noise. At lower speeds, losses of program are replaced by noise created by the radio receiver which is vainly attempting to automatically compensate for a diminishing signal level. The rate of dropout occurrences is usually random, with the greatest incidence occurring in metropolitan areas where numerous buildings may shadow or reflect the transmitted radio signals.

The multipath problem exists to no significant degree in conventional AM broadcasting due to the longer electromagnetic wave lengths characteristic of the AM frequency assignments. However, in FM, with considerably shorter wavelengths, the deleterious effects of buildings and other obstructions are pronounced. On a city street, due to reflections, the radio signal from a single transmitter may arrive at the automobile antenna from several directions at once. Some reflections will reinforce each other, improving reception, while others, in a destructive relationship, will cancel each other and degrade reception. A general model of this scattering problem is very complex, but in many circumstances the carrier power level as a functon of distance is well represented by a Rayleigh probability distribution [1], [2]. During the vehicle's itinerary, the antenna passes though many variations in field strength. During those intervals when the field strength is below an acceptable level, dropout will be heard, resulting in annoyance and probable distraction from listening. However, a remedy appears to exist.

DIVERSITY RECEPTION -- A POTENTIAL SOLUTION

A classical technique for dealing with the problem of audio reception of fading signals is the use of diversity reception. Diversity is typically achieved by the combined (or alternate) use of two or more receiving elements. Any of several diversity modes may be employed -- frequency (more than one channel), polarity (antenna with different polarization), or space. [2], [3], [4], [5], [6]. The latter is especially attractive for automobile reception since it promises

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great benefit with no change of broadcast standards.

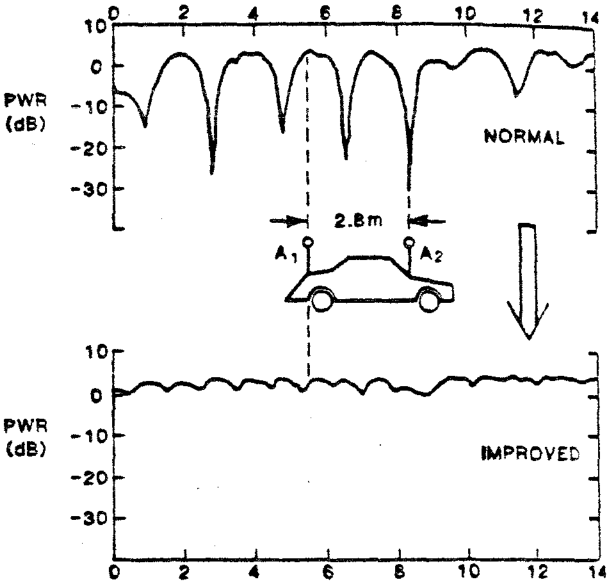
Historically, space diversity has utilized antennas placed many wavelengths apart -- usually ten wavelengths or more (the equivalent of approximately 30 meters at 100 MHz). Such spacing is not possible on an automobile where the overall length translates to typically less than 1.5 wavelengths at FM broadcast frequencies. However, observing that moving the vehicle only a short distance -- often merely a few feet -- usually results in completely adequate improvement in reception, has provided a rationale for investigating theoretically how effectively space diversity reception could be employed in an automobile.

The theoretical study based on CTC's field measurements and computer processing of the data has confirmed that significant improvement of FM reception can be achieved. Figure 1 illustrates this. The upper chart shows a representative plot of relative carrier level (field strength) along a line in space from 0 to 14 meters. The downward fluctuations are of varying severity and may or may not result in audible dropouts depending on station power, distance of the vehicle from the transmitter, and receiver sensitivity. The lower chart illustrates the degree of signal uniformity which would be achieved if a 2.8-meter space diversity system were used. The vehicle shown is drawn to the distance scale of the chart. It is easy to visualize how a receiver, automatically selecting the better output from two antennas, can maintain an optimum signal level as both antennas are moved in tandem along the distance scale. In the illustration, the rear antenna is seen to be receiving the strong signal, clearly the choice over the degraded signal at the front antenna.

MEASUREMENTS AND ANALYSIS

In order to experimentally determine the fading characteristics of signals within the FM broadcast band, an envelope detector tuned to a selected carrier in the center of the band and an analog data recording system were assembled in a small van.

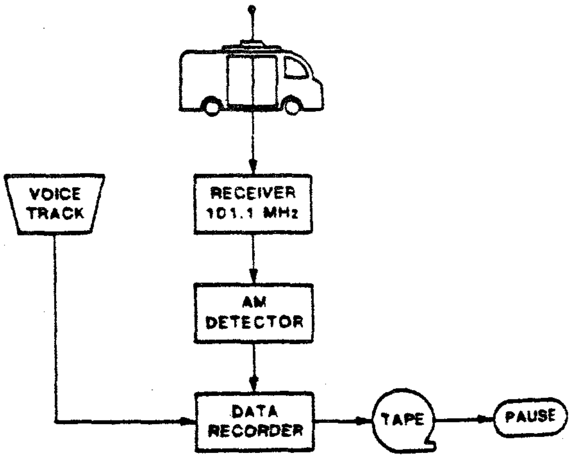
Figure 1



Fading of FM Carrier as a Function of Distance (above) and Resultant FM Carrier Using Space Diversity and Selection Combining.

The instrumented vehicle with a single antenna on its roof was driven through arbitrarily-chosen locations in New York City, Westchester, and southern Connecticut. The data was later replayed and reduced via a digital sampling technique, and analyzed by computer. Figures 2, 3, and

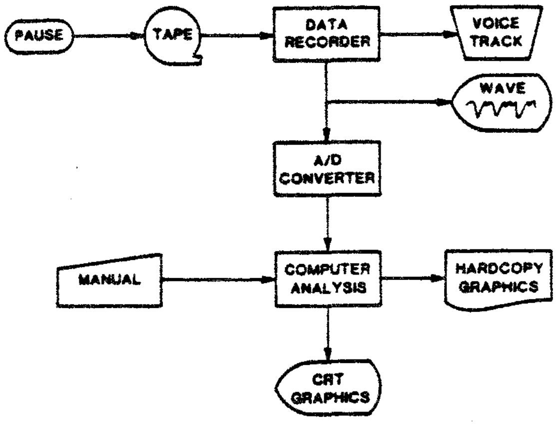
Figure 2



Field Data Gathering

4 depict the data acquisition system, the analysis system, and the receiver modifications, respectively. The sampling was conducted using a 12-bit A/D converter and the number of samples per 100 meters ranged from 500 to 5000 depending upon the parameters of each experiment.

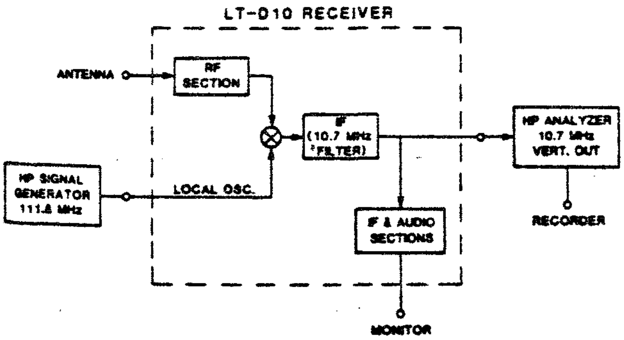
Figure 3



Laboratory Data Analysis

All the data presented herein for individual localities was acquired over a distance of about 100 wavelengths of 101.1 MHz (2.97 m), and was reduced using a rate of 8 samples per meter. The samples so derived constituted a linear array, A(I), of 2560 elements representing the local carrier level (local envelope) as a function of distance. Probability distributions corresponding to the single branch antenna were computed on the first 2048 points (approximately 80 wavelengths).

Figure 4



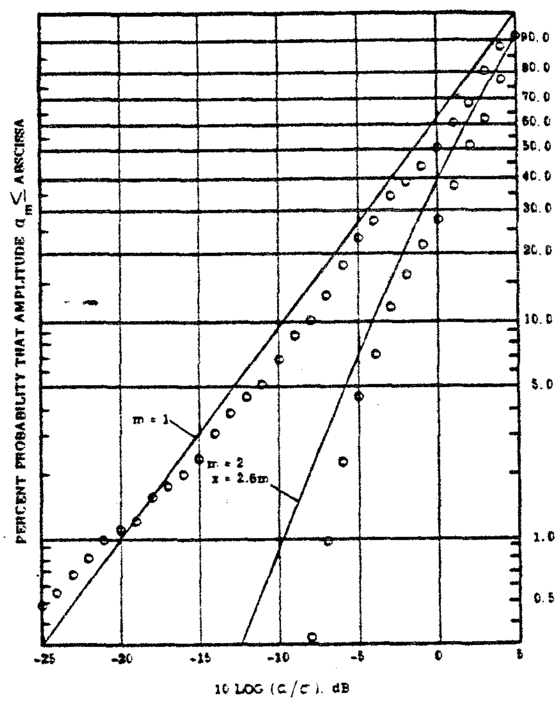
FM Receiver Modifications for the Detection of Carrier AM.

To examine the potential of space diversity and combining by selection, an ideal, non-interacting antenna was assumed to exist on the vehicle and separated from the first antenna by some preselected distance (X_S). The number of sample points corresponding to the antenna separation distance was calculated and given a value, N. As envisioned, one antenna would be observing a local carrier level corresponding to some sample element, say, sample K, while the other would be observing that carrier level associated with the (K + N) sample. If A(I) is the original 2560-element linear array, a second array, ANEW(I), would represent the action of an ideal two-branch selection combiner when constructed by use of the following processing algorithm:

$$\mathrm{ANEW}(I) = \begin{cases} A(I) & \text{if } A(I) \geq A(I+N) \\ A(I+N) & \text{if } A(I+N) > A(I) \\ 1 \leq I \leq 2048 & \end{cases}$$

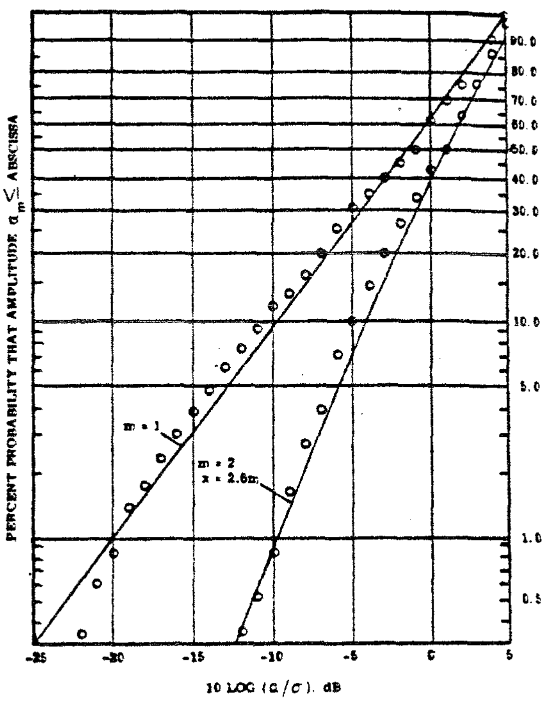
After processing with this "maximum value" algorithm, the distribution corresponding to the two-branch antenna system was calculated using the new 2048-element array. In the manner described, data from each locality was processed using the hypothetical antenna separation as a varying parameter. Figures 5 thru 8 depict results representative of one antenna separation and data from four locations within the New York Metropolitan region (three within Manhattan). Along with the data are included the reference curve for Rayleigh fading which appears as a straight line along the diagonal for the case of a single antenna. Figure 9 is one example of how performance of a diversity array as measured in terms of gain over a single antenna for a constant value of probability varies with antenna separation.

Figure 5



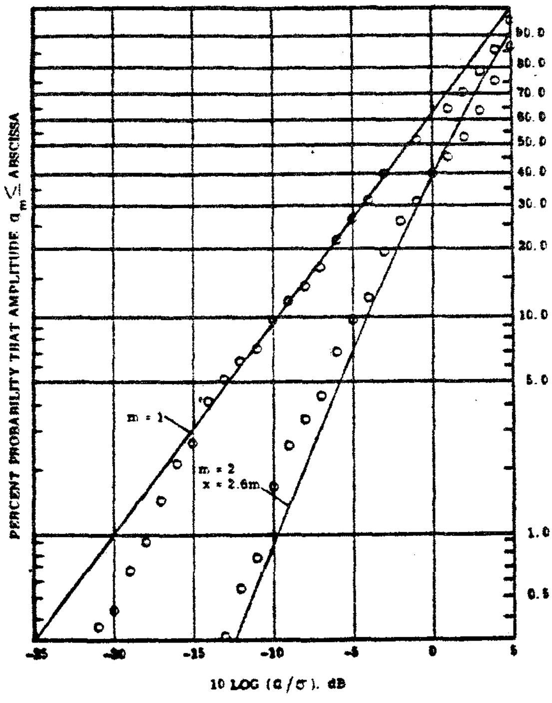
Cumulative Probability Distribution of m-Branch Selection Diversity Combiner. σ = Mean Signal Power for Single Branch. (Crosstown, West 26 Street, N. Y. C.; f_c = 101.1 MHz)

Figure 6



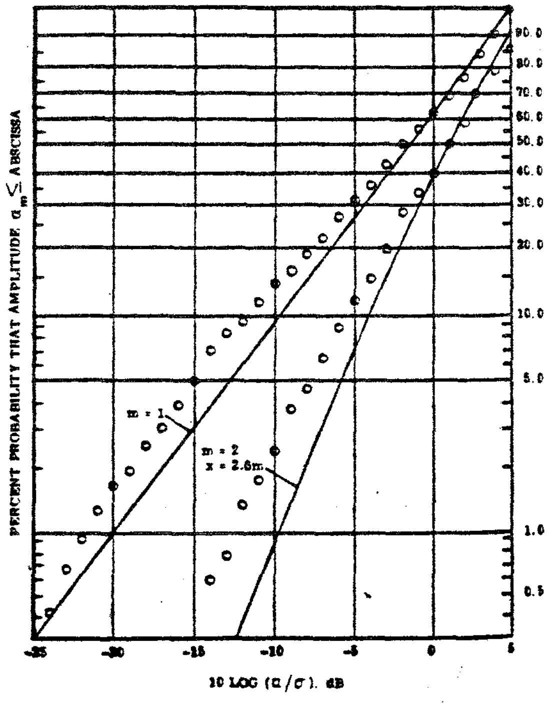
Cumulative Probability Distribution of m-Branch Selection Diversity Combiner. σ = Mean Signal Power for Single Branch (FDR Drive Northbound, N. Y. C.; f_c = 101.1 MHz)

Figure 7



Cumulative Probability Distribution of m-Branch Selection Diversity Combiner. σ = Mean Signal Power for Single Branch. (FDR Drive Southbound, N. Y. C.; f_c = 101.1 MHz)

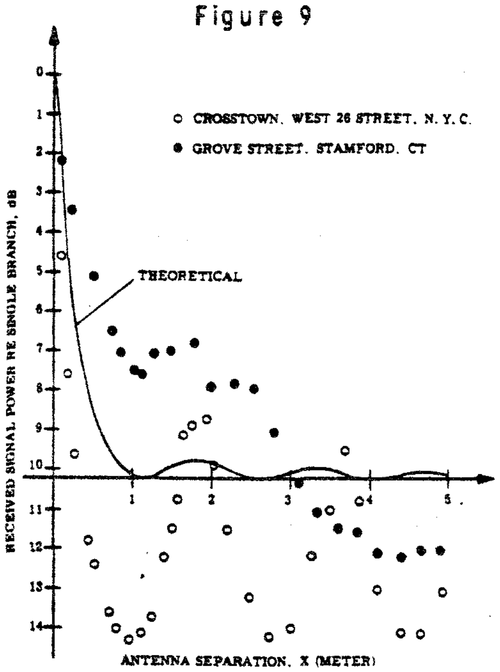
Figure 8



Cumulative Probability Distribution of m-Branch Selection Diversity Combiner. σ = Mean Signal Power for Single Branch. (Grove Street, Stamford, CT; f_c = 101.1 MHz)

Since a model of average system performance was felt desirable, the data from the various locations was used to calculate an overall distribution (8192 total points). The resulting composite data and reference curves are shown in Figure 10. Figure 11 depicts average system performance of the diversity system as a function of antenna separation for a constant value of probability, arbitrarily chosen to be 1.0%

Figure 9



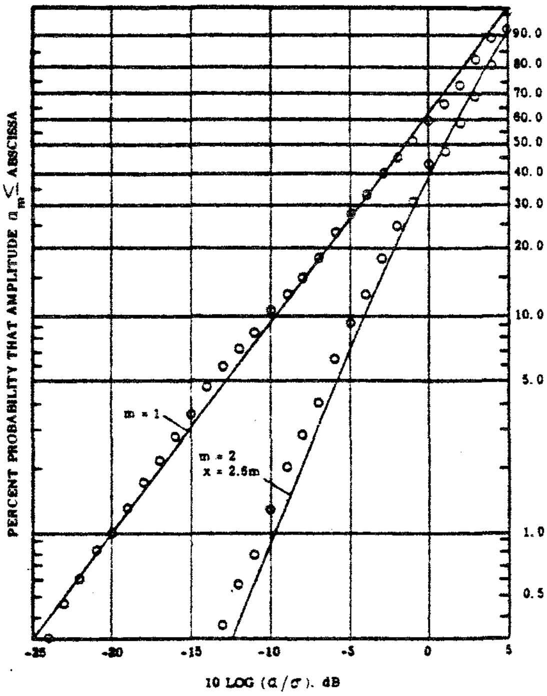
Effects of Antenna Separation on Performance of Two-Branch Selection Diversity Combiner Over That for Single Branch for Equal Values of %P(α) = 1.0%. (Data from Two Separate Locations; f_c = 101.1 MHz)

DISCUSSION OF RESULTS

Based on the findings shown in Figures 5 thru 9, it appears that local anomalies can cause deviations in actual performance from those predicted on the assumption that fading follows a Rayleigh distribution. A close examination, of all the amplitude vs distance data and associated distributions indicates that two situations often arise which tend to produce results which differ from the model:

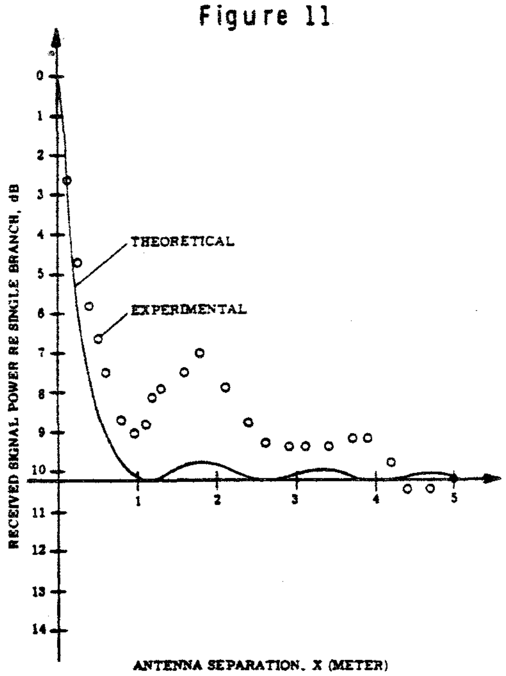
1. In addition to the expected

Figure 10



Cumulative Probability Distribution of m-Branch Selection Diversity Combiner. σ = Mean Signal Power for Single Branch. (Composite Average From Four Separate Locations Within New York City and Vicinity; f_c = 101.1 MHz)

Figure 11



Effects of Antenna Separation on Performance of Two-Branch Selection Diversity Combiner Over That for Single Branch for Equal Values of %P(α) = 1.0%. (Data Represents a Composite Average from Four Separate Locations Within New York City and Vicinity; f_c = 101.1 MHz) rapid changes, the local carrier level often experiences slow changes as a function of distance. These changes may best be modeled by means of another classical distribution, possibly log-normal. Under these circumstances, performance results are not always as favorable as those predicted under the assumption of Rayleigh fading.

2. The second cause for differing results may be associated with a limited number of interfering waves which tend to dominate a fading situation (example, a strong single reflection). The data so derived reveals a more highly periodic and generally deeper fading pattern than that normally expected with Rayleigh fading. Under this latter condition the use of space diversity with a two-branch selection combiner can produce improvements over a single antenna which are significantly better than those predicted if the original distribution were Rayleigh.

Since a practical diversity combiner for FM broadcast reception must operate over a multiplicity of fading situations, antenna placement and performance projections for the entire FM band must be based on some average criteria. As previously described, a composite distribution based on data obtained in four physically different localities was computed and is shown in Figure 10. Results are very close to theoretical predictions based solely on the assumption that fading follows a Rayleigh probability distribution. Figure 11 illustrates performance advantages for a two-branch space diversity selection combiner over a single antenna and is parametized on the basis of antenna separation. With the exception of the region in the vicinity of 1.8 m antenna separation ($X/\lambda = 0.61$) where results for the two-branch system give a 7dB advantage over a single antenna and the theory predicts 10 dB, the data is in good agreement with projections based on Rayleigh distributed fading.

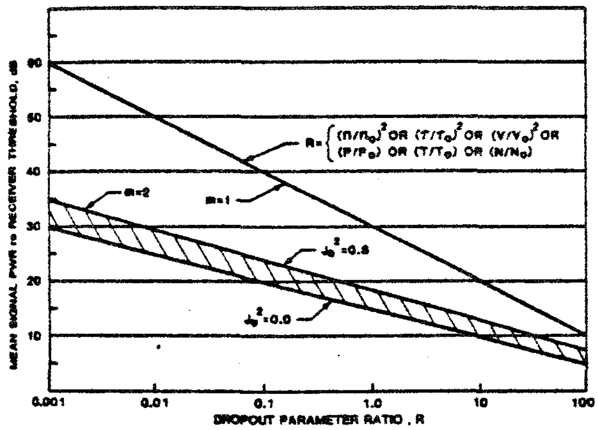
APPLICATIONS TO IMPROVE FM RECEPTION IN AUTOS

While local effects may dominate performance characteristics in a particular fading situation, on average the body of theory based on Rayleigh distributed fading provides an excellent framework to judge overall performance of space diversity systems. From the results obtained in Figures 10 and 11, an ideal embodiment of an FM receiver would achieve nearly the theoretically predicted performance for two totally uncorrelated branches assuming the antennas are separated by a distance greater than 2.8 m. It also appears that a single antenna separation would be suitable for good reception across the entire FM broadcast band. This results from the fact that the band extends only about ±10% from a mid frequency and performance projections are relatively constant for any antenna separation greater than 2.6 m. This distance criteria is consistent with reasonable dimensions of current vehicles. If for some necessity a separation distance less than 2.8 m were required, performance projections based on a Rayleigh fading model and a branch correlation of 0.8 would seem reasonable and conservative. This value of branch correlation corresponds to an antenna separation of 0.3 m and a gain of 7 dB for a dual branch diversity array over that of a single branch if Rayleigh fading is assumed (See Appendix).

Figure 12 is designed as a means for judging the potential of space diversity techniques in improving listening conditions during travel through marginal reception areas. Projections are based on Rayleigh fading with two uncorrelated branches as one bound and two partially correlated branches (0.8) as the other bound. The reference value for the ordinate, 0 dB, was taken to be the equivalent receiver threshold, and no effects of additive noise are included in the calculations of dropout probability. For purposes of this discussion, a dropout exists when the local carrier is below the receiver threshold.

As discussed in the Appendix, there exist relationships between the level crossing rate (n), the vehicle speed (v), average duration of fade (τ) and the probability distributions. For a given speed, the value of τ will change as the mean carrier level, σ_o changes; and, of course, so will the level crossing rate, n, change. In order to compare different fading situations that may have differing values of (τ), it is sometimes convenient to refer to a derived hypothetical threshold crossing rate, N, based on the total amount of time the signal has faded and an average duration of fade specified as some arbitrary value. In the remaining discussion, this value will be standardized at 10 ms. For subjective reasons, dropouts of duration less than 10 ms, assuming they occur on an isolated basis, are usually not objectionable. When (τ) is less than 10 ms, N will be smaller than n and probably be a better measure of listening conditions (i.e., dropout rate). The collection of these parameters in a sense represents a particular fading situation and an approximate measure of how good or bad are the listening conditions.

Figure 12



Normalized Parametric Comparison of Two-Branch Selection Diversity Combiner (m = 2) and Conventional Single Antenna System (m = 1); f_c = 100 MHz).

Reference Parameters:

n_0 = 0.10/sec = 6/min
τ_0 = 0.01 sec
V_0 = 13.6 km/hr = 8.5 mi/hr
P_0 = 0.001 = 0.1%
T_0 = 0.001 = 0.1%
N_0 = 0.1/sec = 6/min

In Figure 12 the abscissa, which would normally be in terms of probability of percent time the local signal is below threshold, %T, has been normalized using the probability value that the local signal would be less than -30 dB re the mean signal level. Thus, the axis is displayed as a ratio of the expected degrees of dropout (example, probability of dropout at any mean signal level to that at a standardized level).

This rearrangement of previously displayed information results in a very convenient way of estimating all the parameters in individual fading situations. It turns out that for mean carrier levels above 10 dB, the ratio, R, in Figure 12 is equal to a non-dimensionalized representation of any of the parameters describing dropout (n^2, τ^2, v^2, P, %T, and N, respectively). Thus, each parameter can be calculated by reading the individual reference value and then multiplying it by either R or $\sqrt{R}$ as required. For purposes of this discussion, subscript 1, 2, and 0 refer to single-branch, two-branch, and reference conditions, respectively. It is assumed for convenience sake that the reference parameter of n_0 used for the single branch applies to the two-branch arrangement. Since the calculation of n_2 may have been biased by the original choice of reference value, comparison of N_1 and N_2 may provide a more objective criteria than using n1 and n2.

An initial observation reveals that the total time of dropout changes by a factor of 10:1 for every 10 dB change in mean signal level. This implies that in a marginal listening area, dropouts due to Rayleigh fading can cause rapid changes in overall listening conditions. An annoying but tolerable situation can change just as quickly for the better or for the worse.

A typical set of listening circumstances may be described in the following way. A listener in an auto moving in heavy traffic at nine miles an hour would experience a dropout (more likely a noise burst) of 10 ms in average duration about six times per minute due to Rayleigh fading even though the mean signal over a distance of 300 meters (100 wavelengths) was on the order of 30 dB above receiver threshold. The above corresponds to a dropout parameter ratio, R, equal to unity. Depending upon other factors this listening situation may already be classified as marginal. If the mean signal began to drop by 10 dB due to local conditions, the noise bursts or dropouts would increase to 19 per minute, since the new value of R equals 10 and $n_1 = 6\sqrt{R_1}$. Also, the average dropout duration would change from 10 ms to 32 ms, $T_1 = 10\sqrt{R_1}$. Notice also that there would be a large increase from the original six to 60 standardized dropouts per minute at this new mean carrier level. As a reference, at the nine-mile-per-hour speed it would take the listener in the auto about one minute to cover the 300-meter distance. This would seem to represent a rather annoying situation, one in which the listener may decide to change stations or even turn off the radio.

The above example can now be further followed to examine what might happen if the hypothetical space diversity receiving system were employed. Figure 12 indicates that initially, with the mean signal level at 30 dB, the parameter ratio using the diversity scheme would be about 400 times less ($R_2 = 0.0025$, if the center of the shaded region is used). The new value of N would be 0.015 per minute or about one dropout of standard duration per hour, $N_2 = 6R_2$. In this case it would be unlikely that the listener would even be aware that the auto was moving through a marginal listening area. If the mean FM carrier signal further dropped by 10 dB to a new value of $R = 10$, as was the case previously described for the single antenna, the resulting parameter ratio for the two-branch combiner would be 0.25 or a change of 40-to-1 over the single antenna. The new values of rate and duration would be $n_2 = 3$, $N_2 = 1.5$, and $\tau_2 = 5$ ms. The listener in this one-minute scenario might experience one 10-ms dropout when the diversity system is employed instead of 19 occurrences (60 if N were used) predicted for the conventional system.

The effect of an increase of auto speed on a given fading situation would be to reduce the average duration of dropout but to increase the dropout rate in equal ratio. Thus, the percentage of time the carrier spent below threshold would not change. If, at the greater speed, τ dropped below 10 ms, the result would probably be favorable, and so N might be chosen as a better measure of listening conditions than n. In the first example, if the speed had increased to 27 mi/hr, T would have changed by about 3:1 or to a new value of 3.3 ms. The value of n would be 18, although the probability of the signal dropping below threshold remained the same. In this case N would remain at a constant value of 6 and probably represent a better measure of the situation than n. Of course, another effect of speed would be to reduce the total time the listener is in the fading zone.

CONCLUSION

The multipath effect produces severe signal dropouts of FM commercial broadcasts in a variety of typical motor vehicle operating environments, and thereby represents an impediment to the acceptance of this listening medium by the public. Space diversity receivers appear to offer significant performance advantages over conventional single-antenna arrangements for the reduction of multipath effects and the improvement of FM broadcast reception in moving vehicles. Results show that the required antenna separation appears to be compatible with present vehicle dimensions. Thus, there exists the potential of changing intolerable listening conditions to good ones for a wide class of problem situations.

APPENDIX: THEORETICAL REVIEW

In a complex physical environment, radio waves often arrive at a point in space having taken paths other than a straight line from the transmitter. When a number of these waves combine, phase and amplitude differences can result in interference and sharp reductions in the local value of the transmitted signal - fading. A mathematical model using physical scattering of the waves has been discussed by Clarke[1], and is often very effective in predicting many observed effects of rapid fading of an FM carrier signal.

There are several different visualizations of the physical combining of the waves which have been shown to be mathematically equivalent. One arrangement assumes that at any instant of time the electric field vector, E, at an arbitrary point of a region is aligned vertically along the z-axis. The amplitude E_z is the result of the superposition of N waves of equal aplitude, E_o; the n^{th} wave making an arrival angle θ_n chosen at random to the x-axis in the horizontal plane, and having random phase, ϕ_n. The variation of E with time at the receiving point is assumed to be sinusoidal. The values of ϕ_n are independent and uniformly distributed between θ and 2Π as are the values for θ_n. The phases and arrival angles θ_n are independent of each other. Thus E_z at any point (say along the x-axis) can be described by:

$$E(x) = E_z(x)\ (\cos \omega t + j \sin \omega t)$$

$$E_z(x) = E_o \sum_{n=1}^{N} [\cos \phi_v(x) + j \sin \phi_v(x)]$$

Under these assumptions, the real and imaginary parts of E_z are closely approximated by a set of independent Gaussian random variables of zero mean and equal variance for sufficiently large N. An important consequence of the model is that the envelope of E within the region of interest is well represented by a Rayleigh probability distribution. A convenient form of the distribution specifies the probability, P, that the received signal power, A, at a given point (local value) is less than a given value, α, when the mean signal power, σ, in the region is known.

$$P_1(A \leq \alpha) = 1 - e^{-\frac{\alpha}{\sigma}}$$

$$P_1(A > \alpha) = e^{-\frac{\alpha}{\sigma}}$$

$$P_1(\alpha) = 1 - e^{-\alpha} = \alpha \quad \text{for} \begin{cases} \alpha << 1 \\ \sigma = 1 \end{cases}$$

At the point in the discussion no mentioned has been made of the motion (assumed now to be uniform) of the vehicle in the zone of Rayleigh fading. Only a description of the local signal level in terms of the mean signal level in the region has been provided thus far. An important element to be considered for a moving vehicle is the Doppler shift f_s which is required to fully characterize the dynamic behavior of fading. This shift in frequency of the received signal, f_c, is proportional to the vehicle speed, v, the speed of light, c, and the relative angle, Θ, between the incoming wave and vehicle motion:

$$f_s = f_c \frac{v}{c} \text{ Cos } \Theta n \qquad (\text{Hz})$$

The uniform motion of the vehicle in a region described by Rayleigh fading causes the RF bandwidth of the received carrier to extend from $f_c - f_s$ to $f_c + f_s$ and thus the base band of the fading carrier has a width of $2f_s$. The speed of the vehicle in terms of the maximum Doppler shift is important in describing the rate and duration of fades. The Rayleigh distribution provides a measure of the probability that the local signal will be below a certain value (threshold). This relationship can be interpreted as the ratio of the time the signal spends below the given threshold, t, to the total time the vehicle spends moving through the region. It is helpful to know how often the local signal falls below (i.e., crosses with negative slope) the stated value per unit time. This is defined as the level crossing rate, n. Closely associated with n is the time or duration of individual fades, τ_i, and the average duration of these fades, τ. The above parameters are related by the following set of equations which are written in terms of the RMS signal levels, ρ.

$$P_1 = 1 - e^{-\rho^2}$$

$$T = \frac{t}{t_o} = \frac{\sum_{i=1}^{m} \tau_i}{t_o}$$

$$m = n\, t_o \quad \text{(total number of fades)}$$

$$\tau = \frac{\sum_{i=1}^{m} \tau_i}{m}$$

$$P_1 = n\,\tau$$

From the theory it can be shown[2], that T and n are related to ρ and f_s by the following:

$$n = \sqrt{2\pi}\, f_s\, \rho e^{-\rho^2}$$

$$\tau = \frac{e^{\rho^2} - 1}{\rho f_s \sqrt{2\pi}}$$

If a set of m ideal non-interacting antennas spaced apart from each other existed on the vehicle as it moved through the region of Rayleigh fading it could be expected that all antennas would not be experiencing deep fades simultaneously. In fact, if the received envelope of the signal on all branches was statistically independent, then the probability distribution for simultaneous fading on all m branches has been discussed by Brennan[3] and is given:

$$P_m(r) = (1 - e^{-r})^m$$

$$P_2(r) = (1 - e^{-r})^2 \quad \text{for 2 branches}$$

$$P_2(r) \simeq r^2 \qquad \text{for} \begin{cases} r = x/\sigma \\ r << 1 \end{cases}$$

The physical embodiment of a receiver which would approximate this performance would instantaneously select, and remain on the antenna with the greatest carrier level. The assumption made above is that the signal envelopes as seen by the branches are statistically independent. A measure of independence is provided by the normalized envelope cross-covariance coefficient, C, parametized on the basis of antenna separation, x, and carrier wavelength, λ, $C = J_o^2\,(2\,\Pi x/\lambda)$. The effects of branch corelation on the probability distribution for selection combining are illustrated by Jakes[2] for values of $\alpha << 1$:

$$p_2(\alpha) = \frac{\alpha^2}{[1 - J_o^2\,(2\pi x/\lambda)]}$$

As a reference, the zeros of J_o^2 occur at values of x/λ of 0.40 0.88, and 1.38. For a carrier frequency of 100 MHz, approximately the midpoint of the broadcast band, the physical separation distances correspond to 1.2 m, 2.6 m, and 4.1 m, respectively. For distances less than 1.2 m, the value of $P_2(\alpha)$ increases (for example $x = 0.3$ m gives $J_0^2 = 0.82$ and $P_2(\alpha) = 3.1\,a^2$). When greater separation distances than 1.2 m are used, P_2 varies only slightly(maximum value of $P_2 = 1.19\alpha^2$ for $x = 1.8$ m) and begins to converge to P_2 as the distance between antennas increases.

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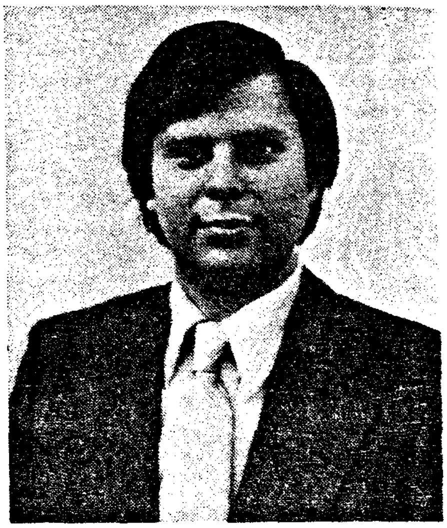

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