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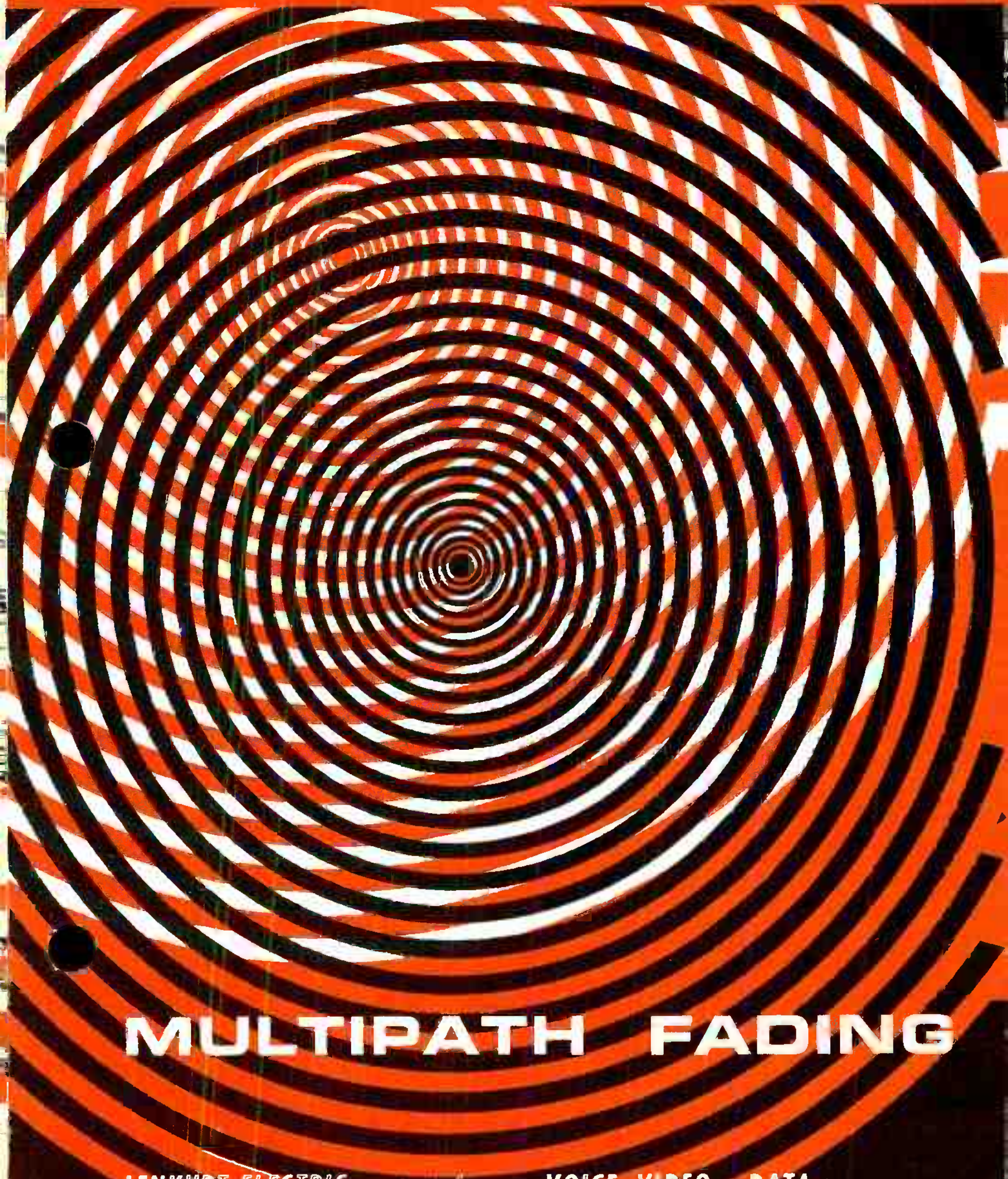
The Lenkurt DEMODULATOR



MULTIPATH FADING

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. . . . wave interference caused by atmospheric discontinuities means trouble for space waves.

Electromagnetic wave propagation depends on a number of varying factors. Each of these factors can cause radical changes in the reception of a radio signal.

The sun, the earth's terrain, the weather all work their peculiar influences. The sun, for instance, has a direct effect on the ion concentration of the ionosphere. The ionosphere in turn refracts radio waves.

How a particular signal is affected by sun, terrain or weather depends on its path through the atmosphere. Three such paths have been identified and designated as sky, ground and space waves.

Ground waves, as the name implies, hug the ground. Sky waves travel to the upper atmosphere where the ionosphere refracts them back to earth. Space waves propagate through the atmosphere just above the ground. They usually travel in straight lines.

At any given frequency only one or at most two of these waves are useful. The others are either attenuated or lost when they are not bent back to earth.

Point-to-point microwave systems rely on space wave propagation. As space waves they are supposed to follow straight lines. Occasionally, however, they do not because as electromagnetic waves they are susceptible to atmospheric bending from diffraction, reflection and refraction.

The Bends

A diffracted wave bends around corners because the edges of the wave tend to fill the areas masked by obstacles. A reflected wave bends because it encounters a reflecting medium. A refracted wave bends because its speed changes. Of the three, reflection and refraction pose the biggest problems in microwave transmission.

Radio waves can be reflected from a smooth surface just as light can. The amount of reflection depends on the angle of incidence or the approach angle and the reflective quality of the material doing the reflecting. At low angle reflection the wave undergoes a 180° phase shift.

Figure 1 shows an electromagnetic wave at the point of reflection. If there had not been an obstruction, the wave front would have continued to a'b. The reflecting surface caused a change of direction which resulted in the wave front acb. As the wave front continues

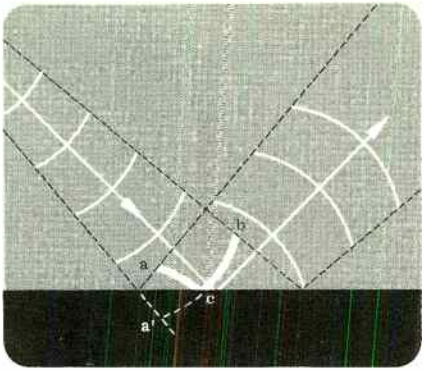


Figure 1. An electromagnetic wave undergoes a change of direction and usually a change of phase at reflection.

to arrive at the reflecting surface, it is redirected and its phase shifted 180°.

The third type of wave bending, refraction, is the least predictable. It is directly related to the condition of the atmosphere and as such also has some influence on the reflection of a radio wave.

Density changes which affect the speed of an electromagnetic wave cause refraction. To describe this effect an index of refraction—the ratio of the speed of light in a vacuum to the speed of light in another medium—was conceived.

The index was originally developed to analyze light rays, but because both light and radio waves are electromagnetic, the principle applies to radio waves as well. The speed of light, or for the purposes of this discussion the speed of a radio wave, decreases as the density of the medium of propagation increases. This relationship of density and speed is an important one.

As a radio wave moves obliquely between two differing densities (Figure 2), its change in speed alters its direction. If the wave enters a more dense area, the forward part of the wavefront slows, causing it to lag behind its upper portion. This uneven increase in speed across the wavefront forces the wave to pivot around its slower end just as a marching line of soldiers does when turning.

Atmospheric Alterations

If there were no atmosphere—therefore no density changes—a radiated signal would proceed in a straight line.

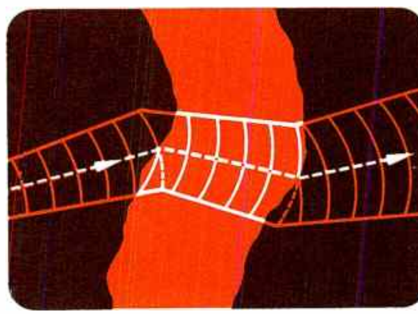


Figure 2. An electromagnetic wave is refracted when it encounters a medium of different density. The resulting speed change usually causes a change in direction.

But there is an atmosphere which can refract waves and therefore alter their relationship with the earth.

A single microwave beam, for instance, might follow a number of available paths. One might bring it down to the earth, another bend it away, or still another might lead it in a curve roughly equivalent to the curvature of the earth.

In a standard atmosphere where density decreases with height, the prevailing tendency of a space wave is to curve but at a slightly slower rate than the curvature of the earth. Unfortunately, the atmosphere does not always conform to a standard density pattern.

Figure 3 illustrates various atmospheric profiles each of which will change the propagation path of a space wave. The graphs use a modified refractive index, M, defined in units which relate the curvature of a microwave beam to the curvature of the earth. The value of M at a given altitude depends not only on the index of refraction at that altitude but also on the ratio of that altitude to the radius of the earth.

Figure 3A shows a slope which is standard for most of the earth. When the slope of the M curve is greater than normal but not negative, the tropospheric condition is known as superstandard (earth flattening), hence the radio horizon distance is increased. When the slope of the M curve is less than normal, the tropospheric condition is known as substandard (earth bulging).

Figures 3B and 3C show two profiles which indicate an atmospheric inversion. In both cases a space wave signal will be trapped at the elbow of the curve. This produces a condition known as ducting which can confine a signal to one height. When this happens, a signal caught in an unfavorably located duct can be at least partially blocked. An unfavorably located duct is one not at the same height as the receiving antenna.

K and the Earth

The need to correlate the conditions of the atmosphere and the curvature of a radio signal has led to the definition of an equivalent earth radius factor K. This factor compensates for apparent variations in the curvature of the earth caused when an electromagnetic wave bends. In effect the earth is flattened, bulged or depressed by the condition of the earth's atmosphere.

In a standard atmosphere K equals 4/3 of the curvature of the earth. With a standard atmosphere the earth does not fall away from a microwave beam in as short a distance as would be expected. The beam has a curvature less than that of the earth.

The earth appears to become increasingly flat as the value of K increases. When K equals infinity the earth ap-

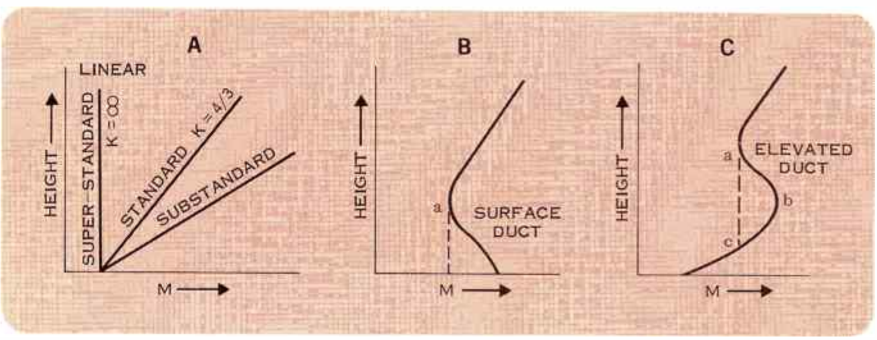


Figure 3. Typical M profiles showing atmospheric conditions. Profiles B and C indicate an inversion which can cause ducting. Each profile has associated with it different propagation characteristics.

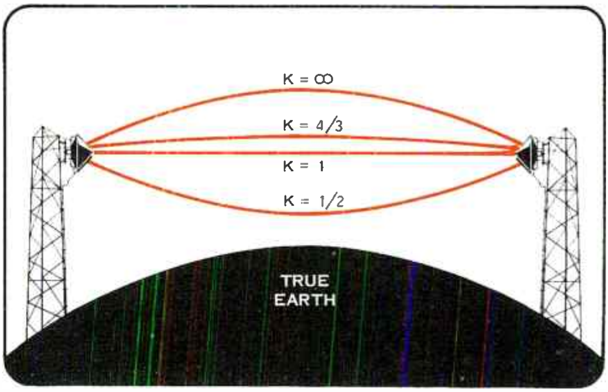


Figure 4. The equivalent earth radius factor K shows the path of a microwave beam relative to the surface of the earth. (For the purpose of illustrating this, the earth's curvature is exaggerated.)

pears to a microwave beam to be perfectly flat. In effect, when K is at infinity, the microwave beam curves at exactly the same rate as the earth.

If the value of K becomes less than one, the curvature of the beam becomes negative. The beam itself curves in a direction opposite to that of the earth. To the beam the earth appears to bulge. The effect of bulging is to put obstacles in the way of the transmission path.

The earth's actual surface also has an influence on the atmosphere. Over certain kinds of terrain the influence is negligible but over others it is especially significant.

The atmosphere over flat lands or water, for instance, is subject to temperature inversions which can cause ducting. Atmospheric turbulence in mountainous areas causes mixing which aids space wave transmission.

The earth's terrain also affects the propagation of microwaves by causing or preventing reflections. Reflections from a rough surface are usually no problem because the incident and reflective angles are quite random. A relatively smooth surface, however, can reflect signals toward the receiving antenna.

Transmission Paths

Both reflection and refraction occasionally complicate transmission paths. In itself this is not a problem. The problem arises because a radio signal is not the neat little beam depicted in most diagrams. In reality radio signals spread as they advance, becoming not just one beam but, theoretically, an infinite number of them (Figure 5).

Each component of the wave, traveling its own unique path, is subject to different reflections and refractions. Some components do not reach the receiving antenna at all. Of those that do, there can be both principal and secondary wave components.

One convenient definition of these components hinges on the paths they follow. The principal component is the direct or unobstructed component and any reflected component of the wave. Secondary components are those which travel multiple paths through the atmosphere.

At any instant the signal strength at the receiving antenna is the vector sum of its components. Combinations of the principal and secondary components produce phase interference—one cause of multipath fading.

Two components of a wave can cause a 6 dB increase in signal strength or a complete null. The degree and character of interference depends on the amplitude and phase difference of the two components.

The exact nature of a cancellation or reinforcement varies with the circumstances. Components 180° out of phase experience a degree of cancellation directly related to amplitude. On the other hand components of the same amplitude experience a degree of interference dependent on phase differences.

There are examples of multipath fading which appear to be the result of more than two interfering waves. Investigations have led to the assumption that very deep multipath fading often results from the coincident arrival of a signal weakened by its reflected component and a secondary wave.

Solutions

Although multipath fading is quite random, there are ways to compensate for it. The least subtle and most obvious solution is to provide extra signal strength—increased by an amount known as the fade margin. This has the effect of increasing the amount of fading a signal can withstand before it becomes unusable.

A fade margin figure for a typical 6-GHz path is 30-40 dB. When the signal path is over a good reflecting surface such as water, additional fade margin must normally be provided.

Fade margin can be obtained in four ways. The first is to increase antenna gain by making the antenna larger. The second is to reduce the distance between antennas. The third and fourth are either to increase the transmitter power output or decrease the receiver noise figure. The effects of these adjustments vary widely and are often limited by expense or location.

Another solution to multipath fading is the use of diversity systems. Three methods have been tested and two are known to have been put into practical operation on microwave systems. Both frequency diversity and space diversity can reduce the amount of outage time due to deep multipath fading on most microwave systems.

The third method is polarization diversity. It requires two synchronized radios transmitting the same information on the same frequency but at different polarizations. The method has been useful in lower frequency radio systems using sky waves, but with space waves both polarizations have been found to fade simultaneously.

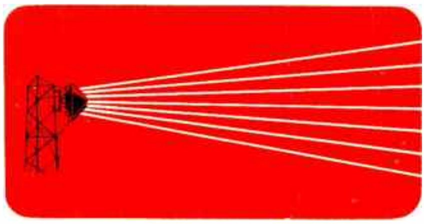


Figure 5. Radio signals spread as they travel through the atmosphere. In effect the signal becomes many beams each subject to the atmosphere's influence.

Frequency Diversity

Frequency diversity systems require at least two separate transmitters and two receivers operating on different frequencies. Normally it is not necessary to have a separate antenna for each transmitter and receiver. The receivers are connected to a diversity combiner which adds the two received signals to form a usable, combined output.

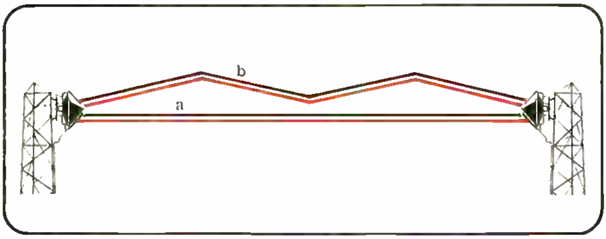


Figure 6. With frequency diversity two wavelengths travel the same refracted path (b) but will not have the same interfering effect on the direct wave (a).

Most frequency diversity systems have frequency separations of 2-5 percent of the lower frequency. This separation keeps the frequencies within the same band. Some systems use frequencies from two microwave bands, for example 6 and 12 GHz, thereby obtaining much greater separation. This latter method is called crossband diversity.

The effectiveness of frequency diversity depends on the wavelength differences of the frequencies in use. Fading occurs when the components of a signal interfere in such a way as to cause cancellation. Interference depends on the relationship of direct, reflected and secondary waves. With signals having different wavelengths but following the same paths, it is unlikely that they will cause simultaneous deep fades.

When considering any given path over which both frequencies must travel, it is easy to see why interference will not occur simultaneously on both frequencies. For each frequency there may be a number of different paths, but neither frequency can follow one path to the exclusion of the other frequency. When the wavelength of one frequency travels a distance which causes interference with the direct component of that frequency, the wavelength of the other frequency—traveling the same distance—will not have been delayed enough in its travels to interfere to the same extent with the direct component of its frequency.

As a solution to multipath fading, frequency diversity is simple and useful. The redundant arrangement of transmitters and receivers gives the system two complete electrical paths. This is a good hedge against equipment failures and an advantage when performing checks where service cannot be interrupted.

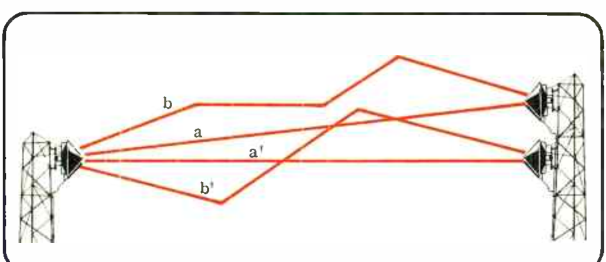


Figure 7. With space diversity the same wavelengths travel different refracted paths (b and b') but will not have the same interfering effect on the direct waves (a and a').

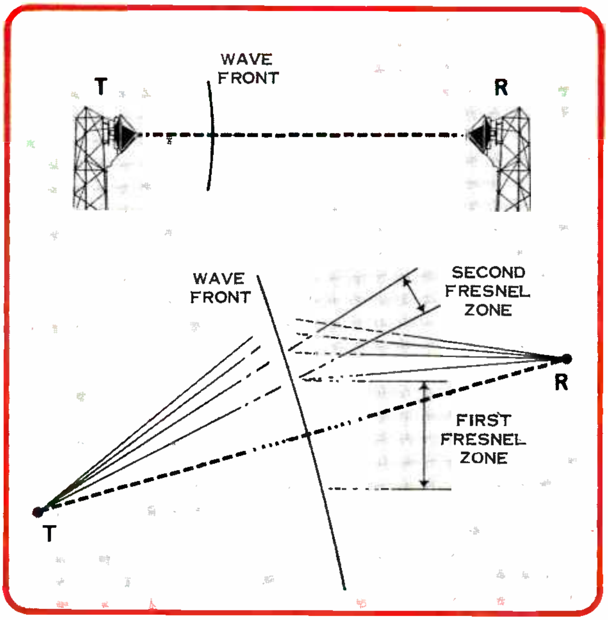


Figure 8. An unlimited number of Fresnel zones surround the direct beam. Here zones 1 through 4 are shown.

Space Diversity

In a typical space diversity system one signal is transmitted to two vertically spaced receiving antennas. At the receiving station the two signals are combined.

A space diversity system requires only one transmitter and two receivers, although most systems have a second transmitter in hot standby. In addition, a system must have at least two receiving antennas in order to provide the required vertical spacing. Each antenna must have its own waveguide.

Normally the additional antenna means a stronger if not separate antenna tower. In all probability the tower will also have to be taller in order to insure adequate vertical separation.

Unlike frequency diversity, which relies on wavelength differences, space diversity relies on path length differences. The working concept behind a space diversity system is that components of the same signal traveling different paths will not have the same interference points. The same wavelength is interfered with differently at two vertically separated points because it travels different length paths to the antenna.

Space diversity is the best protection against multipath fading if microwave frequencies are scarce. Although it does not have the advantage of two complete electrical paths, it avoids the problem of obtaining two frequencies for the same transmission path.

Interestingly, there is a growing controversy as to how the spacing between antennas should be determined. There are two schools of thought on the subject and, appropriately, they are diverse.

One approach is based on the assumption that multipath fading involves a complex interaction from more than one source of interference. This makes it difficult to calculate optimum antenna spacings on anything other than a statistical basis. As a result spacings are usually selected which are as wide as possible (based on the empirical conclusion that improvement would probably increase with separation) considering tower heights and other mechanical factors.

The other approach uses discrete, calculated spacings to combat simple two path, reflected component interference. It relies on a known vertical pattern of signal strength consisting of alternating nulls and maxima.

Fresnel Zones

Analysis of this pattern has shown that interference depends on the vertical distance between the direct component and a reflecting surface. The relationship is conveniently defined by Fresnel zones.

These zones form a series of concentric circles around the direct or shortest path between transmitter and receiver. The positions of the zones are wavelength dependent. Each zone contains wave components traveling paths no more than half a wavelength different in length. Two paths passing through corresponding points in adjacent zones will differ in length by half a wavelength.

Fresnel zones, of which there are an unlimited number surrounding a path, are numbered from the center out. Paths through the first Fresnel zone vary in length from the direct path by as much as half a wavelength. Paths through the second zone vary between half and one wavelength, those through the third by one to one and a half and so on. Each zone number represents an increase of half a wavelength in path length.

Figure 8 illustrates how the Fresnel zones surround the direct path. Each successive zone passes wave components which travel half wavelength differences. These zones can be used to determine where out-of-phase paths occur. Transmission engineers normally refer to paths passing through even zones as having components which cancel and those passing through odd zones as having components which reinforce the direct wave.

A knowledge of Fresnel zones is useful when planning a transmission path over reflecting surfaces. Because even Fresnel zones contain wave components which cancel the direct component, surfaces which reflect even zone components should be avoided. Logically the vertical distance between a direct component and a reflecting surface should

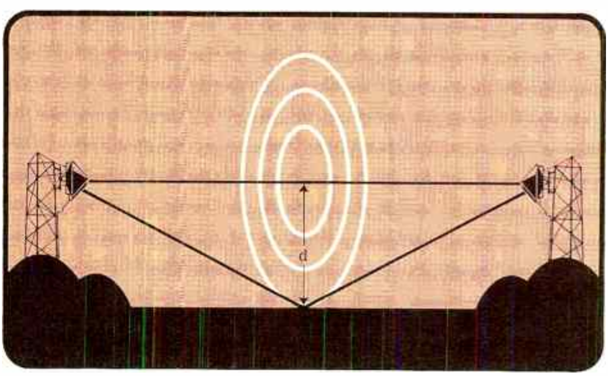
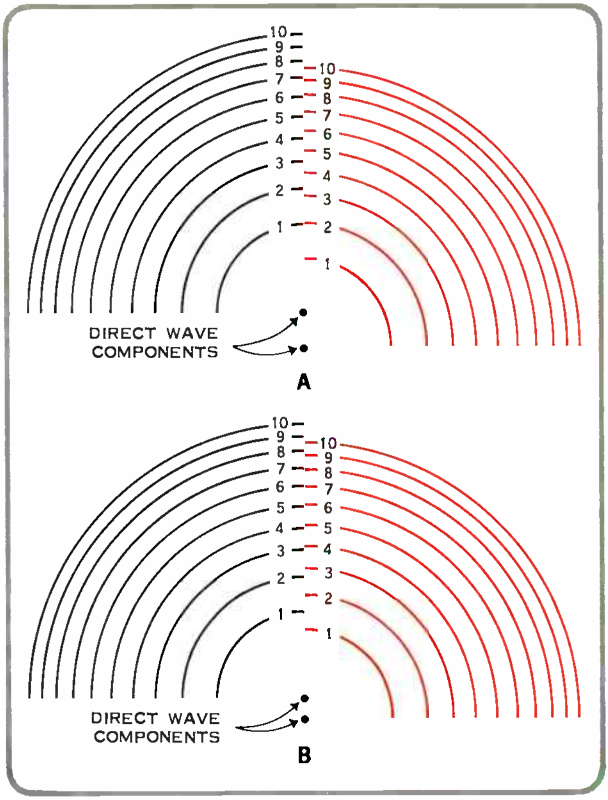


Figure 9. Reflected waves can interfere with direct waves. A distance, d, between reflecting point and direct wave equal to an odd Fresnel zone radius can cause reinforcement. If d equals an even zone radius, the two waves can cancel.

Figure 10. Fresnel zones around two direct waves can coincide. A reflection at zones 6 and 8 in A would cause cancellation. To overcome this other direct waves must be chosen to obtain the pattern in B. This is done by changing the position of at least one of the antennas.



be less than the radius of an even Fresnel zone.

Figure 9 shows the direct and reflected components of a wave. If the reflecting point is so located that components in an even zone are reflected, there will be a cancellation of the direct wave. It is for this reason that transmission paths are engineered to avoid reflections at even Fresnel zones.

On a transmission path receiving antennas are spaced to intercept two direct components. By calculating the reflecting points based on an expected value of K, it is possible to determine which direct components and which antenna heights are best suited to take advantage of the Fresnel zones.

Using the Zones

A rudimentary approach to calculated antenna spacings is to locate one antenna to receive waves reflected at an odd Fresnel zone for standard atmospheric conditions. The other antenna is then placed to receive those reflected at an adjacent even zone.

If the equivalent earth radius factor changes, the height of the direct wave changes. The positions of the Fresnel zones relative to the earth also change.

Unless there is a radical change in K, the antennas will continue to intercept reflections from adjacent Fresnel zones. As K increases, however, it is possible that reflection will occur at adjacent even or odd Fresnel zones.

This can happen because higher numbered Fresnel zones are closer together. This means that the Fresnel zones around two direct components creep up on each other (Figure 10). Eventually an even zone associated with one component can coincide with an even zone of another component. For instance, zone 8 might coincide with zone 6 on another direct component. When this happens at a reflecting point, there will be simultaneous nulls or maxima on both antennas.

To avoid this, antenna positions are sometimes fixed by determining or assuming the maximum possible value of K for the transmission path. With this method the distance between direct paths is chosen so that coincidence between even Fresnel zones will not occur at any reflecting points. There is some inefficiency in this system when K is at its normal value but this does not reduce the diversity effect.

The theory underlying the calculated approach is that reflections from locatable sources are the major contributers to multipath fading. On overland paths this is not always true. It is quite possible to have no reflections or to have two or more of them.

Studies of deep fading microwave signals have been made using paths with low coefficients of reflection. In spite of the low reflectivity, two, three, and sometimes more signal components were found. This discovery led to the belief that ground based reflection is not the only cause of multipath fading.

In Sum

Several years ago Lenkurt engineers, as well as other engineers, determined that diversity improvement would probably increase as vertical antenna separation increased. They concluded that in the 6-GHz band a spacing on the order of 30 to 40 feet offered a reasonable trade off between diversity improvement and tower height. Field experience with many systems has shown that space diversity engineered in this fashion provides extremely good protection against fading of the multipath type, whatever its source.

Based on these results space diversity appears to be an effective protection against multipath fading. It takes into account the disruptive influences of atmospheric reflection and refraction. In fact at times it capitalizes on these phenomena to obtain stronger signals than would be expected.

Whether the biggest fading damage is done by a reflecting surface or a refracting atmosphere depends on the specific path. It seems that over most microwave paths there is more multipath fading from atmospheric refraction than from reflection.

In either case space diversity or frequency diversity can protect against fading. Frequency diversity uses two frequencies and hence two wavelengths traveling over the same path. Space diversity uses two path lengths to send the same wavelength to the receiver. In both cases the different lengths prevent identical interference.

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