Use of Surface Waves in Communication With High Speed Vehicles

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The problem of communicating with and controlling vehicles moving in a one-dimensional frame is becoming more important in view of the increasing demands for fast and convenient transportation means. The future will undoubtedly reveal some form of continuous communication link between moving vehicles (automobiles, as well as mass transport vehicles) and a central control or communication station. Recent concern has been with the possibility of providing a suitable communication link without requiring additional space in the electromagnetic spectrum.

This paper discusses the use of surface waves in communicating with moving vehicles. The results of research being conducted indicate that, although there are still some unanswered questions, the surface wave line shows considerable promise as a potentially useful communication link.

•THE PROBLEM of maintaining a continuous communication link with a moving vehicle is one of pressing importance, not only in the area of mass transport but also in the highway field. Since highways are essentially one-dimensional, the techniques that apply to tracked vehicles may also be applied to the highways of the future. In this regard, one might envision a limited-access superhighway where a car is under the control of the driver only until he clears the entrance ramp. He then signals central control that he wants to "lock on" to the automatic control device, and he is free to read, watch TV, or do paper work. The operation of the vehicle would be completely controlled by a central computer which would maintain the necessary headway, a safe speed, and be alert to impending dangers. The driver thus gives up the right to pass other vehicles or otherwise dictate his own vehicle's performance. Since a person normally uses a private vehicle rather than a mass transport vehicle for reasons of personal convenience, it is quite logical to assume that the driver is willing to relegate the responsibility for vehicle performance to the central control facility. The mechanics of driving the vehicle are not attractive but are necessary if one is to enjoy this personal convenience.

If completely automatic control of private vehicles on the major highways can be achieved, then we are in position to combine the best of the mass transport concept with the convenience and comfort of private transportation. The traveler then need not be concerned with the problem of dealing with traffic and avoiding dangerous situations. In short, the driver can give his attention to matters that are his specialty. Thus, millions of man-hours of effort can be gained by executives and other high-level workers for whom transit time is otherwise lost.

The concept of continuous automatic control of tracked vehicles is more apparent and much more immediate. Even the most conservative highway engineers admit that, in some localities, the convenience of individual vehicles for interurban travel is taxing our economy unduly and an alternative must be found. If travel by mass media can be

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made attractive, the highway congestion problem can be significantly relieved. In this regard, the mass transport concept is being pursued vigorously by the Office of High Speed Ground Transportation of the U. S. Department of Transportation. Research is being sponsored by that office, which is addressed to the problem of meeting the transportation demands of the metropolitan areas. Interurban travel of the future must be largely by mass transport media. To be attractive, however, mass transport media must be clean, efficient, and fast, and must provide the traveler with certain conveniences which he, in fact, has a right to expect.

Of considerable importance in the mass transport medium of the future is a completely automatic control system. This will require a communication link that could also provide certain passenger conveniences such as television and telephone.

The cybernetics of a completely automatic system clearly would designate the central control unit (the computer) as the brain and the communication link as the nervous system. Thus, the brain can function properly only if the nervous system provides a continuous link with the functioning members of the overall system. The link becomes even more important under adverse environmental conditions when the human senses become less functional. In that case the driver indeed should rely on a "nervous system" and a "brain" not limited by environmental conditions.

THE SURFACE WAVE LINE

At the ESSA Research Laboratories, attention is being given to the communications link as it applies specifically to the mass transportation problem. The work is sponsored by the Office of High Speed Ground Transportation and is directed toward the development of a system that is predominantly a guided wave system with a negligibly small component of radiation. This would permit the use of a band of frequencies even though that band is assigned for another use.

The idea of guided waves for use with mass transport vehicles is not new. The British and the Japanese have both considered this concept and have conducted considerable experimental research. An excellent article which describes the position of the British Railways in this regard is given in a recent article by Barlow (1). The British Railways have, in fact, long recognized the need for uninterrupted coupling between the moving vehicle and a central communication facility. They have considered various schemes that would meet the demands of the transportation system (1, 2, 3). The Japanese likewise have concerned themselves with various communications schemes for use on the New Tokaido Line (4). This high speed line between Tokyo and Osaka provides passenger trains running at up to 150 mph. The communication schemes considered in Japan included both guided and leaky waves (5, 6, 7). In the latter, arrangement is made for radiation along the length of a waveguide by virtue of slots which can be adjusted to control the amount of radiation and the pattern.

Figure 1 depicts the nature of the problem and defined tasks; the major items that the Department of Transportation would like to provide are pointed out. It would be highly desirable if we could provide a sufficient bandwidth to satisfy the demands of convenience as well as safety for the interurban traveler. For example, the TV and telephone are conveniences the traveler has a right to expect. The safety aspects include providing key pieces of information to the central control unit—headway, speed, location, and obstacle detection, as a minimum. Ideally, this should be accomplished without requiring space in the already overcrowded electromagnetic spectrum (8).

The nature of the problem is clearly such that one must seek a compromise at the very outset. A good transmission line is, by definition, a poor antenna, and an antenna is a poor transmission line. The nature of a transmission line is such that it provides the guiding mechanism so that energy does not leave the structure. On the other hand, an antenna is a device that encourages energy to become detached; i. e., it is an impedance-matching device that matches the transmitter impedance to free space impedance in an efficient manner, and energy is thus encouraged to radiate from the structure. The problem of communicating with a moving vehicle brings out the basic difference between these two distinct concepts. On the one hand, a transmission line is desired in order that additional space in the electromagnetic spectrum is not required. An efficient device is also desirable in order to reduce the attenuation along the guiding

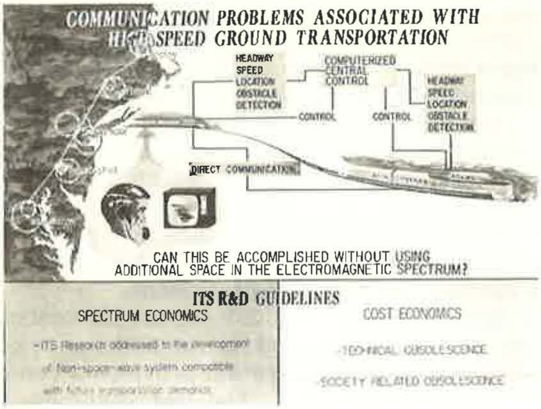


Figure 1. Pictorial representation of communication problems associated with high speed ground transportation.

structure. At the same time, a communication link with the moving vehicle must be maintained without turning to the concepts embraced in the definition of an antenna. Hence, we are led at once to a wired-wireless system (as it is sometimes called)—wired in the sense that there is a main guiding line and wireless in the sense that there is no wired connection to the moving vehicle.

The research being conducted indicates that a surface wave line may economically and adequately serve the needs of the high speed mass transportation program. It can be an efficient device, having low loss, and yet the energy can be coupled off at random points at almost any desired level of coupling.

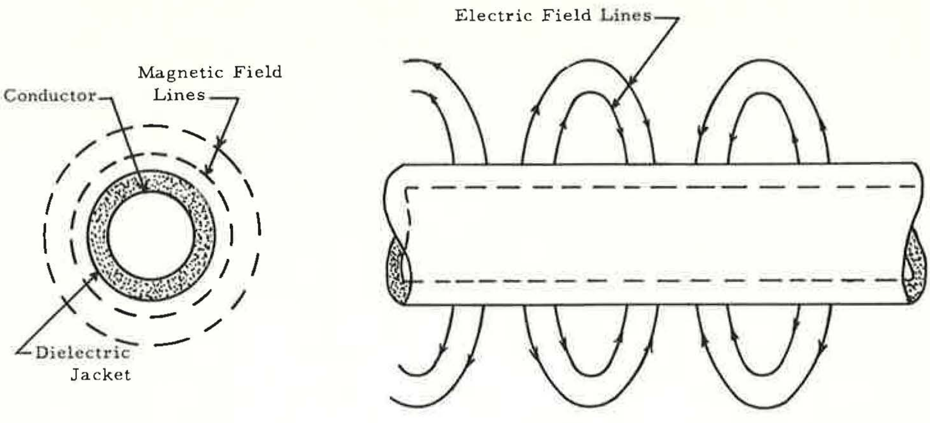
For our purposes, we define a surface wave simply as the wave propagating along the inductive interface between two media without radiation. It is distinguished from the leaky wave by the fact that there is not a continuous radiation of energy but, rather, the wave is bound to the surface by virtue of the boundary conditions. Radiation takes place only at curvatures, nonuniformities, and discontinuities. In this sense, radiation is taken to mean energy converted from the surface wave field to some other form. Because the interface between the two different media acts to bind the wave and guide it, the wave is sometimes called a trapped wave.

The chief characteristic of a surface wave is that its phase velocity is less than that of free space. This means that, in general, the field decays exponentially away from the structure (Fig. 2 shows how this comes about for the G-line, which will be discussed further). Power flow is parallel to the guiding structure except for the power flow into the structure due to the losses. There is a definite relationship between the decay away from the guiding surface and the phase velocity along the guiding surface. As the phase velocity decreases, the field concentration increases, i.e., the decay coefficient increases.

The surface wave structure that appears to be the most promising for purposes of communicating with a moving vehicle is that usually referred to as the G-line or Goubau line (9, 10).

The G-line consists of a circular cylindrical conducting tube with a dielectric jacket (Fig. 2). The dielectric jacket has the effect of reducing the phase velocity to less than the velocity of light, resulting in an exponential decay of the field in the direction normal to the surface of the line, even in the case of a perfectly conducting inner tube. The G-line is undoubtedly the single most important form of surface wave structure in terms of application. The principal mode is symmetrical about the line and has only an electric field component in the direction of propagation. The equations in Figure 2 give the variations of the field components of this mode along with the respective large argument approximations; the demonstration of the exponential decay is thus shown. The equations are valid outside the dielectric coating.

In the G-line configuration, as with any surface wave structure, the surface reactance (the ratio of E_z/H_θ in Fig. 2) that the wave experiences at the surface of the guiding structure is related to the phase velocity and hence to the radial decay coefficient, p. One of the important considerations in the design of a surface wave structure involves a choice of line parameters; the compromise in choice between dielectric constant, dielectric thickness, and inner conductor size must be made on the basis of tolerable attenuation, reasonable cost, and proximity of scattering objects in the field. A change in frequency can offset a change in any of these parameters. The difficult aspect of this stems from the fact that the interrelation between line parameters, frequency,



$$E_z = A K_0(pr)\, e^{-i\beta z} \longrightarrow A\sqrt{\frac{\pi}{2pr}}\, e^{-pr}\, e^{-i\beta z}$$

$$E_r = i\frac{A\beta}{p} K_1(pr)\, e^{-i\beta z} \longrightarrow iA\sqrt{\frac{\pi}{2pr}}\, \frac{\beta}{p}\, e^{-pr}\, e^{-i\beta z}$$

$$H_\theta = i\frac{A\omega\varepsilon}{p} K_1(pr)\, e^{-i\beta z} \longrightarrow iA\sqrt{\frac{\pi}{2pr}}\, \frac{\omega\varepsilon}{p}\, e^{-pr}\, e^{-i\beta z}$$

$$pr = k_0 r\sqrt{\Delta - 1}\,, \qquad \Delta = \left(c/v_p\right)^2$$

Figure 2. Cylindrical surface wave line with expressions for the field quantities and the large argument approximations.

attenuation, and decay coefficient is very complicated and not amenable to analytic considerations. Hence graphical techniques must be used. We have found that 500 MHz is the approximate lower practical frequency for lines of interest.

EXPERIMENTAL RESULTS

The major problems anticipated in the early stages of development included the coupling problem and the unknown effects of the environment. The coupling problem seemed paramount because it involved the unknowns of how to couple energy from the main surface wave line to the mobile receiver without undue spurious radiation. In this respect the advantages of the surface wave concept become evident because the energy is carried largely in the region outside the guide structure; i. e., most of the energy is carried in the air but is guided by the surface wave line. Only a small percent of the energy actually travels in the dielectric region. Because of this, it is simple to visualize a receiving element on the moving vehicle which intercepts a specified percent of the energy. This can be accomplished, in fact, but one must be alert to the possibility of causing a significant scattered field in the process. The surface wave is bound to the guiding structure, but the proximity of any scattering article will cause spurious radiations. Hence, a receiving element intended to couple energy off the main line must introduce minimum discontinuity, insofar as the main line is concerned, to avoid unwanted radiations.

The coupling device that seems most logical is a second G-line, identical with the first, which then acts along a given length parallel to the main line and intercepts a percent of the energy in the main line. The degree of coupling depends on the nature of the lines, the frequency, the length of the mobile section, and the separation of the two lines.

An analysis has been made of the coupling using a coupled transmission line approach, wherein the two coupled G-lines are thought of as four transmission lines with suitable voltage and current in each. A transmission line is associated with the dielectric region in each G-line and a transmission line is associated with the air region surrounding

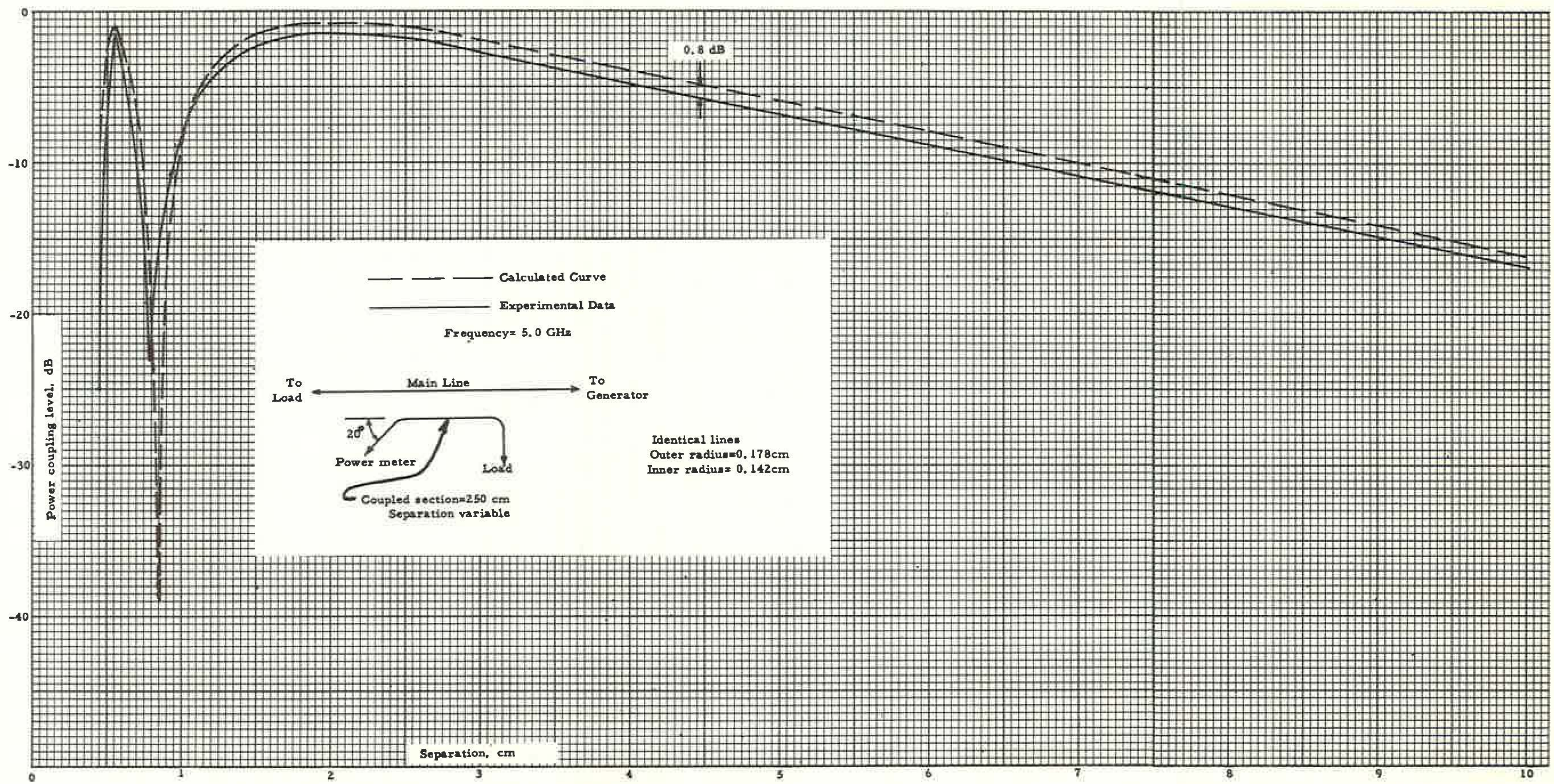


Figure 3. Theoretical and experimental data on the coupling between the main line and the mobile coupled section.

each G-line. The boundary conditions are then used to determine the unknown constants. This approach is possible because of the uniform nature of the lines in the propagation direction. The result of this approach is a description of the coupling between the two lines that depends on two hybird propagation constants; each represents a combination of effects because of the interaction between the two lines.

Data have been taken to demonstrate the feasibility of this technique with very encouraging results. Figure 3 shows the measured and the calculated coupling ratio as a function of separation. The experimental data were taken with a 20° corner as shown. The 0. 8 dB discrepancy is well within experimental tolerance. The data were taken at 5 GHz (λ_0 = 6 cm). The curve reflects a decrease in coupling level of about 12 dB per wavelength for separations of more than about a half-wavelength. This is quite typical for the lines considered. It is interesting to observe this linear dependence on separation. This is rather encouraging because of the implications concerning compensation for motion.

A TV picture has been used to test the fidelity of this coupling scheme, with rather good results. In the upper photograph of Figure 4, the picture was received from a commercial broadcast and cabled to a monitor about 500 ft from the receiver. For the lower photograph, the TV picture was put through the coupling loop, onto the main line, transmitted about 500 ft, received with a horn, and monitored. The difference in quality between the two is hardly noticeable. This was a live telecast and identical pictures could not be made. Television pictures were also observed for the case when the van with the coupling loop was in motion. The quality of the picture remained very high even though the guiding mechanism for the moving vehicle was quite crude.

Figure 4. Photographs showing live telecast as seen directly (upper) and through the mobile coupled section (lower).

The theoretical analysis made by Goubau was based on an infinite isolated line that was perfectly straight. Insofar as these conditions are satisfied, the mode, once launched, will propagate without radiation, the attenuation being due to the dielectric and conductivity losses. However, even in controlled laboratory situations, one has to admit bends and nearby objects. In the final system one has to admit atmospheric extremes also, which undoubtedly will influence the performance of the line as a transmission system.

Some data have been taken on the influence of rain on the line; it depends on the line parameters and the frequency, as expected. The data (Fig. 5) show an attenuation due to water accumulation that varies approximately as f^4 where f is the operating frequency.

The influence of birds and rain can be reduced or even eliminated by shielding the line. This forces the object to be sufficiently removed from the high field strength region and thus have small influence on the field. Since the field strength decay is exponential (at reasonable distances), the shield need not have a large radius. The shield considerations have many concomitants. A metallic shield would obviously shield the field electrically and the field inside the shield could not then be influenced by objects on the shield. However, there would have to be a longitudinal slit to permit coupling to

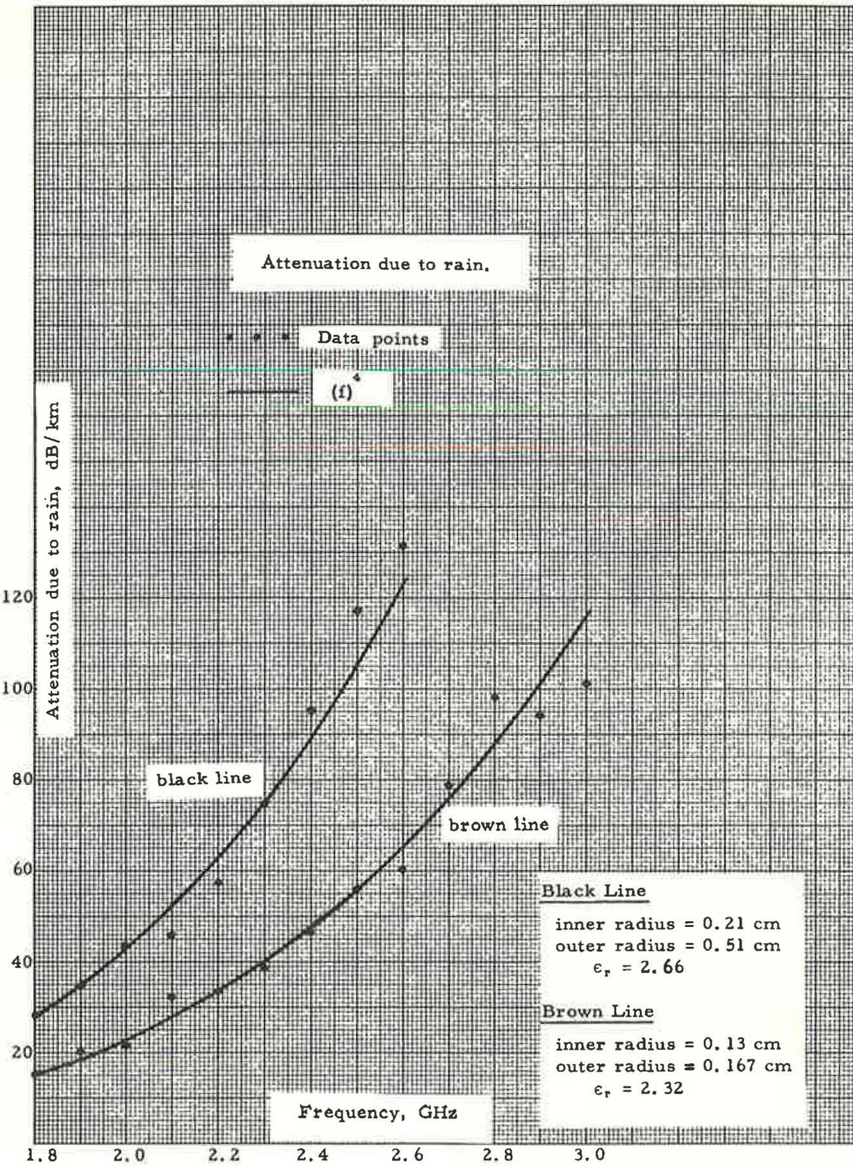


Figure 5. Data on attenuation of surface wave line due to rain.

the mobile line. In the slit region, the field would extend into the surrounding region and coupling could be accomplished. Alternately, a dielectric shield could be used that completely encloses the main line. Since the dielectric would not electrically contain the field, coupling could be accomplished in the usual manner through the shield. In either case, one changes the original line structure sufficiently that other modes could be supported and would propagate if excited. Data have been taken with a dielectric shield surrounding a G-line and the additional attenuation is small, being an additional 10 percent in one case tested. Coupling through the dielectric shield is also no problem, although higher order modes on the shield itself are known to be excited in some cases.

The radiation due to bends in the surface wave line need not be a problem. If the radius of curvature is maintained at a reasonable size, there is very little radiation at the bend. In fact, loss due to bends with 7-cm radius of curvature (which is much smaller than what would be encountered in practice) is a linear function of bend angle. For reasonable bends the loss is quite small. These data were taken using a small line at 5.0 GHz. The phase velocity reduction here was only about 2 percent, so the field decay coefficient was not as small as it might have been. The effects of rain or other objects and bends can be reduced considerably by reducing the phase velocity, thereby increasing the field concentration. This demonstrates the compromise one always faces—the choice of line parameters that gives a suitable balance between line attenuation and field concentration. Ideally, the field concentration should be sufficient to avoid substantial scattering by nearby objects and yet should be such that most of the energy is traveling in air. Indeed, the fact that the line will guide the energy with most of the energy actually existing in the surrounding air, is what makes the G-line so useful. As more and more of the energy is forced to travel in the dielectric jacket itself (by virtue of an increased field concentration factor), the losses increase because of the loss tangent of the dielectric.

CONCLUSION

The research program described here is addressed to the problem of providing a reliable communications link for high speed mass transport vehicles. The Office of High Speed Ground Transportation in the Department of Transportation, the sponsor of this work, is well aware of the crisis that exists in electromagnetic spectrum utilization; hence, they are seeking a communications link that does not radiate. The surface wave line appears to be quite promising in this respect. In this paper, data have been presented that tend to substantiate the feeling that a wired-wireless communications link with a substantial bandwidth can be provided.

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