Open Wire Lines*

GEORG GOUBAU†

Summary—**The properties of two-wire lines and single wire lines (surface wave transmission lines) are discussed on a comparative basis. The two-wire line is actually a system of two coupled single wire lines and thus requires a high degree of symmetry to maintain the desired wave mode. While the single wire line is more affected by bends it has the advantages that it is simpler in construction and is less susceptible to weather conditions. The main domain of the two-wire lines lies in the frequency range below 100 mc and that of the single wire line in the range above 100 mc.**

FUNDAMENTALS OF OPEN WIRE LINES

THE MAJOR representatives of open wire lines are the two-wire line (TWL) and the single wire line or Surface Wave Transmission Line (SWL). Multiwire lines, such as three phase lines, have seen very little application at radio frequencies and shall not be considered in this paper.

The TWL is historically the oldest waveguide. It was introduced by Lecher in 1890 and has been in use ever since. The SWL too goes back to the past century, in that Sommerfeld[1] in 1898 derived the field of a nonradiating wave which is guided by a single wire with finite conductivity. However a single wire had not been used as a waveguide until recently. Sommerfeld did not suggest that the wave he derived might have applications. He actually intended to show in his paper that the velocity of waves on wires is affected by the conductivity of the wires, since Hertz had concluded from his experiments that the velocity is the same as in free space. Sommerfeld considered a cylindrical field on a single wire for simplicity reasons and suggested methods for the treatment of the "actual case" of a two-wire line.

Harms[2] in 1907 extended Sommerfeld's theory to an insulated wire in order to explain the fact that the resonance wavelength of an antenna made of insulated wire is greater than in the case of a plain wire. None of the early publications differentiated between truly guided waves (surface waves) and partially guided or radiating waves, as the waves may be called which are predominantly present on long wire antennas.

When the more rigorous theories on linear antennas were developed by Hallén, King, Schelkunoff, and others, these theories did not yield the Sommerfeld wave. Experiments too showed no evidence of a surface wave. A wire coupled to a power source in the usual manner does not behave like a waveguide since it radiates the energy into space. For these reasons it was frequently believed that surface waves on single wires are nonexistent. Now we know that both types of waves, the radiating and the nonradiating waves exist simultaneously. They are independent solutions of Maxwell's equations satisfying the boundary conditions on the wire and the mutual orthogonality relations:[3]

$$\int_S (E_s \times H_r) n dS = \int_S (E_r \times H_s) n dS = 0$$

where E_s, H_s and E_r, H_r denote the field vectors of the surface wave and the radiating wave respectively; n, the unit vector in the direction of the axis of the wire; and S, the surface of an infinitely extended plane perpendicular to the wire. It is the kind of excitation which determines whether the one or the other wave type is predominant. If the wire is excited by a concentrated source, for instance, by means of a little coil which is inserted into the wire and coupled to a transmitter, only the radiating wave is observed. In order to excite predominantly the surface wave, a special launching device must be used which preshapes a field to match the field distribution of the surface wave. Usually the launching is done with horns, as shown in Fig. 1.[4,5]

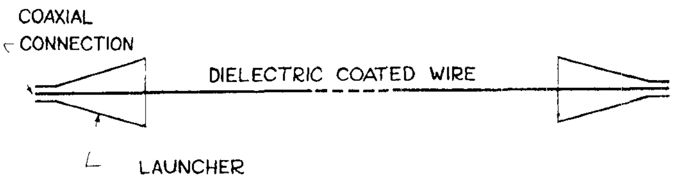

Fig. 1—Sketch of a surface wave transmission line.

In addition, the wire is covered with a dielectric layer which concentrates the field of the surface wave closer to the wire. This not only simplifies the excitation of the surface wave but also makes the wave less susceptible to objects in the proximity of the line. Corrugating the surface of the wire has a similar effect but is not practical for long lines. No special surface treatment is necessary at millimeter waves because the normal conductivity and the oxide layer which forms on the wire cause sufficient concentration of the field at these very high frequencies.

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† Signal Corps Engrg. Labs., Fort Monmouth, N. J.

[1] A. Sommerfeld, "Fortpflanzung elektrodynamischer Wellen an einem zylindrischen Leiter," *Ann. Phys. Chem.*, vol. 67, p. 233–290; March, 1899.

[2] F. Harms, "Elektromagnetische Wellen an einem Draht mit isolierender Hülle," *Ann. Phys.*, vol. 23, p. 44–60; January, 1907.

[3] G. Goubau, "On the excitation of surface waves," PROC. IRE, vol. 40, pp. 865–868; July, 1952.

[4] G. Goubau, "Surface waves and their application to transmission lines," *J. Appl. Phys.*, vol. 21, p. 1119–1128; November, 1950.

[5] G. Goubau, "Single-conductor surface-wave transmission lines," PROC. IRE, vol. 39, pp. 619–624; June, 1951.

The concentration of the field is associated with a reduction in phase velocity. However the reduced phase velocity is not a general requirement for surface waves. Barlow, Cullen, and Karbowiak[6,7] demonstrated recently that a dielectric rod with losses is able to guide a wave with a phase velocity greater than that of light. This is of particular interest as this wave is the cylindrical analog to the Zenneck wave, the reality of which has been the subject of many vigorous discussions. The Zenneck wave is guided by the interface between a nonconducting and a conducting dielectric and was introduced by Zenneck[8] in 1906 in a first attempt to explain the fundamental phenomena of wave propagation along the earth. One of the objections against the Zenneck wave was that its phase velocity is greater than that of light.

Returning to the TWL, the field on this line is not quite as simple as it is usually presented in text books. The standard derivation of the field from Maxwell's equations disregards the conductivity losses. The result is then a TEM wave which propagates with the velocity of light. The currents in the two wires are alike in amplitude, but 180° out of phase, whether the cross sections of the wires are the same or different. The finite conductivity is usually introduced as a perturbation whereby the assumption is made, that the cross-sectional field distribution is not substantially affected by the conductivity. This procedure, however, gives only the correct result, when the two wires are identical. Actually the TWL is a system of two coupled SWL's, and as such has two coupling modes with different phase velocities. If the wires are alike, the currents associated with each of these modes have the same amplitude in both wires. They are in phase for one mode and 180° out of phase for the other mode. The latter mode is the regular two-wire wave. If the wires are not alike the amplitudes of the currents of each mode are different in the two wires. When such a line is excited in the usual manner, the currents in both wires have the same amplitude at the input terminals. However since none of the two coupling modes has equal currents in both wires, the two modes are excited simultaneously. As they propagate with different phase velocities, the ratio between the resulting currents in both wires varies along the line. This effect is more pronounced with increasing frequency. Apparently a TWL with bare wires of different conductors has not been treated in the literature. The behavior of such a line must be essentially the same as in the case of coupled dielectric coated wires of different dimensions, a case which has been first investigated by Meyerhoff.[9]

In the following we consider only TWL's with identical conductors. The fact that the ordinary two-wire mode with equal currents in the two wires requires identical wires indicates that the mode is not stable, in that the wave splits into two waves if the dimensions of the wires vary somewhat along the line. This effect is usually of no importance, except in the microwave range. There, the normally present oxide layers on the wire have a considerable effect on the phase velocity, and if these layers vary along the line, the instability may become quite noticeable.

The TWL requires in general no launching devices. If the excitation of the line is symmetrical, the radiating fields of the currents in the two wires compensate each other to a large extent, provided the spacing d between the wires is very small compared to the wave length λ. However, since the spacing cannot be reduced arbitrarily without greatly increasing the conductivity loss, the condition $d/\lambda \ll 1$ is not satisfied at microwave frequencies. A microwave TWL therefore should also have a launching device if the efficiency of excitation is of importance. Apparently not much attention has been given to this problem. Fig. 2 shows a proposed device for the excitation of a two-wire line from a rectangular waveguide with TE_{10} excitation.[10] The drawings are self-explanatory. Presumably the efficiency of these launchers is not very good because a considerable fraction of the energy of the TE wave will escape where the side walls of the guide are cut away.

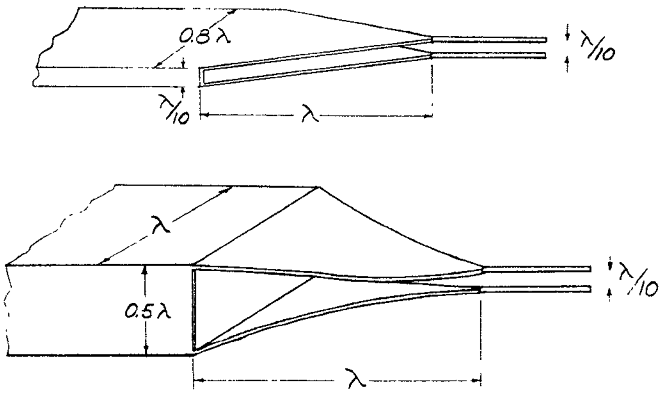

Fig. 2—Excitation of a two-wire line from a waveguide.[10]

PROPERTIES OF TWO-WIRE AND SINGLE-WIRE LINES

In the following the properties of the TWL and the SWL are discussed on a comparative basis. Data on

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[6] H. E. M. Barlow and A. L. Cullen, "Surface waves," *Proc. IEE* (London), part III, vol. 100, p. 329–347; November, 1953.

[7] H. E. M. Barlow and A. E. Karbowiak, "An experimental investigation of axial cylindrical surface waves supported by capacitive surfaces," *Proc. IEE* (London), part III, vol. 102, p. 313–321; May, 1955.

[8] J. Zenneck, "Uber die fortpflanzung elektrodynamischer Wellen Langs eines Drahtes," *Ann. Phys. Chem.*, vol. 23, p. 846–866; September, 1907.

[9] A. A. Meyerhoff, "Interaction between surface wave transmission lines," Proc. IRE, vol. 40, pp. 1061–1068; September, 1952.

[10] French Patent Gr. 12-cl.6.#891,442.

single wire lines given during the panel discussion have been omitted since they will be published in a separate paper.[11]

Field Extension

The cross-sectional field of a two-wire wave on a TWL with bare conductors decreases, within a range of several wavelengths, with the square of the distance D from the line. At very large distances the decrease becomes exponential, due to the finite conductivity of the wires. The field of the wave on a SWL with dielectric coated conductor decreases first only with $1/D$, but approaches the exponential decrease much sooner. Therefore, assuming equal transmitted power, the field around a SWL is larger than that around an ordinary TWL if small distances are considered. However it is smaller around the SWL if the distances considered are several wavelengths. If a SWL of common design is compared with a TWL (with bare conductors) of equal loss per unit length, the field of the TWL exceeds that of the SWL in general at distances greater than 2 wavelengths. The SWL is more sensitive than the TWL to obstacles at a distance of less than 2 wavelengths. This fact restricts the applicability of SWL's to higher frequencies, say frequencies above 50 mc. Any line-supporting structures such as telephone poles must be kept farther away from the line than in the case of a TWL.[11]

Discontinuities

Bends: A bend in any open waveguide causes a certain amount of radiation loss. In the case of a TWL the radiation loss is small at low frequencies because the radiation field of the individual bends in the two wires compensate each other if $d/\lambda \ll 1$. The discontinuity produces primarily a reactive distortion which can be represented by an equivalent circuit shown in Fig. 3.[12] In the microwave range the radiation loss may become large particularly if the bends in the two wires are not identical or if d approaches or exceeds $\lambda/4$. In the case of the SWL with dielectric coated wire the radiation loss of bends is appreciable at all frequencies. It depends mainly on the ratio between outer and inner diameter (conductor diameter) and is only slightly dependent on the frequency.[11] The reactive distortion is usually negligible. The loss of bends in SWL's can be considerably reduced by appropriate supporting methods. One method which is mainly applicable within the uhf range is discussed in a separate paper.[11] Another method particularly adapted for 90° turns in microwave SWL's has been described by Chavance and Chiron.[13] The wire is laid around a dielectric pulley as shown in Fig. 4. By proper dimensioning of the pulley the loss of the bend can be made very small. The following table quotes results obtained by Chavance and Chiron at a frequency of 3150 mc with a polyethylene coated wire of 5 mm outer diameter and 2.5 mm inner diameter. The pulleys were made of polystyrol and had a diameter of 20 cm. The thickness of the pulleys was varied.

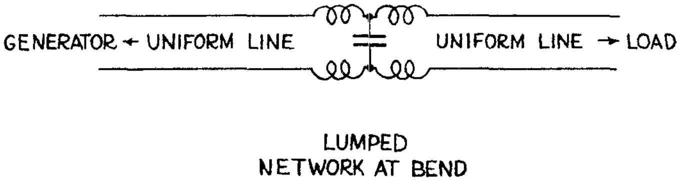

Fig. 3—Equivalent circuit for a bent two-wire line.[12]

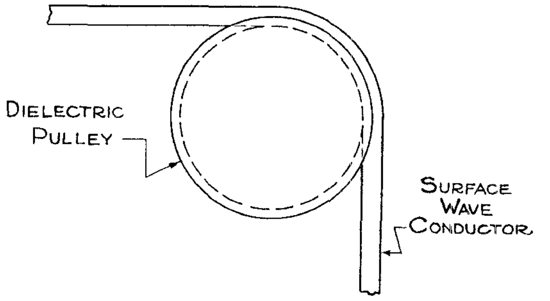

Fig. 4—Loss reducing support of a surface wave transmission line at a 90° bend.[13]

Thickness of the pulley in mm	Loss of the bend in db
5	0.2
8.5	negligible
10	negligible
15.5	negligible
31.5	0.8

Sag: Both the TWL and the SWL are insensitive to sag. However, the bends produced by the sag at the supporting points of long SWL's cause some loss. Results of loss measurements on SWL's requiring supports are given in the above mentioned separate paper.[11]

Spacers and Supports of TWL's: The TWL requires dielectric spacers. They constitute, as well as the support, discontinuities, and cause partial reflection and to some extent radiation. Part of this radiation is caused by the polarization currents induced in the dielectric material of the spacers. At low frequencies the effect of such discontinuities is mainly capacitive reactive and

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[11] G. Goubau and C. E. Sharp, "Investigation with a model surface wave transmission line," submitted in February, 1956 for publication in IRE TRANSACTIONS.

[12] K. Tomiyasu, "The effect of a bend on a two-wire transmission line," Cruft Lab. Tech. Rep. No. 74, part II.

[13] P. Charance and B. Chiron, "Une étude éxperimentale de transmission d'ondes centimétrigues sur guides d'ondes filiformes," *Ann. des Télécommun.*, vol. 8, p. 367–378; November, 1953.

can be compensated, for instance, by inserting small inductances in series with the line. The effects of the spacers are severe at microwave frequencies. The discontinuities can be avoided by embedding the wires in a Polyethylene tape or tubing (twin-leads). Such lines, however, are more susceptible to weather conditions.

Supports of SWL's: The most simple method of supporting long SWL's is by means of slings of nylon cord. The loss caused by such cords is negligibly small. Experimental data are given in the above quoted paper.[11]

Weather Effects

The SWL with dielectric coat is much less sensitive to weather effects than the TWL (at the same frequencies) for several reasons. The dielectric layer of the SWL prevents rain, snow, or ice from reaching the region of highest field concentration. This is at least the case if the thickness of the dielectric layer is in the order of the wire radius. Such layer thicknesses are required for lines used in the uhf range. A TWL becomes unbalanced if the deposits of rain drops, snow, or ice are not equal on both wires. Expecially sensitive to weather effects are the twin-leads since a large area of highly concentrated field is exposed to the precipitation.

The SWL is surprisingly insensitive to weather effects. At frequencies below 500 mc the loss caused by rain or dry snow is hardly measurable and of no practical consequence even if lines of several miles length are considered. Ice as it forms under freezing rain conditions also causes no severe increase in loss. Up to now no data are available on loss measurements made during very heavy ice formation. The effect of weather conditions increases rapidly with frequency. At 2000 mc, for instance, an increase in loss during rain may be measured which exceeds 5 db per 100 feet for horizontally stretched lines. This increase is caused primarily by the drops adhering to the wire. These drops act as little radiating dipoles. If the line is used as an antenna feed and inclined against the ground the number of adhering drops is reduced and the loss due to rain is less than 1 db/100 feet. Preliminary measurements at 5000 mc indicate a loss increase of inclined lines of about 5 db/100 feet. Electric heating of the wire reduces the effect of rain considerably, presumably because the adhesion of the drops to the wire is reduced. An efficient remedy against the effect of rain in the upper microwave frequency range would be to remove the drops mechanically by shaking the line. However, the question is whether such a method is practical. The formation of ice has serious effects in the microwave range and must be prevented by electric heating.

Power Carrying Capacity

The cw-power-carrying capacity of the SWL is primarily determined by the heat breakdown of the dielectric layer and is smaller at low frequencies than that of a TWL. The peak-power carrying capacity (in the case of pulse modulation) however, is considerably greater. It is also high in comparison to that of closed waveguides. Fig. 5 shows the power-carrying capacity of a SWL at 3000 mc for a bare wire and a wire with a thin dielectric coat.[14]

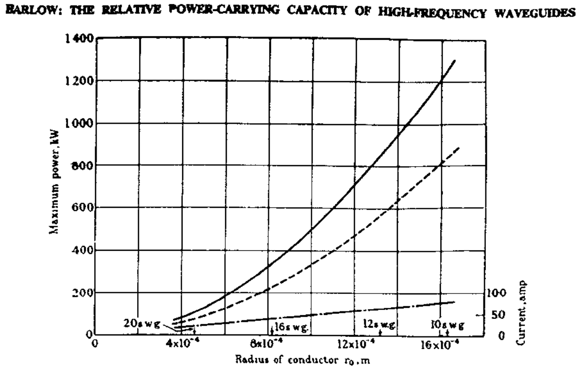

Fig. 5—Maximum power-carrying capacity of surface wave at 3000 mc supported by copper wires of various sizes.[14]
——— perfectly smooth surface.
– – – surface with enhanced reactance (radial decay factor ten times that of smooth surface).
–·–·– current corresponding to maximum power. (Reproduced from *Proc. IEE.*)

CONCLUSION

Compared to closed waveguides the open wire lines have advantages as well as disadvantages. They require little material, are inexpensive, easy to install, and have high power-carrying capacity. Their disadvantages are founded in the fact that they are open waveguides and as such are susceptible to weather conditions. The main domain of the TWL's lies in the frequency range below 100 mc and that of the SWL's in the frequency range above 100 mc. The applications of the two-wire line are well known. The SWL, as a newer device, has not yet seen a widespread application. However, it is successfully in use for antenna feeds in radio relay equipment[15] and recently has been applied also to long distance transmission in a community tv system.[16]

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[14] H. M. Barlow, "The relative power-carrying capacity of high-frequency waveguides," *Proc. IEE* (London), part III, vol. 99, p. 21–27; January, 1952.

[15] C. E. Sharp and G. Goubau, "A uhf surface wave transmission line," PROC. IRE, vol. 41, pp. 107–109; January, 1953.

[16] A. S. Taylor and B. Hamilton, "Community television systems," presented at 1956 Seventh Region Technical Conference and Trade Show, Salt Lake City, Utah, April 13, 1956.