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# CHAPTER I

## INTRODUCTION

### 1. Signalling systems

From the engineering aspect any signalling system is a power transmission system; but whereas in most power transmission systems ordinarily so called it is essential that the power received shall be a large fraction (approaching unity) of the power transmitted, and the switching or control of power is of secondary importance; in a signalling system the switching or control processes are of primary importance, and the received power may be ever so small a fraction provided only it be perceptible.

In every power transmission system energy is conveyed from a *transmitter* T to a more or less distant *receiver* R through a connecting *medium* M. We may picture an identifiable packet of energy entering M at T, and part of it being subsequently handed over at R. We say *subsequently* because, however little may be the practical importance of the time of transit from T to R, we believe that *some* time must elapse before energy located at one place reaches another place*.

An extreme example of a power transmission system is provided by the familiar agricultural wind-driven pump. Here the wind motor T at the top of a tower transmits energy to the vertical rod M connecting it to the pump R in a well underneath. It is true that we are apt to think of the energy which leaves T as passing directly to R; but we do so only because the rod is short—or, more precisely, because the time taken for a stress to be propagated from end to end of the rod is short compared with the period of rotation of the crank. The action of the machine would remain unchanged in principle if the wood rod M joined to cranks T and R were replaced by a column of water filling a pipe joined to cylinders with

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* Whether in the new physics it is necessary or nonsensical to think of energy as possessing the attribute of position, and although the aether of Faraday and Maxwell threatens to introduce intellectual difficulties of a kind it was expressly invented to dispel, it seems certain that for many years to come engineers—even those concerned with free electrons and with radiation—must continue to employ the language and conceptions of the classical mechanics, of Newton and of Maxwell.

pistons. But if now the pipe were much lengthened, or if the piston T were made to vibrate much more rapidly, the machine would operate on the Constantinesco water-wave power-transmission principle, and we should have no hesitation in thinking of the transmission of energy from T to M as an event separate from the subsequent reception of energy by R from M. The significant change is merely the increase in the ratio between the time of propagation of a disturbance along M and the period of T, or (as we shall see later) in the ratio between the distance TR and the wavelength of the disturbance propagated in M.

If the distance TR were lengthened sufficiently, the reaction of R on T would become indefinitely reduced; and with a very long water column the transmitter T would deliver its energy to the medium M without being affected by the conditions at R—indeed, whether or not there were a receiver at R at all.

An ordinary short-distance telegraph or telephone installation is an electrical power transmission system analogous to our mechanical example with a short wood rod or water column. The P.D. at the receiving end of the line is approximately a copy of the P.D. applied at the transmitting end; and if the received power were cut off by opening the circuit at R, the transmitted power would also fall approximately to zero. But as the connecting line is increased in length, an electrical system is approached which is analogous to the Constantinesco system arrived at on sufficiently lengthening the water column in the mechanical example. Thus in a long submarine telegraph cable, the transmitter T may deliver its spurts of energy to the cable M almost unaffected by the conditions at the receiver R. Telephone lines are of all lengths, so that telephone installations may be encountered occupying every position from the indefinitely short line, analogous to the wind pump with the usual short wood rod, to the "infinite" line in which the conditions at the receiving end have no perceptible influence at the transmitting end.

On passing from electrical power transmission with conducting lines as the connecting medium to wireless telegraphy in which the conductors are dispensed with, the same gradual transition from the seemingly direct to the obviously indirect may be discerned. An early demonstration of telegraphy in which conduction currents between transmitter and receiver were clearly not instrumental in effecting communication was made by W. H. Preece across the mouth of the Severn in 1886*. The short stretch (four miles or so) of aether as the medium M between his transmitting and receiving loops T and R corresponds with the wood rod of the wind pump or the short line of a local telephone connection. Nevertheless, energy passed from T to R only by way of a stress propagated across M. To-day a broadcast transmitter T situated in the heart of a city transmits to receivers R situated at all distances ranging from hundreds of feet to hundreds of miles. Whether the receiver be near or far, the energy is communicated from T to R only by propagation across the connecting medium M.

Thus no sharp physical distinction can be drawn between direct and indirect, between short range and long range; in every case a wave of disturbance (mechanical or electrical) is propagated across the connecting medium, be it wooden rod, the atmosphere, or pure aether. Differentiation is a question of practical emphasis only, and appears to depend on the relative lengths of the time of propagation across the connecting medium and the period of the disturbances propagated. The agricultural mechanic is not forced to dwell upon the propagation of mechanical stress along his wood rod, nor the electrician upon the propagation of electrical stress along his bell wires; but the telephone engineer *is* forced to consider how electric disturbances pass along his cables, and still more the wireless engineer how they pass across the aether connecting his transmitter and receiver.

The mechanism of the propagation of the disturbance within the medium is designated wave motion, and the disturbance is called a wave.

## 2. WAVES

It is not easy to give a succinct and general verbal definition of the phenomenon to which the term wave or wave motion is applied. "Speaking generally, we may say that it denotes a process in which a particular *state* is continually handed on without change, or with only gradual change, from one part of a medium to another†." Let

$t$ = time from an arbitrary instant;
$r$ = distance from some fixed point;
$\chi$ = displacement (or stress or strain or other disturbance) in the medium at time $t$ and position $r$.

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[*] See J. J. Fahie, *History of Wireless Telegraphy* (1901), p. 145.
[†] *Encyclopaedia Britannica.*

Then the medium is the seat of a wave if

$$\chi = f(r + vt),$$

where $f$ stands for any function, and $v$ is a constant. The physical meaning of the equation is this: if an explorer, being situated at a definite point in the space-time continuum, sets out to examine neighbouring regions, he finds that the disturbance $\chi$ varies by the same amount if he advances spatially to a position $r'$ (i.e. moves a distance $(r' - r)$) as if he stays where he is and lets time flow past him by an amount $(t' - t)$, provided that

$$r' - r = v(t' - t).$$

At any spot, $\chi$ varies with time $t$; and at any instant, $\chi$ varies with distance $r$; but if, as time passes from $t$ to $t'$, the explorer also retires through the appropriate distance $(r' - r) = v(t' - t)$, the disturbance $\chi$ under his observation remains unchanged.

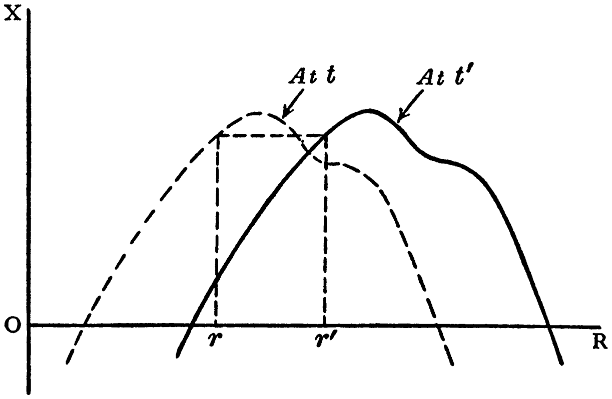

Fig. 1. A wave.

In Fig. 1 the full-line curve is supposed to be the plot of $\chi$ as a function of $r$ at a particular instant $t$. This plot must be shifted along RO at the speed $v$ if it is to show the relation between $\chi$ and $r$ at subsequent instants. A wave of $\chi$-ishness (whatever $\chi$ may be), whose shape depends on the form of the function $f$, moves through the medium (in the negative direction of $r$) with speed $v$. In the same way, $\chi = f(r - vt)$ is a like disturbance propagated in the positive direction with the same speed $v$*.

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* The two waves $\chi = f(r + vt)$ and $\chi = f(r - vt)$ are the solution of the characteristic wave equation $\frac{\partial^2 \chi}{\partial t^2} = v^2 \frac{\partial^2 \chi}{\partial r^2}$, as may be verified by substitution.

In wireless telegraphy (and in telephony) the chief interest is confined to *persistent waves*, that is, those in which the function $f$ is a periodic function. As the simplest persistent wave, we take

$$\chi = A \sin 2\pi \left(\frac{r}{\lambda} - \frac{t}{T}\right).$$

Here $\chi$ repeats itself at every increment $\lambda$ in distance and at every increment $T$ in time. $\lambda$ is called the *wavelength*; $T$ is called the *period*, and the reciprocal $\frac{1}{T} \equiv n$ is called the *frequency*; $A$ is called the *amplitude* of the wave. As before the *velocity of propagation** is $v = \frac{\lambda}{T} = \lambda n$.

The wave $\chi = A \sin 2\pi \left(\frac{r}{\lambda} - \frac{t}{T}\right)$ is an ideal extreme case which in the real world can only be approached, for it continues wholly unchanged over an infinite extent of space $r$ and time $t$. If a steady tone is sounded continuously at one end of an ideal speaking tube whose other end is infinitely remote and whose walls neither transmit nor absorb energy from the air within, then whenever and wherever along the tube an observation is made it is found that the air pressure within the tube goes through the same cycle. But in any real tube, the amplitude must get smaller the further is the point from the source of sound; for the tube does not in fact perfectly confine and preserve the sound energy, but allows some to penetrate to the outer air, and converts some into thermal energy in the metal. The amplitude $A$ is then not a constant, but diminishes as $r$ increases (although the change may be slight for increments of $r$ of the order of a wavelength)†. Such a wave is said to have *attenuation*, and does not conform strictly to our definition $\chi = f(r + vt)$; but the likeness of a moderately attenuated wave to a true wave is as obvious as the likeness of a moderately "damped harmonic motion" to a true (undamped) harmonic motion; and in each case much understanding of the properties of the former is conferred by a study of the latter.

In addition to spatial attenuation—i.e. $A$ not quite independent of $r$—it is obvious that in real waves $A$ can be taken as independent

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* More precisely, the *phase velocity*. See III–5 (a).

† If the tube had a bore which increased with distance from the source—and especially if the directing tube were absent altogether—the amplitude would diminish still more rapidly with increase of distance from the source.

of $t$ only over a limited range of time; and indeed in wireless telegraphy and telephony it is the rise and fall of $A$ with time which constitutes the signal. Thus the electrical disturbance set up around (say) the London (Oxford Street) broadcasting station is a modulated attenuated wave which—in the absence of various complicating factors here ignored—may be written

$$\chi = \frac{a + \alpha \sin 2\pi \frac{t}{\tau}}{r} \sin 2\pi \left(\frac{r}{\lambda} - \frac{t}{T}\right),$$

where the former constant $A$ is replaced by a quantity

$$\frac{1}{r}\left(a + \alpha \sin \frac{2\pi t}{\tau}\right).$$

At any spot—e.g. Hitchin or Huntingdon—this quantity fluctuates with an acoustic period $\tau$ (e.g. $\tau = \frac{1}{1000}$ sec.); and its maxima and minima are roughly twice as great at Hitchin as at Huntingdon. Nevertheless, since at Hitchin and Huntingdon $r \gg \lambda$, and since $\tau \gg T$, in considering the nature of the propagation of energy it is useful to treat the disturbance as a true persistent unattenuated wave

$$\chi = A \sin 2\pi \left(\frac{r}{\lambda} - \frac{t}{T}\right).$$

The inconstancy of $A$ can subsequently be examined, and the necessary corrections be applied.

### 3. SPECIAL FEATURES OF WIRELESS TELEGRAPHY AS A SIGNALLING SYSTEM

In wireless the medium M is the aether, and the wave of $\chi$-ishness is an electric wave; so that $\chi$ might stand for the strength of an electric or magnetic field at the instant $t$ and at the spot $r$ in the medium. The essentials of a complete wireless installation are (i) a collection or box of instruments (often of very simple construction) in which alternating currents of very high frequency are produced from some local source of electric energy; (ii) an antenna, or electric circuit of such a geometrical form that high-frequency electric currents in it are accompanied by a marked radiation of energy into surrounding space; and elsewhere on or near the surface of the earth, (iii) another antenna, with (iv) another box of instruments in which alternating currents are produced by the tiny fraction of the radiated power which reaches them from the sending station.

Electromagnetic radiation, by which energy is transferred from the sending to the receiving antenna, is a phenomenon familiar to all who have eyes to see, or a skin to feel, the Sun's rays. It is, we believe, by electromagnetic radiation that light reaches us; and the same mechanism of the transference of energy with the same mathematical analysis suffices to describe radiation in the case of visible light, where the frequency is about $5 \times 10^{14}$ cycles per second, as in the case of wireless telegraphy, where the frequency commonly lies between $5 \times 10^6$ cycles per second and one-hundredth of that number.

There are these contrasts to be noted, however. Firstly, in the case of light the frequency is so large, and therefore the wavelength and the size of the radiating oscillator so small, that physicists have as yet been able to do little in the way of arbitrarily constructing and disposing their luminous oscillators, but must take them as they find them in the atom; whereas the wireless engineer builds his own radiator, his antenna, long or short, high or low, of this shape or that; for it is, as it were, large enough to give room for his fingers. Secondly, in wireless we are not so much concerned with radiation through free space as along Earth's surface. Even the aeroplane cannot get far enough from the ground to be regarded as unaffected by it. There is, moreover, the further complication of another conducting surface, the ionised upper atmosphere. So radiation in wireless telegraphy is not through free space; or even over a plane conducting surface bounding free space, though this is sometimes a convenient approximation to the actual conditions. It occurs between an uneven heterogeneous spheroidal solid and liquid body, and the even less well-defined gaseous conducting layer. Consequently the exact mechanism of this radiation, whether at the antenna or far away between the antennas, is imperfectly understood and hard to ascertain.

The processes occurring within the boxes of instruments associated with the antennas can be analysed with greater precision and detail. They are those encountered in ordinary alternating current theory, with only such quantitative differences as follow from the much higher frequencies of the currents to be handled.

The power engineer who has studied alternating currents, including transient phenomena, already knows much of the theory of wireless circuits. But as the admittance of a condenser and the impedance of a coil are proportional to the frequency, with the vastly greater frequencies of wireless tiny capacitances and tiny inductances become important which would be utterly ignored in alternating current power circuits, or even in telephone circuits.

It is well to get an idea of actual values. In wireless, particularly of course in short-wave work, a capacitance of (say) 1 micromicrofarad may be very perceptible. This is the capacitance in air between two parallel sixpenny pieces spaced about twice their total thickness apart ($\frac{3}{32}$ inch), or between the earth and a distant sphere of about 1 cm radius. At $3 \times 10^6$ cycles per second (which corresponds with a wavelength of 100 metres), an inductance of 1 microhenry might be of equal importance; and this would be provided by two or three close turns of wire round an ordinary glass tumbler. Now the 50-cycle engineer does not worry about a micromicrofarad, for three thousand million of his volts would be needed to drive an ampere through it; nor does he much appreciate a microhenry, for three thousand of his amperes would produce a P.D. of only 1 volt across it. The efficient wireless experimenter, however, must be constantly alive to the effects of such small capacitances and inductances. He develops a habit of mind which classifies the points of a circuit as sacred, and profane or earthy, from the high-frequency aspect. The sacred point is one at which high-frequency potentials are developed, and no liberties must be taken there; the profane or earthy point is one at which no high-frequency potentials should be developed, and if any necessarily earthy instrument, such as a pair of headgear telephone receivers or a bulky battery, is to be inserted in the circuit it should be at this point. Fig. 2 illustrates this in the very simple case of a receiving circuit comprising the antenna A, the rectifier R and the telephone T. Capacitance between telephone and earth would be without effect in the Right arrangement, but in the Wrong would shunt the rectifier and distune the antenna.

Regarded as a system of power transmission, wireless telegraphy occupies a peculiar place in the extreme smallness of the fraction of the transmitted power which reaches the receiver. In the ordinary electric power line, energy may be poured into one end at an enormous rate, but at the other end the power is on a correspondingly large scale. In submarine telegraphy moderate power is transmitted and very small power received; in ordinary telephony, the power transmitted is only a small fraction of a watt, and, over a line with the conventional commercial limit of attenuation ($\alpha l \fallingdotseq 5$), only about one ten-thousandth of this is received at the other end; but in both these cases the power received much exceeds that in a wireless receiver working at full commercial range. The telephone receiver, although itself a machine of very poor efficiency, in conjunction with the human ear is a marvellously sensitive indicator, and is used as such in wireless telegraphy. In telephony it must reproduce intelligible speech, and this demands much greater power than is necessary for the merely audible buzz required in the wireless telegraph receiver. Consequently in wireless telegraphy the ratio between power received and power transmitted may reach a degree of smallness quite unapproached in telephony. The Table shows in a rough illustrative way the orders of magnitude of the powers transmitted and received in the several signalling

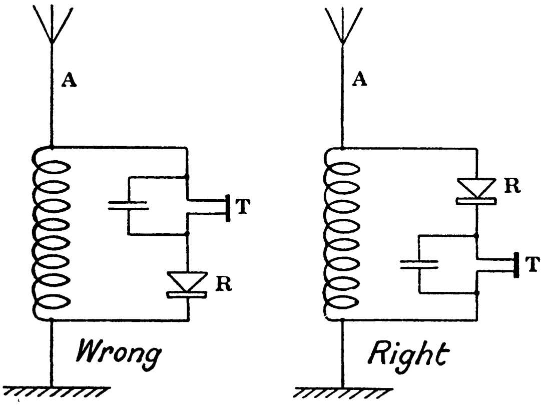

Fig. 2. The importance of small stray capacitances.

| | Watts transmitted | Watts received | Ratio |
|---|---|---|---|
| Power line ... ... | say $10^6$ | $10^6$ | 1 |
| Submarine telegraph | 5 | $5 \times 10^{-7}$ | $10^{-7}$ |
| Telephone ... ... | $10^{-2}$ | $10^{-6}$ | $10^{-4}$ |
| Wireless telegraph ... | say $10^5$ | $10^{-12}$ | $10^{-17}$ |

systems named, "watts received" signifying the power as taken from the connecting medium and before conversion to any other form.

In the wireless telegraph receiver of Fig. 2, the overall efficiency of antenna, rectifier and telephone, as a converter from electrical high-frequency input to acoustic output, is itself excessively small. It has been estimated as 0·015 per cent. for just perceptible signals*.

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* W. H. Eccles, *Continuous Wave Wireless Telegraphy*, Part I (1921), p. 13.