Wireless Transmission of Energy—I*

An Explanation of its General Nature and Relationship to Transmission By Wire

By Elihu Thomson

It will be my purpose in the present discourse to outline the general nature of wireless transmission and to indicate its relationship to transmission by wire. It will also be my object to show why the wireless energy sent out follows the curvature of the earth and to explain other features which to many have been more or less puzzling. In short, I desire to present in simple terms a view of the nature of such wireless work, so that anyone reasonably informed about electrical actions can obtain, as it were, a mental picture of the process. I may here state the fact that perhaps one of the earliest experiments bearing on wireless transmission was made in company with Prof. E. J. Houston, while we were both teachers in the Central High School in Philadelphia. This old experiment to which I refer was made about the latter part of 1875, and briefly described in the *Franklin Institute Journal* early in 1876. It consisted in using an induction coil which would give a spark length of several inches, then known as a Ruhmkorff coil, the coil resting on the lecture table, one terminal of the fine wire or secondary of which was connected to a water-pipe ground, while the

other was connected by a wire 4 or 5 feet long to a large tin vessel supported on a tall glass jar, insulating the tin vessel from the lecture table. The coil had an automatic interrupter for the primary circuit, and when in operation the terminals of the secondary were approached so that a torrent of white sparks bridged the interval between them, the gap being about 2 inches or so in length. Fig. 1 shows this arrangement. When the coil was worked in this way, it was found that a finely sharpened lead pencil approached to incipient contact with any metallic object, such as door knobs within the room and outside thereof, would cause a tiny spark to appear at the incipient contact between the pencil point and the metal. This, of course, was not a very delicate detector, but was improved, as in Fig. 2, by putting two sharpened points in a dark box, a device due to Edison. One or both points were adjusted so as to make incipient contact, and the tiny spark observed between the points was an indication of a shock, commotion or wave, electrical in its character, in the ether surrounding the tin vessel mounted on the glass jar. The tests for detecting the impulses were carried on not only in rooms on the same floor, but on the floor above and on the floor above that, and finally at the top of the building, some 90 feet away, in the astronomical observatory. Metallic pieces, even unconnected to the ground, would yield tiny sparks, not only in the basement of the building, but in the highest part, with several floors and walls intervening. I mention this old experiment particularly because it has in it the elements, of course in a very crude form, of wireless transmission, the wire and tin vessel attached to one terminal of the coil being a crude antenna with its spark-gap connection to ground, as afterwards used in wireless work by Marconi, and it also shows a rudimentary receiver or detector, a metallic body arranged in connection with a tiny spark gap, so that electrical oscillations in such body would declare themselves by a faint spark at the gap. It was understood by us at the time that after each discharge of the coil there was, as it were, a shock, or wave in the ether consisting of a quick reversed electrical condition, and it was even imagined that there might be in this process the germ of a system of signaling through space. This old work was almost forgotten when it was recalled by the later work of Hertz, about 1887, who demonstrated by suitable electrical

apparatus that waves of the general nature of light or heat could be generated, which waves are transmitted with the velocity of light, 186,000 miles per second, and that by suitable resonators or detectors these waves could be made to declare themselves by tiny sparks. The Hertzian oscillator was, as it were, an electrical tuning fork, having an actual rate of vibration peculiar to itself and dependent on its form and dimensions. It was fed with energy from an induction coil and across its spark gap an oscillating discharge took place, which, at each impulse, died out like the discharge of a condenser, but during this discharge it electrically stressed the ether in one and the other senses, so that an electrical wave was radiated in certain directions from the oscillator. It was found that these waves could be refracted, reflected and polarized, and, in general, dealt with as extremely coarse light or heat waves. We shall refer to these, however, farther on. The general result, however, of the Hertzian experiments was to connect electrical waves in the ether surrounding the apparatus with the light and heat waves and prove the identity of the two kinds of radiation, the differences being only those of wave length or pitch.

Since the Hertzian waves were sent out from the Hertzian oscillator in substantially straight lines, and since in the early days of wireless telegraphy it was common to regard wireless waves as of the same nature or as almost identical with Hertzian waves, the fact that the wireless waves were found to follow the curvature of the earth became a difficulty to be explained. Speaking for myself, I have never found the difficulty to exist. There is really no reason why the waves should not follow the curvature of the earth, as it will be one of my purposes to show. We will, however, approach the conditions of wireless somewhat gradually.

We will first consider an ordinary wire transmission of the simplest type. Let us assume a line of wire, as in Fig. 3, insulated and connected to one terminal of the battery while the other terminal is earthed or grounded. A simple telegraph system on open circuit would represent this arrangement. The only effect is that the battery supplies a small charge to the line, producing a potential difference between the insulated line and the earth, assuming, of course, that there is no leakage of any kind to disturb the conditions. As soon as the charge is established in the line at the full potential of the battery, which, in ordinary cases, would take place within a very small fraction of a second, a steady or static condition is reached, which might be indicated by electrostatic stress lines drawn from the wire to the ground, as illustrated in Fig. 3 by the fine dotted lines connecting the horizontal line to the ground surface below. If the wire be viewed on end (Fig. 4), we must represent these stress lines as extending out radially from the wire and bending over to meet a considerable portion of the ground surface below. As this arrangement is constituted, there is no energy transfer and the condition is static only. If now the far end of the line is earthed, as through an instrument or device which uses energy, as in Fig. 5, at the moment of such connection there would be a lowering of the intensity of the stress toward the receiving instrument and the line would be discharged were it not for the maintaining action of the battery, which still keeps up the difference of potential between line and ground. If the line is without resistance, this potential will have the same value all along the line, especially if the line is of uniform section and of uniform distance from the ground. The moment, however, the instrument at "I" takes energy from the line a current is found in the wire and a return in earth, and there is, so to speak, a flow of

energy in the space between the wire and the earth and in the ether surrounding the wire, in the direction of the arrow; that is, from the generating end to the receiving end. Surrounding the wire at this time there will be a magnetic field, which may be represented by whorls or lines of magnetism, so called, wrapped around the wire like so many hoops of all sizes (Fig. 6), expanding in size away from the wire in all directions; and a similar magnetic effect, of course, is also produced by the return current in the earth. But, on account of the conditions of conduction in earth being very devious and irregular, it would be difficult to map the magnetism generated. The system of magnetic whorls so developed on the flow of the current in the system reaches, for any definite current, a definite density after a short interval. In other words, the density of the magnetic field between the wire and the earth increases only up to a certain point. If the current, however, be doubled in any way, that field is doubled in density or there are twice as many lines packed in the space around the wire. If now we took instead of an earth-connected circuit one in which there are two wires extending from the generating battery or generator, the

Figs. 7, 8 and 9.

conditions will be the same except that the stress lines will now radiate from each wire and connect the wires by lines directly between them and by other curved lines outside. Such lines, or otherwise conceived "tubes of force," represent the static field or the density and directions of electrostatic stresses in the electrostatic field where one wire will be positive while the other is negative. If, as before, the ends of the wires are free or open-circuited, no energy is transmitted, and the mere static stress exists. If, however, the wires are connected through an instrument receiving energy or utilizing the energy, then the magnetic system is developed, surrounding each wire and passing between the wires, and on the establishment of any given current these lines accumulate at a rapid rate until, in a small fraction of a second usually, a limit is reached. The magnetic field may then be said to be fully developed. Outside of the pair of wires the magnetic disturbance extends to very great distances, but is necessarily weak far away. The magnetic whorls in this case do not center themselves in circular paths around the wires and at equal distances therefrom; but between the wires they are more condensed or pushed toward the wires themselves—crowded, so to speak—while outside of the wires they expand (Figs. 8 and 9). It must be remembered that these lines of force are merely symbols for what may be likened to a magnetic atmosphere. They indicate the density and direction of certain actions in the ether, called magnetic. It will be important to note, both in wire and wireless transmission, that the energy is transferred in the surrounding medium. The wire in ordinary wire transmission is, in fact, a sort of guiding center or core around which this ether disturbance carrying the energy exists. The wire may be bent or coiled, expanded or contracted without altering the essential nature of the process. So far, then, ordinary wire transmission is really a case of wireless transmission, with the wire for a guiding core for the energy (Fig. 10).

It would take us too far to attempt to explain or theorize on the modern view of the passage of electrons in the wire forming the current, and the field they carry with and about them in giving rise to the stresses in the ether surrounding them. Suffice it to say that a moving electron must not only be accompanied or surrounded by the static stress field which it produces in the ether, but also by a magnetic effect representing the energy of motion possessed by it. When a current which has been started in a circuit reaches a definite

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value it may be said to have reached a steady state. It would then be a continuous current of constant value. Energy can be steadily extracted from such a system only by introducing some apparatus connected with the wire which is the guiding core for this energy.

Let us now consider the case of current of a different character, a fluctuating, or better, an alternating current. Let us substitute for the battery an alternating current generator, and assume a single wire with an earth or wire return, as in Figs. 3 and 5. Here the wire merely becomes positive and negative alternately, for the circuit is incomplete or unconnected as a circuit, and the stress lines from wire to earth or to other wires reverse periodically their direction plus to minus and

Fig. 10.

minus to plus. This is true, of course, whether the earth be replaced by a second wire or whether three or more wires be involved, as in a three-phase alternating current circuit. By connecting any two of the wires through an energy-receiving apparatus *R* (Fig. 11), the same action that takes place with the continuous current may be reproduced except that the energy now comes in waves and is not a continuous flow. In ordinary cases there are sixty complete waves or complete changes from plus to minus and back to plus in each second, and the system is then called one of 60-cycle frequency. A further important difference is to be noted between the alternating-current condition and the continuous. The action in the ether around and between the wires is now in the form of waves, both magnetic and electrostatic. Between wires there is an increase of electrostatic stress to a maximum, a diminution to zero, a reversal, etc. The magnetic field also rises, falls, reverses, and so on synchronously. The condition is no longer static, the medium around the wires is in a dynamic state, and it is now possible to abstract energy steadily from it without actually diverting current from the line. We can, in fact, by such a system produce in neighboring conductors similar disturbances or currents, and along with these disturbances we may deliver energy.

The alternating-current transformer is then merely a device for bringing two or more circuits together as near as possible and enhancing the magnetic values which would normally exist around such circuits by the addition of an iron atmosphere, the iron core, so that the greatest possible transfer of energy from one (the primary circuit) to the other (the secondary circuit) may be accomplished. But in the wire itself, which leads from an alternating-current source, since there is an action called a current which changes, pulsates, or alternates, we have also around the wire core waves in the ether which, in fact, spread to very great distances; some small portion of the energy of each impulse not returning to the system, but passing outward into space as radiated energy.

This radiation may be a very small amount per cycle, especially where the outgoing and return wires are near together and parallel, and with low frequencies, such as 60 cycles, on account of the low number of waves per second and the low speed or rate of change in the fields surrounding the wire, the amount of energy carried off by free radiation into space is indeed negligible. But if we raise the frequency we raise the amount of energy which can be radiated proportionately to the number of waves per second, and we also make the rate of change higher and the wave slopes steeper, so that as the frequency rises the radiation factor becomes more and more important in dissipating the energy of the system. It is diffused through space around the electric system at work and passes off to illimitable distances. Since these impulses in the wire, the electrical waves sent along the wire (with the wire as a guiding core), can at the maximum move with the speed of light—186,000 miles per second—it follows that if the line is sufficiently long or the transmission sufficiently extended or the path of radiation sufficiently distant the wave stresses or fields or currents can exist at different parts of the system in phases either much displaced or entirely

opposite. This may be rendered clear by stating that while one portion of a very long line might be positive to earth another portion half a wave-length distant from the first along the same line would be negative to earth (Fig. 12). In other words, there may exist upon the system at the same instant a succession of waves in opposite phase. Just as in vibrating strings in musical instruments or vibrating columns of air in organ pipes there are stationary waves, nodes, and internodes, so in electrical systems in vibration there can be nodes and internodes if the conditions are selected for obtaining that effect. Here the dotted vertical line indicates the nodes of the waves. We may thus have so-called stationary electric waves (Fig. 12).

We find that on raising the frequency of an alternating-current system from, say, 60 cycles, the ordinary frequency, to 600 cycles, an effect which at first was hardly detectable now becomes important. It is the so-called "skin effect" whereby the current in a wire tends to concentrate itself on the outer skin of the conducting wire, neglecting the inner copper, so that the inner core of the wire might be left out. Consider the frequency still further raised, say, to 6,000 cycles, this "skin effect" of the conductor still further increases until the copper in the interior of a circular wire of a considerable size is now quite useless, and to get the advantage of such copper we must, as it were, take it out or spread it in a number of parallel wires spaced apart, or make the metal of the conductor in the form of a long sheet or in the shape of a thin tube or a cage of wires (Fig. 13). This, in electrical terms, improves the conductivity and reduces the opposition due to self-induction; the inductance counter electro-motive force. Let now the frequency be still further increased to tens of thousands or hundreds of thousands of cycles per second; then our conductor must necessarily become a still thinner or a still more extended sheet.

At the same time, if there are considerable differences

Figs. 11 and 12.

of potential between the conductors thus arranged, the radiation factor may at last become very important, so that if the parts of the circuit are far apart, free radiation into space may dispose of a large fraction of the energy sent out. In the Hertzian oscillator, deducting that lost in the spark gap, practically the whole of the remaining energy supplied is radiated into space. The wave frequency may be very many millions per second, and the waves produced are in the nature of coarse light and heat waves. Fig. 14 exemplifies diagrammatically the fact that with very high frequency waves a conductor carrying such waves will have surrounding it, if the space is unrestricted, magnetic systems of lines reversed in direction with nodes between, the distance apart of these waves or nodes being determined by the frequency in relation to the velocity of light, each complete wave outside the wire occupying a length equal to the velocity of light, 186,000 miles per second, divided by the wave-length or frequency.

Figs. 15 and 16 represent forms of Hertzian oscillator, consisting of plates or spheres *ab* of metal, separated by a small spark gap and charged in any suitable way,

Figs. 13, 14, 15 and 16.

plus and minus with respect to each other, and allowed to discharge across the gap. The charges are then interchanged between *a* and *b* at a very high rate, though the waves decay rapidly, and the system vibrates only for a short time or until the energy of the charge is dissipated in ether waves of exceeding high pitch into the surrounding medium. Were there no energy lost in the gap itself for forming the spark, and if the metal were a perfect conductor, the full amount of energy represented by any initial charge would be dissipated in the ether in these ether waves. Marconi, however, in his development of wireless telegraphy did not use the complete Hertzian oscillator. In setting up his

Figs. 18, 19 and 20.

transmitting antenna he took substantially half an oscillator, the other half being, so to speak, a phantom—the reflected image of the first half, as it were, in the surface of the earth, generally the sea surface. It would be represented by taking an extended copper sheet or surface coated with a fairly good conductor to represent the earth's surface and mounting above it, but insulated from it, a metal body, such as a vertical rod, which could be charged and which could discharge to the sheet through a small air gap. In this arrangement not only would waves be sent out into the surrounding ether space, but there would be current traversing the sheet as waves of current around the spot where the discharge of the insulated body took place. In fact, I think it would be possible to represent experimentally a modern wireless system with a diminutive antenna to represent the transmitting station, and extended copper sheet to represent the earth's surface, and with investigating or receiving antennae set up here and there or moved from point to point on the extended surface.

Here, although the disturbance and the energy conveyance is in the ether around the antenna (or the part representing the half of the Hertzian oscillator), the energy is guided in its direction by the current in the sheet representing the surface of the sea, just as in the wire transmission the energy is guided by the wire as a core. On account of the enormous extent of the earth's sea surface, there is no need of a return circuit. The energy sent out moves in all directions, guided by the conducting water surface or land surface, as the case may be. There will necessarily be a rapid attenuation of the energy as it leaves the sending or transmitting antenna and spreads out to fill a wider and wider space around it. The higher the sending antenna the greater the distance which can be reached before the attenuation is too great for imparting signals.

Let us consider for a moment by the aid of a figure the actions which must occur in wireless transmission on the sending out of energy from the transmitting antenna. Referring to Fig. 17, we will represent by *e-e* the surface of the earth as if it were flat, and for moderate distances this will be substantially the case. We will erect on that surface a tall mast *A* of conducting wire or wires which, at the top, shall have an extension to increase its capacity. This might be a large ball of sheet metal. Usually, for construction to be practicable, it is a set of wires—a sort of cage or a skeleton body. Now, by any system, inductively, conductively, or otherwise, or by what is known as close or loose inductive coupling or what not (Figs. 18, 19, 20) we cause electric disturbances, such that at one instant the top of the antenna becomes positive and at the next instant

Fig. 17.

negative, many thousands, even hundreds of thousands, of times per second. In other words, we impress a high-frequency wave upon this vertical mast. We will try to present an instantaneous picture or form an instantaneous image of what the condition is at the beginning of the process.

(To be continued.)