CHANNELS OF COMMUNICATION

Why and How They Require Bands of Frequency

By "CATHODE RAY"

IT is interesting to notice how the emphasis shifts during the development of a new art.

When the brothers Wright were attempting to fly, their thoughts were no doubt more concerned with getting their contraption into the air than with the fear that lack of international air traffic regulations might increase the risk of their bumping into some other aviator.

Similarly, fifty years ago the achievement of sending wireless messages at all was too absorbing to leave much time for considering what might happen when overcrowding set in. But when wireless caught on and spark transmitters were installed wholesale, it was soon clear that the risk of one "bumping into" another was far from negligible. The word "jamming" dates from this period. Messages were generally quite brief, however, and a number of ships (for example) could share the same wavelength —or *channel*. If it was completely jammed it was just a case of waiting one's turn.

But when some stations' transmissions came to be more or less continuous, they had to be given exclusive rights to channels. And as they became more numerous the problem arose of packing the channels more and more closely in order to have enough to go round.

At first the solution appeared to be just a matter of making receivers more and more selective. It was true that certain theorists had talked learnedly about "sidebands," but these were dismissed by others as mathematical fictions, devoid of any practical reality or significance. This question came to a head in the great Stenode controversy of 1929-1932. The reality and non-reality of sidebands were both stoutly defended to influential circles, and things got to such a pass that a Government-sponsored investigation was put in hand. Its report settled any lingering doubts about the physical reality of sidebands and the inescapable necessity for spacing transmitters apart by a frequency which depended on the frequency of the "information" they carried.

Meanwhile the growth in the number of transmitters, broadcasting and otherwise, was making an acute international situation of this one-time highbrow scientific controversy. On the one hand the need for a wide frequency channel in order to transmit speech and music faithfully had been established; on the other, all the nations wanted to grab as many channels as they could, and were not always content with frequencies that limited effective range to their own frontiers. And, of course, all sorts of other radio services kept on joining the competition, so the conflict between the irresistible force of commercial and political radio development and the immovable object of necessary channel width gets worse day by day.

But is the channel difficulty so immovable? What exactly is the difficulty?

In the first place, it may be as well to realize that it is not an exclusive radio problem. If the "information"—morse, speech, music, pictures, etc.—were sent over a line channel instead of by radio it would still occupy a frequency band. For the reproduction of reasonably clear speech it is necessary to include all frequencies from, say, 100 to 3,000 c/s. That is a frequency band of 2,900 c/s. Sent directly over a

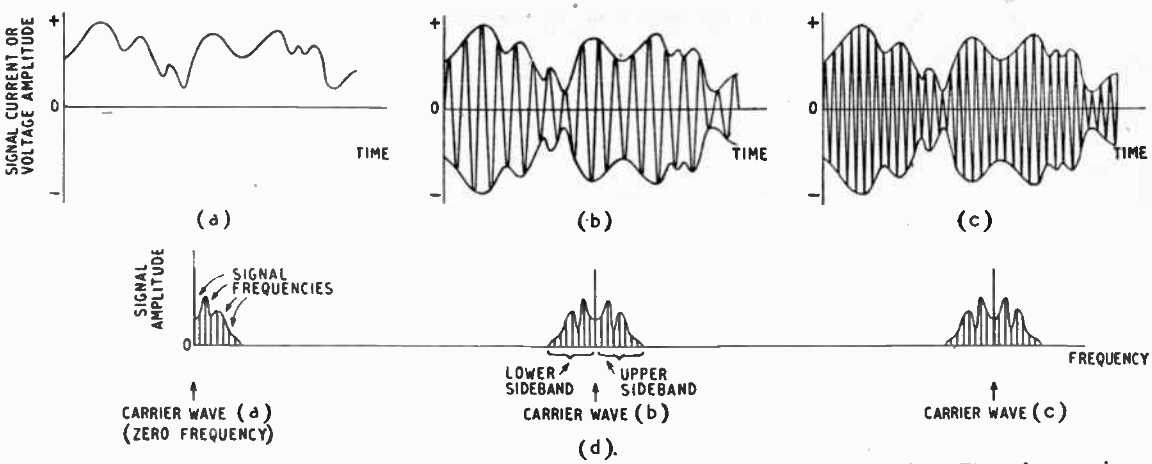

Fig. 1. (*a*) is a sample of audio-frequency programme ; a mixture of a number of frequencies. These frequencies can be individually represented on a frequency scale, as at the left of (*d*). When (*a*) is used to modulate a carrier wave, the result is shown on time and frequency scales by (*b*) and the middle of (*d*) respectively. (*c*) and the right-hand end of (*d*) represent an alternative carrier wave, of higher frequency. (*a*) can be regarded as having a zero-frequency carrier wave. In all cases the programme is fully communicated by one sideband only. (*a*)—(*c*) and (*d*) are two different ways of graphing signals.

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line, this band would occupy the position 100-3,000 c/s in the frequency scale (for what that means, see later).

The modulator in a radio transmitter is just a device for shifting this same band into a region of frequencies that can be radiated effectively. If the carrier wave is, say, 1,000,000 c/s, amplitude modulation causes sidebands to appear, from 997,000 to 999,900 c/s and 1,000,100 to 1,003,000 c/s; a total band of 6,000 c/s (including the small gaps extending for 100 c/s each side of the carrier wave). This is more than double the original 2,900 c/s; but it need not be. One sideband and the carrier wave can be suppressed, whereupon what is left occupies exactly the same frequency band as the original. Given a suitable receiver, no more is needed. The difficulty is that this sort of receiver costs more and is much more difficult to tune than the sort that deals with transmissions consisting of carrier wave and both sidebands. So, in broadcasting, where the number of receivers is enormous, it is an unfortunate practical necessity for transmitters to occupy a channel more than twice as wide as in line communication. For point-to-point radio, the extra trouble and cost of single-sideband working is relatively small, and well worth it for the saving in channels.

Whatever carrier-wave frequency is used, the frequency band occupied by the information is, of course, exactly the same. In fact, the original band, 100-3,000 c/s, can be regarded as a sideband of a zero-frequency carrier wave; see Fig. 1.

What is meant by "occupying" a 100-3,000 c/s frequency band? It can hardly mean that there is a signal going on all the time at every frequency from 100 c/s to 3,000 c/s, because the number of such frequencies is infinitely large. (However closely together you number them, somebody can always come along with another decimal place to the right and stick nine more in between every pair of yours!) The nearest approach to complete occupation is "fluctuation noise" caused by the restless movements of electrons, in which the probability is that something will happen sometimes however narrow a frequency band you select. In practice, however, there is no sense in dividing the frequency scale into narrower units than one can select by the sharpest tuning circuits or filters. The band 100-3,000 c/s covers a good many such units, and can be said to be occupied if there is a chance that all the units may be needed some of the time. In any particular spoken message terms of the height of a vertical line on a cathode-ray tube, just as in Fig. 1*d*. With a variable signal such as speech or music these lines keep popping up and down all the time. This type of display is an alternative to the ordinary time-base oscilloscope, which shows Fig. 1*a*-*c*.

The next question is whether it is possible to reduce the frequency bands occupied, so as to make room for more channels. 2,900

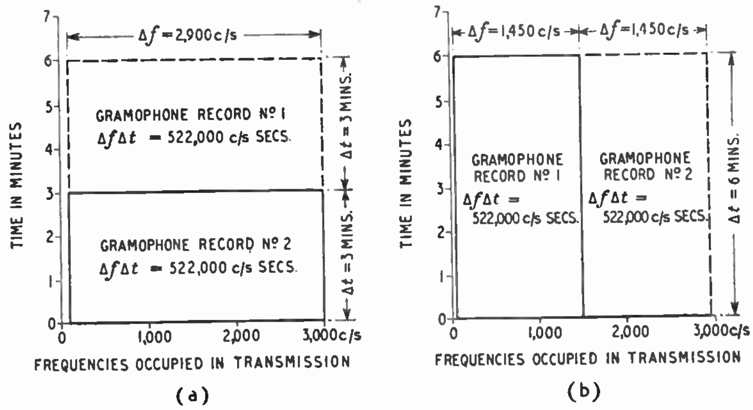

Fig. 2. If a transmission channel 2900 c/s wide is available, two recorded speeches, each lasting 3 minutes, would together occupy it for 6 minutes (*a*). By running the records at half-speed, each occupies only half the band width, and by means of modulators, band-pass filters, etc., both could be transmitted simultaneously along a 2900 c/s channel (*b*); but as each takes twice as long, there is no net advantage, and the process is technically much more difficult. In practice a frequency gap would have to be allowed between the two channels.

or musical programme, some of them may go unused all the time, but you never know. Renting a communication channel is rather like renting an hotel. You have to pay for the whole place all the time, even though some of the rooms may not always be full. In speech or music, the hotel guests are very much of the type referred to in America as "transients." (The U.S.A. must have known I was going to use this analogy!)

Incidentally, a frequency-occupation diagram, such as Fig. 1*d*, is often called a spectrum, as it is, in fact, the extreme low-frequency end of the same thing as is shown by an optical spectroscope. One type of communication-frequency spectroscope consists of an array of filters or resonators, between them covering the whole band of frequencies involved, with an arrangement for showing the response of each in c/s for speech is already some reduction, because the frequencies actually present in the voice extend considerably higher. It is possible to cut off still more, but in doing so one runs an increasing risk of losing important and perhaps vital parts of the information.

Instead of sacrificing some of the frequencies completely, it is possible to lower them all. By recording the speech and running the record into the transmitter at half-speed, the resulting frequency band (50-1,500 c/s) is half what it was; and by re-recording at the receiving end and reproducing at twice the speed it is restored to 100-3,000 c/s. But although it would be possible in this way to transmit two speech messages simultaneously in a frequency band normally occupied by one, each would take twice as long to transmit, so the arrangement would show no advantage over the much simpler process of sending the two messages straightforwardly one after the other along the full-width channel. This is shown in Fig. 2, where frequency band-widths are denoted by Δf and time periods occupied by Δt. (The Greek capital D, Δ, stands for *difference* between two boundary frequencies or times.)

It seems, then, that what determines the quantity of information that can be transmitted along a channel—line or radio—is not just the width of the channel, Δf, but the width multiplied by the time, Δt, during which it is available. This $\Delta f \Delta t$ is represented on a diagram of the Fig. 2 type by an area. A given message can—theoretically—at any rate—be transmitted in a short time along a wide channel, or in a proportionately longer time along a narrower channel. The unit of the amount of information that can be transmitted might be said to be one cycle per second multiplied by one second, viz., one cycle.

Before this statement can be regarded as fully buttoned-up it is necessary to establish a more definite relationship between information and cycles. This is difficult, because "information" is not readily measurable. Hartley, of oscillator fame, discussed it in America in 1928, and arrived at what has since been named the Hartley Law, which is more or less what we have just said—"the total amount of information which may be transmitted is proportional to the product of frequency range which is transmitted and the time which is available for transmission." Even his fairly advanced argument didn't get the length of fixing a numerical rate of exchange between information and $\Delta f \Delta t$. Not long ago Dr. Gabor tackled this part of the problem.[1] But before going on to his results, is it true that the unit of $\Delta f \Delta t$ is the cycle? It may seem to fit nicely into the Hartley Law, because it is a plausible idea that one cycle is a sort of elementary signal, like a morse dot perhaps; so a whole message can be built up from a suitable number of cycles. A pity, but it is a fallacy. Try sending even a simple message with identical cycles, as many as you want! An infinitely large number would be insufficient.

"How absurd!" you may say. "Give me an audio oscillator and a morse key and I'll soon crack off the message." Yes, but I said *identical* cycles. If you interrupt the flow of cycles you are modulating it, and that creates sidebands, which consist of cycles of other frequencies and therefore not identical.

Whatever one may do in order to convey information necessitates some sort of choice or selection of alternatives, such as the choice of letters in written words, or sequence of dots and dashes in morse or of sounds in speech, and that means variation or *modulation*. And that, as has been proved mathematically and by experiment, spreads out the frequencies, so that it is impossible to send a message with a single frequency. The cycle, as a unit of message capacity, won't do; it is the cycle per second frequency band width multiplied by the second.

So now perhaps the Hartley Law looks less obvious, and the abstruse reasoning behind it more necessary. (This reminds me of the professor who suddenly interrupted his lecture at the words ". . . from which it is obvious that . . .," and saying, "Excuse me, gentlemen," retired into his study for deep and prolonged thought. At length, emerging into the now empty classroom he beamingly announced, "Yes, gentlemen, it *is* obvious!")

After people realized that signalling by *amplitude* modulation necessitated a channel at least as wide as the highest modulation frequency, every now and then some of them who didn't know about the Hartley Law, or didn't believe it, rubbed their hands with glee and said, "Ha! We can get round this by using *frequency* modulation. We have only to keep the depth of modulation down to, say, 100 c/s each side of the carrier wave, and we'll be able to send speech over a 200-c/s-wide channel!" Well, of course, that is too good to be true, but there was some excuse for not realizing it at first—the mathematics this time was beyond all

[1] *Journal I.E.E.*, Part III, Nov. 1946, pp. 429-457.

but a select few, of whom J. R. Carson was the first to prove that the sidebands with F.M. were even wider than with A.M., however narrow the frequency deviation.

The pursuit after some way of dodging the Hartley Law seems to be as fruitless as the search for Perpetual Motion; but that is not to say there is no scope at all for progress. A deep, clear, rounded voice is not likely to need quite such a wide frequency band as a very high, squeaky one delivering the same message in the same time. The high voice is less efficient in its use of a transmission channel. On the other hand, the same words can be sent as quickly by high-speed morse through an even narrower channel than the deep voice, and telegraphy is, therefore, more efficient in this respect than telephony, at least if only the mere words are counted as "information." An interesting question is : What is the smallest signal—that is, the smallest time + frequency-band—that is capable of transmitting one elementary item of information? That is the problem Dr. Gabor investigated, and to do so he had to invoke mathematics of many terrifying kinds, and used an analogy with quantum mechanics to make it easier—so you may know! But it is not too difficult to follow the gist of it. In doing so one gets some light on the sort of ideas that are coming into an increasing number of papers on communication nowadays. As the Cathode-Ray screen is just about filled up, however, the shining of that light will have to wait until next month, when we will discuss some of the possibilities.