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Millimeter-Wavelength Radio Systems

Use of millimeter wavelengths for radio systems may alleviate crowding at lower frequencies.

L. C. Tillotson

Millimeter waves, that is, that part of the electromagnetic wave spectrum between 30 gigahertz (wavelength = 10 millimeters) and 300 gigahertz (wavelength = 1 millimeter) but sometimes used loosely to include also the region between about 15 and 30 gigahertz, are beginning to attract considerable attention as a possible means for relief of the crowding which is becoming increasingly troublesome at lower frequencies. The basic fact is that, whereas the communication capacity of a band is determined by its width in hertz, the number of hertz available in a given percentage bandwidth increases directly with the carrier frequency. Thus, a 10 percent band centered at 100 gigahertz (wavelength = 3 millimeters) has as much communication potential as the entire radio spectrum up to 10 gigahertz. At present this portion of the spectrum is relatively less used than the longer-wavelength portion, for reasons which will become apparent.

Most of the features which distinguish millimeter waves from the more widely used lower frequencies are a direct consequence of the shorter wavelengths. At these shorter wavelengths it is possible (necessary) to reduce the size of most system components. High-gain, narrow-beam antennas, for example, are of modest size at millimeter wavelengths and hence are more practical at these high frequencies than at lower frequencies. On the other hand, most transmission losses increase with increasing frequency, and this creates problems, especially when millimeter waves are to be propagated through the earth's atmosphere (*1*). The challenge we face is to design around the problems in such a way as to produce a communication system which provides either a new service or performs an old task with reduced cost. The burden of this article is to indicate how this might be done.

Status of Current Technology

Millimeter-wave systems will require terminals which accept from the user in a form convenient to him the information to be carried, process (or modulate) it into a suitable format, and place it at the desired carrier frequency. Also required at intervals are repeaters, including power amplifiers, which strengthen and redirect the signal. Both of these functions require simple and inexpensive millimeter-wave electronics if systems using these frequencies are to compete successfully with alternate means to accomplish the same objectives. Until quite recently, coherent sources of millimeter-wave power have been less than ideal for system use because of high initial cost, short operating lifetime, and burdensome power supply requirements. The advent of solid-state oscillators and amplifiers operating in this portion of the spectrum, and the promise of even more power at still higher frequencies,

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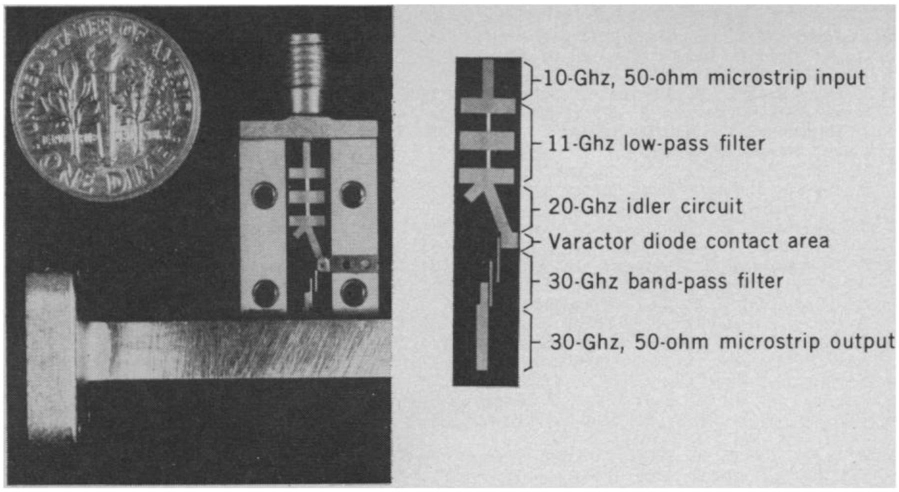
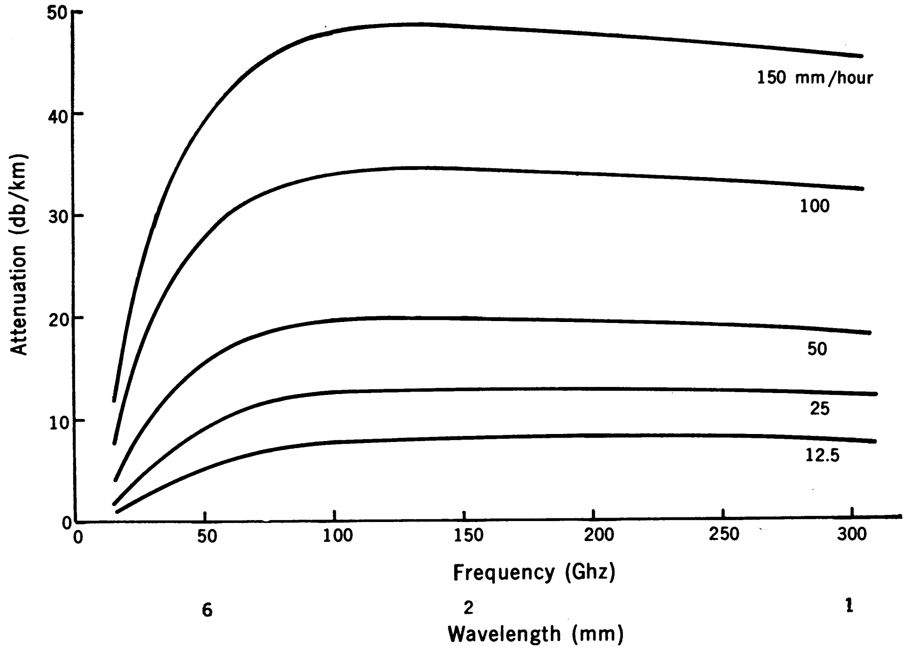
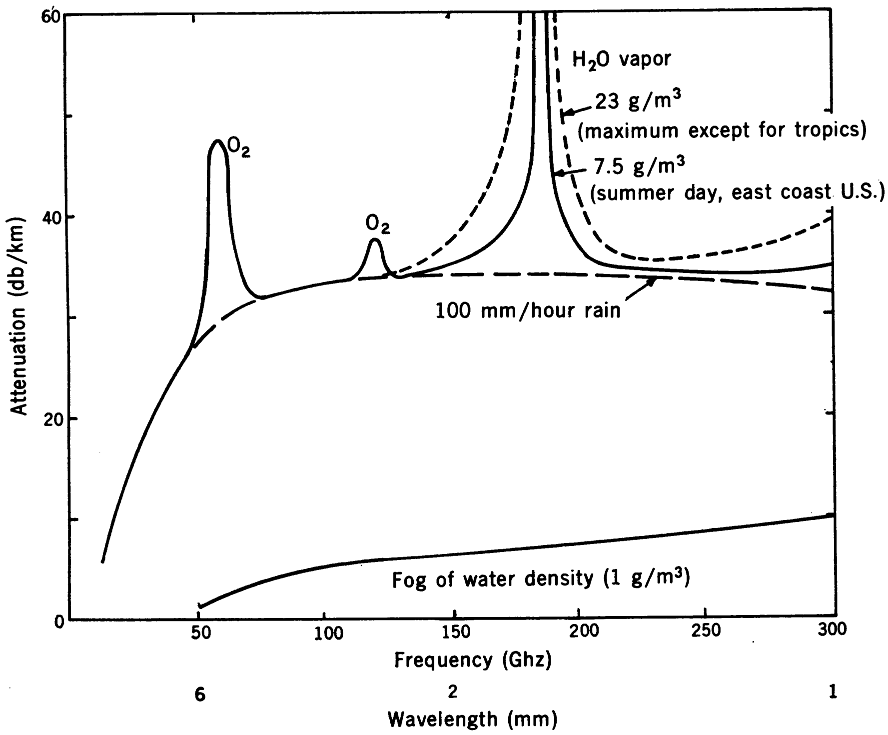






has dramatically improved this situation (*2*). Other components such as antennas, wave guides, and nonlinear and nonreciprocal devices have been available for several years and are being further refined and improved. In particular, millimeter-wave integrated circuits, including solid-state devices, are being devised which are expected to improve reliability and to reduce costs to a level not much greater than that of lower frequency circuits having the same number of components. An example of the type of circuitry now becoming feasible is shown in Fig. 1; this unit is one of several of the same type built for a 30-gigahertz radio repeater (*3*). These developments are expected to make inexpensive and reliable repeaters and terminals available for use in millimeter-wave systems.

The possibility, now amply demonstrated, of placing radio repeaters on board artificial earth satellites for use

Fig. 1 (top left). Example of a millimeter-wave, integrated-circuit harmonic multiplier. This unit was designed to supply 50 milliwatts of power at 30 gigahertz to lock in phase a high-power, solid-state oscillator. The 10-gigahertz input signal is obtained from another harmonic multiplier which in turn is driven by a quartz crystal oscillator; this method provides the frequency and phase stability required of modern radio systems. The light areas of the printed circuit are gold conductors deposited by evaporation on a quartz substrate. The required precision of ± 1 micrometer is obtained by the use of photolithographic methods as discussed by Schneider and Snell (*3*).

Fig. 2 (middle left). Calculated values of attenuation by rain due to absorption and scattering by raindrops. A drop-size distribution determined by Laws and Parsons (*7*) was used in these calculations; this distribution is known from other measurements to be valid for most but not for all rainstorms. The values of attenuation shown here have been checked by experiment up to about 100 gigahertz; other experiments are now under way to extend this knowledge to 300 gigahertz.

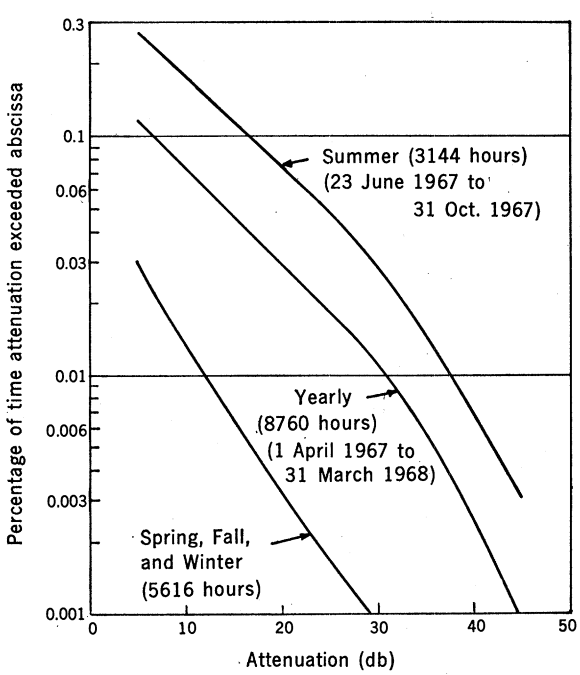
Fig. 3 (bottom left). Calculated values of *total* attenuation of radio waves by the earth's atmosphere during inclement weather with precipitation as indicated and with water vapor and oxygen molecular resonance absorption included. Also shown separately is the effect of a rather heavy fog. Values of attenuation by rain have been checked experimentally only to about 100 gigahertz. Attenuation by oxygen has been adequately verified, and values for water vapor are accurate near the resonance where the effect is most important. In these calculations uniform conditions along the entire radio path have been assumed.

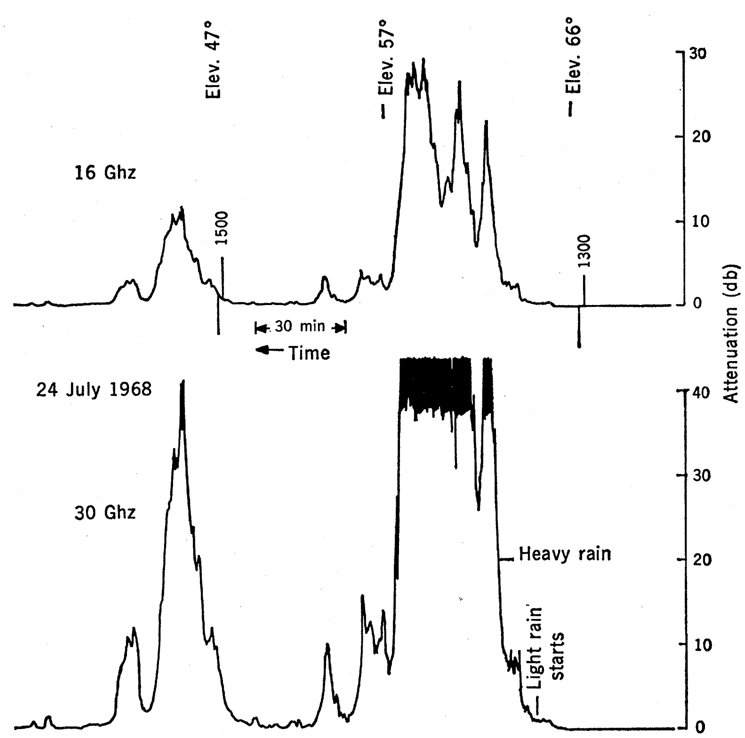
in communicating between locations on the earth's surface has considerably extended the potential application of radio relay (*4*). If the ability to place in synchronous orbit the large and sophisticated satellites which are now becoming feasible is exploited, a nearly ideal repeater platform can be provided. Such a station is well adapted for the use of millimeter waves, as I shall try to illustrate below.

Other technological developments of importance to the application of millimeter waves are modulation techniques which permit use of bandwidth to achieve interference resistance. These include quantized and coded signals such as pulse code modulation (PCM) which can be regenerated, and, in the analog case, large-index frequency modulation. Since we are making a fresh start, we have the option to allocate bands in a manner that will provide the greatest total communication. In particular, broad bands can be justified if the additional channels (provided by multiple antenna beams and orthogonal polarizations) made usable by the increased resistance to interference of broad-band modulation methods more than offset the increased bandwidth which they require. Of course, these ideas are applicable at any frequency but they are more feasible at millimeter wavelengths where antennas of reasonable size produce very sharp beams and broad-band frequency allocations are possible.

Effects of the Earth's Atmosphere on Millimeter Waves

For terrestrial services the entire transmission path is within the troposphere and thus the effects of that environment on the propagation of millimeter waves are of importance (*5*, *6*). All forms of precipitation are of concern but at frequencies below about 300 gigahertz only water in the liquid





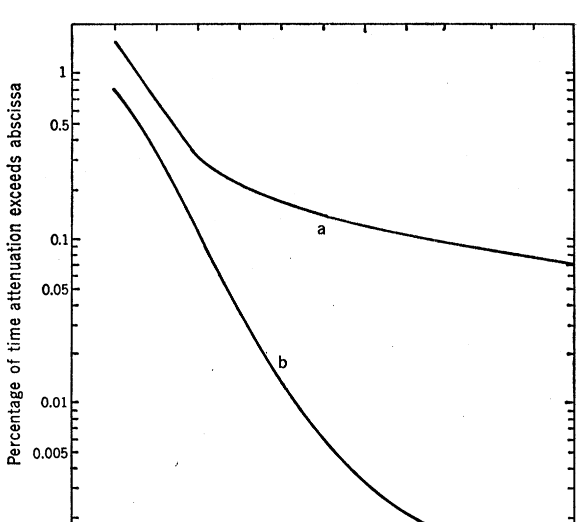


Fig. 4 (above left). Percentage of time during which attenuation exceeded a specified value on a terrestrial path. These data were taken on the eastern coast of the United States (New Jersey) at a radio frequency of 18.5 gigahertz on a 6.4-kilometer path. Note the wide variation from summer to winter. Other rainfall environments are known to have very different characteristics.

Fig. 5 (above). Attenuation on an earth-space path caused by rain. The records show the reduction in signal level (noise) received from the sun during an intense rainstorm. Signal level has been normalized so that 0 decibel corresponds to the clear weather value. The attenuation exceeded 20 decibels at 16 gigahertz and 30 decibels at 30 gigahertz for about 30 minutes; the elevation of the sun was above 45° during this period. These and other similar data make it evident that diversity earth stations will be required in order to provide reliable service at these frequencies.

Fig. 6 (left). Diversity advantage at 16 gigahertz as measured for two earth stations located in New Jersey. Curve a shows the percentage of time during which a specified value of attenuation was experienced at the Crawford Hill earth station. Curve b shows the reduction in attenuation experienced when a choice between that station and another 7 miles away was available. In this instance a satellite repeater able to work with either earth station and having a 6-decibel margin for rain would have been out of service less than 0.01 percent of the time during the 1969 *rainy season* in New Jersey.

state is of practical significance. Power loss occurs both by absorption and by scattering, with the relative importance of these two factors dependent on the size of the particles (that is, raindrops) relative to the carrier wavelength. Calculated values of attenuation by rain for frequencies between 30 and 300 gigahertz and for rain rates of 12.5 to to 150 millimeters per hour are shown in Fig. 2 (*7–10*). Attenuation caused by rain increases rapidly with frequency up to about 100 gigahertz and then levels off. This is a fortunate circumstance for the applications considered herein.

Precipitation is not the only absorber at these wavelengths, however; resonances of oxygen and water vapor molecules are known to occur, and these produce additional losses. The attenuation caused by resonances of the oxygen molecule in the vicinity of 60 and 120 gigahertz are accurately known and are stable with time. Absorption caused by water vapor is not so well understood; the loss measured at frequencies well removed from resonance peaks are greater by a factor of 2 to 4 than would be predicted by theory. Also, of course, the water vapor content of the atmosphere varies over a wide range with time and location. The total attenuation caused by 100 millimeters of rain per hour (this occurs about ½ hour per year in New Jersey) and the oxygen content of the troposphere at sea level for two values of water vapor content are shown in Fig. 3. Also shown is the loss caused by a dense fog of 1.0 gram of water per cubic meter; fog is less important than rain at frequencies below 300 gigahertz.

With this background we are well equipped to calculate the loss caused by various atmospheric constituents, provided we know the composition of the atmosphere in exact detail. However, because of the wide variability in the density and extent of water in all of its forms in the earth's atmosphere, it is not feasible to predict by calculation the attenuation to be expected on a given path at a particular time. The best one can hope for is a prediction of the percentage of time during which a given level of attenuation will be equaled or exceeded. At the present state of our knowledge of the earth's atmosphere, these data must be obtained from experiments made on typical propagation paths located in climates of interest, with enough simultaneous meteorological observations being made to allow the maximum possible use of existing weather data which have been gathered over large areas and for many decades. A sample of data taken at Bell Telephone Laboratories for use in the design of terrestrial radio systems operating near 20 gigahertz are shown in Fig. 4 (*11*); depicted is the percentage of time during which a given level of attenuation is equaled or exceeded. Similar data for other climates for which it is desired to construct radio systems must be obtained either by direct measurement or by inferring the result from meteorological records for the new locations. Many studies have been conducted and many data have been obtained but still more are needed (*9, 12*).

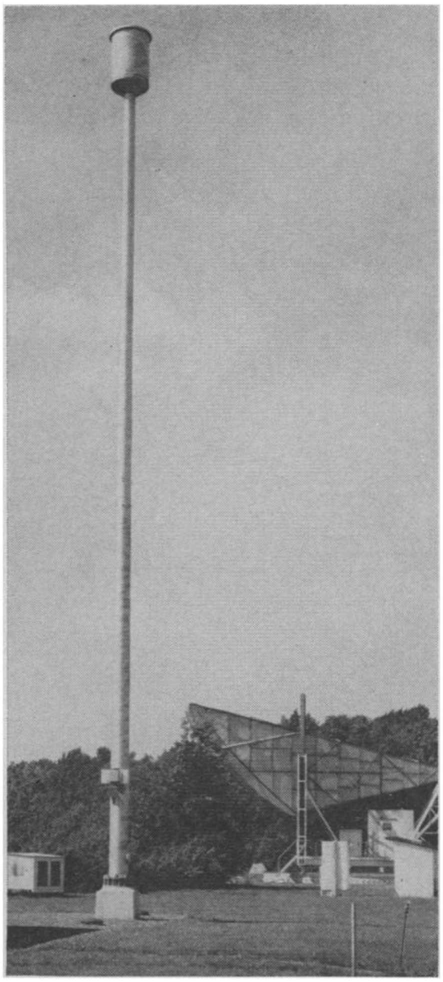


Fig. 7. A prototype solid-state repeater for short-hop terrestrial systems as constructed by Bell Telephone Laboratories. In this design concept the antenna and all of the solid-state electronics are mounted in a weatherproof housing at the top of the tapered aluminum mast selected to be just tall enough that the radio beam clears nearby obstructions (usually trees). This particular unit is powered by a thermoelectric generator mounted near the base of the mast which is fueled from underground storage tanks; this makes the unit self-sufficient for up to 1 year. If the required frequency allocations were available, a repeater of this type could be built (the unit in the photograph is a terminal; the repeater is the same except that two canisters are used for two-way transmission) to handle 16,000 (2-level PCM) or 32,000 (4-level PCM) voice-grade circuits in a 2-gigahertz band between 18 and 20 gigahertz.

Transmissions from an earth station to a space vehicle will traverse an amount of the earth's atmosphere dependent on the elevation angle of the line-of-sight to the spacecraft. If very low elevation angles are excluded (less than 5°), a transmission path having good broad-band capabilities is obtained (*13*). Precipitation, especially rain, can cause large attenuations, an example of which is shown in Fig. 5. From these and other such measurements, it is clear that reliable operation (that is, less than 0.01 percent or 1 hour per year of outage time) will require more than one earth station operating in a diversity arrangement which makes possible, by switching, a choice between either of two (or more) earth station locations. The number and separation of such earth stations required to achieve a specified degree of reliability will vary with location and climate. Results obtained at Bell Telephone Laboratories in which two stations spaced a few miles apart on the east coast of the United States were used are shown in Fig. 6 (*14*). These data show that an allowance of 6 decibels for attenuation by rain and provision of two earth stations spaced about 7 miles (11.2 kilometers) apart would result in an outage time of less than 0.01 percent. It is also evident from the near horizontal slope of the graph for the single station that the amount of margin required to achieve reliable single-station operation in New Jersey, where these data were taken, is likely to be excessive.

Data of this type will be needed for each of the various climatic regions where it is desired to locate an earth station. Similar studies at frequencies in the range above 30 gigahertz are needed to determine the usefulness of this portion of the radio spectrum.

Possible Applications

Users of radio frequencies above 10 gigahertz who require reliable earth-to-earth or earth-to-space communication must face up to the vagaries of transmission of millimeter waves which occur during inclement weather. In most instances provision of reliable service is not an insurmountable problem but the cost of providing such service will be increased. For terrestrial services the large loss that occurs during heavy rain can be accommodated if repeaters are placed at frequent intervals (between 1 and 10 kilometers, with the exact distance dependent upon the frequency) (*15*); for earth-space service, diversity earth stations can be used as indicated above.

On the other hand, users who are content with a communication channel that is available *most* of the time can employ these frequencies without alternate earth stations in the earth-space service and can use much longer hops limited primarily by line-of-sight requirements for terrestrial systems. Such compromises can save considerable expense, but many years' experience serving the needs of telephone subscribers makes it apparent that most users are not, in fact, willing to tolerate an unreliable service; this is particularly true when large amounts of communication capacity are involved. In any case, sufficient understanding of the basic propagation mechanism and system possibilities makes possible the design of reliable systems and a realistic appraisal of their costs. This is the objective of much of the propagation and system research now under way.

A specific example of a repeater intended for point-to-point service is shown in Fig. 7 (*16*). As this example indicates, it is possible to design a solid-state repeater for short-hop service which has a sizable communication capacity if adequate frequency allocations are made available. A short-hop system of this type can be designed to be simple and economical enough for single-hop applications, for example, a high-speed data link connecting a computing center with an outlying terminal. In this application a short-hop millimeter-wave system is more reliable than a similar optical system during heavy fog and snow; either system can be interrupted by intense rain but in most climates this will be very rare. A possible application of such a repeater to provide broad-band services between telephone central offices in an imaginary urban area is shown in Fig. 8 (*17*). This study, the original purpose of which was to demonstrate the ad-

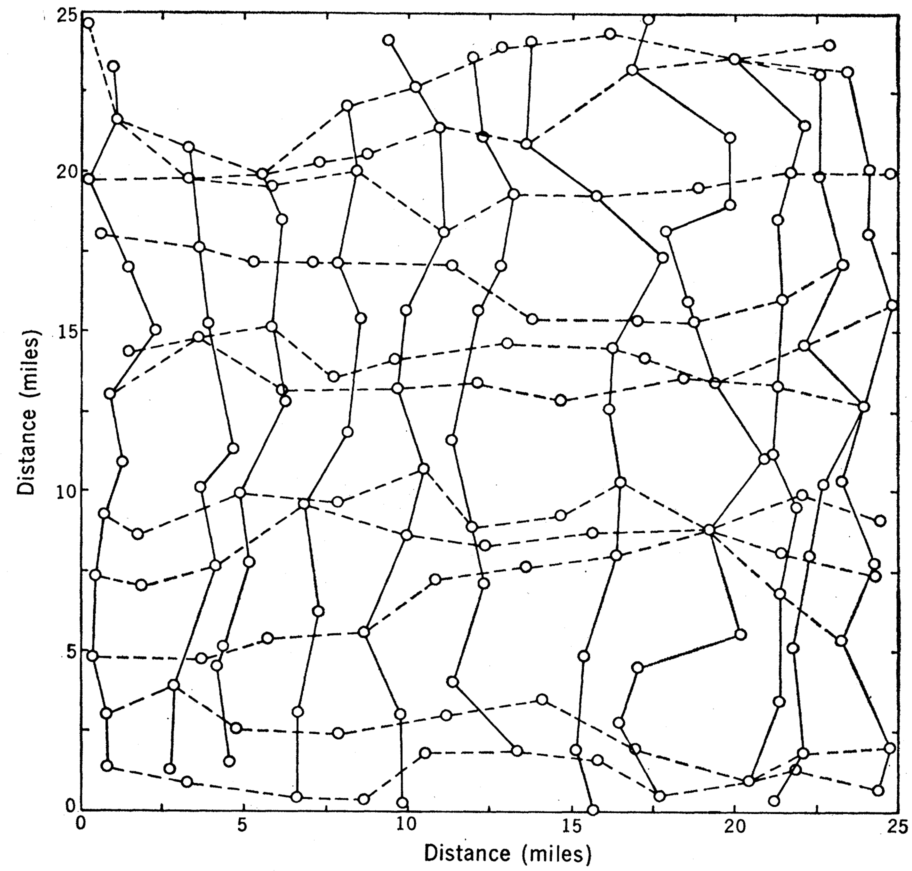


Fig. 8. Schematic diagram of a short-hop radio network applied to a hypothetical urban area. A detailed study (*16*) shows that the cochannel interference experienced in this rather extreme case can be tolerated if interference-resistant modulation methods and repeaters with narrow-beam, high-quality antennas—such as those used in the model shown in Fig. 7—are used. Each of the repeater chains shown could handle up to 32,000 voice circuits, 320 Picturephone circuits, 24 National Television System Committee TV circuits, or any appropriate combination of these, in a total 2-gigahertz bandwidth.

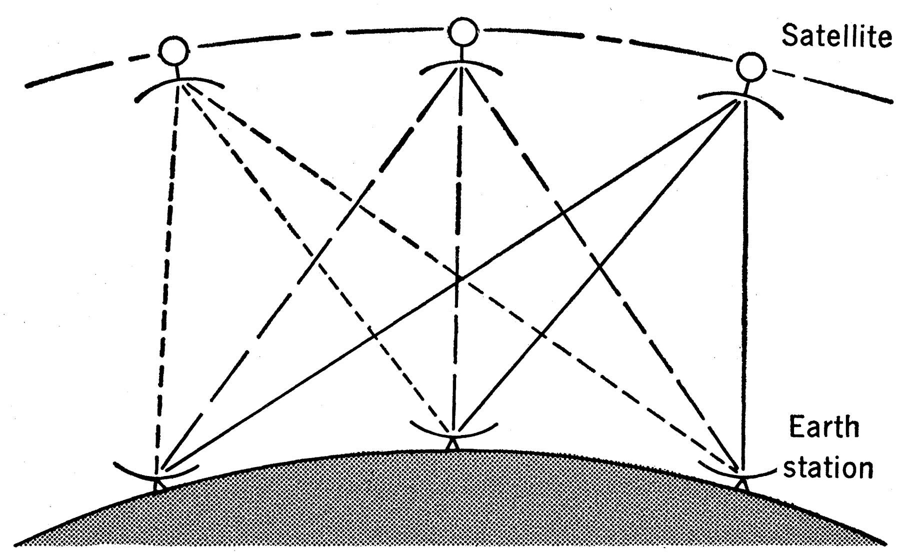


Fig. 9. Schematic diagram of a large-capacity satellite system in which each earth station communicates with every satellite and each satellite communicates with every earth station. If very precisely constructed multibeam antennas of many wavelengths aperture and interference-resistant modulation methods (for example, PCM) are used, all of these paths can operate on the same channel. The inherent short wavelength and the broad bands available at millimeter wavelengths makes the concept feasible. With tens of earth stations and tens of precisely stabilized satellites in synchronous (24-hour) orbits operating in bands a few gigahertz wide, this approach could result in a very large total communication capacity.

vantages of interference-resistant modulation methods, also illustrates that many locations in a restricted area can be served by broad-band radio channels when narrow-beam antennas are used. A system of this type could be of considerable assistance in meeting the exponentially increasing communication needs for which we must continually plan new facilities. At the other extreme, since a digital repeater can be designed to regenerate the signal with negligible error, many repeaters can be operated in tandem. Hence, systems having a total length of hundreds of miles are possible but long-haul systems which meet common carrier standards for reliability are likely to require some form of route diversity in most climates.

Another possible application is depicted in Fig. 9. This concept exploits the very sharp antenna beams provided at millimeter wavelengths when antennas of reasonable size are mounted on a very precisely stabilized space platform (satellite) in earth orbit. Millimeter waves are particularly attractive in this application since they make feasible narrow beams of radiation which can be designed to illuminate only a small portion of the earth's surface. This permits communication between a satellite and many earth stations with the use of only one frequency assignment, and, conversely, one assignment can be used between an earth station and many satellites. When combined with the broad bandwidths available at these frequencies, a system of very large potential capacity results. Although attitude-stabilization systems having the precision and operating lifetime required to exploit the full potential of large millimeter-wave antennas are not available today, a sizable effort is being devoted to these techniques and it is reasonable to expect considerable progress.

Since a frequency allocation can be reused many times at each satellite, efficient use of the orbit space and radio-frequency spectrum is obtained. For example, if 16 earth stations operating in bands at 20 and 30 gigahertz, each 4 gigahertz wide (*18*), communicate with a single satellite, the total traffic carried by the satellite's repeaters will be 8×10^{10} bits per second, which is adequate for 640,000 two-way voice-grade circuits or the equivalent (*19*). The system capacity can be further expanded if more suitably placed satellites are provided. If four-phase PCM and high-quality earth station antennas are used, satellite spacing can be as little as 1°, which would permit the use of tens of satellites. The resulting total system capacity would be comparable to that of any competing facility. The large communication capacity made possible by this approach is probably the best available means for making satellite communication systems competitive with terrestrial facilities. Of course, this whole approach is contingent upon allocation of adequate frequency space.

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