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Use of Frequencies Above 10 GHz for Common Carrier Applications

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We discuss problems and opportunities inherent in the use of frequencies above 10 GHz for common carrier applications. We also argue that if short hops are used to ameliorate the severe attenuation caused by excessive rainfall and if integrated solid-state electronics are used to achieve cost and reliability goals, a viable system can result. Interference-tolerant modulation methods and high performance antennas are used in order to permit many repeaters to operate co-channel in a restricted geographical area. The paper also includes several references to other papers in this issue and elsewhere which describe studies and experiments conducted to demonstrate feasibility of the system concept and components and subassemblies designed especially for broadband short-hop system application.

I. PROLOGUE

One of the distinguishing features of the history of radio is an inexorable trend toward higher frequencies. We have witnessed in succession the use of long waves, the "broadcast" band, short waves, ultrashort waves, and microwaves; we are now on the threshold of large scale use of frequencies above 10 GHz. In each case the use of the new frequency band was accompanied by a significant change in technology. Indeed, such changes were necessary to enable us to exploit the new portion of the radio spectrum. Radio wave propagation at higher and higher frequencies has in each case been significantly different, at each step, from that at the older more familiar wavelengths. Thus the straightforward application of the prevailing art to a new frequency band was fraught with many obvious and very severe difficulties which tended to make the new frequencies appear useless; but fundamental advances in the associated technology, new system concepts, and an ever increasing need for communications have made it possible to exploit in turn each of these new regions of the radio frequency spectrum.

The several papers accompanying this introduction are a description, in part, of work being carried on at Bell Telephone Laboratories to exploit the potential of frequencies above 10 GHz for common carrier applications. Greatest emphasis is placed on possible terrestrial systems since these are judged to be nearest in time. The potential for domestic communication by satellite repeaters operating at frequencies above 10 GHz has also been studied briefly and is reported elsewhere.[1]

The thesis of the present series of papers is to show that progress in the radio and related arts, particularly solid state millimeter wave devices and the availability of quantitative statistical data on attenuation caused by rain, has now provided a portion of the base required for such an undertaking. In addition, the vast expansion of conventional common carrier microwave systems has begun to exhaust the frequencies presently allocated and thus make it imperative to open up new regions of the radio frequency spectrum for these services.

II. GENERAL CONSIDERATIONS

Most present day common carrier radio relay systems operating at frequencies below 10 GHz are characterized by 20- to 30-mile spacings between repeaters. They use low index frequency modulation. That these systems have proven very useful is indicated by the increasing density of such routes in the United States. In fact, in some urban areas this density is approaching saturation in the sense that, because of radio interference, it is becoming more and more difficult and will eventually be impossible to add another system. If the use of radio for such applications is to grow and to prosper, new space in the radio frequency spectrum must be found; this will be easier to accomplish if frequencies not now used for other services can be used. This paper and the companion papers describe current work which is basic to the design of systems for use at frequencies above 10 GHz where liquid water (normally rain) severely attenuates electromagnetic waves and hence profoundly influences system design.

A measure of the problem one faces in designing a multilink radio system for use at frequencies above 10 GHz is shown on Fig. 1. These repeater spacings were determined by assuming arbitrary but reasonable system parameters (40 dB fade margin) and a very arbitrary rain rate of 100 millimeters per hour, falling uniformly over the entire path. At 4 and 6 GHz, attenuation caused by rain plays no part in determining repeater spacing; spacing is determined by terrain features and tower heights and is usually in the range 20 to 30 miles as shown. Above 10 GHz the situation is very different; repeater spacing is almost entirely determined by attenuation caused by rain and becomes only a few miles at 18 and 30 GHz as is also shown. This analysis is oversimplified but it is an adequate basis for an important conclusion: at 10 GHz and above, radio repeater spacing must be decreased, which at the highest frequencies results in very short hops. The consequences of this fact are many. If radio systems with ten times the number of repeaters needed at the lower frequencies are to be competitive, a new low-cost system concept must be evolved. Since an order of magnitude increase in the num-

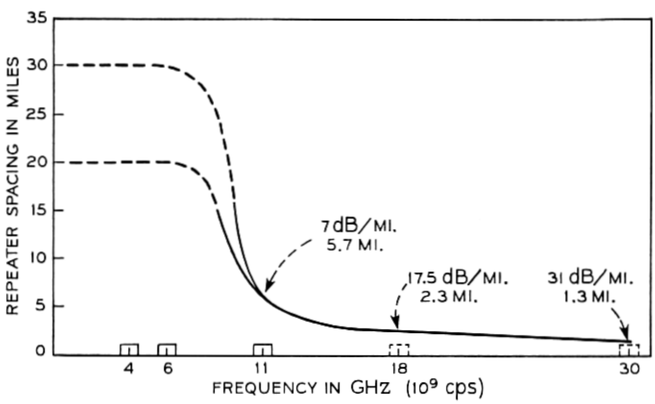

Fig. 1 — Repeater spacing as determined by a rain rate of 100 mm per hour (4 inches per hour). This assumes uniform rain over the entire path and a 40 dB fade margin.

ber of intermediate repeaters produces a like increase in the amount of transmission impairment incurred, either better repeaters or more tolerant modulation methods must be used. Further, when such a vital parameter as repeater spacing is controlled by the characteristics of rainstorms, it becomes important to know much more about this natural phenomenon.

The present state of our knowledge concerning attenuation of radio waves by rainfall has been summarized in a paper by Hogg from which Figs. 2 and 3 were selected.[2] Figure 2 shows, for various parts of the United States and a locality in England, the number of minutes per year that a given level of attenuation at 30 GHz is exceeded. Large differences exist between Corvallis, Oregon, and Miami, Florida; hence allowable repeater spacings vary widely in different parts of the United States and appear to be prohibitively short in some regions. A possible improvement has been suggested by Hogg which is based on the intuitively reasonable assumption that the most intense rainstorms are also the most limited in area.[2] Figure 3, which

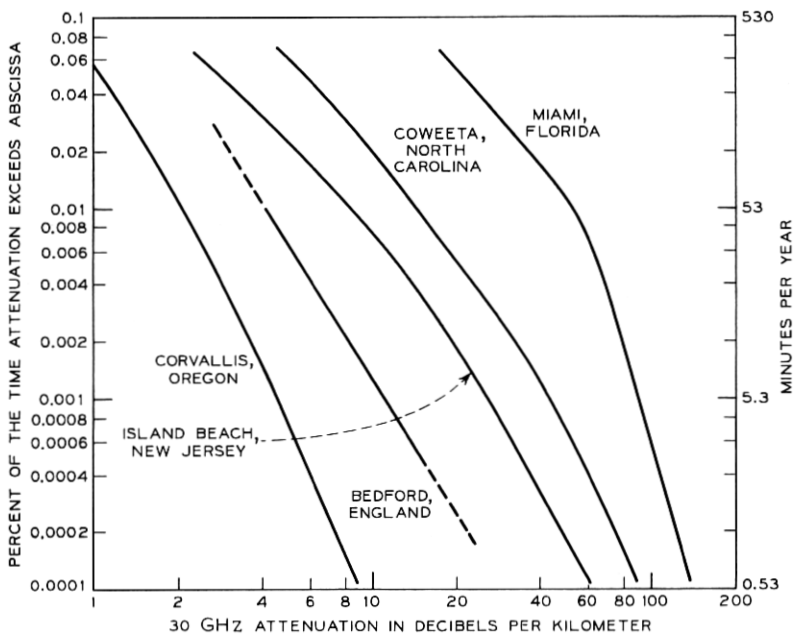

Fig. 2 — The number of minutes per year that a given level of attenuation at 30 GHz is exceeded for parts of the United States and England.

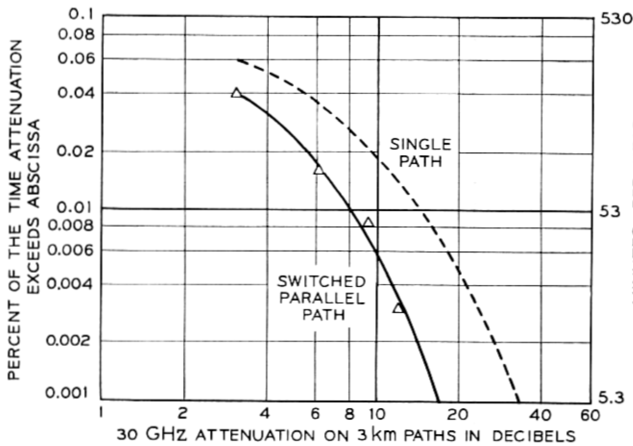

Fig. 3 — Improvement made possible by providing a parallel path spaced by 2 km and by providing for switching the traffic to the better path.

is based on a four-year accumulation of data, illustrates the improvement made possible by provision of a parallel path spaced by 2 km and provision for switching of the traffic to the better path. These and other related data lead us to hope that successful system designs can be devised for even the most hostile regions if only we know enough about the rainfall environment.[3–6]

One of the earliest suggestions for use of 10 to 30 GHz for terrestrial radio repeater applications was made in 1949 by J. R. Pierce and W. D. Lewis.[7] Many of the system features described below, such as short hops to ameliorate the rain problem, use of binary pulse-code modulation, and pole-mounted repeaters were discussed. But the technology available in 1949 was not adequate to support such a system. Another paper which has influenced the present studies was written by C. B. Feldman and W. R. Bennett.[8] One of the main features of this paper is an argument that band spread modulation techniques are not wasteful of the radio frequency spectrum if all factors, especially interference, are adequately taken into account. While these arguments were valid in 1949, just as they are today, no system of the suggested type resulted. In this second instance, the reasons are more complex, but a major factor once again was the lack of an adequate technology to support the system proposals.

Another important feature of radio systems having many closely spaced repeaters is tolerance to interference. This problem becomes especially acute where, assuming a viable system concept, one must eventually reckon with many parallel and crossing routes which results in many repeaters in a given area, all of which can be within line-of-sight of each other. These considerations lead to emphasis on two aspects of system design: (*i*) well-shielded antennas having sharp beams and little off-angle radiation and (*ii*) a modulation method which provides the maximum possible communication through a given area. More antenna discrimination always makes things better; but more rugged modulation methods, while more tolerant of interference, always require more bandwidth per unit of information. Thus total communication capacity increases with bandwidth expansion as long as the capacity of the added routes, made possible by the increased tolerance to interference, exceeds the loss in capacity per radio channel. Hence an optimum bandwidth expansion exisits for a given environment, as is demonstrated in a companion paper.[9]

These problems have been studied; some of the results are reported in the accompanying papers, some in more detail than others. In particular, the repeater concept which was devised to meet the challenge of many closely spaced repeaters and the experimental system designed and built to verify the ideas are discussed in considerable detail, whereas the study of interference is not since the problem of maximizing communication through an area is a large and complex one and is as yet incomplete.[9–15] As noted above, a knowledge of the amount of attenuation which will be caused by rainstorms is vital to the entire program; this high priority problem has received considerable attention. Some of the results are reported in this issue.[3–6]

While frequencies above 10 GHz suffer the disadvantage of attenuation caused by rain and this becomes a basic limitation in the system design, there are also some advantages. Antennas with quite sharp beams and high gain are feasible at these short wavelengths, that is, antennas one meter or less in aperture provide 2° beams and gains of about 40 dB. Thus a repeater package of modest size can provide high gain and sharp beams; if the antenna is designed to control wide-angle radiation, good interference protection is also provided. These are valuable attributes for any radio system. High gain antennas together with short hops and low noise receivers which are feasible with present technology result in a requirement of only a few tens of milliwatts of transmitter power for bandwidths of the order of 100 MHz. Hence an all solid-state repeater which will handle at least 100 millon bits per second (adequate for one color television channel in digital form or about 1400 voice circuits) is feasible. This is important since at the present time our best hope of building a repeater with adequate reliability at a competitive cost is based on solid-state devices and integrated microwave circuits. In fact, a useful system will result only if the repeaters require no maintenance and very little electrical power. A good model for the design of a repeater of the type envisaged here is one intended for submarine cable or satellite application; in each of these cases, frequent repair or replacement of a faulty repeater is so expensive as to be prohibitive. Realization of such repeaters at a low cost will be a challenge to the skill and ingenuity of both designers and production people, but several years' experience with solid-state microwave systems leaves little doubt that this can be accomplished.

We mentioned that the amount of electrical power required was an important factor in a system design. This is not because power itself is expensive but because reliable power delivered at the repeater site is expensive. Such power usually takes the form of an on-line power supply plus a standby which is typically a battery. Batteries have life, maintenance, and temperature problems, must be kept charged, and require accessible housing. While it may appear at the outset to be a detail, providing reliable power without maintenance or a bulky and unsightly housing at the base of the tower is a crucial element in the design of the repeater. The solution proposed here is to keep the power required to an absolute minimum by using efficient solid-state devices to provide a small amount of transmitter power. High transmitter power is not a panacea in any case since a 10 dB increase under the assumptions accompanying Fig. 1 would make possible an increase in path length of only 0.33 miles at 30 GHz. The situation is much like that on wire lines or waveguides where a twofold increase in repeater spacing results in a twofold increase in attenuation measured in dB instead of a 6 dB increase as in free-space propagation. The use of short hops and lower power can keep the total power requirement for a multichannel repeater to a value small enough to make feasible use of a reliable on-site source of primary power without backup as discussed in a companion paper.[10]

Another factor of importance is appearance. While it is undoubtedly true that for many locations where one might presently wish to locate a repeater, appearance would not matter, there are certainly other locations where it would be a controlling factor. It also seems likely that short hop systems are apt to be most needed in urban and suburban areas where appearance is becoming increasingly important. Subjective matters are difficult for engineers to treat, and final judgment must be left to those skilled in the art of product design. The approach used here was to avoid cumbersome towers, guy wires, equipment huts, and so forth, and to try for a clean appearance modeled after the familiar street lighting standard and fixture. Evaluation of the degree to which we have succeeded must necessarily be left to the judgment of the reader. In the very long run, appearance and general acceptability may place more important constraints on the use of microwaves than purely economic or technical problems.

III. REPEATER CONCEPT

It is a consequence of the required close repeater spacing that a successful short-hop system requires repeaters which are economical to install and which need no maintenance. In this application suitably designed solid-state repeaters can open up new possibilities in contrast to their use at lower frequencies where present solutions to the repeater problem are adequate and only marginal improvement is possible. This comes about in part because at the longer wavelengths where hops of 20 to 30 miles are common, microwave electronics is only a small fraction of the total repeater station cost. For the short-hop system, the opposite is true; studies have shown that one half to two thirds (depending on number of channels) of the total repeater station cost will be for repeater electronics.

In the past, towers for microwave radio repeaters have been regarded as platforms on which antennas, waveguides, and associated electronics are mounted in somewhat the same manner as switching equipment is installed in a central office building; design and construction of the tower has been kept separate from the design of the repeater electronics. Where high towers for large and expensive repeater stations are involved, each of which tends to be a project in its own right, this is a reasonable approach.

When we are considering closely spaced repeaters where the tower cost can be a crucial part of the total system cost, the entire problem must be considered at one time. At one extreme we can design the radio repeater to use antennas which are as large as seem feasible and then insist that the tower be stable enough to keep the antennas aimed properly under any weather conditions; this is more or less what has been done in the past. At frequencies above 10 GHz, where antenna sizes which are quite feasible result in sharp beams requiring very stable towers, this approach can result in a tower so costly that the entire system concept becomes unattracive.

In the present study, we have examined another alternative. The repeater package which includes the antenna and all of the required electronics is made compact and lightweight in order to minimize wind loading on the tower which is designed to be just adequate to prevent its destruction under any likely weather conditions. The radio repeater must then be designed to give satisfactory transmission performance in face of maximum movement of the tower. This can be accomplished by proper choice of antenna size, transmitter power output, receiver noise figure, repeater spacing, modulation method, and possibly in the future some form of self-steering array antenna. Thus it will be possible to achieve a better balance between the cost of the tower and the cost of repeater amplifying and signal processing equipment.

In selecting a tower for the present system, we assume that the enclosure for the repeater electronics and associated antenna is completely symmetrical and of small diameter so that any twisting moment is small enough that changes in azimuth can be neglected. Hence we can use an antenna whose beamwidth in the azimuth plane is governed only by the precision of initial line-up, provided that its beamwidth in the vertical plane is broad enough to allow the full expected movement of the tower. These requirements can be fulfilled by using an antenna with a smaller effective aperture in the vertical plane than in the horizontal plane.*

Figure 4 shows a repeater concept which involves most of the features required for short-hop service. In this design, all of the electronic circuitry serving a specific direction is contained in a tower-mounted package which also houses the antenna and power conversion equipment. A stack of two or more such assemblies mounted at the top of a tapered cylindrical self-supporting tower makes up the complete repeater. Power and other leads are contained within the tower. Since individual repeater assemblies are free to turn relative to each other preliminary line-up to within a few degrees can easily be accomplished during installation; final line-up is done electrically with the repeater in place on the tower using vernier adjustments built into the repeater housing. This arrangement eliminates long waveguides which are required when radio apparatus is mounted at the tower base and also maintains a good antenna pattern which is vital in an interference environment.

* The initial repeater design as described in companion papers does not use this feature, but the idea has importance for the future when interference will become a paramount problem.[10,11]

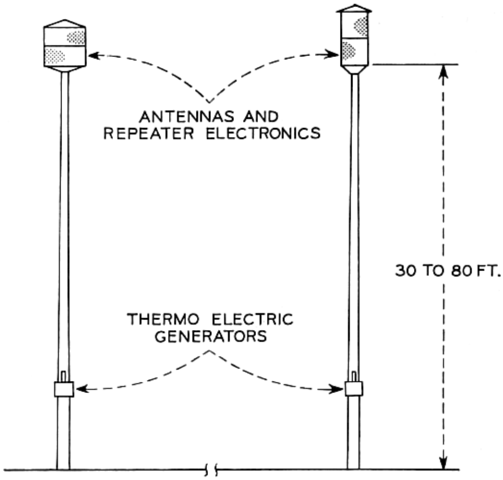

Fig. 4 — Alternative repeater concepts.

Two problems are created: (*i*) once it has been installed the repeater apparatus is not readily accessible, and (*ii*) it must withstand the entire range of ambient temperatures. Our solution to both of these problems in a solid-state repeater designed accordingly. If the repeater is in fact reliable, the lack of accessibility is not a real handicap; initial installation and changes in repeater apparatus to accommodate changes in traffic can be planned ahead of time. In addition, route diversity, as discussed above, offers a possible solution to the problem of rain outage and also affords a worthwhile degree of protection against equipment failure. The very wide range of ambient temperatures which must be accommodated by a system which is expected to operate anywhere in the United States makes the repeater design problem considerably more difficult, but it does not introduce any new problems; every repeater must operate over at least a limited temperature range. If we understand the circuits and their interactions well enough and provide adequate margins for changes in component characteristics, a reliable repeater can be built; a first step toward this goal has been taken.[10]

IV. SHORT-HOP REPEATER DESIGN

A wide variety of possible repeater designs for short-hop systems exist, but best economy will usually be achieved when broadband radio channels are used up to the limits set by traffic needs and by available technology. This comes about because a broadband repeater will not cost much more to build than a narrowband design; in fact, some design problems such as heat losses in filter and the stability with time and temperature of filters and certain other components are made easier by this approach. Of course, when bandwidth is doubled, transmitter power must also be doubled if margins are to remain intact; but this does not cost much as long as the power is about 100 mW where reliable solid-state devices are available. On those routes where a large volume of traffic must be handled, considerable economy can be achieved by use of broadband channels; a multiplicity of radio channels may also be used at each repeater to further increase the total system capacity. Of course this is possible only if an adequate frequency band has been allocated to such service.

Transmission through a large number of tandem connected repeaters, many of which are exposed to interference, can be tolerated only when a suitable bandwidth-expanding modulation technique is used. A basic decision has to be made whether to expand bandwidth using digital or analog techniques. A digital modulation method such as PCM is clearly superior when a very high signal-to-noise ratio must be obtained using a noisy transmission medium. On the other hand, some analog techniques, such as large index FM, are equally effective in overcoming noise and interference at S/N values of interest for common carrier applications. Analog terminal equipment is simpler, but large numbers of tandem connected repeaters which are exposed to severe interference cannot be accommodated.

In practice, however, all of these considerations are likely to be overruled by another factor—the nature of the traffic to be carried. Frequent analog-to-digital conversion is to be avoided because of signal degradation and cost; hence a radio system is most useful if it can be designed to accommodate both analog and digital signals.* For short distances, analog signals can be accommodated by using large index FM; signals which are supplied in a suitable PCM format can be carried over either short or long distances.

Table I gives a set of parameters for a possible repeater and shows the communication capability of such a repeater equipped to handle either digital or analog traffic. This is intended only as a hypothetical example; actual designs need to be tailored to a specific application

* As discussed in the companion paper interchangeable plug-in repeaters suited either for analog or digital signal can be used, as required.[10]

TABLE I—ILLUSTRATIVE REPEATER PARAMETERS

Radio frequency	18.5 GHz
Antenna effective area	0.375 m^2
Receiver noise figure	7 dB
Receiver noise bandwidth	150 MHz

Transmitted power required to provide 40 dB for attenuation (by rain) and a C/N = 14 dB at the receiver is:

Distance between repeaters (Km)	Transmitted power (mW)
1	1.3
2	5.2
4	20.8
8	83.2

COMMUNICATION CAPABILITY

Digital—two-phase PCM

Pulse rate	130×10^6/s
Bit rate	130 Mb/s
Approximate voice circuit capacity	1900

For two-phase coherent PSK with one interferer and a C/I = 15 dB, a C/N = 14 dB will result in $P_\epsilon < 10^{-9}$ in one link.

Analog—Large index phase modulation

Baseband width	7 MHz
Modulation index	8
Approximate voice circuit capacity	1600
S/N at baseband (one hop and no rain)	>70 dB
S/N, 40 dB attenuation	36 dB

About 30 dB reduction in cochannel interference results from the large index.

since, as noted above, per circuit costs computed for broadband channels are always less than those computed for narrowband channels; this calculation is valid only when a reasonable "fill" is achieved.

Binary PCM impressed on the radio carrier by angle modulation and coherently detected at the following receiver is used for digital transmission. While this makes complete regeneration at each repeater possible, a hybrid scheme which uses mostly linear repeaters interspersed with a few of the digital variety, as described by Chang and Freeny, may prove desirable in situations where interference does not affect many repeaters since intense rain occurring simultaneously on several hops is also expected to be rare.[16] For the repeater parameters shown in Table I even 40 dB excess attenuation by rain does not cause many errors per hop, and hence a route with many links in tandem could be used. As is also indicated, a single co-channel interferer only 15 dB below the desired signal could be tolerated with an error less than 1 in 10^9 pulses.* This is a calculated value based on a perfect receiver;[17] in practice a few dB margin would be required.

In the analog case, interfering co-channel signals will be reduced about 30 dB as a result of the large index, but such interference accumulates along the system and hence is more of a problem than in the digital case where frequent regeneration is possible. In addition, the analog repeater will handle fewer voice channels as Table I indicates. This difference will be even larger if in the future improved technology and understanding make possible a doubling of the bit rate with only a slight increase in bandwidth by use of four-phase angle modulation instead of two-phase angle modulation. Before this is undertaken, however, the effect of such a change on tolerance to interference and other system parameters needs more study. In summary, a system which uses quantized modulation permits a large number of repeaters connected in tandem, provides greater tolerance to interference, and makes more efficient use of the RF channel.† Analog repeaters are simpler, but fewer can be used in tandem; they seem particularly well suited to short-haul service where the traffic to be handled is presented in analog form.

V. SUMMARY AND CONCLUSIONS

A program of research has been described which has as its objective the establishment of an adequate base for the design of common carrier radio systems operating at radio frequencies above 10 GHz. Because these short radio waves are highly attenuated by intense rainfall, closely spaced repeaters are mandatory and new lower cost repeaters are required to make such a system concept competitive. A possible solution to this problem is described which uses low-power solid-state pole-mounted repeaters. Work is also being done to learn more about intense rainfall (in New Jersey) for which a new fast-acting rain gauge has been devised and used to instrument a dense rain-gauge network. Since a successful system concept could result in many repeaters within radio line-of-sight of each other, interference is a vital aspect of system design; it has been suggested that interference tolerant modulation methods and high-quality antennas be used as a means for obtaining a large amount of communication through a given area.

* Such an interfering signal might be produced, for example, during heavy rain by a cross-polarized co-channel signal used to derive a second channel.

† This statement is true when the repeater must operate in the presence of severe interference; if thermal noise is the only limitation, a repeater using analog modulation methods can be designed to be more efficient.

VI. ACKNOWLEDGMENTS

In addition to people identified in the text and the references to other papers in this issue of the B.S.T.J., R. Kompfner has contributed to many fruitful discussions and has made specific suggestions, particularly concerning over-all repeater design and appearance.

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