NEW TECHNOLOGY: ITS EFFECT ON USE AND MANAGEMENT OF THE RADIO SPECTRUM*

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In view of the rapid technological advances occurring in the field of telecommunications,[1] pressing questions arise about the implications for the worrisome shortage of radio spectrum.[2] Introduction and assimilation of new technologies will have major significance for the future problems and prospects of using and managing the spectrum. Some advances will open up regions of spectrum now lying fallow and expand enormously the size of the usable portion; others will facilitate more intensive use of the available spectrum; still others will satisfy telecommunications needs without employing atmospheric transmission.

At the same time, these advances will reduce the cost of existing services and render economically feasible marketing of new kinds of services.[3] The responsiveness of telecommunications users to price reductions, combined with the spectrum-use characteristics of these advances, will determine the magnitude of additional demand imposed on the spectrum as a consequence of these advances.

In this paper I shall discuss a number of new technologies within the context of spectrum use and management. First is a discussion of opportunities that communications satellites present for employing unused portions of the spectrum. Then, drawing from evidence presented in a recent FCC inquiry, I shall disentangle and appraise issues relating to shared spectrum used by satellites and terrestrial systems.[4] The impli-

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*This paper was among those commissioned jointly by Resources for the Future, Inc. and the Brookings Institution, both of Washington, D.C., and served as the basis of discussion at a symposium held September 11 and 12, 1967, at Airlie House, Warrenton, Virginia. The views expressed by the author do not necessarily represent those of the trustees, officers, or staff of either sponsoring organization.

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1. Telecommunications—any communication of information in verbal, written, coded, or pictorial form by electrical means, whether by wire or radio.

2. Radio spectrum—the part of the spectrum of electromagnetic radiation lying between the frequency limits of approximately 10,000 and 100,000,000,000 cps (cycles per second).

3. For the sake of expository convenience, the term "cost," when appearing without qualification, will be employed in this paper to refer only to use of non-spectrum resources. Use of spectrum resources will be labeled appropriately.

4. Terrestrial systems—networks of transmitting and receiving points which are located on the earth, as opposed to such points which are located in space, as are satellites.

cations for spectrum use of a single satellite system versus multiple systems for domestic use, a central issue in an FCC inquiry, will receive special attention. Satellites broadcasting directly to home television receivers, and other technologies will be more briefly treated with respect to their prospects for employing the available spectrum more intensively. Finally, I must include the exciting prospects presented by non-atmospheric forms of transmission: waveguides, laser pipes, transistorized underseas cable, and cable television to the home.

In general, given the many attractive possibilities to be discussed, one may come away with the feeling that the spectrum problem is certainly not unmanageable—that the "silent crisis" surely need not escalate into anything catastrophic. However, the process of introducing, absorbing and adjusting to technological advances will strain the existing arrangements for managing the spectrum. To guide and promote research and development activities, to exploit trade-offs that arise between spectrum and non-spectrum resources, and to price telecommunications services to reflect both spectrum and non-spectrum resource cost, will require management practices far removed from those of today.

I. Expanding the Resource Base

A striking characteristic of our concern about spectrum shortage is that we are dealing with only a tiny portion of spectrum potentially usable for communications purposes. Virtually all present-day use is confined to frequencies below 15 Gc/s. Other regions stretching as high as 1,000,000 Gc/s would, if tapped, contribute enormously to the spectrum resource base.

To be sure, there are good reasons why these higher regions are not now being exploited. Signal attenuation[5] is generally severe through clear and dry atmosphere, as well as through rain, snow, fog and clouds. Variations in atmospheric temperature also create serious problems, particularly at frequencies near and in the visible range.[6] For transmission over long distances along the surface of the earth, these characteristics do not lead to appealing prospects.

However, the elevated beam angles of satellite ground transmitters and receivers, involving much shorter travel through the troublesome atmos-

5. Signal attenuation—the diminution of current, voltage, or power in an electrical communicating channel.

6. Visible spectrum—the range of frequencies manifesting itself as light, producing visual sensation in the normal eye. The range is from red light at 400 trillion cycles per second through orange, yellow, green, blue, and violet at about 700 trillion cycles per second.

phere, open up exciting new possibilities. Moreover, the higher frequencies carry an advantage over the lower regions in that their use permits narrower satellite beams to focus and concentrate more precisely electromagnetic energy over the area to be served. It is notable that both Comsat and AT&T have proposed satellite systems for domestic use in the 1970's, operating at frequencies in excess of 10 Gc/s, to supplement bands at 4 Gc/s and 6 Gc/s currently shared by satellite and terrestrial microwave[7] users.[8]

Exploring briefly the potential bandwidths[9] available for satellite operations, we find that the level of attenuation through the clear and dry atmosphere varies widely from one region to another within the range 15 Gc/s to 1,000,000 Gc/s. While the atmosphere is generally not very transparent at such high frequencies, even at elevated satellite beam angles,[10] regions of low attenuation (which might be thought of as "windows" into space) are wide and numerous enough to encompass thousands of times the total bandwidth now in use. The effects of rain, fog and the like also vary from one window to another. Taking these factors together, we find that windows in the single region 15 Gc/s to 100 Gc/s encompass a spectrum space

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7. Microwave—electromagnetic waves having wavelengths of less than 20 centimeters. Waveguides are conventionally used in this range of wavelength instead of conventional transmission lines.

8. AT&T, *An Integrated Space-Earth Communications System to Serve the U.S.*, & Communication Satellite Corporation, *Technical Submission of Communication Satellite Corporation*, both filed in connection with F.C.C. No. 16495 (Dec. 1966). AT&T mentions use specifically of the 18 and 30 Gc/s bands. That attenuation varies greatly as a function of beam elevation is shown graphically in TELECOMMUNICATIONS SCIENCE PANEL, ELECTROMAGNETIC SPECTRUM UTILIZATION—THE SILENT CRISIS, 27 (Oct. 1966).

9. BANDWIDTH—the important range of frequencies in a given signal. A given electrical circuit can transmit only a certain limited range of frequencies; this frequency is called the bandwidth of the circuit. If a signal is sent that has frequency components outside the transmission band, some frequencies will be attenuated and lost along the way. Consequently, the received signal will not be a good replica of the signal which was sent. The received signal may even be unacceptable. To illustrate the point, suppose that there is a transmission link—an undersea cable—that can carry signals of a specified bandwidth. By using the appropriate electronic equipment, a signal having a narrow bandwidth may be sent. For the given cable, many narrow bandwidths may be used instead of a single broad bandwidth. Specifically, if the cable has a bandwidth capability of 4,000,000 cycles per second (*i.e.*, 4 megacycles), then at a given time, the cable could be used to transmit one television program, since 4 megacycles is the bandwidth required for a single television program. Instead of using the cable for a single television program, 400 speech signals could be sent (supposing that the required bandwidth is 10,000 cps).

10. Elevated beam angles—the change in the angle of the transmitting and receiving beam of energy caused by the variation in the height of the transmitting or receiving antenna.

roughly 100 times that now allocated to VHF[11] and UHF[12] television. In this region attenuation due to fog, clouds and snow appears to be mild, while rain has severe consequences.[13]

Several possibilities come to mind for employing satellites in this region: (1) confining ground stations to western desert areas and to other locations of low rainfall (this approach would be of dubious value insofar as the strongest demands for spectrum are concentrated around major urban areas where, by and large, annual rainfall is substantial); (2) locating ground stations widely and employing the system to satisfy peak load requirements[14] and to serve as emergency backup; (3) locating ground stations widely and employing additional resources to mitigate the rainfall problem. In their recent proposals both AT&T and Comsat mention use of dual interconnected ground stations separated by sufficient distance so that the probability of *both* simultaneously being out of operation due to heavy rain would be reduced to an acceptably low level. In addition, widening the bandwidth for each video and voice channel[15] and other practices that ordinarily would be considered "wasteful" of spectrum might be warranted in this case as a way to achieve greater protection against attenuation.

In any event, a substantial research and development effort will be required to bring this region into use. Among other things, much more knowledge is needed about the severity and time distribution of local rain storms and high-altitude precipitation by geographic region; transmission experiments will need to be conducted in a variety of atmospheric conditions to verify and supplement laboratory data; new kinds of power tubes and other hardware will have to be developed for use in these higher frequencies.

Questions immediately arise regarding the appropriate level and timing of research and development to exploit the higher regions of the spectrum. Among the reasons why no satisfactory answer can be given is simply the

11. VHF band—very high frequency band lies approximately in the range of frequencies between 30 megacycles per second and 300 megacycles per second.

12. UHF band—the ultra high frequency band lies approximately between the range of frequencies of 300 megacycles per second and 3000 megacycles per second.

13. A good concise discussion of the problems and prospects of using frequencies above 10 Gc/s, from which I have drawn some of the above, is provided by R. Kompfner, *Windows to Space,* PROCEEDINGS OF THE AMERICAN ASTRONAUTICAL SOCIETY 67-94 (1967). Windows are defined as regions in which one-way attenuation upward through the clear and dry atmosphere is less than one-half, or 3 decibels.

14. Peak load requirements—the highest required signal output for a given system which is needed to satisfy a given need.

15. Channel—the range of frequencies occupied by a transmitted signal.

fact that existing arrangements for managing the spectrum provide little clue about the social cost of employing the lower frequency bands more intensively as an alternative to expanding into the higher regions. Present-day incentives for existing users of lower frequencies to engage in research and development in the frequencies above 15 Gc/s leave much to be desired. User C may feel great pressure to engage in research and development in the higher frequencies because continued expansion of C's services in the lower frequencies would lead to interference with the services provided by D and E. Yet, perhaps only at a small cost (relative to that involved in C's using the higher frequencies), D and E might be able to protect themselves from this added interference. But today there is no easy way by which C can compensate D and E for these added costs, or for C even to determine what the magnitude of costs would be. On the other hand, B might not feel under pressure because his allocations in the lower region are "adequate" for his needs. Yet F and G may be badly squeezed in their allocations; while they could not themselves employ the higher frequencies due to the very nature of their operations, they might find extremely valuable the spectrum allocation that B is now occupying if somehow B could be induced to move into the higher frequencies and vacate his existing allocation.

More specifically, since it is satellite systems that would use these higher frequencies, the value of moving into these higher frequencies would reflect the spectrum and non-spectrum costs that otherwise would be imposed on society if satellite services were confined to the lower, already congested bands. As a first approximation, these costs would arise out of expanding satellite services in the 4 Gc/s and 6 Gc/s bands presently shared with terrestrial microwave facilities. It is to the question of shared use that we now turn.

II. SHARED USE

A. *Some General Considerations*

Clearly, the magnitude of future problems of spectrum use will depend substantially on the degree to which domestic satellite users are able to share spectrum with each other and with terrestrial systems. The issue of shared use is particularly urgent because near-term prospects for employing satellites domestically are bright. In response to an FCC inquiry regarding the desirability of establishing domestic communications satellites by nongovernmental entities, extensive debate has centered around questions of spectrum use. On one side, the Ford Foundation and the American Broadcasting Company have concluded that for purposes of distributing television programming via satellite, interference[16] with terrestrial microwave facilities would not be serious, even with several satellites and a large number of ground stations. In contrast, AT&T feels that the interference problem is potentially so serious that satellite service might have to be denied to virtually the entire northeastern portion of the United States because of the heavy concentration of terrestrial microwave in that area.[17] While the debate has involved a multitude of factors far too complex to summarize here, I think it is fair to say that some technical dimensions of the interference problem are not well understood, especially the phenomenon of precipitation scatter,[18] and that a test and experimentation program is badly needed.

For our purpose one point is especially noteworthy. To say that a satellite system should not operate in a shared band if it interferes with terrestrial microwave, or vice versa, is clearly to miss the point: many trade-offs exist between cost and reductions in interference. Site shielding of ground antennae[19] and changes in relative locations of interfering stations immediately come to mind. Among other things, special equipment can be installed at one antenna site to cancel the sidelobe interference[20] emanating from another site. Quite conceivably, the added cost to either satellite users or to terrestrial microwave users of reducing interference to a tolerably low level would be less than the social value gained by conserving the spectrum through greater shared use. In such cases, society would benefit, on balance, by permitting the expanded shared use in combination with some means by which the cost of protection from interference would be appropriately borne. Unfortunately, current practice in spectrum management simply avoids this issue. In general, users of *existing* facilities are accorded assurance that new or proposed interfering facilities will not be permitted; little, if any, attention is directed to the possibilities of trade-offs between cost and interference protection. In the words of an FCC report:

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16. Interference—any signal, whether naturally generated, such as atmospherics, or generated by radio transmitters or electrical machinery, other than that to which it is intended that a radio receiver should respond.

17. The Ford Foundation, *Technical and Economic Data, Vol. III*, filed in connection with F.C.C. No. 16495 (Dec. 12, 1966); American Broadcasting Company, *Comments on FCC Inquiry*, filed in connection with F.C.C. No. 16495 (Aug. 1, 1966); AT&T, *supra* note 8, especially at 15-17.

18. Precipitation scatter—the general re-radiation of wave energy caused when the radiation is incident on particles of precipitation. The re-radiation may distort the signals and introduce unwanted frequency components.

19. Site shielding of ground antennae—a metallic shield surrounding an antenna situated on the ground in order to prevent its being influenced by external electric fields.

20. Sidelobe interference—the interference with the signal caused by the frequencies lying to either side of the bandwidth of the transmitted signal.

> We have also instituted a mandatory coordination procedure to ensure that once an [satellite] earth station is established its capacity will not be expanded in such a way as to cause harmful interference to existing microwave systems and conversely, that new microwave stations will not cause harmful interference to existing earth stations.[21]

Rather than asking whether satellites interfere with terrestrial microwave, a more general question is: to provide a *given* volume of service between given points by either satellite or by microwave, would use of satellite involve a higher or lower spectrum cost than use of microwave? On one hand, the elevated beam angles of satellite systems contribute an additional spatial dimension to enhance the prospects for sharing spectrum with microwave. In its study Comsat concluded that:

> . . . interference coordination of a satellite earth station within the existing microwave environment is much less problematic than that of microwave-to-microwave interference coordination. It would be possible in many cases to locate satisfactorily a satellite earth terminal for domestic communications services in an area which is saturated from the viewpoint that no further terrestrial microwave stations could be located in this area without interfering with other terrestrial microwave stations.[22]

On the other hand, the satellite designs postulated in the responses to the FCC inquiry employ a *wider* bandwidth per channel[23] than does terrestrial microwave. Given the very limited power output of satellites (at least in the near future), use of a wider bandwidth per channel is an appealing way to reduce the cost of ground station antennae and other components. In its system recommended for 1970, Comsat proposes a 40 Mc/s bandwidth per video channel in contrast to roughly a 6 Mc/s bandwidth per video channel used by terrestrial microwave.[24]

On *a priori* grounds we cannot say whether the broader bandwidth per satellite channel involves a greater or lesser spectrum cost than does the narrower bandwidth of microwave. While a 40 Mc/s bandwidth employed by a satellite would represent a lower spectrum cost than the same bandwidth employed by microwave, insofar as the additional spatial dimension afforded by satellite use involves a lower level of interference, it does not

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21. FCC, Report on the Technical Aspects or Considerations of Frequency Assignment 23 (1965).

22. Communications Satellite Corporation, *supra* note 8, at 73-76.

23. Bandwidth per channel—the range of frequencies occupied by a transmitted signal, measured in terms of the bandwidth. That is, the channel is defined in terms of the range of frequencies which compose the bandwidth of the transmitted signal.

24. The 40 Mc/s requirement is computed on the basis of a 12 video channel satellite transmitting or receiving over a 500 Mc/s total bandwidth. *See* Communications Satellite Corporation, *supra* note 8, at 28.

necessarily follow that a given number of video channels transmitted by satellite would involve a smaller spectrum cost than the same number of channels carried by microwave.

Clearly, in comparing the relative merits of satellite and terrestrial microwave systems for domestic use, the costs of spectrum should be taken into account. And in doing so it is not enough to say simply that a particular satellite system either will or will not interfere with the existing microwave system. Other factors of paramount importance include the cost of interference (in terms of living with it or designing against it) and the magnitude of the interference problem in the face of continued *growth* of facilities competing for spectrum space.

B. *Ownership, Operation and Spectrum Use*

Problems of interference and sharing cannot be examined independently of arrangements by which satellite systems are owned and operated. If the FCC were to permit several entities to establish satellite systems for domestic use, to what extent would additional demands be imposed on spectrum space in comparison with a system in which a single entity owns and operates the entire system? In examining questions about employment of satellites for domestic purposes the FCC has, for good reason, been concerned about the implications for spectrum use. In its recent inquiry the FCC asked specifically whether it would be in the public interest to authorize noncommon carriers to construct and operate domestic satellite facilities, considering "the amount of frequency spectrum now available for the communication satellite service under the Commission's rules." The subsequent debate has been confined largely to the pros and cons of a separate system for television distribution. However, several important issues extend far beyond considerations of television use. Moreover, some of the analysis presented in the FCC inquiry is subject to question. Treating separately the satellite portion and the ground environment, I shall attempt to untangle and to treat briefly a few points.

1. *The Satellite Portion*

One area of concern has been the so-called "orbital slot" problem. Satellites sharing the same frequencies cannot be placed less than some minimum distance from each other because ground transmitting and receiving stations are limited in their ability to discriminate between adjacent satellites;[25]

25. Discrimination by ground station to distinguish signals from adjacent satellites—the ability of a ground receiving station to distinguish from which of two adjacent satellites a given signal emanates. The closer the satellites, the more difficult is the task of determining which satellite is the source.

since synchronous satellites must remain in an equatorial orbital plane,[26] only a limited number of slots are available for satellites in the line-of-sight of the United States. For example, with 3 degree longitudinal spacing spread from 64° to 130° West, 22 slots would be available. Concern has been expressed in some quarters that a proliferation of "small" satellites would be wasteful of the potentially limited number of orbital slots.[27]

Actually, the orbital slot issue as it has been presented is misleading. Given a 500 Mc/s band to be shared between satellite and terrestrial facilities, a proliferation of small-capacity satellites would be no more wasteful of orbital slots than large ones so long as the *bandwidth per channel* remains constant for both. A large-capacity satellite having 12 channels each with 40 Mc/s requires no more orbital space than 12 closely packed satellites each with one channel. Expressed differently, a large satellite employing a dozen 40 Mc/s repeaters[28] could, so far as spectrum use is concerned, just as well be divided into a dozen satellites with one repeater each. Thus the 22 slots mentioned above could be divided into 22n slots with each appropriately sequenced satellite having 1/n of the total bandwidth. To be sure, there exists what might be called an orbital "plane" limitation, in the sense that if the multitude of system parameters are fixed (including a given spectrum allocation) the total capacity that can be wrung out of the equatorial plane is limited.[29] But all this says is that the larger the capacity (hence bandwidth used) of a satellite, the fewer can be put into orbit. This relationship by itself would not provide a basis to conclude that numerous satellites orbited by separate entities would be more wasteful of orbital space than fewer, larger satellites owned by a single entity.

One would question a proliferation of small satellites for other reasons. On a per-channel basis, larger satellites are less expensive to construct and to place in orbit than is the case with smaller units. But here we have the familiar economies of scale issue involving the relationship between cost per channel and total number of channels in the satellite. It is clear that economies of scale do exist over a substantial range of capacity. Based on the state-of-the-art predicated in responses to the FCC inquiry, a satellite having

26. Equatorial orbital plane—a satellite orbit which forms a plane perpendicular to the equator.

27. *See* Communications Satellite Corporation, *supra* note 8, at 77-81; Ford Foundation, *supra* note 17, at 31-32.

28. Repeater—a special type of amplifier which is inserted in a telephone circuit at intervals, the function of which is to overcome the loss in the signal which occurs as a result of the resistance, capacitance, and inductance inherent in any transmission line.

29. We must remember that the many parameters in the system are subject to great variation and to trade-offs among themselves; therefore this limitation must be interpreted as an extremely loose one.

12 television channels would clearly involve a cost less than 12 times that of a satellite with only one channel. But this relationship does not depend on any assumption that bandwidth per channel varies as a function of capacity.[30] In other words, economies of scale in terms of hardware costs may be strongly positive, while the economies of scale for spectrum use remain essentially zero.

In one dimension of economies of scale, however, spectrum considerations re-enter through the backdoor. If small-capacity satellites were owned and operated by separate non-cooperating entities, B and C, diseconomies would result insofar as excess capacity afforded by B's satellite during times of slack demand for B's service could not be employed to satisfy peak demands simultaneously imposed against C's service. At the same time that portions of demand for C's service might have to go unsatisfied (or supplied by C at additional cost), resources tied up in B's satellites (including B's allocation of spectrum) would be in excess supply.[31] In this sense separate non-cooperating satellite systems would be wasteful of spectrum space—but they would be wasteful of satellite hardware and other resources too; spectrum use would not involve a unique problem.

Finally, we must consider one potentially very important relationship between economies of scale and spectrum use: the larger a satellite both in physical size and capacity, the wider the latitude for designing it to reduce interference with terrestrial facilities or with other satellite systems sharing the same frequencies. Greater latitude would exist for equipping the satellite with a larger transmitting antenna and other equipment to narrow the beam and to focus it on the territory or specific ground stations to be served, perhaps a single time zone over the United States, rather than illuminating[32] the whole area of contiguous states. (This option would be especially attractive for television distribution where transmission tailored to each time zone would be desirable.) This would reduce, if not eliminate, the problem of interference with ground receivers located in the expanded non-illuminated areas.[33] Greater latitude would also exist for designing di-

30. This is not to imply that bandwidth per channel must remain fixed. In fact it too can be varied against other parameters of the system, as mentioned earlier. But this option exists for both small and large capacity satellites.

31. The severity of this problem depends, of course, on the degree to which the peak demands against B and C would be staggered over time. If peak demands against B and C tend to occur simultaneously the possibilities for trading capacity back and forth would be restricted.

32. Illuminated areas—geographic areas which receive transmitted signals.

33. In AT&T's proposal for satellite telephone service, the satellites would have a large number of very narrow beams, each focused on a specific ground station. The design for television use proposed by the Ford Foundation calls for seven-beam satellites to cover separately the four contiguous time zones, Hawaii, Alaska, and Puerto Rico.

rectional receiving antennae[34] on the satellite so that signals from terrestrial microwave transmitters outside the narrower satellite receiving beam would not feed into the satellite antenna. With smaller satellites, greater physical constraints would be encountered in designing large antennae and other hardware due, in part, to the smaller launch shrouds and boosters. More generally, the per-channel cost of including features to reduce interference with terrestrial microwave would tend to be higher than that for the larger capacity units.

2. *The Ground Environment*

Similar considerations would apply in the proliferation of small ground stations owned by separate entities. On one hand, the number of locations would be increased where interference would potentially be a problem. On the other, so long as smaller stations operated only a portion of the total allocated bandwidth in proportion to their capacities, the problem of interference would correspondingly be reduced. The larger the stations, the less is per-channel cost in reducing interference by designing and tailoring the antenna to reduce sidelobe radiations, installing equipment to cancel sidelobe interference from other locations, constructing shields to reduce radiation levels. Moreover, smaller ground terminals with smaller antennae and consequently wider beams would suffer a reduced capacity to discriminate between adjacent satellites; hence, satellite spacings would have to be increased, thereby reducing the number of orbital slots available to the United States for satellites sharing the same frequencies. Here, the orbital slot issue legitimately emerges, but not in terms of small-capacity versus large-capacity satellites in which the issue is irrelevant, but rather in terms of small-antenna versus large-antenna ground stations.

3. *Spectrum Management and Market Structure*

Is one to conclude from all this that the FCC should restrict ownership and operation to a single entity operating a domestic system essentially as a monopoly? Not at all! At least four more points need to be made.

(1) Quite possibly, several separate systems would each handle sufficiently large volumes of traffic so that each would be able to enjoy most of the economies of scale, including both spectrum and non-spectrum considerations. For example, on the basis of evidence submitted in the FCC

34. Directional receiving antenna—an antenna in which the receiving properties are concentrated along certain directions.

inquiry, I would judge that a separate system for television distribution would likely constitute such a case.

(2) One must distinguish between the structure of ownership and the structure of operation. Today, cases abound where separate competing entities undertake cooperative arrangements to exploit economies of scale. In the satellite business, too, opportunities would arise for joint ownership, leasing, and other cooperative arrangements to avoid some of the diseconomies of spectrum use mentioned above. For example, joint ownership of large ground stations, and satellite capacity leased back and forth to meet peak load and emergency requirements are possibilities.

(3) Even if operation of multiple domestic satellite systems were to enlarge the demand for spectrum, this would not necessarily mean that separate systems should be prohibited. We face again the question regarding the value of spectrum versus the value of other goals such as promotion of competition.

(4) Since current spectrum management does not include a satisfactory mechanism for isolating the cost of a given case of interference between users, or for providing a means by which the cost can appropriately be borne, one might argue in favor of a single entity owning *all* facilities within which interference is likely to arise. With all costs and benefits "internalized," the single entity would be better able to adjust use of the various facilities—install special interference-reducing equipment here, alter the location of an antenna there, tolerate interference situations elsewhere—in order to minimize cost for a given total output. In the hands of separate entities these adjustments would not so easily be made. Given the arbitrary character of existing practices, requests for frequency allocations for new facilities would likely be disapproved if this would lead to interference with existing facilities. Desirable trade-offs between spectrum conservation and interference protection would remain unexploited; and, more generally, the total cost to these separate users, and to society, would be greater than in the case of single ownership. Applying this reasoning to the satellite case, one might argue that the common carrier owning the terrestrial microwave networks in question should also own the satellite ground stations, and perhaps the satellites as well. An unfortunate characteristic of present-day spectrum management practice is the temptation to take the easy way out. Rather than coming to grips with the problem of achieving efficient allocation of spectrum in a competitive environment, current spectrum management practice encourages the kind of thinking described immediately above leading to spectrum allocations that block entry to new competitive users. This enhances the monopolistic or oligopolistic power of existing users.

C. *Television Broadcast Satellites*

There has been much talk, and some serious study, devoted to the possibilities of orbiting satellites sufficiently powerful to broadcast television programs *directly* to home receivers. Such systems must be carefully distinguished from the proposals made by the Ford Foundation and others in response to the FCC inquiry. In these proposals, satellites would be employed to distribute television programming from network centers to outlying local broadcasting stations; these stations would then broadcast the material in the conventional manner to home receivers. As such, "distribution" satellites would embody far more modest technological advance than would direct broadcast satellites. In addition to the implications for spectrum use of distribution satellites discussed above, we might also examine the implications of direct broadcast satellites—especially since most observers probably share the suspicion that this latter class of satellites would impose a severe strain on spectrum resources.

The degree to which a broadcast satellite would impose such a strain depends on what it is being compared with. Let us consider first a broadcast satellite system sharing spectrum with terrestrial microwave users, in comparison with a distribution satellite feeding into local broadcasting stations.

In this case the outcome is ambiguous. On one hand the small home antennae would have less ability to reject spurious terrestrial signals. Analogous to the earlier discussion about small versus large ground stations, designing special features into the home system to reduce interference from terrestrial microwave would involve relatively high cost. The small home terminals would also have less ability to discriminate between adjacent satellites on the same frequencies; either more orbital space would be required for a series of such satellites, or frequency bands could not be shared among adjacent satellites in the equatorial plane. Moreover, the broadest satellite would operate at a much higher power than the distribution satellite and would, therefore, be more likely to interfere with terrestrial microwave facilities in the illuminated area. Thus the prospects for sharing spectrum with terrestrial microwave appear less good than those for distribution satellites. On the other hand, by going directly to the home, the broadcast satellite would replace the local frequency assignments from local broadcasting stations to the home. On *a priori* grounds, it is not possible to determine whether the broadcast satellite would be inferior in terms of spectrum use to the distribution satellite-local rebroadcasting station combination.

A second relevant comparison, however, is between the broadcast satellite and a distribution satellite system feeding into the ground station connected by *cable* rather than by conventional broadcast to the home. In this case the broadcast satellite would clearly be inferior to the distribution satellite-cable combination since spectrum for local rebroadcast would not be required in either case.

Actually, I doubt that we will need be concerned about broadcast satellites for a long time to come; for they seem unpromising on the basis of their economics, quite apart from considerations of spectrum use. A satellite sufficiently powerful to broadcast directly to home receivers would still require that each home owner invest an additional $50 to $100 for a preamplifier[35] and other equipment to boost the signals;[36] even then chances are that the signal would be no better than average. One can entertain serious doubts about how many viewers would be willing to spend that amount of money to receive one or several channels from a satellite—especially if they have access to a cable system in which, for a few dollars a month, they would have available 12 or more channels of excellent quality.[37] Moreover, broadcast satellites would involve a far higher cost than distribution satellites, and even that higher cost is predicated on technology far in advance of what we enjoy today. In contrast to a distribution satellite weighing perhaps 800 pounds boosted into orbit by an Atlas-Agena costing $6-7 million, one broadcast design calls for an 8000 pound satellite boosted into orbit by a Saturn-IB-Centaur combination costing about $50 million. In contrast to the fairly straightforward solar arrays required for distribution satellites, this particular broadcast design calls for more complicated deployable arrays[38] that would roll out like windowshades and have a total span in orbit of over 200 feet. Another broadcast design would include a nuclear reactor for power instead of solar cells, a phased-array antenna,[39] and gravity gradient stabilization[40]—all representing large if not enormous leaps beyond today's capabilities.[41]

35. Preamplifier—an amplifier which often immediately follows the output of a high-quality microphone, and sometimes is integral with it. The output power level of high-quality microphones is too low to be transmitted over a line, or to be mixed with other channels, induced noise or clicks being liable to occur.

36. Boost the signals—increase the power level of a signal by means of an amplifier.

37. For today's CATV systems, the viewer typically pays approximately $20 initially and $5 a month. Improved cable technology available in the time frame of broadcast satellites will probably afford substantially lower rates.

38. Deployable array—a broadcast satellite carries its own antenna array which can be opened, or deployed, for broadcast.

39. Phased array antenna—an antenna may be tuned in such a way that the phase of the transmitted signal may be varied by varying the frequency of the transmitted signal. When this change continuously occurs, the beam of the transmitted signal scans over a sector.

40. Gravity gradient stabilization—the gravity gradient of the earth marks the rate of change of the magnitude of the earth's gravity with increasing distance from the

D. *Other Possibilities for Sharing*

In addition to the latitude that satellite systems provide for sharing spectrum, other promising approaches exist for expanding use of existing allocations. I shall very briefly treat a couple of them.

One would entail shared use of existing TV bands with facsimile transmission into the home. RCA has requested authority from the FCC to test an experimental system to broadcast printed copy into the home along with standard television programming. The system would convert the copy into electromagnetic signals blended at the transmitter with those of regular TV programs. This would require no additional frequency allocation because the facsimile signals would be inserted during the vertical blanking intervals[42] that occur 60 times a second in a conventional TV signal. With present equipment four different messages can be transmitted simultaneously in this manner.[43]

Another possibility for sharing involves "spread spectrum" techniques for use by fixed and mobile radio. Each transmitter sharing the common band would hop rapidly from one frequency to another in a pattern to which only the receivers in the network of that particular transmitter would be keyed. With a unique time pattern of hopping for each transmitter-receiver network, the level of interference would be reduced to permit more use of a given frequency band than is now the case. Also, the fact that outsiders could not tune into the broadcasts would constitute an added advantage, especially for police radio. Spread spectrum techniques are attractive particularly as a means to conserve spectrum precisely in those bands serving mobile radio in which crowding is severe today, and so much concern is being expressed that vital future demands will not be met.[44]

earth. The stabilization system will provide a means of correcting alterations in the orbit of the satellite caused by changes in the forces exerted on the satellite due to the orbit of the satellite through the gravitational field caused by the fact that the orbit may be elliptical, rather than circular.

41. *See, e.g.*, GENERAL ELECTRIC, MISSILE AND SPACE DIVISION, DIRECT TV BROADCAST FROM SPACE; Gubin, *Direct Satellite Broadcast*, PROCEEDINGS OF THE AMERICAN ASTRONAUTICAL SOCIETY 67-95 (1967).

42. Vertical blanking intervals—the time interval of a pulse which causes a blackening of the retrace pulse of a television scanning signal, which initially causes the images to appear on the screen.

43. TELECOMMUNICATIONS REPORTS 34 (June 19, 1967).

44. One indication of this concern is the fact that two of the three examples of the potentially dire consequences of spectrum shortage enumerated in the Forward to the TELECOMMUNICATIONS SCIENCE PANEL REPORT, *supra* note 8, at iii, are drawn from the field of mobile radio.

However, these techniques would involve additional equipment, and they would probably require a frequency band to be cleared for exclusive use of spread spectrum transmissions.

III. Non-Atmospheric Transmission

A. *Waveguides and Laser Pipes*

Since it is the atmosphere, and precipitation and condensation in it, that presents the severe problems discussed earlier for using the frequencies above 15 Gc/s, the possibility comes to mind of confining the emissions to a pipe or tube, evacuated or filled with a gas transparent to the frequencies employed. Not only would it then be possible to exploit the enormous channel capacities of the wide bandwidths in these regions, but also this use would not conflict with simultaneous employment of the same frequency bands elsewhere. Waveguides[45] and laser pipes[46] would operate precisely in this fashion.

One particular waveguide described in the literature would consist of a tube about 2 inches in diameter consisting of a fine wire helix wound on a mandrel[47] and coated with glass fiber. Operating in range 50 Gc/s to 100 Gc/s (which is about 100 times the total bandwidth presently allocated to VHF and UHF television), the tube would have a capacity of about 100,000 voice circuits. The principal drawback is one of high total cost. The tube must be constructed to very close tolerances; it must be installed underground with no more than moderate bending; and it requires new kinds of elaborate terminal equipment and repeaters still in the development stage. On a *per-channel* basis, however, the cost may fall well below that of conventional systems. The basic problem is that telecommunications demand has not grown sufficiently, even in major metropolitan areas, to absorb such enormous capacities.[48]

45. Waveguides—normally a waveguide consists of a hollow cylinder of an arbitrary cross-section which will propogate electromagnetic radiation. A waveguide offers lower attenuation, greater power-carrying capacity, and more mechanical simplicity than a transmission line.

46. Laser pipe—a hollow cylinder whose internal walls are coated with silver, the cylinder being about one inch in diameter. The tube furnishes a path for the laser beam to follow. Laser (Light Amplification by Stimulated Emission of Radiation) is a device producing a nearly parallel beam of light which is theoretically capable of being focused to a spot a few ten millionths of an inch in diameter, producing an enormous electric field over that spot.

47. Mandrel—a rod used to retain the cavity in hollow metal products during working.

48. A good description of waveguides and other transmission techniques, from which portions of this discussion are drawn, is presented by Kidner, *Telephone Transmission*

The laser pipe is in an earlier stage of development. Consisting of an internally-silvered tube[49] perhaps 1 inch in diameter, and operating in the region of 420,000 Gc/s, a laser pipe might have a capacity running as high as 100 million voice channels! Experimentation has been progressing rapidly since the construction of the first laser model in 1960. Among the many problems that remain, containing the laser light beam in such a narrow pipe over long distances and guiding it around curves requires a complicated series of focusing lenses not yet fully perfected. Extremely close tolerances are required in construction, and only future work will determine whether these requirements can be met at an attractive cost.

While waveguides and the laser pipes will not be operationally available in the very near future, they are strong candidates to satisfy the levels of needs we might envision to the end of the century. These technologies provide some basis for hope that regardless of how high the demand may grow for telecommunications between fixed points over land, the demand can be satisfied at a channel cost lower than today's, and without drawing spectrum away from other uses.

B. *Transistorized Cables*

A technology available today, in contrast to that of waveguides and laser pipes, is the recently developed transistorized repeater for use with underseas cable as a way to greatly increase capacity and reduce the cost per channel. The FCC has recently approved installation of a 1250-mile transistorized cable between Florida and the Virgin Islands. The cable, having a total cost of about $33 million, is designed for an ultimate capacity of 720 voice channels. It involves a per channel cost of only one-third that of existing trans-Atlantic cables.[50] Plans are also well underway to install a second such cable in the Caribbean and there is talk of yet other installations over high-traffic density routes.

Questions immediately arise about the extent to which cable construction ought to be emphasized, especially at the expense of satellites, on grounds of spectrum conservation. The answer depends in part on (a) the addi-

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Media—A Survey of Land, Sea and Space Systems, TELECOMMUNICATIONS 52-69 (No. 2, 1966).

49. Internally silvered tube—a tube which has been coated on its inside wall with a layer of either silver, or an amalgam, in order to enhance the conductive properties of the tube.

50. Useful tabulations of the cost and physical characteristics of existing and projected underseas cables is presented by R. NICHOLS, SUBMARINE TELEPHONE CABLES AND INTERNATIONAL TELECOMMUNICATIONS (RAND paper RM-3472-RC, 1963); R. NICHOLS, HIGH CAPACITY SUBMARINE TELEPHONE CABLES: IMPLICATIONS FOR COMMUNICATIONS SATELLITE RESEARCH AND DEVELOPMENT (RAND paper RM-3877-NASA, 1963).

tional cost entailed in operating satellites in the higher frequencies and (b) the spectrum and non-spectrum costs imposed by continued sharing between terrestrial microwave and satellites. Difficult choices may be required especially since, on other than spectrum grounds, satellites appear to have a substantial edge over transistorized cable. If we were concerned only with transoceanic communication between two major points, such a cable might involve no higher cost than a satellite. But satellites, together with a group of ground terminals scattered in countries in both sides of the Atlantic, would provide a whole network of links; and more than that, the capacity over each link could be adjusted within limits to conform to peak daily traffic demands over that link.[51]

At the same time, one must be careful not to over-estimate the spectrum saving afforded by cable; for much depends on where the cable is landed and, therefore, on where spectrum is actually saved. As a case in point, the two most recently constructed cables between the United States and Europe, TAT-3 and TAT-4, extend from Tuckerton, New Jersey (about 75 miles south of New York City) to isolated points respectively on the coasts of Cornwall in England and Brittany in France. Obviously, it does little good so far as spectrum is concerned to bring the cable across the Atlantic and then link it by conventional means to the already congested New York area. Or expressed differently, a satellite ground station could also be installed in the Tuckerton area which is far enough from New York City so that the interference between the station and land line microwave would probably not be serious. The most crucial factor is the *final* link into the badly congested areas.[52] The moral is clear: so far as spectrum conservation is concerned, any new cables built across the Atlantic ought to be brought directly into the major communication centers, or linked into other non-atmospheric transmission systems.

C. *Broadband Cable to the Home*

I have left to the end discussion of one of the most promising applications of all—the use of cable brought into the home to provide not only a dozen or so television channels of excellent technical quality, but also (in combina-

51. We must note on the other side that for telephone use satellite does suffer a quality handicap relative to cable due to the time delay problem.

52. In the same vein, it is sometimes said that shared spectrum use between satellite and terrestrial microwave would not give rise to serious interference, because even in the worst congested areas satellite ground stations could be located within one or two microwave hops of the central area. This ignores the problem of interference between these extension hops and existing microwave facilities—a problem perhaps even more severe than in the case where the satellite ground station is located in the central area in the first place.

tion with technological advances elsewhere) facsimile mail, shopping, instruction, video telephone and other services. Several factors combine to make cable systems extraordinarily attractive as a technique to conserve spectrum.

First, by substitution for atmospheric television broadcast, it would release frequency bands for alternative uses in the most congested regions of the spectrum. The 30 to 50 Mc/s band allocation for land mobile services lies just under the VHF television band; the 150.8 to 162 Mc/s mobile allocation lies between VHF channels 6 and 7; and the 450-470 Mc/s mobile allocation falls between the VHF and UHF television allocations. Transferring use from television to land mobile not only would permit operations in frequency regions for which present-day mobile radio equipment is designed, but it would also greatly expand the regions available to mobile radio. The 492 Mc/s total bandwidth allocated to television is nearly 10 times as great as that currently allocated to land mobile. A single 6 Mc/s television channel is equivalent to 200 mobile radio 30 Kc/s bands.

Second, expanded cable use is technically feasible here and now. The basic technology has been demonstrated and applied over a period of many years in CATV systems. We know that costs (if not prices) for cable television service are already attractively low, and we can be confident that with continuing technological advance in cable and repeater design (and with an increase in the density of subscribers per unit area) these costs will decline.

Third, cable television is growing rapidly in public acceptance. By early 1967, approximately 1700 CATVs, serving 8 million viewers, were in operation. An additional 1250 franchises had been granted, and franchise applications were under consideration in 1500 other towns and cities. In earlier years, CATVs were concentrated in small- and medium-sized cities (especially in hilly or mountain regions) where reception from even close-in broadcasting stations was poor. More recently it has become obvious that CATVs can be profitable, even in the largest urban areas. The freedom from interference caused by tall buildings, airplanes, and the like, and the additional variety in programming has strong appeal. By now we have abundant evidence of the willingness of many viewers to pay a charge for cable service, even if they already have access off the air to a number of local stations. Systems are now operating or under construction in New York, Los Angeles, and other major cities.

While cable television is one of the most promising examples of conserving the use of spectrum, it is also the best example I can recall to illustrate the following proposition: in many cases the greatest difficulties encountered in introducing and rapidly absorbing new technologies involve not questions of economic and technical feasibility, but rather questions of how uses of these technologies are to be promoted, restricted, and guided as a reflection of conscious choices and judgments about what constitutes the "public interest" and how it ought to be served. Issues of cable versus conventional television broadcast will surely rank among the most difficult and sensitive that will confront the FCC over the next decade. Without going into detail about these issues, I shall note the following.

(1) Ownership and regulation of cable systems. Expanded cable systems would include services in addition to television; some would compete directly with existing telephone service; to reduce overall cost, telephone channels should probably be brought in on the same cable. How then should cables be owned and regulated? If owned by existing telephone common carriers, by what procedures can existing CATVs be absorbed into the system? How should rates and conditions of access be set to television stations and other originators; especially, to what degree if any should local originators be protected from competition by "outsiders"?

(2) The position of commercial television networks and local broadcasters. By what means should local broadcasters be induced or required to switch from conventional atmospheric transmission to use of a cable network? How severe would be the increase in competition in their now-protected local markets? To what extent would cable networks encourage formation of new networks competing with existing ones? What are the implications for the quality and quantity of television, with the opening up of local markets to distant broadcasting stations, independent program producers, and new networks? To what extent would cable systems render less costly the operation of pay-TV?

(3) The position of the viewer. How should the welfare be weighted of those groups who would prefer today's "free" but limited off-the-air reception to cable service for which they, presumably, would be charged? What about rural viewers now served by over-the-air broadcast, but too far away to be served economically by cable?

IV. Some Notes on Demand

The preceding discussion focused on the implications of new technologies for the supply of spectrum resources. These technologies will, of course, affect demand as well. For example, if use of satellites reduces drastically the per-channel cost for domestic and international services, and if the cost reduction is reflected directly in prices, the price-induced response of consumers for additional service would impose additional loads on the spectrum. If, on the other hand, satellite development does not pan out so well, but waveguide technology does, additional telecommunications demand can be satisfied without drawing spectrum from alternative uses. Much will depend, of course, on FCC decisions with respect to cable television. The effects of technological advance on the demand for spectrum will rest, primarily, on the response of users to price reductions, the relative speed at which these technologies are developed, introduced, and absorbed into the economy, and the spectrum-using characteristics of these technologies.[53]

One basic point that merits emphasis is that some of the new services attracting publicity and attention can, with appropriate peakload pricing, be dovetailed with other demands to reduce the load on the spectrum as well as against other resources. As a leading example, facsimile mail transmission in both domestic and international markets has a very promising future. An especially attractive feature of facsimile mail is that much of it could be transmitted in the dead of night over otherwise idle facilities, without great loss of utility to users. For example a home facsimile machine might transmit information by cable to a central or local post office where it would be stored on tape for delayed transmission by a satellite or microwave in the evening. Of course, very high priority mail (hopefully at an appropriate higher price) would be transmitted during peak periods as well.[54]

The Telecommunications Science Panel noted in its report that investment in computers will nearly quadruple by 1975, and that commercial information processing networks will be required for high capacity storage, processing and transmission. "These capabilities will depend on *vastly increased communication capabilities, not now in general existence.*"[55] Much of this traffic would be generated during off-peak periods, given the widespread practice of round-the-clock computer operation. A pricing

53. At a second-order level, these technologies (along with technological advance in general) will contribute to growth of national income. The response of consumer demand for telecommunications services as a function of income constitutes an additional variable affecting the demand for spectrum.

54. One of the more startling uses of facsimile transmission is suggested by tests scheduled for August 28, 29 and September 6 in which facsimiles of documents for Trans-World Airlines Flight 709 departing from Frankfurt are to be transmitted via the Early Bird Satellite before the plane lands at Dulles. The aim is to expedite cargo and passenger handling. Documents will consist of cargo manifests and passenger data including Polaroid photos of passengers. AVIATION WEEK, Aug. 7, 1967, at 43.

55. TELECOMMUNICATIONS SCIENCE PANEL, *supra* note 8, at 18 (italics in original). An interesting discussion of the problems and prospects for computer communications networks is presented by P. BARAN, THE COMING COMPUTER UTILITY—LAISSEZ-FAIRE, LICENSING OR REGULATION? (RAND paper P-3466, 1967).

structure adequately reflecting both the low spectrum and non-spectrum cost would provide additional incentive to shift demand for communications facilities to off-peak periods.

CONCLUSION

So far as the technological possibilities are concerned, one has reason for optimism. Attractive trade-offs exist between spectrum resources and other resources; there are opportunities for greater sharing of frequency bands; improved non-atmospheric forms of transmission are available now and exciting developments are on the horizon. In the near-term, prospects are good that satellites will be able to share spectrum with microwave facilities without serious problems of interference; use of cable television as a substitute for atmospheric broadcast, even on a gradual basis, would give substantial immediate relief in the frequency regions now most congested. Through the 1970's use of higher frequency regions by satellites is promising. Depending in part on how these developments turn out, transistorized cable under water and on land could be employed as a supplement. In the more distant future, waveguides and laser pipes would meet any conceivable growth of point-to-point traffic over land.

The degree to which these technological possibilities will be exploited to make efficient use of both spectrum and non-spectrum resources is something else again. This will depend in good part on the nature of spectrum management. Ideally, a measure of the cost of spectrum varying by service, time, and place should be explicitly included with other resource costs to: (a) serve as a basis for pricing telecommunications services to reflect the scarcity and abundance of spectrum resources as well as non-spectrum resources, (b) stimulate and guide research and development activities in making more efficient use of the existing spectrum resource base and in expanding it, and (c) more generally, to serve as a criterion for weighing spectrum considerations against other factors in the policies and practices of the FCC and of the Office of Telecommunications Management. However, the difficulties of developing such a measure, and the widespread disruptive effects its application would have, provide no strong basis for optimism.