SHARING THE UHF BETWEEN SPACE AND TERRESTRIAL SERVICES

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PREFACE

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I. INTRODUCTION

The struggle for the allocation of more spectrum for the rapidly burgeoning land and other mobile services, and the resistance of television and government interests to the release of spectrum previously allocated to their exclusive uses, attest to the fact that the demand exceeds the supply for the exclusive use of the choice portions of the UHF. If the benefits from future growth are not to be severely limited, ways are needed to share this spectrum more intensively and efficiently. Sharing with space relay techniques appears to be an attractive way to increase the service capacity. Most of the increased capacity is needed for services involving area coverage to small terminals for which satellite relays offer great promise (1). Mobile and broadcast services are typical of these involving area coverage to small terminals. The technology is not conceivable that would make feasible a separate independent antenna beam to track each terminal, hence the requirement for area coverage to all the terminals to be accommodated within a specified area.

If this service is to be provided from satellites, the flux density required at the earth's surface over the coverage area will then determine the total RF power that must be generated in the satellite relatively independently of the number of beams that are used to cover the area. However, if an area is covered by partitioning it into many beams, the spectrum in each could be used independently so as to satisfy better any independent interests that are geographically separated, such as the various jurisdictions of police, fire, or taxi operations. Thus when the possible applications become limited by the spectrum available, there is justification to partition the area of coverage into smaller beams to provide greater independent capacity to any geographically independent interests.

The small terminal area-coverage services potentially involve thousands to many millions of earth terminals so that the small earth terminals dominate the total system costs. Thus the focus of design effort tends to be on the many small earth terminals in order to reduce their cost and burden to other systems, i.e., to make them simple, small, and reliable at the expense of complication and size of the satellite relay. Even so, because of their great numbers, these small terminals involve potentially more direct users and greater systems investments than may be involved in the use of all the rest of the spectrum at UHF and higher frequencies. Thus they should become important in the consideration of how their spectrum needs are to be satisfied.

This paper first treats the important factor of frequency choice--how this affects the satellite relay performance which is limited by the RF power that can be generated, and how it affects the earth terminals and total system costs. In both cases the lower UHF is favored. The sharing of this spectrum is then considered and it is shown how the highest quality mobile and TV services can be provided by sharing a significant portion of the UHF with terrestrial services. This is shown to be feasible if wide band FM is used for the space services. It can be done by superimposing the space spectrum use over the terrestrial uses without harming or significantly limiting the terrestrial operations or the space services. Very large additional new spectrum use can be achieved in this way to increase greatly the circuit capacities and service benefits that can be derived from the UHF.

II. EFFECTS OF FREQUENCY CHOICE

The choice of frequency can determine the system capability of a space service as limited by the state-of-art for the satellite relays, and it may have an important influence on the earth terminals and the total system cost. Each of these effects will be examined in more detail.

SATELLITE RELAY PERFORMANCE

For area coverage from satellite relays to small terminals where the available down-link power is the most limiting constraint on system performance, the relative capacity figure of merit of the frequency chosen for the down link is indicated in Table 1. The frequencies sampled in the first column span the range from 1 to 40 GHz. The values of RF power generated shown in the second column, are those that might be produced from 12 kW of primary power obtained from 200 m^2 of sun-oriented solar cells after two years of environmental degradation. The conditioned primary power could be obtained for about 1000 lb in orbit, and is about as large an operational supply as might be feasible to consider by the mid-1970s. The radiated powers assume solid-state transmitters suitable for use with antenna arrays of many elements, and at the higher frequencies credit the transmitters with higher efficiencies than are currently available in the laboratory, but give these higher frequencies the benefit of what might be achievable with further development.

The third column represents the attenuation for one-way propagation through the atmosphere and will depend on geographic location and other parameters, many of which are as yet undetermined. The attenuation values for frequencies up through 6 GHz are representative of those that will not be exceeded 0.01 percent of the time. They assume an integrated value of precipitation along the propagation path equivalent to a rain rate of 100 mm/hr over a 3 km path length. The values indicated for frequencies of 12 GHz and higher are representative

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of the attenuations that will not be exceeded 0.01 percent of the time if space diversity is employed. They assume that there will be a usable diversity path that will not experience greater than an integrated value of precipitation equivalent to a rain rate of 20 mm/hr over a 3 km path length. This space diversity could be achieved either by redundant earth terminals (e.g., separated, say, by 10 km) or by switching to a satellite relay that offers a suitably different propagation path. Although there is considerable uncertainty and variation with location for the attenuation that might be experienced, this will not alter significantly the conclusions which will be drawn with respect to the relative utility of the various frequencies for satellite down-links.

The earth station system temperatures of the fourth column are typical of those that might be achieved easily, reliably, and cheaply for any environment of significant interest. The relative receiving area required in the fifth column is the effective earth antenna aperture area in square meters required to obtain a carrier-to-thermal noise ratio referred to the input of the receiver of 20 dB when the satellite radiated power covers the earth, with a frequency bandwidth of 500 MHz. The column of reference antenna dimensions indicates what might be appropriate for a fixed, linear adaptive array that could operate with 2.5° longitudinal spacing of the satellites. The dimension orthogonal to that of adaptation is limited to the adaptive dimension at the higher frequencies and to a value that provides an area of 2 m^2 for the lower frequencies. All of these antennas would be of comparable complexity and systems performance, and they would not dominate the total systems cost.

The last column gives the relative capacity figure of merit of the system in MHz of bandwidth at each frequency for the reference antenna dimensions and other systems parameters of Table 1. It is obvious that the system capacity performance degrades rapidly with increasing frequency, e.g., 16 dB between 1 and 12 GHz, as determined by the potential satellite relay down-link capacity.

EARTH TERMINAL AND TOTAL SYSTEM COST

If the small earth terminals are constrained to a specified aperture area (e.g., 2 m^2), and if single-feed, fixed reflectors are used in an interference excluded environment, the earth terminal and total system cost might not be a very sensitive function of the frequency between 1 and 10 GHz. However, if the terminal is on a vehicle that requires antenna pointing, or if the terminal must operate in a spectrum sharing or interference environment, an adaptive array may be required for satisfactory operation. For arrays filling a given aperture size, the number of adaptive elements varies as the square of the frequency and the complexity and cost of the adapting antenna will tend to behave similarly, so that for sufficiently high frequency or large aperture the antenna costs become dominating and favor lower frequencies for smaller total system costs. This should clearly be the case in comparing 2 m^2 adapting aperture areas at 1000 and 12,000 MHz, and the differences become more pronounced at higher frequencies.

III. SHARING CONSIDERATIONS

It is usually difficult to share the same frequencies in the same place by different services. However, it will be shown here that such sharing between terrestrial and space services is feasible while providing the highest quality in all the services. This can be accomplished if wide band FM or pulse code modulation is employed appropriately in the space links. This will be treated in detail for TV broadcast and some mobile services to show that there is more than 10 dB of margin in the most difficult situations before degrading interference is encountered in any service when 1-m^2 or greater effective antenna areas are used for the earth terminals. These antennas need to be adaptive arrays, however, if they must operate successfully in an environment of strong terrestrial radiations within the earth station receiving bands.

INTERFERENCE TO TERRESTRIAL TELEVISION

The exact way in which the various pertinent parameters influence interference to conventional television is not generally understood. It has not even been possible to establish a satisfactory quantitative subjective measure of the degree of objectionableness of various interference conditions. This has permitted interpretations to develop which if extrapolated beyond experience would be truly paradoxical. The analysis presented here will develop a way of interpreting the effects of varying the interference parameters that should be consistent with any experimental data and be extrapolatable to other conditions of interest within a few decibels.

Most of U.S. production of UHF TV receivers in current use were designed to provide noise figures in the range 10 to 14 dB. Some of the older and substandard sets may be operating with degraded performance, but it would not be unreasonable to assume that by 1975 more than 90 percent of the UHF receivers in operation could have noise figures in the range 10 to 14 dB, with one-half having 12 dB or better noise figures. It would seem inappropriate to require or to try to protect a lower noise figure than 10 dB for use with conventional TV antennas, because the man made noise will dominate in most urban environments. If the situation warrants better performance, special antennas with preamplifiers could be used to lower the system temperature as desired. In this analysis it will be assumed that the terrestrial receivers will be protected to a 10 dB noise figure, i.e., referred to the receiver input, the thermal noise in the nominal 4 MHz bandwidth is assumed to be -128 dBW.

The subjective measure, picture quality, does not seem to be definable with precision; however the TASO (2) "mean observer" grade description, averaged over color and monochrome for conventional reception in the United States, will be used as a reference for the comparison of the effects of interference on television reception. This classification into grades of picture quality as determined by TASO when the noise was measured in a 6 MHz bandwidth and as converted to the thermal noise in the nominal 4 MHz bandwidth of the conventional receiver is illustrated in Table 2. The "mean observer" classification provides a measure set that seems less vulnerable to criticism from the limiting effects of transmitter noise than some of the other TASO derived classification sets that have been used. The conversion of the "mean observer" measure of noise in a 6 MHz channel to the "reference" classification for the noise in the nominal

4 MHz receiver bandwidth provides a convenient reference for the comparison of the effects of a variety of interfering signals on AM/VSB TV reception.

The interference effectiveness of noise within the video bandwidth of the receiver depends on the frequency of the noise among other things. This relative effectiveness has been represented by various weighting functions (3), two of which are illustrated in Fig. 1. The CCIR/BELL Monochrome curve provides an integrated video weighting factor of 6 dB, as compared with 4 dB for the EIA/BELL color curve. Both weightings apply to conventional television in the United States.

The effectiveness of white noise interference is also modified by the receiving band-widths preceding the video stages. When this is taken into account, the maximum effectiveness of white interference noise (not coherent with the transmitter carrier) as a function of its bandwidth and relative to an equal power of thermal noise in the nominal 4 MHz receiver bandwidth is indicated in Fig. 2. For greater than 4 MHz bandwidth the relative effectiveness is just the fraction of the bandwidth effectively intercepted by the receiver. For narrower bandwidths than the receiver, the noise band can be tuned near the TV carrier so as to be more effective than an equal power of thermal noise by as much as 4 dB for monochrome and 2+ dB for color. However, if the noise band is tuned away from the carrier, but still within the nominal receiver bandwidth, it may be many dB less effective than thermal noise as indicated in Fig. 1.

With the aid of Fig. 2 it will now be illustrated how to determine the maximum interference effectiveness of any nonwhite noise relative to that of white noise. First, consider any narrow bandwidth (<4 MHz) signal such as a typical land mobile FM voice circuit. Its maximum interference effectiveness when tuned near the VSB/AM TV carrier would be 4 dB greater than an equal power of thermal noise within the bandwidth of a monochrome receiver, and 2 + dB greater than an equal power of thermal noise for a color receiver. Similarly, a cochannel signal from another VSB/AM TV transmitter is so heavily concentrated near the carrier that its maximum interference effectiveness is nearly equivalent to that of a narrow bandwidth signal.

The case of interference from a wideband-FM TV signal needs careful consideration. If no carrier dispersal techniques are used, the ratio of time spent by the FM carrier at the synch frequency to the total carrier time is just -11 dB. Thus in the absence of dispersal, the synch signal alone would have a maximum interfering effectiveness equivalent to a narrow bandwidth signal about 11 dB below the FM carrier power, independent of the FM modulation index (above unity) used. Similarly, the picture could be all black, all white, or any other single level, and the maximum interfering effectiveness would be equivalent to a narrow bandwidth signal about 1 dB below the FM carrier power, again nearly independent of the FM modulation index used. In practice the picture signal is dispersed over more than one level in order to carry any information. Furthermore, it should be feasible to disperse the synch, blanking, and black and white picture signals so that the maximum interfering effectiveness of the total wideband-FM TV signal would approach (within 1 or 2 dB) that of white noise over the same band. Its interference effectiveness would then be determined by the fraction of the power falling within the receiver bandwidth, and it would vary with the modulation index used. Further study and experiment are needed to determine how close to the equivalence of white noise can be approached in a practical wideband-FM TV system.

Noise-like interference is the most effective against the AM/VSB picture signal, although any type of narrow-bandwidth modulation can be of comparable effectiveness to that of noncoherent white noise indicated in Fig. 2 if it is not nearly synchronized or accurately tuned to the TV signal. The important question is, How much interference is degrading to the picture quality? This question has not yet been answered adequately by suitable experiments, however it would seem logical to assume that an interfering signal about 3 dB below the total weighted noise in the system (including transmitter, propagation, and receiver noise) would produce recognizable degradation in the picture quality for nearly any kind of picture and any quality grade. On the other hand, interference to a stationary scene may be perceptible at 5 to 10 dB or more below the total weighted noise in the system. Also, the perceptibility of interference may be influenced by the quality grade and a variety of viewing conditions not normally defined in the tests. Until or unless a consensus of tests establishes a more appropriate value, 3 dB below the total weighted noise in the system might be used as the interference that will produce recognizable degradation to the picture quality nearly independent of the picture quality or viewing conditions. There would be approximately three such recognizable degradation steps between adjacent TASO grades as defined in Table 2, and the tests seem to indicate that under some conditions the steps between some grades are difficult to recognize.

Using the above defined "recognizable degradation" from interference to specify the maximum permissible interfering power at the receiver input within its 4 MHz bandwidth we obviously obtain a value 3 dB below the total noise, independent of the quality grade or type of service. Thus if thermal noise is dominant in the system and a 10 dB noise figure is to be protected (-128 dBW in the 4 MHz bandwidth), then the maximum permissible white-noise interfering power in the 4 MHz bandwidth at the receiver input is -131 dBW, relatively independent of the TV signal strength or picture quality.

In order to translate the interfering power at the receiver input into a flux density limit, reference values will be used for transmission line loss, antenna aperture loss, and polarization loss. Then the fraction of the antennas for which pointing changes will need to be made to avoid degrading interference can be determined from the fractions of the receivers departing from the reference loss values by given amounts.

The transmission losses in the mid-UHF TV band for 30 ft of transmission line were found (2) to be a minimum of 3 dB, an average of 6 dB, and a maximum of 9 dB. Of course the losses in penetrating buildings to reach indoor antennas can be as much as 15 dB or higher. The reference case will assume the minimum 3 dB loss.

The reference antenna for terrestrial TV reception will assume an isotropic gain for its design polarization in the direction of the interfering satellite. The antenna loss with respect to 1-m^2 of aperture at 600 MHz is then 17 dB. If the satellite transmissions are circularly polarized there will be an additional polarization loss of 3 dB. Thus the total reference loss for transmission line, antenna, and polarization is 23 dB; and the reference maximum permissible circularly-polarized interfering flux density becomes -108 dBW/m^2/4 MHz.

If the wideband-FM satellite transmissions are dispersed to within 1 dB of the interference equivalence of white noise over a 50 MHz RF bandwidth, the maximum permissible circularly polarized flux density becomes -98 dBW/m^2/50 MHz.

In order to determine the minimum usable flux density for space TV broadcast with wideband FM using a 50 MHz RF channel, the following parameters are used. A 4 dB receiver noise figure is assumed giving a noise power in a 50 MHz bandwidth of -123 dBW. Then if an effective antenna area of 1-m^2, a transmission loss and operating margin of 5 dB, and an FM threshold carrier-to-noise ratio of 10 dB for highest quality output are assumed, the minimum usable power flux density becomes -108 dBW/m^2/50 MHz. This is 10 dB below the maximum permissible flux density previously indicated even for only 1-m^2 of antenna aperture, and allows an adequate margin for additional systems degradation or failures to accommodate to specification limitations.

The reference interference parameters were chosen obviously conservatively in the cases of the lowest conventional TV receiver noise figure (10 dB) and the least transmission line loss (3 dB), while the effect of the antenna loss (isotropic gain) needs further evaluation. This will be done by estimating the fraction of the conventional TV receivers that would experience recognizable degradation from the reference maximum permissible interfering flux density. Only 0.5 of the UHF receivers would have less than a 12 dB noise figure (as compared with the reference 10 dB value). Also, only 0.5 of the UHF receivers have outdoor antennas, less than 0.5 of these antenna gains are greater than 5 dB, and only 0.5 of these would have transmission line losses less than 6 dB (as compared with the reference value of 3 dB). Therefore, only 0.06 of the receivers with high gain (~12 dB) antennas have losses within 5 dB of the reference losses, i.e., less than 28 dB as compared with the reference losses of 23 dB.

If the terrestrial TV receivers have equally likely azimuthal distributions about the broadcast TV stations, then the directional discrimination obtained with their antennas according to CCIR-Recommendation 419 (4) will exclude all but less than 0.2 of these with antenna gains in the direction of the satellite exceeding 5 dB above isotropic. Thus only about 1 percent of the receivers would experience recognizable degradation from the reference maximum permissible interfering flux density. If the satellite is more than about 15 deg above the horizon, all the interfered with receivers could be easily remedied by small changes in antenna pointing. If the satellite is on the horizon only about half of them could be cured in this way. However, if the maximum interfering flux density is lowered by 7 dB from the reference case, the last vestige of recognizable degradation could be removed, independent of satellite location or antenna pointing.

INTERFERENCE WITH OTHER SERVICES

Another important case to consider is that of the earth receiver in satellite TV service required to operate in the strong interference environment of local VSB/AM TV transmitters within the earth receiver bandwidth. The previous determination of the minimum usable power flux density of -108 dBW/m^2/50 MHz for operating with an effective antenna area of 1-m^2 was concerned only with thermal noise. The direct and scattered signals from local TV broadcast may have interfering flux densities greatly exceeding the power densities of the wanted satellite signals, and successful operation of the satellite broadcast link using conventional receiving antennas may not then be feasible. However, the promise of small adaptive arrays (5) makes them seem ideally suited for this type of operation. They could in effect automatically steer nulls in the directions of a limited number of much stronger interfering signals and adequately reject them, while still obtaining nearly full gain in the direction of the wanted satellite signals. This type of operation should be possible with only about 3 dB greater minimum usable power flux density than required for thermal noise alone, and it should permit operating the satellite down-link while sharing the spectrum with intense terrestrial use for TV broadcast and mobile services. Any increases in the minimum usable power flux density that are required could, of course, be provided instead by increasing the receiver aperture by a corresponding amount.

The sharing of spectrum between space and terrestrial mobile services with smaller terrestrial receiving antenna gains, and usually with much smaller required protection ratios, than for VSB/AM TV systems is much less difficult. The margins between minimum usable and maximum permissible flux densities will usually be great enough so as not to require as stringent performance of the earth station adaptive arrays. This type of sharing should permit the complete reuse of the UHF for space mobile services without hindering the current terrestrial services or limiting their future development.

IV. CONCLUSIONS

The demand for spectrum at UHF has exceeded the supply for exclusive use of the contending services. Satellite relays offer great promise for area coverage services to small terminals which potentially will involve more direct users and greater investment than all other services combined. The UHF is the choice portion of the spectrum for these satellite relay services from the standpoints of both the satellite relay performance and the total systems costs (the latter being dominated by the total costs of the many small earth terminals). It appears to be entirely feasible for the UHF to provide double duty with its complete sharing reuse for the new highest quality space services, without hindering the current terrestrial services or limiting their future development. The most difficult case of the sharing between the two types of TV broadcast service was examined in detail, and although there are many unknowns remaining, it appears that sharing will be feasible with adequate margins using earth terminals with as small receiving antennas as 1-m^2 effective area.

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TABLES AND ILLUSTRATIONS

TABLE I. RELATIVE CAPACITY MERIT OF DOWN-LINK FREQUENCIES

Freq. (GHz)	P (kW)	Atmos. Atten. (dB)	System Temp. (°K)	Relative Rec. Area Required (m^2)	Reference Antenna Dimensions (m × m)	Relative Capacity Merit (MHz)
1	5.0	~0	290	8	8 × .25	625
2	4.0	~0	290	10	4 × .5	500
4	3.0	~0	290	13.3	2 × 1	375
6	2.5	3	290	32	1.4 × 1.4	156
12	2.0	3*	580	80	.7 × .7	15.6
20	1.5	7*	580	267	.4 × .4	1.5
40	1.0	20*	580	8000	.2 × .2	0.012

*With space diversity.

TABLE II. CLASSIFICATION OF PICTURE QUALITY

Picture Quality	TASO "Mean Observer" (C/N)*(dB)	Reference in 4-MHz (C/N)*(dB)
Excellent (no perceptible effect)	42	44
Good (just perceptible effect)	36	38
Passable (not objectionable)	30	32
Marginal (somewhat objectionable)	25	27
Inferior (definitely objectionable)	19	21
Unusable (too bad to be watched)	<13	<15

*(C/N) is the carrier-to-white-noise ratio referred to the input of the AM/VSB receiver.

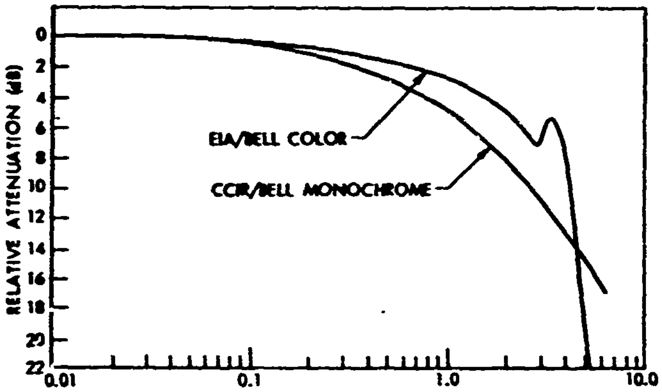

Fig. 1—Television Noise Weighting

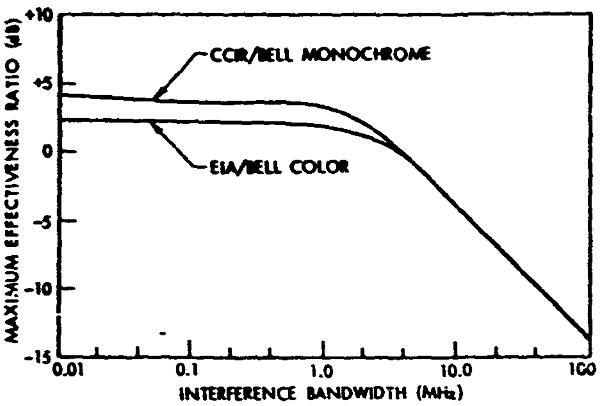

Fig. 2—Interference Effectiveness Relative to Equal Power of Thermal Noise in 4-MHz Bandwidth