Frequency Economy in Mobile Radio Bands

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The various factors affecting the usability of mobile radio channels are discussed, and estimates are obtained for the number of usable channels per megacycle for several present and proposed methods of operation. The lack of radio-frequency selectivity is the principal barrier to maximum frequency economy, but this difficulty can be avoided by sufficient geographical and operational coordination.

The increasing demand for all types of radio services emphasizes the need for efficient use of the radio frequency spectrum. In mobile radio operation the number of usable channels that can be obtained in the VHF and UHF mobile bands depends not only on the width of the individual channels, but also on how and where each channel is to be used. Activity on the same frequency at neighboring locations, and on neighboring frequencies at the same location both affect the usefulness of a channel. Halving the channel spacing doubles the number of potential assignments, but it does not double, and in some cases it does not appreciably increase the number of usable channels.

The usefulness of a single isolated channel is determined by the intensity of its signal above the noise level. Because of the very wide variation in received signal strength caused by distance, terrain, building shadowing, etc., the coverage area of a channel can be discussed only in statistical terms. There are likely to be islands of poor signal-to-noise ratio even close to the transmitter, and the coverage gradually fades out into more spotty conditions at greater distance.

If the same frequency is used at a neighboring location, the familiar problem of co-channel interference arises. There will now be locations where the desired signal is above noise, but the undesired signal is still stronger. Thus, the coverage area of a channel is reduced by the existence of the co-channel transmitter; again, it is possible to discuss this reduction only in statistical terms.

When two channels are being operated on different frequencies in the same general area, the coverage area of each is limited by signal-to-noise considerations. In addition, each channel may affect the other because of spurious radiation from transmitters, insufficient receiver selectivity, receiver oscillator radiation, etc. The recent trend toward receivers with greatly improved IF selectivity is worthwhile, but even infinite IF selectivity cannot solve many of the present interference problems.

When three or more channels are operating in the same general area, another type of interference occurs because of intermodulation in transmitters or receivers. If it were technically feasible to build into the equipment sufficient radio frequency selectivity to separate the working channels, this interference could be removed. In fact, this is not feasible, and it is necessary to consider possible modulation products from channels falling within a frequency band several percent wide. The number of possible interference conditions that result from intermodulation (third order) rises from 9 for 3 working channels to 50 for 5 channels, to 450 for 10 channels, and to 495,000 for 100 working channels. Some of these interference combinations overlap and fall on the same channel; but even considering all possible duplication, intermodulation interference rapidly becomes controlling as the number of closely spaced channels working in the same area is increased.

It is not technically feasible to achieve enough radio frequency selectivity to permit unrestricted and uncoordinated use of many channels in a given area, unless the channels are, on the average, separated by about 1 per cent of the operating frequency. For any kind of efficiency of frequency utilization, it is necessary to have some coordination in the location of fixed transmitters and in the use of channels. The maximum efficiency of utilization requires the maximum coordination.

The technical factors that determine channel width, channel spacing, and the number of usable channels are described and tabulated below. The first section discusses the principal factors that affect the usefulness of channels equipped with transmitters and receivers with perfect filtering. This is followed by a consideration of the limitations imposed by insufficient total filtering and by insufficient radio frequency filtering. The next section shows the reduced requirements that are possible by coordination between systems. Finally, the quantitative data are used to illustrate the capabilities and efficiencies of various present and proposed methods of mobile system operation.

CHANNELS WITH PERFECT FILTERING

It has been found by experiment that the radio path loss between antennas in a mobile radio system can be ascribed to three principal factors: distance, shadowing and standing wave patterns. The variation with distance from the base station follows the theoretical free space loss up to 500 feet or more, as long as the points are within line of sight. Typical values of the free-space loss are shown in Table I. Beyond about one-half mile the median path loss over plane earth increases about 12 db each time the distance is doubled out to distances of 20–30 miles.[1, 2]

In addition to the increase in path loss with distance, which is accounted for reasonably well by the theory of radio propagation over plane earth, bold features of geography such as mountains and large buildings cause shadow losses that result in irregular coverage patterns. For example the median loss at street level for random locations in New York City is about 25 db greater than the plane earth values computed for the distance and antenna heights involved; the corresponding 10 per cent and 90 per cent losses are about 15 and 35 db respectively.[3]

Superimposed on the above effects which vary relatively slowly with location are standing wave patterns whose effect on path loss can change substantially within a foot or so. The standing waves are the result of random additions of multiple reflections from nearby buildings or terrain, and the variation in path loss follows the Rayleigh distribution for small changes in distance in urban areas. In other words, there is no theoretical limit on the deviation from the median but in 1 per cent of the possible locations the signal is likely to be more than 8 db above the median value and in 99 per cent of the possible locations the signal level is not expected to be more than 18 db below the median value.

The motion of the mobile unit through the standing wave patterns causes signal fluctuations or flutter in the received signal. The flutter

TABLE I — FREE SPACE LOSS BETWEEN DIPOLES

Separation Between Transmitting and Receiving Antennas	Free-Space Loss	
	150 mc	450 mc
5 ft.	16 db	26 db
50 ft.	36	46
500 ft.	56	66
½ mile	70	80

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[1] Young, W. R., Jr., Comparison of Mobile Radio Transmission at 150, 450, 900 and 3700 Mc. Bell Sys. Tech. Jl., **30**, pp. 1068–1085, Nov., 1952.

[2] Aikens, A. J., and L. Y. Lacy, A Test of 450-Megacycle. Urban Transmission to a Mobile Receiver. I.R.E., Proc., pp. 1317–1319, Nov., 1950.

[3] Bullington, K., Radio Propagation Variations at VHF and UHF. I.R.E., Proc., pp. 27–32, Jan., 1950.

rate at 150 mc may be as much as 15 cycles per second for a speed of 30 mph and increases as either the radio frequency or the speed of the mobile unit is increased. The fast acting gain control needed to minimize the flutter effects is obtained automatically with frequency modulation but is more difficult to obtain with amplitude modulation. This factor is one of the principal advantages of the use of FM instead of AM for mobile radio systems.

The co-channel interference to be expected between stations having equal transmitter powers depends on the path loss statistics for both the desired and undesired signals. At the edge of the desired coverage area there must be a high probability that the desired signal will be strong enough to be useful and only a small probability that the undesired signal will be strong enough to be troublesome. The geographical separation needed between co-channel stations varies from about four to six times the desired coverage radius when FM is used and from six to eight times when AM is used.[4] If the needs for mobile channels were uniformly distributed geographically only a small part of the potential channel assignments would ever be used in a given area. However, the needs for mobile channels are usually concentrated in areas of high population density so that a large percentage of the channel assignments may be needed in the same area.

The above estimates on co-channel spacing depend somewhat on the antenna heights and the type of terrain, and assume that the same frequency is used in both directions of transmission. When the two-frequency method is used with adequate separation between the transmitting and receiving frequencies, the co-channel spacings can be reduced to about three to five times the coverage radius for FM and to about four to six times for AM. This reduction of approximately 30 per cent is possible because the most troublesome interfering path in the single frequency method (from base transmitter to base receiver) can be eliminated in the two-frequency method by sufficient selectivity.

The principal reason for using the single frequency method is to provide communication between two mobile units when they are relatively near each other but are beyond the range of the base station. When transmission of all messages through the base station is desirable, or at least not objectionable, the two-frequency method is preferable. It is shown in a later section that close geographical and operational coordination is needed to achieve maximum efficiency in the use of frequency space and that this coordination can be obtained only with the two-frequency method.

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[4] See reference in Footnote 3.

The bandwidth needed to pass the desired signal depends on the frequency stability that can be maintained as well as on the type of modulation. The allowance for frequency drift includes the variations in both transmitters and receivers. The importance of these figures is indicated in Table II which shows the tolerances needed for frequency instability. For example, with an overall frequency stability of ±0.002 per cent the channel width at 450 mc needs to be 18 kc wider than the minimum bandwidth required to pass the modulated signals.

The use of frequency modulation has several important advantages that cannot be readily obtained with AM. The instantaneous gain control and the closer co-channel spacings have already been mentioned. In addition, for the same radiated power, FM with a frequency swing greater than about ±3 kc has the well known advantage of providing a higher output signal-to-noise ratio throughout most of the coverage area than is possible with double sideband amplitude modulation; this FM advantage is substantially reduced when the IF bandwidth is large compared with the bandwidth required to pass the desired sidebands.

The bandwidth required for frequency modulation of a 3 kc voice band must be at least ±3 kc. For reasonable FM signal-to-noise advantage, particularly in the presence of impulse noise, the frequency swing should be at least ±5 kc which requires a bandwidth of ±8 kc for good quality. The corresponding bandwidth for amplitude modulation is ±3 kc; the use of single sideband AM transmission does not seem feasible, at least not for single channel operation.

LIMITATIONS IMPOSED BY INSUFFICIENT (TOTAL) FILTERING

The frequency separation between carrier frequencies must be greater than the bandwidth required to pass the desired signal because additional frequency space or guard bands are needed to build up receiver selectivity against undesired signals and to avoid the extra band radiation from transmitters. The power of a 100 watt transmitter is about

TABLE II — TOLERANCE NEEDED FOR OVERALL FREQUENCY DRIFT

Frequency Stability	Allowance for Frequency Drift	
	150 mc Band	450 mc Band
±0.001%	±1.5 kc	± 4.5 kc
±0.002	±3	± 9
±0.005	±7.5	±22.5

Table III — Required Suppression versus Distance Between Antennas

Distance Between Transmitting and Receiving Antennas	Total Selectivity or Filtering Required	
	150 mc	450 mc
0 ft.	160 db	160 db
50 ft.	124	114
500 ft.	104	94
½ mile	90	80

160 db greater than the minimum signal that is useful in the receiver (140 db below one watt), so ideally no appreciable interference would result if the overall selectivity of the receiver and the suppression of extra band radiation in the transmitter could be in excess of 160 db. This amount of isolation is difficult to obtain by filtering. The interaction between transmitter and receiver of the same system is frequently avoided by the use of "push-to-talk" operation, but the potential interference between different systems requires the full 160 db (based on 100 watt transmitters). Fortunately, a substantial part of the desired isolation can be obtained by modest geographical separation. The net requirements for either receiver selectivity or transmitter filtering are less than 160 db by the losses shown in Table I and are summarized in Table III.

Receiver selectivities of 90–100 db or more are feasible except on nearby channels and possibly on certain image channels. Typical values of the guard bands that are required between the edge of the desired pass band and the frequency at which the desired attenuation to interfering signals can be obtained are estimated in Table IV.

Even if the guard band, shown in Table IV, required to provide adequate selectivity in the receiver could be reduced to zero by providing infinitely steep sides on the IF selectivity curve, there would still remain the guard band needed to avoid the extra band radiation from the transmitter. The amount of suppression of extra band radiation needed

Table IV — Guard Band versus IF Selectivity

Desired IF Selectivity	Required Guard Band
40 db	12 kc
60	15
80	20
100	25
120	30

for unrestricted operation is equal to the required receiver selectivity given in Table III and can be translated into frequency space in the following manner.

Both AM and FM transmitters radiate some noise and distortion products outside of the ideal modulation bandwidth. In addition, some of the sideband energy in FM falls outside the desired modulation bandwidth. The magnitude of the undesired FM sideband radiation is higher than the noise immediately outside of the desired band, but it decreases more rapidly with the result that the noise is usually controlling in the region where the extra band radiation is more than 60 to 70 db down.

The guard bands that are required between the edge of the desired transmitted band and the frequency at which the necessary suppression of extra band radiation can be obtained are estimated in Table V. These values depend on the width of the voice band and are relatively independent of the radio frequency since r.f. selectivity is not possible.

Measurements on present day transmitters correspond to the above estimates for values of suppression less than 80 db, but a frequency separation of nearly one megacycle or more is needed for suppressions of 100 and 120 db. This limitation is not expected to be inherent so more optimistic estimates are indicated in Table V. If the present characteristics cannot be improved, that is, if suppressions greater than about 80 db cannot be obtained, Table III indicates that some interference may be expected within about one-half mile of an unwanted transmitter.

A comparison of the information given in Tables III, IV and V indicates that the guard bands required for unrestricted operation are approximately 100, 50 and 25 kc for minimum separations between transmitter and receiver of 50 feet, 500 feet and one-half mile, respectively. These values together with the bandwidth needed for modulation and for frequency instability determine the frequency separation required between channels operating in the same area and are summarized in Table VI.

TABLE V — GUARD BANDS REQUIRED TO AVOID EXTRA BAND RADIATION

Suppression of Extra Band Radiation	Guard Bands Required	
	AM	FM
40 db	3 kc	9 kc
60	10	15
80	25	25
100	50	50
120	100	100

TABLE VI — CHANNEL SPACING REQUIRED FOR UNRESTRICTED OPERATION OF TWO FM CHANNELS IN SAME AREA VERSUS ANTENNA SEPARATION

Minimum Separation Between Transmitting and Receiving Antenna	Channel Spacing, Neglecting Intermodulation			
	150 mc		450 mc	
	±0.002%	±0.005%	±0.002%	±0.005%
50 ft.	112–122 kc	121–131 kc	124–134 kc	151–161 kc
500 ft.	62– 72	71– 81	74– 84	101–111
½ mile	37– 47	46– 56	49– 59	76– 86

The above table shows that if interference of the types so far considered is to be kept below the minimum usable signal at all distances greater than about 500 feet from undesired transmitters, the channel spacing needs to be at least 62 to 75 kc in the 150 mc band and 74 to 105 kc in the 450 mc band. The channel spacings for AM are equal to the minimum shown above, while the higher figure is for FM with ±5 kc swing (a modulation bandwidth of ±8 kc).

Since the above channel spacings are considerably greater than the necessary IF bandwidth, it should be possible to use intermediate channels in adjacent non-overlapping areas. This geographical limitation does not appreciably decrease the overall efficiency in the use of frequency space as long as the needs for mobile channels are more or less uniformly distributed within a large region, but it becomes important where a large percentage of the available channels are needed in the same metropolitan area.

In a later section it is shown that channel spacings less than the values given in Table VI are feasible in the same area providing sufficient coordination is achieved in both geographical spacings and operating methods.

The estimated channel spacings shown in Table VI do not take into account the effect of intermodulation interference which is discussed in the following section. Intermodulation interference may limit the number of usable one-way channels to only 1 or 2 per megacycle instead of the above 6 to 20 per megacycle, unless further restrictions are placed on the selection of frequencies and on the method of operation.

LIMITATIONS IMPOSED BY INSUFFICIENT RF FILTERING

When a strong unwanted signal on a frequency within the RF bandwidth is present at the input to a receiver, overloading occurs and the receiver

TABLE VII — REQUIRED RF RECEIVER SELECTIVITY VERSUS ANTENNA SEPARATION

Minimum Separation Between Transmitter and Receiver	RF Selectivity	
	150 mc	450 mc
0 ft. (common antenna)	95 db	95 db
50 ft.	59	49
500 ft.	39	29
½ mile	25	15

is said to be desensitized. When two or more strong unwanted signals are present desensitization also occurs, but in addition, extraneous frequencies are generated by intermodulation in the receiver itself. As the levels of the unwanted signals become greater than about 75 db below one watt (1 or 2 millivolts across a typical receiver) the intensity of the modulation products rises rapidly above the set noise. The resulting interference can be 60 db or more above set noise and the number of the modulation products increases by at least the cube power of the number of operating channels.

Ideally, the intermodulation interference in the receiver caused by 100-watt transmitters (20 db above one watt) can be eliminated by $20 + 75 = 95$ db RF selectivity even when the receiver and the unwanted transmitters are connected to the same antenna. In practice, the effect of geographical separation assuming the free space loss given in Table I reduces the RF selectivity requirement to the values given in Table VII.

The RF selectivity requirements given in Table VII cannot be obtained on nearby channels. The approximate RF bandwidths associated with various amounts of RF selectivity in mobile receivers is shown in Table VIII. For example, in mobile receivers it seems feasible to provide 40 db of RF selectivity at frequencies removed from the desired channel by about 3 mc in the 150-mc band and by about 10 mc in the 450-mc band. At fixed stations the RF bandwidth required for a given selec-

TABLE VIII — FREQUENCY SPACING FROM MIDBAND VERSUS RF SELECTIVITY

Desired RF Selectivity	Frequency Spacing from Midband	
	150 mc	450 mc
20 db	±1.5 mc	± 5 mc
40	±3	±10
60	±6	±20

TABLE IX — SIGNIFICANT RF BAND VERSUS ANTENNA SPACING

Minimum Separation Between Receiver and Unwanted Transmitters	RF Band	
	150 mc	450 mc
50 ft	±6 mc	±14 mc
500 ft.	±3	± 7
½ mile	±2	± 4

tivity can be reduced to one-third and possibly to one-fourth of the above values by the use of bulky and expensive filters.

The critical frequency band that needs to be considered in determining the usefulness of any given channel can be obtained by combining the information given in the two preceding tables with the results shown in Table IX. For example, if it be desired to work mobile receivers unrestricted to within 500 feet of two or more unwanted transmitters, all frequency assignments within ±3 mc in the 150-mc band (or within ±7 mc in the 450-mc band) must be carefully chosen if intermodulation interference is to be avoided.

When the ±3-mc band is divided into 100 potential channel assignments of 60 kc each and when the channels assigned to a given area are chosen at random, 7 channels working 50 per cent of the time (or 37 channels working 10 per cent of the time) will, on the average, cause third order intermodulation interference about 10 per cent of the time on each channel within the band. The interference is expected to be above the minimum usable signal level in all receivers located less than about a mile from the unwanted transmitters. Even if the operating frequencies are selected carefully instead of at random, no more than 11 channels out of 100 can be found that are free of third order intermodulation when used simultaneously in the same general area. These results are discussed more completely in a companion paper.[5] When the number of potential channel assignments is greater or less than 100, the corresponding number of usable channels limited by third order modulation alone is shown in Table X. The numbers of usable channels shown above are further reduced when fifth and higher order intermodulation products are considered.

A reduction in the nominal channel spacing from 60 kc to 20 kc means a three-fold increase in the potential channel assignments, but Table X shows that the number of usable channels increases much more slowly.

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[5] Babcock, W. C., Intermodulation Interference in Radio Systems. Page 63 of this issue.

TABLE X — NUMBER OF USABLE CHANNELS VERSUS NUMBER OF POTENTIAL CHANNELS

No. of Potential Channel Assignments in RF Band Shown in Table IX	No. of Usable Channels			
	Careful Selection No Interference	Random Selection 10% Chance of Interference		
		% of Time Transmitter Is On		
		50%	25%	10%
20	7	5	10	25
50	9	6	12	30
100	11	7	15	37
200	12	9	18	45
500	14	12	24	60

Thus far, only the intermodulation interference generated in the receivers has been considered. Intermodulation also occurs at the same frequencies in the transmitters, but it usually can be made less important than the corresponding interference in the receivers. Ideally, the intermodulation products generated in the transmitters should not be stronger than 140 db below one watt (about 1 microvolt at the input to the receiver) which requires about 75 db RF filtering in each transmitter output. This ideal requirement is based on 100 watt transmitters with both the transmitters and receiver working on the same antenna. In practice, the RF filtering requirement is less than 75 db because of physical separation between transmitters and receivers, and typical values based on free space transmission are shown in Table XI.

A comparison of the filter requirements on 100 watt transmitters with the corresponding receiver selectivity requirements given in Table VII shows that the receiver requirements are greater as long as the effective

TABLE XI — RF TRANSMITTER FILTERING VERSUS ANTENNA SEPARATION

Distance Between Receiver and Unwanted Transmitters	RF Filtering Needed in Each Transmitter in db							
	150 mc Distance Between Transmitters				450 mc Distance Between Transmitters			
	0 ft	10 ft	50 ft	500 ft	0 ft	10 ft	50 ft	500 ft
0 ft.*	75	—	—	—	75	—	—	—
50 ft.	57	46	39	—	52	36	29	—
500 ft.	47	36	29	19	42	26	19	9
½ mile	40	29	22	12	35	19	12	2

* Common antenna.

separation between transmitters is greater than about 50 feet. For example, with a 500-foot separation between the transmitting and receiving antennas, Table VII shows that the 150 mc requirement on r.f. selectivity is 39 db. The bandwidth between the 39 db points on the receiver selectivity characteristic determines the number of potential channel assignments to be used in Table X.

INCREASED EFFICIENCY OBTAINED BY COORDINATION

The preceding selectivity and filtering requirements are severe and in some cases virtually unattainable except at considerable sacrifice in frequency space. The principal reason for these exacting requirements is that the assumed unrestricted and independent operation results in large differences in field intensities among closely spaced frequencies. In order to pick out the weak signals from among the strong, sufficient selectivity must be provided to suppress the potential interference to below the minimum usable signal.

An alternative is to reduce the level differences and hence the filtering requirements by geographical and operational coordination. This means that the level of the potential interference can be permitted to be many db above set noise as long as it is always at least 10–20 db below the desired signal at all possible locations. By proper coordination the troublesome RF filtering problems can be eliminated within the coordinated system and the remaining IF selectivity problems can be minimized.

The first step is to use the two frequency method of operation with adequate separation between the frequencies used for the opposite directions of transmission. In this way substantial RF filtering can be obtained to eliminate the interference between one or more base transmitters and a base receiver. This type of interference is particularly troublesome between single frequency systems because of the relatively high base transmitter power and because the high antennas at both locations reduce the radio path loss to a minimum. The corresponding possible interference between transmitters and receivers on different mobile units is also reduced by the two frequency method but interference between mobile units is much less important because of the lower power and much lower antenna heights.

The potential interference between base transmitters and mobile receivers caused by insufficient total filtering can be reduced by locating all base transmitters at or near a common point so the level differences between the desired and undesired signals will never be excessive. When all transmitters radiate from a common antenna, a selectivity or filtering requirement of about 40 db (instead of the values shown in Table III) is sufficient for a reasonable signal to interference ratio plus an allowance for differential path losses resulting from standing wave effects.

The RF selectivity or intermodulation problem in the mobile receiver can be eliminated by reducing the power level at the first converter to about 75 db below one watt. This can be done by providing a simple automatic gain control in the RF stage of the mobile receiver. In regions where the desired and undesired signals are weak the receiver has full sensitivity, while at locations near the transmitters both the desired and undesired signals are reduced in level before reaching the first converter. The result is that the intermodulation products generated in the receiver are reduced about 3 db for every db that the desired signal is lowered and the distortion becomes negligible before the output signal-to-noise ratio is reduced appreciably. In order that the a.g.c. circuit can be fully effective it is necessary that the transmitters be grouped together and that the desired carrier be transmitted to control the gain of the receiver.

Grouping the base transmitters at or near a common point together with the associated measures of transmitting the carriers and using a.g.c. greatly reduces the requirements on the mobile receiver, but these measures complicate the design of the base transmitter. The intermodulation products generated in the closely associated transmitters result in potential interference both within and outside of the desired transmitting band. The intermodulation that falls on the mobile receiver frequencies needs to be suppressed by at least 25 db below the carrier on any channel to prevent mutual interference within the coordinated system. The intermodulation that appears as extra band radiation outside the frequency range of the coordinated system must be suppressed by RF filters. The guard band needed to prevent mutual interference between the coordinated system and its neighbors is small compared with the frequency space that is saved by the close spacing of the channels within the coordinated system.

In the direction of transmission from the mobile transmitters to the base receivers, the above coordinating methods cannot be used but equally effective ones are available. The RF selectivity requirements shown in Table VII can be reduced 20 db by using 20 db less power in the mobile transmitter than in the base transmitter. This measure is somewhat analogous to the use of a.g.c. in the opposite direction of transmission; a further step would be automatic control of the radiated power but this complication does not appear to be necessary.

In order to regain the full coverage area, multiple base receivers at different locations are needed and this use of space diversity techniques provides an opportunity to pick the receiver having the best signal-to-noise ratio. Moreover, the low power in the mobile transmitter together with the better RF filters that are possible in fixed locations reduces the critical bandwidth within which intermodulation interference can arise to about ±0.4 mc at 150 mc and to about ±0.6 mc in the 450 mc range. In these bandwidths approximately 20–25 channels can be obtained which with random location of the mobile units would be divided more or less uniformly among five or more base receiving stations. Since no more than 4 or 5 channels would be operating within the critical RF bandwidth at any one receiving location, the possibility of intermodulation interference is almost negligible. Finally, an off-channel squelch circuit is provided which disables the base receiver at a location where serious adjacent channel interference is most likely to occur and forces the choice of another base receiver in a different location. Another effect of the off-channel squelch circuit is that it keeps the base receiver quiet during idle times, and in this respect it is analagous to the advantage gained in the mobile receiver by continuous transmission of the desired carrier at the base transmitter.

Most of the above coordinating methods tend to emphasize and to increase the characteristic differences between the two directions of transmission. The net effects are that greater frequency economy is obtained and that the electrical requirements are reduced on the mobile equipment where size, weight and power are critical and where cost savings are important because of the large number involved. An increase in complexity occurs at the multi-channel base station but this seems economically justified because the cost can be divided among many working channels.

When the above methods of coordination are fully utilized, the RF requirements are eliminated in the mobile equipment and can be met in the base station equipment. In addition, the IF selectivity requirement on nearby channels is reduced to about 40 db in the mobile receiver and to about 60 db in the base receiver. The extra band radiation requirement on nearby channels is reduced to about 25–40 db in the base transmitter, depending on whether one or more than one antenna is used; and to about 60 db in the mobile transmitter.

These requirements coupled with the data given in Tables II, IV and V lead to the frequency separation between coordinated channels operating in the same area as given in Table XII. The channel spacings are shown for AM and for FM with a frequency swing of ±5 kc (which requires a bandwidth of ±8 kc for good quality).

The spacings shown in Table XII assume that each channel is trans-

TABLE XII — CHANNEL SPACING VERSUS SYSTEM STABILITY—COORDINATED SYSTEMS IN SAME AREAS

Stability	Channel Spacing							
	150 mc				450 mc			
	Mobile Receiver		Base Receiver		Mobile Receiver		Bass Receiver	
	AM	FM	AM	FM	AM	FM	AM	FM
±0.001%	21	31	25	35	27	37	31	41
±0.002%	24	34	28	38	36	46	40	50
±0.005%	33	43	37	47	63	73	67	77

mitted on an individual carrier. Single-channel operation seems to be the only practical arrangement for transmission from the mobile transmitter to the base receiver. In the other direction of transmission, from base transmitter to mobile receiver, the question naturally arises whether additional frequency economy could be achieved by multichannel methods. In this case individual carrier operation is also indicated for transmission and economic reasons. The multiple echoes that exist at street level in urban areas limit the number of usable channels that can be transmitted on a single carrier.[6] While the exact number is somewhat indefinite, it appears to be less than about 20 and perhaps less than 10 channels. In addition the selectivity and linearity requirements on multi-channel receivers (even for two channels) are much more severe than for single channel equipment. From these considerations it appears that the use of more expensive receivers and channel separation equipment in each mobile unit is not economically feasible.

FREQUENCY ECONOMY IN PRESENT AND PROPOSED MOBILE SYSTEMS

The technical factors given above provide a basis for estimating the number of usable mobile channels that can be obtained in a given bandwidth. This bandwidth must be sufficiently large to be isolated by RF filtering if the results are to be well defined.

The following examples assume two different geographical distributions: (1) the number of usable channels with overlapping coverage areas that can be obtained within a city or metropolitan area, and (2) the number of usable channels that can be obtained when the channels are distributed more or less uniformly over a state or other large area. The examples are based on the use of frequency modulation with a

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[6] Young, W. R., Jr., and L. Y. Lacy, Echoes in Transmission at 450 Megacycles from Land-to-Car Radio Units. I.R.E., Proc., pp. 255–258, March, 1950.

modulation bandwidth of ±8 kc and a frequency stability of ±.002 per cent; with these assumptions, the IF passband should be at least 22 kc in the 150 mc band and 34 kc in the 450 mc band. Narrower bandwidths could be used but this would result in a substantial sacrifice in coverage under impulse noise conditions.

Five cases are considered:

(1) *Single Frequency Semi-Coordinated*—In this case, substantially no interference is expected from third order modulation problems, which are avoided by careful selection of operating frequencies, but higher order modulation products may be important. Base station locations are unrelated geographically to other systems in same general area, except that a minimum spacing of 500 feet between receiver and interfering transmitter is assumed.

(2) *Single Frequency with Interference*—In this case, the choice of frequencies is unrestricted, but a 10 per cent chance of third order intermodulation interference is accepted within 500 feet of unwanted transmitters, when transmitters are in operation 25 per cent of time.

(3) *Two Frequency Semi-coordinated*—This is the same as (1), except with two-frequency operation.

(4) *Two Frequency with Interference*—Same as (2) except with two frequency operation.

(5) *Fully Coordinated Broad-band*—This case assumes: (a) two frequency operation with the land transmitters coordinated in location, power, antenna height and emission of protective carriers; (b) low power mobile transmitters; (c) multiple land receivers; (d) no interference from third or higher order intermodulation; and (e) guard bands to protect mobile and neighboring services from mutual interference.

The number of usable channels that can be obtained in the same area is estimated in Table XIII for frequencies near 150 mc.

The minimum channel spacing shown in the first column of Table XIII is calculated as follows: in cases (1), (2), (3) and (4), the extra band radiation from the base transmitter is controlling. As shown in Tables III and V, to avoid interference for distances greater than 500 feet from the interfering transmitter requires a guard band of about 50 kc. This is added to the 22 kc required IF pass-band of which ±8 kc is allowed for the FM signal, and ±3 kc for 0.002 per cent system instability. In (5), the adjacent channel receiver selectivity is controlling: Table IV shows the required 60 db can be obtained in 15 kc, which added to the required 22 kc IF band gives approximately 40 kc.

It will be noted from Table VII that the assumption of a separation of 500 feet between the receiver and the interfering transmitter requires

TABLE XIII — USABLE CHANNELS IN CITY AT 150 MC

Method of Operation	Minimum (Not Average) Channel Spacing in Same Area	Number of Usable Channels in 6 mc
(1) Single frequency semi-coordinated	75 kc	10
(2) Single frequency with interference	75	14
(3) Two frequency semi-coordinated	75	5
(4) Two frequency with interference	75	7
(5) Fully coordinated broad-band*	40	45

* Includes three guard bands of 0.8 mc each to protect mobile and neighboring services from mutual interference.

about 40 db RF selectivity, and from Table VIII that the 40 db selectivity requires that all frequencies within ±3 mc need to be considered. With 75 kc channel spacing, there are 80 potential assignments in 6 mc. Table X indicates that 10 one-way channels can be found that are free of mutual third order intermodulation interference. If the available bandwidth were 12 mc the number of interference-free channels would be doubled.

By the same process from Table X, we derive the number of usable channels shown for case (2).

For cases (3) and (4), the methods are the same, but the number of usable channels is reduced to one-half that shown for the single frequency cases.

In the fully coordinated broad-band system (case 5) a usable one-way channel can be obtained every 40 kc. However, three guard bands totaling 2.4 mc are provided to protect both the mobile and neighboring systems from mutual interference. If the available bandwidth were 12 mc the number of interference-free channels would be increased from 45 to 120 since no additional guard bands would be required.

The comparison between various methods of operation given in Table XIII applies to 150-mc channels operating in the same city. When the channels are distributed more or less uniformly over a large area, the number of usable channels is increased by several factors. The separation between carrier frequencies in non-overlapping areas needs to be only slightly greater than the IF pass-band of the receiver, say, 30 kc at 150 mc. The guard bands needed in one location can be used in other areas at geographical separations less than co-channel spacings. Finally the required geographical separation between co-channel stations is less for the two frequency method than for the single frequency method and is less for FM than it would be for AM.

An estimate of the maximum number of usable channels within a large

TABLE XIV — USABLE CHANNELS IN STATE OR LARGE AREA AT 150 MC

Method of Operation	Minimum Channel Spacing*	Number of Usable Channels in 6 mc
(1) Single frequency semi-coordinated	25 kc	108
(2) Single frequency with interference	25	171
(3) Two frequency semi-coordinated	25	108
(4) Two frequency with interference	25	171
(5) Fully coordinated broad-band	25	240

* Assumes adjacent channels are not assigned in same area.

area can be obtained by considering an area whose radius is about six times the coverage radius of the individual transmitter. A larger area is unnecessary because single frequency FM channel assignments can be repeated at this distance, while a smaller area would tend to approach the common area concept used above. The large area can be divided into 9 subareas, each of which can be treated in the manner used in Table XIII. The results are shown in Table XIV, which again assumes an FM modulation bandwidth of ±8 kc and ±0.002 per cent overall system frequency stability.

The entries in Table XIV are calculated as follows: Once again, the smallest band to be considered is limited by the RF selectivity in mobile receivers to 6 mc; with 25 kc as the minimum channel spacing, there are $6000/25 = 240$ potential assignments. From Table X, only 12 can be found to be free of third order intermodulation. With 12 channels in each of 9 subareas, there is a grand total of 108 channels usable in the state or large area. With more frequency space, the usable number is increased in proportion.

By the same process, from Table X we derive the number shown for case (2).

In the two frequency cases, the co-channel separation can be made smaller than in the single frequency cases, since the most troublesome case of interference (that between base transmitters and base receivers) is eased by RF selectivity. Thus, the co-channel separation needs to be only about 0.7 that for single frequency operation, which means that there are now effectively 18 instead of 9 subareas. It follows that the grand total of usable channels is the same in cases (1) and (3) and cases (2) and (4).

In considering case (5), we note from Table XIII that 40 kc is the minimum channel spacing usable in a single subarea. However, the largest grand total of channels is found by using 50 kc spacing in the subareas, and assigning the adjacent 25 kc channels to other subareas.

TABLE XV — USABLE CHANNELS IN CITY AT 450 MC

Method of Operation	Minimum (Not Average) Channel Spacing	Number of Usable Channels in 14 mc
(1) Single frequency semi-coordinated	85 kc	12
(2) Single frequency with interference	85	17
(3) Two frequency semi-coordinated	85	6
(4) Two frequency with interference	85	9
(5) Fully coordinated broad-band*	50	68

* Includes three guard bands of 2.4 mc each to protect mobile and neighboring services from mutual interference.

Similarly, the guard bands of one subarea can be used for channels elsewhere so all of the available 240 channels can be used.

The examples given in Tables XIII and XIV represent the two extreme conditions and the practical situation lies in between the two.

By similar reasoning it is possible to estimate the number of usable channels that can be obtained at frequencies around 450 mc. The number of usable channels shown in Table XV is for overlapping coverage areas in a city or metropolitan area and the estimates given in Table XVI are based on a uniform distribution over a state or other large section of the country.

Again, FM modulation with a bandwidth of ±8 kc and a system frequency stability of 0.002 per cent are assumed.

For a bandwidth of 28 mc instead of 14 mc the number of usable channels is doubled for the first four cases and is increased from 68 to 208 for the fifth case. The corresponding estimates for bandwidths less than 14 mc are indefinite because of insufficient r.f. selectivity.

CONCLUSIONS

The principal conclusions that result from Tables XIII, XIV, XV and XVI, and from the preceding discussion can be summarized as fol-

TABLE XVI — USABLE CHANNELS IN STATE OR LARGE AREA AT 450 MC

Method of Operation	Minimum Channel Spacing*	Number of Usable Channels in 14 mc
(1) Single frequency semi-coordinated	35 kc	117
(2) Single frequency with interference	35	198
(3) Two frequency semi-coordinated	35	117
(4) Two frequency with interference	35	198
(5) Fully coordinated broad-band	35	400

* Assumes adjacent channels are not assigned in same area.

lows:

1. A fully coordinated system requires a band of several megacycles that can be treated as a unit, but it offers substantial overall frequency economy and freedom from interference that can be obtained in no other way. This is particularly true in large metropolitan areas where the demand is greatest. With the same equipment and the same standards of quality and reliability, coordinated channels can always be spaced much closer in frequency than uncoordinated systems.

2. The advantages of coordination increase rapidly as the number of channels per unit area is increased. However, in areas where only three or four channels are required, the advantages of complete coordination are sufficiently small that only the semi-coordination of careful frequency allocation is required to preserve overall frequency economy.

3. For maximum economy, where full coordination is not used, the channels should be assigned as in FM and TV broadcasting first to areas and then to users within areas. The allocation of a block of channels to a particular service with a minimum of operational and geographical restriction frequently results in an ever-increasing interference problem as each additional station is placed in operation.

4. Single-frequency operation is most suitable where the operational need for single channel communication between mobile units (as contrasted with fixed-to-mobile) is more important than frequency economy.

5. A frequency separation between potential channel assignments of 25 kc in the 150 mc range, and 35 kc in the 450-mc range seems technically feasible; but adjacent channels with these minimum spacings cannot be assigned in the same area. These values may be reduced to about 20 and 30 kc, respectively, at the sacrifice of an appreciable reduction in coverage under impulse noise conditions. A further reduction in channel spacing would not appreciably increase the total number of usable channels, since the controlling factors are RF selectivity and extra band radiation, rather than IF selectivity or the total number of potential channel assignments.

6. The *average* spacing needed between channels operating in the same area varies from about 40 to 500 kc or more, depending on the method of operation and the criterion of usability.

7. The need is for a certain small number of channels in all areas, plus a peaked demand in centers of population. In the semi-coordinated cases, the maximum number of channels that can be allocated to the peak area is a small fraction of the total number of channels available. In the fully coordinated, broad-band case, there is much more flexibil-

ity and the peak area can be allocated a large fraction of the total available.

8. FM is preferable to AM for land mobile service because its instantaneous gain control feature minimizes the flutter caused by the motion of the mobile unit through standing wave patterns. This advantage increases in importance as the carrier frequency increases. In addition, FM with an adequate frequency swing provides an increased signal-to-noise advantage over most of the coverage area. The somewhat greater channel width required by FM is more than offset on an area coverage basis by the closer co-channel spacing.