THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 51, No. 7, September, 1972
Printed in U.S.A.

Dynamic Channel Assignment in Two-Dimensional Large-Scale Mobile Radio Systems

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(Manuscript received April 4, 1972)

A computer simulation of two-dimensional mobile radio systems arranged with square coverage areas on a square grid and using dynamic channel assignment techniques is described. Parameters for the simulation are: (i) 729 distinct coverage areas (27 on a side), (ii) 160 radio channels and (iii) a radio channel reuse interval of every fourth coverage area. Three different channel assignment strategies are considered and the results are compared to previous one-dimensional simulated systems and to a fixed channel assignment system. At call blocking rates below about 10 percent, the two-dimensional dynamic channel assignment systems carry more traffic and produce fewer forced call terminations at coverage cell boundaries than do fixed channel assignment systems. For example, at a blocking rate of 1 percent, the traffic carried, TC, expressed in Erlangs per channel per coverage area by the various systems are as follows: fixed channel assignment systems, TC = 0.44, one-dimensional dynamic channel assignment system, TC = 0.62, two-dimensional dynamic channel assignment system, TC = 0.63.

I. INTRODUCTION

When a large pool of radio channels is available for use in a large-scale multiple base station mobile radio system, its assignment to individual base stations on the basis of instantaneous demand can improve systems performance.[1–3] Previous studies of coordinated dynamic channel assignment in one-dimensional systems (that may be used along an expressway or major air route for example) have shown that at blocking rates below 10 percent these assignment procedures produce increased channel occupancy over systems using the same channels but with channel allocation to each base station fixed.

The most general form of dynamic channel assignment assumes that any channel can be used at any base station. Efficient use of channels requires the simultaneous assignment (reuse) of the radio channel in radio coverage areas which are spaced as close together as possible without incurring excessive cochannel interference. Mobile radio systems which reuse channels within a metropolitan area often are referred to as small-cell or small coverage area systems.[3–6]

The analysis of dynamic channel assignment systems which employ complex channel assignment algorithms appears to be intractable. For this reason, the performance of these systems is most readily determined by large-scale computer simulation. The overall system performance of two-dimensional dynamic channel assignment mobile radio systems is expected to be similar to that of the one-dimensional systems previously studied.[1,2] However, the performance of the one-dimensional systems was shown to depend upon the total number of channels available to the radio system as well as the average number of channels available in each coverage area. Thus, since the channel reuse situation is more complex for two-dimensional systems, some difference in the performance of the two-dimensional systems was expected.

This paper describes a computer simulation of a large-scale two-dimensional mobile radio system using different dynamic channel assignment strategies and compares the performance characteristics of these systems with both a one-dimensional dynamic channel assignment system and with a fixed channel assignment system.

II. THE SIMULATION MODEL

2.1 *The Model of the System Configuration*

The system simulated consists of a set of square radio coverage areas arranged to completely cover a square grid with no overlap as illustrated in Fig. 1. For this model, a channel used in a specified coverage area, such as the shaded area at coordinates m, n may be reused anywhere on or outside of a specified square ring which surrounds that particular coverage area. This reuse ring is defined by those coverage areas which have either an x or y coordinate which is a specified integral number of coverage areas separated from the center coverage area. This specified interval of coverage areas is referred to as the channel reuse interval. In the example in Fig. 1, the cross-hatched coverage areas on the reuse ring surrounding the coverage area at $x = m$, $y = n$ are at a reuse interval of 4. Several coverage areas on the reuse ring may also use the same channel as long as all coverage areas are separated by at least

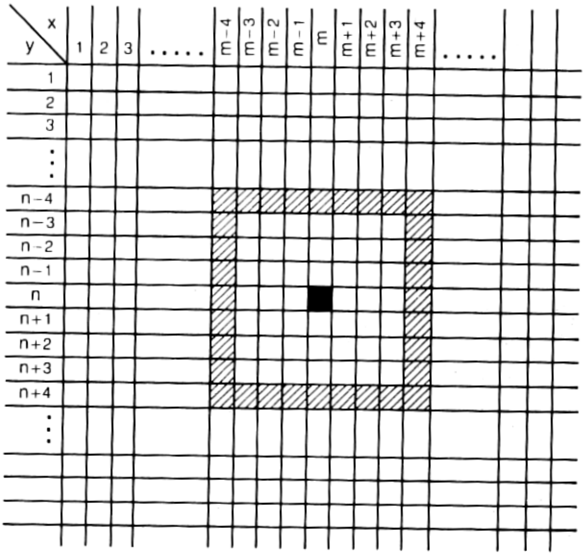


Fig. 1—Coverage area configuration for the simulation.

the reuse interval. Thus, in the example, the maximum number which can use the same channel simultaneously on the reuse ring is eight. For the simulation the coverage squares were specified to be 2 miles on a side.

The "local" mean (average over several wavelengths) signal strength in an urban area measured on a circle of constant radius from an omnidirectional base station has a log normal distribution.[7,8] The variance of the log normal distribution is sufficiently large (σ = 5 to 9 dB) so that circular coverage areas are seldom realized. Since traffic handling capabilities of dynamic channel assignment systems are the primary concern of this study, it is desirable to define geometric coverage areas which completely cover a region with no overlap. The only candidates are triangles, rectangles, and hexagons. Of these, the geometry associated with squares is simplest to manipulate. Since the propagation is highly irregular, radio channels obviously may not be used simultaneously in immediately adjacent coverage areas regardless of the geometry defining the coverage area. Thus, square coverage areas on a square grid with the reuse intervals described previously provide a reasonable model for these traffic studies. Such a system could be approximated by placing base stations at the corners of the coverage areas and radiating into them with directional antennas.

2.2 *The Stimulus to the Simulated System*

The initiation of call attempts and the movement of vehicles in this simulation is almost identical with that described previously[1] for a one-dimensional simulation. Call attempts are generated in the simulation as a Poisson process in time which has a controllable average attempt rate in each coverage area. For this study, initial call attempts from vehicles are uniformly distributed in both the x and y coordinates and the x and y locations are independent. Call attempts are tapered at the edges of the simulated universe, and the performance data accumulated only from the central portion of the system, so that the results are representative of an infinite system.

In this method of simulation, vehicles making calls are identifiable entities the locations and movements of which are stored in the computer. Vehicle velocities (speeds and direction) are chosen randomly from a population having statistical characteristics which can be prescribed. Vehicle motions are primarily parallel to one of the coordinate axes with 45 percent of the vehicles having an x velocity component only, and 45 percent a y component only. Ten percent of the vehicles have both x and y velocity components which are mutually independent. The velocity components (x and y) have a truncated Gaussian distribution with a zero mean, a standard deviation of 30 miles per hour, and a maximum velocity magnitude of 60 miles/hour (see Figure 8 of Ref. 1).

Call attempts that are assigned a channel remain on in the system for call durations which are taken from a random population with a specified distribution. Part of the data to be presented later is for a call duration distribution which is exponential with a mean of about 98 seconds. Other data are for a call duration distribution which is a truncated Gaussian with a minimum call duration of 30 seconds, a maximum call duration of 10 minutes, and a true mean of 103.5 seconds. The mode of this distribution is 90 seconds (see Figure 7 of Ref. 1). Some of the vehicles which cross coverage area boundaries have their calls prematurely terminated by the system because of the unavailability of channels in the new coverage area. This effect shortens some calls and thus perturbs the specified distribution slightly. This is discussed in more detail later.

2.3 *The Simulated Operating Systems*

The method of handling call attempts, calls in progress and call terminations is similar to that described in Ref. 1 for a one-dimensional system. The first step in processing a new call attempt is to assign a coverage area. Since coverage areas are geometrically defined and the vehicle coordinates known, the appropriate coverage area is readily determined. In the simulation, vehicles within a particular coverage area are required to be served by channels available in that coverage area. The next step is a channel search which tries to find a radio channel to serve the awaiting call attempt. Some channel search procedures are discussed in detail later. If no channel can be found, the call is immediately blocked and cleared from the system. This blocking strategy is the same as that used in deriving the Erlang B (block call cleared) telephone traffic formula.[9]

The simulated system detects vehicles crossing coverage area boundaries and checks to see whether the call can continue on the original channel or on a new channel. If no channel is available, the call is immediately forced to terminate and is cleared from the system. In an actual system, the crossing of coverage area boundaries will not be critical and, hence, some delay could be tolerated in finding a new channel for boundary crossing vehicles. When a significant number of the calls handled by the system experience a boundary crossing, the calls forced to terminate have an effect on other system performance parameters. With the coverage area size and the velocities used in this simulation the effect of boundary crossings on traffic carried and call blocking is small.

2.4 *Channel Assignment Strategies*

Information which identifies the coverage area and the channel being used by each active subscriber in the network is stored in the memory of the simulated system control computer. In addition, a list is kept of every channel being used in each coverage area. The second list, although redundant, is in a form which permits rapid access to the information needed for the dynamic channel assignment procedures. A channel search is initiated after the coverage area of a call attempt has been determined.

The procedures used in the channel assignment strategies are best described in terms of an example which can be referred to Fig. 1. Assume that a call attempt located at coverage area $x = m$; $y = n$ is awaiting channel assignment. The first step is to determine which channels (if any) are available to serve the call attempt. This is accomplished by compiling a list of the channels which are not being used currently within any coverage area surrounding the designated coverage area out to but not including the reuse ring defined previously. If more than one radio channel is available within this reuse interval, then some channel assignment strategy must be applied to determine the channel that should be assigned. The main object of a channel assignment strategy is to increase the channel occupancy or to optimize some other system parameter. Briefly, the two-dimensional channel assignment strategies considered here are as follows:

First Available

This strategy assigns the first available radio channel encountered during a channel search. This strategy obviously minimizes the system computation time and as shown later its performance may be adequate for some applications.

Selection of a Channel With Maximum Usage on the Reuse Ring (RING)

A search is made through the list of available channels to determine which of these channels is currently in use in the most coverage areas lying on the reuse ring. If more than one channel has this maximum usage, an arbitrary selection of one of the channels is made to serve the call attempt. If none of the available channels is in use on the reuse ring (an infrequent event as illustrated in Fig. 8), then selection is made on a first available basis. This strategy is described in detail in Ref. 10.

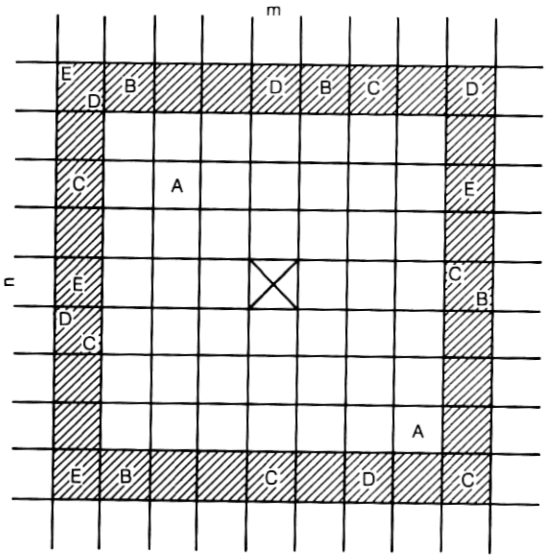
Selection of a Channel With Maximum Usage on a Side(s) of the Reuse Ring (Orthogonal NN)

A search is made through the list of available channels to determine which channel(s) meets the following criteria:

(*i*) On some side of the square reuse ring channel usage is a maximum.
(*ii*) Of those channels having a maximum usage on some side, channel usage is again a maximum on a side adjacent (orthogonal) to that first maximum usage side.

If none of the available channels are in use on the reuse ring, channel assignment is made on a first available basis. If only one channel has a maximum channel usage on some side, that channel is assigned without regard to the usage on other sides. If more than one channel has maximum usage on some side and equal secondary maximum usage on an adjacent side, one of these channels is selected at random. For this simulation optimization was not carried to the third and fourth sides. This strategy is one possible extension of the best performing one-dimensional channel assignment strategy[2] previously described.

Figure 2 illustrates some of the differences in these channel assignment strategies. In this figure, assume that channels are designated by the



STRATEGY	CHANNEL ASSIGNED
1ST AVAIL	B
RING	C
⊥ NN	D

Fig. 2—A channel assignment example.

letters A through E. Channel A is not available for assignment because it is being used in coverage areas within the reuse interval. For channel selection by the RING strategy, channel B is used four times on the reuse ring, C six times, D five times, and E four times. Thus the RING strategy selects channel C for assignment.

For the orthogonal NN strategy the maximum side usage is three, and occurs for channel D on the upper side and channel E on the left side. Channel usage on a corner is included in the usage count for each side which includes that corner. For example, the channel D usage on the upper left-hand corner of Fig. 2 results in a channel usage count of three for the upper side and a count of two for the left side. Thus, the adjacent side usages for channel D are two on the left and one on the right. The corresponding adjacent side usages for channel E are only one each on the top and bottom. Therefore, channel D has the maximum adjacent side channel usage and is thus selected for assignment by the orthogonal NN strategy.

If the channel assignment search is assumed to proceed in alphabetical order, the first available strategy would select channel B for assignment.

2.5 *System Parameters*

The simulated operating systems were run for a 27 by 27 grid of coverage areas which were 2 miles on a side. The systems had available

160 duplex radio channels. With the assumed reuse interval of 4, this results in 10 channels (160/16) available on the average at each base station. Of course, depending upon the system activity and the instantaneous demand, some coverage areas will have more than 10 channels in use simultaneously and some will have fewer. Because of the uniform spatial and temporal statistics of the call-attempt process, averages of system parameters taken over a large number of coverage areas at a particular time must yield the same results as averages taken over an extended time interval for one coverage area. Thus, the stability of the statistics for performance parameters depends upon the product of the number of coverage areas included and the run time. Statistics were taken from only the central 225 coverage areas (15 by 15) to avoid any effects from the edges of the finite system. Call loading and system response at the edges of the finite system were tapered in a way which insured that these central areas were operating as members of an infinite set. The simulation was started initially with no calls on in the system and statistics of parameters were monitored until the initial transients died out. The time required for stability was about 2 minutes. Data were collected after stabilization for about 7 minutes (in simulated time). This run time and spatial size was sufficient produced data points which lie on smooth curves and have very little scatter.

The data presented in the following sections were obtained by counting and storing the number of actual events which occurred in the stabilized system. Some of the events counted were new call-attempts, new call-attempts blocked, coverage boundary crossings and calls forced to terminate after crossing coverage boundaries. In addition, the actual number of calls in progress in the system was counted and stored periodically during each simulation run.

III. COMPARISONS OF SYSTEMS PERFORMANCE

The computer simulation was run at several call attempt rates for the channel assignment strategies and system parameters described in Section II. The data from the simulation, which show directly the relationship between channel occupancy (traffic carried per channel per coverage area) and the blocking of new call attempts, are plotted in Fig. 3. The solid data points are for the exponential call duration distribution and the open data points are for the truncated Gaussian call duration distribution described in Section 2.2. The triangles and circles are for the two-dimensional systems with a reuse interval of four. The solid curve is drawn through the data points for both the RING and the orthogonal NN two-dimensional channel assignment

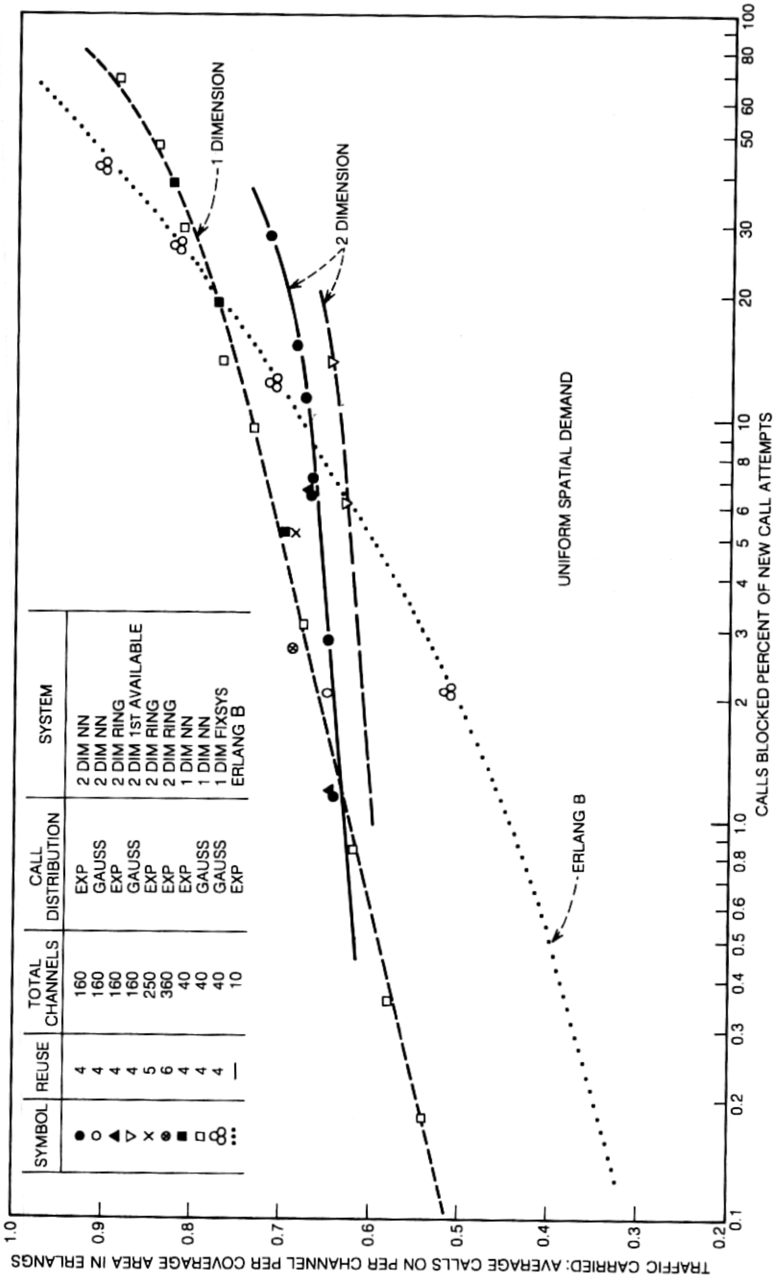


Fig. 3—Normalized channel occupancy.

strategies. The performance of these two strategies in terms of these parameters is nearly identical, as indicated by the fact that the solid triangles at 1.1 percent and 6.6 percent blocking lie nearly on top of the solid circles. All of the points for these two strategies fall on the smooth curve over the blocking range indicated (1 through 30 percent). In fixed channel assignment systems for which the Erlang B telephone traffic formula is applicable, it has been shown[11] that the shape of the call duration (holding time) distribution has no effect on the relationship between traffic carried and the blocking of new call attempts. The open circle at 2 percent blocking that lies on the solid curve is for a different call duration distribution than the solid points as noted in the key. This indicates that for these dynamic channel assignment strategies the performance parameters are also not affected by the shape of the call duration distribution. The inverted triangles connected by the long dashed curve are for the two-dimensional first available channel assignment strategy. This strategy results in slightly lower channel occupancy for a given blocking. It is much simpler to implement, however, and may be acceptable in some applications.

The short dashed curve through the open square data points is from a one-dimensional channel assignment system with a reuse interval of 4, as described in detail in Ref. 2 (NN strategy). The solid squares are for the same one-dimensional channel assignment strategy, but for an exponential call duration distribution. The fact that the points lie on the curve for the truncated Gaussian call duration distribution further illustrates the independence of the performance of dynamic channel assignment to the type of call duration distribution. Over a wide blocking range, the traffic carried by the two-dimensional system is more nearly constant than for the one-dimensional system. We would expect that at very low blocking rates the two-dimensional system would perform better (carry more traffic at a given blocking rate) because it has more channels available to the system (160 channels) than the one-dimensional system (40 channels) even though the average number of channels available per coverage area is the same. However, as seen from Fig. 3, the two-dimensional system does not perform as well as the one-dimensional system above a blocking rate of about 1 percent. This is probably due to the fact that the simultaneous use of the same channel in coverage areas separated by exactly a reuse interval is more difficult to achieve in the two-dimensional area situation than on a one-dimensional line. To further check the performance of the simulations, the two-dimensional orthogonal NN strategy system was run as a one-dimensional system by restricting the location of call attempts and vehicle motion to one axis. The resulting data points for this simulation were located along the performance curves from the previous one-dimensional simulation.

The four data points denoted as & are from a simulation of a one-dimensional fixed channel assignment system.[1,2] In this system, specific channels are allocated to each coverage area and the same channels are reallocated at coverage areas separated by exactly a reuse interval. For the simulated fixed channel assignment system, 10 channels were allocated to each coverage area and the reuse interval was 4. The performance of the fixed channel assignment system can be determined directly from the Erlang B telephone traffic equations.[3,9] The relationship between the traffic carried and call blocking from the Erlang B formula is the dotted line in Fig. 3. This curve represents the performance of fixed channel assignment in both one and two dimensions since the curve depends only on the number of channels available per coverage area. The fixed channel assignment system performs worse at low blocking than any of the dynamic channel assignment systems because it is less able to meet the peaking of call attempts in the randomly offered traffic. At high blocking rates, fixed channel assignment systems handle more traffic because channel reuse is fixed in an optimum configuration.

The two-dimensional simulation using the RING strategy was also run for a reuse interval of five with 250 channels, and for a reuse interval of six with 360 channels. The resulting data points are indicated by the X and Ⓧ in Fig. 3. As was found in the one-dimensional case,[2] there was a small increase in the traffic carried at a specified blocking as the reuse interval increased even though the average number of channels available per coverage area was held constant. The factors affecting this increase in traffic carried are discussed in Ref. 2.

Another measure of system performance is the behavior of the blocking and traffic-carried parameters plotted as functions of the new call-attempt rate as shown in Fig. 4. The symbols and the types of lines denote the same system parameters and channel assignment strategies as they did in Fig. 3. At low attempt rates, no new call-attempts are blocked in any of the systems and the traffic carried (average calls on per channel per coverage area) is a linear function of the new call-attempt rate. As the attempt rate increases, the fixed channel assignment system begins to block calls before any of the dynamic channel assignment systems. The two-dimensional systems are the last to experience significant (greater than 1 percent) blocking.

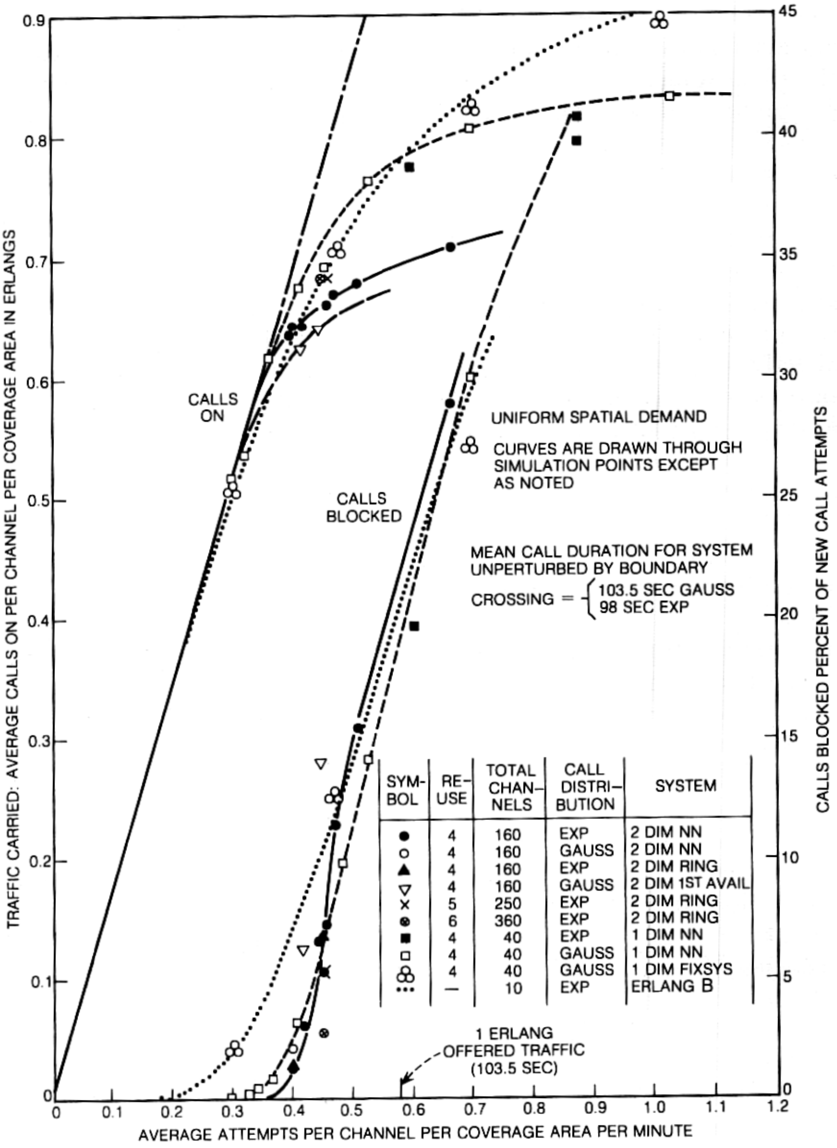


Fig. 4—Comparative performance of mobile radio systems.

The curves labeled "calls on" illustrate that at high attempt rates the fixed channel assignment systems carry more traffic than the dynamic channel assignment systems.

With no vehicle motion, the loading or traffic offered to these systems is the product of the new call-attempt rate and the mean call duration determined by the stimulus part of the simulation. One Erlang of offered traffic (one channel occupied 100 percent of the time) for the system unperturbed by motion is indicated on the call attempt axis. When vehicles cross coverage area boundaries and do not find channels available for continuing their calls, their premature termination reduces the actual average call duration. The fact that these systems must attempt to find new channels for some of these boundary crossing calls produces additional loading on the system. The actual average call duration of the exponential call duration distribution (98 seconds) is

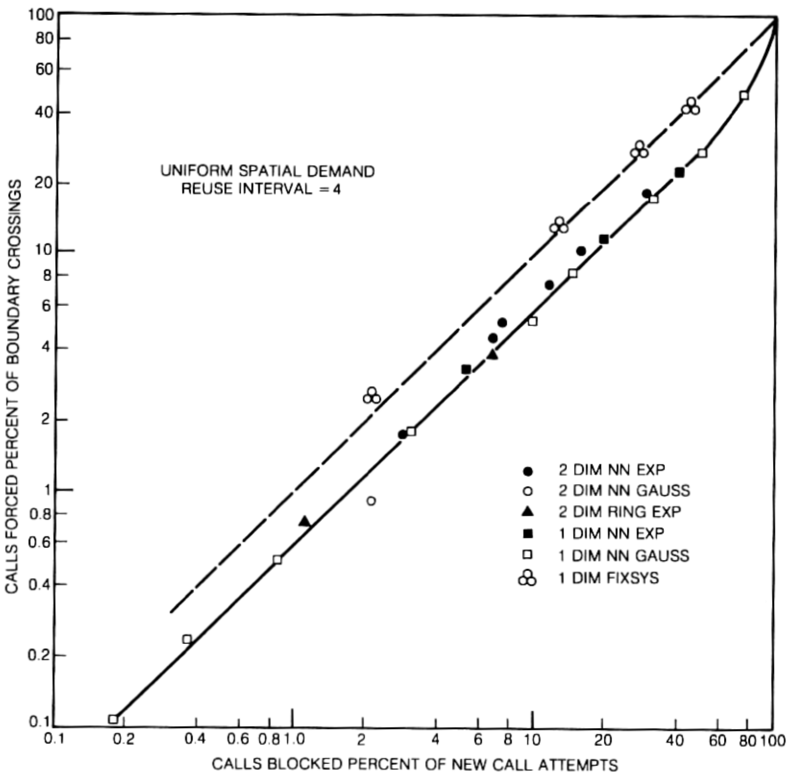


Fig. 5—Forced call terminations relative to boundary crossings.

less than that for the truncated Gaussian distribution (103.5 seconds). This difference in call duration causes the actual loading on the systems to be different at a given new call-attempt rate and accounts for the displacement of the data points for the exponential call duration distribution from those of the truncated Gaussian in Fig. 4. This effect is not seen in Fig. 3 because the traffic carried contains the actual call durations. The small difference in call durations resulted from different quantization effects in the methods used to generate samples from the two distributions.

Since some of the boundary crossing calls in the dynamic channel assignment systems keep their originally assigned channels, the forced call termination rate is less than the blocking rate in these systems. In the fixed channel assignment system, all boundary crossing calls require a new channel, and thus the forced termination rate is the same as the blocking rate. In Fig. 5, the forced call termination rate expressed as the ratio of the number of calls forced to terminate in a time period to the total number of active call boundary crossings in that time period is plotted vs the blocking rate of new call-attempts. This function appears to be the same for all of the dynamic channel assignment systems included in Fig. 5.

In Fig. 6, the ratio of the number of calls keeping the same channel

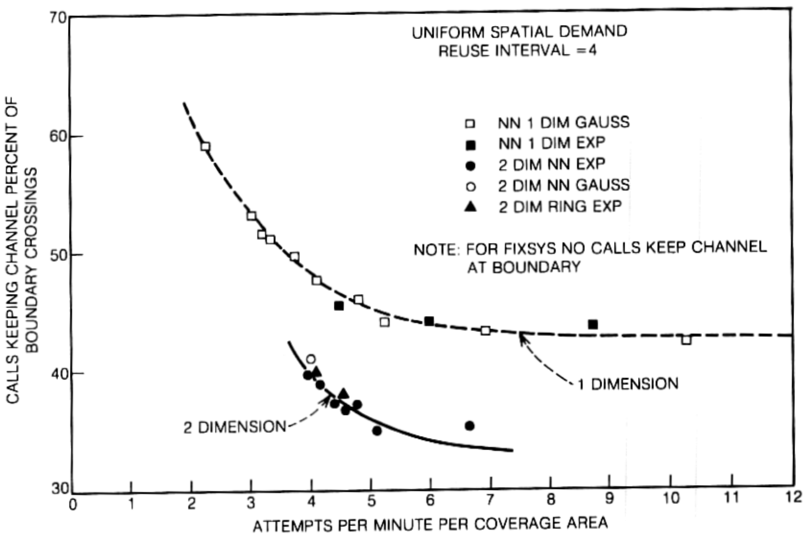


Fig. 6—Calls keeping channel at boundary.

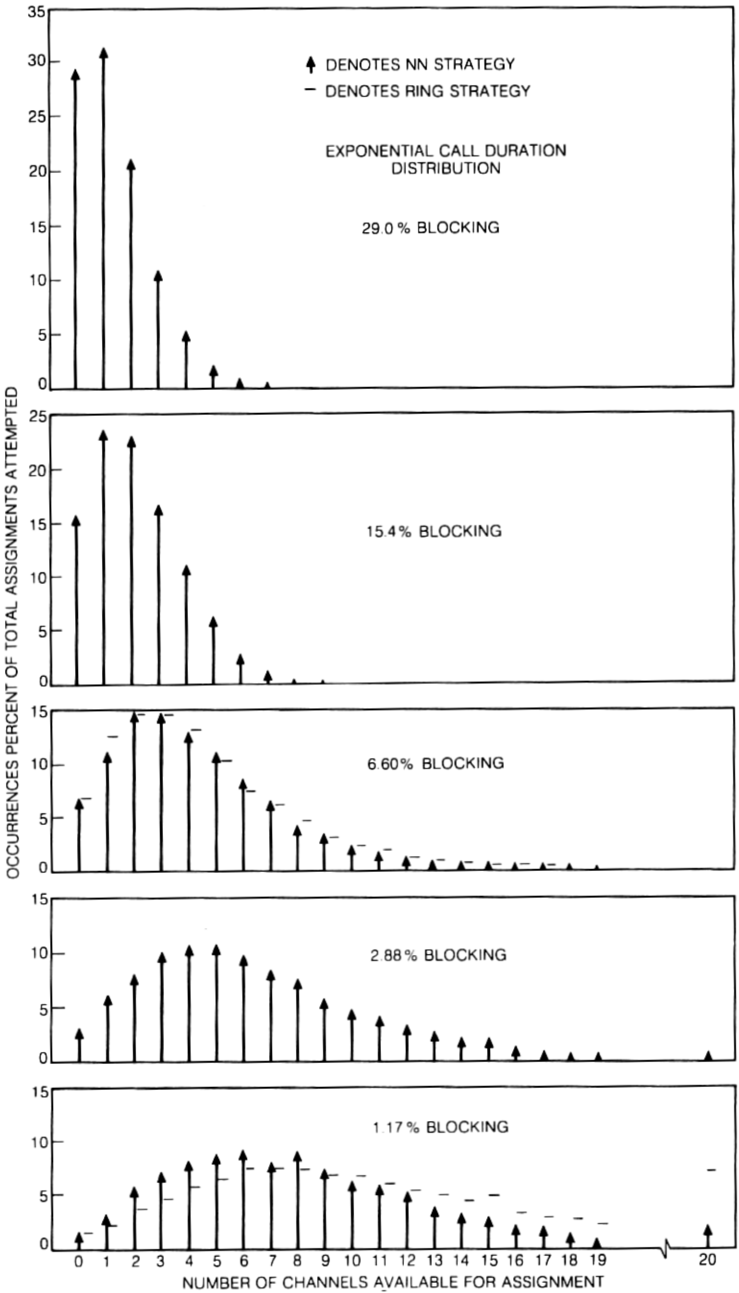


Fig. 7—Channel availability two-dimensional systems.

when crossing a coverage boundary to the total number of boundary crossings is plotted as a function of the new call-attempt rate. This relationship indicates the extent to which the originally assigned radio channel "floats" with the vehicle. The behavior of the two-dimensional RING and orthogonal NN strategy are similar for these parameters also. Fewer callers keep their originally assigned channels when crossing boundaries in the two-dimensional systems than do in the one-dimensional systems.

IV. OPERATING CHARACTERISTICS OF THE TWO-DIMENSIONAL DYNAMIC CHANNEL ASSIGNMENT SYSTEMS

More than one channel must be available for assignment in a particular coverage area if a channel assignment strategy is to improve system performance. Figure 7 shows the number of channels available for assignment expressed as the percentage of total channel assignments (new call attempts plus boundary crossing calls having channels reassigned) attempted for several blocking rates. At low blocking rates, several channels are available to select from for most of the channel assignments attempted. As the loading on the system increases, fewer channels are available from which to choose. Thus, the effectiveness of the channel assignment strategies decreases as the system loading increases. Although slight differences exist in the histograms for the different channel assignment strategies, the overall availability of channels for each assignment strategy is about the same.

4.1 *RING Strategy*

The two-dimensional RING strategy attempts to maximize channel usage on the reuse ring. Figure 8 illustrates the degree to which this is achieved for two blocking rates. The percentage of total channel assignments made (new call attempts plus boundary crossings having channels reassigned) is given for each possible number of simultaneous channel usages on the reuse ring. The histograms of Fig. 8 show that this dynamic channel assignment strategy is not able to maximize channel reuse as it serves the randomly-offered call attempts. It should be possible to reassign channels to calls in progress so that the channel reuse is more concentrated and thus the average channel occupancy is increased for a given blocking rate.

The number of occurrences of channel assignments with each possible number of simultaneous channel usages on the reuse ring is expressed

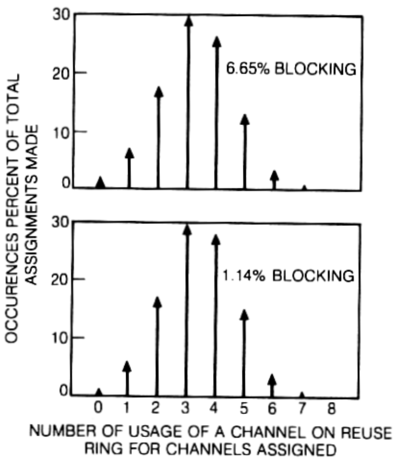


Fig. 8—Channel usage on reuse ring for two-dimensional ring strategy.

as the percentage of the total number of channel assignments made. For example, at a 6.65 percent blocking rate, the channel assigned was in use in three coverage areas on the reuse ring for about 30 percent of the total channel assignments made. It is interesting to note that the assigned channel was being used in the maximum possible number (8) of coverage areas on the reuse ring in fewer than 0.1 percent of the assignments made.

4.2 *Orthogonal NN Strategy*

Some characteristics of the behavior of the two-dimensional orthogonal NN channel assignment strategy are shown in Fig. 9 as a function of the blocking rate of new call-attempts. The curve through the open squares shows that for very few of the channel assignments attempted there was no usage of the channel assigned in any coverage area on the reuse ring. The curve through the open triangles indicates that channel assignment was made on the basis of the maximum usage on only one side of the reuse ring for 40 to 50 percent of the assignments attempted. Below a 10 percent blocking rate, about 50 percent of the channel assignments attempted benefitted from orthogonal side optimization as indicated by the curves through the open circles and the X's. The curve through the X's indicates that up to about 25 percent of the assignments attempted could have benefitted from usage maximization on the third side.

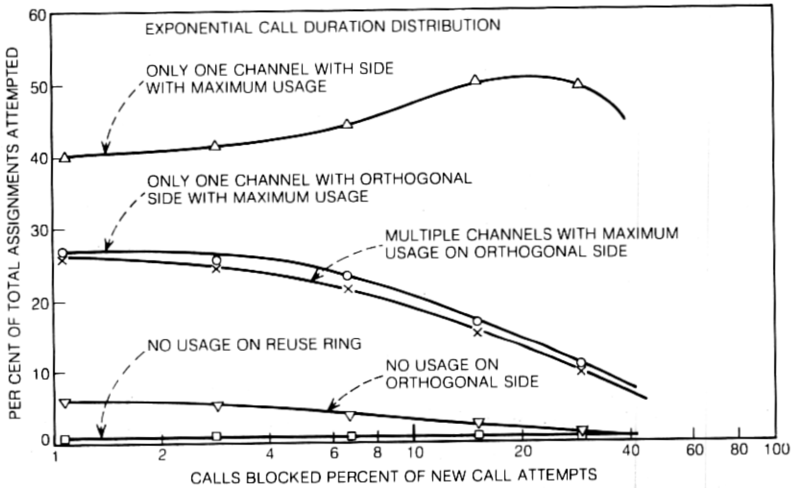


Fig. 9—Performance characteristics of two-dimensional NN channel assignment.

V. CONCLUSIONS

The results from the simulation of the two-dimensional dynamic channel assignment mobile radio systems show that these systems operate at very low blocking until the traffic offered reaches some critical value. Small increases in loading above this value produce a considerable increase in the blocking of new call attempts and result in very little increase in the traffic carried by the system. The loading at which blocking begins to occur in the two-dimensional systems is somewhat greater than the loading at which blocking begins to occur in one-dimensional dynamic channel assignment systems, and is considerably greater than the loading at which a fixed channel assignment system begins to incur significant blocking. For example, at a blocking rate, B of 1 percent, the traffic carried, TC, in Erlangs per channel per coverage area and the traffic offered, TO, in Erlangs per channel per coverage area ($TO = TC/(1 - B)$) for the systems studied which had an average of 10 channels available per coverage area and a reuse interval of 4 are: two-dimensional dynamic channel assignment TO = 0.636, TC = 0.630; one-dimensional dynamic channel assignment systems, TO = 0.631, TC = 0.625; fixed channel assignment systems, TO = 0.444, TC = 0.440.

It was found that the two strategies aimed at channel reuse optimization performed similarly and that both were somewhat better (carrying approximately 5 percent more traffic at a given blocking rate) than a channel assignment strategy which chose the first available channel encountered in a channel search without any regard to reuse optimization. The reason that these dynamic channel assignment systems do not carry as much traffic at high blocking rates as fixed channel assignment systems is that they are not able to maximize channel reuse as they serve the randomly-offered call attempts. It should be possible to reassign channels to calls in progress so that the channel reuse is more concentrated and thus more traffic could be carried per channel at a given blocking rate.

VI. ACKNOWLEDGMENTS

The authors wish to thank Mrs. Wanda Mammel and Mrs. Diane Vitello for their help in debugging and running the computer programs.

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