PERFORMANCE OF A THIN CELLULAR NETWORK WITH DYNAMIC CHANNEL ASSIGNMENT

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1. INTRODUCTION

1.1. Background

The possibility of using radio waves for communicating with moving vehicles was conceived in the earlier part of this century. As early as 1921, the Detroit Police Department carried out experiments using one way radio broadcasts for police cars. The police cars were instructed to respond by stopping to call back on the wired telephone system. Two way mobile communications were experimented in 1930s. A sudden and pressing need for two-way mobile communications was realized in the second World War. Wireless communications revolutionized the battlefield permitting the deployment of large armies, moving rapidly over large areas. Mobile communication was essential for coordination of armour, infantry and air support.

Even though commercial applications of mobile communications started in the late forties, the progress towards providing a mobile telephone service or 'car phones' has been very slow. The traditional approach to mobile radio telephony, before the onset of cellular system, was to have a high power transmitter at the tallest point in the coverage area. This was similar to the radio broadcasting approach. Even though a large area of 50 mile radius could be covered this way, the capacity of such a system was severely limited. For example, the Bell mobile system in 1970s in New York city could support only twelve simultaneous conversations and the thirteenth caller was blocked [2, p.45].

Department of Communications in Canada) for cellular systems has been a source of constant debate among system planners [2]. It is clear that the existing Single Carrier Per Channel (SCPC) analog FM cellular networks use the spectrum inefficiently and are costly to operate [2, Chap. 5; 3, Chap. 14]. Considerable research has been done to alleviate the problem of spectrum scarcity. Digital cellular systems using Time Division Multiple Access seem to be an alternative to analog systems [2,4,5,6,7,8]. Besides addressing the problems of cost, digital systems would offer all the advantages of digital technology. But the transition from analog to digital cellular networks would be gradual.

While research is continuing towards a digital alternative, considerable work has been done in the recent past regarding channel occupancy duration and channel assignment strategies for existing analog networks [15,14]. Results have shown that dynamic and hybrid channel assignment schemes improve system performance compared to fixed channel assignment [9,10,11,16,17,18]. In the dynamic assignment method, all the channels are assigned to various cells by the system controller in a dynamic way. Hybrid channel assignment methods incorporate a combination of the fixed and dynamic assignment. Depending on the size of the network, a judicious choice of channel assignment method can lead to a reduction in the number of channels required to handle a certain amount of traffic with a desired quality of service. This quality of service is generally measured by the blocking probability or the probability of an attempted call not getting through the network.

1.2. Thesis Objectives

An analog cellular system became operational in Saskatchewan in the Fall of 1989. The cellular service is offered both by Saskatchewan Telecommunications Corporation (SaskTel) and a radio common carrier company CANTEL. In this thesis, application of dynamic channel assignment is studied for SaskTel cellular network using computer simulation. The thesis objectives may be laid down as:

(i) Develop a computer simulation model for analyzing the blocking probability of the fixed assignment SaskTel cellular network.

(ii) Incorporate dynamic assignment and compute the system performance advantages with dynamic assignment.

(iii) A related objective is the analysis of channel occupancy in different cells and handoff rate with variation in key system parameters such as average mobile velocity, cell radius and mean call duration.

1.3. Thesis Organization

In addition to this introductory chapter the thesis is organized into six more chapters. Chapter 2 gives an overview of the cellular concept. In Chapter 3, spectrum efficiency methods for cellular systems are introduced, and in Chapter 4 different channel assignment methods are described. In Chapter 5, a simulation model for a cellular system is presented and on the basis of this model a computer program has been developed for fixed, dynamic and restricted dynamic channel assignment methods. Results from this program are presented in Chapter 6. The results include comparison of blocking probability performance for cellular networks using fixed and dynamic channel assignment. Finally, conclusions are presented in Chapter 7.

2. CELLULAR MOBILE TELECOMMUNICATIONS

2.1. BACKGROUND

Mobile communication systems are employed when either the transmitter, the receiver, or both are mobile. Such communication systems have been employed since the second World War. The need for mobile communications evolved due to its application to military operations. Ever since, there has been tremendous growth in the applications of this type of communications. Some of these applications could be listed as :

Marine: rescuing ships in distress.

Land: police and medical services, car phones.

Aeronautical: Communication between pilots and air traffic control towers.

With the advances in technology, the applications in each of the three broad categories of transport systems have become much more diversified. New features and facilities have been incorporated in various mobile communication services being provided. The growing demand for facilities from mobile communication subscribers is leading to new developments in these systems. As an example, mobile communication is being increasingly used for data in addition to voice. In this chapter, land mobile communications systems are briefly reviewed and various features needed for these systems are examined.

2.2. LAND MOBILE COMMUNICATIONS

As mentioned above, land mobile communications evolved since the second World War. There are a number of different services provided using mobile communication systems. A one way communication, better known as paging, merely signals to the user that someone is trying to reach him or her. This system is still very popular and telecommunication service providers offer this service to a large number of users. Doctors use this service frequently because they are generally mobile and are likely to receive emergency calls. Another service offered is the communication for essential services like police. This is a two-way system and is popularly known as the "wireless" system. In this mode, both the parties are able to exchange messages which may be initiated by either party. However, only one party is able to transmit (or receive) at a time. Such systems are referred to as half-duplex systems. A recent, and a very significant extension of land mobile communication service has been to provide a subscriber the use of telephone from a car. Such systems are referred to as full-duplex because both parties are able to transmit (or receive) at the same time. This form of mobile telecommunication has developed rapidly during the past 10-15 years.

2.3. PRECELLULAR LAND MOBILE TELECOMMUNICATIONS

The earlier mobile communication systems evolved from the basic concept of providing a transmitter in the centre of a geographical area. The transmitter uses a certain set of frequencies to communicate with the mobiles, i.e., the transmitter is radio-linked with all the car phones that are in its range of transmission. The subscribers using these phones are linked with the central transmitter on different carrier frequencies. Different geographical areas are served in a similar fashion by other central transmitters. A pair of frequencies providing a two-way communication constitute a mobile frequency channel. Each transmitter has access to a certain number of channels and it can use only these channels. Some of the commercial mobile services in North America which use this concept for providing telecommunication services are; Mobile Telephone Service (MTS) and Improved Mobile Telephone Service (IMTS). It is necessary to mention here that all the land mobile communication services mentioned in Section 2.2 and 2.3 suffered from a poor quality of signal reception as well as other system limitations. The MTS and the IMTS had fundamental flaws briefly described below.

1. Limited Capacity: The total number of users simultaneously using the service can never be more than the number of channels allocated.

2. Inconvenient service: The users wishing to move from one geographical area to another were forced to have their calls disconnected and had to make a fresh request for another connection when entering a new coverage zone.

3. Poor service performance: Since the number of channels was limited, the number of subscribers far outweighed the number of channels allocated. This resulted in a large number of calls getting blocked.

4. Poor use of available frequency spectrum due to limited capacity of the system: The frequency spectrum allocated for mobile telecommunications, which was already quite

scarce, was used very inefficiently.

5. Lack of privacy: The analog modulation and demodulation used for these schemes did not provide the users with a secure and private conversation.

6. High system cost: Since the cost of erecting very high transmitters and other hardware far outweighs the revenue generated from a few customers, the service was not found to be very attractive from a financial point of view.

7. Poor quality of transmission: The quality of voice transmission was very poor compared to the quality provided in a landline telephone network.

These were the basic shortcomings in the earlier mobile communication systems. The increased demand for service, coupled with the inability to get frequency spectrum allocation in proportion to that demand, resulted in this concept being unacceptable for future commercial systems. These problems were instrumental in the development of the cellular concept. The cellular concept alleviates the problems encountered in conventional systems. The cellular concept is introduced in the next section.

2.4. CELLULAR MOBILE TELECOMMUNICATIONS

The cellular system employs the division of the geographical service area into cells, and the division of the available frequency spectrum into sets of channels. Figure 2.1 shows how the geographical area is divided into cells of hexagonal shape. The division of frequency spectrum is discussed in section 2.5.

One portion of the spectrum is assigned for use by the mobiles and the other portion is assigned for the use by the base stations. Each cell has a central base station (though other configurations are also possible) which has radio links with all the mobiles in its range on the channels available to it. There is a mobile switching office which is linked through cables to different base stations of different cells in the system. The

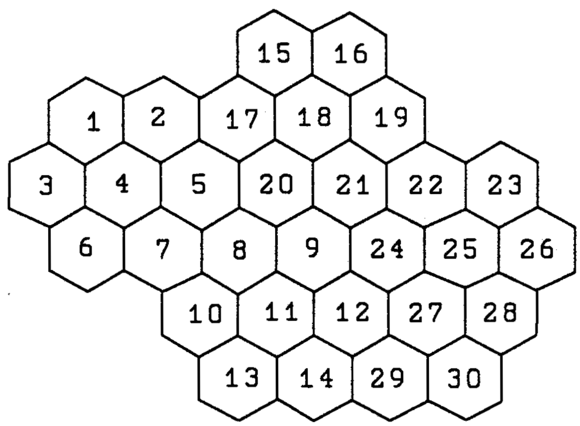


Figure 2.1: Layout of a cellular system

schematic in Figure 2.2 shows how a cellular system is linked to the landline telephone network. The Switching Office is also connected to the Public Switched Telephone Network (PSTN). Thus the mobile user can talk to any landline telephone user or to another mobile user in any cell of the system. The cellular system virtually offers the same facilities to a mobile user as the conventional system offers to users of landline telephones. Also, the voice quality provided by cellular systems is much better than the quality provided by the previous services to the mobile users.

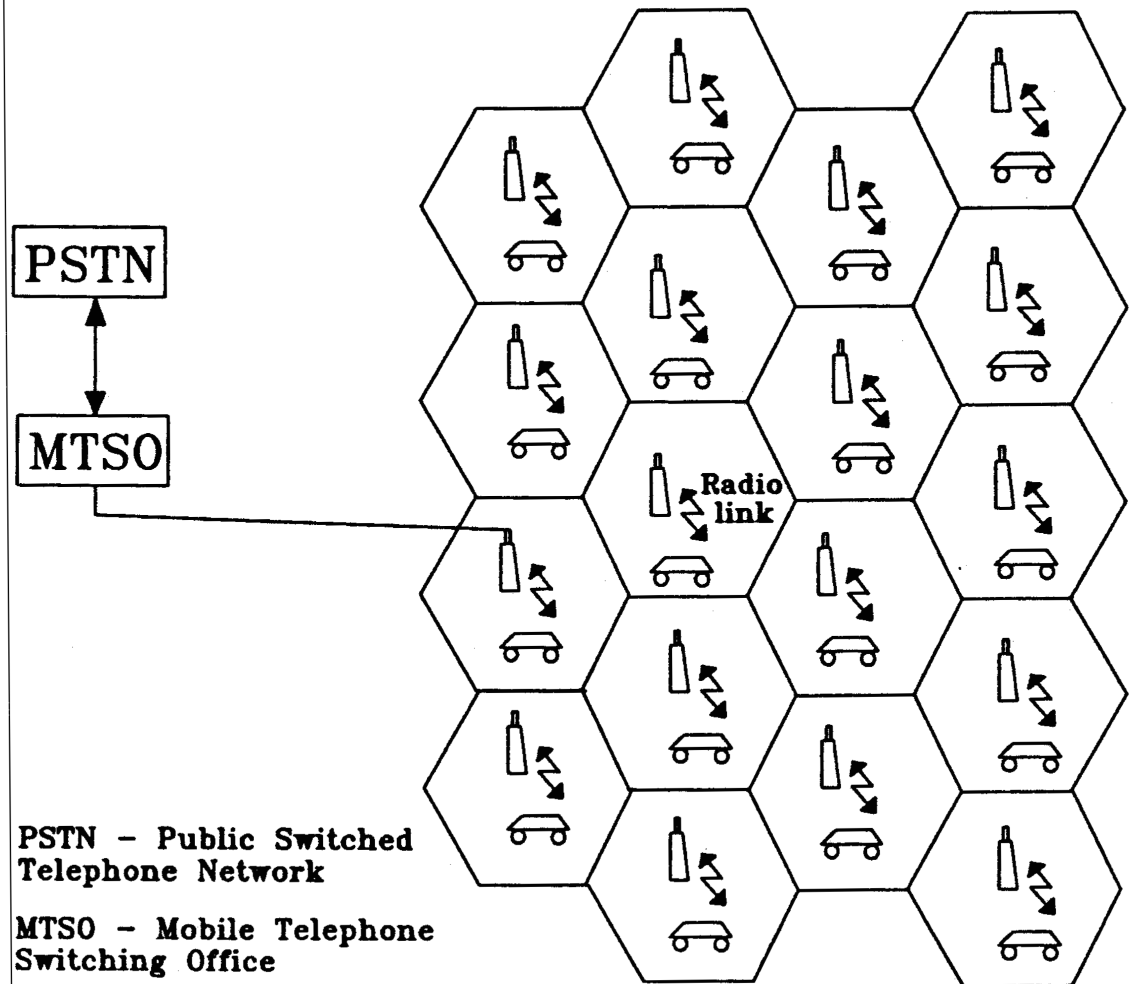


Figure 2.2: A cellular telecommunication network

2.5. SPECTRUM AND SERVICE AREA DIVISION IN A CELLULAR SYSTEM

As mentioned above, the service area is divided into cells of a fixed size. The cells may be ideally considered to represent a hexagon. Such a representation simplifies system design. The available channels (spectrum) are divided into different sets which may or may not have the same number of channels. These sets are allocated to a predetermined number of cells that are neighbours to each other, forming a cluster. The cluster of cells is only a small subset of the total cells in the system. The shape of the cluster can vary and would depend upon how many cells form the cluster. The division of frequencies into sets results in each cell of the cluster using a different set of channels. The sets of frequencies are formed such that channels in each cell are spaced well apart in frequencies. This provides reduced adjacent channel interference that may otherwise exist due to imperfections in the transmitter filters. Same set of frequencies can be used in different cell clusters. This allows reuse of the frequencies in different clusters and results in the high spectrum efficiency of the cellular system. Frequency reuse is further discussed in this section and in section 3.4.1. As an example, a cellular system with a 7-cell reuse plan is shown in Figure 2.3. This system has three clusters - a, b and c. Each

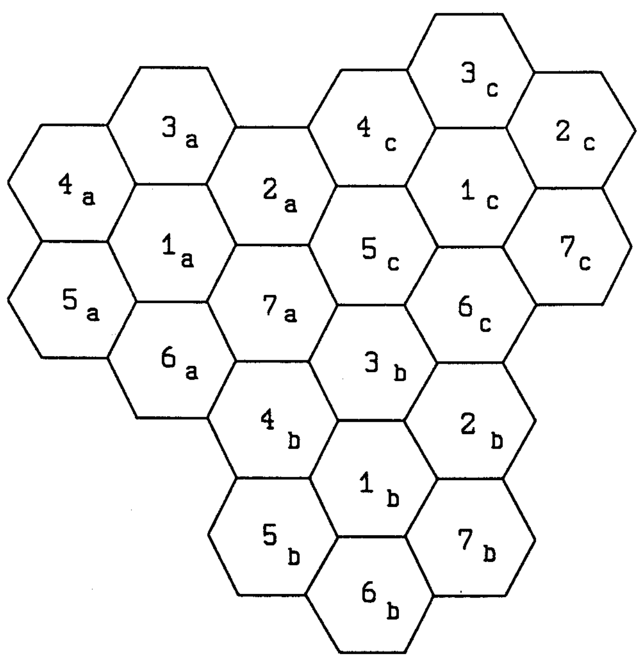


Figure 2.3: The 7-cell reuse structure

has 7 cells, with each cell of the cluster using a different set of frequencies. The cells 1_a, 1_b and 1_c use channels from the same subset. For the cellular system shown in Figure 2.1, the frequency allocation is given in Table 2.1.

Table 2.1: Reuse groups with different cells

Reuse Group	1	2	3	4	5	6	7
Cell Number	1 8 15 22 29	2 9 16 23 30	3 10 17 24	4 11 18 25	5 12 19 26	6 13 20 27	7 14 21 28

It is necessary to discuss the geometry of the cell in order to appreciate the advantages provided by the cellular system compared to the earlier systems. Figure 2.4 shows a cell approximated to a circle. The cell centre may be considered to be the point where all the angle bisectors of the hexagon meet. The cell radius may be considered to be the distance from the centre to any of the vertices. The distance between two cells is considered to be the distance between their cell centres. The interference between the two cells using the same set of frequencies depends on the ratio of the distance between the cells to the radius of each cell. With a rule that the same set of frequencies are used in

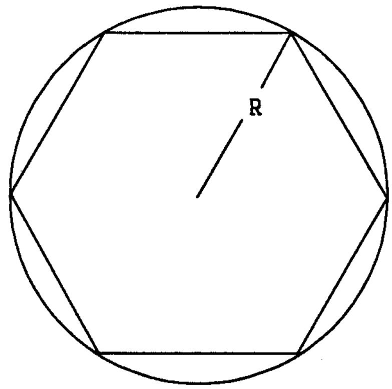


Figure 2.4: Approximation of a hexagonal cell to a circle

any two cells that have a certain minimum ratio of cell distance to the cell radius, two important advantages can be realized. The frequency sets could be reused not once but many times in the entire system, and secondly, the interference from different transmitters would not be severe. The basic idea in a cellular system is to use different sets of frequencies in cells that have common boundaries so that their transmissions do not interfere with each other. At the same time, the transmitter powers are so designated that the transmission on a channel in one cell causes acceptable interference to the transmission on the same channel in another cell that is reusing that channel. Thus, with the same available spectrum a much larger subscriber population can be served. The above method of spectrum and area division in a cellular system results in better spectrum efficiency, higher subscriber density and low cost per subscriber. There are certain other features that distinguish the cellular system from the earlier mobile communication systems. The earlier systems used a transmitter with high transmitting power to establish communications with the subscribers in a large coverage zone. However, the cellular system transmitters use low power. The power needed is determined by the cell coverage area and other factors like geographical terrain and signal attenuation (fading). Further, in a cellular system, users are not forced to have their calls disconnected when they move to different cells. In fact, their calls are handed-over automatically to an available channel of the new cell. The procedure of call-transfer when the mobile enters a new cell is called a handoff or handover. Handoffs are based on signal strength measurements from all the base stations of the system. This feature of the cellular system is outside the scope of this thesis. It is adequately described in a number of references [2,3].

To summarize, the cellular concept makes use of the geographical division of the service area into different cells and allocates a carefully designed subset of the available channels to a small cluster of cells. The same sets of channels are reused in other cells while keeping signal interference to a minimum. Because of mobile users and the typical spectrum allocation in a cellular system, such systems have a number of other characteristics which are different from fixed-user communication services.

To understand cellular systems, a thorough knowledge of a variety of concepts from communication theory is required. However, there are certain issues that are of special interest to Cellular Engineers. Some of these issues are briefly discussed below.

2.6. OTHER ISSUES RELATED TO CELLULAR SYSTEMS

The channel allocation in a cellular system to serve a call directed to, or, originating from a mobile user, involves significant processing. There are further complexities in the successful completion of the call. In particular, a user transparent handoff process has to be incorporated. Some of these complexities arise because the transmission takes place in a scenario very different from that with the fixed transmitter and the receiver. The signal transmission phenomenon is very different not only due to the mobile environment but also due to the frequency spectrum available for these systems. Usually, the spectrum allocated for cellular mobile communication systems is in 800-900 MHz band. Some of the important issues in the study of cellular systems are listed next.

1. Signal attenuation for a particular geographical area.
2. Modulation/Demodulation/Coding methods for cellular systems.
3. Analog vs Digital cellular systems.
4. Channel design; narrowband or broadband.
5. Traffic studies and future growth.
6. Spectrum utilization studies.
7. Choosing the cell size, cell separation, transmitter powers etc. for a new system.
8. Handover mechanism.
9. Switching involved for cellular systems.

10. Channel assignment to the cells when different traffic loads are offered.

Detailed discussion of these issues is outside the purview of this thesis. There are many good references [2,3] available which address these in detail. As stated in Chapter 1, the objective of this thesis is to study the dynamic channel allocation for SaskTel cellular network. The next two chapters are devoted to the issues of spectrum efficiency and various channel assignment methods.

3. SPECTRUM EFFICIENCY IMPROVEMENT METHODS FOR CELLULAR SYSTEMS

In the previous chapter, basic concepts for a cellular telecommunications system were presented. In this chapter, some parameters and definitions about the cellular system are introduced. These parameters are used for performance analysis of cellular networks and would be frequently referred to in this thesis. Various spectrum efficiency improvement methods are also introduced in this chapter.

3.1. IMPORTANT PARAMETERS OF A CELLULAR SYSTEM

Some of the important parameters of a cellular system commonly used in performance analysis are as follows:

1. Circuit Spectrum efficiency: The circuit spectrum efficiency is defined as the number of telephone voice circuits per MHz of spectrum. In a digital cellular system this parameter measures the efficiency of the source encoder and the modulator. For example, a 64 kb/s channel rate can be used to carry a single pulse code modulation (PCM) voice circuit, or two 32 kb/s adaptive differential pulse code modulation (ADPCM) voice circuits, or four 16 kb/s residual excited linear predictive (RELP) coding circuits. Obviously, a system which creates four telephone circuits per 20 kHz channel is more efficient than another coder that creates only one. A detailed description

of coding methods and their efficiencies can be found in [19].

2. Geographical spectrum efficiency: This relates to the average size of the cell and the degree to which cell-splitting has been applied. The number of cells serving an area, in conjunction with the frequency reuse pattern determines the geographical spectrum efficiency. If cells of a smaller radius are employed, the same area could be served by a larger number of cells. For the same frequency reuse pattern, there is an increase in the number of circuits/MHz when smaller cells are used. As mentioned in Chapter 2, reuse factor depends on the co-channel interference criterion (co-channel interference is the interference generated by cells using the same set of frequencies).

3. Channel utilization: As mentioned before, the available spectrum is divided into different channels. These channels are assigned to different cells for the purpose of voice and data transmission. A system is considered efficient if it uses a minimum number of channels to serve the maximum possible subscribers at the desired grade of service, thereby utilizing its channels properly. Channel utilization and spectrum efficiency are important parameters used in the design and the performance analysis of an analog cellular network. This is further discussed in the subsequent chapters.

The importance of spectrum efficiency and channel utilization in a cellular system arises because of three main considerations:

1. Scarcity of the spectrum for cellular use.

2. Capacity (number of subscribers that the network is capable of serving).

3. Cost of cell-sites.

To better understand the implications of the above factors, it is illustrative to elaborate the spectrum allocation as well as the traffic objectives of a cellular service.

3.2. SPECTRUM ALLOCATION FOR LAND MOBILE TELECOMMUNICATIONS

A major problem facing the radio communication industry is the limitation of the available radio frequency spectrum. In setting allocation policy, the spectrum regulation agencies seek systems which need minimal bandwidth but provide high usage and consumer satisfaction. In the United States, the spectrum allocated for land mobile communication is in different bands. These are:

1. 450 - 512 MHz
2. 806 - 902 MHz
3. 935 - 941 MHz
4. 1427 - 1435 MHz

These allocations have been made because of severe spectrum limitations at lower frequency bands. These bands are not ideal for mobile radio transmission but it is possible to implement the cellular systems using these bands.

An ideal mobile telephone system would operate within a limited assigned band and would serve an almost unlimited number of users in an unlimited area. Three common methods used to achieve the ideal are :

1. Single-sideband (SSB) modulation: In single side band modulation, only one side band of a double sided amplitude modulated spectrum is used. A channel bandwidth of about 5 kHz per voice channel can be achieved. In spite of this high spectrum efficiency there are some practical problems with this method [2, p.45] and it is not used in practice.

2. Cellular: As mentioned before, in this method the allocated frequency band is reused in different geographic locations.

3. Spread spectrum: In this method, the signals are spread over a wide frequency band. Different codes are used to separate these signals.

In 1971, in a report submitted to FCC by the researchers at Bell Laboratories, the cellular approach was shown to be a spectrally efficient system [3, Chapter 1]. A comparison of the cellular approach with other methods is discussed in [3]. This thesis is concerned with the cellular systems only.

3.3. TRAFFIC OBJECTIVES OF THE CELLULAR SERVICE

The scarcity of spectrum and poor performance of earlier mobile communications systems led to the evolution of cellular system. One of the major objectives for the cellular service was to achieve a grade of service comparable to wireline telephony, both in terms of voice quality and circuit availability. One measure of availability is the blocking probability. Cellular systems are generally required to achieve a blocking of 2 % or less [2]. This blocking probability implies that no more than 2 % of all calls attempted during the busiest hour fail to obtain access to the network; 98 out of 100 calls must go through.

The blocking probability depends upon the amount of calling traffic that is offered on the average by the cellular subscribers as well as on the number of radio channels available for a given population of subscribers. Calling behaviour can be analyzed and predicted statistically. This information is used by the system designer to implement the system with a given number of radio channels. Not all customers will attempt to place their calls at the same time. The user traffic is measured in Erlangs. An Erlang of traffic is equivalent to one person using a circuit for 3600 seconds in an hour. The Erlang B model [25] is used to determine the number of channels required to serve a certain volume of traffic at a fixed blocking probability. This model assumes that:

1. Traffic sources are infinite.

2. Calls occur at random.

3. Call durations are distributed exponentially about an average value.

4. Lost calls are cleared, i.e., a call unable to find a free channel disappears from the system.

The Erlang B traffic tables give the number of channels required for a given traffic and a given blocking probability. Such tables are useful in designing telecommunication networks. The Erlang B formula is given by

$$p = \frac{\frac{A^n}{n!}}{\sum_{x=0}^{n} \frac{A^x}{x!}} \quad ; \tag{3.1}$$

where p is the probability that a single source will be busy, A is the expected traffic density (in Erlangs), n is the number of channels in the group of channels, and x is the number of busy sources or busy channels [20,25]. For a given number of subscribers offering a known amount of traffic and sharing a given number of trunked radio channels, the blocking probability can be readily calculated. The higher the ratio of customers to channels, the higher is the blocking. Similarly, higher the average amount of traffic offered by each customer, higher is the blocking. To provide a better grade of service, the ratio of customers to channels should be reduced. This can be done in two ways:

1. Providing more base-station equipment and channels (if spectrum allocation permits).

2. Optimizing the channel assignment in different cells for a given subscriber population .

Option 1 is costlier and may not be always practical. Option 2 is not straightforward and involves careful estimation of the various traffic parameters, e.g., traffic behaviour during different hours of the day, subscriber population, the expected future growth, etc. A well organized channel assignment based on the above parameters could make the network efficient in providing a good grade of service using minimum spectrum.

From the above discussion it should be clear that spectrum efficiency is a very important factor in the design of cellular systems. An inefficient system would always require additional spectrum to meet the demands of the growing subscriber population. It would suffer performance degradation in terms of poor availability of voice circuits as the traffic grows. Hence, spectrum efficiency improvement is quite important to conserve spectrum. This subject is dealt with in the next section.

3.4. METHODS FOR IMPROVING SPECTRUM EFFICIENCY

There are a number of methods for improving the spectrum efficiency of a cellular network. These methods can be used for a new system being designed as well as for an existing system. Some of these techniques can be classified as:

1. Reducing the bandwidth per voice channel with more efficient modulation, encoding.
2. Improving spatial frequency-spectrum reuse
3. Better frequency management and channel assignment
4. Improving spectrum efficiency by offering a multiplicity of services matched to the traffic needs.

5. Reducing the load using:

(a) Off-air call set-up

(b) Call forwarding

(c) Queuing

As each system may have unique features, the choice of improvement method depends upon the particular system. As an example, a network supporting very few subscribers and anticipating very little subscriber growth in future may not be short of spectrum but may require the capital cost to be minimum. Besides the methods outlined above, other methods such as directed retry can improve spectrum efficiency. These methods are examined below.

3.4.1. Frequency reuse and reuse partitioning

Frequency reuse implies reusing the available spectrum in cells separated by a predetermined distance. Reuse partitioning involves splitting a cell into two or more tiers. The distribution of voice channels between the inner and outer tiers is a function of traffic distribution, blocking criteria, and overflow routing [21]. It has been shown that controlled traffic overflow from the inner tier causes increased capacity and voice channel utilization while maintaining interference levels. By freeing critical channels, traffic congestion can be relieved and increased capacity is realized. This is done by placing a new cell not where there is more congestion but where the new cell relieves critical channels [22]. The spectrum efficiency is an inverse function of N where N is the number of cells in the reuse pattern.

3.4.2. Directed retry

Another way to improve channel utilization is to use a system with directed retry [14]. For such a system, subscribers can not only access channels available in their cells but can also access channels available in neighbouring cells if their calls experience blocking in the home cell. A suitable analytical model has been developed for such a scheme in [14]. Using this model it was demonstrated in this reference that a substantial increase in traffic capacity can be realized. In this model, traffic is considered to be divided between streams such as:

(a) Traffic stream originating in home cell which has ability to make a directed retry,

(b) Traffic stream originating in home cell which doesn't have the ability to make a directed retry,

(c) Traffic stream originating in neighbouring cells which overflows to the cell in consideration (home cell).

Further details of this method are available in [14].

3.4.3. Fixed and dynamic assignment

This is another method which may be used for improving spectrum efficiency. In

Chapter 2 it was explained how the frequency spectrum can be divided into certain subsets and these subsets allocated to a cluster of cells in such a way that each cell of the cluster uses a different subset. This method of channel allocation is called fixed channel assignment because a cell uses only those channels that are allotted to it. But this method of assignment is not always the most efficient. In certain cases higher spectral efficiency may be achieved by using dynamic or hybrid assignment of channels. A dynamic channel assignment method is similar to the fixed channel assignment method. Channels, in this case, are assigned to the cells in the same way as for the fixed assignment method. However, in this case, channels from one cell may be used by its neighbouring cell, if required. There are certain criterion that govern the assignment. Some of the dynamic assignment algorithms have been presented in [16]. A combination of the dynamic and fixed assignment methods is also used. This method is called the hybrid channel assignment. In this method the spectrum is divided into two parts. One part is divided into subsets and made available to the cells as in fixed channel assignment. The other part constitutes a pool from which cells can borrow channels if they need additional channels to handle their traffic. As in the dynamic assignment case, the assignment of channels from the pool of dynamically assignable channels is made based on certain algorithms. This subject is discussed at some length in the next chapter.

One form of hybrid assignment uses dynamic reassignment of channels. Reassignment implies that if at any given instant a call in a cell is being handled on a channel from the pool of dynamically assignable channels and one of the (fixed) assigned channels from that cell is free, then reassignment would take place. The call on the dynamically assignable channel would be reassigned to the free (fixed) channel and the dynamically assignable channel would be rendered free. This is done so that this channel is available for any cell that requires to borrow a channel. The computer simulation results reported before [9] have shown that dynamic channel reassignment with an optimum choice of fixed and dynamically assignable channels results in a significant improvement of system capacity. Kahwa and Georganas [11] have analyzed the performance of a system under different allocations of fixed and dynamically assignable channels. Their results show the performance of the system for various values of the offered traffic. Simplified assumptions of uniform distribution of channels and uniform spatial distribution of traffic were made in these references. Uniform spatial distribution of traffic implies that all the cells in the system have the same traffic load and are assigned the same number of channels. Non-uniformities of traffic are expected to degrade the performance of such a system.

3.4.4. Channel organization

Yet another important issue which determines spectrum and channel utilization is the channel organization. The European Digital Mobile Communication System (EDMCS) will have three types of channels [23]. These may be classified as:

(a) Common control channel (CCCH)

(b) Dedicated control channel (DCCH)

(c) Traffic channel (TCH)

In such a channel organization, TCHs are used to carry the voice and data traffic. Call origination (either by mobile or a landline user) set-up, location-updating etc. are done through a random access initially on the CCCH. Once the Mobile Telephone Switching Office (MTSO) has acknowledged the random access, a DCCH is allocated to that mobile on which further signalling sequences are exchanged. Once the signalling sequences are over, the MTSO allocates a TCH to the mobile. The use of a DCCH reduces the load on the CCCH. Factors such as time spent for the signalling sequence, mean time spent in the waiting queue, call forwarding delay, etc. determine the control channel loading. The provision of a DCCH improves the spectrum efficiency. Further details of this method can be obtained from [23].

Although a number of methods for spectrum efficiency improvement are available (as outlined above), dynamic channel assignment is one of the most effective method for low traffic (thin) cellular networks [11]. This method is studied in detail in this thesis. As the SaskTel cellular network is such a thin network, performance of dynamic assignment is proposed and studied for this network. Before carrying out the performance analysis a further detailed description of this method is included in Chapter 4.

4. CHANNEL ASSIGNMENT METHODS

Spectrum efficiency and channel utilization are important parameters that affect the performance of a cellular telecommunication network. In Section 3.4 of the previous chapter, different methods for improving spectrum efficiency were outlined. In Section 3.4.3, fixed and dynamic channel assignment methods were briefly explained. These methods come under the broad classification of fixed and non-fixed channel assignment. In this chapter, fixed and non-fixed channel assignment methods are presented in greater detail.

Before going into the details of different channel assignment methods it is necessary to understand the concept of frequency management. In the next section this concept is introduced.

4.1. FREQUENCY MANAGEMENT

The Federal Communications Commission (FCC) in United States and the Department of Communication (D.O.C.) in Canada assign and manage the spectrum for cellular telecommunications. The assignment is given for both the voice channels and the call set-up channels. Voice channels are further grouped into subsets. This grouping can be done depending on the system requirements. The designation of channels into set-up and voice, and the division of voice channels into subsets, comes under frequency management. An analogy can be drawn between frequency management and the "rules" of a game. Just as the rules of any game ensure discipline, fair play and maximum likelihood of a result, frequency management ensures that channels assigned for setting up a call perform that function, and channels assigned for voice traffic do likewise. The division of frequency channels into subsets ensures that the channels in a particular cell are well separated in frequency.

4.1.1. Numbering of channels

The total number of channels available in a cellular system are 666. A channel consists of two frequency bands, one of which is in the low band and the other is in the high band. For example, the two frequencies in channel 1 are 825.03 MHz (mobile transmit) and 870.03 MHz (cell-site transmit). The two frequencies in channel 666 are 844.98 MHz (mobile transmit) and 889.98 MHz (cell-site transmit). Thus, the bandwidth assigned for mobile transmit is 20 MHz (825-845 MHz). Similarly, the bandwidth assigned for cell-site transmit is 20 MHz (870-890 MHz). The 666 channels are divided into two groups; block A and block B. Each block has 333 channels and a bandwidth of 20 MHz. These blocks are shown in Figure 4.1. Each city has two designated cellular operators, and the division of spectrum into two blocks allows both to operate on separate blocks. Obviously, this is designed to prevent mutual interference of the two networks.

	1A	2A	3A	4A	5A	6A	7A	1B	2B	3B	4B	5B	6B	7B	1C	2C	3C	4C	5C	6C	7C	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	
	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	
	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	
	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	
	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	
	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	
	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	
	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	
	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	
	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	
	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	
Block	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	
A	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	
system	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	-	-	-	
	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	Control
	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	} channel sets
Block	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	
B	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	
system	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	
	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	
	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	
	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	
	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	
	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	
	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	
	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	
	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	
	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	
	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	
	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	
	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	-	-	-	

Figure 4.1: Frequency-management chart (from [3])

Out of the total 666 channels, 42 are set-up channels.

Set-up channels:

Channels 313-333 block A

Channels 334-354 block B

Voice channels:

Channels 1-312 (312 voice channels) block A

Channels 355-666 (312 voice channels) block B

It may be noticed that the middle channels are used as set-up channels. This is done to facilitate scanning of these channels by frequency synthesizers. This scanning is done in MTSO during the call set-up procedure.

4.1.2. Grouping of channels into subsets

As stated above, the number of voice channels in each block is equal to 312. These channels can be grouped into any number of subsets. Generally, these are grouped into 21 subsets. As there are 21 set-up channels, this division ensures that each subset has a set-up channel. All, but three, subsets consist of 16 channels (including the set-up channel). As shown in Figure 4.1, the closest adjacent channel is 21 channels away in each set. Wide separation between adjacent channels ensures that the adjacent channel interference is low. In a seven-cell frequency-reuse plan with uniform traffic, each cell contains three subsets, iA, iB, iC; where i is an integer from 1 to 7. For example, cell 1 could contain subsets 1A, 1B and 1C. The total number of voice channels in a cell is about 45. The minimum separation between the three subsets is 7 channels. For example, the three subsets of cell 1 could have channels 1, 8 and 15, respectively, each having a separation of 7.

From the above discussion, it can be seen that allotting subsets of channels to different cells ensures sufficient bandwidth-separation between the channels in a given cell. In a practical system, the exact number of subsets assigned to a cell would depend on the traffic to be handled in that cell. Similarly the number of channels used from a subset in a particular cell would depend on the traffic. This would also depend on the availability of spectrum and geographical features unique to the cell. A particular cell might experience greater interference on a particular channel in which case that channel may not be assigned to that cell. Grouping and numbering of channels are two aspects of frequency management. A number of different methods of assigning channels for handling calls are used in practical cellular systems. These methods are discussed in the next section.

4.2. CHANNEL ASSIGNMENT

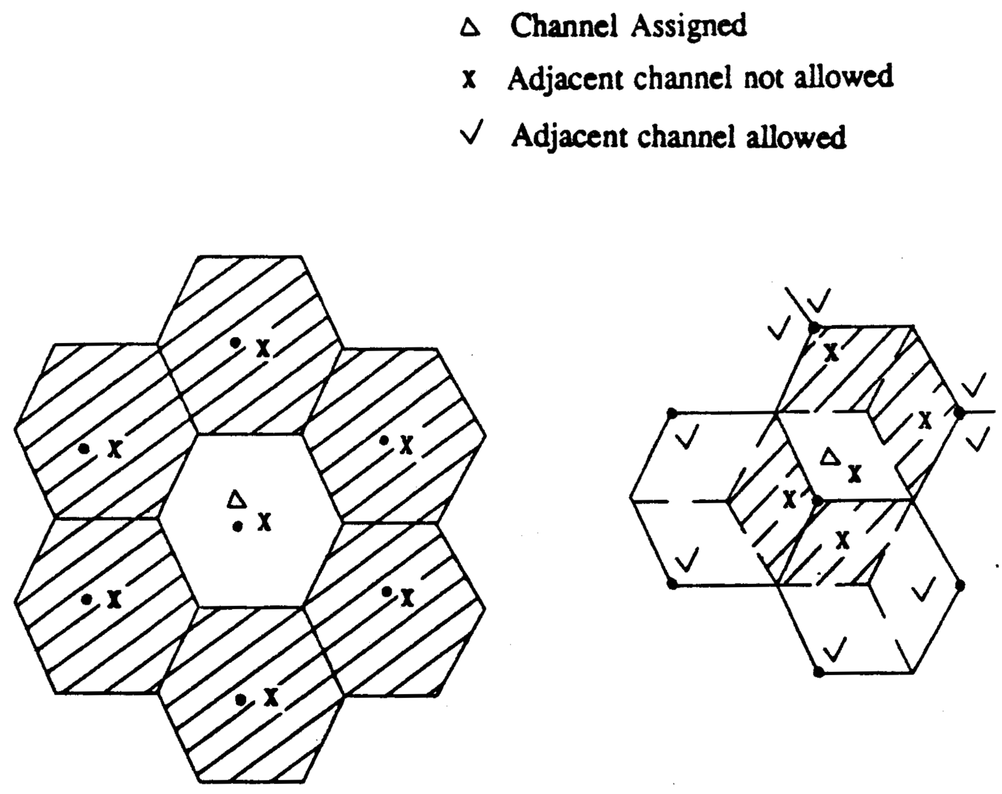
Mobile subscribers can use telecommunications facilities if a radio link is provided between the mobile and the cell-site in whose coverage area the mobile is located. This means that a set-up channel is required for setting up a call and voice channels have to be assigned to the mobile and the cell-site.

Channel assignment is done by the cellular system operator. While mobiles occupy channels on a short term basis (depending on the duration of the call) cell-sites are permanently assigned one or more subsets (depending on the traffic in that cell). The MTSO governs which channel (i.e., a pair of carrier frequencies) would be used by the mobile and cell-site in handling a call. Ideally, channel assignment should be done such that there is minimum interference in the system. Both fixed and non-fixed channel assignment methods may be used in practice.

4.2.1. Fixed channel assignment

In this scheme, channels are allocated to the cells on a permanent basis, i.e., specific channels are allocated to specific cells. In directional cells (cells with sectorized coverage patterns), each sector is assigned a particular subset of channels. Some aspects of fixed channel assignment are considered next.

Adjacent-channel assignment: In a cellular system, the assignment of adjacent channels has to be carefully made depending on whether the cell has omnidirectional or directional coverage. Figure 4.2 shows how the assignment of adjacent channels is made. If one channel is assigned to the middle cell of seven cells, adjacent channels cannot be assigned to the same cell. Also, no adjacent channels should be assigned in the six neighbouring



(a) (b)

Figure 4.2: Adjacent channel assignment.

(a) Omnidirectional-antenna cells;
(b) directional-antenna cells; (from [3]).

sites in the same cell-cluster. In a directional-antenna cell system the cells are sectorized. Three sectors per cell is most common. If one channel is assigned to a sector, the next channels cannot be assigned to the same sector or to the other two sectors in the same cell. However, as shown in Figure 4.2(b), adjacent channel may be assigned to certain sectors of the neighbouring cells.

Channel sharing: Channel sharing is a method that allows short-term relief to cells experiencing congestion. A scheme of channel sharing for a seven-cell three-sector system is shown in Figure 4.3. For a 20 MHz bandwidth system there are 21 channel sets, with each set consisting of about 16 channels. Each cell-site transmits in three 120-degree

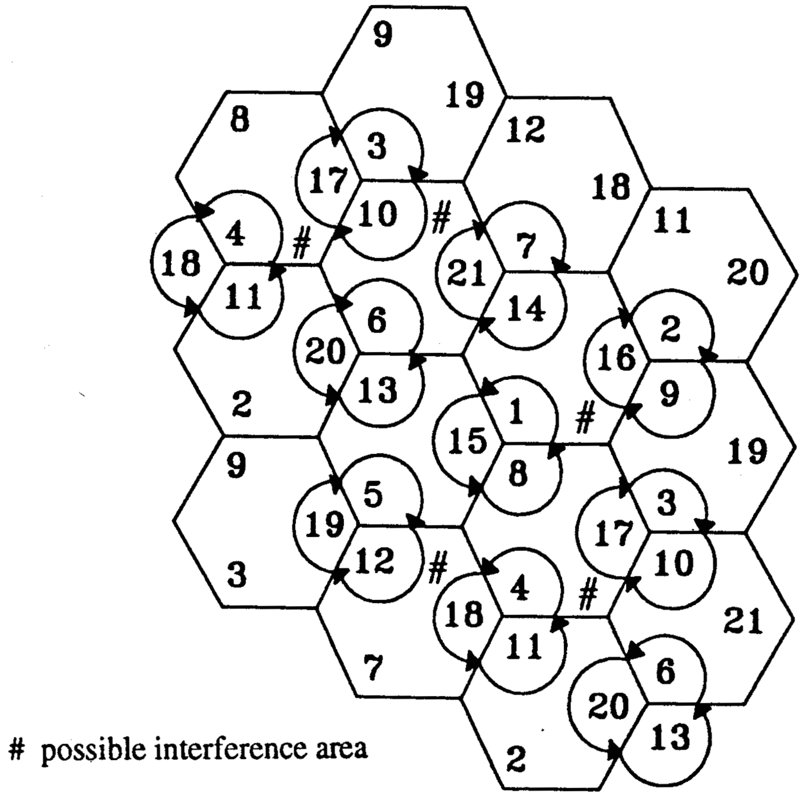


Figure 4.3: Channel-sharing algorithm; (from [3]).

sectors. From Figure 4.3, a cell-site transmits on channel set numbers 5, 12 and 19. When a cell needs more channels, the channels of another face at the same cell-site can be shared to handle the short-term overload. Sharing always increases the trunking efficiency of channels. Since we cannot allow adjacent channels to share with the nominal channels in the same cell, channel sets 4 and 5 cannot both be shared with channel sets 12 and 18.

The grid marks (shown by #) indicate the possible interference areas if adjacent channel sets are used. However, the upper subset of set 4 can be shared with the lower subset of set 5 with no interference. Channel combiners are used in the cell-site transmitter to combine signals for different channels before feeding to the antenna. In channel-sharing systems, the channel combiner should be flexible so that it can combine up to 32 channels in one sector.

Sectorization: There are generally three sector configurations in cellular networks: the 120 degree sector system, the 60 degrees sector system, and the 45 degrees sector system. A seven-cell system usually uses three 120 degrees sectors per cell. The total number of available channels can be divided into sets (subgroups) depending on the sectorization of the cell configuration. In a seven-cell system with sectors of angles 120 degrees, there are a total of 21 channel sets. Further details of this method can be found in [3, p.310].

4.2.2. Non-fixed Channel Assignment

There are different ways in which non-fixed channel assignment can be realized. Two most common methods are described below.

Dynamic channel assignment: In the fixed channel assignment method, a set of channels is permanently assigned to a cell and communication within that cell can only be carried out on those channels. This is not the case in dynamic channel assignment. In this method no fixed channels are assigned to any cell in a system. Any channel from the 312 voice channels can be assigned to the mobile unit. Dynamic channel assignment takes into consideration the overall system performance. Different algorithms may be employed to implement this type of channel assignment. These algorithms are designed to keep congestion low and interference to a minimum.

Hybrid Channel assignment: As stated in Chapter 3, this method is a combination of the fixed assignment method and the dynamic assignment method. A portion of the total frequency channels is assigned to the cells in the usual fixed channel assignment method and the rest is available for use in a dynamic way.

In this thesis, the blocking performance of a SaskTel thin cellular network is compared using fixed and dynamic channel assignment methods. The dynamic channel assignment algorithm used is described in the next section.

4.3. DYNAMIC CHANNEL ASSIGNMENT ALGORITHMS

In dynamic channel assignment, cells are initially assigned a group of channels on a non-fixed basis. If the call can not be served using the group of channels assigned to its host cell, a search is made for a free channel in the neighbouring cells. If a free channel is found, the call is assigned to that channel. This implies that a call in a cell can be served by a channel even if the channel was not originally assigned to that cell. Such a channel is commonly referred to as a "borrowed" channel. This is not possible in the case of fixed assignment where calls in a cell can only be handled by channels assigned to that cell. The temporary assignment made in the case of dynamic assignment is referred to as nominal channel assignment.

The borrowing of channels, to serve calls during congestion, may be performed in different ways depending upon how the search is made for a free channel. In the simplest case, the first free channel searched from the neighbouring cell could be borrowed. Anderson has studied three dynamic channel algorithms [16]. In this thesis a simulation model using algorithm 2 has been developed. The complete algorithm is shown in Figure 4.4. Before the rationale behind this choice can be explained, it is important to introduce terminology commonly used in describing dynamic assignment. This terminology is introduced below.

Nominal channels: given a cell, those channels nominally assigned to it are called nominal channels.

Nominal cells: given a channel, those cells to which it is nominally assigned are its nominal cells.

Interferable cells: given a cell, any other cell with which it will interfere (the two cells are assigned the same channels and are in closer proximity than the minimum reuse separation) is one of its interferable cells. Note that there may be more than one interferable cells because of frequency reuse.

In the algorithm of Figure 4.4, if a cell doesn't have a free channel to host a call, a search is made in all its neighbours for free channels. If a channel is found free (say, A) in the first neighbouring cell, the nominal cells of that channel are determined. If these nominal cells are found to be interfering cells to the cell hosting the call, the number of free channels in each of these interfering cells is determined and the lowest number of free channels is stored in the variable 'min'. This value of 'min' is also stored in the variable 'max'. The identity of the channel (A) is also stored. A similar search is carried out for the second channel (say, B) of the same neighbouring cell. The lowest number of free channels in the interfering cells obtained in this case is again stored in 'min'. If the new value of 'min' is greater than 'max' (which had the value of 'min' corresponding to channel A), then this new value is assigned to 'max' and channel B is considered as the best channel so far. The variable 'max' stores the largest value of 'min', i.e., it stores the largest value of the free nominal channels available in the interfering cell that has the least number of free channels. The search is carried out for all the free channels of all the neighbouring cells. In the end, the channel corresponding to the contents of 'max' is the channel assigned for borrowing. The basic idea behind the algorithm is to ensure that when a channel is borrowed, interfering cells to the host cell (using that channel) have

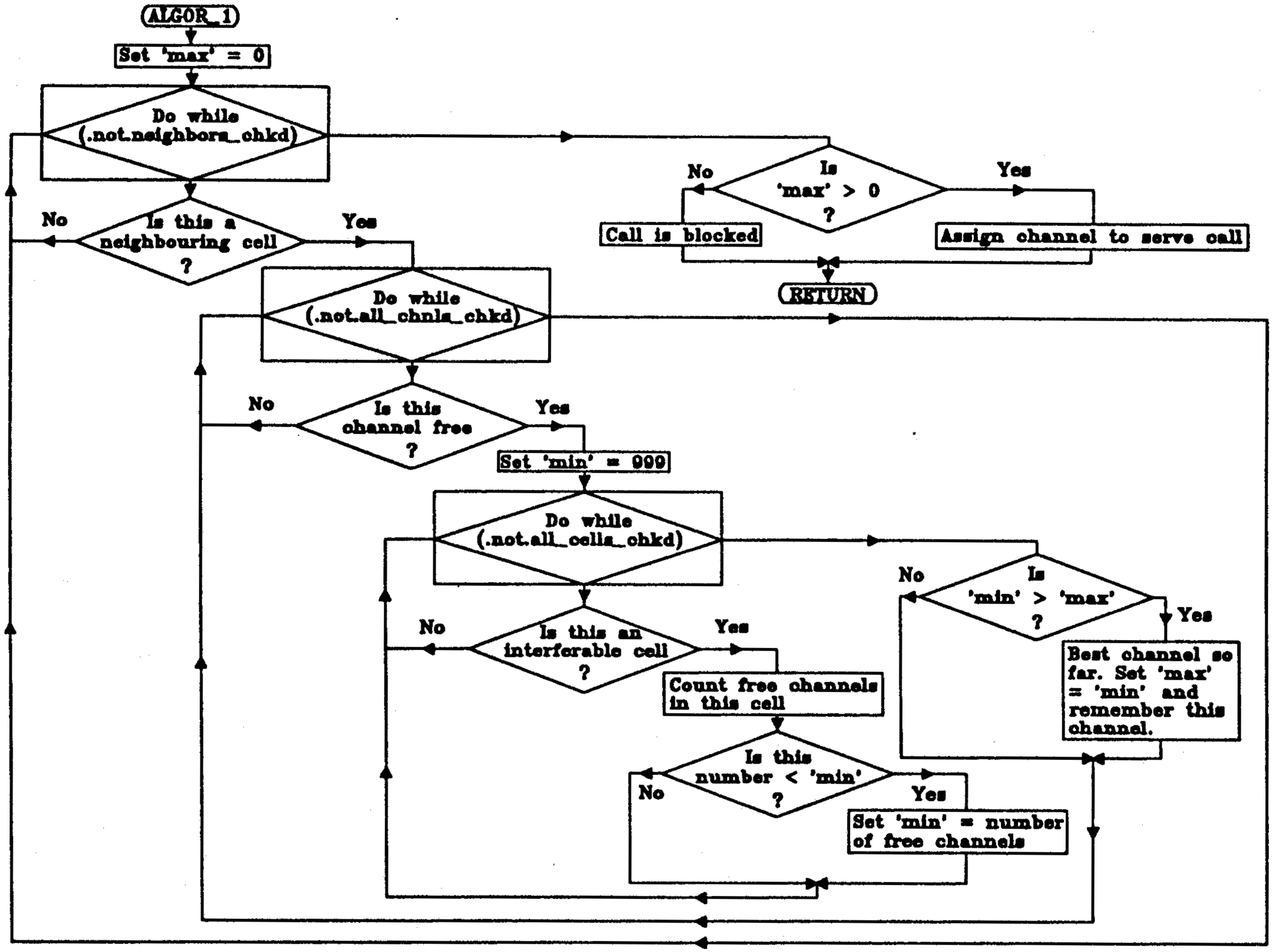


Figure 4.4: Dynamic Channel Algorithm (from [16])

minimum blocking probability. Hence this dynamic channel assignment algorithm assures that borrowing of channels from neighbouring cells by the cells experiencing congestion is done with minimum future blocking as a result of this borrowing.

5. SIMULATION USING DYNAMIC CHANNEL ASSIGNMENT

In the previous chapters, basic operational concepts of a cellular network were described. In Chapters 2 and 3, commonly used terminology for cellular systems was presented. Frequency management and channel assignment methods as well as the dynamic channel assignment algorithm were discussed in the previous chapter. In this chapter the simulation model itself is developed.

To perform a simulation study of any cellular network, the dynamics of the cellular network have to be incorporated in the simulation model. One of the main characteristics of a cellular network is that subscribers are mobile. This factor complicates the modelling. Voice channels have to be assigned/de-assigned when a mobile enters a new cell. As there is a radio communication link between the mobile and the base station, the motion of the subscriber may result in a situation in which this link may be temporarily or permanently broken due to a natural or man-made obstruction. For example, the subscriber may be traversing through a mountain or a crowded downtown area surrounded by tall buildings which may affect or destroy the link. The impact of these disturbances in the communication link on the processing load of the system controller (at MTSO) could be quite large. Channels may frequently have to be assigned/de-assigned by the mobile/base station to keep the communication link strong.

Another characteristic of the cellular network is that the probability of a subscriber engaging in a telephone call depends upon factors like road vehicular traffic, geographical terrain through which the mobile is traversing, time of the day, etc. A subscriber would be least expected to talk on the mobile phone when traversing a very difficult terrain. On the other hand, the probability of the subscriber engaging in a telephone conversation may be safely considered to be much higher when the subscriber is held up in a traffic-jam. These factors also have an impact on the duration of the call.

A complete analysis of a cellular network has to take into account all of the above mentioned details. However, to examine the impact of each of these, not all the factors have to be necessarily incorporated at the same time. This reduces the complexity of the model without compromising the accuracy significantly. This approach was adopted in the simulation model described below.

As the dynamic assignment makes much better use of the available channels, it is expected that the blocking probability using this method will be considerably better than that for a fixed assignment. Blocking probability is the most important performance criterion. Another useful performance measure is the occupancy statistics of the channels. These statistics refer to the time for which channels in different cells are busy. The simulation model developed in this thesis is used to obtain occupancy of channels expressed as a percentage of the total time during which the calls were processed. Using the simulation model, handoff statistics were also obtained along with the channel occupancy cumulative distribution. The simulation model itself along with the various assumptions is described in the next section.

5.1. SIMULATION MODEL

To develop a realistic simulation model, some basic characteristics of the mobile cellular network have to be incorporated in the model. These characteristics are discussed below. Also, some simplifying assumptions have to be made. These assumptions are outlined later in this section. For the purpose of simulation, it is necessary to consider

(1) Traffic of the network

(2) Call-arrival instants

(3) The cell hosting the call

(4) The number of channels available in the cells

(5) The random location of the mobile

(6) The mobile's direction of travel

(7) Average mobile velocity

(8) Call duration.

Also, the sequence in which various events occur has to be properly simulated. All of the above factors are briefly discussed in sections 5.2.1 to 5.2.6 below.

5.1.1. Network traffic and system layout

SaskTel's cellular network is a thin (low volume traffic) network, i.e., the population density of the network is less than the population densities of networks in metropolitan areas like New York, Los Angeles, Toronto, etc. The populations of the existing cells of SaskTel's cellular network were arrived at using Census Canada statistics. Eight mobile subscribers per thousand people were assumed. A total of thirty cells were considered for the simulation. Figure 2.1 gives the layout of the system and Table 2.1 shows the reuse plan. Table 5.1 gives the population of each cell. The thirty cells are arranged in a 7-cell reuse plan. Table 2.1 gives the cells in their respective frequency-reuse groups. In this simulation, cells that are relatively dense have been placed in the centre. The model considers handoff of calls when mobiles enter a new cell. It is reasonable to assume that most of the traffic flow will be "from" and "to" the denser cells. Thus the arrangement where the denser cells are in the centre of the layout represents a realistic scenario.

It is also assumed that the voice traffic between mobiles is negligible, and mobiles either receive calls from sources external to the system (e.g. a landline subscriber) or initiate calls to destinations external to the cellular system.

5.1.2. Call-arrival (initiation) rates

It is well known that calls arrive or originate with a Poisson distribution and the call duration is an exponentially distributed random variable [20]. If A is the average number of call arrivals per unit time then the probability P_x that x calls originate/arrive during a specified time T is given by:

$$P_x = \frac{(AT)^x e^{-AT}}{x!} \quad . \tag{5.1}$$

The probability that the next call originates after time t is given by:

$$P\,(\text{time before next call occurs} > t) = e^{-At} \; . \tag{5.2}$$

So that the probability that the next call occurs within a time interval t is given by:

$$P\,(\text{ next call occurs before time} \leq t\,) = 1 - e^{-At} \; . \tag{5.3}$$

The cumulative distribution function F_c of inter-arrival time t is given by:

$$F_c\,(t) = 1 - e^{-At} \quad . \tag{5.4}$$

Therefore the probability density function for t is given by:

$$f(t) = \frac{dF_c(t)}{dt} = Ae^{-At} \quad . \tag{5.5}$$

This is the negative exponential distribution. This implies that while calls arrive with a Poisson distribution, the intervals between call arrivals are exponentially distributed.

The mean time interval between call arrivals can be calculated as

$$\text{mean } t = \int_{t=0}^{\infty} t\, A\, e^{-At}\, dt \quad . \tag{5.6}$$

Number of calls and the call durations have the same probability distribution for a cellular system.

5.1.2.1. Host cell

Call-arrival rate in each cell depends on two factors:

1. The traffic volume

2. The subscriber population.

Table 5.1 gives the population statistics of the SaskTel network. The table shows the population of each cell arranged in ascending order. Column 4 shows the cumulative proportion of each cell's population. To account for the subscriber population variation in each cell, weights were determined for each cell. The weights were calculated by dividing the cumulative proportion of each cell by the average of the cumulative proportions of the 15th and 16th cell. This is done merely to obtain approximately unity weights for cells in the middle of the table. In effect, the weights are proportional to the cumulative proportion. These weights are arranged in the last column of the table. To arrive at the cell's call-arrival rate, the weight of the cell was multiplied by a constant. The value of this constant was increased as the traffic is increased.

Table 5.1: Population statistics of the network

Cell Number	Population	% of Total Population	Cumulative Proportion	Weight
2	6	0.14	0.14	0.23
10	6	0.14	0.28	0.23
6	8	0.19	0.47	0.31
23	12	0.29	0.76	0.46
15	15	0.36	1.12	0.58
22	15	0.36	1.48	0.58
1	15	0.36	1.84	0.58
4	16	0.39	2.23	0.62
7	16	0.39	2.62	0.62
17	18	0.43	3.05	0.69
25	20	0.48	3.53	0.77
8	21	0.51	4.04	0.81
30	21	0.51	4.55	0.81
9	23	0.55	5.10	0.88
26	24	0.58	5.68	0.92
13	28	0.68	6.36	1.08
3	29	0.70	7.06	1.12
14	31	0.75	7.81	1.19
16	33	0.80	8.61	1.27
11	37	0.89	9.50	1.42
29	71	1.71	11.21	2.73
18	93	2.24	13.95	3.58
19	109	2.63	16.58	4.19
24	128	3.09	19.67	4.92
28	150	3.62	23.29	5.77
21	283	6.83	30.12	10.88
27	720	17.37	47.49	27.69
12	722	17.41	64.90	27.77
5	736	17.75	82.65	28.31
20	740	17.85	100.0	28.46

For all the new calls, a method to determine the cell hosting the call as well as the call origination instant is needed. To determine the cell hosting the call, a pseudorandom number between 0 and 100 is generated from the uniform distribution. This number lies in the 0-100 range of cumulative proportion in Table 5.1. The corresponding cell in the first column of this table is designated as the host cell.

The inter-arrival time is the inverse of call-arrival rate. An exponentially distributed pseudorandom number is generated and multiplied with the mean inter-arrival time to obtain the inter-arrival time for the next call. From this, the instant when the next call arrives/originates is determined.

5.1.3. Mobile initial location and direction of travel

The mobile can be located anywhere in the cell and could be moving in any direction. To model this characteristic of a cellular system, a few simplifications have been made. First, the cell was approximated to a circle as shown in Figure 2.4. The cell radius varies for different cellular systems. For SaskTel's network the cell radius is approximately 12 miles. If the centre of the circle in Figure 2.4 represents the origin then the x-coordinate of the mobile's position would satisfy the condition

$$-12 \leq x \leq 12 \quad . \tag{5.7}$$

The variable x was determined using a pseudorandom number with uniform distribution scaled to satisfy the above condition. Once the x-coordinate is fixed, the y-coordinate was similarly determined using a pseudorandom number with uniform distribution which is scaled to satisfy the condition

$$-\sqrt{12^{2}-x^{2}} \leq y \leq \sqrt{12^{2}-x^{2}} \quad . \tag{5.8}$$

Another assumption made in the model was that the mobiles move only in four directions, namely North, South, East and West. This is a reasonable assumption as the SaskTel network consists of many highways and few urban areas. It may be assumed that the mobile user would not change the direction of motion till at least the duration of the call. The average mobile velocity was assumed to be 35 miles/hour.

5.1.4. Handoff

As mentioned before, the process of a mobile carrying over its call from one cell to another is called 'handoff'. When a handoff is made the mobile is assigned a free channel in the new cell. Thus the subscriber can carry on the conversation in a new zone of coverage without any perceptible break in communication link or difference in quality of service. This is one of the main features of the cellular system.

Whether or not a mobile experiences a handoff depends upon many factors. Cell radius, direction of travel of mobile, mobile velocity, rate of change of direction, call duration and initial location of mobile are some of the factors that determine the occurrence of a handoff. The probability of a handoff varies inversely with the cell radius and varies directly with the call duration and the mobile velocity.

The past number of changes of direction made by the mobile does not give any information about the future number of changes of direction the mobile would make. Thus, the process of mobiles changing their directions of travel is memoryless. Similarly, the information regarding the length of a subscriber's conversation up to an instant can be assumed to have no influence on the future duration of that conversation. Also, the duration of one call by a subscriber doesn't give any information about the duration of a future call by the same subscriber. All these processes can be assumed to be memoryless. Due to this, the distribution of the time spent by a mobile in a given cell is exponential. Based on these properties an expression for handoffs was presented in [15]. This expression relates the average number of handoffs per call to the cell radius, mobile velocity and mean call duration and is given by:

$$h = \frac{0.7182\, t\, v}{r} \quad ; \tag{5.9}$$

where h represents average number of handoffs per call, t represents mean call duration in minutes, v represents the average mobile velocity, and r represents cell radius. The complete derivation of this result can be found in [24].

Handoffs in a cellular network determine the control channel loading and the processing load on MTSO. These are important parameters in the design of any cellular network. A higher handoff-rate would create a greater processing load and require more control channels.

In this simulation model it was assumed that the communication link between the mobile and the base station is not affected or destroyed while the mobile is in the cell in which the call originated/arrived. When a mobile is in the process of leaving the boundaries of its parent cell (i.e., the cell in which its call originated), the determination of the cell to which the mobile would make a handoff could be computationally complex. This is due to the geometry of the hexagonal cell. Except for the cells on the edges, each boundary (side) of a cell (hexagon) in the cluster is also a boundary (side) of another cell (hexagon). Even though only four directions of travel have been assumed, the mobile could exit a cell from any of the three boundaries in the East-West directions and any of the two boundaries in North-South directions. This depends upon its random initial location. To simplify the analysis, mobiles were assumed to move into the densest of its neighbours in the direction of its motion. Since in the dynamic assignment system, a call arriving (or originating) in a cell could be assigned a channel from another cell (using the selected dynamic assignment algorithm), it is quite possible for a mobile to have its call on the same channel before and after the handoff.

Cells which are on the edges of a coverage area do not have a neighbour in at least one of the four directions. Mobiles moving in these directions and crossing the cell boundaries would experience blocking on their calls in the new cell. The simulation model can also be used to obtain the number of handoffs and calls blocked after handoffs. The system was considered to be a "lost calls cleared" system implying that calls that are unable to seize channels are lost and do not remain (in queues) in the system.

5.1.5. Channel occupancy

Channel occupancy time is dependent on two events. A channel can be freed either when there is a call termination (voluntary or due to any fault in the system) or when the mobile leaves the cell during the progress of the call. In [15] it has been assumed that total service time and mobile motion are independent, i.e., the vehicle motion has no influence on the call duration.

Based on this memoryless nature, total call duration as well as the time spent by a mobile in the cell are considered to be exponentially distributed. It has been shown in [15] that the channel occupancy time is also exponentially distributed of the type $Ae^{-\theta t}$. Based on the above considerations, the two parameters θ and η may be defined as:

$$\theta = \eta + \mu \tag{5.10}$$

and $$\eta = h\,\mu \;; \tag{5.11}$$

where $1/\eta$ denotes the average time spent in a cell by a mobile, $1/\mu$ denotes the average call duration and h denotes the average number of handoffs. Equations 5.10 and 5.11 define the parameter θ in the exponential distribution.

From this model, channel occupancy statistics can be obtained for all the channels of all the cells. Time samples during which different channels are busy can also be obtained. For example, it is possible to find out how many times channel A of cell 3 was busy for continuous durations of 5 minutes, 7 minutes etc. This information can be used to compute average channel utilization and is very useful to system operators. It can be used to estimate the expected revenue. Further, it can be used in conjunction with other information such as the blocking probability to optimize the network.

5.1.6. Event protocol

The simulation comprises of three different events. These events are call-arrival, call-departure, and handoff. Only integer inter-arrival times and call durations were considered (i.e., an inter-arrival time of 1.234 was taken as 1). Thus, the time difference between the instants at which different events take place would be 0, 1, 2, 3, .. etc. The simulation is a discrete event simulation and not continuous-time. For example, if one event occurs at time 10 and the next event at time 25 then the clock in the simulation proceeds from time 10 to 25 skipping the intermediate intervals.

The event protocol is such that if the arrival of one call and the termination of another call occur at the same time, call termination will be processed first. Similarly, if a new call-arrival and a handoff of another call occur simultaneously, handoff is processed first.

5.2. FLOWCHART AND COMPUTER PROGRAM

The flowchart of the simulation program is given in Figure 5.1. The coded program is given in the Appendix. The coding was done in VAX FORTRAN 77 V5.5. The file 'common.inc' contains all the global variables of the program. The variable names were chosen, as far as possible, to be indicative of their function. The Random Number Generators were taken from IMSL library. The program consists of different subroutines. The three main events in the program are:

1. Call-arrival
2. Call-departure
3. Handoff.

Information related to call arrivals and handoffs are updated in their respective subroutines. Information regarding call departure and handoff instants is arranged in queues in chronological order. This allows the simulation to proceed in a logical sequence. The simulation starts with no calls in the system and with all channels in all cells free. Data files provide information regarding channels in cells, neighbouring cells to each cell, cells to which mobiles make handoff when travelling in a particular

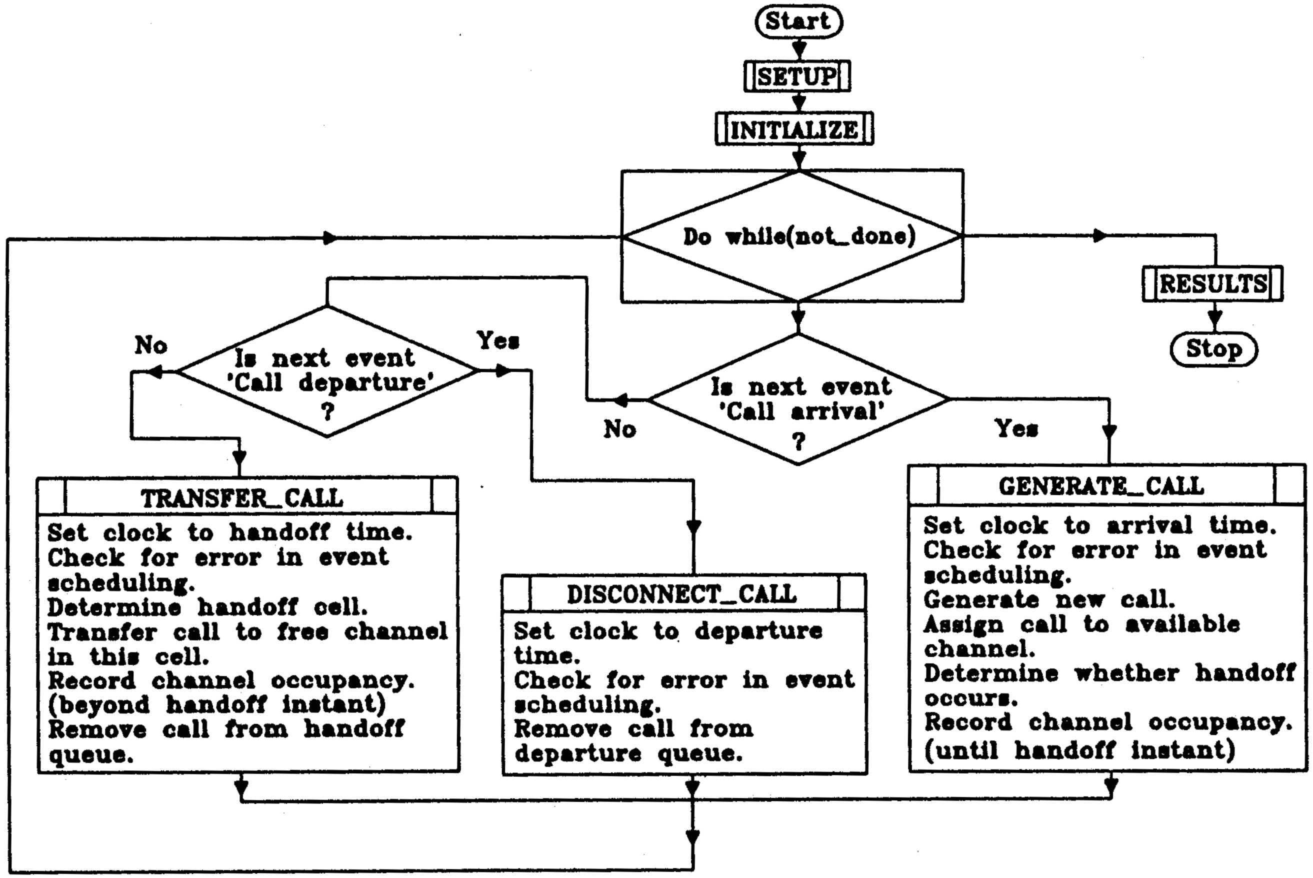


Figure 5.1: Flowchart for the simulation program

direction, and populations of different cells.

The main input variables to the program are:

1. Number of calls to be processed
2. Cell radius
3. Mean call duration
4. Average mobile velocity
5. Channels allocated to different cells
6. Multiplication factor (to get different traffic values) using the weights in Table 5.1

The program provides information regarding:

1. Blocking probability
2. Number of handoffs
3. Number of calls blocked after handoffs due to
    (a) no channels in the cell to which handoff is made
    (b) no neighbour of the previous cell (from which the mobile made handoff) in the direction of mobile's travel
4. Channel occupancy in all channels of all cells

Using different values for the input variables a wide range of information may be obtained from the program. The effect of variation in each parameter may be studied. The results obtained from the simulation are presented in the next chapter.

6. RESULTS

A simulation using FORTRAN was employed to obtain the results for the simulation model described in the previous chapter. The network layout is shown in Figure 2.1. Ten thousand calls were processed. Channels in individual cells, mean call duration, arrival rate, cell radius and average mobile velocity were the input variables to

Table 6.1: Channel assignment for the network

Cell no.	Channels	Cell no.	Channels	Cell no.	Channels
1	3	11	4	21	5
2	3	12	8	22	3
3	4	13	4	23	3
4	3	14	4	24	5
5	8	15	3	25	3
6	3	16	3	26	3
7	3	17	3	27	8
8	4	18	4	28	5
9	4	19	5	29	4
10	3	20	8	30	3

the computer program. The results obtained in this chapter have been grouped under different headings; namely, blocking probability variation, handoff rate and channel occupancy. The number of channels in each cell are as shown in Table 6.1.

6.1. BLOCKING PROBABILITY VARIATION WITH TRAFFIC

Simulation was performed using a cell radius of 12 miles, average mobile velocity of 35 miles/hour and mean call duration of 2 minutes.

In the first case, simulation was performed for non-uniform traffic using Fixed Channel Assignment. The flowchart for this assignment method is presented in Figure 6.1. A starting value of 1.0 was chosen for the multiplication factor. This was used to compute the initial traffic for each cell. Traffic was increased by fixed increments of 10% and the corresponding blocking probabilities were obtained.

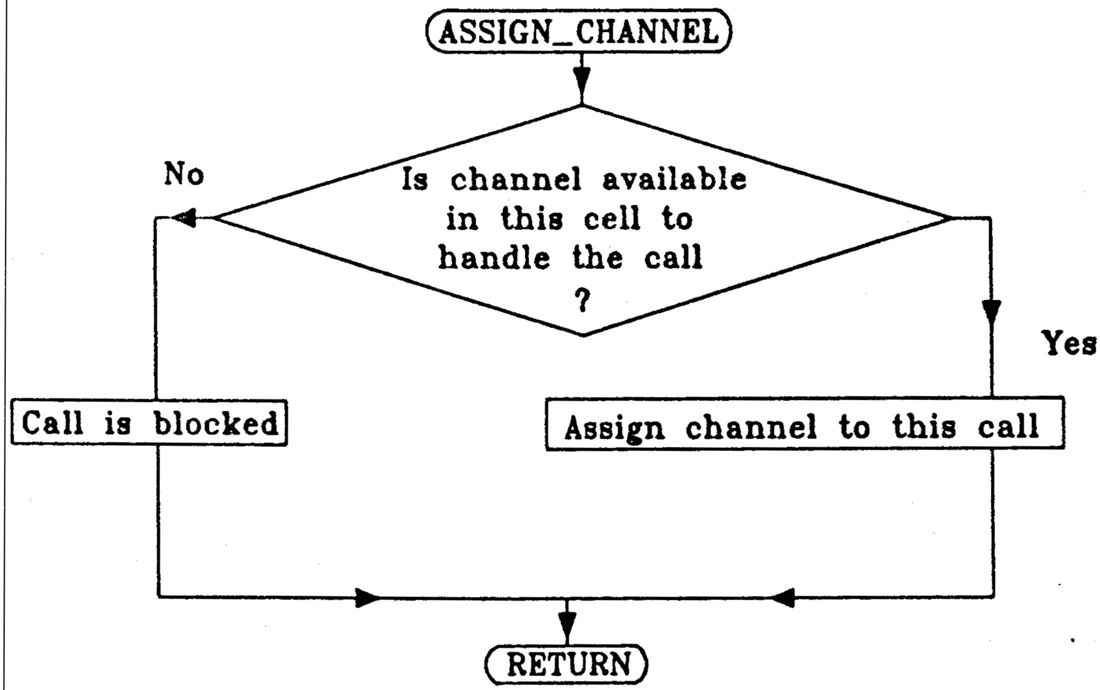


Figure 6.1: Flowchart for Fixed Channel Assignment

Next, for the same network and traffic values, simulation was performed incorporating Dynamic Channel Assignment. The flowchart for Dynamic Channel Assignment is shown in Figure 6.2. The algorithm used for channel assignment is presented in Figure 4.4.

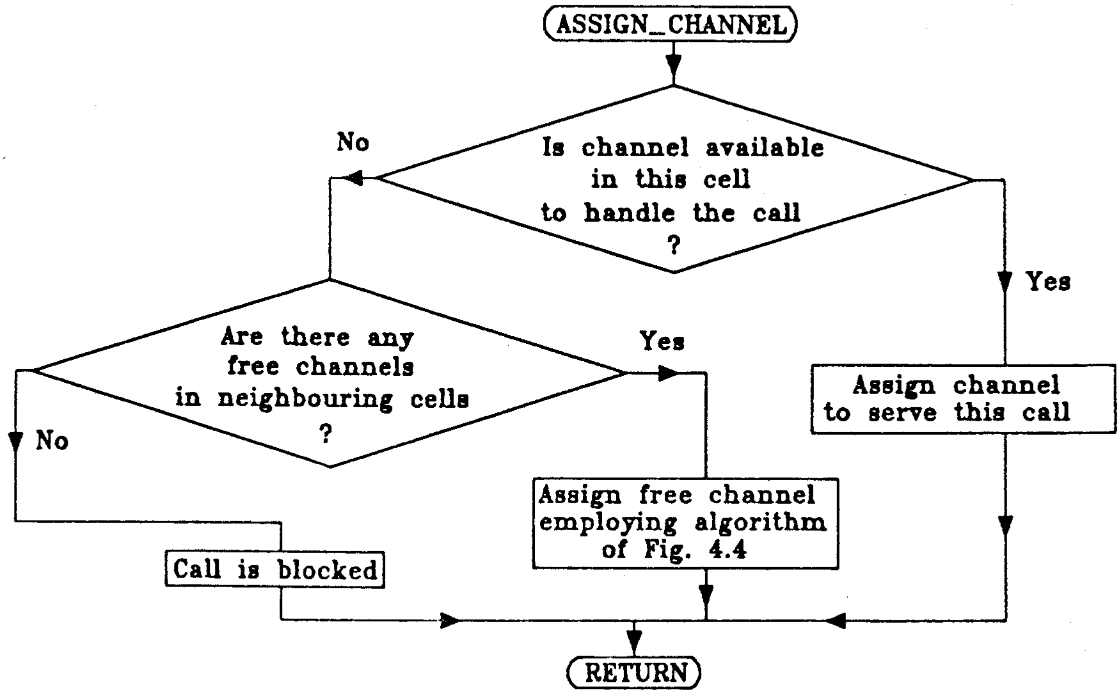


Figure 6.2: Flowchart for Dynamic Channel Assignment

The blocking probability variation is plotted in Figure 6.3. It may be seen that a significant improvement in blocking probability is achieved when Dynamic Channel Assignment is employed. The increase in blocking probability with increasing traffic is at a much lower rate for Dynamic Assignment than that for Fixed Assignment.

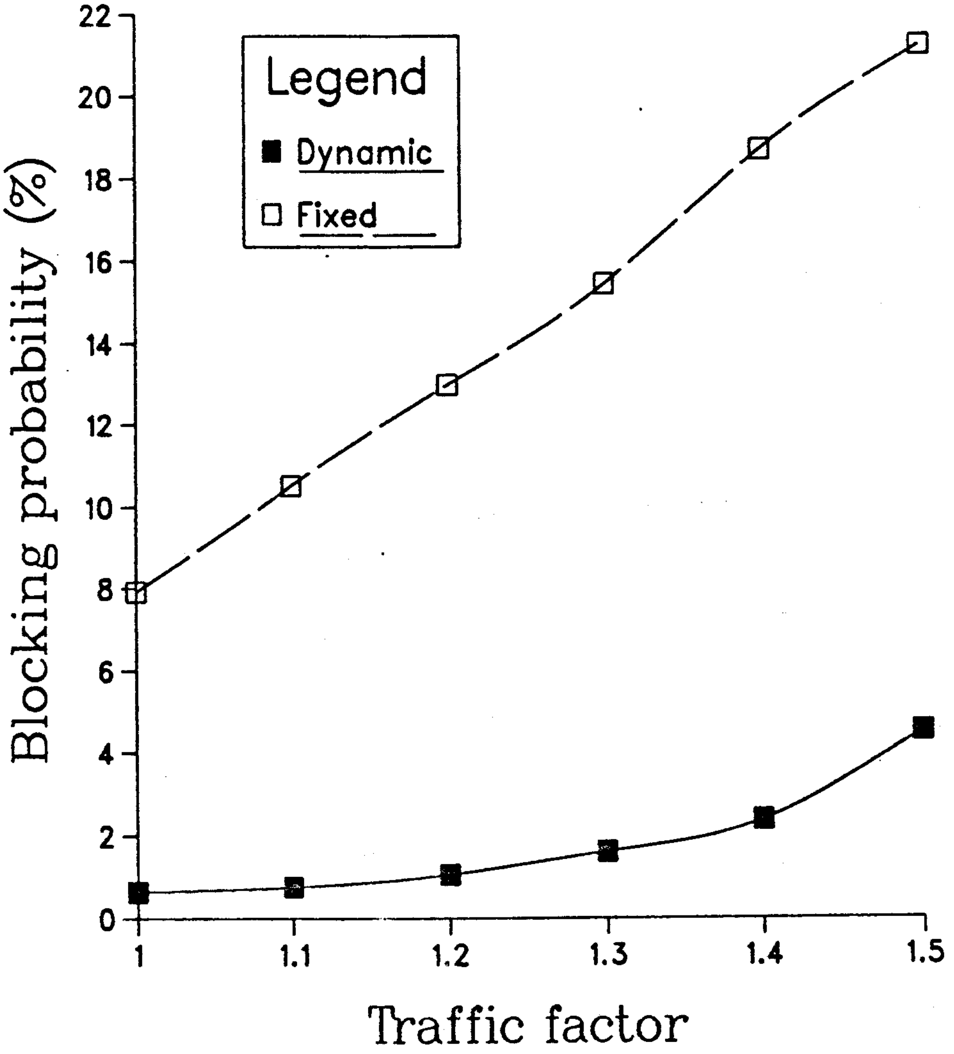


Figure 6.3: Blocking probability variation with traffic (non-uniform traffic in cells).

The case of uniform traffic in all cells is considered next. Four channels are assigned per cell, with each cell having the same population (i.e., the weight of each cell is equal to 1.0). Blocking probability variation with traffic was obtained in exactly the same way as for the non-uniform case. In this case, the traffic corresponding to a multiplication factor of 3.0 has been considered as base traffic. The results are shown in

Figure 6.4. As can be seen, the blocking variation for the two cases shows almost the same rate of increase. A comparison of Figures 6.3 and 6.4 shows that the improvement in blocking performance using Dynamic Channel Assignment is more significant for thin cellular networks when the traffic is non-uniform.

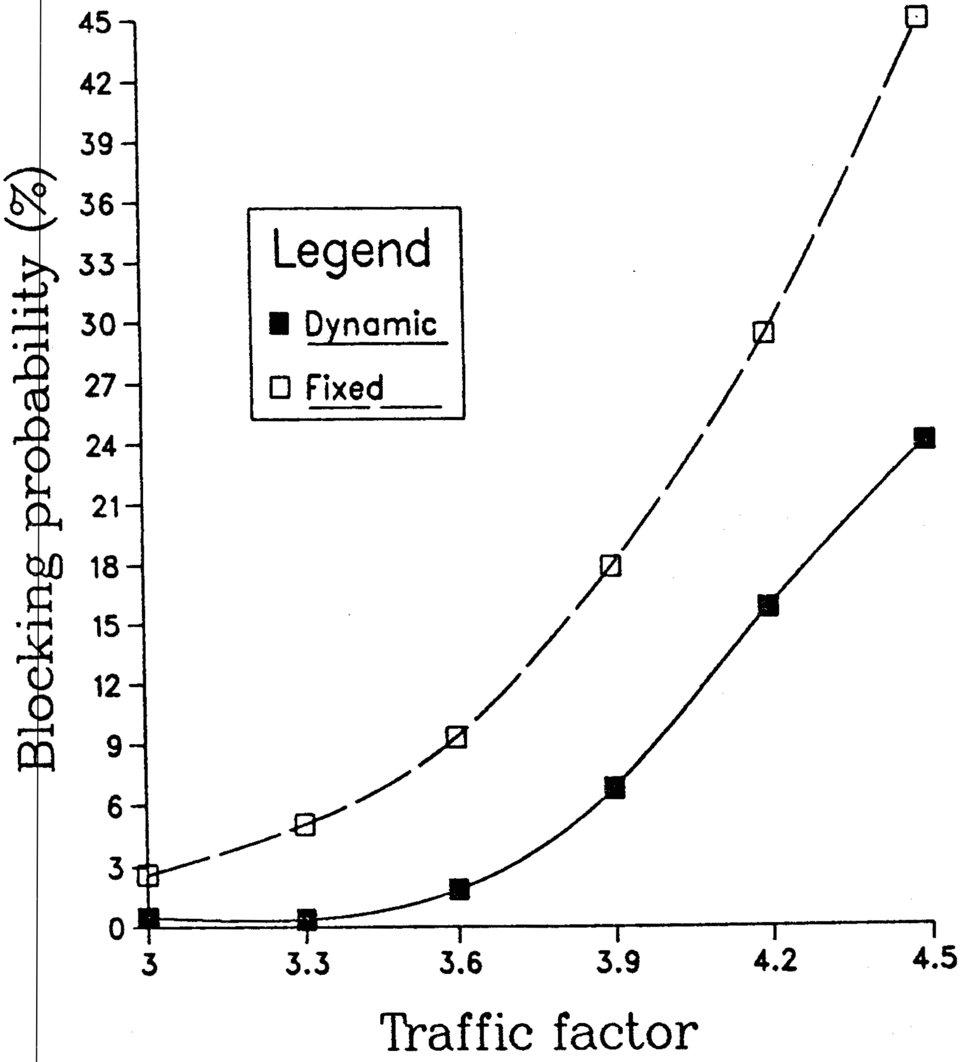


Figure 6.4: Blocking probability variation with traffic (uniform traffic in cells).

The improvement in blocking probability using Dynamic Channel Assignment implies that fewer channels would be required by the network to provide the same grade of service as the Fixed Channel Assignment. This results in high spectrum efficiency.

As is evident from the Dynamic Channel Assignment algorithm of Figure 4.4, each cell must have more radio equipment so that more channels can be accommodated at each site. This increases the network equipment cost. To reduce this requirement of radio equipment, without losing much of the advantage of Dynamic Channel Assignment, an algorithm that restricts the number of channels in a cell assigned for borrowing is attractive. Such an algorithm is called Restricted Dynamic Channel Assignment Algorithm (RDCAA). The flowchart for RDCAA is given in Figure 6.5.

RDCAA (subroutine ALGOR_2) searches the first available assignable channel from a neighbouring cell and dedicates this channel to the call arriving/originating in the busy cell. The elaborate search in the algorithm of Figure 4.4 has been deliberately avoided as the borrowed channels could have a provision of being reassigned. These channels are used for a short period by the borrowing cell, and a detailed search for ensuring minimum co-channel interference is therefore not necessary.

RDCAA allows only the designated subset of the channels assigned to a cell for borrowing. The channel(s) within a cell that is/are designated for borrowing can be chosen

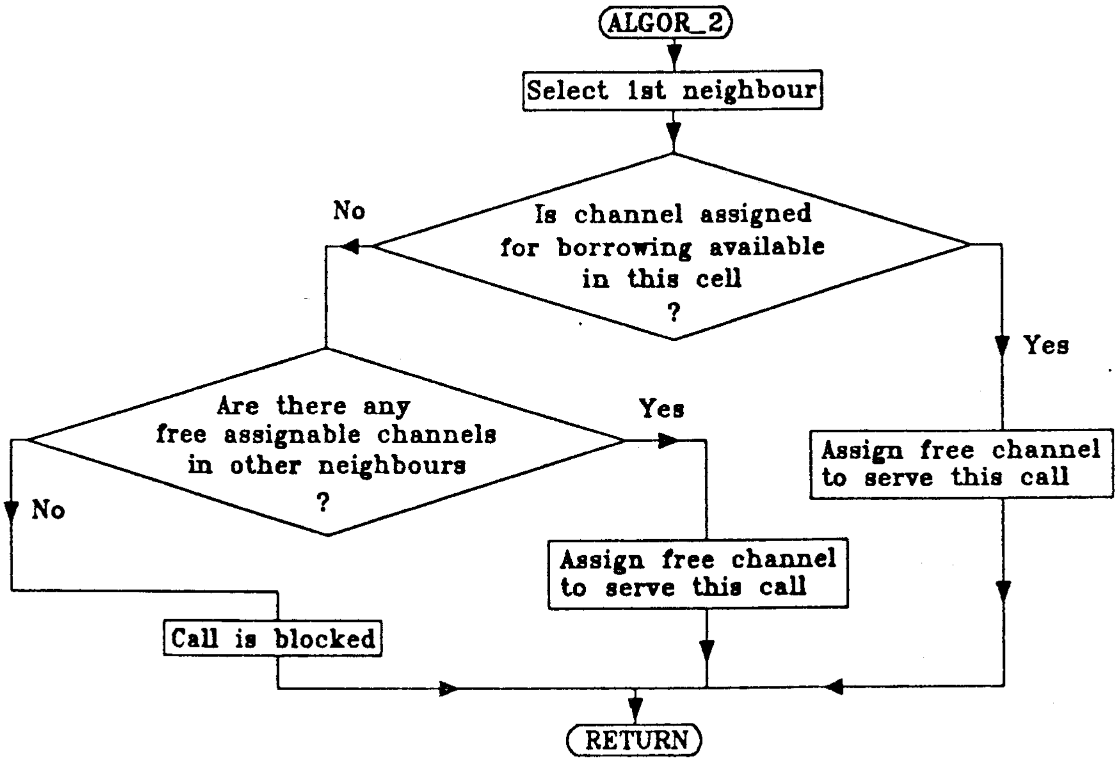


Figure 6.5: Flowchart for Restricted Dynamic Channel Assignment

beforehand by the network operator. When only specific channels are assignable for borrowing, the radio equipment of any cell needs only the capability to tune to the assignable channels of its neighbouring cells. This can result in substantially reduced volume of radio equipment.

Since the channels that can be assigned for borrowing are restricted, the algorithm may employ reassignment of channels for calls in progress within a cell to keep these channels free for making them available for borrowing. For example, if a cell has a call termination on one of its non-assignable channel (say, A) and it already has a call on a borrowed channel (i.e., an assignable channel of one of its neighbouring cells), then the call on the borrowed channel will be reassigned to the non-assignable channel (A). The borrowed channel will be freed. This channel could be used for borrowing again.

Figure 6.6 shows the difference introduced in the simulation when RDCAA is used

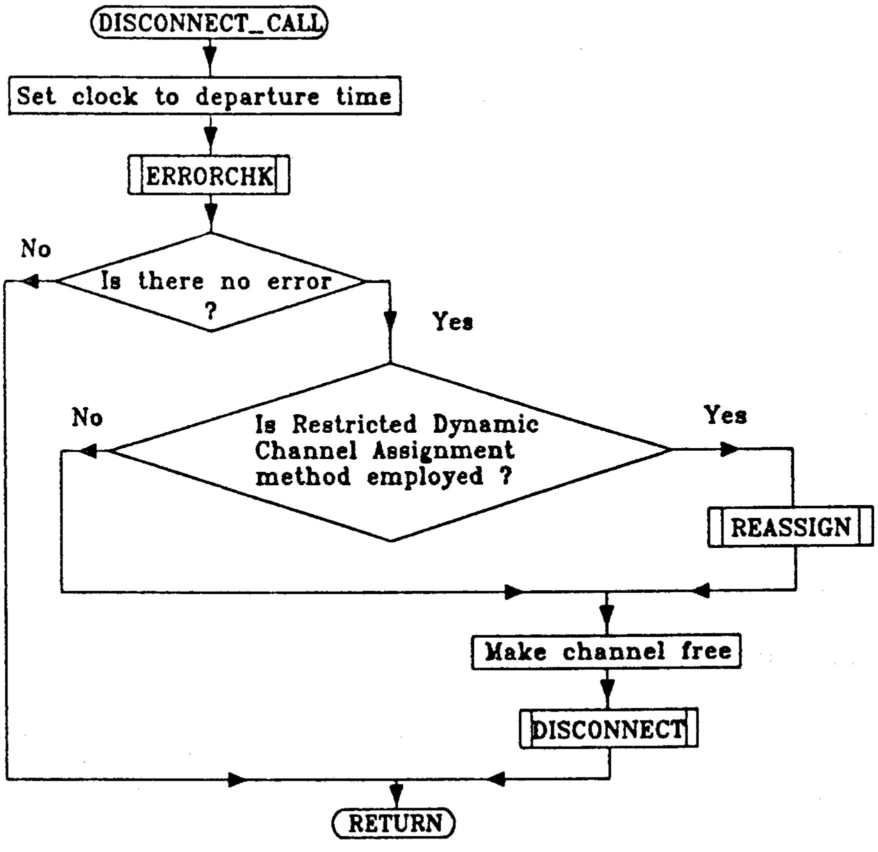


Figure 6.6 (a): Simulation procedure for employing reassignment during a call-departure

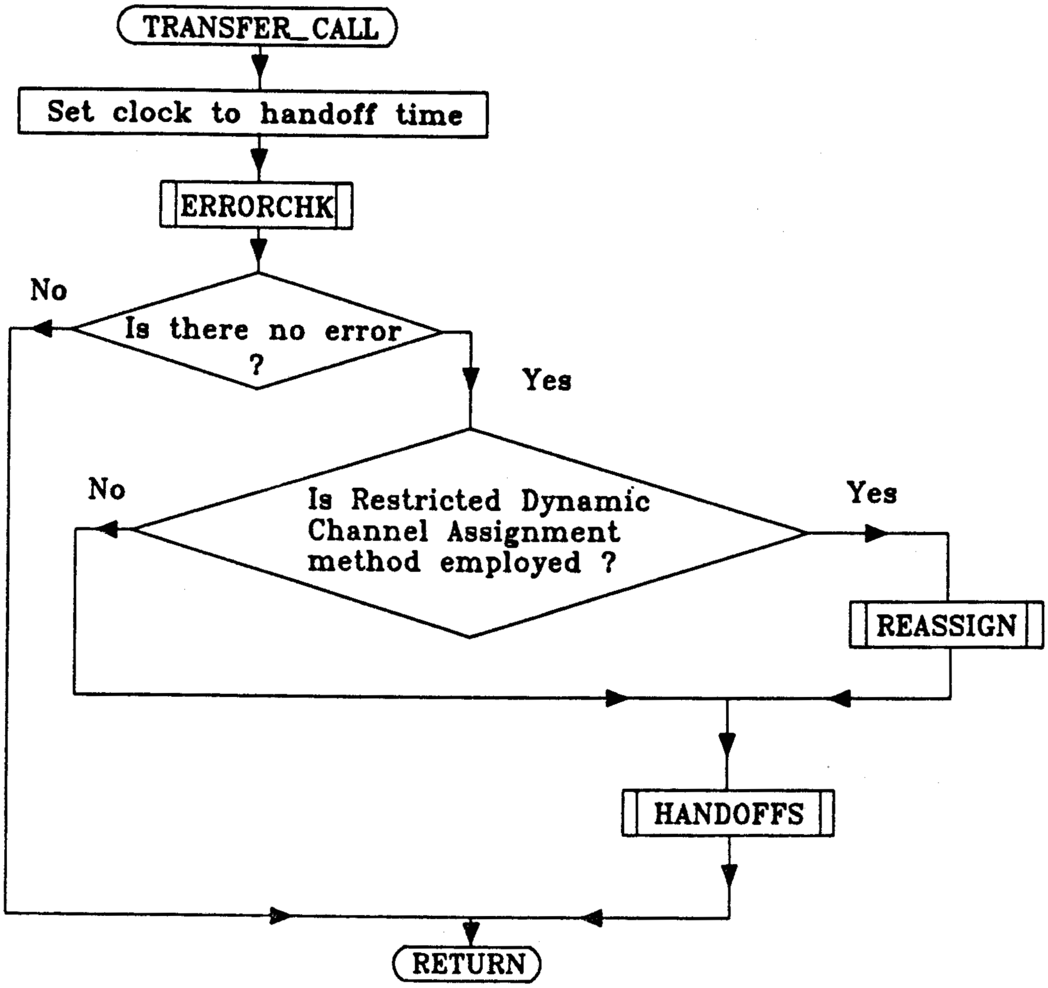


Figure 6.6 (b): Simulation procedure for employing reassignment during a handoff

and reassignment is employed. The reassignment of channels is done during a handoff or call-departure, and is incorporated in subroutine REASSIGN.

The blocking performance of the network employing RDCAA with reassignment is considered next. Figure 6.7 shows the blocking performance for the uniform traffic case when RDCAA is used with channel reassignment. Different number of assignable channels were considered. It can be seen that when only two channels are assigned for borrowing, blocking performance is the best. This is due to the randomness in the simulation model. In a scenario where all the channels are designated for borrowing, there might be an instant when all the channels of a cell are borrowed by its neighbours and

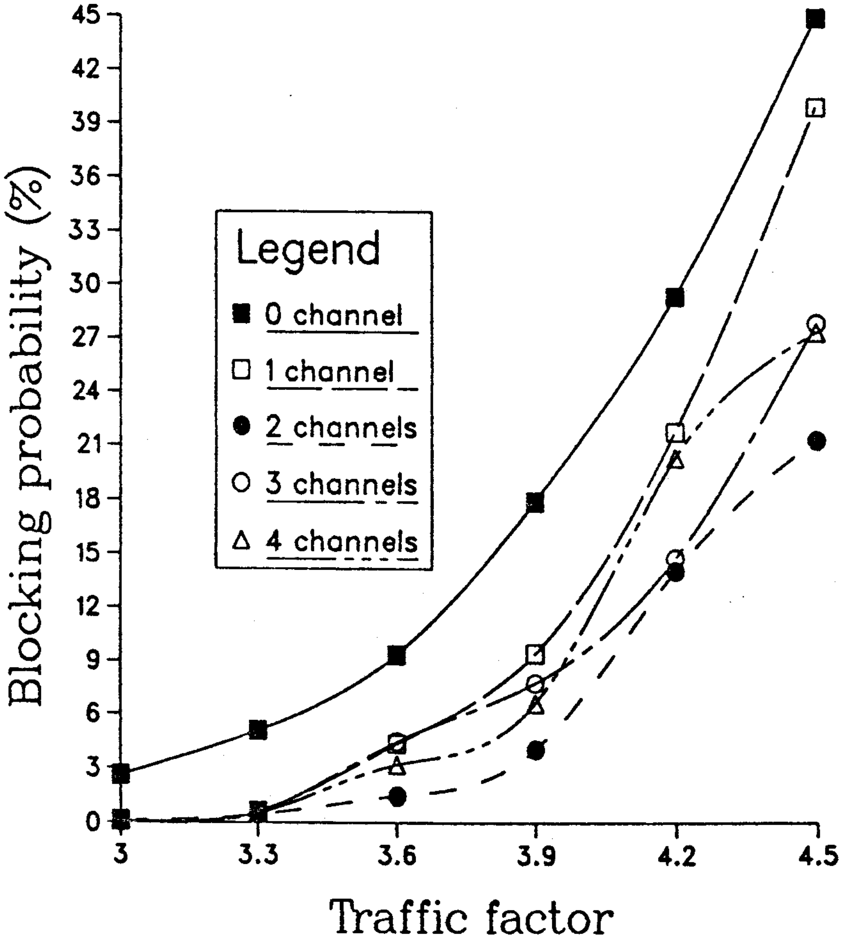


Figure 6.7: Blocking probability variation with traffic using RDCAA with reassignment (uniform traffic in all cells).

the cell has no available channel to assign to a call arriving/originating at that instant. Such a call would be blocked. When no channels are assigned for borrowing, the network behaves as if it is implementing a Fixed Channel Assignment. The blocking performance for this case is obviously the worst.

Next, the performance of RDCAA is obtained for the case when reassignment is not used. Figure 6.8 shows the blocking performance of the network using the same set of input variable as used to obtain the results in Figure 6.7 but employing RDCAA without reassignment. Here too, the blocking performance when only two channels are assignable is best till 30% traffic increase over the base traffic (corresponding to a multiplication factor of 3.0). Beyond 30% traffic increase, four assignable channels give the best blocking performance. This behaviour can once again be attributed to the randomness of the simulation.

By comparing the results in Figures 6.7 and 6.8, it may be seen that RDCAA will not necessarily result in the best blocking performance when all the channels are assignable. There is an optimum number of assignable channels. These results are in agreement with results presented in [9]. The reduced complexity of radio equipment and good blocking performance make RDCAA an attractive choice for Dynamic Channel Assignment.

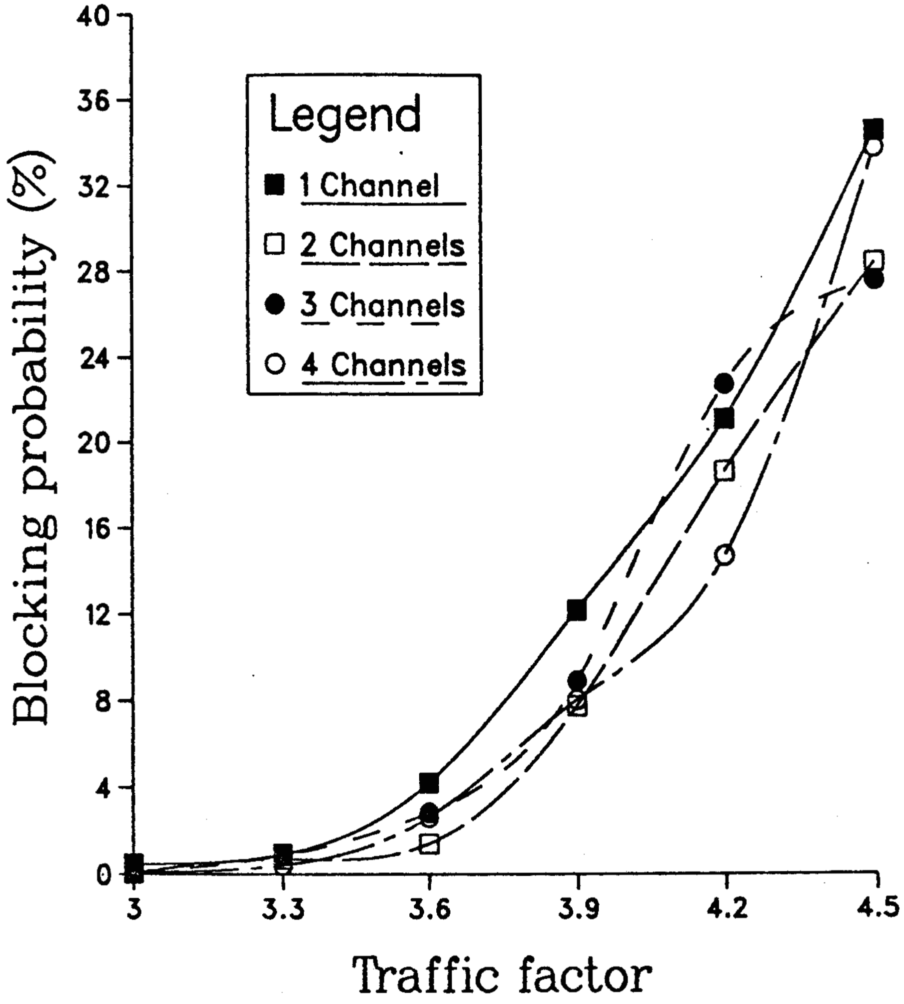


Figure 6.8: Blocking probability variation with traffic using RDCAA without reassignment (uniform traffic in all cells).

The blocking probability was computed for RDCAA with and without reassignment, with the number of assignable channels as the parameter. The results are presented in Figure 6.9. It can be seen that the improvement in blocking performance due to reassignment is quite random. For certain value of traffic, reassignment improves

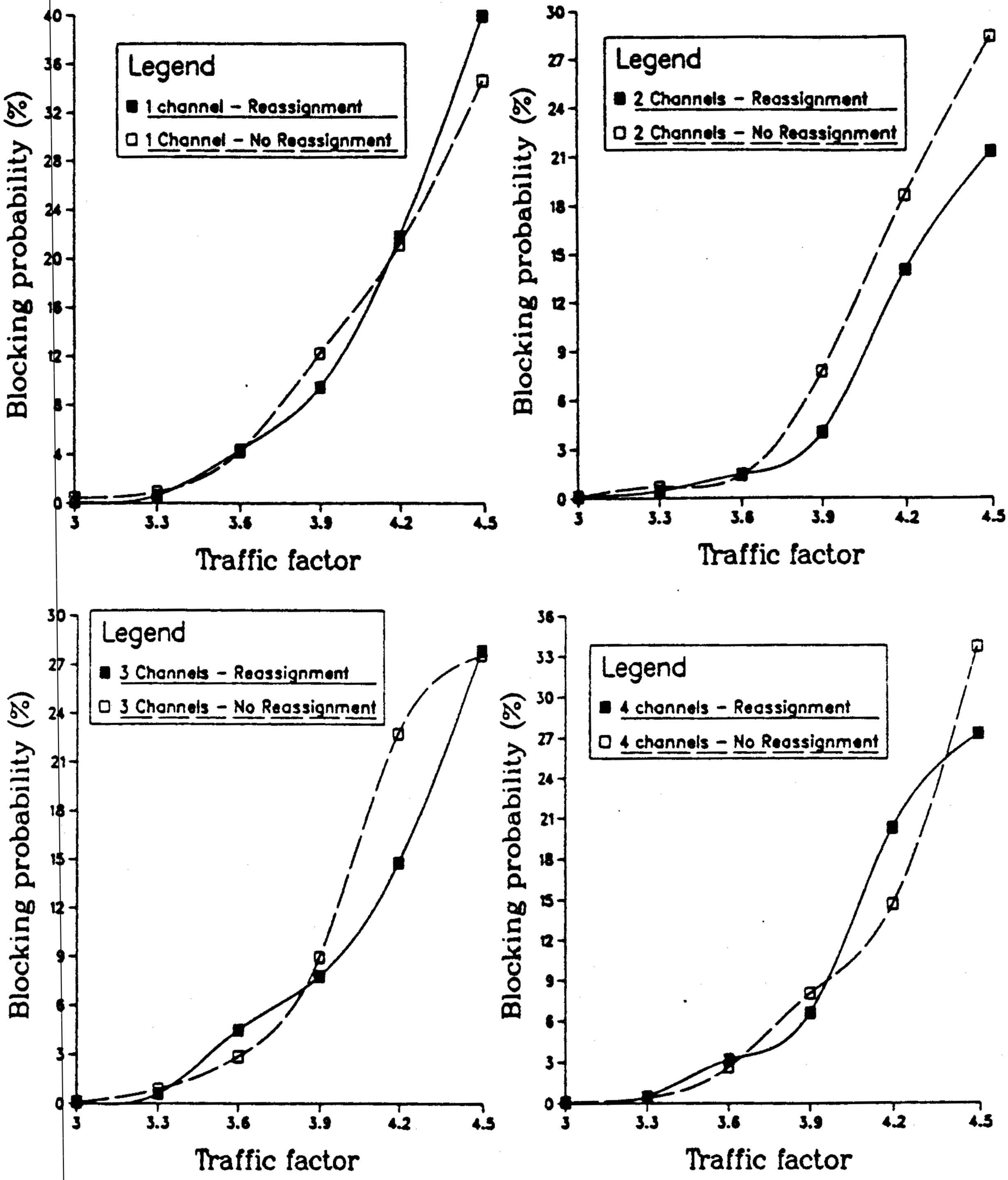


Figure 6.9: Comparison of blocking probability variation with traffic using RDCAA with and without reassignment (uniform traffic in all cells).

blocking performance while for other values there is a degradation. These results also give an idea regarding the usefulness of employing reassignment in a given system. It may be mentioned that employing reassignment causes a greater processing load on the MTSO since it has to constantly keep track of the calls that are supported by borrowed channels.

6.2. HANDOFF RATE

As mentioned in the previous chapter, the determination of handoffs is an

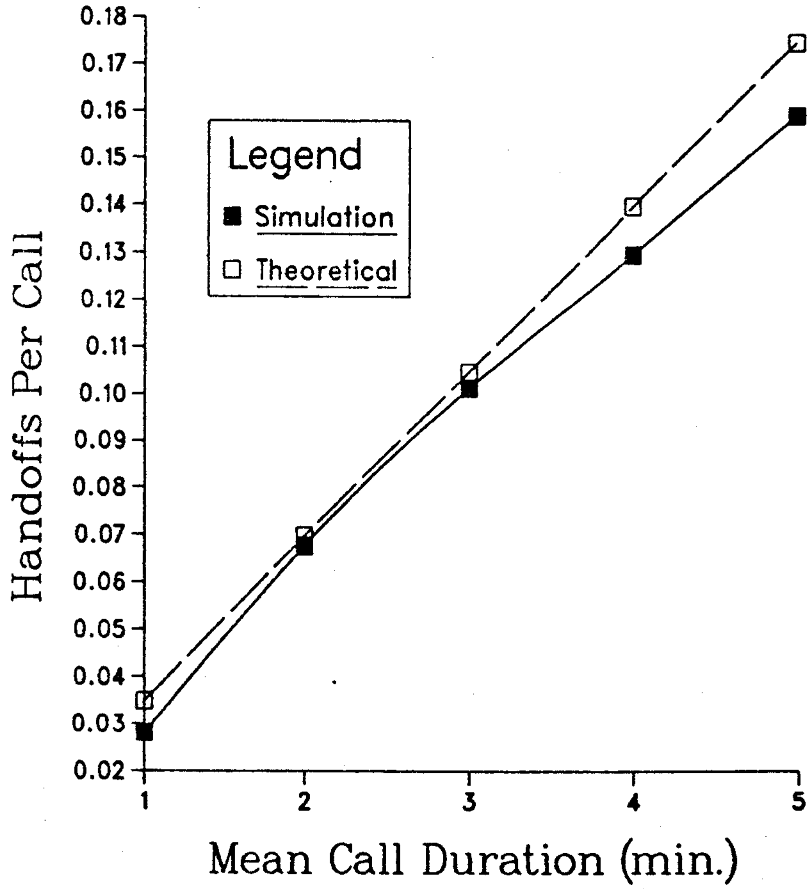


Figure 6.10: Variation of handoff per call with mean call duration.

important consideration for determining the control channel loading and the processing load for MTSO. For both uniform and non-uniform traffic cases, it was found that handoffs per call increased when cell radius was reduced or mean call length was increased or average mobile velocity was increased. Figures 6.10, 6.11, and 6.12 show the variation of handoff rate as functions of mean call duration, cell radius, and average

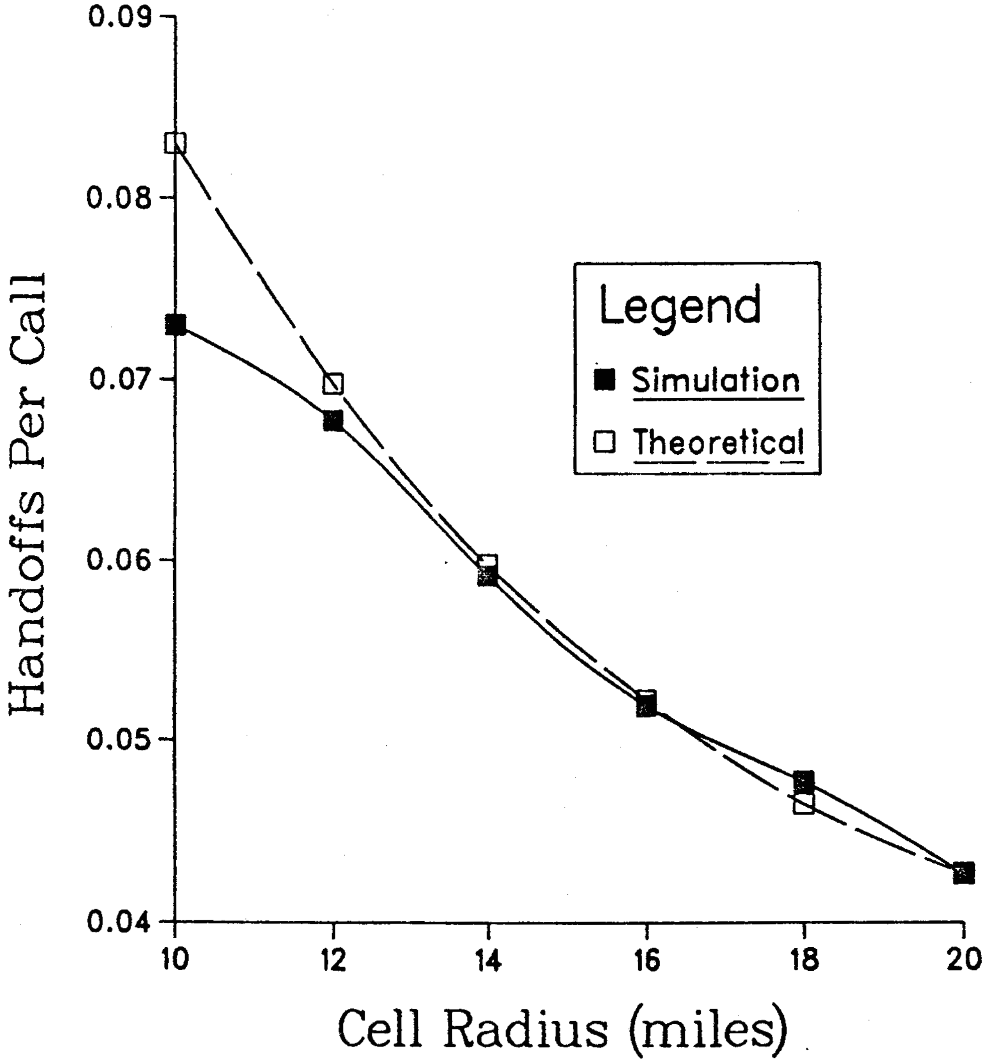


Figure 6.11: Variation of handoff per call with cell radius.

mobile velocity, respectively, for the Fixed Assignment case. Theoretical results (equation

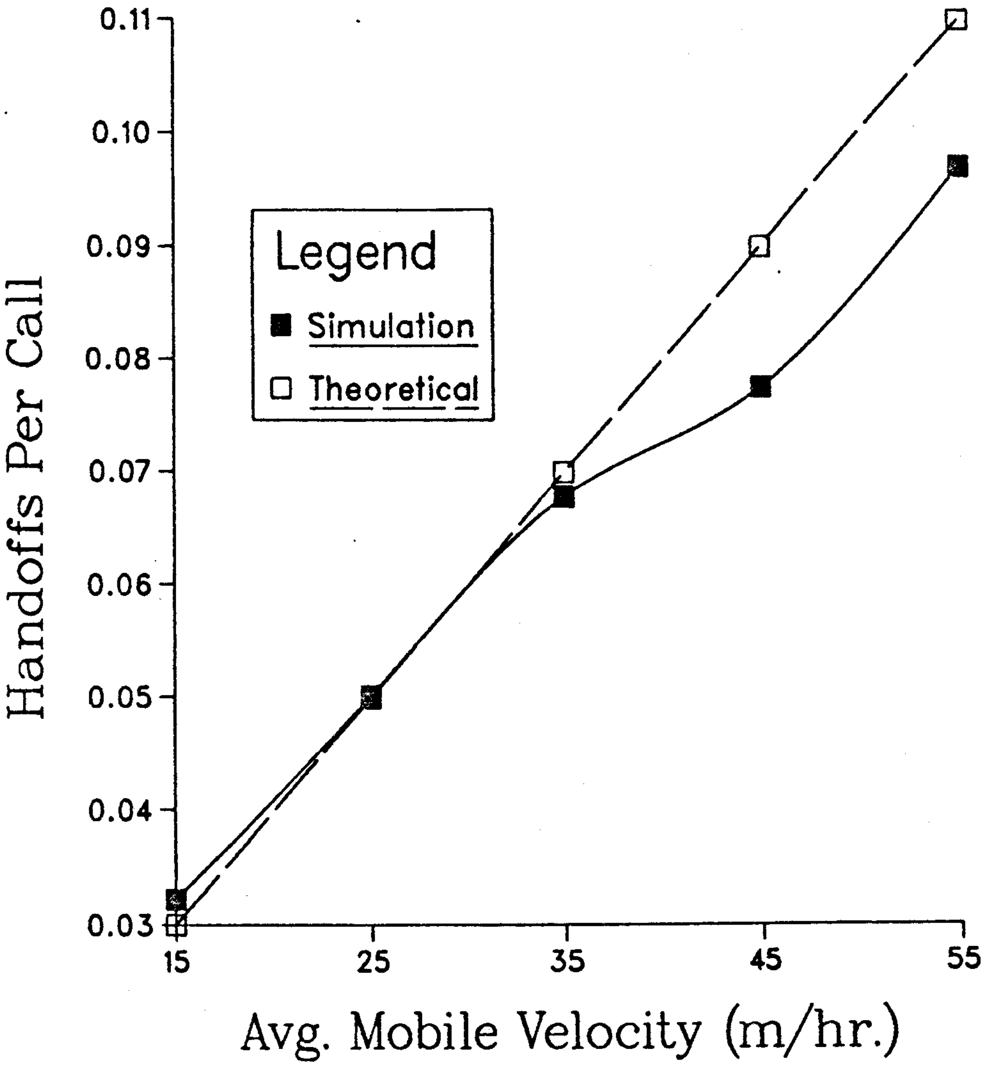


Figure 6.12: Variation of handoff per call with average mobile velocity.

5.9) based on the model in [15] are also shown in these figures along with the results obtained from simulation.

These results have been obtained using four channels per cell for a network of uniform traffic. An average mobile velocity of 35 miles/hour has been chosen. The simulation results are in good agreement with the theoretical results. The disagreement between the theoretical and simulation results increases when cell radii less than 10 miles are chosen. Some of the simplifying assumptions used in the simulation are not valid when the cell radius gets small. This explains the higher discrepancy for low values of cell radius. A similar argument can be made for the case of high mobile velocity.

Using the handoff values obtained from the simulation the cumulative channel

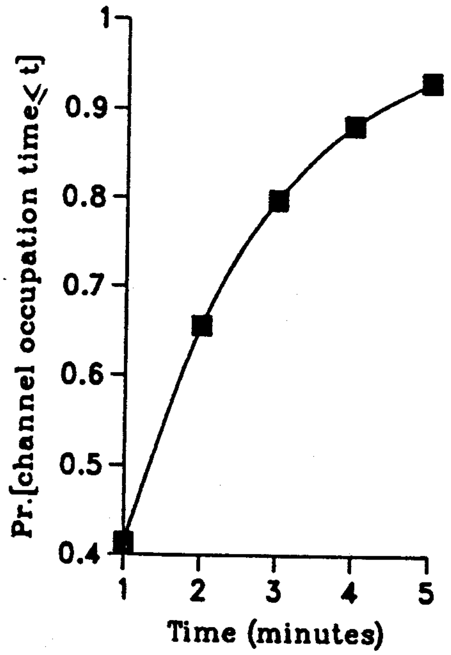


Figure 6.13: Cumulative channel occupancy distribution from simulation

occupancy distribution was computed. The results are shown in Figure 6.13. An exponential distribution for channel occupancy is evident from this figure. This result is in agreement with the theoretical prediction for this distribution.

6.3. CHANNEL OCCUPANCY STATISTICS

A call arriving (originating) in one cell but terminating in another cell (due to handoffs) will be served by at least two channels. Such a call, therefore, will have at least two channel occupancies. On the other hand, a call not making a handoff will end in the cell in which it arrived (originated). Such a call will have only one channel occupancy. In this simulation model, statistics regarding the channel occupancy in every cell was gathered for all the channels. This was done as follows. For each channel, the product of occupancy times t_i and frequency of this occupancy was taken. These products were summed up and divided by the total clock time for which the simulation was carried out. This gave the percentage occupancy for each channel. The percentages of occupancy for all channels in a cell were further summed up to give a value representing the total occupancy for all the channels in that cell.

The channel occupancy statistics are plotted in Figure 6.14 as the number of cells with higher percentage occupancy when Dynamic Assignment is used. Non-uniform traffic was considered in this case. The results for uniform traffic are presented in Figure 6.15.

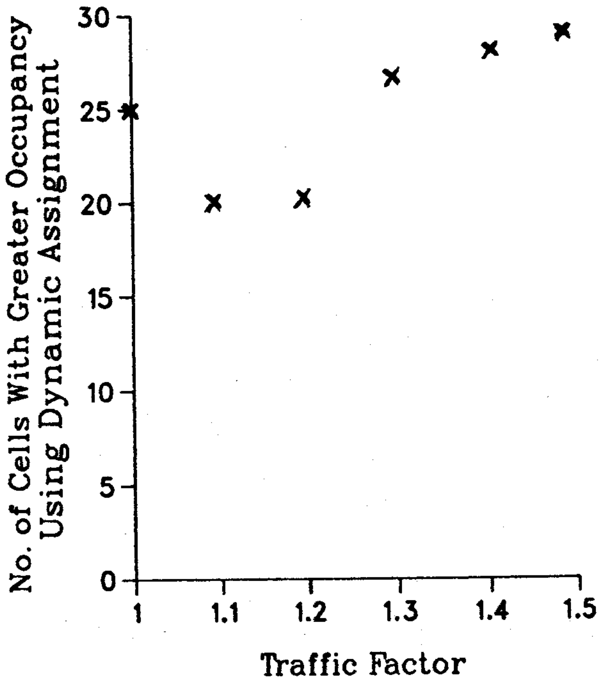


Figure 6.14: Number of cells showing higher channel occupancy using Dynamic Channel Assignment (non-uniform traffic)

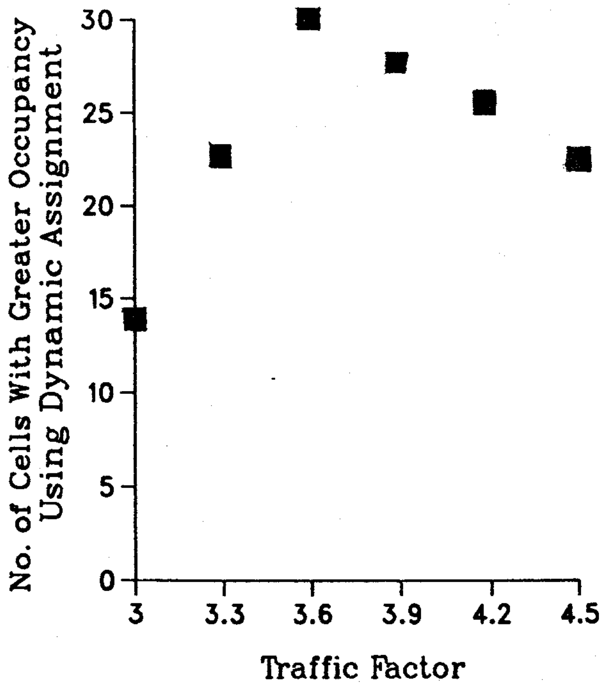


Figure 6.15: Number of cells showing higher channel occupancy using Dynamic Channel Assignment (uniform traffic)

As expected, the results show that Dynamic Channel Assignment results in a considerable improvement in percentage channel occupancy. This will translate to a higher revenue when Dynamic Channel Assignment is used. The extent of improvement varies with the traffic.

To summarize, the computer program developed was used to obtain the performance of a cellular network with respect to some of the key parameters, such as blocking probability and channel occupancy. The results indicate that Dynamic Channel Assignment improves the performance of the cellular network significantly. The handoff results are useful to estimate the processing load on the MTSO. Such results can be obtained for a network using any set of values for cell radius, average mobile velocity etc.

7. CONCLUSIONS AND SUMMARY

Application of dynamic channel assignment to SaskTel network has been studied using computer simulation.

The work reported in this thesis may be summarized as:

1. A computer program was developed for processing the calls in a cellular systems using Fixed, Dynamic, and Restricted Dynamic Channel Assignment methods.

2. Using the simulation program, blocking probability was determined for different values of traffic. It was found that while blocking of calls increases as the traffic is increased, the increase is substantially lower for thin cellular networks when dynamic channel assignment method is used.

3. The complexity of the radio equipment in cells can be reduced without compromising the advantages of dynamic channel assignment by using restricted dynamic channel assignment.

4. For different values of average mobile velocity, mean call duration and cell radius, handoffs per call were determined from the simulation program. These results were found to be in good agreement with the theoretical results.

5. Channel occupancy statistics were gathered for all the channels of all the cells. Dynamic Channel Assignment was found to use channels more effectively. Networks with dynamic assignment would generate greater revenue and would need fewer channels to

serve same subscriber population.

7.1. Conclusions

In Chapter 1 three objectives were laid down. The three statements below show that these objectives were realized.

1. A computer simulation program analyzing the blocking probability with Fixed Channel Assignment has been developed for SaskTel cellular network in Saskatchewan.

2. System performance improvement with Dynamic Channel Assignment has been obtained for different values of traffic.

3. Channel occupancy statistics and handoff rate has been obtained for different values of system parameters.

7.2. Recommendations for future study

Some other characteristics of a cellular communication system such as fading have not been incorporated in the simulation model. These characteristics can be included in a future extension of this work. Also, data transmission using the channels freed as a result of implementing dynamic channel assignment is possible and needs further study. Processing load for the Mobile Telecommunication Switching Office can be studied in greater detail using the channel occupancy statistics from this simulation program.

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Appendix

C **FORTRAN COMPUTER PROGRAM FOR A CELLULAR NETWORK**

C This program gives the performance analysis of a cellular telecommunication network. It takes into
C account the handoff mechanism that is associated with the cellular system. The file that gives information
C on the neighbouring cells for each cell in the four directions of travel is DIR.DAT. NEIGHBOR.DAT
C provides complete information regarding neighbouring cells for each cell. C_CH_S.DAT indicates the
C channels assigned to each cell. The relationships between cells, as given in files DIR.DAT and
C NEIGHBOR.DAT, is based on the layout of the network given in Figure 2.1. In files NEIGHBOR.DAT
C and C_CH_S.DAT, a "1" indicates existence and a "0" indicates non-existence. File POP.DAT provides
C the population for each cell, and based on the cumulative proportion the host cells are determined. Queues
C are updated as and when the departure and handoff times of a call are determined. The handoff and
C departure events are placed in the queues in chronological order. The simulation is discrete-event. Data
C is collected for channel-occupancy time samples. A suitable constant MULT_ARR has been chosen to
C determine the arrival rates.

C The main parameters analyzed are **Blocking Probability, Handoff Rate**, and **Channel Occupancy.**

C **MAIN PROGRAM**

```
              include 'common.inc'
              not_done = .true.
              CALL SETUP
              CALL INITIALIZE

      Do while(not_done)

              CALL NEXT_EVENT

        if(arrival) then

              CALL GENERATE_CALL
        else

              if(departure) then

                      CALL DISCONNECT_CALL
              else

                      CALL TRANSFER_CALL

              endif

        endif
      endDo
    CALL RESULTS
    STOP
    END
```

```
      SUBROUTINE REASSIGN(a,b,c)

C In this subroutine, attempt is made to free
C borrowed channels whenever there is a call
C departure or handoff.

              include 'common.inc'
              integer a,b,c,d,e
              logical call_on_borrowed_chnl

              call_on_borrowed_chnl = (a.ne.c)

         IF(call_on_borrowed_chnl) then

C This implies that the handoff/departing call was on a
C borrowed channel. In this case, the borrowed channel
C is made free and no reassignment needs to be done.

              CALL FREE_BORROWED_CHANNEL(a,b,c)

         ELSE

C A search is made in the cell (in which the call is
C departing, or, from where the mobile is making handoff)
C for a call on borrowed channel.

              CALL SEARCH_BORROWED_CHANNEL(c,d,e)

              If(borrowed_chnl_found) then

C If a call on borrowed channel is found then the
C channels are reallocated.

                   CALL REALLOCATE_CHANNELS(a,b,c,d,e)

              endif

         ENDIF

      RETURN
      END
```

SUBROUTINE REALLOCATE_CHANNELS(a,b,c,d,e)

```
C In this subroutine, channels are allocated so as to
C free borrowed channels.

        include 'common.inc'
        integer a,b,c,pos1,pos2,pos3,pos,d,e
        integer borrow_ch,temp_cel,temp_ch

        borrow_ch = notassch(d,e)
        CALL LOCATE_D(a,b,pos)
        pos1 = pos

C pos1 denotes position of the handoff/departing call in
C the departure queue.

        CALL LOCATE_D(d,borrow_ch,pos)
        pos2 = pos

C pos2 denotes position of the call on borrowed channel
C in the departure queue.

        CALL LOCATE_H(d,borrow_ch,pos)
        pos3 = pos

C pos3 denotes position of the call on borrowed channel
C in the handoff queue.

        temp_cel  = a
        temp_ch   = b

      if (handoff) then

C For the case when a call undergoing handoff is NOT on
C a borrowed channel, but the cell has a call on a
C borrowed channel, the channels are reassigned so that
C the borrowed channel is rendered free.

        q_handoff(1,1) = kend(pos2,1)
        q_handoff(1,2) = kend(pos2,2)
      endif

        kend(pos1,1) = kend(pos2,1)
        kend(pos1,2) = kend(pos2,2)
        kend(pos2,1) = Temp_cel
        kend(pos2,2) = temp_ch
```

```
C This interchanges the cell and channel address of the
C handoff/departing call with the call on borrowed
C channel.

            If(pos3.ne.0) then

C The call on borrowed channel may or may not have a
C handoff. Hence the following reassignment is done
C only when the borrowed call has been located in the
C handoff queue.
                 q_handoff(pos3,1) = temp_cel
                 q_handoff(pos3,2) = temp_ch
            endif
          reass(e,d,c) = 1


      RETURN
      END
```

```
      SUBROUTINE SEARCH_BORROWED_CHANNEL(c,d,e)

C In this subroutine, calls on borrowed channels
C are searched within the cell in which a call is
C departing, or, from where a mobile is making a
C handoff.

              include 'common.inc'
              integer c,j,jk,d,e

              borrowed_chnl_found = .false.
              j = 1
         Do while(no_ass.and.(.not.borrowed_chnl_found).
     u             and.(j.le.numcell))
              jk = 1
          If(neighbor(c,j).eq.1) then
           Do while((jk.le.ch_xxx).and.(.not.
     u               borrowed_chnl_found))
            if(reass(jk,j,c).eq.-1) then
                   borrowed_chnl_found = .true.
                   d = j
                   e = jk

C d and e return the address of the call on borrowed
C channel.

            else
             jk = jk + 1
            endif
           endDo
          endif
              j = j + 1
         endDo

      RETURN
      END
```

```
      SUBROUTINE STOP_PROGRAM


C This subroutine sets the flags for the
C termination of the program due to an error.


        include 'common.inc'

        error = .true.
        not_done = .false.
        iwrong = clock_time


      RETURN
      END
```

```
SUBROUTINE FREE_BORROWED_CHANNEL(a,b,c)


C This subroutine matches the borrowed channel
C with the array Notassch and renders the borrowed
C channel free.


    include 'common.inc'
    integer a,b,c
    logical free


   i = 1
   free = .false.

  Do while((i.le.ch_xxx).and.(.not.free))
   If(notassch(a,i).eq.b) then
        reass(i,a,c) = 1
        free = .true.
   else
        i = i + 1
   endif
  endDo


  RETURN
  END
```

SUBROUTINE LOCATE_D(x,y,pos)

```
C This subroutine locates the position of a call on
C channel y from cell x in the departure queue.The
C position is stored in 'pos'.



        include 'common.inc'
        integer pos,x,y
        logical trace

        trace = .false.
        k = 1
        pos = 0
        j2 = 0
       Do while(.not.trace)
        If((kend(k,1).eq.x).and.(kend(k,2).eq.y)) then
              j2 = k
              pos = k
              trace = .true.
        else
              k = k + 1
        endif
       endDo

  RETURN
  END
```

```
      SUBROUTINE LOCATE_H(x,y,pos)

C This subroutine locates the position of a call on
C channel y from cell x in the handoff queue. The
C position is stored in 'pos'.

          include 'common.inc'
          integer x,y,pos
          logical trace

           j3 = 0
           pos = 0
           K = 1
           trace = .false.
      Do while((k.le.600).and.(.not.trace))
        If((q_handoff(k,1).eq.x).and.
     u      (q_handoff(K,2).eq.y)) then

              j3 = k
              pos = k
              trace = .true.
        endif
              k = k + 1
      endDo

      RETURN
      END
```

SUBROUTINE SETUP

```
C This subroutine reads the data files, inputs variable
C values, initializes variables and arrays, and
C arranges cells in increasing order of population.

                include 'common.inc'
                logical correct1_entry,correct2_entry,correct3_entry

                open(unit=2,file ='c_ch_s.dat',status='old')
                open(unit=3,file ='Neighbor.dat',status='old')
                open(unit=4,file='Pop.dat',status='old')
                open(unit=9,file='Dir.dat',status='old')
                open(unit=13,file='results.out',status='new')
                open(unit=14,file='cell.stat',status='new')

C   INPUT DATA TO PROGRAM

      write(*,*)'ENTER NUMBER OF CALLS TO BE PROCESSED'
      Read(*,*) NUM_CALL
      write(*,*) 'ENTER MEAN CALL LENGTH IN MIN.'
      Read(*,*) CALL_LENGTH
      write(*,*) 'ENTER RADIUS OF CELL IN MILES'
      Read(*,*) RADIUS
      write(*,*) 'ENTER VELOCITY OF MOBILE IN MILES/HR'
      Read(*,*) VEL
      write(*,*) 'ENTER MULTIPLICATION FACTOR FOR ARRIVAL'
      write(*,*) '              RATE'
      Read(*,*) MULT_ARR

      correct1_entry = .false.

      Do while(.not.correct1_entry)

      write(*,*) 'ENTER 0 for FIXED CHANNEL ASSIGNMENT,'
      write(*,*) '       1 for DYNAMIC CHANNEL ASSIGNMENT,'
      write(*,*) ' and  2 for RESTRICTED DYNAMIC CHANNEL'
      write(*,*) '              ASSIGNMENT.'
      write(*,*) ' '
      Read(*,*) METHOD
       If((method.eq.0).or.(method.eq.1).or.
     u        (method.eq.2)) correct1_entry = .true.
      endDo

      correct2_entry = .false.
      correct3_entry = .false.
```

```
      if(method.eq.2) then
      Do while(.not.correct2_entry)
        write(*,*) 'ENTER NUMBER OF ASSIGNABLE CHANNELS,'
        write(*,*) ' maximum =4'
        Read(*,*) CH_XXX
        If(ch_xxx.le.4) correct2_entry = .true.
      endDo

      if(ch_xxx.ne.0) then
       Do while(.not.correct3_entry)
        write(*,*) 'ENTER 1 for Reallocation of channels,'
        write(*,*) '      0 otherwise'
        Read(*,*) REALOCATE
        If((realocate.eq.0).or.(realocate.eq.1)) then
           correct3_entry = .true.
        endif
       endDo
       endif
      endif


C INITIALIZE VARIABLES

                  error = .false.
                  izero = 0
                  inzero = 0
                  iba = 0
                  ica = 0
                  irun = 0
                  sum = 0.0
                  seed = 163467
                  in_seed = 163467
                  inf = 2147483647
                  finish_time = inf
                  clock_time = 0
                  numblock = 0
                  call_comp = 0
                  q_length = 0
                  h_length = 0
                  tot_call = 0
                  ij = 1
                  cell_q = 0
                  handover = 0
                  ih_block = 0
                  h1_block = 0
                  ip = 1
                  q_cell(1) = 0
                  q_cell(2) = 0
                  dynamic = .false.
                  fixed = .false.
                  restricted = .false.
```

```
      If(method.eq.0) fixed = .true.
      If(method.eq.1) dynamic = .true.
      If(method.eq.2) restricted = .true.

C     CONVERT TO FLOATING POINT

      alngth = call_length

C      READ AND INITIALIZE THE ARRAY VALUES

      CALL LIB$INIT_TIMER

      Read(4,*) N_pop
      Read(2,*) NCH
      Do i =1,600
        kend(i,3) = inf
        q_handoff(i,3) = inf
      endDo
      Do i = 1,Numch
        Do j = 1,numcell
          Do k = 1,50
           time(i,j,k) = 0
           w_o(numch,numcell,50) = 0.0
           t_o(numch,numcell) = 0.0
           c_o(numch,numcell) = 0.0
           cell_c_o(j) = 0.0
          endDo
        endDo
      endDo
        Do 2  I= 1,Numcell
                 Read(3,*) (Neighbor(i,j),j=1,Numcell)
2       Continue
        Do 12  I = 1,Numch
                 Read(2,*) (c_ch_s(i,j),j=1,numcell)
12      Continue
        Do 22 i = 1,numcell
                 Read(2,*) cell_ch(i)
22      Continue
        Do 32 I=1,Numcell
                 Read(9,*) (bb(i,j),j=1,4)
32      Continue

        Do I= 1,N_pop
                 Read(4,*) pop(i)
                 sum = sum + pop(i)
        endDo
        Do I = 1,N_pop
                 prop(i) = pop(i)/sum * 100
        endDo
      write(13,*) '       OUTPUT DATA  '
      write(13,*) ' '
```

```
C     INCREASING CELL PROPORTION AND CUMULATIVE PROPORTION

        Do i=1,n_pop
                ik(i)=i
        endDo
      Do j = 1,N_pop
                A = prop(j)
                Ia=ik(J)
                l = j + 1
        Do k = l,N_pop
                B = prop(k)
                ib=ik(k)
          If(A.gt.B) then

                prop(J) = B
                prop(K) = A
                A =B
                IK(J)=ib
                IK(k)=ia
                ia=ib
          endif
        endDo
      endDo
                cum_prop(1) = prop(1)
                nn = n_pop - 1
        Do 42 i = 1,nn
                j = i + 1
                cum_prop(j) = prop(j) + cum_prop(i)
42      Continue

44     CALL SVRBN(30,pop,pop_srt)
      pop_avg = (pop_srt(15) + pop_srt(16))/2
        Do 52 i = 1,n_pop
                arr_wt(i) = pop_srt(i)/pop_avg
52      Continue

        Do 62 i = 1,n_pop
                rate(i) = arr_wt(i) * mult_arr
62      Continue

        If(restricted) then
                CALL REASS_INITIALIZE
        endif

      RETURN
      END
```

SUBROUTINE RESULTS

```
C This subroutine calculates channel occupancy and
C prints the results.

      include 'common.inc'

C  OUTPUT STATISTICS

      write(*,*) ' '
      r_call = tot_call
      ablock = numblock

C Only real values can be used to calculate blocking.

      blo_prob = (ablock/r_call) * 100
      r_handoff = handover
      sim_hpc = r_handoff/r_call
      anal_hpc =(0.7182 * call_length * vel)/(60 * radius)
      hpc_err = ((anal_hpc - sim_hpc)/anal_hpc) * 100

C sim_hpc and anal_hpc are handoff values per call from
C simulation and analytical formula respectively. hpc_err
C denoted error in the two values.

      write(*,*) ' '
        if(method.eq.0) then
                write(*,*) ' OUTPUT  FOR  FIXED  ASSIGNMENT '
                write(13,*) ' OUTPUT  FOR  FIXED  ASSIGNMENT '
        else
         if(method.eq.1) then
                write(*,*) ' OUTPUT  FOR  DYNAMIC  ASSIGNMENT '
                write(13,*) ' OUTPUT  FOR  DYNAMIC  ASSIGNMENT '
         else
          if(method.eq.2) then
                write(*,*) 'OUTPUT FOR RESTRICTED DYNAMIC ASSIGNMENT'
                write(13,*) 'OUTPUT FOR RESTRICTED DYNAMIC ASSIGNMENT'
          endif
         endif
        endif
      write(*,*) ' '
     write(*,*) 'TOTAL NO. OF RUNS            = ',IRUN
     write(*,*) 'TOTAL SIM. PROCESSED CALLS  = ',TOT_CALL
     write(*,*) 'TOTAL COMPLETED CALLS       = ',call_comp
     write(*,*) 'TOTAL zero length CALLS     = ',izero
     write(*,*) 'TOTAL non-zero length CALLS = ',inzero
```

```
      write(*,*) 'NUMBER OF BLOCKED CALLS      = ',numblock
      write(*,*) 'NUMBER OF HANDOFFS           = ',handover
      write(*,1111) SIM_HPC
1111  Format(1x, 'HANDOFFS PER CALL (sim.)    = ',3x,F9.5)
2222  Format(1x, 'HANDOFFS PER CALL (anal.)   = ',3x,F9.5)
      write(*,2222) ANAL_HPC
      write(*,*) 'ERROR% SIM. AND ANAL.RESULTS= ',HPC_ERR
      write(*,*) ' '
      write(*,*)'Number of handoffs blocked due to'
      write(*,*)' busy channel',ih_block
      write(*,*)'Number of handoffs blocked due to'
      write(*,*)' no neighbors',h1_block
      write(*,*) '  '
      write(*,3333) BLO_PROB
3333  Format(1x, 'BLOCKING PROBABILITY %      = ',F6.2)
      write(*,*) ' '
      write(*,*) ' I N P U T '
      write(*,*) '  '
      write(*,*) 'TOTAL SIM. PROCESSED CALLS = ',NUM_CALL
      write(*,*) 'MEAN CALL LENGTH IN MIN. =',CALL_LENGTH
      write(*,*) 'CELL RADIUS IN MILES       = ',RADIUS
      write(*,*) 'AVERAGE MOBILE VEL.(M/Hr.) = ',VEL
      write(*,*) 'MULTIPLYING CONSTANT       = ',MULT_ARR
       if(method.eq.2) then
        write(*,*) 'ASSIGNABLE CHANNELS      = ',CH_XXX
        If(realocate.eq.1) then
         write(*,*) 'REASSIGNMENT DONE '
        else
         write(*,*) 'REASSIGNMENT NOT DONE '
        endif
       endif
      write(13,*) ' '
      write(13,*) '  '
      write(13,*) 'TOTAL NO. OF RUNS          = ',IRUN
      write(13,*) 'TOTAL SIM. PROCESSED CALLS  = ',TOT_CALL
      write(13,*) 'TOTAL COMPLETED CALLS      = ',call_comp
      write(13,*) 'TOTAL zero length CALLS    = ',izero
      write(13,*) 'TOTAL non-zero length CALLS = ',inzero
      write(13,*) 'NUMBER OF BLOCKED CALLS     = ',numblock
      write(13,*) 'NUMBER OF HANDOFFS          = ',handover
      write(13,1111) SIM_HPC
      write(13,2222) ANAL_HPC
      write(13,*) 'ERROR% SIM. AND ANAL.RESULTS= ',HPC_ERR
      write(13,*) ' '
      write(13,*)'Number of handoffs blocked due to'
      write(13,*)' busy channel',ih_block
      write(13,*)'Number of handoffs blocked due to'
      write(13,*)' no neighbors',h1_block
      write(13,*) '  '
      write(13,3333) blo_prob
      write(13,*) ' '
```

```
      write(13,*) '            I N P U T '
      write(13,*) '  '
      write(13,*) 'TOTAL SIM. PROCESSED CALLS  = ',NUM_CALL
      write(13,*) 'MEAN CALL LENGTH IN MIN. = ',CALL_LENGTH
      write(13,*) 'CELL RADIUS IN MILES        = ',RADIUS
      write(13,*) 'AVERAGE MOBILE VEL.(M/Hr.)  = ',VEL
      write(13,*) 'MULTIPLYING CONSTANT        = ',MULT_ARR
      write(13,*) 'INITIAL SEED                = ',in_seed
      write(13,*)'  '
      write(13,*) 'CLOCK                       = ',CLOCK_TIME
      write(13,*) '  '
         if(method.eq.2) then
                 write(13,*) 'ASSIGNABLE CHANNELS        = ',CH_XXX
          If(realocate.eq.1) then
                 write(13,*) ' *****  REASSIGNMENT DONE *** '
          else
                 write(13,*) ' *****  REASSIGNMENT NOT DONE ****'
          endif
         endif

C CALCULATION OF CHANNEL OCCUPANCY

        riclock = clock_time

        Do i = 1,numch
          Do j = 1,numcell
            If(c_ch_s(i,j).ne.0) then
              Do k = 1,50
                If(time(i,j,k).ne.0.0) then
                  w_o(i,j,k) = k * time(i,j,k)

C Array w_o contains occupancy of channel i from
C cell j for different values of sample times k.

                  if(k.eq.50) w_o(i,j,k) = 0.0
                  t_o(i,j) = t_o(i,j) + w_o(i,j,k)

C Array t_o contains total occupancy of channel i from
C cell j for all values of sample times k.

                endif
              endDo

              c_o(i,j) = (t_o(i,j)/riclock) * 100

C Array c_o expresses occupancy of channel i from cell j
C as a percentage of the simulated clock time.

            endif
          endDo
        endDo
```

```
      Do j = 1,numcell
         Do i = 1,numch
            cell_c_o(j) = cell_c_o(j) + c_o(i,j)

C Array cell_c_o adds the channel occupancies for all
C channels within each cell.

         endDo
      endDo
      write(13,*) '               '
      write(13,4444) (i,i=1,10)
4444  format(//(1x,10(1x,i4,2x)))
      write(13,*) '     '
      write(13,5555) (cell_c_o(j),j=1,10)
5555  format(//(1x,10(f7.2)))
      write(13,4444) (i,i=11,20)
      write(13,5555) (cell_c_o(j),j=11,20)
      write(13,4444) (i,i=21,30)
      write(13,5555) (cell_c_o(j),j=21,30)
      write(13,*)'NUMBER OF CHANNELS = ',nch
      write(13,*) ' '
      write(13,*)'CELL      CHANNELS'
       Do6666 I = 1,30
            write(13,7777) i,cell_ch(i)
7777        format(3X,I2,9X,I3)
6666   Continue
      write(*,*) 'CLOCK TIME = ',clock_time
      write(13,*) 'CLOCK TIME = ',clock_time
      CALL LIB$SHOW_TIMER

       If(.not.error) then
            write(*,*) ' ALL EVENTS SCHEDULED IN CORRECT ORDER'
            write(13,*) 'ALL EVENTS SCHEDULED IN CORRECT ORDER'
       else
            write(*,*) 'error is at time ',iwrong
       endif

      RETURN
      END
```

```
      SUBROUTINE TRANSFER_CALL

C In this subroutine, the clock is advanced to the
C handoff time at the top of the handoff queue
C (i.e.,least handoff time). For Restricted Dynamic
C Channel Assignment, channels are reassigned. The
C cell to which the mobile is making a handoff is
C determined.

        include 'common.inc'

        clock_time = q_handoff(1,3)

        CALL ERRORCHK
          if(.not.error) then

            if(restricted) then
                  CALL REASSIGN(q_handoff(1,1),q_handoff(1,2),
     u                q_handoff(1,4))

C During a handoff, reassignment of the channels needs
C to be done for Restricted dynamic channel reassignment
C method. Subroutine REASSIGN searches for calls on
C borrowed channels and reassigns channels to free these.

            endif

                  CALL HANDOFFS

C This subroutine allows the call to be Continued in the
C cell towards which the mobile is travelling.

          endif

      RETURN
      END
```

```
      SUBROUTINE HANDOFFS


C This subroutine frees the channel occupied by the
C mobile prior to the handoff. It finds the position
C of this call in the departure queue, the cell to
C which the mobile is making a handoff, and whether
C the new cell can support the call. If the call is
C Continued in the new cell, the status of the
C channel supporting the call is set to busy, and
C channel occupancy in recorded in the new cell. The
C call is finally removed from the handoff queue.


        logical found
        include 'common.inc'

C     HANDOFF OF CALL

                  c_ch_s(q_handoff(1,2),q_handoff(1,1)) = 1

C The channel occupied by the mobile making the handoff
C is made free.

                  j = 1
                  found = .false.
            Do while ((j.le.600).and.(.not.found))
              if((kend(j,1).eq.q_handoff(1,1)).and.
     u          (kend(j,2).eq.q_handoff(1,2))) then

                  ip = j

C The position of the call undergoing handoff is determined
C in the departure queue and is stored in ip.

                  found = .true.
              else
                  j = j + 1
              endif
            EndDo
            IF(.not.found) then
                  CALL STOP_PROGRAM
            ELSE
             if(BB(q_handoff(1,4),i_dir).ne.0) then
                  host_cell = BB(q_handoff(1,4),i_dir)

C If there is a neighboring cell in the direction of the
C mobiles travel, then that cell is the new hostcell for
C the call.
```

```
            CALL ASSIGN_CHANNEL

        if(.not.blocked) then

          c_ch_s(opt_ch,opt_cel) = -1
          kend(ip,1) = opt_cel
          kend(ip,2) = opt_ch
          kend(ip,4) = host_cell
          occupancy = kend(ip,3) - q_handoff(1,3)

C The occupancy of channel for the remainder of call in
C the new cell (i.e. occupancy of channel kend(ip,2) ) is
C stored in variable 'occupancy'.

     time(opt_ch,opt_cel,occupancy) = time(opt_ch,opt_cel,
    u        occupancy) + 1

C This finds the frequency of channel occupancy duration
C for this particular sample value (stored in 'occupancy')
C for channel opt_ch from cell opt_cel.

        else
          ih_block = ih_block + 1
          CALL DISCONNECT

C If there is no free channel in the new cell to serve
C the call, the call is disconnected.

        endif
       else
         h1_block = h1_block + 1

C If there is no neighboring cell in the direction of
C travel, the call is disconnected.

         CALL DISCONNECT
       endif
         ip = 1

        CALL H_SHORTEN

C The handoff queue is shortened once this handoff is
C completed.

      ENDIF


   RETURN
   END
```

```
      SUBROUTINE DISCONNECT_CALL

C In this subroutine, reassignment of channels is
C done for restricted dynamic channel assignment. The
C status of the channel supporting the departing call
C is made free and call is removed from the depart
C queue.

                  include 'common.inc'

                  clock_time = finish_time
                  CALL ERRORCHK
         if(.not.error) then

            if(restricted) then

C For restricted dynamic assignment case, reassignment
C is done when a call is getting disconnected.

                  CALL REASSIGN(kend(1,1),kend(1,2),
     u                         kend(1,4))
            endif

C The channel serving the departing call is made free.

                  c_ch_s(kend(1,2),kend(1,1)) = 1
                  CALL DISCONNECT

         endif

      RETURN
      END
```

```
      SUBROUTINE ASSIGN_CHANNEL


C In this subroutine, a search is made for a channel
C to support the call in host_cell. First a search is
C made employing the algorithm of fixed channel
C assignment. If no free channel is found during this
C search, then for the fixed assignment method, the
C call is blocked. However, for the dynamic assignment
C and restricted dynamic assignment cases, a search is
C made employing ALGOR_1 and ALGOR_2 respectively.


              include 'common.inc'
              logical chan_found

C       host_cell is the cell that gets the call
              blocked = .false.


*****************************************************
C ALGORITHM FOR FIXED CHANNEL ASSIGNMENT

              chan_found = .false.
              i = 1
        Do while ((.not.chan_found).and.(i.le.numch))
          if (c_ch_s(i,host_cell).eq.1) then
              opt_cel = host_cell
              opt_ch = i
              chan_found = .true.
          else
              i = i + 1
          endif
        endDo
*****************************************************

        If(.not.chan_found) then

C If no free channel is found in the host cell, then
C for dynamic channel assignment and restricted dynamic
C channel assignment cases a search is made in the
C neighbouring cells according to the algorithms.

          block = .true.
          If(dynamic) CALL ALGOR_1
          If(restricted) CALL ALGOR_2

        endif
```

```
      If(.not.block) then
C Available channel is made busy.

              c_ch_s(opt_ch,opt_cel) = -1
      endif

   RETURN
   END
```

```
      SUBROUTINE GENERATE_CALL

C In this subroutine, the clock_time is advanced
C to the arrival time and a new call is generated.

              include 'common.inc'

              clock_time = arrival_time
              CALL ERRORCHK
              IF(.not.error) CALL ARRIVALS

C Generate new call.

      RETURN
      END
```

```
      SUBROUTINE NEXT_EVENT

C In this subroutine the next event is determined
C on comparing the arrival, departure and handoff
C times, and using the protocols.

        include 'common.inc'

           arrival = .false.
           departure = .false.
           handoff = .false.

C If a handoff and a call-arrival occur at the same
C time, handoff holds precedence. The order of
C precedence is : departure > handoff > arrival.

        If(q_handoff(1,3).le.arrival_time) then
            If(finish_time.le.q_handoff(1,3)) then
                 departure = .true.
            else
                 handoff = .true.
            endif
        else
            if(arrival_time.ge.finish_time) then
                 departure = .true.
            else
                 arrival = .true.
            endif
        endif

      RETURN
      END
```

SUBROUTINE INITIALIZE

```
C In this subroutine, the cell number hosting the
C first call, and the call arrival time in this cell
C is generated.

        include 'common.inc'

C   compute first arrival

        CALL HOSTCELL
        CALL HOST_Q
        call_min = rate(icount)
C     arrival_time -   next future call arrival time

C inter-arrival times are exponentially distributed.

        IAT = (1/call_min) * EXPONENTIAL (seed)
        ica = ica + 1
        arrival_time = iat + clock_time

C iat=inter arrival time, ita = time of arrival of call.

        clock_time = arrival_time
        itest = clock_time

C itest will be used to check event scheduling.

     if (clock_time.lt.0) then
        CALL STOP_PROGRAM
     else
        CALL ARRIVALS

     endif

   RETURN
   END
```

```
      SUBROUTINE ERRORCHK

C In this subroutine, proper scheduling of
C different events is checked.

        include 'common.inc'
        If(clock_time.lt.itest) then
          CALL STOP_PROGRAM
        else
          itest = clock_time
        endif

      RETURN
      END
```

```
      SUBROUTINE ARRIVALS

C In this subroutine, the cell number hosting the
C next call, and the call arrival time in this cell
C is generated.

              include 'common.inc'

              CALL HOSTCELL
              CALL HOST_Q

              call_min = rate(icount)
C arrival_time =  next future call arrival time

              iat = (1/call_min) * EXPONENTIAL (seed)

              ica = ica + 1
              arrival_time = iat + clock_time

              host_cell = q_cell(1)

C Host cell is determined from the queue in
C subroutine host_q. After that, the queue is
C shortened in subroutine NXT_IN-Q.

              CALL NXT_IN_Q
              CALL ALLOCATE

C In subroutine ALLOCATE, a free channel is searched
C for the cell, and if found, the call duration is
C generated and handoff is determined.

              tot_call = call_comp + numblock

C Total calls processed are incremented.

         If(tot_call.eq.num_call) then
              not_done = .false.
         endif

         If (kend(1,3).lt.finish_time) then
              finish_time = kend(1,3)

C The depart time corresponding to the first entry
C of the departure queue is assigned to the finish
C time.

         endif
        RETURN
        END
```

SUBROUTINE DISCONNECT

```
C In this subroutine, the departing call is removed
C from the depart queue and processed calls are
C incremented.

            include 'common.inc'

            CALL SHORTEN_Q

C The departing call is removed from the system by
C shortening the departure queue.

            call_comp = call_comp + 1
            inzero = inzero + 1
            tot_call = call_comp + numblock
            If(tot_call.eq.num_call) not_done = .false.

      If(ij.eq.0) then
            CALL STOP_PROGRAM
      endif

   RETURN
   END
```

```
SUBROUTINE HOSTCELL

C In this subroutine, cell numbers are generated by
C generating a random number from the uniform
C distribution. The random number is then matched with the
C cumulative proportion to determine the cell no.

      include 'common.inc'

      random_no = 100 * UNIFORM (seed)

      Do while (random_no.eq.0.0)
              random_no = 100 * UNIFORM (seed)
      endDo

              icount = 1

C The random number generated is matched to the
C cumulative proportion of populations of different
C cells. The match determines the cell hosting the
C call.

      Do while (random_no.ge.cum_prop(icount))
              icount = icount + 1
      endDo

              ih_cell = ik(icount)
              cell_nxt = ik(icount)

   RETURN
   END
```

SUBROUTINE HOST_Q

```
C In this subroutine, the cell numbers generated
C are placed in a queue in the order in which
C they were generated.

        include 'common.inc'

        cell_q = cell_q + 1

    if(cell_q.le.2) then
        q_cell(cell_q) = cell_nxt
    else
        CALL STOP_PROGRAM
    endif

    RETURN
    END
```

```
      SUBROUTINE NXT_IN_Q

C This subroutine shortens the queue of cell
C numbers.

            include 'common.inc'

            cell_q = cell_q - 1

            q_cell(1) = q_cell(2)
            q_cell(2) = 0

      RETURN
      END
```

SUBROUTINE ALLOCATE

```
C In this subroutine, a call is assigned a free
C channel. Call duration is generated and handoffs
C are determined.

            include 'common.inc'
            logical traced

            iba = ica - 1
            CALL ASSIGN_CHANNEL

      IF(.not.blocked) then
            ilngth = call_length * EXPONENTIAL (seed)
            end_time = clock_time + ilngth
       If(end_time.eq.clock_time) then

C This means that the call duration is zero. Such
C a call is removed from the system and statistics
C are updated.

            c_ch_s(opt_ch,opt_cel) = 1
            call_comp = call_comp + 1
            tot_call = call_comp + numblock
            izero = izero + 1
            occupancy = 50
            time(opt_ch,opt_cel,occupancy) = time(opt_ch,opt_cel,
  u           occupancy) + 1

C This finds the frequency of calls of length zero.

C The borrowed channel serving a call of zero duration is
C rendered free below.

         if(restricted) then
          if(opt_cel.ne.host_cell) then
            i = 1
            traced = .false.
          Do while((i.le.ch_xxx).and.(.not.traced))
            If(notassch(opt_cel,i).eq.opt_ch) then
                  traced = .true.
                  reass(i,opt_cel,host_cell) = 1
            else
                  i = i + 1
            endif
          endDo
```

```
          endif
        endif


      else
              CALL IDEPART

C Since the call is of non-zero duration, it is placed
C appropriately in the departure queue.

C  FINDING LOCATION OF MOBILE AND DIRECTION OF MOTION

              rand1 = UNIFORM (seed)
              x = radius * (2*rand1-1)
              rand2 = UNIFORM (seed)_
              y = sqrt(radius * radius - x*x) * (2*rand2-1)

C x and y co-ordinates of the mobile's initial location
C are generated above. Next, the direction of travel is
C determined. i_dir has values of 1, 2, 3 or 4
C corresponding to the four directions of travel.

              rand3 = UNIFORM (seed)
              i_dir = (4 * rand3) + 1
              If(i_dir.gt.4) jdir4 = jdir4 + 1

C s is the distance from the mobile's initial location to
C the cell boundary in the direction of travel.

              s = abs(sqrt(radius * radius - x*x)-y)

              If(i_dir.eq.2) s = abs(-sqrt(radius * radius-x*x)-y)
              If(i_dir.eq.3) s = abs(sqrt(radius * radius-y*y)-x)
              If(i_dir.eq.4) s = abs(-sqrt(radius * radius-y*y)-x)

              r_ilngth = ilngth

C d gives the distance travelled by the mobile during the
C course of the call in progress. vel is mobile velocity.

              d = (r_ilngth/60.0) * vel

        if(d.ne.0) then
          if(d.ge.s) then
              cross_time = (s/vel)*60.0

C cross_time is the time after which the mobile makes a
C handoff. The mobile makes the handoff at time ih.

              ih = clock_time + cross_time
```

```
            handover = handover + 1

C If a handoff is made, the call is supported by a
C channel in the cell in which it arrived, and by
C another channel in the cell to which handoff is
C made. Thus, a handoff call has more than one channel


C occupancies. The variable 'occupancy', here, stores the
C channel occupancy before the handoff is made.

            occupancy = cross_time
            If(occupancy.eq.0) occupancy = 50

C The handoff times are placed in the handoff queue.

            CALL H_DEPART
         else
            ih = inf
            occupancy = ilngth

C When no handoff is made, channel occupancy is the
C time equal to the call duration.

         endif
        else
            ih = inf
            occupancy = 50
        endif
            time(opt_ch,opt_cel,occupancy) = time(opt_ch,opt_cel,
  u         occupancy) + 1
            iht = ih
            idep = end_time
       endif
      ELSE
            numblock = numblock + 1

C numblock stores the number of blocked calls.

      ENDIF
            irun = irun + 1


   RETURN
   END
```

```
      SUBROUTINE H_DEPART

C This subroutine inserts a new handoff call in
C the queue at the appropriate position.

                  include 'common.inc'

                  h_length = h_length + 1

                  ia = 1
            Do while (ih.gt.q_handoff(ia,3))
                  ia = ia + 1
            endDo

C Above part searches for insertion point.

                  j = h_length
            Do while (j.gt.ia)
                  jjj = j - 1
                  q_handoff(j,1) = q_handoff(jjj,1)
                  q_handoff(j,2) = q_handoff(jjj,2)
                  q_handoff(j,3) = q_handoff(jjj,3)
                  q_handoff(j,4) = q_handoff(jjj,4)
                  j = j - 1
            endDo

C Above part moves items in queue down one position to
C insert.
                  q_handoff(j,1) = opt_cel
                  q_handoff(j,2) = opt_ch
                  q_handoff(j,3) = ih
                  q_handoff(j,4) = host_cell

C Above part inserts new information in queue.

      RETURN
      END
```

```
      SUBROUTINE H_SHORTEN

C This subroutine shortens the handoff queue once
C the handoff has been processed.

            include 'common.inc'

      if(h_length.le.0) then
            write(*,*) ' There is an error in queue'
            ij = 0
      else
            h_length = h_length - 1
      endif

            i = 1
      Do while (i.le.h_length)
            iii = i + 1
            q_handoff(i,1) = q_handoff(iii,1)
            q_handoff(i,2) = q_handoff(iii,2)
            q_handoff(i,3) = q_handoff(iii,3)
            q_handoff(i,4) = q_handoff(iii,4)
            i = i + 1
      endDo

            iq = h_length + 1
      Do 12 k = 1,4
            q_handoff(iq,k) = 2147483647
12    Continue

      RETURN
      END
```

```
      SUBROUTINE SHORTEN_Q

C This subroutine shortens the departure queue once
C the call has been processed.

            include 'common.inc'

      if(q_length.le.0) then
            CALL STOP_PROGRAM
      else
            q_length = q_length - 1
      endif

            i = ip
      Do while (i.le.q_length)
            iii = i + 1
            Kend(i,1) = Kend(iii,1)
            Kend(i,2) = Kend(iii,2)
            Kend(i,3) = Kend(iii,3)
            Kend(i,4) = Kend(iii,4)
            i = i + 1
      endDo

            iq = q_length + 1
      Do 12 k = 1,4
            kend(iq,k) = 2147483647
12    Continue
            finish_time = kend(1,3)

      RETURN
      END
```

```
      SUBROUTINE REASS_INITIALIZE


C In this subroutine, the variables and arrays used
C in Restricted Dynamic Channel Assignment are
C initialized.


              include 'common.inc'
              integer identity


C INITIALIZE ARRAYS AND VARIABLES

              no_ass = .false.
              If(realocate.eq.1) no_ass = .true.

         Do i = 1,4
          Do j = 1,30
           Do k = 1,30
              reass(i,j,k) = 0
           endDo
          endDo
         endDo
         Do i = 1,30
          Do j = 1,4
              notassch(i,j) = 0
          endDo
         endDo

         if(ch_xxx.gt.0) then

          Do j = 1,numcell
            Do i = 1,numch

                 if(c_ch_s(i,j).eq.1) identity = i

            endDo

C The variable identity stores the last channel no. for
C each cell.

            Do i = 1,ch_xxx

C The numbers of the channels that are designated for
C lending to neighbouring cells are stored in array
C notassch. For example, notassch(5,2) = 15 implies
C that the second assignable channel in cell 5 is
```

```
C channel number 15. If a cell has 4 channels, and
C two of them are assignable, then these will be

C the third and fourth channels. For this reason, the
C variable 'identity' helps in determining the channel
C numbers of the assignable channels.

                  notassch(j,i) = (i - ch_xxx) + identity

        endDo
      endDo
    endif

  RETURN
  END
```

```
      SUBROUTINE ALGOR_1

C This subroutine is for the assignment of channel
C in the case of Dynamic Channel Assignment.
C The algorithm used is given in Figure 4.4 of thesis.

                  include 'common.inc'

                  logical neighbors_chkd
                  logical all_chnls_chkd
                  logical all_cells_chkd
                  logical free_channels_checked
                  integer free_ch,max,channels,neighbors
                  integer cells,available_channels

                  max = 0
                  neighbors_chkd = .false.
                  neighbors =1

         Do while (.not.neighbors_chkd)
          If(neighbor(host_cell,neighbors).eq.1) then

C This checks if the cell "neighbors" is a neighbour of the cell "Host_cell"

                         all_chnls_chkd = .false.
                         channels = 1

           Do while(.not.all_chnls_chkd)
            If(c_ch_s(channels,neighbors).eq.1) then

C This checks if the channel "channels" in cell "neighbors" is free

                         min = 999

C min is assigned any large value
                         all_cells_chkd = .false.
                         cells = 1

              Do while(.not.all_cells_chkd)
                 If((cells.ne.host_cell).and.(cells.ne.neighbors)) then
                  If(c_ch_s(channels,cells).ne.0) then

C A channel can be busy (status -1) or free (status 1). This checks for interferable cells.

                         free_ch=0
```

```
                              free_channels_checked = .false.

                              available_channels = 1

                    Do while(.not.free_channels_checked)
                        If(c_ch_s(available_channels,cells)
u                          .eq.1) then

C This counts the number of free channels in interferable cell "cells"

                              free_ch = free_ch + 1
                        endif
                              available_channels = available_channels + 1
                              free_channels_checked = (available_channels.gt.numch)
                    enddo

                        If(free_ch.lt.min) min = free_ch

                  endif
                endif
                              cells = cells + 1
                              all_cells_chkd = (cells.gt.numcell)

          enddo
          if(min.gt.max) then
                              max = min
                              opt_ch = channels
                              opt_cel = neighbors
          endif
      endif

       channels = channels + 1
       all_chnls_chkd = (channels.gt.numch)

     enddo
    endif

                              neighbors = neighbors + 1
                              neighbors_chkd = (neighbors.gt.numcell)

   enddo
   If(max.gt.0) then
                block = .false.
   else
                block = .true.
   endif

 RETURN
 END
```

SUBROUTINE ALGOR_2

```
C This algorithm is for the assignment of channel
C in the case of restricted dynamic channel
C assignment. In this algorithm, a cell can borrow
C the first free assignable channel that is found
C during the search of its neighboring cells.

        include 'common.inc'
        logical search

C host_cell is the cell that gets the call.

        search = .false.

C ch_xxx is the number of assignable channels.

    If((ch_xxx.gt.0).and.(.not.search)) then

        j = 1
     Do while((j.le.numcell).and.(.not.search))
      If(neighbor(host_cell,j).eq.1) then

        k = 1
       Do while((k.le.ch_xxx).and.(.not.search))

C Array notassch contains the channels numbers of the
C k assignable channels of each cell j.

        If(c_ch_s(notassch(j,k),j).eq.1) then
              opt_ch = notassch(j,k)
              opt_cel= j
              reass(k,j,host_cell) = -1
              search = .true.
        else
              k = k + 1
        endif
       endDo
      endif

       j = j + 1

     endDo
    endif
```

```
If(.not.search) then
      blocked = .true.
else
      blocked = .false.
      c_ch_s(opt_ch,opt_cel) = -1
endif


RETURN
END
```

FUNCTION EXPONENTIAL

```
C This function generates random numbers from the
C exponential distribution.

      include 'common.inc'
      external  rnexp,rnset,umach
      call umach(2,nout)
      nr = 1
      call rnset(seed)
      call rnexp(nr,r)
      exponential = r
      call rnget(seed)

      end
```

FUNCTION UNIFORM

```
C This function generates random numbers from the
C uniform distribution.

      include 'common.inc'
      external rnset, rnun, umach
      call umach (2, nout)
      nr = 1
      call rnset (seed)
      call rnun (nr, r)
      uniform = r
      call rnget(seed)

      end
```

```
C   FORTRAN PROGRAM FOR ASSIGNING CHANNELS TO CELLS

C  THIS PROGRAM ASSIGNS THE CHANNELS TO THE DIFFERENT CELLS OF
C  THE 7-CELL REUSE PATTERN SASKTEL CELLULAR NETWORK. IT CREATES
C  A DATA FILE 'C_CH_S.DAT' WHICH IS READ BY THE MAIN SIMULATION
C  PROGRAM. THIS PROGRAM HAS TO BE RUN IF THE NUMBER OF CHANNELS
C  ASSIGNED TO DIFFERENT CELLS NEEDS TO BE CHANGED

              integer cell(30), max1, max, c_ch_s(150,30)
              open(unit = 2, file = 'c_ch_s.dat', status = 'new')
              kk = 0
        Do 20 j = 1,30
         Do 10 k = 1,150
         c_ch_s(k,j) = 0
10       Continue
20      Continue
        Do 40 i = 1,30
                    Write(*,30) i
30                  Format(1x,'ENTER CHANNELS FOR CELL ',I2)
                    read(*,*) ichannel
                    cell(i) = ichannel
40      Continue
                    i = 0
                    igroup = 1
                    max1 = 1
        Do while (igroup.le.7)
                    max = 0
                    i = i + 1
         Do while (i.le.30)
                    k = cell(i)
              Do 50 j = max1, k + max1 - 1
                    c_ch_s(j,i) = 1
50            Continue
                    If(max.lt.k) max = k
                    i = i + 7
         endDo
                    kk = kk + 1
                    i = kk
                    igroup = igroup + 1
                    max1 = max + max1
        endDo
                    max1 = max1 - 1
                    write(2,60) max1
60                  format(1x,i5)
                    write(2,70) ((c_ch_s(i,j), j = 1,30),i = 1,max1)
70                  format(1x,30i2)
              Do 90 i = 1,30
                    write(2,80) cell(i)
80                  format(1x,i3)
90            Continue
        END
```

DATA FILE C_CH_S.DAT SHOWING AN ASSIGNMENT OF 4 CHANNELS/CELL
(A "1" in column 8 of row 1 indicates the presence of channel number 1 in cell 8)

```
28
1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0
1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0
1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0
1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0
0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1
0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1
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DATA FILE DIR.DAT SHOWING NEIGHBOURING CELLS TO EACH CELL IN THE 4 DIRECTIONS OF TRAVEL

(A "0" in row 1 column 4 indicates that there is no neighbouring cell for cell 1 in direction 4)

0	4	2	0
0	5	17	1
1	6	4	0
2	7	5	3
17	8	20	4
4	0	7	0
5	10	8	6
5	11	9	7
21	12	24	8
8	13	11	0
9	14	12	10
9	29	27	11
11	0	14	0
12	0	29	13
0	18	16	0
0	19	0	15
15	5	18	2
16	21	19	17
16	22	0	12
18	8	21	5
19	9	22	20
0	25	23	21
0	26	0	22
22	27	25	9
23	28	26	24
23	28	0	25
25	30	28	12
26	30	0	27
27	0	30	14
28	0	0	29

DATA FILE NEIGHBOR.DAT SHOWING NEIGHBOURING CELLS

(A "1" IN COLUMNS 2, 3, AND 4 OF ROW 1 INDICATES THAT CELLS 2, 3, AND 4 ARE NEIGHBOURING CELLS TO CELL 1)

```
0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
1 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1 1 1 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 1 0 1 0 0 1 1 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 1 1 1 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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```

FILE COMMON.INC

```
PARAMETER (NUMCELL = 30,NUMCH = 28)

integer reass(4,30,30),notassch(30,4),ch_xxx,realocate
integer host_cell,opt_ch,opt_cel,q_length,numblock
integer kend(600,4),q_handoff(600,4),bb(30,4),nch,occupancy
integer finish_time,ip,q_cell(2),cell_q,i_dir,h1_block
integer c_ch_s(numch,numcell),ik(30),Tot_call,handoff_
integer neighbor(30,30),cell_ch(30),n_pop,cell_nxt,n
integer time(numch,numcell,50),call_comp,method,handover
integer call_length,seed,end_time,clock_time,cross_time
real w_o(numch,numcell,50),t_o(numch,numcell)
real cell_c_o(numcell),riclock,c_o(numch,numcell)
real sum,pop(30),prop(30),cum_prop(30),random_no,radius,vel
real pop_srt(30),arr_wt(30),rate(30),mult_arr
logical no_ass,handoff_yes,n_free,busy_detect
logical blocked,error,arrival,departure,handoff
logical fixed,dynamic,restricted,not_done
logical borrowed_chnl_found

common /i1/c_ch_s
common /i2/opt_cel,opt_ch
common /i3/neighbor
common /i4/ij,handover
common /i5/blocked
common /i6/end_time
common /i7/kend
common /i8/ik,cum_prop,n_pop
common /i9/ip
common /i10/ih
common /i11/q_length
common /i12/h_length
common /i13/q_handoff
common /i14/ih_cell,icount
common /i15/ clock_time,method
common /i16/iht,arrival_time
common /i17/iba,ica,jdir4,handoff_,radius,irun,call_length
common /i18/host_cell
common /i19/cell_nxt
common /i20/cell_q
common /i21/q_cell
common /i22/call_comp
common /i23/tot_call,numblock
common /i24/izero,inzero
common /i25/time,occupancy
common /i26/error,in_zero,sum,in_seed,alngth
common /i27/nch,pop_avg,w_o,t_o,c_o,cell_c_o,cell_ch,prop
common /i28/pop_srt,arr_wt,pop
common /i29/inf
```

```
common /i30/mult_arr
common /i31/r_handoff,sim_hpc,anal_hpc,hpc_err,blo_prob
common /i32/ablock,riclock
common /i33/itest
common /i34/rate
common /i35/num_call
common /i36/finish_time
common /i37/bb
common /i38/iwrong
common /i39/i_dir
common /i40/h1_block,ih_block
common /i41/not_done
common /i42/arrival,departure,handoff
common /i43/fixed,dynamic,restricted

common /speed/vel
common /isd/seed
common /reassign_c/no_ass
common /bor_lend/reass
common /ass_chnl/notassch
common /yes_chnl/ch_xxx,borrowed_chnl_found
common /allocation/realocate
common /jr/j2
common /jrk/j3
```