Performance Modeling of the Digital Communications System

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1. Introduction

In this project, simulation and analytical models are developed for the performance evaluation of the IBM Digital Communication System (DCS) Radio Frequency Network. The goal of this modeling effort is to provide both the inbound and outbound response time for various traffic intensities in this system. From these statistics, the users and especially the operators of DCS will gain better knowledge about the behavior of this system. In this report, we first describe the structure and operation of DCS. Next, the flow chart and data structure of the simulation program are presented. Section 5 includes some selected results to show the performance of the system. From these results, we can identify that the bottleneck of this system is the outbound traffic. Therefore, the analytical model focuses specifically on the behavior of outbound traffic. Sections 6 to 8 are devoted to the formulation, derivation and discussion of this model. Also, we will look into the upper and lower bounds of the outbound messages delay. Finally, we will make some comment about the results and offer suggestion for future work.

2. System description

This network is a two-way radio frequency data communications system. the DCS links the users, using the DCS Portable Terminal (PT), described in detail later, with the IBM Host computer to which the users are assigned. The network components are:

2.1 Host computer

The Host computer is used primarily for dispatching, updating, and closing customer service calls. Additional applications are used for parts ordering and for service data collection.

2.2 General communication controller (GCC)

This device was built for IBM by Motorola. The functions of the GCC are:

a. Interface via SNA/SDLC to the Host(s).
b. Interface via HDLC to Base Station.
c. Translate messages from Host protocol to PT protocol.
d. Remove inbound duplicate messages.

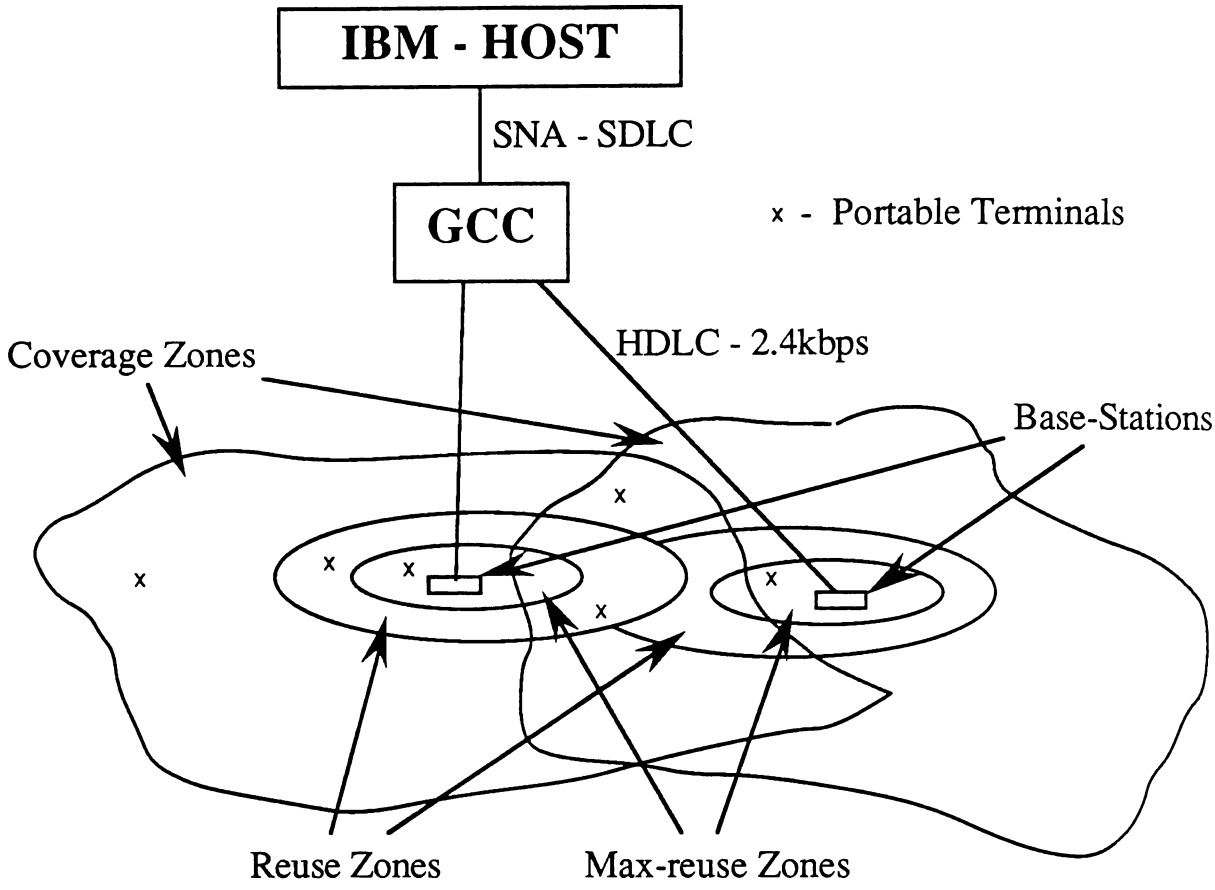

Figure 1. DCS - OVERVIEW

e. Track location of each PT.
f. Maintain database, by PT, of message statistics and message routing information.
g. Control PT registration.
h. Control transmitter selection for outbound.
i. Control transmitter operation for outbound.
j. Provide service interface (alarms, testing, etc.) to network.

2.3 Base station

The Base Station provides the following functions:

a. Receive messages from GCC and encode for RF transmission.
b. Convert digital signal to analog for RF modulation and transmission.
c. Receive inbound messages.
d. Convert from analog to digital.
e. Decode inbound messages for GCC.

f. Measure signal strength and append signal strength indicator (SSI) to inbound message.
g. Sense Base Station faults and forward to GCC.
h. Test Base Station upon command from GCC.

2.4 Portable terminal (PT)

The DCS PT is a 2 lb. hand held device. Its characteristics are:

a. Two line, 27 character LCD display.
b. Alphanumeric keyboard.
c. Up to 80K bytes of RAM (DCS has 32K RAM).
d. Up to 160K bytes of ROM.
e. 6801 type main processor.
f. Parallel and serial interface "external" connector.
g. 103A compatible modem for telephone connection and data transmission.
h. 800Mhz RF transceiver:
    1) Consists of 6801 type processor.
    2) Encodes and decodes RF transmissions.
    3) Senses "busy" on inbound channel.

2.5 Radio channel characteristics

The RF channel is licensed for private business radio. It is a 25Khz channel for inbound and a 25Khz channel for outbound traffic. The inbound and outbound channels are 45Mhz apart and are in the 800Mhz range. The data rate in the RF range is 4800bps with a Forward Error Correction Code that uses 112RF bits to transport 48 data bits.

3. Operating principle

The major feature of this system is the coverage principle that exists for the portable terminals in the system (see Fig. 1). This coverage principle permits a PT to have its communication picked up by a number of base stations. The ready terminal senses the outgoing transmission channel, i.e. transmission from the base station to the PT. If a busy signal is sensed on this channel, the PT waits with its transmission since this is an indication that another PT is currently transmitting on the inbound channel. This protocol is equivalent to a busy-tone protocol. The transmission begins as soon as the PT senses, through the absence of a busy tone, that the inbound channel is available . The inbound transmission is then relayed through the base station to the GCC.

The operation of the outbound channel is as follows. The GCC maintains a directory of interference tables such that the response to a PT can be delayed due to the fact that a currently transmitting base station may be interfered with if the response to the PT is issued immediately. Consequently, there is a possibility that the base station may have an outbound message to send and the capacity to send that message exists but the transmission cannot take place due to the fact that this transmission may interfere with an ongoing transmission.

If errors have ever occurred and no ACK is received, the transmitter, either PT or GCC, will wait a 4-second time-out period before it tries again. For an inbound PT, it will give up after three attempts have failed. For the outbound case, the GCC will try to send a message to a designated PT through a certain base station. It will try again if the first transmission did not get through. If both attempts fail, the GCC will use another base station to send this message. After another two failures, GCC will give up and notify the host computer.

4. Flow charts and data structures for the simulation program

The simulation program is written in C language with an interactive user interface. The user will be asked to input system specifications and to provide interference information and traffic distribution. The program will be run until a fixed stopping time, user defined, is met.

4.1 Flow charts

There are nine events (cases) in this event-driven program (see Fig. 2). The first three cases are related to inbound traffic. The next four events are due to outbound activities. Event IDLE takes care of those events which have run out their 20 second window periods by simply removing them from the *awake_que*. The *awake_que* collects all PT's which have finished their inbound or outbound events. These PT's will be kept in the *awake_que* for 20 seconds. During this window period, the GCC will assume that these PT's are active. If the GCC has a message to send, it will send this message out to these active PT's without paging them. Event RECORD does the bookkeeping in order to calculate the statistics and their confidence intervals. The flow charts of the main procedure and the first seven events are shown in the following figures.

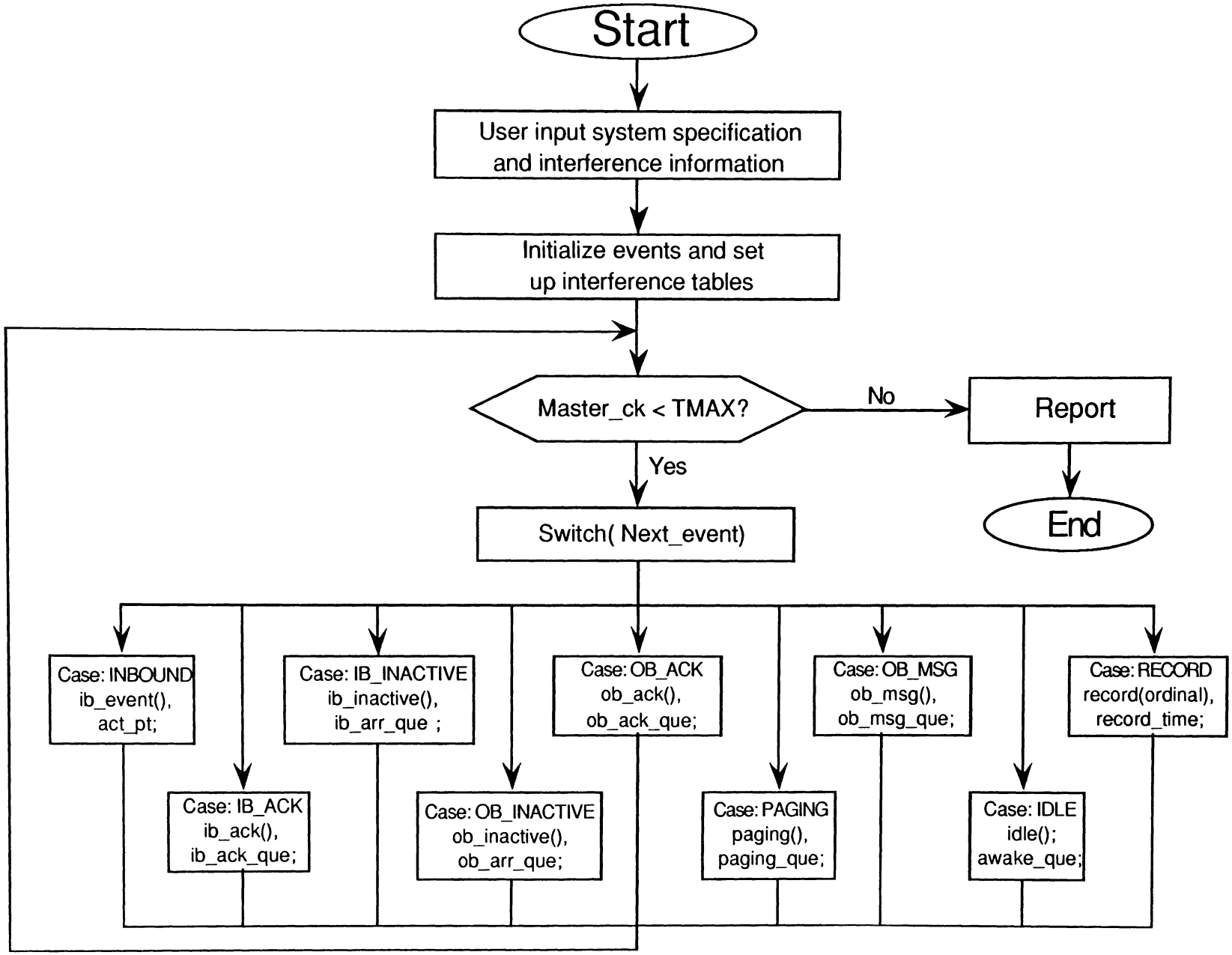
Start
User input system specification and interference information
Initialize events and set up interference tables
Master_ck < TMAX?
No
Report
End
Yes
Switch(Next_event)
Case: INBOUND ib_event(), act_pt;
Case: IB_ACK ib_ack(), ib_ack_que;
Case: IB_INACTIVE ib_inactive(), ib_arr_que ;
Case: OB_INACTIVE ob_inactive(), ob_arr_que;
Case: OB_ACK ob_ack(), ob_ack_que;
Case: PAGING paging(), paging_que;
Case: OB_MSG ob_msg(), ob_msg_que;
Case: IDLE idle(); awake_que;
Case: RECORD record(ordinal), record_time;

Figure 2

Case: INBOUND

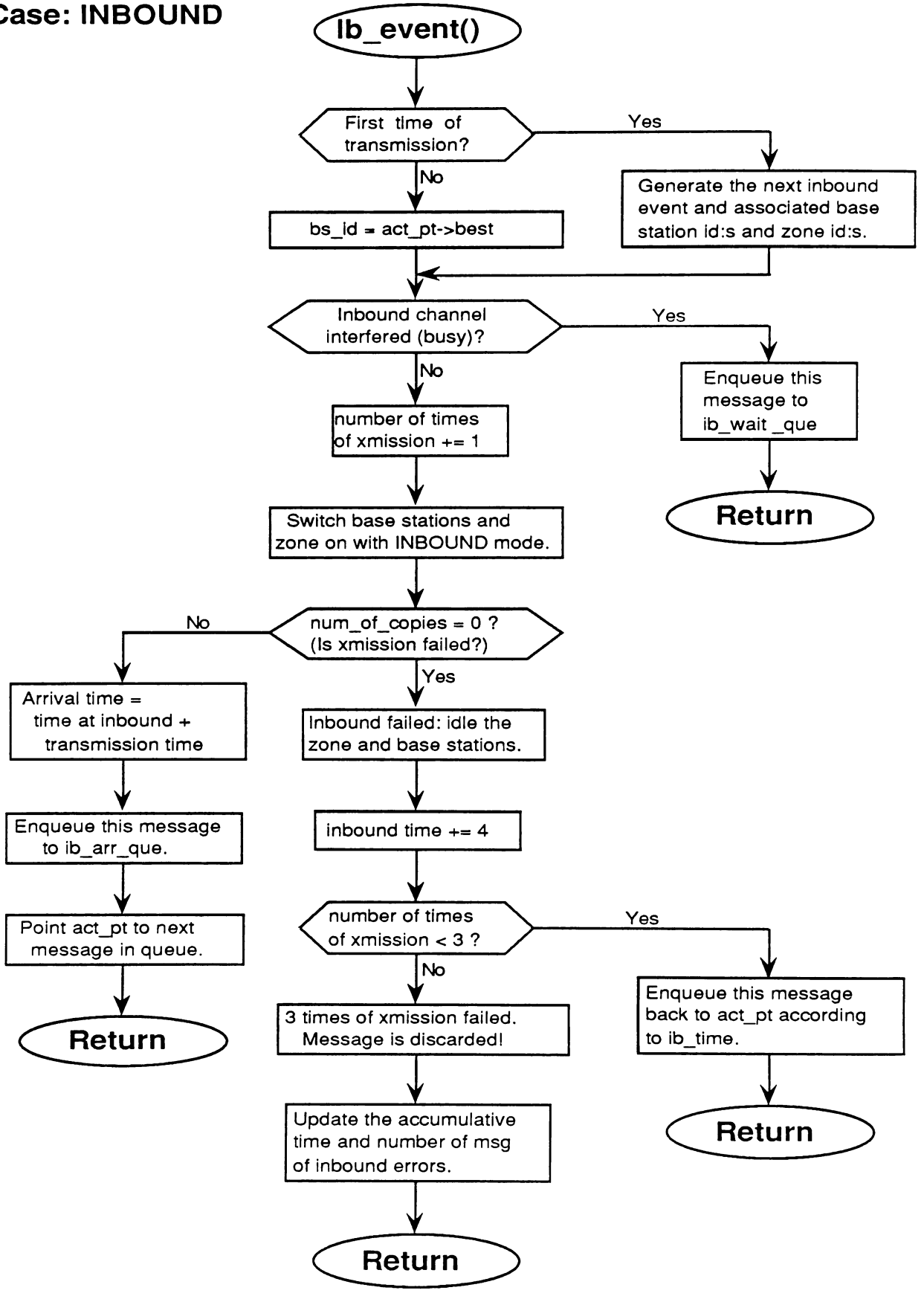

Figure 3

Case: IB_ACK

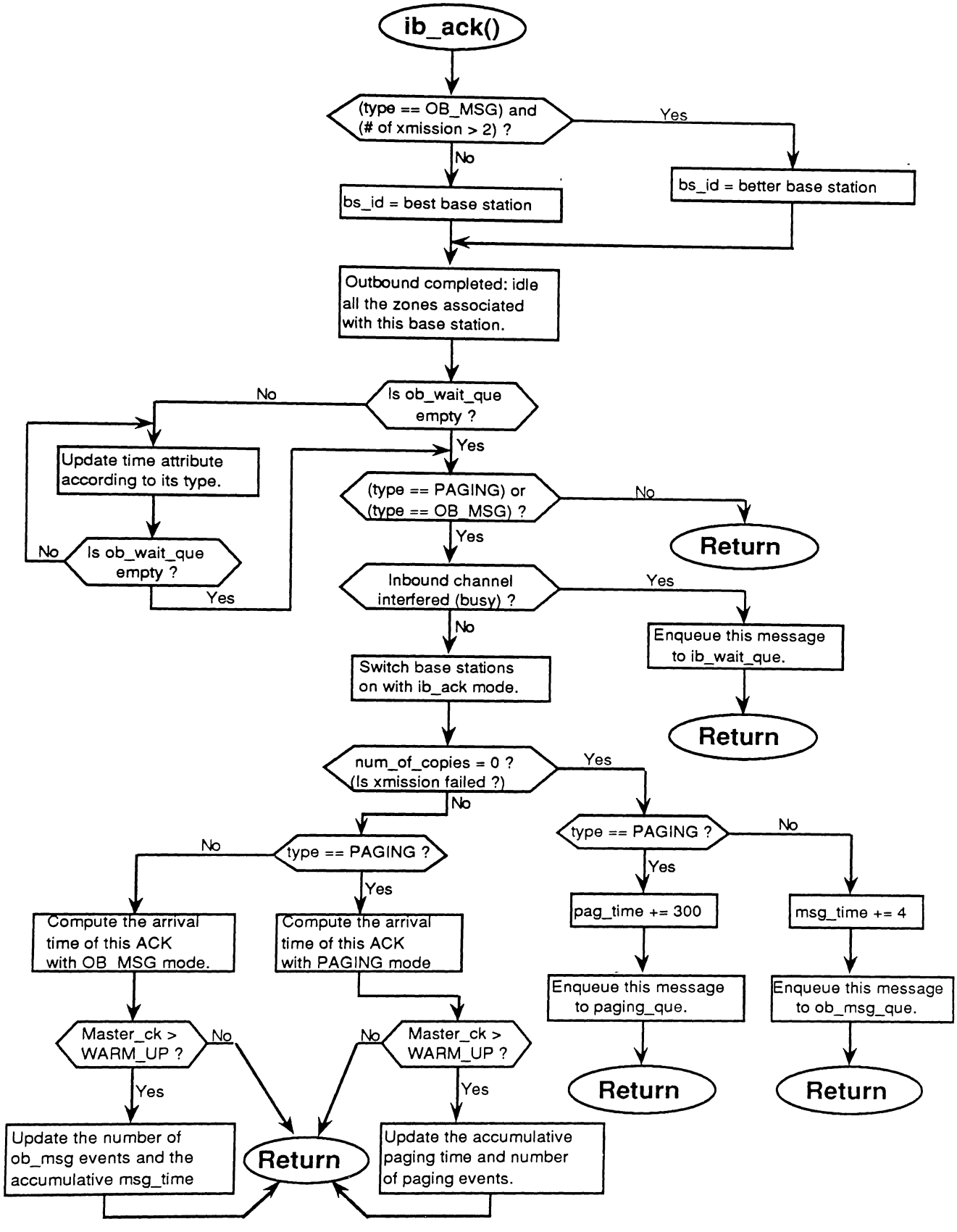

Figure 4

Case: IB_INACTIVE

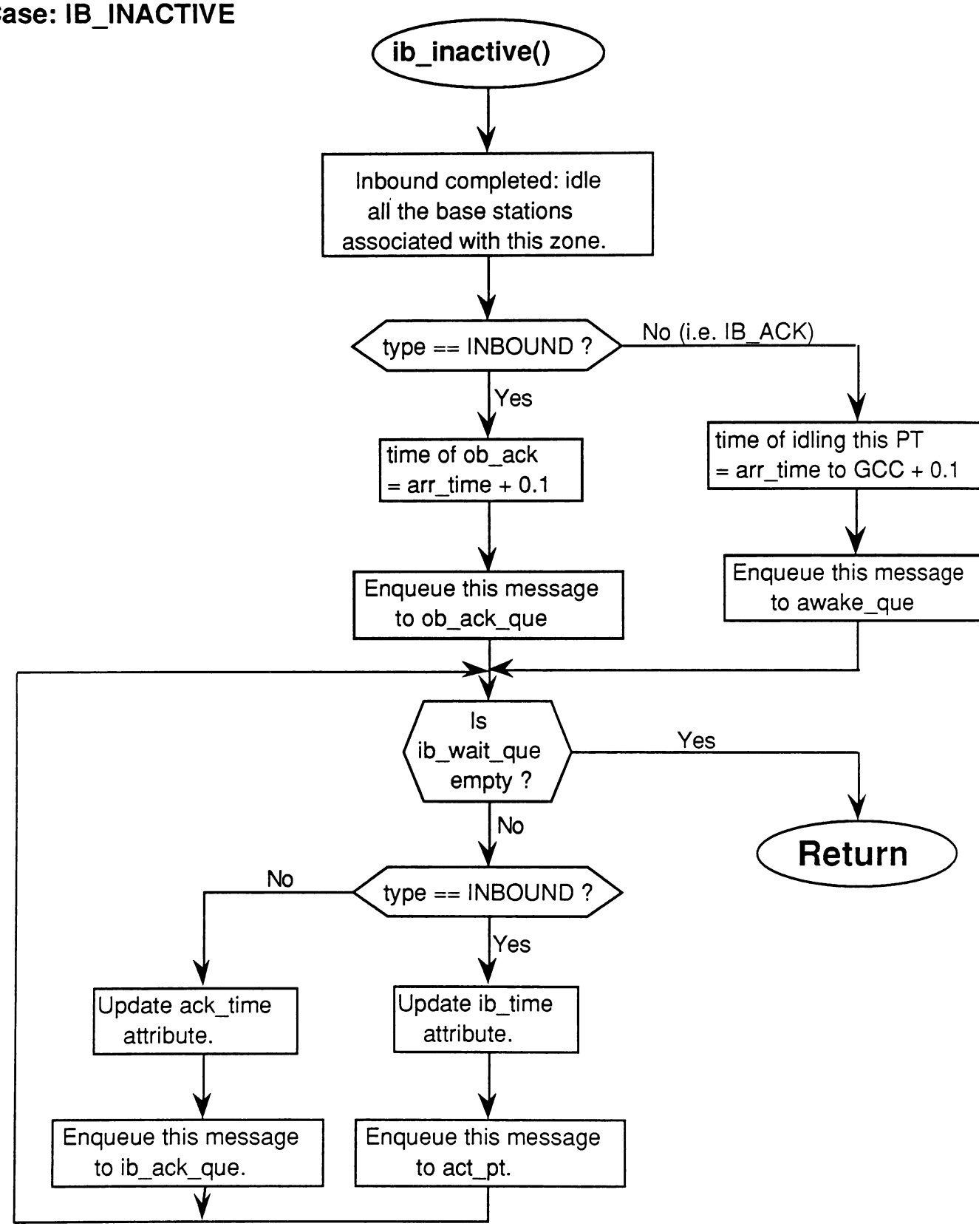

Figure 5

Case: OB-INACTIVE

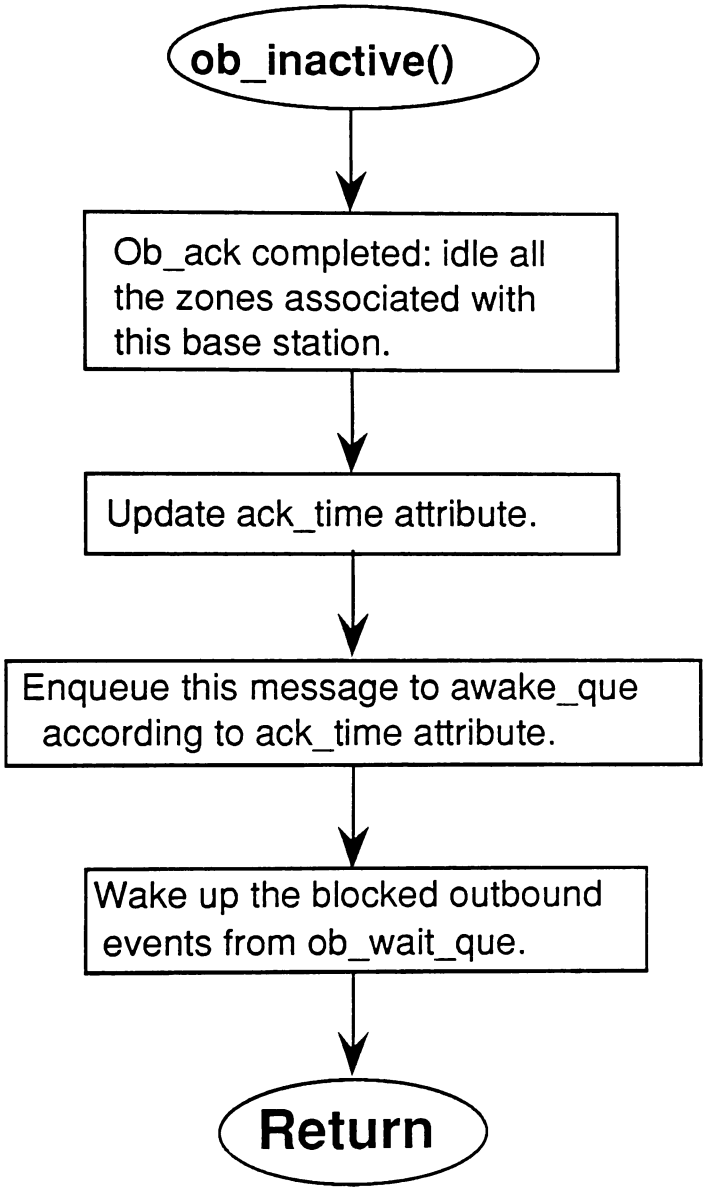

Figure 6

Case: OB_ACK

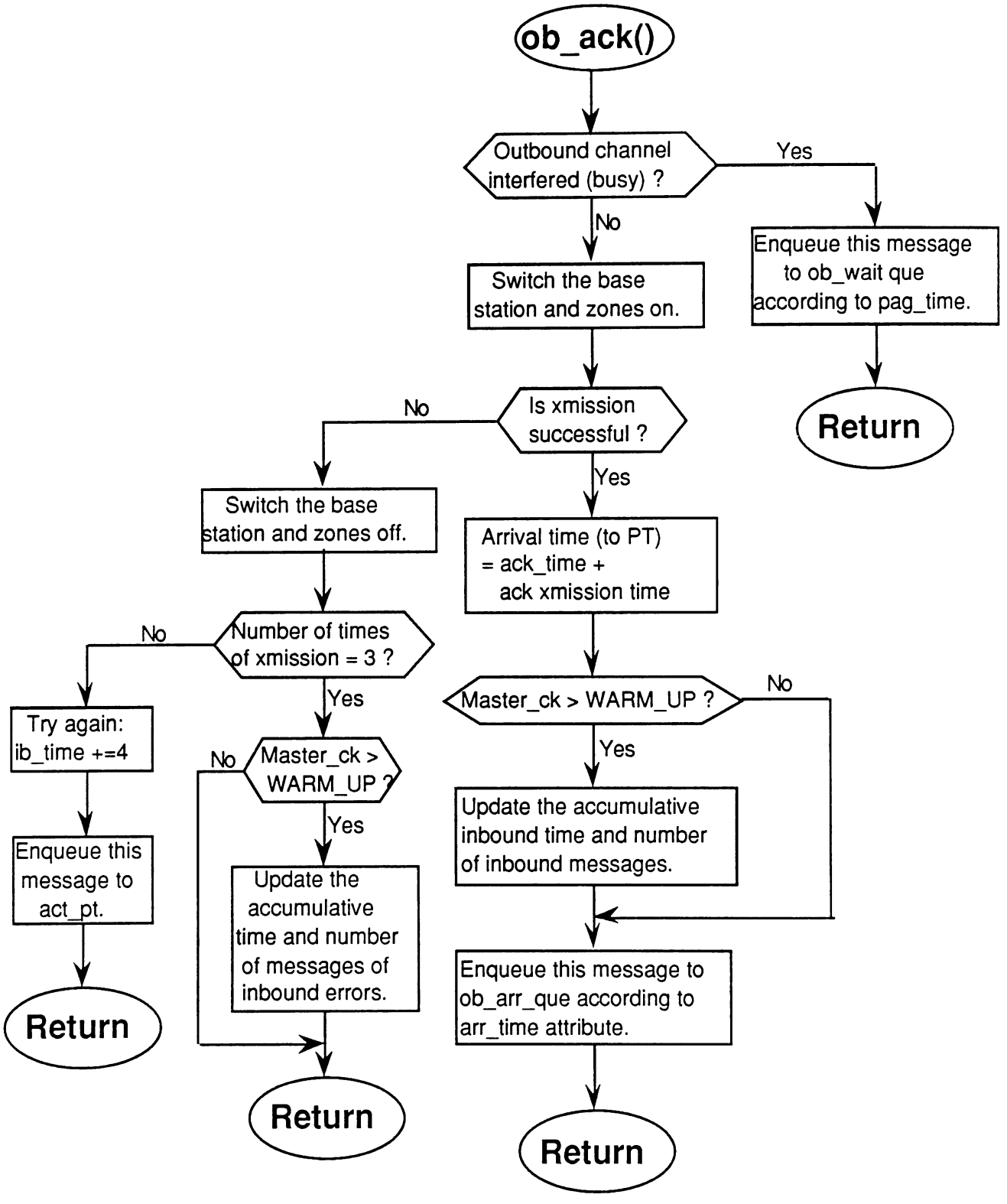

Figure 7

Case: OB_MSG

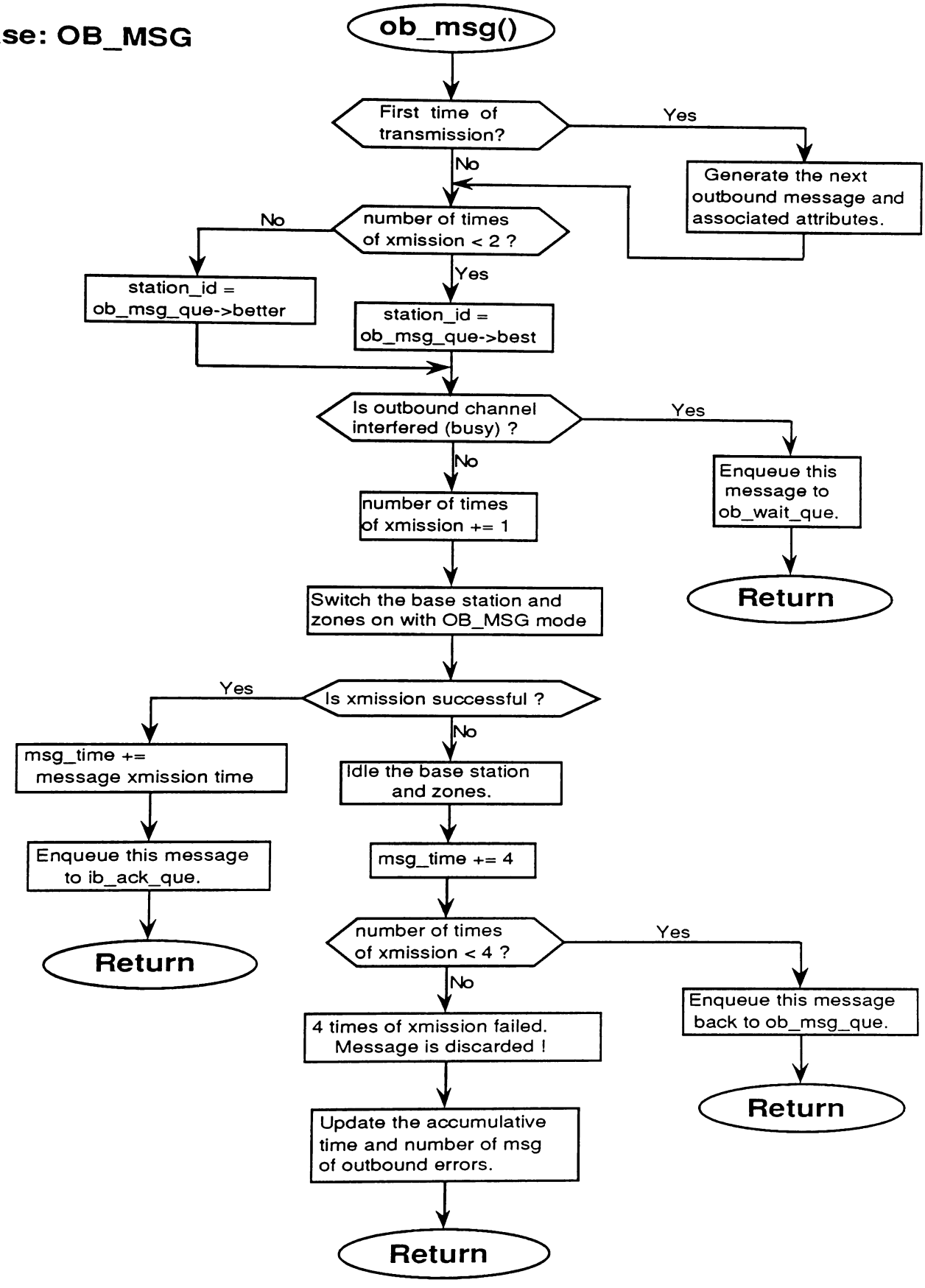

Figure 8

Case: PAGING

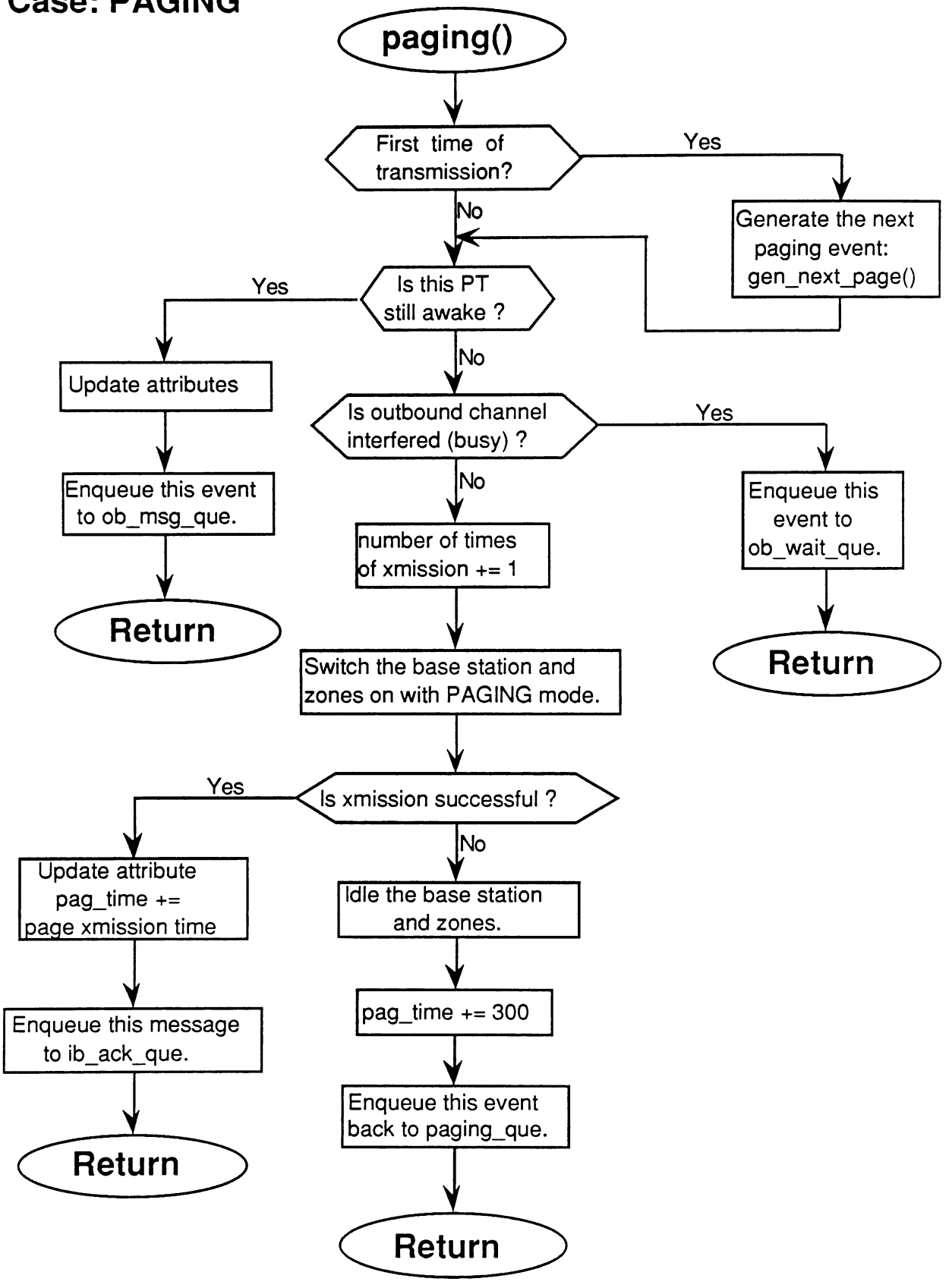

Figure 9

4.2 Data structures

1. The following types of data structures are defined in this program:

QUE: defining a structure which is a linked list.

```
typedef struct queue
{
   int entity;
   struct queue *next;
}QUE;
```

TERMINAL: defining a structure which has all the attributes of a terminal.

```
typedef struct terminal
{
   int id;
        the identification number of a portable terminal(PT).
   int type;
        the event type which this PT is holding.
   int zone;
        the zone area in which this PT is located.
   int best;
        the best base station decided by GCC.
   int better;
        the better base station decided by GCC.
   int num_tx;
        number of times this PT has tried a transmission.
   double gen_time;
        the time at which the event is generated.
   double ib_time;
        the time at which the inbound message starts its
        transmission.
   double arr_time;
        the time at which the inbound message arrives at GCC.
   double pag_time;
        the time at which the page event starts its transmission.
   double msg_time;
        the time at which the outbound message starts its
        transmission.
   double ack_time;
        the time at which an ACK is transmitted from a PT to
        GCC or from GCC to a PT.
   double try_time;
```

```
            the time at which the inbound or outbound message
            resume its transmission after an error occurs.
        struct terminal *next;
            pointer which points to next PT with the same event
            type.
    } TERMINAL;

STATION:   defining the structure of a base station.
    typedef struct base_station
    {
        QUE zone_covered;
            linked list which includes all the zone areas interfered
            by this base station.
        int active;
            the status that the station is holding.
        int correct;
            the indication of correctness of an inbound transmission.
        int max_zone;
            the max_reuse zone of this station.
        int cov_zone;
            the coverage zone of this station.
        QUE reuse;
            the reuse zones of this station; it is a linked list.
    } STATION;

ZONE:  defining the structure of zone in this system.
    typedef struct zone_area
    {
        QUE pt;
            the portable terminals which are located in this zone.
        QUE bs_interfered;
            linked list which includes all the base stations that
            could be interfered by an active PT in this zone.
        int bs_id;
            the identification number of the base station to which
            this zone belongs.
        int active;
            the status of this zone, indicating whether it is idle or
            certain PT's are active in this zone.
        int pt_id;
            indicating the identification number of the PT which is
            active.
    } ZONE;
```

FLOW: defining the accumulative percentage of traffic with respect to zone identification numbers.

```
typedef struct flow_distribution
{
    int zone_id;
    float sum;
        the accumulative percentage of traffic with respect to
        this zone_id.
} FLOW;
```

2. The following pointers point to linked lists which keep track of all the transmission events.

*act_pt:
pointer pointing to a linked list of active PT's with inbound messages.

*ib_wait_que:
pointer pointing to a linked list of PT's which are blocked by other active inbound PT's.

*ib_ack_que:
pointer pointing to a linked list of active PT's with ACK's to GCC.

*ib_arr_que:
pointer pointing to a linked list of PT's with messages or ACK's arriving at GCC.

*ob_arr_que:
pointer pointing to a linked list of outbound ACK's arriving at PT's.

*ob_ack_que:
pointer pointing to a linked list of PT's which are the receivers of outbound ACK's from GCC.

*paging_que:
pointer pointing to a linked list of PT's which are the receivers of pages from Host through GCC.

*ob_msg_que:
pointer pointing to a linked list of PT's which are the receivers of messages outbound from GCC.

*ob_wait_que:
pointer pointing to a linked list of outbound events blocked by other outbound activities.

*awake_que:

pointer pointing to a linked list of PT's which are awake in their window period.

5. Selected results

The following two figures, Figs. 10 and 11, present the simulation results obtained from using the specification of the DCS in Chicago. Figure 10 is the comparison of inbound and outbound message delays with respect to different inbound traffic intensities when the outbound message rate is fixed at 1 msg/sec. Figure 11 shows the delays incurred by inbound and outbound messages when the outbound traffic rate is varied and the inbound message rate is fixed at 1.0665 msg/sec. There are 34 base stations with 110 zones on site. The interference table was given and the traffic distribution was made up randomly. The other common parameters used in both figures are as follows:

(1). Mean length of inbound messages: 128 bytes (uniform distrib.)
(2). Mean length of outbound messages: 128 bytes (uniform distrib.)
(3). Percentage of pages response / inbound arrival: 10%
(4). Percentage of pages / outbound arrival: 10%
(5). Error rate inbound: 0
(6). Error rate outbound: 0
(7). Percentages of messages outbound to coverage zone, reuse zone and max reuse zone by base stations are 20%, 40% and 40% respectively.
(8). Number of portable terminals in network: 200

Figure 12 indicates the difference of inbound and outbound delays when both the inbound and outbound error rates are at 0%, 5% and 10%, respectively. Figure 13 shows the inbound and outbound delays when both the percentage of pages response per inbound arrival and the percentage of pages per outbound arrival are raised from 10% to 20%. The rest of parameters of figures 12 and 13 are the same as being shown above.

6. Formulation of the analytical model

From figures 10 and 11, It is clear that the delay of outbound messages is much more sensitive to both inbound and outbound traffic intensities than the delay of inbound messages. The reason for this result is due to the fact that pages and outbound ACK's have a higher priority than outbound messages. This fact tends to delay outbound message

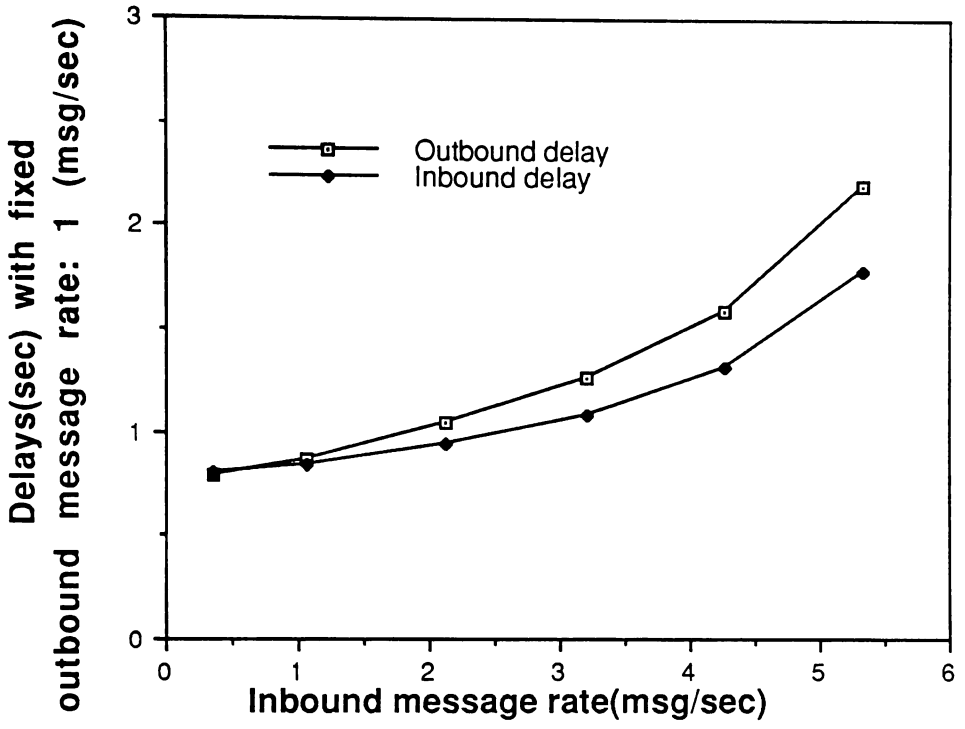

Figure 10

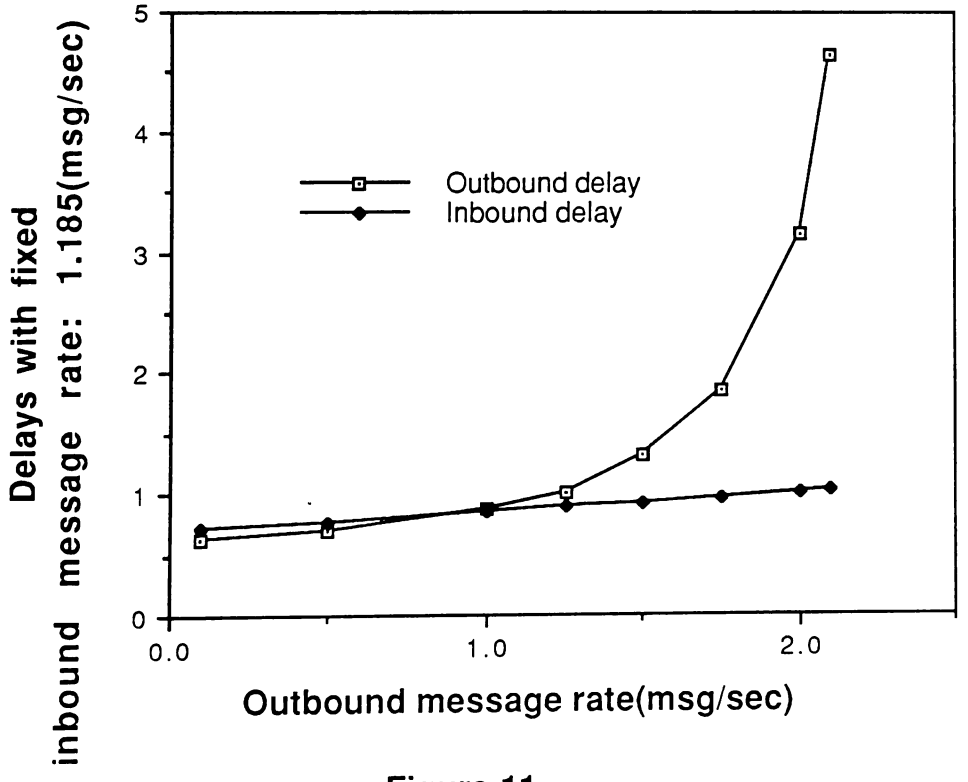

Figure 11

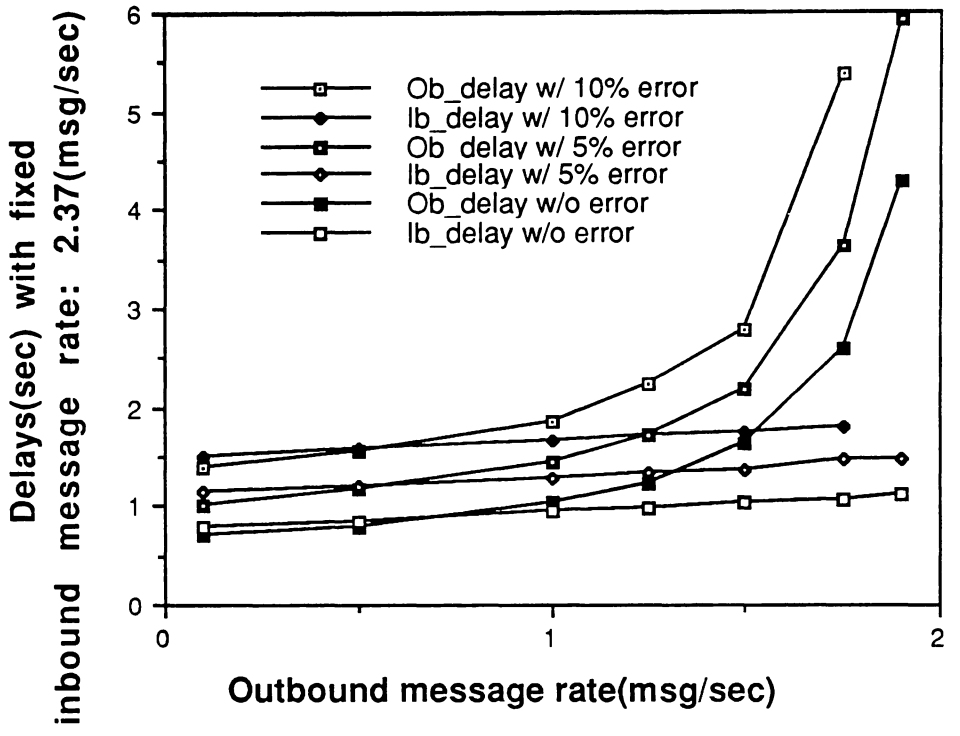

Figure 12

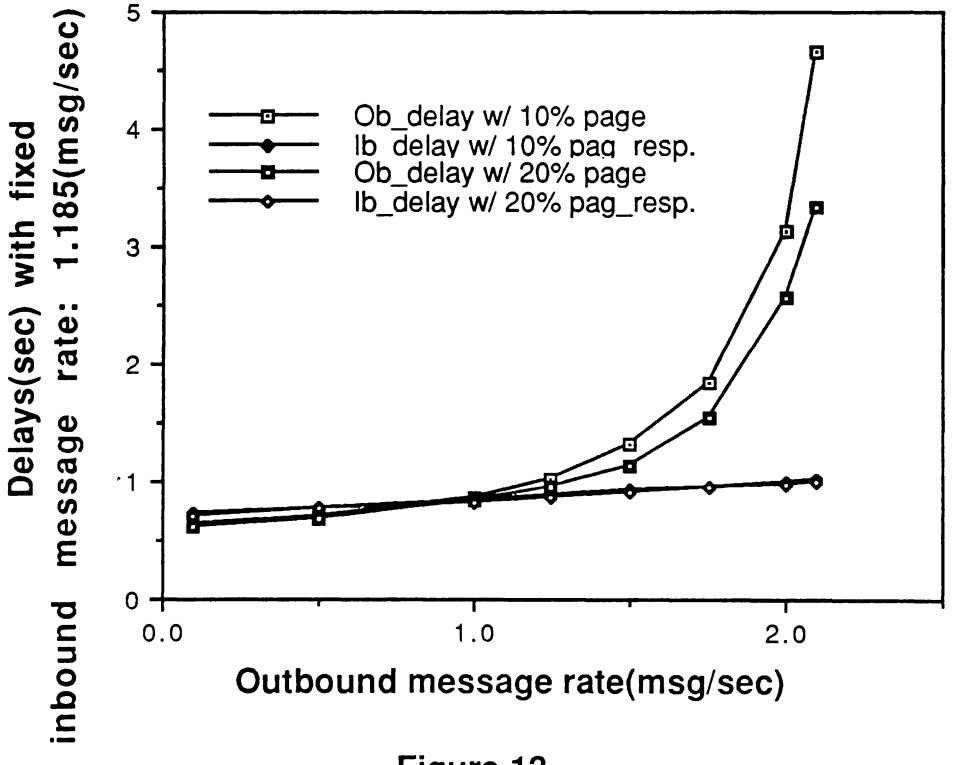

Figure 13

transmission. On the other hand, inbound ACK's do not have priority over inbound messages. For heavy traffic intensity, the outbound messages may not be able to receive their ACK's within 4 seconds (time-out period). Hence, the retransmission rate of outbound messages tends to get higher and increase the probability of outbound traffic congestion. Therefore, from the system operation point of view, we know the outbound behavior is the bottleneck of this system.

Based on this observation, we now proceed to formulate the analytical approach for outbound transmission. The model of the outbound channel can be viewed as a multi-server queueing model where there is a possibility that there are demands waiting to be served in the queue, but those demands cannot currently be served due to the coverage interference effect. In principle, this queueing model does not have a closed form solution and, thus, we will develop an approximate analytical model which uses a statistical decision mechanism that mimics the interference effect.

6.1 Model of the outbound operation

The GCC with its outbound HDLC-links will be modeled as a multi-server queue, i.e. the GCC will roughly be viewed as the queue, and the HDLC-links will be the servers in this model (see Figure 14).

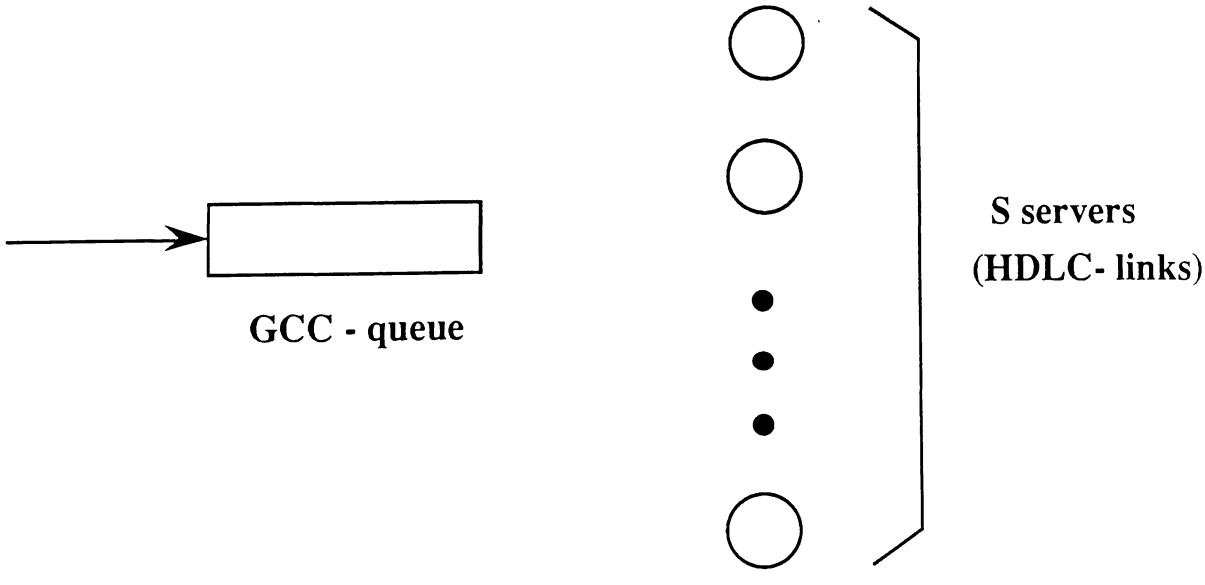

Figure 14

Due to interference there will be certain servers that cannot be used, due to the fact that there are transmissions currently in

progress that would interfere with the transmission of a new outbound packet.

6.2 Definition of notation

(1). S : number of servers (base stations or HDLC links) in the system

(2). λ : outbound arrival rate (msg/sec)

(3). μ : outbound service rate (msg/sec)

(4). f(n) : blocking probability
f(n) is the conditional probability that a new outbound arrival will be blocked given there are n servers busy, i.e.
f(n) = prob[a new arrival will be blocked | n servers busy].

(5). p(n, q) : steady state distribution
where n denotes the number of active servers (base stations or HDLC links), q denotes the number of customers (outbound messages) in queue.

6.3 State transition diagram and global balance equations

The overall state transition diagram is depicted in figure 15. We will derive the global balance equations from this diagram. It is found that, when

1. $n = 0, q = 0$
$$\lambda p(0, 0) = \mu p(1, 0),$$

2. $1 \le n \le s-1, q = 0$
$$(\lambda + n\mu)\, p(n, 0) = \lambda[1 - f(n-1)]p(n-1, 0) + n\mu[1 - f(n-1)]p(n, 1) + (n+1)\mu p(n+1, 0),$$

3. $n = s, q = 0$
$$(\lambda + s\mu)p(s, 0) = \lambda[1 - f(s-1)]p(s-1, 0) + s\mu[1 - f(s-1)]p(s, 1),$$

4. $1 \le n \le s-1, q = 1$
$$(\lambda + n\mu)p(n, 1) = \lambda f(n)p(n, 0) + n\mu[1 - f(n-1)]p(n, 2) + (n+1)\mu f(n)p(n+1, 1),$$

5. $1 \le n \le s-1, q \ge 1$
$$(\lambda + n\mu)p(n, q) = \lambda p(n, q-1) + n\mu[1 - f(n-1)]p(n, q+1) + (n+1)\mu f(n)p(n+1, q),$$

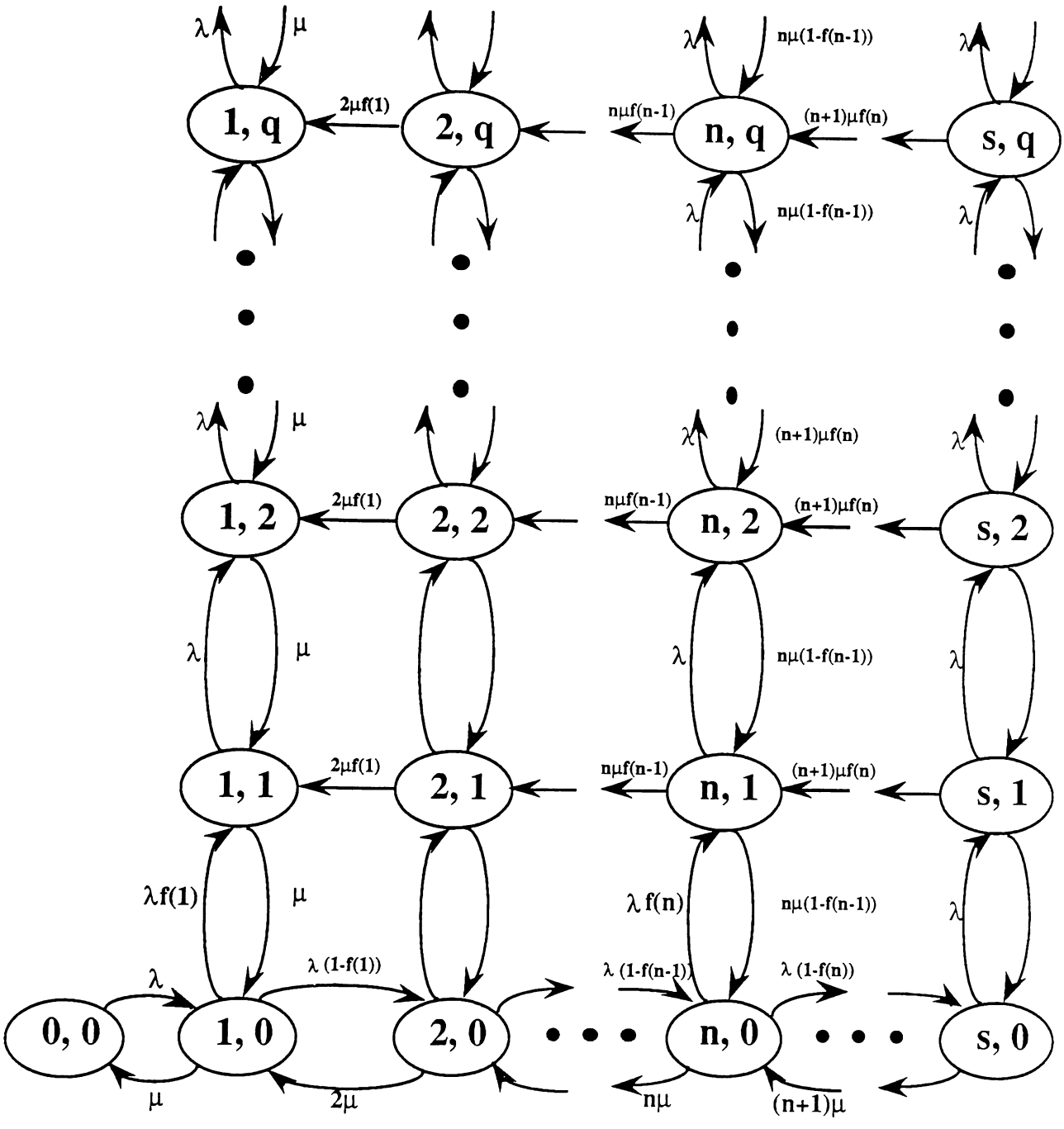

Figure 15 Transition diagram

6. $n = s,\ q \geq 1$

$$(\lambda + s\mu)p(s,\ q) = s\mu[1 - f(s-1)]p(s,\ q+1) + \lambda p(s,\ q-1).$$

6.4 Transition matrix and equations

These global balance equations can be composed into a concise matrix form. Let

$$\Pi(q) = \begin{bmatrix} p(1, q) \\ p(2, q) \\ \vdots \\ p(S, q) \end{bmatrix} \qquad \Lambda_0 = \begin{bmatrix} \lambda \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

$$\Lambda_1 = \begin{bmatrix} \lambda f(1) & & & 0 \\ & \lambda f(2) & & \\ & & \ddots & \\ 0 & & & \lambda f(S) \end{bmatrix} \qquad \Lambda_2 = \begin{bmatrix} \lambda & & & 0 \\ & \lambda & & \\ & & \ddots & \\ 0 & & & \lambda \end{bmatrix}$$

$$B_0 = \begin{bmatrix} -(\lambda+\mu) & 2\mu & & & 0 \\ \lambda[1-f(1)] & \ddots & \ddots & & \\ & \ddots & \ddots & \ddots & \\ & & \ddots & \ddots & S\mu \\ 0 & & & \lambda[1-f(S-1)] & -(\lambda+S\mu) \end{bmatrix}$$

$$B = \begin{bmatrix} -(\lambda+\mu) & 2\mu & & 0 \\ & \ddots & \ddots & \\ & & \ddots & S\mu f(S-1) \\ 0 & & & -(\lambda+S\mu) \end{bmatrix}$$

$$C = \begin{bmatrix} \mu[1-f(0)] & & & 0 \\ & \mu[1-f(1)] & & \\ & & \ddots & \\ 0 & & & S\mu[1-f(S-1)] \end{bmatrix}$$

Now the global balance equations can be written as follows:

7. For $q = 0$
$$p(0, 0)\Lambda_0 + B_0 \Pi(0) + C\, \Pi(1) = \underline{\mathbf{0}},$$

8. For $q = 1$
$$\Lambda_1 \Pi(0) + B\, \Pi(1) + C\, \Pi(2) = \underline{\mathbf{0}},$$

9. For $q \geq 2$
$$\Lambda_2 \Pi(q - 1) + B\, \Pi(q) + C\, \Pi(q + 1) = \underline{\mathbf{0}}.$$

7. Derivation of the analytical results

Our goal is to obtain the steady state distribution, $\Pi(q)$, in order to compute the mean queue length. Once the mean queue length is known, the system delay will be determined by applying Little's result.

It can be seen from equations 7 to 9 that the vector $\Pi(q)$ is in a recursive form. This observation implies that we may solve $\Pi(q)$ by applying the matrix-geometric method. Assume that $\Pi(q)$ can be represented as:

10. $\Pi(q) = R^{q-1}\Pi(1)$ for $q \geq 1$,

where the matrix R is to be found. From equations 7 to 10, we have

11. $p(0, 0)\Lambda_0 + B_0 \Pi(0) + C\, \Pi(1) = \underline{\mathbf{0}}$ $q = 0$,
12. $\Lambda_1 \Pi(0) + B\Pi(1) + CR\, \Pi(1) = \underline{\mathbf{0}}$, i.e.
$\Pi(0) = -\Lambda_1^{-1}(B + CR)\Pi(1)$ $q = 1$,

and

13. $CR^2 + BR + \Lambda_2 = \underline{\mathbf{0}}$ $q \geq 2$.

Substituting eq. 12 in eq. 11, we can express the elements of the vector $\Pi(1)$ in terms of $p(0, 0)$. The value of $p(0, 0)$ will be determined by normalization. After $p(0, 0)$ is known, we can find $\Pi(q)$.

We now are in the position of computing matrix R. Observing the forms of matrix B and C, we can prove that matrix R has an upper triangular form. (This can be verified from eq. 13 by the argument of the iterative algorithm.). The diagonal elements can be easily obtained by solving S

second order equations. Note that there are two solutions (with plus and minus signs) from each second order equation. It turns out that only the one with a minus sign is a valid solution. The one with a plus sign will generate negative elements of $\Pi(q)$; it is obviously incorrect and should be discarded. The values of the other elements are as follows:

$$14. \quad r_{i,i+k} = 1 - \frac{\sum_{j=i}^{i+k}(r_{ij} + b_{ij})\, r_{j,i+k}}{r_{ii} + b_{ii} + r_{i+k,i+k}} \quad 1 \le k \le S-1,$$

where b_{ij} is the ij^{th} element of the matrix B. The next step is to express the elements of $\Pi(1)$ in terms of p(0, 0). From eq.10, we have

$$15. \quad \sum_{q=1}^{\infty} \Pi(q) = \sum_{q=0}^{\infty} R^q \Pi(1) = (I - R)^{-1}\Pi(1).$$

Substituting eq. 12 in eq. 11, we get

$$16. \quad p(0, 0)\Lambda_0 + B_0[-\Lambda_1^{-1}(B + CR)]\Pi(1) + C\,\Pi(1) = \underline{0}$$

or

$$17. \quad \{B_0[\Lambda_1^{-1}(B + CR)] - C\}\,\Pi(1) = p(0, 0)\Lambda_0.$$

Solving equation 17 (S subequations), we could express p(n, 1), i.e. $\Pi(1)$, in terms of p(0, 0). The real value of p(0, 0) will be obtained by normalization, i.e.

$$p(0, 0) + \underline{1}\,\Pi(0) + \underline{1}\,(I - R)^{-1}\Pi(1) = 1,$$

where $\underline{1}$ is a unit vector with dimension 1xS.

We now have to compute the mean queue length N_q by using $\Pi(q)$:

$$N_q = \sum_{q=1}^{\infty} q\,\underline{1}\,\Pi(q).$$

The waiting time in queue W_q, by Little's relation, is

$$W_q = \lambda N_q.$$

And, the system delay T is determined as

$$T = \frac{1}{\mu} + W_q.$$

Before leaving this section, we again discuss the blocking probability f(n). This probability is a function of system topology and traffic intensity. We know that f(0) and f(S) are 0 and 1, respectively. However, it will not be realistic to compute the exact values of f(n) for $0 < n < S$. Knowing the interference effect among RF channels, we expect that the curve of f(n) will have a shape like the curve of figure 16. Many functions could generate curves like the one in fig.16. The one we use is

$$f(n) = (n/S)^{const},$$

where const is a positive constant which can be adjusted according to the traffic intensity.

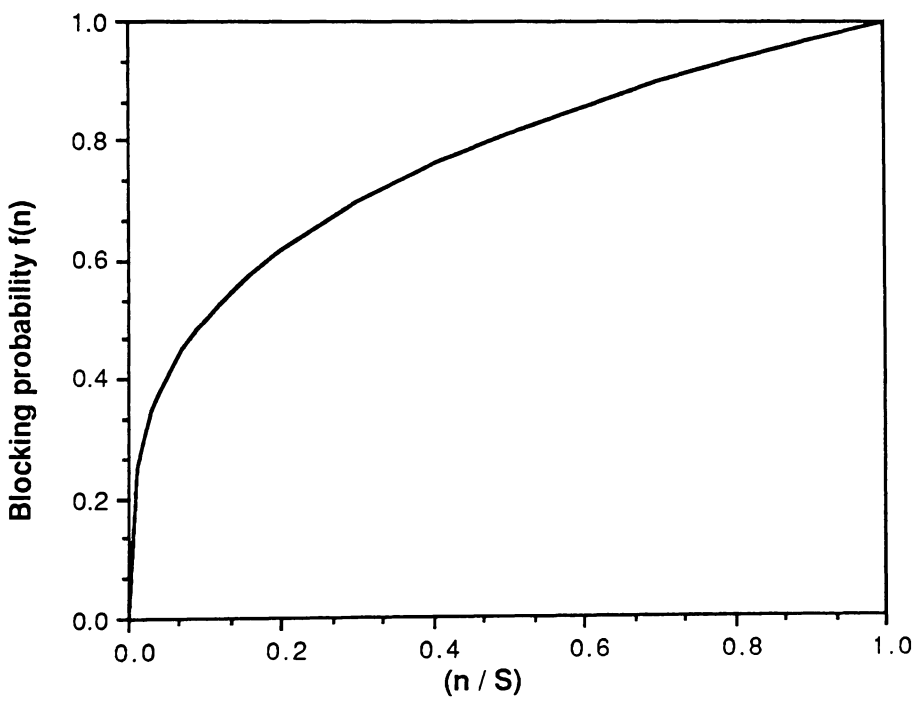

Figure 16.

8. Discussion of the analytical results

There are two classes of messages in this analytical model. The first class which includes pages and ACK's has higher priority. However, we are interested in the mean delay of outbound messages. The variable λ in this model is the arrival rate of outbound messages only. It does not take the traffic from pages and ACK's into account. In order to

account for this fact, we reduce the capacity used to transmit pages and ACK's from channels. Therefore, the variable μ in this model is as follows:

$$\mu = \frac{300 - 22 * (\text{page and outbound ACK rates})}{\text{mean length of outbound messages}}.$$

From the results of this model, it can be shown that the system delay is strongly affected by the blocking probability f(n). This probability is determined by the topology of the network. Hence, it is not realistic to give an exact expression of f(n). Rather, by gaining some knowledge from simulation experiments, the user of this model is expected to decide his own f(n) according to the topology of the system.

Examining the state transition diagram in section VI, we notice that some types of transition are neglected. For instance, transitions (n, q) $\rightarrow$ (n+1, q-2) or (n, q) $\rightarrow$ (n+2, q-3) is not considered in order to reduce the complexity. The contribution of these neglected transitions is minor, especially with low traffic intensities.

9. Upper bound of the outbound message delay of the DCS

Figure 14 shows us that the GCC with its outbound HDLC-links could be modeled as the multi-server queue. However, due to interference, the number of servers which transmit messages at the same time will be between 1 and S (S = 34 with the configuration of the DCS in Chicago). Therefore, if we take the extreme case, the upper and lower bounds of the outbound message delay could be modeled by M/G/1 and M/G/S queueing systems with priority respectively.

From the experience of running the simulation program, we determined that with a total of 34 links available, the number of HDLC-links which could transmit messages at the same time is 5 or 6 links at most. The majority case is only 1 to 3 servers busy at the same time under moderate traffic intensity. The remaining links cannot transmit due to the effect of interference. Hence, if we use M/G/S with priority to model the lower bound of the outbound delay, the result will be far away from reality and of little use. Also, solving the model of M/G/S with priority involves additional difficulties which will be discussed later. Therefore, we will focus on finding the upper bound of the outbound message delay.

As mentioned earlier, the first class of packets includes pages and ACK's and has a higher priority. The outbound messages go to the second class. We develop below an equation for the average delay for each priority class, which is similar to the derivation of the P-K formula for M/G/1 system without priority. Let

N_Q^k: Average number in queue for priority k

W_k: Average queueing time for priority k

ρ_k: System utilization for priority k

R: Mean residual service time

We assume that the overall system utilization is less than one, a reasonable assumption, i.e.,

$$\rho_1 + \rho_2 < 1.$$

When this assumption is not satisfied, the average delay of customers of priority 2 (outbound messages) will be infinite while the average delay of customers of the first priority will be finite, given that ρ_1 is less than unity.

Similar to the derivation of P-K formula, we have for the highest priority class

$$W_k = R + \frac{1}{\mu_1} N_Q^1.$$

Eliminating N_Q^1 from this equation by using Little's Theorem,

$$N_Q^1 = \lambda_1 W_1,$$

we obtain

$$W_1 = R + \rho_1 W_1,$$

and, finally

$$W_1 = \frac{R}{1 - \rho_1}.$$

For the second class, we have a similar expression for the queueing delay, W_2, except that we have to add the additional queueing delay due to pages or ACKs that arrive while an outbound message is waiting in queue. We find that

$$W_2 = R + \frac{1}{\mu_1} N_Q^1 + \frac{1}{\mu_2} N_Q^2 + \frac{1}{\mu_1} \lambda_1 W_2 .$$

Using Little's Theorem, we obtain

$$W_2 = R + \rho_1 W_1 + \rho_2 W_2 + \rho_1 W_2 ,$$

which yields

$$W_2 = \frac{R + \rho_1 W_1}{1 - \rho_1 - \rho_2} .$$

Using the expression $W_1 = R/(1 - \rho_1)$ obtained earlier, we finally have

$$W_2 = \frac{R}{(1 - \rho_1)(1 - \rho_1 - \rho_2)} .$$

The average delay per customer of class k is

$$T_k = \frac{1}{\mu_k} + W_k .$$

The mean residual service time R must now be derived. We have

$$R = \frac{1}{2} (\lambda_1 \overline{X_1^2} + \lambda_2 \overline{X_2^2}),$$

where $\overline{X_i^2}$ denotes the second moment of service time of each priority class. For the first class, pages and ACK's have a fixed packet length. Hence, we have

$$\overline{X_1^2} = 1/\mu_1^2 ,$$

where μ_1 is 300/22 in our case.

For the second class, let a and b denote the lower and upper bounds of the uniform distribution of outbound message lengths. We have

$$\overline{X_2^2} = Var(X_2) + (\frac{1}{\mu_2})^2 ,$$

which yields

$$\overline{X_2^2} = \frac{1}{300^2}\frac{(b-a)^2}{12} + \frac{1}{4}\frac{(b+a)^2}{300^2},$$

and, finally,

$$\overline{X_2^2} = \frac{1}{27000}(a^2 + ab + b^2).$$

Once $\overline{X_1^2}$ and $\overline{X_2^2}$ are known, it is straightforward to calculate T_2.

The analysis given above does not extend easily to the case of multiple servers, primarily because there is no simple formula for the mean residual time . If, however, the service times of all priority classes are identically exponentially distributed, there is a convenient characterization of R. Unfortunally, this is not the case here. For deterministic and uniformly distributed service time, it is very difficult to obtain a closed-form expression for the average waiting time W_k.

10. Comparison of the results from the simulation and analytical models

The following six figures are divided into two groups. Figures 17 to 19 compare the simulation and analytical results for the outbound delays when both the percentage of page response per inbound arrival and the percentage of page per outbound arrival are 10%. In figures 20 to 22 both percentages are 20%. The other common parameters used in these figures are as follows:

(1). Mean length of inbound messages: 144 bytes
(2). Mean length of outbound messages: 144 bytes
(3). Error rate inbound: 0
(4). Error rate outbound: 0
(5). Percentages of messages outbound to coverage zone, reuse zone, and max reuse zone by base stations are 20%, 40%, and 40%, respectively.
(6). Number of portable terminals in network: 200

Notice that the mean length of messages here is 144 bytes, which include 16 bytes overhead plus 128 bytes mean message length. These figures show that the outbound delays from the simulation and analytical models follow each other closely. It proves that the analytical model provides a very good approximation.

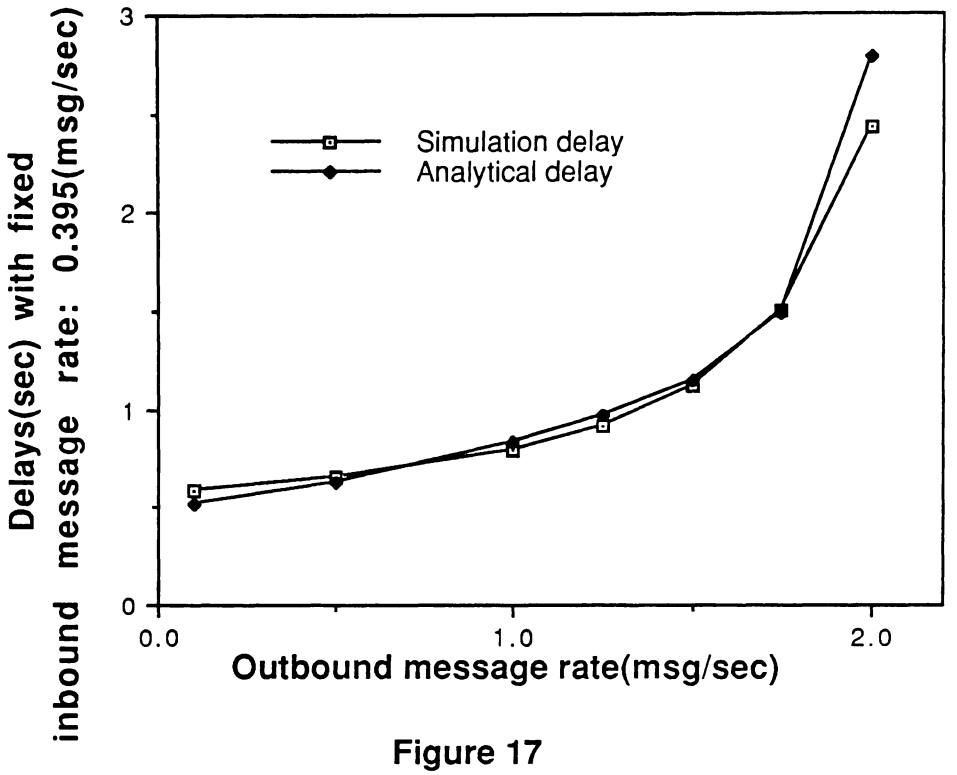

Figure 17

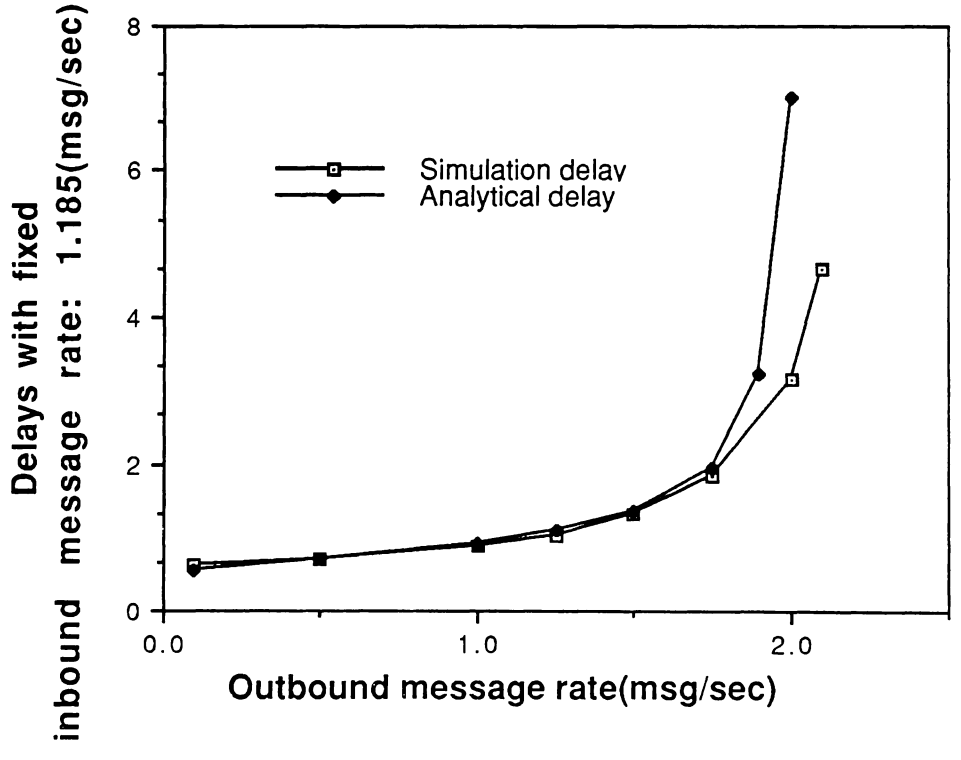

Figure 18

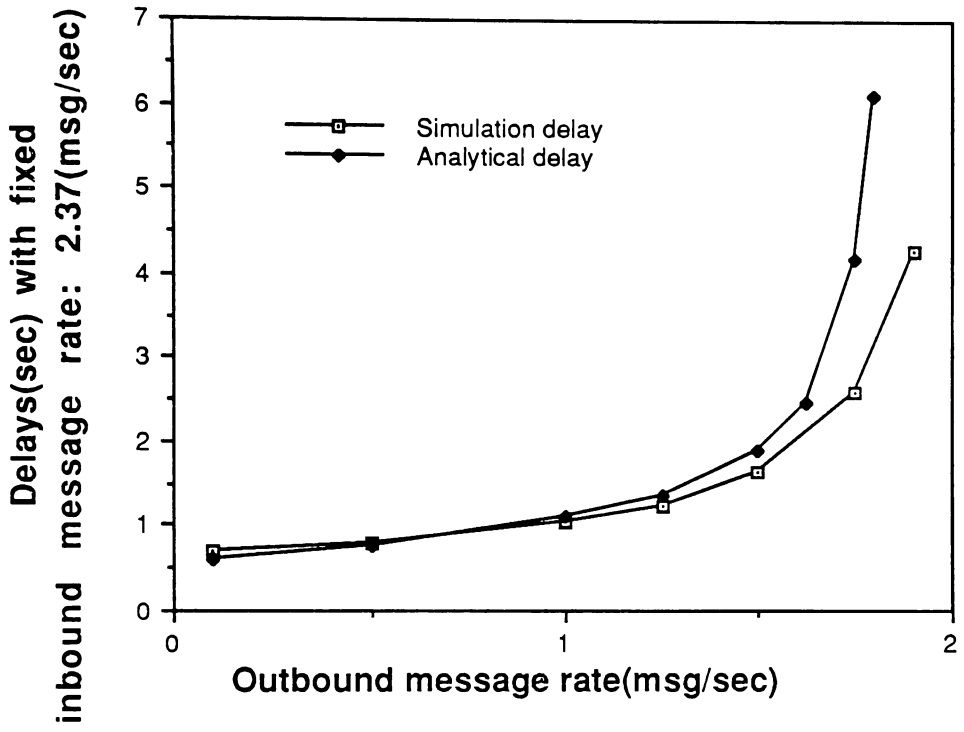

Figure 19

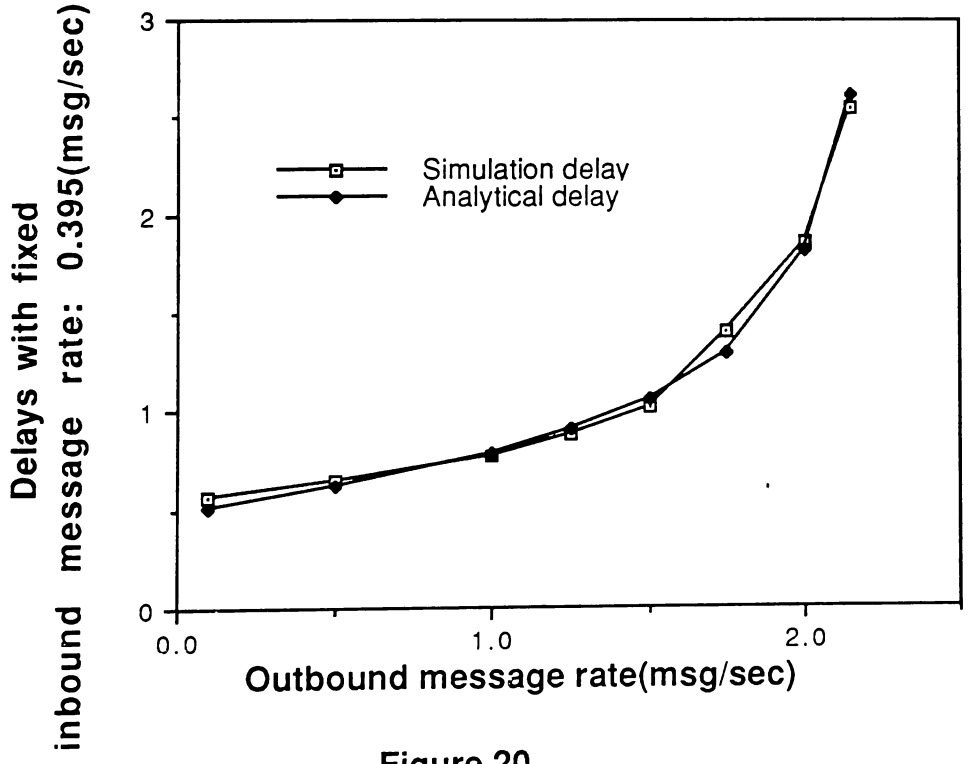

Figure 20

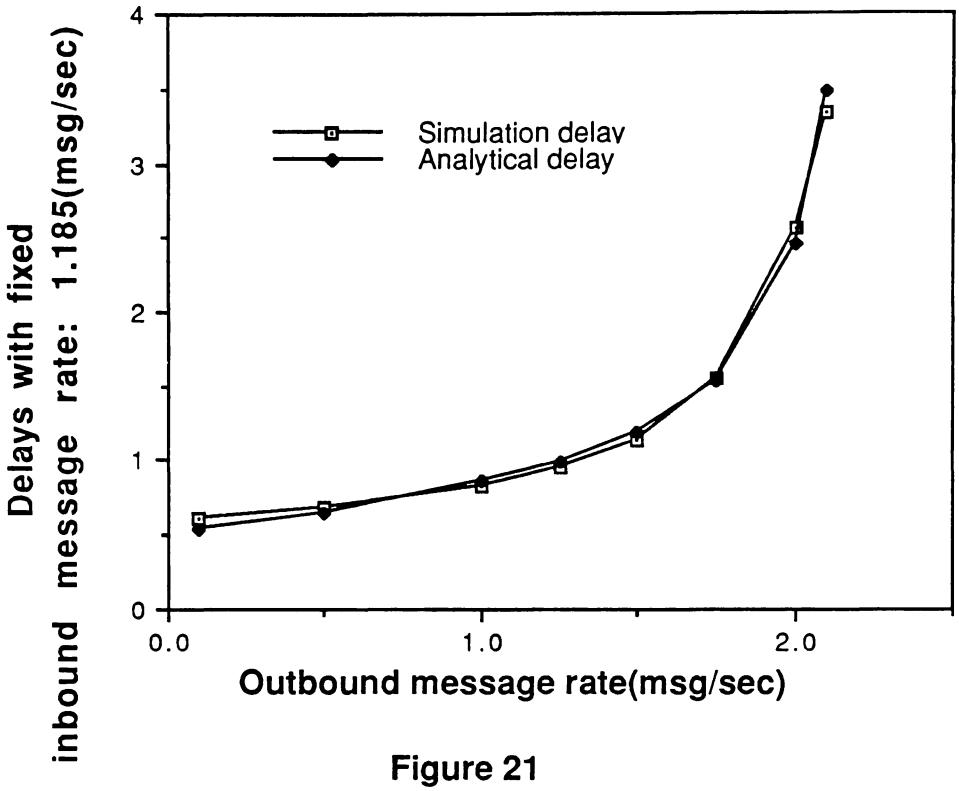

Figure 21

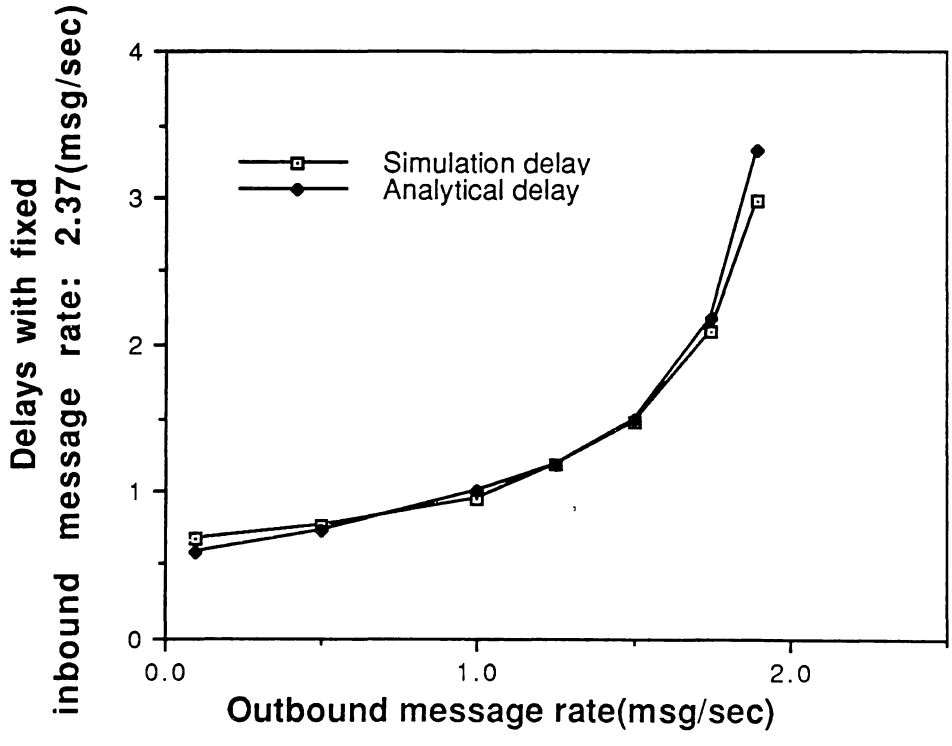

Figure 22

11. Conclusion

Due to the acknowledgement mechanism, inbound and outbound traffic is mutually interactive. Since ACK's receive a higher priority from the GCC, the transmission of the outbound messages in queue will be blocked and experience longer delays. The simulation results show that the outbound transmission is indeed the bottleneck of this network. Figure 11 indicates that the operation limit of outbound transmission is around 2 messages per second. Of course, this operation limit also depends on the inbound traffic intensity as well as the retransmission rates. When errors occur, the offered traffic to the system increases and the message delay becomes longer. Figure 12 indicates the extent to which the delays are affected by different error rates.

For the simulation model, we assume that the arrival of messages is Poisson and the message length is uniformly distributed between 0 and 256 bytes. We know that the Poisson assumption is fairly reasonable for the network of this nature. However, the observation of the pratical operation indicates that the distribution of message length has peaks close to both the lower and upper bounds. It will be fairly easy to fit the data and find their distribution once these data are collected. Before the real distribution is available, the uniform assumption seems to be a reasonable option.

For the analytical model, the transmission is assumed without error in order to reduce the complexity. With 10% page and page response rates, figures 17 to 19 show that the results from the analytical model tend to overestimate when the inbound traffic is heavy. However, these curves give us a conservative estimate and could serve as the upper bounds of outbound delays. When both percentages are at 20%, as in figures 20 to 22, the difference between the simulation and analytical results is less than 10% in the low and high traffic regions and less than 5% when the traffic intensity is in the medium range. It is a great advantage that we can use this analytical model to obtain a reasonable approximation without spending a long time to run the simulation program.

12. Future work

The validation of these simulation and analytical models will be done by comparing the results from the models with measured data collected from a real system.

References

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[4] Stewart, W. *Markov Chains and Stochastic Matrices.* Technical Report, NCSU, Dept. of Computer Science, Raleigh, NC, 1989.

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Appendix

A. Selected output of DCS simulation model

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 0.355500 messages/sec
Paging_rate = 0.100000 pages/sec
Ob_msg_rate = 0.900000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 5402 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 5402 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 4343.291486 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 0.804015 +- 0.010038 sec/message
Inbound throughput : 0.360133 +- 0.009876 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 14060 messages
Total outbound messages which try twice: 0 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 14060 messages
Total pages which try once: 1073 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 1073 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 11152.634243 sec
Total page delay : 300.835307 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 0.793217 +- 0.031515 sec/message

Average page delay : 0.280368 +- 0.014022 sec/page
Outbound throughput : 0.937333 +- 0.015808 message/sec
Paging throughput : 0.071533 +- 0.004222 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 0.355500 messages/sec
Paging_rate = 0.200000 pages/sec
Ob_msg_rate = 1.800000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 5214 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 5214 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 4924.579588 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 0.944492 +- 0.011883 sec/message
Inbound throughput : 0.347600 +- 0.009746 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 28945 messages
Total outbound messages which try twice: 0 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 28945 messages
Total pages which try once: 1435 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 1435 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 70243.205265 sec
Total page delay : 630.931782 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 2.426782 +- 0.212021 sec/message
Average page delay : 0.439674 +- 0.019202 sec/page
Outbound throughput : 1.929667 +- 0.020701 message/sec

Paging throughput : 0.095667 +- 0.005342 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 1.066500 messages/sec
Paging_rate = 0.100000 pages/sec
Ob_msg_rate = 0.900000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 16125 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 16125 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 13642.357686 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 0.846038 +- 0.007114 sec/message
Inbound throughput : 1.075000 +- 0.015870 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 14117 messages
Total outbound messages which try twice: 0 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 14117 messages
Total pages which try once: 867 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 867 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 12307.309837 sec
Total page delay : 274.281892 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 0.871808 +- 0.023023 sec/message
Average page delay : 0.316357 +- 0.018577 sec/page
Outbound throughput : 0.941133 +- 0.017564 message/sec
Paging throughput : 0.057800 +- 0.003696 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 1.066500 messages/sec
Paging_rate = 0.200000 pages/sec
Ob_msg_rate = 1.800000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 16079 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 16079 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 16156.169433 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 1.004799 +- 0.008642 sec/message
Inbound throughput : 1.071933 +- 0.018215 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 29011 messages
Total outbound messages which try twice: 0 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 29011 messages
Total pages which try once: 1271 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 1271 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 91280.736173 sec
Total page delay : 650.631091 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 3.146418 +- 0.385326 sec/message
Average page delay : 0.511905 +- 0.024707 sec/page
Outbound throughput : 1.934067 +- 0.022149 message/sec
Paging throughput : 0.084733 +- 0.004577 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 2.133000 messages/sec
Paging_rate = 0.100000 pages/sec
Ob_msg_rate = 0.900000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 32200 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 32200 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 30487.445208 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 0.946815 +- 0.009576 sec/message
Inbound throughput : 2.146667 +- 0.023181 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 14371 messages
Total outbound messages which try twice: 9 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 14380 messages
Total pages which try once: 691 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 691 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 15025.999635 sec
Total page delay : 303.572650 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 1.044923 +- 0.029798 sec/message
Average page delay : 0.439324 +- 0.052242 sec/page
Outbound throughput : 0.958667 +- 0.016392 message/sec
Paging throughput : 0.046067 +- 0.003190 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 2.133000 messages/sec
Paging_rate = 0.190000 pages/sec
Ob_msg_rate = 1.710000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 31938 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 31938 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 35435.071423 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 1.109496 +- 0.011478 sec/message
Inbound throughput : 2.129200 +- 0.022842 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 27780 messages
Total outbound messages which try twice: 10 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 27790 messages
Total pages which try once: 849 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 849 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 119211.349775 sec
Total page delay : 559.606165 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 4.289721 +- 0.653179 sec/message
Average page delay : 0.659136 +- 0.037682 sec/page
Outbound throughput : 1.852667 +- 0.018867 message/sec
Paging throughput : 0.056600 +- 0.004054 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 0.316000 messages/sec
Paging_rate = 0.200000 pages/sec

Ob_msg_rate = 0.800000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.200000
Percentage of Pages Responses/inbound message : 0.200000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 4700 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 4700 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 3691.719934 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 0.785472 +- 0.009647 sec/message
Inbound throughput : 0.313333 +- 0.008533 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 12830 messages
Total outbound messages which try twice: 0 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 12830 messages
Total pages which try once: 2075 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 2075 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 9951.350011 sec
Total page delay : 560.742833 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 0.775631 +- 0.028553 sec/message
Average page delay : 0.270238 +- 0.010162 sec/page
Outbound throughput : 0.855333 +- 0.014334 message/sec
Paging throughput : 0.138333 +- 0.006756 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 0.316000 messages/sec
Paging_rate = 0.400000 pages/sec
Ob_msg_rate = 1.600000 messages/sec
Mean length of inbound message : 128 bytes

Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.200000
Percentage of Pages Responses/inbound message : 0.200000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 4789 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 4789 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 4385.880235 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 0.915824 +- 0.009295 sec/message
Inbound throughput : 0.319267 +- 0.008720 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 26633 messages
Total outbound messages which try twice: 0 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 26633 messages
Total pages which try once: 3186 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 3186 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 49514.374000 sec
Total page delay : 1280.429681 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 1.859136 +- 0.114292 sec/message
Average page delay : 0.401893 +- 0.010133 sec/page
Outbound throughput : 1.775533 +- 0.025107 message/sec
Paging throughput : 0.212400 +- 0.008763 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 0.948000 messages/sec
Paging_rate = 0.200000 pages/sec
Ob_msg_rate = 0.800000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.200000

Percentage of Pages Responses/inbound message : 0.200000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 14511 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 14511 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 11954.936579 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 0.823853 +- 0.007545 sec/message
Inbound throughput : 0.967400 +- 0.016070 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 13096 messages
Total outbound messages which try twice: 0 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 13096 messages
Total pages which try once: 1802 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 1802 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 10925.729864 sec
Total page delay : 553.349653 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 0.834280 +- 0.021405 sec/message
Average page delay : 0.307075 +- 0.013625 sec/page
Outbound throughput : 0.873067 +- 0.016959 message/sec
Paging throughput : 0.120133 +- 0.005411 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 0.948000 messages/sec
Paging_rate = 0.400000 pages/sec
Ob_msg_rate = 1.600000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.200000
Percentage of Pages Responses/inbound message : 0.200000
Error rate inbound : 0.000000

Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 14164 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 14164 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 13815.250179 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 0.975378 +- 0.008676 sec/message
Inbound throughput : 0.944267 +- 0.018426 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 27433 messages
Total outbound messages which try twice: 0 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 27433 messages
Total pages which try once: 2563 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 2563 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 70376.938147 sec
Total page delay : 1204.228478 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 2.565412 +- 0.320246 sec/message
Average page delay : 0.469851 +- 0.015540 sec/page
Outbound throughput : 1.828867 +- 0.019662 message/sec
Paging throughput : 0.170867 +- 0.005678 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 1.896000 messages/sec
Paging_rate = 0.200000 pages/sec
Ob_msg_rate = 0.800000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.200000
Percentage of Pages Responses/inbound message : 0.200000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000

Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 28240 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 28240 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 25540.639987 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 0.904414 +- 0.007389 sec/message
Inbound throughput : 1.882667 +- 0.020144 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 13465 messages
Total outbound messages which try twice: 5 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 13470 messages
Total pages which try once: 1465 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 1465 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 12819.722611 sec
Total page delay : 575.720895 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 0.951724 +- 0.027079 sec/message
Average page delay : 0.392984 +- 0.016920 sec/page
Outbound throughput : 0.898000 +- 0.013349 message/sec
Paging throughput : 0.097667 +- 0.004632 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 1.896000 messages/sec
Paging_rate = 0.380000 pages/sec
Ob_msg_rate = 1.520000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.200000
Percentage of Pages Responses/inbound message : 0.200000
Error rate inbound : 0.000000
Error rate outbound : 0.000000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000

Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 28369 messages
Total inbound messages which try twice: 0 messages
Total inbound messages which try three times: 0 messages
Total inbound messages : 28369 messages
Inbound messages which do not go through : 0 messages
Total inbound delay : 30059.799538 sec
Delay of error messages : 0.000000 sec
Average inbound delay : 1.059600 +- 0.008395 sec/message
Inbound throughput : 1.891267 +- 0.021035 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 26684 messages
Total outbound messages which try twice: 6 messages
Total outbound messages which try three times: 0 messages
Total outbound messages which try four times: 0 messages
Total outbound messages : 26690 messages
Total pages which try once: 1900 pages
Total pages which try twice: 0 pages
Total pages which try more than twice: 0 pages
Total number of pages : 1900 pages
Outbound messages which do not go through : 0 messages
Total outbound delay : 79575.581103 sec
Total page delay : 1141.079777 sec
Delay of error messages : 0.000000 sec
Average outbound delay : 2.981476 +- 0.434527 sec/message
Average page delay : 0.600568 +- 0.024480 sec/page
Outbound throughput : 1.779333 +- 0.019185 message/sec
Paging throughput : 0.126667 +- 0.005466 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 2.133000 messages/sec
Paging_rate = 0.050000 pages/sec
Ob_msg_rate = 0.450000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.050000
Error rate outbound : 0.050000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000

Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 29487 messages
Total inbound messages which try twice: 2221 messages
Total inbound messages which try three times: 182 messages
Total inbound messages : 31890 messages
Inbound messages which do not go through : 20 messages
Total inbound delay : 38416.056452 sec
Delay of error messages : 247.107885 sec
Average inbound delay : 1.204643 +- 0.015011 sec/message
Inbound throughput : 2.126000 +- 0.022314 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 6504 messages
Total outbound messages which try twice: 490 messages
Total outbound messages which try three times: 54 messages
Total outbound messages which try four times: 6 messages
Total outbound messages : 7054 messages
Total pages which try once: 365 pages
Total pages which try twice: 18 pages
Total pages which try more than twice: 3 pages
Total number of pages : 386 pages
Outbound messages which do not go through : 1 messages
Total outbound delay : 8187.636046 sec
Total page delay : 7335.616918 sec
Delay of error messages : 16.907795 sec
Average outbound delay : 1.160708 +- 0.219600 sec/message
Average page delay : 19.004189 +- 7.683150 sec/page
Outbound throughput : 0.470267 +- 0.009852 message/sec
Paging throughput : 0.025733 +- 0.002786 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 2.133000 messages/sec
Paging_rate = 0.100000 pages/sec
Ob_msg_rate = 0.900000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.050000
Error rate outbound : 0.050000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 29736 messages
Total inbound messages which try twice: 2245 messages
Total inbound messages which try three times: 193 messages
Total inbound messages : 32174 messages
Inbound messages which do not go through : 19 messages
Total inbound delay : 41416.637764 sec
Delay of error messages : 233.478151 sec
Average inbound delay : 1.287270 +- 0.016698 sec/message
Inbound throughput : 2.144933 +- 0.023101 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 13190 messages
Total outbound messages which try twice: 1077 messages
Total outbound messages which try three times: 81 messages
Total outbound messages which try four times: 11 messages
Total outbound messages : 14359 messages
Total pages which try once: 638 pages
Total pages which try twice: 37 pages
Total pages which try more than twice: 2 pages
Total number of pages : 677 pages
Outbound messages which do not go through : 1 messages
Total outbound delay : 20864.175063 sec
Total page delay : 12604.850944 sec
Delay of error messages : 17.341187 sec
Average outbound delay : 1.453038 +- 0.159967 sec/message
Average page delay : 18.618687 +- 6.574767 sec/page
Outbound throughput : 0.957267 +- 0.015356 message/sec
Paging throughput : 0.045133 +- 0.003324 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 2.133000 messages/sec
Paging_rate = 0.150000 pages/sec
Ob_msg_rate = 1.350000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.050000
Error rate outbound : 0.050000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 29830 messages
Total inbound messages which try twice: 2216 messages
Total inbound messages which try three times: 208 messages
Total inbound messages : 32254 messages
Inbound messages which do not go through : 10 messages
Total inbound delay : 44407.076711 sec
Delay of error messages : 125.352559 sec
Average inbound delay : 1.376793 +- 0.015543 sec/message
Inbound throughput : 2.150267 +- 0.019499 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 20290 messages
Total outbound messages which try twice: 1525 messages
Total outbound messages which try three times: 140 messages
Total outbound messages which try four times: 9 messages
Total outbound messages : 21964 messages
Total pages which try once: 773 pages
Total pages which try twice: 46 pages
Total pages which try more than twice: 4 pages
Total number of pages : 823 pages
Outbound messages which do not go through : 1 messages
Total outbound delay : 48028.057106 sec
Total page delay : 16706.102186 sec
Delay of error messages : 29.111508 sec
Average outbound delay : 2.186672 +- 0.244934 sec/message
Average page delay : 20.299031 +- 6.277802 sec/page
Outbound throughput : 1.464267 +- 0.020051 message/sec
Paging throughput : 0.054867 +- 0.003450 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 2.133000 messages/sec
Paging_rate = 0.190000 pages/sec
Ob_msg_rate = 1.710000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.050000
Error rate outbound : 0.050000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 30060 messages
Total inbound messages which try twice: 2226 messages
Total inbound messages which try three times: 207 messages
Total inbound messages : 32493 messages
Inbound messages which do not go through : 22 messages
Total inbound delay : 47641.867329 sec
Delay of error messages : 268.551553 sec
Average inbound delay : 1.466219 +- 0.017035 sec/message
Inbound throughput : 2.166200 +- 0.018654 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 25315 messages
Total outbound messages which try twice: 2020 messages
Total outbound messages which try three times: 171 messages
Total outbound messages which try four times: 10 messages
Total outbound messages : 27516 messages
Total pages which try once: 823 pages
Total pages which try twice: 21 pages
Total pages which try more than twice: 1 pages
Total number of pages : 845 pages
Outbound messages which do not go through : 1 messages
Total outbound delay : 163128.299967 sec
Total page delay : 7501.254025 sec
Delay of error messages : 21.527201 sec
Average outbound delay : 5.928489 +- 1.477965 sec/message
Average page delay : 8.877224 +- 4.945732 sec/page
Outbound throughput : 1.834400 +- 0.020830 message/sec
Paging throughput : 0.056333 +- 0.004325 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 2.133000 messages/sec
Paging_rate = 0.100000 pages/sec
Ob_msg_rate = 0.900000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.100000
Error rate outbound : 0.100000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 27027 messages
Total inbound messages which try twice: 4016 messages
Total inbound messages which try three times: 658 messages
Total inbound messages : 31701 messages
Inbound messages which do not go through : 146 messages
Total inbound delay : 52765.053885 sec
Delay of error messages : 1791.735617 sec
Average inbound delay : 1.664460 +- 0.019754 sec/message
Inbound throughput : 2.113400 +- 0.023045 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 12268 messages
Total outbound messages which try twice: 1792 messages
Total outbound messages which try three times: 273 messages
Total outbound messages which try four times: 49 messages
Total outbound messages : 14382 messages
Total pages which try once: 531 pages
Total pages which try twice: 64 pages
Total pages which try more than twice: 4 pages
Total number of pages : 599 pages
Outbound messages which do not go through : 16 messages
Total outbound delay : 26854.919329 sec
Total page delay : 21886.080603 sec
Delay of error messages : 283.189395 sec
Average outbound delay : 1.867259 +- 0.184934 sec/message
Average page delay : 36.537697 +- 8.646364 sec/page
Outbound throughput : 0.958800 +- 0.013896 message/sec
Paging throughput : 0.039933 +- 0.002764 pages/sec

********** System Specification--Input Data **********

Simulation time: 1.6e+004 sec(TMAX), Warm_up time: 1.0e+003 sec
Lambda_in = 2.133000 messages/sec
Paging_rate = 0.175000 pages/sec
Ob_msg_rate = 1.575000 messages/sec
Mean length of inbound message : 128 bytes
Mean length of outbound message : 128 bytes
Percentage of Pages/outbound message : 0.100000
Percentage of Pages Responses/inbound message : 0.100000
Error rate inbound : 0.100000
Error rate outbound : 0.100000
Percentage of messages outbound to coverage zone by Base Station : 0.200000
Percentage of messages outbound to reuse zone by Base Station : 0.400000
Percentage of messages outbound to max reuse zone by Base Station : 0.400000
Number of Portable Terminals in network by Base Station : 200
Number of Base Stations in network : 34

********** Output of the Simulation Model **********

======= INBOUND =======
Total inbound messages which try once: 27408 messages

Total inbound messages which try twice: 3988 messages
Total inbound messages which try three times: 657 messages
Total inbound messages : 32053 messages
Inbound messages which do not go through : 116 messages
Total inbound delay : 57887.181939 sec
Delay of error messages : 1427.443600 sec
Average inbound delay : 1.805983 +- 0.020263 sec/message
Inbound throughput : 2.136867 +- 0.024257 messages/sec

======= OUTBOUND =======
Total outbound messages which try once: 21647 messages
Total outbound messages which try twice: 3218 messages
Total outbound messages which try three times: 520 messages
Total outbound messages which try four times: 104 messages
Total outbound messages : 25489 messages
Total pages which try once: 697 pages
Total pages which try twice: 70 pages
Total pages which try more than twice: 7 pages
Total number of pages : 774 pages
Outbound messages which do not go through : 30 messages
Total outbound delay : 137159.926745 sec
Total page delay : 26339.402247 sec
Delay of error messages : 837.457065 sec
Average outbound delay : 5.381142 +- 0.874193 sec/message
Average page delay : 34.030235 +- 9.389106 sec/page
Outbound throughput : 1.699267 +- 0.018060 message/sec
Paging throughput : 0.051600 +- 0.003590 pages/sec

B. Selected output of DCS analytical model

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = 1.000000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.100000
Inbound Arrival Rate = 0.395000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 18
Average number of customers in queue is 0.303859 messages.
Mean outbound delay of these network is **0.834209 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = 2.000000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.100000
Inbound Arrival Rate = 0.395000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 124
Average number of customers in queue is 4.096714 messages.
Mean outbound delay of these network is **2.776336 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = 1.000000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.100000
Inbound Arrival Rate = 1.185000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 19
Average number of customers in queue is 0.360269 messages.
Mean outbound delay of these network is **0.925201 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = 1.900000 messages / sec

Percentage of Pages Response Per Outbound Message = 0.100000
Inbound Arrival Rate = 1.185000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 129
Average number of customers in queue is 4.610415 messages.
Mean outbound delay of these network is **3.224867 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = 2.000000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.100000
Inbound Arrival Rate = 1.185000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 257
Average number of customers in queue is 11.686363 messages.
Mean outbound delay of these network is **7.021569 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = 1.000000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.100000
Inbound Arrival Rate = 2.370000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 22
Average number of customers in queue is 0.479118 messages.
Mean outbound delay of these network is **1.106347 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = 1.750000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.100000
Inbound Arrival Rate = 2.370000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 139
Average number of customers in queue is 5.692374 messages.
Mean outbound delay of these network is **4.191999 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = 1.800000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.100000
Inbound Arrival Rate = 2.370000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 195
Average number of customers in queue is 8.947207 messages.
Mean outbound delay of these network is **6.101016 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.200000
Outbound Arrival Rate = 1.000000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.200000
Inbound Arrival Rate = 0.395000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 15
Average number of customers in queue is 0.231237 messages.
Mean outbound delay of these network is **0.787924 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.200000
Outbound Arrival Rate = 2.000000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.200000
Inbound Arrival Rate = 0.395000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 65
Average number of customers in queue is 2.090034 messages.
Mean outbound delay of these network is **1.812871 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.200000
Outbound Arrival Rate = 1.000000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.200000
Inbound Arrival Rate = 1.185000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 16
Average number of customers in queue is 0.267388 messages.
Mean outbound delay of these network is **0.858359 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.200000
Outbound Arrival Rate = 2.000000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.200000
Inbound Arrival Rate = 1.185000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 84
Average number of customers in queue is 3.069624 messages.
Mean outbound delay of these network is **2.451169 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.200000
Outbound Arrival Rate = 1.000000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.200000
Inbound Arrival Rate = 2.370000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 18
Average number of customers in queue is 0.338700 messages.
Mean outbound delay of these network is **0.990554 sec.**

********** System Specification -- Input Data **********
Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Pages Per Outbound Message = 0.200000
Outbound Arrival Rate = 1.900000 messages / sec
Percentage of Pages Response Per Outbound Message = 0.200000
Inbound Arrival Rate = 2.370000 messages / sec

********** Output Data **********
Num_in_que to meet LIMIT = 1.000000e-007 is 101
Average number of customers in queue is 4.186285 messages.
Mean outbound delay of these network is **3.330301 sec.**

C. Selected output of M/G/1 model

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **0.355500 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **0.500000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **0.640698 sec.**

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **0.355500 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **1.000000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **0.932879 sec.**

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **0.355500 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **1.500000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **1.632221 sec.**

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **0.355500 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **2.000000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **5.480410 sec.**

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **1.066500 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **0.500000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **0.662620** sec.

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **1.066500 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **1.000000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **1.005279** sec.

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **1.066500 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **1.500000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **1.908013** sec.

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **1.066500 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **2.000000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **10.616013** sec.

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **2.133000 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **0.500000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **0.704114 sec.**

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **2.133000 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **1.000000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **1.151229 sec.**

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **2.133000 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **1.500000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **2.585397 sec.**

********** System Specification -- Input Data **********

Number of Base Stations in This Network : 34
Mean Length of Outbound Message = 144
Percentage of Page Response Per Outbound Message = 0.100000
Inbound Arrival Rate = **2.133000 messages / sec**
Percentage of Pages Per Outbound Message = 0.100000
Outbound Arrival Rate = **1.750000 messages / sec**

The upper_bound delay which is derived from M/G/1 model is **5.921538 sec.**

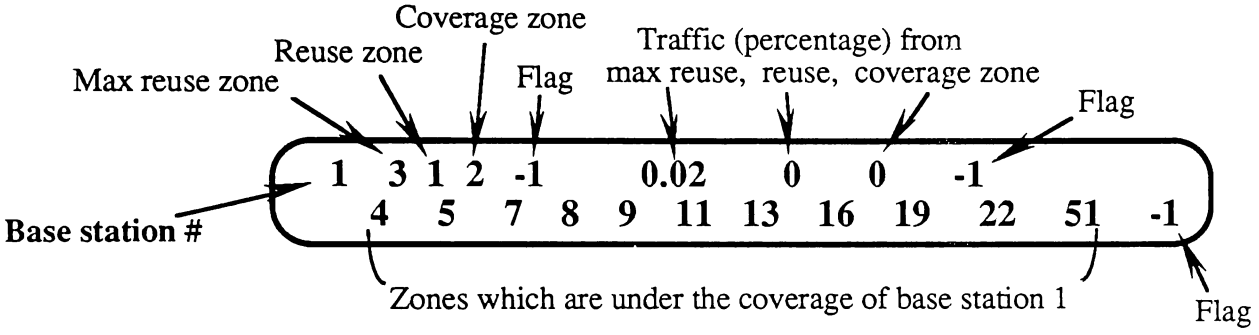
D. Example of the DCS input format

1. Mean length of inbound messages = 136
2. Mean length of outbound messages = 136
3. Percentage of pages responses/inbound message = 10.00
4. Percentage of pages/outbound message = 10.00
5. Error rate inbound = 10.00
6. Error rate outbound = 10.00
7. Percentage of messages outbound to coverage zone by base station = 20.00
8. Percentage of messages outbound to reuse zone by base station = 40.00
9. Percentage of messages outbound to max reuse zone by base station = 40.00
10. Number of portable terminals in network = 200
11. Number of base stations in network = 34
12. Number of zone areas in network = 110
13. Simulation time, TMAX = 1.60E+004
14. Warm up time, WARM_UP = 1.00E+003
15. Outbound rate = 1.500
16. Percentages of PTs which generate high, medium and low inbound rate,
    High percentage = 15.000000 Medium percentage = 25.000000 Low percentage = 60.000000
17. High, medium, and low inbound rates which correspond to three classes of PTs,
    High inbound rate = 3.000000 Medium inbound rate = 1.500000 Low inbound rate = 0.600000

(P.S. Inbound rate = High inbound rate * High percentage + Medium inbound rate * Medium percentage + Low inbound rate * Low percentage)

E. Interference and traffic table

Explanation of the format:



1 3 1 2 -1 0.02 0 0 -1
4 5 7 8 9 11 13 16 19 22 51 -1
2 6 4 5 -1 0.01 0 0 -1
1 2 7 8 9 11 13 16 19 22 -1
3 9 7 8 -1 0.02 0.01 0.02 -1
1 2 4 5 9 11 13 16 17 19 22 25 28 31 34 37 51 75 87 90 -1
4 12 10 11 -1 0.01 0 0.01 -1
1 2 4 5 7 13 16 19 20 22 23 25 28 31 34 37 43 51 57 75 87 90 100 -1
5 15 13 14 -1 0.01 0 0 -1
4 7 10 16 19 22 25 28 31 34 37 40 43 48 75 87 -1
6 18 16 17 -1 0.02 0 0.01 -1
4 7 10 13 19 20 22 25 28 29 31 34 37 40 43 48 51 57 60 72 75 87 90 95 100 -1
7 21 19 20 -1 0.05 0.01 0.01 -1
1 4 7 10 11 13 16 17 22 23 25 26 28 29 31 34 37 43 48 51 57 60 72 75 87 90
95 100 -1
8 24 22 23 -1 0.02 0.01 0.01 -1
1 4 7 10 11 16 19 20 25 28 31 34 37 43 48 51 52 57 60 72 75 87 90 95 100 -1
9 27 25 26 -1 0.03 0 0 -1
25 7 10 13 16 19 22 28 29 31 32 34 37 38 40 43 48 49 51 57 60 72 75 87 88 90
95 100 105 -1
10 30 28 29 -1 0.02 0 0 -1
4 7 10 13 16 17 19 20 22 25 26 31 34 37 38 40 43 48 51 57 60 72 75 87 88 90
95 100 -1
11 33 31 32 -1 0.01 0.01 0.01 -1

4 10 16 19 22 25 26 28 34 37 38 40 43 48 51 52 54 57 60 61 66 69 72 75 87 90 95 100 105 -1

12 36 34 35 -1 0.02 0 0 -1

4 7 13 14 16 19 22 25 28 31 37 40 41 48 75 76 78 87 88 -1

13 39 37 38 -1 0 0 0 -1

10 13 16 19 22 25 26 28 29 31 32 34 40 43 48 49 51 57 60 69 72 75 76 78 87 88 90 95 100 105 -1

14 42 40 41 -1 0.02 0 0.01 -1

16 25 28 31 34 35 37 48 75 76 78 79 87 105 -1

15 47 43 44 45 46 -1 0.02 0.0 0.008 -1

10 16 19 22 25 28 31 37 48 51 52 57 60 66 69 72 90 91 92 95 96 100 101 102 -1

16 50 48 49 -1 0.02 0.01 0.01 -1

10 13 16 19 22 25 28 31 34 37 38 40 43 51 54 57 60 61 66 69 72 75 76 78 79 87 90 95 100 105 106 -1

17 53 51 52 -1 0.03 0.0 0.01 -1

4 10 16 19 22 23 25 28 31 32 37 43 44 45 48 57 60 69 72 87 90 91 93 95 100 -1

18 56 54 55 -1 0. 0 0. -1

57 60 63 66 69 70 72 81 84 90 95 105 106 108 109 -1

19 59 57 58 -1 0.02 0 0.01 -1

10 16 19 22 25 28 31 37 43 48 51 54 60 61 63 66 69 72 73 75 87 90 95 96 97 98 100 105 -1

20 62 60 61 -1 0.06 0.04 0.05 -1

10 19 22 25 28 31 37 43 48 51 54 57 58 63 66 69 72 75 78 87 90 95 100 105 106 -1

21 65 63 64 -1 0.025 0.025 0.015 -1

54 55 57 60 66 69 72 81 82 84 85 105 108 109 -1

22 68 66 67 -1 0 0 0 -1

43 54 57 60 63 69 70 72 81 84 90 95 100 105 -1

23 71 69 70 -1 0.017 0.003 0.005 -1

43 54 55 57 60 63 64 66 67 72 81 84 90 95 100 105 -1

24 74 72 73 -1 0.005 0.002 0.003 -1

10 19 22 25 31 37 43 44 46 48 51 54 57 58 60 66 69 90 95 96 100 101 102 103 105 -1

25 77 75 76 -1 0.009 0.006 0.012 -1

13 19 25 28 31 34 35 37 38 40 41 48 49 78 79 87 88 90 95 105 -1

26 80 78 79 -1 0.011 0.006 0.006 -1

34 37 40 48 54 60 69 75 87 105 106 108 109 -1

27 83 81 82 -1 0.002 0.002 0.001 -1
63 84 85 108 -1
28 86 84 85 -1 0.002 0.005 0.0 -1
63 64 66 69 81 82 108 -1
29 89 87 88 -1 0.02 0 0.005 -1
4 7 10 13 14 16 19 22 25 28 29 31 34 35 37 38 40 41 48 49 51 57 60 72 75 76
78 90 95 105 -1
30 94 90 91 92 93 -1 0.012 0.003 0.02 -1
10 16 19 22 25 28 31 37 43 44 45 48 51 52 57 60 66 69 72 95 96 100 -1
31 99 95 96 97 98 -1 0.008 0.005 0.002 -1
10 16 19 22 25 28 31 37 43 44 46 48 51 57 58 60 66 69 72 90 100 101 103 -1
32 104 100 101 102 103 -1 0.014 0.007 0.004 -1
10 16 19 22 25 28 31 37 43 44 45 46 48 51 57 60 66 69 72 76 90 95 96 97 -1
33 107 105 106 -1 0.022 0.0 0.008 -1
25 31 34 37 40 48 49 54 55 57 60 61 63 66 69 72 75 78 79 87 90 108 109 -1
34 110 108 109 -1 0.02 0.008 0.012 -1
54 55 63 64 78 79 81 84 105 106 -1

F. Example of portable terminals' id's in each zone

1	1	2	3			-1
2	1	2			-1	
3	1	2	3	4	5	-1
4	1	2			-1	
5	1	2			-1	
6	1	2	3			-1
7	1	2	3			-1
8	1	2	3			-1
9	1	2	3	4		-1
10	1			-1		
11	1	2			-1	
12	1	2			-1	
13	1	2			-1	
14	1	2			-1	
15	1	2	3			-1
16	1			-1		
17	1	2			-1	
18	1	2	3			-1
19	1	2	3			-1
20	1	2			-1	
21	1	2	3		-1	
22	1	2			-1	
23	1	2			-1	
24	1	2			-1	
25	1	2			-1	
26	1	2			-1	
27	1	2	3	4		-1
28	-1					
29	1			-1		
30	1	2	3			-1
31	1	2			-1	
32	1			-1		
33	1	2			-1	
34	1			-1		
35	-1					
36	1	2	3			-1
37	-1					
38	-1					
39	1			-1		
40	1			-1		
41	1			-1		
42	1	2			-1	
43	-1					
44	1			-1		
45	1			-1		
46	-1					
47	1	2			-1	
48	1			-1		
49	1	2			-1	
50	1	2			-1	
51	1			-1		

52	1		-1		
53	1	2		-1	
54	1		-1		
55	1		-1		
56	-1				
57	-1				
58	1	2		-1	
59	1		-1		
60	1		-1		
61	1	2		-1	
62	1	2	3		-1
63	1		-1		

106	1	2		-1		
107	1	2	3		-1	
108	1			-1		
109	1	2	3	4		-1
110	1	2	3	4		-1