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SIMULATION MODELING OF A TRUNKED RADIO NETWORK

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ABSTRACT

Trunked radio schemes are used to increase the spectral utilization of radio networks. In this paper we develop a performance evaluation model for a trunked radio network. The model specifications are based on an actual centrally controlled trunked frequency network. The detailed model was simulated using the QNAP2 network analysis package. The effects of changes in system control parameters on the system performance was investigated using the model.

1 INTRODUCTION

Communication radio systems generally operate in one of two extreme configurations: 100% channel utilization characterized by long queues at each channel; and low utilization schemes which achieve (near) zero waiting time using dedicated channel allocation. Trunked Radio Systems (TRS) were developed to achieve greater spectral efficiency, while maintaining low connection wait time. A trunked radio system allows many users to share a group of frequency channels and still maintain the best service possible under heavy traffic conditions. Trunked radio networks can be used effectively for radio communications in systems with frequency congestion, limited resources, and varying traffic demands.

The trunked system uses an access subsystem through which a user is allocated a communication channel from a pool of channels. When the user is finished using the channel, the channel is returned to the pool for allocation to other users. In most trunked radio systems, channel allocation and accessing is done through a system controller. The system controller has three main functions: receive requests for channel allocations; order the received requests according to priorities; and allocate free channels to the order queue. The system controller can be of *pure loss* type or of *queuing type*. A pure loss controller rejects all incoming allocation requests when all channels are busy. A queuing controller queues incoming requests using specific queuing disciplines, defined *a-priori*. General radio systems, in contrast to ordinary telephone communications, are characterized by a simplex mode of operation, shorter conversation lengths, fewer users, and in some cases, grouped operational modes. They are therefore ideally suited for a trunked mode of operation. The Federal Communications Commission (FCC) authorizes operators in the 800 Mhz band to operate trunked radio systems with 5-20 channels, but a significant performance improvement over conventional systems is possible using as few as 3 channels.

The performance characteristics of a general radio system can be defined in terms of the *load* and the *grade* of service. The load of a queuing system can be defined as a product of the request arrival rate and the average waiting time. The load is measured in Erlangs, with one Erlang being the load definition for a 100% busy channel. The grade of service is used to quantify the congestion of the system. This can be written in terms of probability of finding all channels busy or in terms of the probability of waiting time exceeding certain threshold. The load and grade of service are related through the Erlang's formula. For a trunked system with traffic load ρ and N number of channels, the probability of a request experiencing a delay is

$$p_d = \frac{\rho^N}{\rho^N + N(1-\rho/N)\sum_{k=0}^{N-1} \rho^k/k!}$$

The probability that a request will have to wait for a time greater than time T is

$$P(W > T) = p_d \, e^{[-(N-\rho)T/\theta]}$$

Here θ is the mean waiting time for a request. Figure 1 (from Parsons and Gardiner (1989)) shows the probability of delay being greater than 20 seconds for different N with $\theta = 20$ seconds. As is clear from

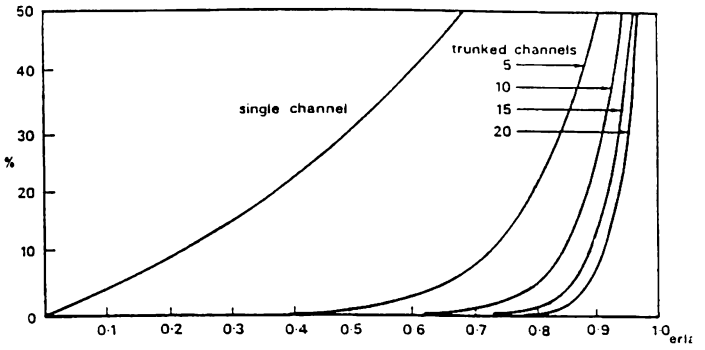

Figure 1: $P(W > 20)$ vs $\frac{\rho}{N}$. $\theta = 20$

the figure, the trunked system performs much better than the single channel case. For a fixed probability of delay, the percentage utilization per channel ($\frac{\rho}{N}$) increases as the number of channels increases, but the marginal increase goes down as the number of channels increases. Hence, systems with more than 20 channels show little improvement over systems with fewer channels. Thus, the marginal cost of adding new channels outweighs the increase in performance, and hence, in practice a maximum of 20 channels is used.

In the next section we describe various components of a trunked radio system and present the model specifications. In Section III, we present implementation details and examine the effects of variations in control parameters on system performance.

2 TRUNKED RADIO SYSTEM NETWORK SPECIFICATIONS

The layout of a typical trunked radio system is shown in Figure 2. The operation of the TRS network is centrally controlled by the Central System Controller (CSC). In general, the CSC is a microprocessor based control unit which directs operation of the TRS. In addition to processing call requests, the central controller also performs network management functions such as channel control, statistics gathering and alarm reporting.

Each TRS network has a fixed number of communication channels and a single control channel. The control channel is used for signaling, receiving call requests, and assigning communication channels. Each communication channel is supported by a Base Station Repeater (BSR). The repeater consists of a transmitter, receiver and control/interface circuitry required to integrate the individual control stations into the TRS network. The base station repeaters

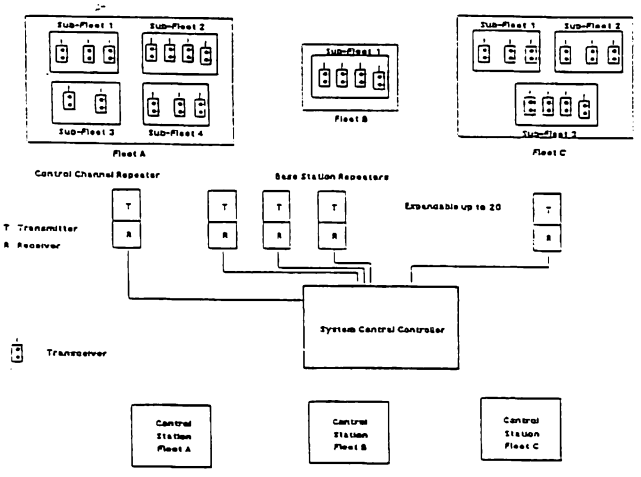

Figure 2: Layout of a typical Trunked Radio Network

are used for transceiver to transceiver communication. There is a dedicated BSR for the control channel (Control Channel Repeater).

The mobile transceivers are the peripheral components of this TRS network. The mobile units consist of receivers and transmitters and are frequency agile; i.e., they have built in crystal frequency oscillators which allow them to tune to different communication frequencies. They also contain the appropriate electronic logic necessary for the trunking function of tuning the receiver and the transmitter on commands issued by the CSC. The mobile transceivers are grouped together in fleets and in some cases the fleets are sub-grouped into sub-fleets. Each fleet has a RF control station assigned to it. The control station is a stationary transceiver and acts as a fleet controller.

Three types of calls are allowed in a TRS network: *system*, *fleet* and *subfleet* calls. A system call is used to transmit a message to every unit in the system. A system call has priority over all other types of calls. Fleet calls, as the name suggests, are used to deliver a message over the whole fleet. A sub-fleet call allows any transceiver in the sub-fleet to request a communication channel, which will automatically be able to communicate with all other units in that sub-fleet. This provides the effect of a *private channel* at the subfleet level.

In its role as a central controller, the CSC automatically executes the following tasks:

i) Communicating with the transceivers to handle call set up requests.
ii) Monitoring all communication channels.
iii) Assigning available channels.
iv) Verifying the assignments.

The sequence of events from the initiation of call request to the final assignment of a communication channel is as follows:

User keys the handset on the transceiver.
⇓
Channel request is sent on the control channel to the CSC.
⇓
CSC determines free channel availability by sampling the frequencies for each channel.
⇓
If available, a channel is allocated, else the call is queued in the System Queue (SQ).
⇓
On channel allocation, the frequency assignments (transmit/receive frequencies) for the allocated channel are sent to the transceivers involved in the call request.

The normal conversation scenario that occurs as users engage in a communication session on TRS Network is as follows:

- Channel request and assignment are made as described above.
- After the first part releases the Press to Transmit(PTT) switch, the second party has 1-3 seconds to key his unit and retain the same channel. This exchange may continue until the conversation is complete.
- If the timer expires before the second party hits the PTT switch, the channel is released for general use. If the conversation was intended to continue, a fresh channel must be requested.
- If the unit is keyed for 30 seconds continuously, the channel will be automatically disconnected. This automatic disconnect feature prevents a malfunction or accidental keying from locking a channel for long periods of time.
- When the channel is disconnected, all units are automatically switched to the control channel.

As discussed in the previous section, in the queuing type of system controller, if all channels are busy, the call requests are directed to the appropriate priority queues. The priority queue setup definition is, in general, application specific. The most common is the First Come First Serve (FCFS) discipline. The other commonly used discipline is the priority queuing system. In this the call requests are entered into the appropriate priority queues according to: (i) Priority level assigned to the transceiver that generated the call; and (ii) A higher priority assignment based on the recent usage of channels, by the fleet/sub-fleet from which the call request originated. The second type of priority assignment, leading to channel allocation, is termed as Recent User Assignment (RUA) in the trunked radio literature. A sample RUA and a priority queue configuration are described in the next section.

Based on the system model, we can now define the following control parameters which affect the TRS network performance:

Carrier Time-Out Period: This is the time period for which an allocated channel remains active, receiving only carrier and no handshake connect tones. The timer is activated after the disconnect tone is detected by the central controller. After the time-out expires, the channel assumes the disconnect phase. (Range 0-7 seconds)

Fade Time-Out Period: This determines the time period for which an assigned channel remains active, even though no tones or carrier are received. The timer is activated after the central controller fails to detect a disconnect tone after the loss of connect tone and on time-out expiration, the channel is unassigned. (Range 0.1-7 seconds)

Message Trunk Time-Out Period: This determines the time period for which a voice channel remains active after receiving a disconnect tone from the transceiver. Here again the channel is unassigned after the time-out expires. (Range 0-7 seconds)

Carrier Malfunction Time-Out Period: This determines how long an interfering carrier must be present on an unassigned channel before that channel is removed from system use. (Average value 250 seconds)

Recent User Assignments: This defines the maximum number of consecutive assignments of a fleet/sub-fleet to the high priority recent user queue. (Range 0-255 assignments)

In the next section, we present the some additional details of the specific TRS network model used for

FLEET NO.	SUB-FLEET NO.	NO.of TRANSCEIVERS A	B	C
1	1	1	12	0
2	1	1	3	0
3	1	1	13	0
4	1	1	3	0
5	1	1	3	0
6	1	1	14	0
7	1	1	20	0
8	1	1	6	0
9	1	1	10	0
10	1	1	6	0
11	1	1	26	0
11	2	1	16	0
12	1	1	9	0
12	2	1	5	0
12	3	1	6	0
12	4	1	2	0
13	1	1	49	4
13	2	1	54	0
13	3	1	34	0
13	4	1	28	0
13	5	1	46	0
14	1	1	21	2
14	2	0	5	0
14	3	0	2	0
14	4	0	2	0
14	5	0	2	0
14	6	0	2	0

Figure 3: Trunked Radio Network: An example configuration

simulation. Performance results with respect to selected variations in control parameters are also presented.

3 SIMULATION MODEL AND RESULTS

The TRS network simulation model was developed using an existing US airport TRS as a benchmark. The model has 14 fleets, each having one or more subfleets. There are three types of transceivers labeled A, B and C. The detailed configuration of different types of transceivers is shown in Figure 3.

The simulation model was developed using the following additional assumptions:

- A channel request by a member of a fleet/subfleet causes a channel assignment to the entire fleet/sub-fleet, provided a channel is available.
- A call request by a member of a fleet while a channel is assigned to that fleet but not used by other members of that fleet, shall be processed by the system as a call arrival.
- A call request by a member of a sub-fleet which occurs while another member of that sub-fleet is transmitting is suppressed by the system as a call arrival, since the frequency is already in use.
- A call request by a member of a subfleet while the subfleet already has a call request placed on queue, is ignored as a call arrival by the system.
- A fleet call request shall trigger a request for a channel for that fleet as follows:
  - If a channel is available, then it will be assigned to the entire fleet. All other channels that may already be assigned to subfleets of that fleet shall be released.
  - If no channel is available then the fleet call request shall be placed on a queue. When a channel becomes available it will be assigned to the fleet in the same manner as described earlier.

The TRS network model used in the simulation study had a five channel configuration, one of which is a control channel, and the remaining four are for customer conversation. During the simulation, for each subfleet, time is divided into non-active and active time intervals. Call requests are generated during the active time intervals, either deterministically or stochastically, by the simulation. The duration of active time could also be stochastic/deterministic. In the scenario presented below, we used the following schedule for active time definition:

Each one of the first ten fleets is active, sequentially and consecutively, every ten minutes for a duration of one minute as follows: Fleet 1 is active during the first minute, Fleet 2 is active during the second minute, and so on.

Fleets 11 and 12 are active alternately for one minute each as follows: Fleet 11 is active during the odd numbered minutes, while the Fleet 12 is active during even numbered minutes.

The starting times and the duration of activities for Fleet 13 are represented probabilistically by normal distributions. The mean starting times are every 5 minutes and the standard deviation for these starting times is 0.5 minutes. The expected length of active time intervals is 1 minute with standard deviation of 0.5 minute.

The durations of active and non-active time intervals for Fleet 14 are exponentially distributed with a mean of 4 minutes for non-active time intervals and 1 minute for active time intervals.

The call holding time, defined as the time duration during which a channel is "being used" by a particular transceiver, is assumed to be distributed exponentially with mean = 1.1 seconds per call. The call requests, during active time intervals are assumed to be Poisson distributed with calling rates as follows:

Type A: $\lambda_1 = 0.10$ calls per second
Type B: $\lambda_2 = 0.01$ calls per second
Type C: $\lambda_3 = 0.05$ calls per second

As defined in the previous section, each TRS network has its characteristic priority or FCFS queuing discipline. For our model, we have used the following 4 priority level queuing protocol:

Priority I: A call request shall be placed in queue Q1, if it was requested by a transceiver belonging to a subfleet for which a channel has been released within τ_1 seconds from serving that fleet. (In our study we used $\tau_1 = 0.5$ seconds).

Priority II: A call request shall be placed in queue Q2, if it was requested by a transceiver belonging to a subfleet for which a channel has been released from serving that subfleet during a time interval τ_2. τ_2 is the time interval preceding the time interval specified for Priority I. (In our simulation we use τ_2 = 1.0 second).

Priority III: All call requests shall be placed in queue Q3, if they are fleet calls or if they are requested by transceivers which belong to Fleet 11.

Priority IV: A call request shall be placed in queue Q4, if the call could not be placed in any of the higher priority queues, Q1-Q3.

When call requests are queued and a channel becomes free, it will be allocated to the first available queued call in the ordered sequence Q1-Q4, i.e., higher priority calls shall be processed first.

We are interested in the steady state performance of the TRS network, and since only the Message Trunk Timer (MTT) period and the Recent User Assignments (RUA) directly affect the normal operating conditions, we did not simulate, nor analyze the effect of the remaining three control parameters. The MTT period for the simulation was initially set to 1.5 seconds. For the RUA, if the last 5 consecutive calls, which were placed on either Q1 or Q2, belong to a particular subfleet, then the next call which may be placed on either of the queues must be from any of the other sub-fleets.

This TRS Network model was simulated using the object oriented Queuing Network Analysis Package (QNAP2). For a sample simulation run, Figure 4-5 depict the number of allocated channels over time and the number of calls on each channel respectively. The histogram in Figure 6 shows the busy-percentage of each channel. In Figure 7, the detailed breakdown of the various calls generated by each fleet/sub-fleet and the percentage utilization for each fleet/subfleet is presented.

The model was simulated using different values for the MTT time-out period. The effect on system performance, measured in terms of channel holding times and average waiting time in system queue, was determined. Setting the MTT to a large value, lengthened the channel hold times. Lowering the timer, on the other hand, led to smaller channel hold times. This led to more frequent call disconnections and request re-queuing. Figures 8 and 9 show the channel allocations over time for MTT = 0.1 and 5.0 respectively. It is clear from the figures, that from a user's point of view, the best setting of the timer is as long as possible, while from the efficiency point of view the time value should be set low.

4 CONCLUSIONS

In this paper we presented the specifications and detailed description of a trunked radio network. We incorporated all the main characteristics of TRS networks in our model. We analyzed the system performance under different sets of control parameters. Due to space constraints all the results cannot be presented here. The detailed simulation code and results available in Dhingra,*et al* (1991). Additional features of TRS networks, which will be incorporated in future studies are: Privacy features, multiple control channels, interference control, robustness to CSC, BSR

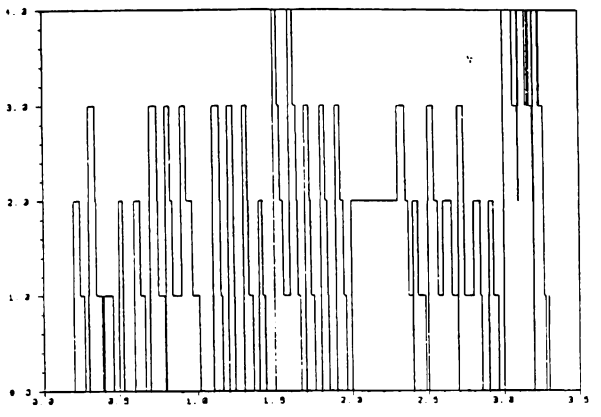

Figure 4: Number of allocated channels over time

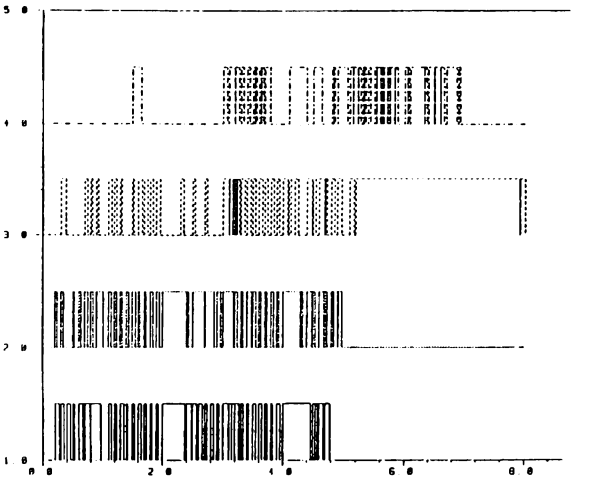

Figure 5: Channel utilization for the 4 communication channels (MTT = 1.5 seconds)

and communication channel failures, etc.

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AUTHOR BIOGRAPHIES

JASTEJ S. DHINGRA received his B. Tech. degree in electrical engineering from the Indian Institute of Technology, Kanpur in 1986. In 1988, he received the M. S. degree from Virginia Tech., Blacksburg. Since Fall 1988, he has been a Ph. D. candidate at the University of Maryland, College Park. He was a consultant with Texas Instruments Inc. and Techno-Sciences Inc. during summers of 1990 and 1991 respectively. His research interests include stochastic signal processing, modeling, analysis and control of discrete event dynamic systems. He is a member of Phi Kappa Phi.

RAKESH C. MEHTA was born on August 21, 1966 in Bombay, India. He emigrated to the United

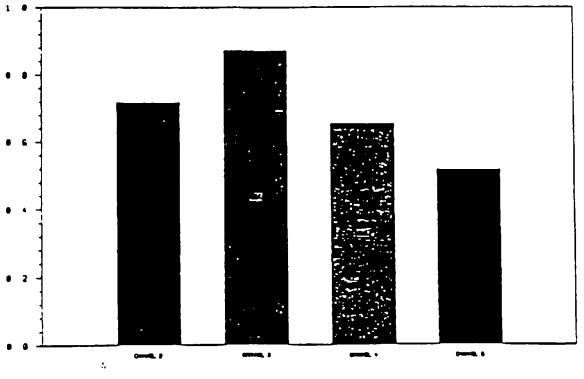

Figure 6: Busy Percentage for each channel

*FLEET ID	SUB ID	%CHANNEL TIME	#MTT	#CALLS A	B	C	*
* 1	1	5.43	20	21	58	0	*
* 2	1	3.28	25	21	20	0	*
* 3	1	5.84	19	18	72	0	*
* 4	1	2.90	21	21	13	0	*
* 5	1	3.01	20	19	13	0	*
* 6	1	5.21	26	20	60	0	*
* 7	1	6.28	21	21	76	0	*
* 8	1	3.85	20	17	28	0	*
* 9	1	3.86	20	16	43	0	*
*10	1	3.50	21	19	30	0	*
*11	1	36.63	112	111	497	0	*
*11	2	28.52	126	108	319	0	*
*12	1	19.88	123	86	151	0	*
*12	2	16.58	115	95	85	0	*
*12	3	16.14	114	89	94	0	*
*12	4	12.00	90	86	31	0	*
*13	1	19.85	1	27	294	70	*
*13	2	16.55	0	27	345	0	*
*13	3	10.80	1	32	205	0	*
*13	4	10.67	0	27	188	0	*
*13	5	14.43	0	28	290	0	*
*14	1	20.09	80	68	155	82	*
*14	2	2.70	20	0	40	0	*
*14	3	1.79	11	0	28	0	*
*14	4	1.70	10	0	22	0	*
*14	5	1.84	11	0	30	0	*
*14	6	2.37	16	0	31	0	*

Figure 7: Detailed simulation run output

States in 1970, and became a U.S. citizen in 1980. He received his Bachelor of Science degree in Electrical Engineering from the University of Maryland at College Park in May, 1988. He also received his Bachelor of Science degree in Computer Science at the University of Maryland at College Park in May, 1988. He has been an employee of Techno-Sciences, Inc, Greenbelt, Maryland since September, 1987. He has been involved in the computer and data communications area since 1984.

GILMER L. BLANKENSHIP was born in Beckeley, West Virginia on September 11, 1945. He received the S.B., S.M., and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, Mass., in 1967, 1969, and 1971, respectively. He is a Professor in the Department of Electrical Engineering, University of Maryland, College Park. He served as Associate Chairman of the Department for more than five years. He is faculty associate with the Systems Research Center and is a member of the Applied Mathematics Faculty. Since 1971 he has held visiting positions with New York University, New York, the University of Illinois, Urbana-Champaign, The University of Maryland, the U.S. Department of Energy, and with Erasmus University, Rotterdam. From 1971 to 1979 he was with the Department of Systems Engineering, Case Western Reserve University, Cleveland, Ohio. His research interests include discrete event systems scheduling theory and applications, nonlinear and adaptive control theory, scattering theory and the mechanics of advanced materials, and the applications of AI methods and computer algebra in these areas. Dr. Blankenship is also Vice-President of Techno–Sciences, Inc., a Maryland high technology firm specializing in advanced control and signal processing. Dr. Blankenship has been an Associate Editor of the *IEEE Transactions on Automatic Control* and Chairman of the Technical Committee on Stability, Nonlinear, and Distributed Systems of the Control Systems Society. He is an Advisory Editor of the journal *Acta Applicandae Mathematicae*. He has also served as Chairman of the AACC Theory Committee, as a delegate to the IFAC Theory Committee, as a member of the IEEE Edison Medal Committee, and as Chairman of the IFAC Working Group on Singular Perturbations and Asymptotic Analysis. Dr. Blankenship is a member of the Society for Industrial and Applied Mathematics, and the Association of Computing Machinery. He is a Fellow of the IEEE.

ABRAHAM SHARON was born in Israel and received his B.A. in Economics (1968) from Bar-Ilan University, where he also taught and pursued research

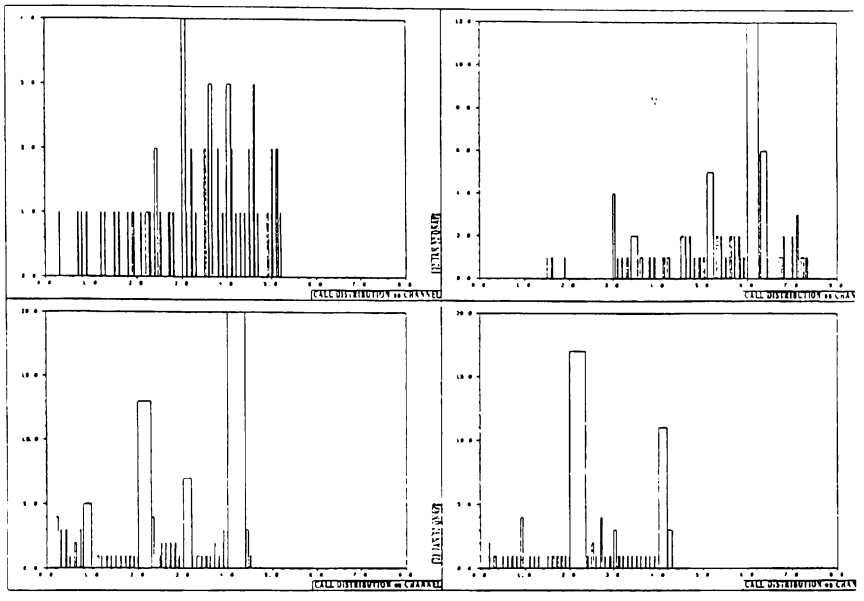

Figure 8: Channel utilization for the 4 communication channels (MTT = 0.1 seconds)

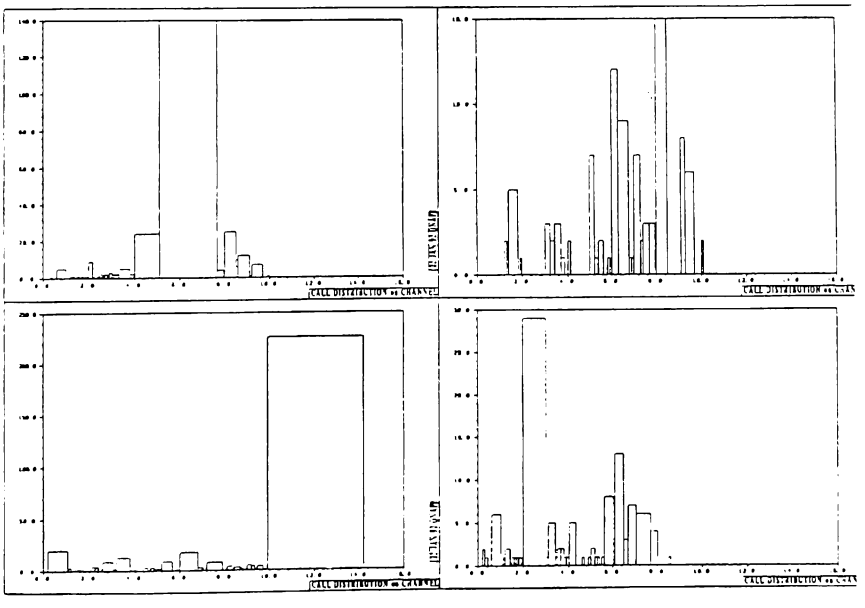

Figure 9: Channel utilization for the 4 communication channels (MTT = 5 seconds)

in Agricultural Economics. He completed his Masters degree in Operations Research (1972) and his Ph.D. in Systems Engineering (1977), specializing in control theory, from Case Western Reserve in Cleveland, Ohio. Subsequently, Dr. Sharon concentrated in the field of telecommunications, focusing on network modeling and architecture, and contributed to the area of traffic theory. Among the companies for which he worked were Bell Laboratories, Sperry, MCI, and ARINC. Currently, he is employed by Sprint International and develops Switched Voice Networks.