Simulation and Performance Evaluation of a Public Safety Wireless Network: Case Study

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In this article, the authors describe simulation and performance evaluation of a deployed radio communication network operated by a public safety agency. The network consists of a central site and multiple cells. Each cell has a finite number of available radio channels. The network is circuit-switched. Hence, the system utilization is a time and space distribution of the number of concurrent calls. To determine the traffic load variations, the authors analyze activity data from sample weeks in 2002 and 2003. They simulate the network by using the OPNET simulation tool and a newly developed network simulator named WarnSim. Simulation models are based on the collected activity data and are used to evaluate the utilization of system resources and to locate network bottlenecks.

Keywords: Emergency communications, trunked radio system, simulation of communication networks, network utilization, traffic analysis

1. Introduction

Simulation and analysis of deployed networks are used to determine their performance and to identify and locate possible network congestion. The scope of the performance evaluation and the parameters of interest depend on the network and its characteristics, such as technology, topology, and user behavior [1]–[3]. Such studies may be used to improve network reliability, which is essential for networks used by public safety agencies (police, fire department, and ambulance).

Emergency Communications for Southwest British Columbia (E-Comm) [4] operates a public safety wireless network (PSWN) that provides radio communications to mobile users who belong to various public safety agencies. The E-Comm network is circuit-switched and its wireless infrastructure has a cellular architecture. Each cell covers a certain geographical area within the Greater Vancouver Regional District. The number of frequencies available in each cell is predefined and it determines the cell capacity. Individual radio users access the network via trunking [5], [6] that implies sharing a set of frequencies (radio channels) among the agencies rather than dedicating subsets of frequencies to individual agencies.

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Prior traffic analysis of trunked radio systems dealt with statistical analysis of the collected traffic [7]–[9] and mathematical modeling based on traditional queuing theory [10]. Traffic in telephone networks was modeled by M/M/n queues: Poisson arrivals (exponentially distributed interarrival times), exponential call holding times, and n parallel servers [11]. Based on this theory, voice traffic in circuit-switched networks has been modeled by the Erlang B and C models [12]. However, trunked radio systems possess characteristics that distinguish them from telephone networks, such as trunking-based network access and one-to-many type of conversations. For example, prior analysis of traffic from the E-Comm network indicated that call holding and call interarrival times were not best described by exponential distributions [8], [13]. Therefore, the Erlang models may not capture the statistical characteristics of the traffic in trunked radio systems.

Analysis of channel utilization is a common approach for allocating network resources. Industry Canada channel-loading guidelines for land mobile radio systems used by safety services recommend below 50% channel occupancy in conventional systems and a 3% probability that calls will not be delayed more than one call holding time in trunked systems during the average busy period [14]. We adopted here a simulation approach to model the utilization of the E-Comm network based on collected traffic data. We used the OPNET network simulator [15] to model the basic circuit-switched functionalities of the E-Comm network [16]. In order to simulate events characteristic to circuit-switched PSWNs, such as call queuing and retrying of blocked calls, we have also developed the Wide Area Radio Network Simulation (WarnSim) tool [17], [18].

The developed simulation models do not capture the wireless segment of the E-Comm network that handles communications between the base stations and the mobile radio transceivers. The E-Comm network serves several thousand users and the analyzed activity data do not contain the location of the users during a call. Furthermore, link errors and propagation phenomena in the wireless section of the network do not affect the establishing and discarding of the calls and, hence, they do not affect the network utilization. The limited cell capacities (number of available radio channels) are the network bottlenecks. Therefore, it is important to simulate the number of occupied channels in each cell.

Mobility of radio devices and call handover are two major concerns for micro-cell cellular networks. However, they do not affect the operation of the E-Comm network. The E-Comm network is a wide-area radio network with each cell (system) covering a citywide area. Because an emergency call lasts 3.8 seconds on average, there is only a negligible probability that one radio device moves between two cells during such a short time interval.

We used activity data collected by E-Comm to examine network utilization over sample weeks in 2002 and 2003. E-Comm activity data table contains records of network events. The relevant data were processed into a format suitable for OPNET and WarnSim trace-driven network simulations. We examined the instantaneous utilization of radio channels (the number of occupied radio channels) in each cell in order to observe the traffic change over the period of two years.

We describe the E-Comm network in section 2. The data model is given in section 3. The OPNET network model is presented in section 4. The WarnSim tool is introduced in section 5. Simulation results and analysis of network performance are given in section 6. We conclude with section 7.

2. E-Comm Network

2.1 Architecture of the E-Comm Network

A simplified schematic diagram of the general structure of a trunked radio system is shown in Figure 1.

The E-Comm wireless radio network utilizes the Enhanced Digital Access Communications System (EDACS), manufactured by M/A-Com [19]. The EDACS architecture is shown in Figure 2. It contains a central system controller (network switch), several repeater sites (base stations), a management console, one or more fixed user sites (dispatch consoles), a private branch exchange (PBX) gateway to the public switched telephone network (PSTN), and hundreds of mobile users. Individual cells that cover separate geographic regions in the E-Comm network are connected to the network switch by high-speed optical fiber or microwave data links. System events and call activities are recorded by base stations and are forwarded every hour through the data gateway to the central database.

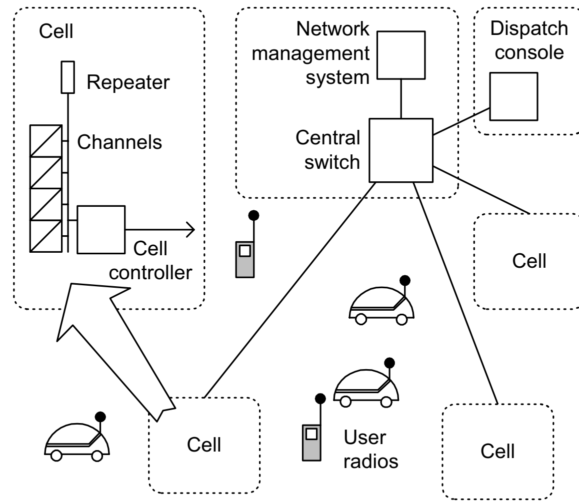


Figure 1. Schematic diagram of a trunked radio system

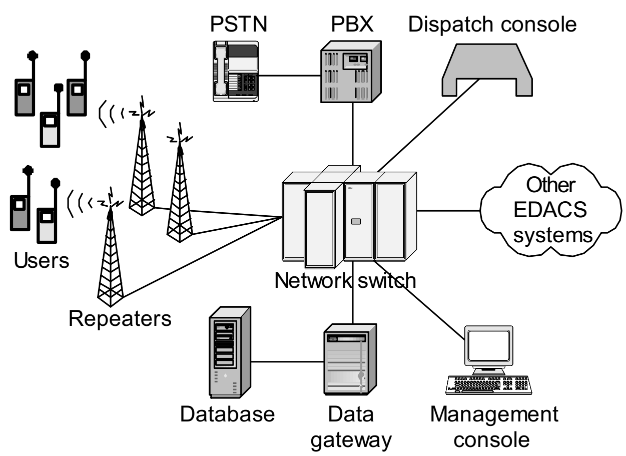


Figure 2. System architecture of the Enhanced Digital Access Communications System (EDACS)

2.2 Operation of the E-Comm Network

In this study, we consider only the circuit-switched network segment that carries user traffic between mobile users. It consists of eleven cells connected to a central switch. Each cell has a number of radio repeaters capable of transferring data using a set of frequencies. Adjacent cells are covered by different frequencies and there is no interference among cells. Repeaters belonging to one cell use an identical set of frequencies. This method of radio transmission is known as simulcast. The number of frequencies in each cell is predefined and it determines the number of available radio channels. Each radio channel occupies one frequency. Thus, we can define the capacity of a cell as a number of its radio channels. This number also determines the maximum number of simultaneous radio transmissions in a given cell. Every radio transmission is treated as one call. Each call in a given cell occupies one radio channel.

In each cell, one frequency is dedicated to the exchange of control information before, during, and after the call. Hence, the capacity of a cell (number of user channels) is one less than the number of available frequencies. No protocol and traffic data for the control channel were available in the collected data. Hence, we only analyzed the utilization of user channels.

In the E-Comm network, users are organized into talk groups. The system serves approximately 600 talk groups, consisting of a variable number of users (units) that often ranges between 20 and 150. For the sample week in 2002, members of a single talk group appeared in 2.26 cells on average. For the sample week in 2003, the average number was 2.54 cells. A single call might use simultaneously several channels. If members of a talk group reside in several cells, the network controller will allocate to the call a free channel in each cell. If all users of a talk group reside within a single cell, the network controller will allocate one free channel to the call.

A call is established by using a push-to-talk mechanism. A user (member of a talk group) talks to other members of the talk group by pressing the push-to-talk button on the mobile radio transceiver. The central system controller then determines the locations of the talk group members and checks for availability of radio channels in every cell where the members are located. If there is at least one free channel in every cell, the call is established. The one-way communication (call) lasts as long as the initiator holds the push-to-talk button. If there are no available channels in at least one cell with members of the talk group, the call is blocked and queued. The call is discarded if it cannot be established after a certain period of time. In the analyzed data set, the number of queued calls is negligible ($< 0.5\%$) compared to the number of established calls.

3. Traffic Data Model

Activity data from the deployed network recorded by E-Comm consist of records of network events: established, queued, and discarded calls, as well as talk group dynamics. By neglecting the mobility and call handover components, the analyzed data may be captured by two random processes: call arrival process and call duration process. A data model was created based on two weeks of activity data from the E-Comm records. We compare network performance during similar time periods in the two years. The 2002 sample data span the week between 0:00 on February 25, 2002 and 24:00 on March 3, 2002. The 2003 sample data span the week from 0:00 on March 10, 2003 to 24:00 on March 16, 2003. Timestamps end in either 0 or 7 (e.g., 2003-03-10 0:10:27.280 and 2003-03-10 0:10:27.877) due to the limitation of the "datetime" data type in the MS SQL Server [20] that is used by E-Comm to record events. Hence, the resolution of the timestamps is at least 10 msec. The resolution of the call durations is 10 ms. In order to analyze the utilization of radio channels in individual cells, the sample data were aggregated. The data model, formatted as a trace file, was used as input for OPNET and WarnSim trace-driven simulations. Figure 3 illustrates the four stages of the data transformation.

From the sample data, we extracted only the records relevant to established voice calls, indicating the caller, the called talkgroup (callee), the time of a call (timestamp), and how long a channel in a given cell was occupied (duration). An excerpt from the 2003 sample data showing only the relevant fields is given in Table 1. Each user has a unique user ID, and each talk group has its unique identification number. In this example, the four rows correspond to one call. The call began at approximately 0:10:27 on March 10, 2003. It lasted 2,490 msec and involved cells 1, 2, 6, and 8. (To maintain confidentiality of the data, the IDs of the caller, callee, and caller agency were labeled A, B, and C, respectively.) Caller agency identifies the corresponding public safety agency. This field is not used in the OPNET simulations. It is used by WarnSim to analyze traffic from individual agencies.

A call can be represented by one or more rows in the sample data. The number of rows represents the number of cells where the call terminates. A call in the deployed network is uniquely identified by four fields: timestamp, duration, caller (ID of the user who initiated the call), and callee (ID of a talkgroup that receives the call). Nevertheless, timestamps and durations corresponding to a single call differ due to discrepancies in the records (sample data), as shown in Table 1. For the data model, we arbitrarily chose the smallest timestamp. The largest call duration was chosen in order to simulate the worst-case scenario. We also modified the format of the timestamp. The original timestamp represented the date and time of the beginning of a call. For simulation purposes, it was convenient to express the timestamp as a difference between the original timestamp and an arbitrary reference time. The reference

Table 1. Excerpt from the 2003 sample data

Timestamp	Duration (msec)	Caller	Callee	Cell	Caller Agency
2003-03-10 0:10:27.280	2,480	A	B	1	C
2003-03-10 0:10:27.300	2,470	A	B	2	C
2003-03-10 0:10:27.790	2,490	A	B	6	C
2003-03-10 0:10:27.877	2,490	A	B	8	C

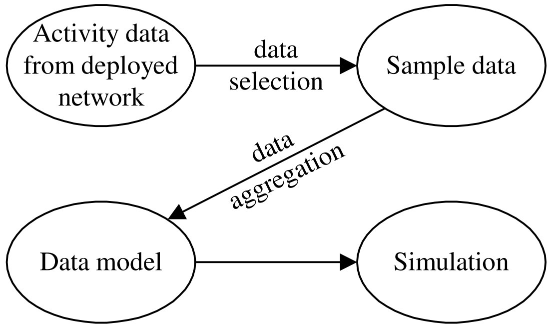


Figure 3. Preparing the traffic trace file from the E-Comm activity data

times were chosen to be 0:00 on February 25, 2002 and 0:00 on March 10, 2003 for the 2002 and 2003 data models, respectively. In order to create trace files used in simulations, we modified the sample data so that one row corresponds to one call. As a result, one record in the OPNET model trace file (the data model) that corresponds to the four rows of data shown in Table 1 is {627280, 2490, 1, 2, 6, 8}, where 627,280 is the timestamp (milliseconds), 2,490 is the duration of the call (milliseconds), and the remaining numbers are the cell IDs where the call terminated. WarnSim uses a slightly different format for the trace file. The WarnSim record in the trace file that corresponds to the data shown in Table 1 is {627280, 2490, A, B, C, 1, 2, 6, 8}.

4. Simulations Using the OPNET Simulator

We used the OPNET [15] network simulator to analyze the E-Comm network performance. OPNET network models have a hierarchical architecture with three layers: network, node, and process. Network topology represents the top layer of the OPNET network model and consists of network nodes. Nodes consist of interconnected modules that perform defined tasks and exchange information using packet streams and statistical wires. The functionality of each module is defined using a process model (finite-state machine). The process model, created using OPNET specific functions, captures the behavior of the finite-state machine and defines the transitions between states.

4.1 OPNET Network Model

The OPNET network model, shown in Figure 4, consists of a central switch and eleven cells located in various regions of the Greater Vancouver Regional District. The cells are connected to the switch via point-to-point simplex links. In the deployed system, after call establishment, voice information flows from the originating cell to the central site and then to the destination cell(s). The call establishment procedure is performed by exchanging information over the control channel. The data model does not contain information about the originating cell of a call, and, therefore, the traffic in the OPNET model is generated in the central site and is then sent to the corresponding cells.

Each link has a number of channels equal to the number of frequencies available in a cell. The cell capacities (number of user channels) are shown in Table 2. One occupied frequency in a cell corresponds to one busy channel in the link that connects the cell with the central site. Therefore, during simulations, we recorded the number of used frequencies (the instantaneous utilization of radio resources) by monitoring the utilization of each point-to-point link (number of occupied channels). All channels in a link have an identical bit rate (arbitrarily chosen to be equal to 1,000 bits per second). In the OPNET model, calls are represented by packets. When a call is forwarded to a cell, the central site generates a packet of 1,000 $\times$ CD bits, where CD is the duration of the call (in seconds). The packet is sent to an idle channel in the link that connects the central site and the cell. The channel in the corresponding link will be occupied CD seconds, starting from the instance when the call is established.

4.2 OPNET Node and Process Models

We created OPNET node and process models for the elements of the E-Comm network. We used standard OPNET process models for point-to-point transmitters, point-to-point receivers, and packet sinks.

The OPNET network model consists of the central site node and the eleven cell nodes. The node model of the central site (network switch) is shown in Figure 5. Its functions are reading the trace file, generating packets that correspond to calls, sending the packets to appropriate cells, and collecting statistics. These functions are implemented in the modules that constitute the central site node model: *source*, *dispatcher*, *channel_selector*, and *tx* (point-to-point transmitter). There is one *source* module, one *dispatcher* module, and eleven pairs of *channel_selector* and *tx* modules (one pair for each cell). The *source* module reads the trace file and forwards to the *dispatcher* module the information about the calls to be established (call duration and destination cells). The central module in the OPNET node model is the *dispatcher*. Its process model is shown in Figure 6. It consists of four states. Initialization of the statistics that are collected during the simulation is performed in the *init* state. After the *init* state, the process proceeds to the *idle* state. When the *dispatcher* receives a notification from the *source* that a call is to be established, it proceeds to the *call* state. In this state, it checks for availability of free channels in the cells and it decides whether or not the call could be established. If the call can be established, the process creates a packet of a length proportional to the duration of the call and forwards it to the corresponding *channel_selector* module(s). If the call cannot be established, the number of discarded calls is updated and the packet that corresponds to the call is destroyed. (The model

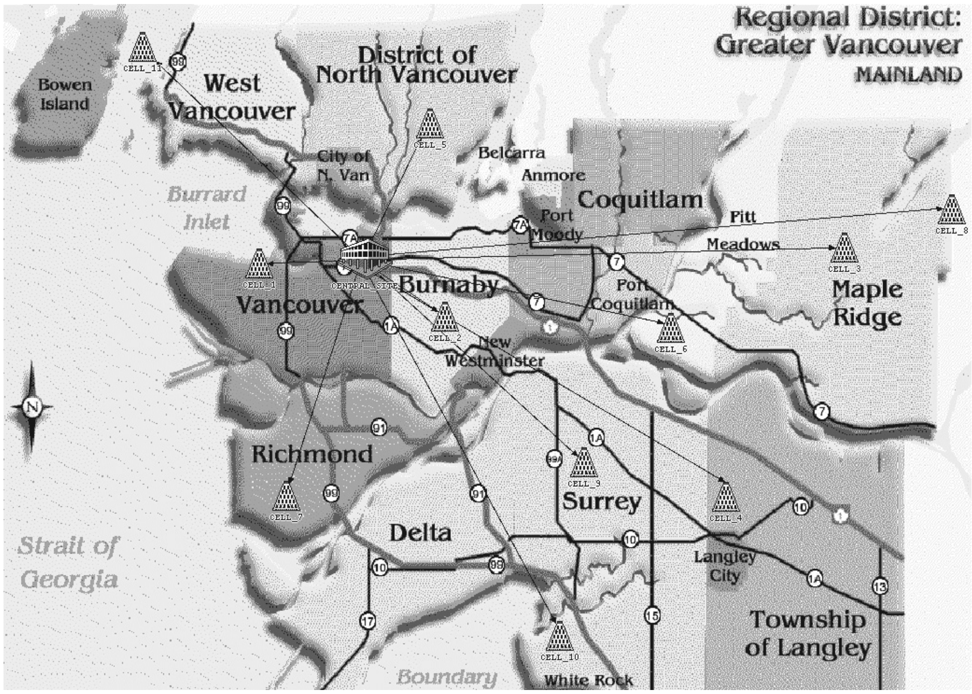


Figure 4. OPNET model of the E-Comm network. The network model consists of a central site located in East Vancouver and 11 cells covering various municipalities of the Greater Vancouver Regional District. The cells are connected to the central site via point-to-point links.

Table 2. Number of user channels per cell

Cell	1	2	3	4	5	6	7	8	9	10	11
Channels (2002)	12	7	4	5	3	7	6	4	6	6	3
Channels (2003)	12	7	4	5	3	7	6	4	7	6	3

Note: The only difference between the 2002 and 2003 data is the capacity of cell 9.

does not support call queuing: blocked calls are discarded immediately.) After the *call* state, the process returns to the *idle* state. The *dispatcher* is connected to each transmitter *tx* by statistical wires that monitor the channel occupancy in each link. One statistical wire monitors a single channel. When the *dispatcher* receives a notification that the status of a channel has changed, it proceeds to the *calc_stat* state. There, the values of the collected statistics are updated and the process returns to the *idle* state. Each *channel_selector* module registers free and occupied channels in its connected link. When a packet from the *dispatcher* arrives, the *channel_selector* sends the packet via one of the free channels and marks the channel as busy. When a cell receives a packet, which is equivalent to a call being completed, the *channel_selector* marks the corresponding channel as free.

The node model of a cell is shown in Figure 7. It consists of a point-to-point receiver *rx*, a *receiver* module, and a *sink*. When a packet arrives, the *receiver* module notifies the corresponding *channel_selector* in the central site of the free channel in the link and sends the packet to the *sink*.

5. WarnSim Network Simulator

We developed WarnSim using Microsoft Visual C# .NET, which has a performance comparable to Java. WarnSim works on any Windows platform with .NET framework support and it has a graphical user interface. WarnSim permits variable number of cells organized in a star network topology, choice of traffic sources and simulation parameters, and graphical presentation of simulation results.

5.1 Modules and Call Flowchart

WarnSim consists of seven modules. They are shown in Figure 8.

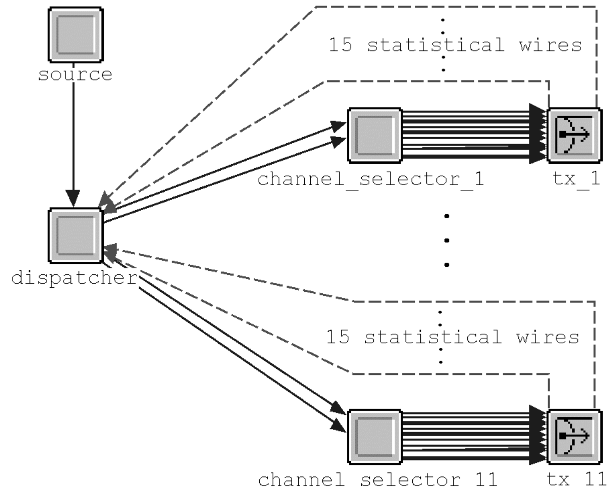


Figure 5. OPNET node model of the central site

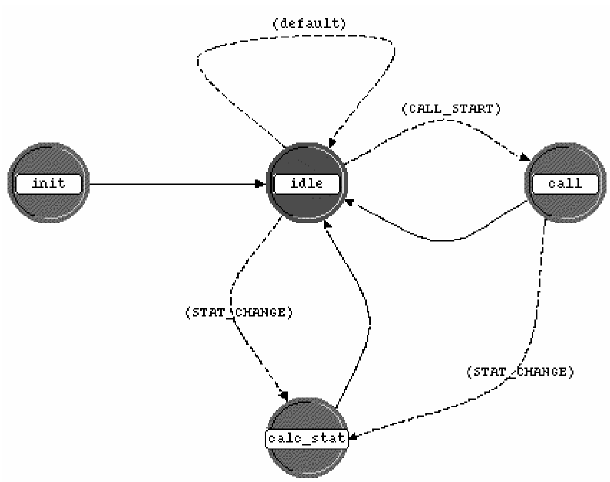


Figure 6. OPNET process model of the dispatcher module in the central site node model

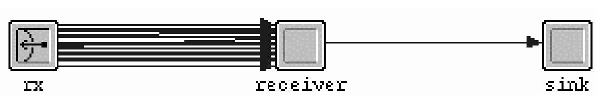


Figure 7. OPNET node model of a cell

The *network module* models the cells of a PSWN. Each cell has one or more channels with the attribute *busy duration*. The channel is free if *busy duration* = 0. Otherwise, the channel is occupied for the duration of time specified by the "busy duration" attribute. The *network module* distributes calls to cells, tracks the status of the system (number of free or occupied channels), and periodically updates the channel status in every cell.

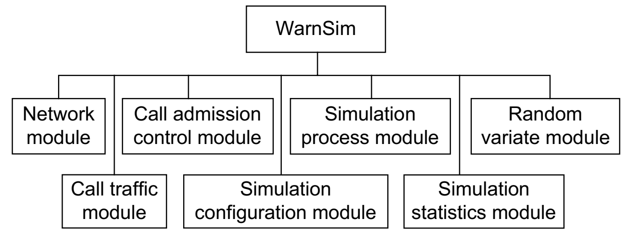


Figure 8. Module diagram of WarnSim

The *call traffic module* prepares traffic data for simulation. It can import traffic trace files from text files/databases, generate call traffic based on user-defined distributions, or combine them during a single simulation run.

The *call admission control module* uses the data from the *call traffic module* and checks with the *network module* to determine if there are available channels for a call to be established. It also manages the retrying mechanism of blocked calls.

The *simulation configuration module* keeps track of call queuing mechanism and parameters, such as the maximum call queuing time, simulation duration, and granularity.

The *simulation process module* uses a global timer to control and synchronize the operation of the WarnSim modules.

The *simulation statistics module* collects real-time and summary statistics from other modules (number and cumulative number of calls and blocked calls, call-blocking probability, cumulative call blocking probability, channel utilization and cumulative channel utilization). It is also used to display and visualize simulation results.

The *random variate module* generates random numbers and random variables. We adopted the MT random number generator [21] suitable for stochastic simulations. We also implemented several types of random distribution functions: uniform, exponential, gamma, normal, lognormal, loglogistic, and Weibull. The *random variate module* is used to generate call traffic based on user-defined distributions.

A high level diagram illustrating the call flow mechanism of WarnSim is given in Figure 9. The WarnSim basic functionality is described by the pseudo-code shown in Figure 10.

5.2 WarnSim Interface

Two samples of WarnSim interfaces are shown in Figure 11 and Figure 12. The network configuration (cells and number of channels) is shown in Figure 11. A dialog window is used to configure the system ID, system name, and number

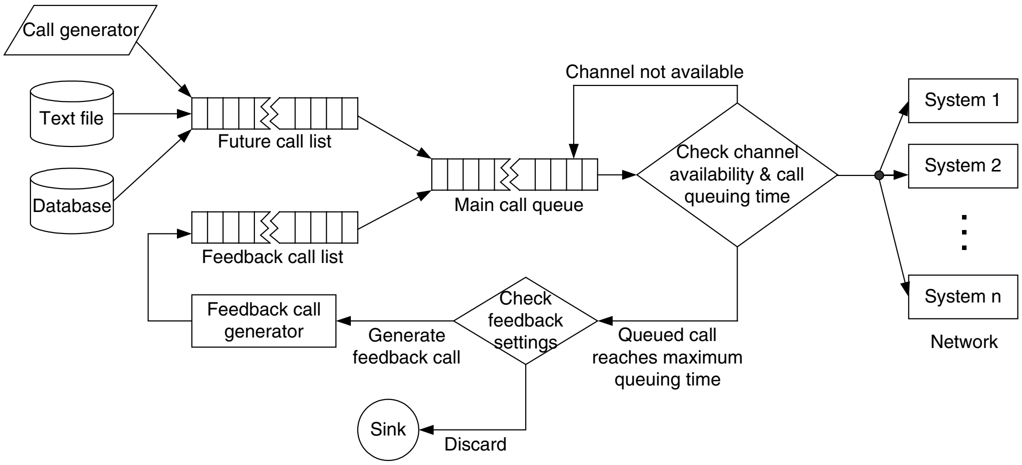


Figure 9. High-level diagram of the WarnSim simulator

```
Load call traffic traces from the call generator or text files/databases;
Save call traffic traces into FutureCallList and sort them by CallArrivalTime;

for (SimTime=SimStartTime; SimTime<SimEndTime; SimTime++)
{
    Update network status (system/channel status) and statistics;
    Load all calls with (CallArrivalTime<SimTime) from FutureCallList and FeedbackCallList into
MainCallQueue;

    for (each call in MainCallQueue)
    {
        if (there are enough channels in network to establish that call)
                Call is assigned to network and is removed from MainCallQueue;
        else if (CallArrivalTime-SimTime>=MaxQueuingTime)
        {
                if (Call feedback mechanism is enabled)
                        Generate a feedback call and add it to FeedbackCallList;
                else
                        Call is discarded;
        }
    }
}
```

Figure 10. Pseudo-code corresponding to the high-level diagram of the WarnSim simulator

of channels. The traffic source configuration window and a dialog window used to import traffic traces are shown in Figure 12.

5.3 WarnSim Features

WarnSim is a publicly available software tool designed to simulate circuit-switched radio networks [18]. It provides flexibility in choosing the network size and cell capacities (number of channels). Traffic traces are either imported from activity data collected from deployed networks or generated using a variety of statistical distributions for the call duration and call interarrival times (the difference between two successive timestamps/arrivals). Traffic trace generators are configured during the simulation setup. An external traffic trace may be imported from a comma-separated value (CSV) text file or a database. This feature enables simulating networks with a wide variety of traffic patterns and loads. WarnSim is suitable for simulating wide-area radio networks, such as PSWNs. However, simulations with WarnSim are slower compared to OPNET simulations.

Unlike the developed OPNET model of the E-Comm network, the WarnSim model can capture queuing of blocked calls. The call is blocked when a call is destined for cells with no available channels. It is not discarded immediately and it is queued instead. If the call is not established before the maximum queuing time expires, the

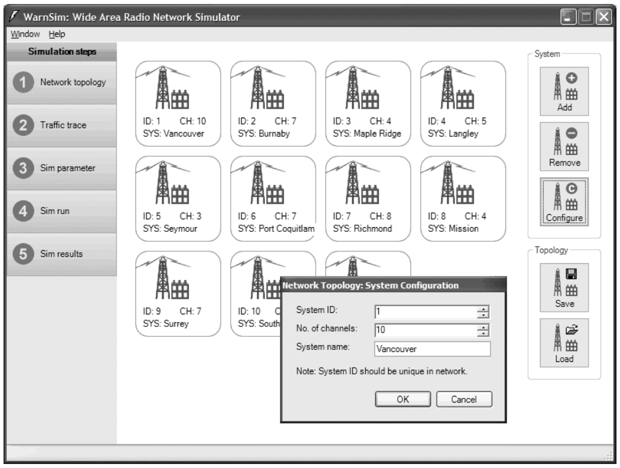


Figure 11. WarnSim interface: network configuration

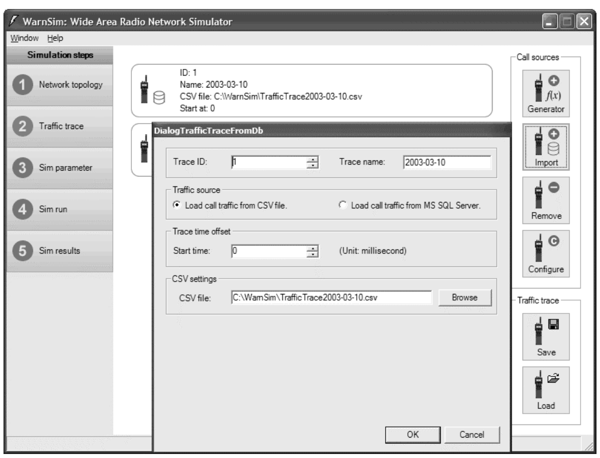


Figure 12. WarnSim interface: traffic source configuration

call is either discarded or retried with a certain probability. Retrying blocked calls simulates a user behavior pattern where a user attempts to reestablish a call that was previously discarded. The maximum call queuing time and the probability of a call being retried are selected during the WarnSim simulation setup. The OPNET model corresponds to the case when the maximum queuing time is set to zero and the retrying of blocked calls is disabled (all blocked calls are discarded).

6. Network Activity and Traffic Trends

We simulated network activity during the two sample weeks: February 25 to March 3, 2002, and March 10 to March 16, 2003.

6.1 OPNET Simulation Results

OPNET simulation results are shown in Figures 13 and 14. The horizontal axes represent time (common to all graphs). In Figure 13, the first tick (marked 0d) corresponds to 0:00 on February 25, 2002, while the last tick (marked 7d) corresponds to 24:00 on March 3, 2002. In Figure 14, the first tick (marked 0d) corresponds to 0:00 on March 10, 2003, while the last tick (marked 7d) corresponds to 24:00 on March 16, 2003. The numbers of occupied radio channels during the simulated week in 2002 are shown by the first 11 graphs in Figure 13. They are named "Occupied channels [i]," where i corresponds to the cell ID (1 to 11). The second graph from the bottom in Figure 13 corresponds to "Discarded calls." Its value is equal to 1 when a call is discarded. The total number of discarded calls over time is shown on the bottom graph in Figure 13, labeled "Cumulative discarded calls." The same holds for graphs shown in Figure 14.

The "Occupied channels [i]" graphs indicate the presence of daily (diurnal) cycles in the activity data. The minimum number of used channels is observed at approximately 2 p.m. every day, while the maximum utilization is reached between 9 p.m. and 3 a.m. As expected, discarded calls occur during periods of high utilization. The simulation results from the 2002 data, shown in Figure 13, indicate that most cells seldom reach their capacity. Cell 11, with a capacity of 3 channels, is an exception and often has all available channels occupied during the busy hours. Cell 10 had all its channels occupied only once during the 2002 sample week. Simulation results for the 2003 data are shown in Figure 14. During the busy hours, several cells operate at their full capacities. (Cell capacities are given in Table 2.) For example, every channel in cells 2, 4, 7, and 9 is occupied during the periods of high utilization. In both 2002 and 2003 sample data, the average number of used channels in each cell is small compared to its capacity. This is to be expected because of the design requirements that the system meets certain grade of service (GoS) criteria during busy hours. The average number of used channels and the average utilization of each cell for both sample weeks are given in Table 3. Except for cell 11, the average utilization of every cell increased from 2002 to 2003. The average utilization of cell 4 increased by almost a factor of four.

The OPNET model does not match the behavior of the deployed system with respect to discarded calls. The trace file (data model) was created from the sample data by considering only the established calls. Discarded calls in the simulation results are due to discrepancies in the sample data. As described in section 3, there are records corresponding to one call that may have multiple values for the timestamp and the duration. Since the trace file (data model) was created by taking the largest value for the call duration, it is possible that the simulation model exhibits larger utilization than the deployed network. Another discrepancy is the existence of records showing overlapping

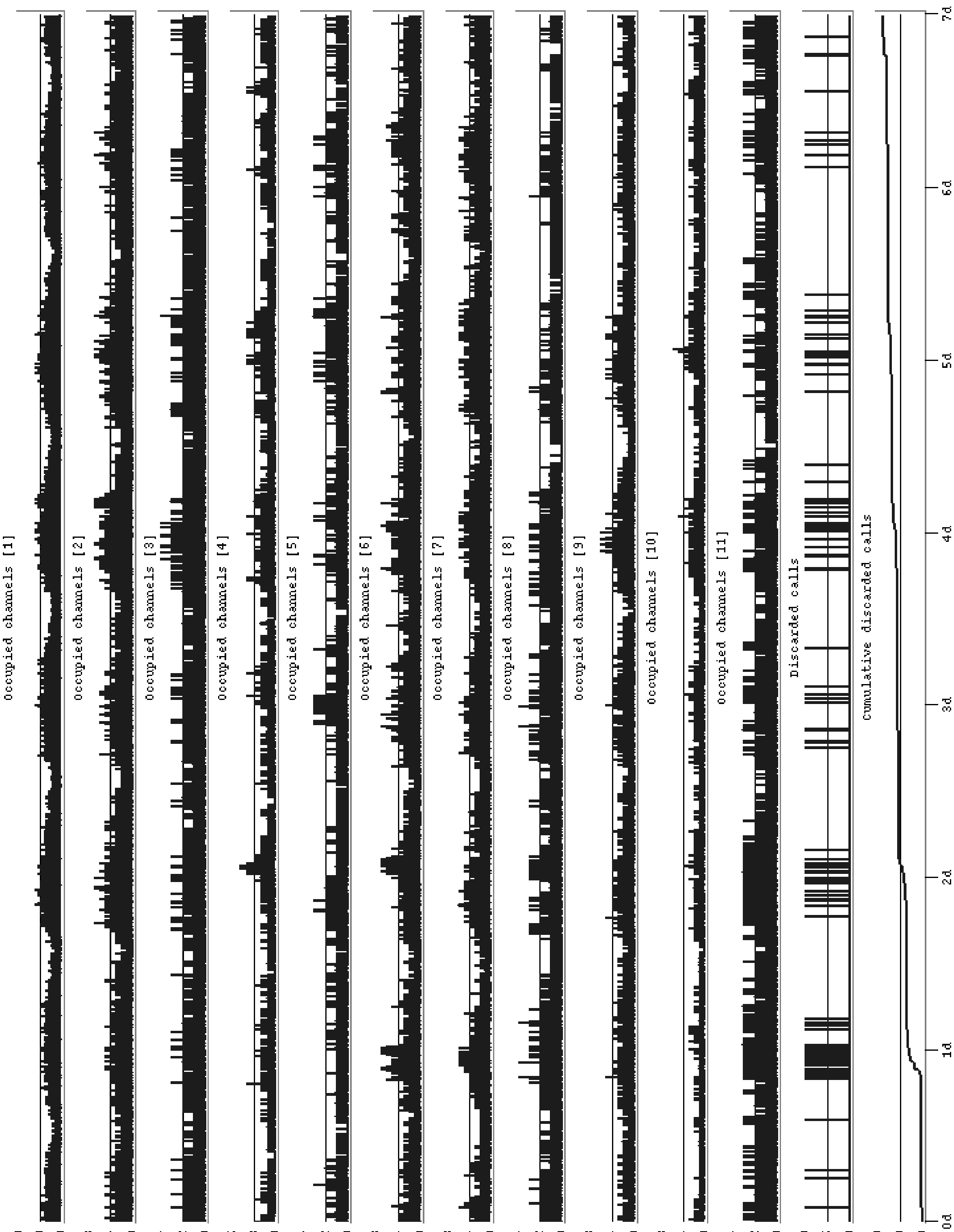


Figure 13. OPNET statistics collected during the simulation of network activity in 2002. “Occupied channels” [1] to [11] shows the utilization of each cell (number of occupied radio channels). “Discarded calls” indicates the instances when calls are discarded. “Cumulative discarded calls” shows the cumulative number of discarded calls.

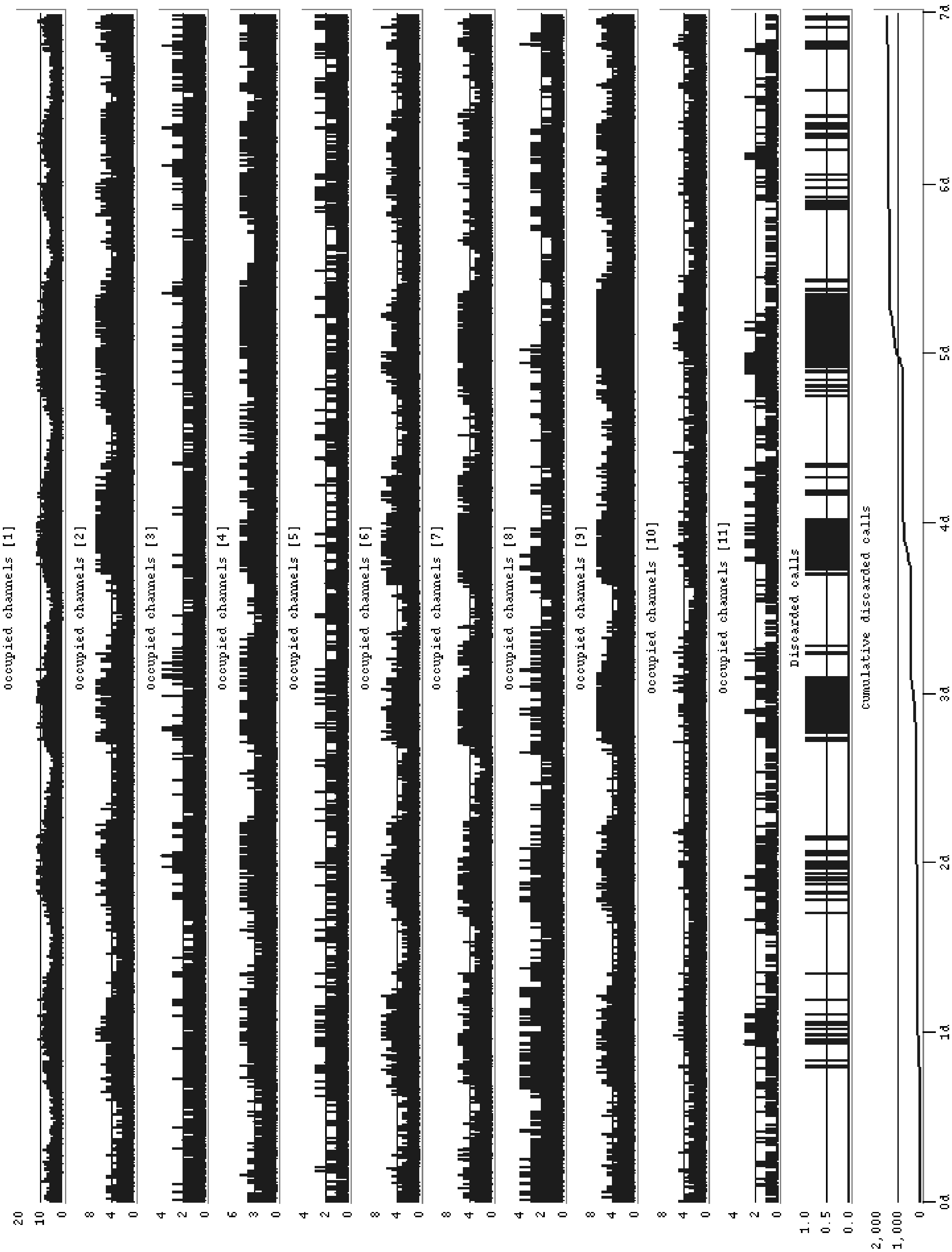


Figure 14. OPNET statistics collected during the simulation of network activity in 2003. “Occupied channels” [1] to [11] shows the utilization of each cell (number of occupied radio channels). “Discarded calls” indicates the instances when calls are discarded. “Cumulative discarded calls” shows the cumulative number of discarded calls.

Table 3. OPNET model: Average number of used channels and average utilization

	2002			2003		
Cell	Number of Calls	Average Number of Used Channels	Average Utilization (%)	Number of Calls	Average Number of Used Channels	Average Utilization (%)
1	387,640	2.45	20.42	401,212	2.70	22.50
2	132,083	0.80	11.43	202,958	1.33	19.00
3	48,314	0.27	6.75	51,839	0.31	7.75
4	41,741	0.25	5.00	150,033	0.95	19.00
5	24,620	0.14	4.67	32,587	0.19	6.33
6	112,393	0.70	10.00	167,878	1.11	15.86
7	132,662	0.81	13.50	184,634	1.22	20.33
8	36,576	0.22	5.50	60,445	0.37	9.25
9	75,019	0.46	7.67	229,615	1.50	21.43
10	40,863	0.23	3.83	116,491	0.74	12.33
11	56,770	0.33	11.00	26,871	0.18	6.00

Table 4. Overlapping usage of channels

Timestamp	Duration (msec)	Cell	Channel
2003-03-10 0:53:57.467	14,820	1	7
...	...	...	...
2003-03-10 0:54:12.180	2,640	1	7

usage of radio channels in the cells. One channel in a given cell can be occupied by only one call at a time. As indicated in Table 4, channel 7 in cell 1 is busy with a call lasting from 0:53:57.467 until 0:54:12.287 (= 0:53:57.467 + 14.820). However, there is a record corresponding to a call that originates at 0:54:12.180, occupying the very same channel 7 in cell 1. These records of overlapping usage of channels are due to errors in the recording of the activity data in the deployed network. Therefore, in the simulation scenarios, these calls are established using two channels instead of one. If a second channel is not available, one of the calls is discarded.

The simulation results showed 343 and 1,487 discarded calls in 2002 and 2003, respectively. The total number of calls was 477,953 (2002 sample week) and 625,898 (2003 sample week), respectively. The number of discarded calls in OPNET simulations is small compared to the total number of calls and, hence, it does not affect the analysis of the network utilization.

6.2 WarnSim Simulation Results

We simulated channel utilization and discarded calls for the 2002 and 2003 data. In order to compare OPNET and WarnSim simulation results, the queuing and retrying of blocked calls were disabled and, hence, all blocked calls were discarded.

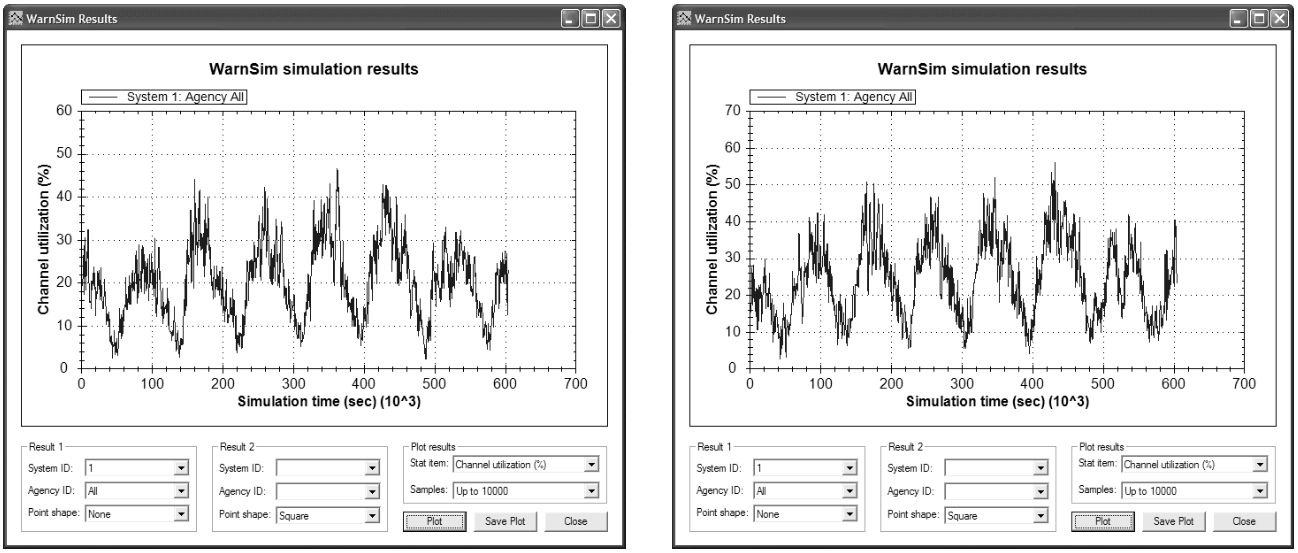
Channel utilization (running average calculated over 10-minute intervals) in cell 1 for the 2002 and 2003 sample weeks is shown in Figure 15(a) and Figure 15(b), respectively. The graphs indicate presence of daily cycles, with minimum utilization in the early afternoon (approximately 2 p.m.) and maximum utilization between 9 p.m. and 3 a.m. Other cells show the same daily cyclic pattern. Figure 16(a) and Figure 16(b) illustrate the cumulative number of blocked (discarded) calls in cell 1 for the 2002 and 2003 sample weeks, respectively. In the 2003 sample week, the number of blocked (discarded) calls in cell 1 is significantly larger than in 2002.

The WarnSim simulation results are summarized in Table 5. There is a visible increase in traffic volume from 2002 to 2003. These results are in agreement with the average number of used channels and the average utilization of each cell obtained by OPNET simulations (Table 3).

6.3 Analysis of Discarded Calls and Traffic Trends

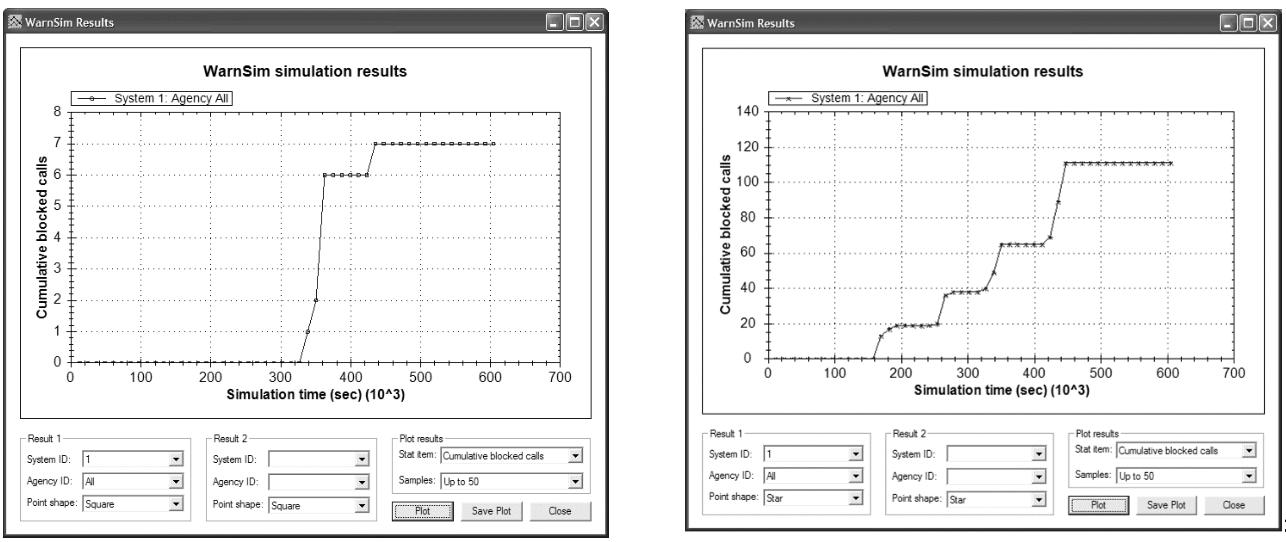
Grade of service (GoS) is an important parameter when analyzing and provisioning circuit-switched networks. It represents the probability of discarded calls for systems without queues or probability of a call being delayed or blocked in systems with queues. Although the data model consists only of established calls, the discarded calls may be used to locate network bottlenecks. They are indicators of network congestion and occur at periods of high network utilization. They may also indicate future network congestion problems if the traffic loads of the busy cells increase.

The busiest cells are most likely to cause call drops. Cell(s) that caused a call to be discarded could not be determined from the collected OPNET simulation statistics. From the graphs shown in Figure 13, it is only possible to identify the cells that operate near the full capacities (given in Table 2). For example, as shown in Figure 13, cell 11



(a) (b)

Figure 15. WarnSim: channel utilization of system 1 during the sample week in (a) 2002 and (b) 2003. The graphs show the running average calculated over ten-minute intervals.



(a) (b)

Figure 16. WarnSim: cumulative number of blocked calls in system 1 during the sample week in (a) 2002 and (b) 2003

and, to a smaller extent, cells 2 and 7 have every channel occupied during busy hours in 2002 when most of the discarded calls occur. Similarly, from the simulation results for the 2003 sample week shown in Figure 14, cells 2, 4, 7, and 9 may be identified as the busiest cells. We varied the capacities of cells 2, 7, and 11 (2002 data) and cells 2, 4, 7, and 9 (2003 data) as indicated in Table 6, while maintaining capacities of other cells as shown in Table 2. The number of discarded calls decreased significantly. This implies that the originally identified busiest cells indeed contributed to most of the discarded calls.

Unlike the OPNET model, WarnSim collects statistics of blocked and discarded calls for each cell individually. Hence, it is possible to determine the number of discarded

Table 5. WarnSim: Total number of calls, average number of used channels, and average utilization

	2002			2003		
Cell	Number of Calls	Average Number of Used Channels	Average Utilization (%)	Number of Calls	Average Number of Used Channels	Average Utilization (%)
1	387,640	2.42	20.20	401,212	2.67	22.27
2	132,083	0.81	11.51	202,958	1.34	19.10
3	48,314	0.27	6.77	51,839	0.32	7.89
4	41,741	0.25	4.98	150,033	0.96	19.16
5	24,620	0.14	4.78	32,587	0.20	6.73
6	112,393	0.70	10.04	167,878	1.11	15.85
7	132,662	0.81	13.49	184,634	1.23	20.46
8	36,576	0.21	5.29	60,445	0.36	9.10
9	75,019	0.45	7.54	229,615	1.49	21.31
10	40,863	0.23	3.89	116,491	0.74	12.41
11	56,770	0.33	11.14	26,871	0.17	5.69

Table 6. OPNET simulation results for various cell capacities

Sample Data	Cell Number	Number of Channels	Number of Discarded Calls
2002	Original capacities		343
	11	3 + 1	113
	11	3 + 2	91
	11	3 + 1	
	7	6 + 1	58
	2	7 + 1	
2003	Original capacities		1,487
	9	7 + 1	863
	7	6 + 1	
	9	7 + 1	
	7	6 + 1	435
	4	5 + 1	
	2	7 + 1	

calls in each cell and to identify the cells that experience most of the discarded calls. The number of discarded calls and the call-blocking probability for each cell for the two sample weeks are shown in Table 7. Call blocking probability in a cell is calculated as the number of discarded calls divided by the total number of calls in the cell. In the 2002 sample week, the majority of discarded calls occurred in cell 11, followed by cells 2 and 7. In 2003, cells 2, 4, 7, and 9 contributed to most of the discarded calls. This agrees with the OPNET results shown in Table 6.

The differences in network traffic loads in 2002 and 2003 were shown in Table 3 and Table 5 and in Figure 13 and Figure 14. The number of calls increased by $\sim$30%. This increase was not uniform among the cells. Several cells (4, 9, and 10) experienced a larger increase in the traffic load. If the same trend of nonuniform increase of traffic load persists, cells 4, 9, and 10 may experience queued and discarded calls. As shown, queued and discarded calls may be avoided by increasing the capacities of these cells.

WarnSim simulation results indicate that, except for cell 11, the number of discarded calls increased from 2002 to 2003. Call blocking probability also increased in most cells. The increase in discarded calls and call-blocking probability is significant for cells 2, 4, 7, and 9, which implies decreased grade of service (GoS) in these cells.

7. Discussion and Conclusion

Radio networks are currently designed according to specific spectrum policies and cannot adapt to policy changes without being redesigned. This has motivated the development of software-defined radios (SDRs) and dynamic spectrum utilization [22]. The SDR radio device first "senses" the spectrum, identifies spectrum opportunities (frequency and time), and utilizes spectrum by considering the level of interference with primary users. Hence, the management of the spectrum is placed in each radio device. The Defense Advanced Research Projects Agency (DARPA) XG (neXt Generation) communication program will enable dynamic access to temporarily unused frequencies and implementation of SDR in military and commercial areas. The XG communication protocols address the use of the spectrum, the architecture, system components, the concept of XG communications, the behavior and organization of the XG system, and the policies for spectrum access [23].

SDRs will enable communications between public safety agencies even if they use various types of radio devices and/or reside in different cities. System-level failures are of concern for emergency communication, which require high reliability and security for their operations. Hence, the SDR technology needs to guarantee security and avoidance of system failures and interferences with adjacent frequencies.

In this paper, we used collected call activity data to simulate a deployed circuit-switched PSWN. We simulated network performance using the OPNET and WarnSim

Table 7. WarnSim: Simulation results of discarded calls and call-blocking probabilities

	2002		2003	
Cell	Discarded Calls	Call-Blocking Probability (%)	Discarded Calls	Call-Blocking Probability (%)
1	7	0.00	30	0.01
2	15	0.01	211	0.10
3	0	0.00	2	0.00
4	2	0.00	290	0.19
5	5	0.02	9	0.03
6	7	0.01	41	0.02
7	44	0.03	513	0.28
8	0	0.00	4	0.01
9	1	0.00	301	0.13
10	0	0.00	5	0.00
11	237	0.42	38	0.14

simulation tools. Simulation results show daily cycles in the network utilization. The average number of busy channels in most cells is small compared to their capacities. Nevertheless, there are busy periods of high utilization. The data model used for the trace-driven simulations only included established calls. Between February 2002 and March 2003, the number of calls increased by nearly 30%. This increase caused several cells that were underutilized in 2002 to be used near their full capacity in 2003. This simulation study may be used to address existing and future network congestion problems.

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