Modeling and Performance Analysis of Public Safety Wireless Networks

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Abstract

Public safety wireless networks (PSWNs) play a vital role in the operation of emergency agencies. In this paper, we describe analysis and modeling of traffic data collected from E-Comm, the public safety wireless network deployed in Southwestern British Columbia. We also introduce a newly developed wide area radio network simulator, named WarnSim. The simulator is used to validate traffic models and to evaluate and predict the performance of the E-Comm network.

1. Introduction

Sharing vital voice information via radio in a timely and reliable manner is critical for operations of various public safety agencies, such as law enforcement, fire departments, and emergency medical services. Hence, public safety wireless networks (PSWNs) employed for on-scene communications play an important role in ensuring public safety. Public safety community has identified the limited and fragmented radio spectrum as one of the key issues that adversely affect public safety wireless communications [1]. The emergency wireless communication service providers are also concerned with the spectrum shortage and the high cost of deploying and operating voice channels. For example, emergency agencies covering city of Vancouver, British Columbia, share only eleven wireless voice channels. We use a modeling/simulation approach and a customized simulator (WarnSim) to evaluate and predict the performance of the Emergency Communications for Southwestern British Columbia (E-Comm) PSWN.

In Section 2, we describe the structure of E-Comm network. We introduce the design and implementation of WarnSim in Section 3. E-Comm traffic data analysis and modeling are presented in Section 4 and Section 5, respectively. We present simulation results in Section 6 and conclude with Section 7.

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2. Public safety wireless network

The E-Comm network is a public safety wireless network currently deployed in the Greater Vancouver Regional District of British Columbia, Canada.

As its infrastructure wireless radio network, E-Comm utilizes Enhanced Digital Access Communications System (EDACS), manufactured by M/A-Com. The architecture of EDACS is shown in Fig. 1. It contains a central system controller (network switch), several repeater sites (base stations), one or more fixed user sites (dispatch consoles), a public exchange (PBX) gateway to the public switched telephone network (PSTN), and thousands of mobile users. E-Comm network is managed from a management console. System events and call activities are recorded by base stations and are forwarded every hour through the data gateway to a central database. Individual systems that cover separate geographic regions in the E-Comm network are interconnected by high-speed data links. Systems similar to EDACS are employed by various emergency agencies worldwide.

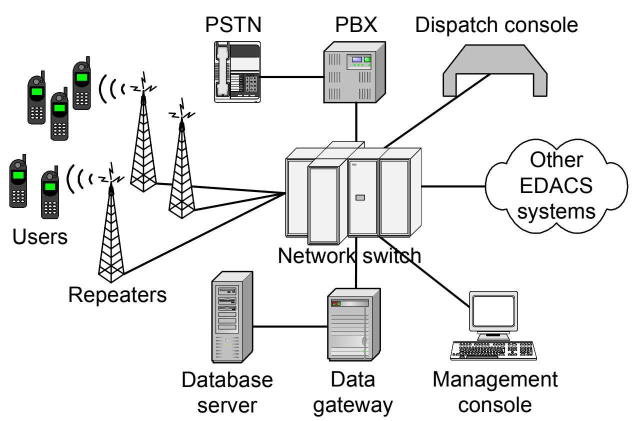

Fig. 1. System architecture of EDACS.

Transmission trunking: Communications within the E-Comm network are conducted via transmission trunking rather than the traditional message trunking. With message trunking, a radio channel is assigned to a call for the entire duration of the conversation. Because gaps of silent periods usually exist during a conversation, occupying the channel during the entire conversation time is inefficient in terms of channel utilization. With transmission trunking, the radio channel is automatically released as soon as the caller completes the sentence and releases the push-to-talk (PTT) button. The next speaker may begin a call by pushing the PTT button on his/her radio device. The system then checks the channel availability and assigns one or more channels to the call. Transmission trunking is 20–25% more efficient than message trunking.

Simulcast: Systems (cells) in the E-Comm network are simulcast systems that employ multiple repeaters to transmit and receive identical audio and data information over the same carrier frequency. Simulcast systems are used when it is necessary to use a limited number of frequencies to cover an area too large for a single repeater.

Talk group: In the E-Comm network, talk groups are defined at various levels for better coordination of operations: agency level, fleet level, and sub-fleet level. Each radio device belongs to one or more talk groups and may be switched between talk groups.

Group Call: A group call is the standard call type in the E-Comm network. Call recipients are members of a talk group. The advantage of a group call is that it eliminates the need for radio users to know the target device number in order to reach an individual user. Users can call a target group without a need to know the current members of the group. It is important to note that a single call might use several channels simultaneously. If all users of a talk group reside within a single system, the network controller will allocate one free channel to the call. However, if members of a talk group are distributed across several systems, the network controller will allocate to the call a free channel in each system.

Mobility of radio devices and call handover: Mobility of radio devices and call handover are two major concerns for micro-cell cellular networks. However, they are of little importance in the E-Comm network. The E-Comm network is a wide area radio network with each 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 systems during such a short time.

3. WarnSim: a simulator for PSWN

Several network simulation tools are currently available for simulating packet-switched networks (OPNET, ns-2, and J-Sim). However, they are not suitable for simulating circuit switched networks such as a PSWN. Hence, we developed WarnSim, an effective, flexible, and easy to use tool to simulate PSWN systems.

WarnSim is developed using Microsoft Visual C# .NET. It operates on Windows platforms and has a graphical user interface. Most simulations with WarnSim can be performed in five steps: setup network topology, setup traffic sources, configure simulation parameters, run simulation, and analyze simulation results. Figs. 2 and 3 capture two WarnSim screenshots during a simulation experiment.

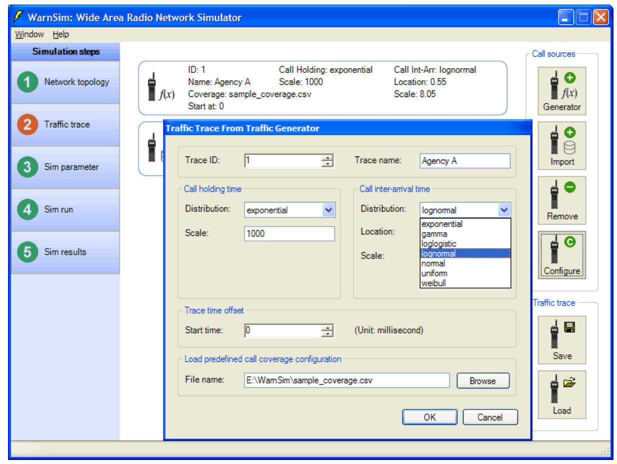

Fig. 2. WarnSim: traffic trace generation.

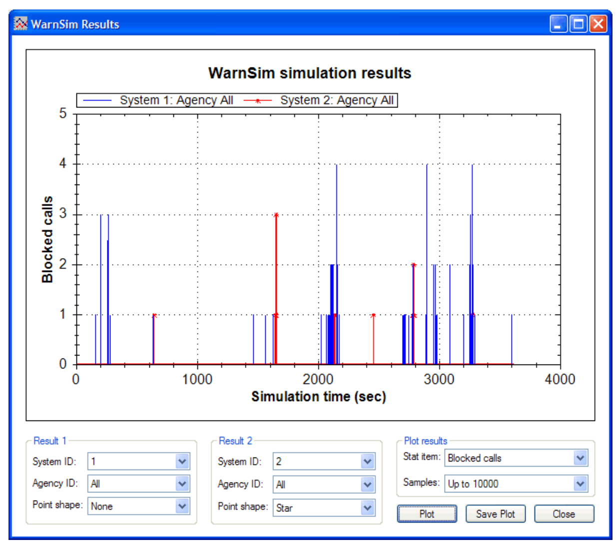

Fig. 3. WarnSim: simulation result (blocked calls).

WarnSim supports functionalities of a typical simulator. It consists of seven modules:

Network module models the systems. It tracks the status of the systems, distributes calls to covered systems, and periodically updates channel status in each system.

Call traffic module prepares call traffic for simulation. It either generates call traffic based on user-defined distributions or imports traffic trace files from text files/databases.

Call admission control module communicates with the call traffic module and 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.

Simulation configuration module keeps track of parameters such as simulation duration and interval.

Simulation process module uses a timer to control and synchronize the operation of the WarnSim modules.

Simulation statistics module collects real-time and summary statistics from other modules. It is also used to display and visualize simulation results.

Random variable module generates random numbers and random variables. It uses the MT random number generator [2], which is suitable for stochastic simulations. It generates random variables based on uniform, exponential, gamma, normal, lognormal, loglogistic, and Weibull distributions [3].

A high level diagram illustrating the call flow mechanism of WarnSim is shown in Fig. 4.

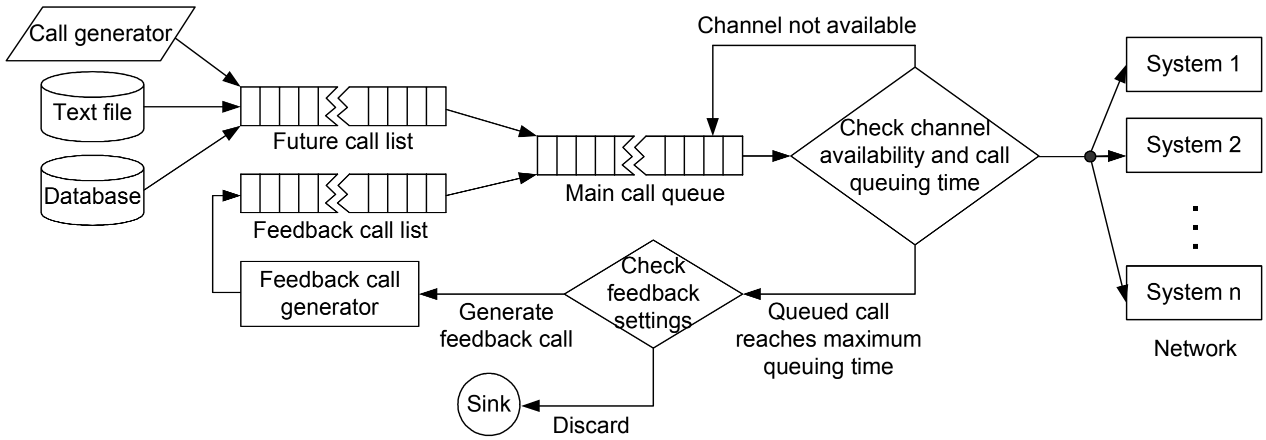

Fig. 4. High level diagram of WarnSim.

4. Traffic data analysis

We analyze three sets of call traffic data from the E-Comm network. The sets contain (year-month-day) 2 days (2001-11-01 to 2001-11-02), 30 days (2002-02-09 to 2002-03-10), and 92 days (2003-03-01 to 2003-05-31) of call traffic data.

The raw traffic data contain 26 data fields, from which we extracted fields and records of interest. A sample shown in Table 1 depicts a call made by caller 9999 to callee 1111 at 2003-05-01 00:00:09.620. The call lasted for 1,990 ms and covered Systems 1 and 7 using channels no. 3 and 4, respectively. The caller belonged to Agency 5.

Table 1. A sample of processed call traffic data.

Call arrival time		Duration (ms)	Caller agency
2003-05-01 00:00:09.620		1,990	5
Caller	Callee	System ID	Channel no.
9999	1111	1, 7	3, 4

Traffic data cyclic patterns: We consider 2,208 hours (92 days) of continuous traffic data in the 2003 dataset and use Fourier analysis to analyze the hourly call arrival rate in the frequency domain [4]. The power spectrum is shown in Fig. 5. Power spectrum analysis indicates that average hourly call holding time has a weekly cyclic pattern. Further analysis reveals that the busiest hour in a day is around midnight, while the least amount of traffic is expected between 2 pm and 3 pm. Furthermore, Thursday is the busiest day of a week while Monday has the least number of calls.

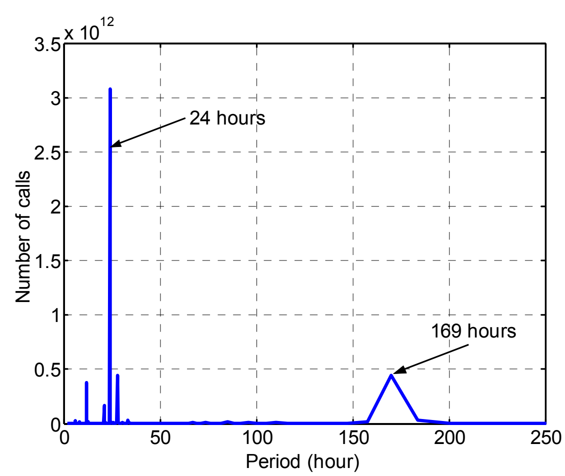

Fig. 5. Power spectrum of hourly call arrival rate indicates strong daily and weekly cycles.

Busy hours: PSWNs are designed to meet the Grade of Service standards during busy hours. Industry Canada requires that less than 3% of calls may be queued for an average call holding time during the busy hour [5].

The average hourly call arrival rate for the 2003 dataset is 3,966. Table 2 shows that the number of calls during busy hours is more than twice the average call arrival rate. For the statistical modeling of call traffic, we only consider the busy hour traffic.

Table 2. Top three busiest hours in the 2003 dataset.

Busy hours	Number of calls
2003-05-29 22:00 – 23:00	8,922
2003-05-15 02:00 – 03:00	8,664
2003-05-08 21:00 – 22:00	8,471

5. Call traffic modeling

We consider several call traffic models and use the maximum likelihood estimation (MLE) and Kolmogorov-Smirnov (K–S) goodness-of-fit test [6] to evaluate the proposed model of the E-Comm call traffic.

Erlang traffic models: The Erlang B and Erlang C models [7] are widely used by call traffic engineers to plan the network resources such as number of links and channels. Erlang models assume exponentially distributed call holding time. In the Erlang C mode, blocked calls are queued infinitely. These assumptions do not hold for the E-Comm network. Moreover, Erlang models are not designed to model group calls (one-to-many caller-callee relation). Hence, it is necessary to use alternative approaches to evaluate and predict network performance. We adopt a modeling/simulation approach to analyze performance of the E-Comm network.

Modeling call holding time: A number of probability models, such as lognormal [8], mixture of lognormals, Erlang-jk [9], and Hyper-Erlang [10], have been proposed to model call holding time in various wired and wireless networks. However, few models of call holding time have been developed for PSWNs because traffic data from such networks are rarely available due to their confidential nature. The large difference between the mean value of call holding times in PSWNs and in PSTN/cellular networks suggests that models of call holding time developed for other networks might not be suitable for PSWNs. Recent study of E-Comm aggregate traffic [11] shows that call holding time during busy hours fits the lognormal distribution.

We investigate the call holding time of the E-Comm traffic on the agency level. We model the busy hour traffic of the two heaviest user agencies (Agencies 2 and 5) that account for 80–90% of the overall call traffic. We first extract 500 sequential data samples (call holding times) from the traffic data. We select a candidate distribution (exponential, lognormal, or gamma) and use the MLE to estimate its parameters. The K-S goodness-of-fit test is used to evaluate the candidate distribution. Results listed in Table 3 indicate that lognormal distribution is adequate to model the call holding time for Agencies 2 and 5 (p-value > 0.01). The same conclusion holds for other busy hours in the 2002 and 2003 datasets.

Table 3. Distribution of call holding time in a sample busy hour in the 2002 dataset.

Agency 2	Distribution parameters and the K–S test
Exponential	β=3683.6, p-value=0
Lognormal	σ=8.0538, μ=0.5505, p-value=0.0832
Gamma	β=1108.0657,k=3.3246, p-value=0.0002
Agency 5	
Exponential	β=4269.78, p-value=0
Lognormal	σ=8.0882, μ=0.7256, p-value=0.0258
Gamma	β=2141.4626, k=1.994, p-value=0

Modeling call inter-arrival time: The Poisson model for the call arrival time is widely used in PSTNs [12]. It implies that the call inter-arrival time is exponentially distributed. Exponentially distributed call inter-arrival time was also originally assumed for cellular networks. It was shown that exponential distribution is only suitable for modeling inter-arrival times of "fresh" (new) calls in micro-cellular networks [13]. It is not suitable for modeling all (new and handover) call inter-arrivals in micro-cellular networks due to the frequent call handovers.

The E-Comm network is a macro-cellular network where call handover seldom occurs. Call inter-arrival time in the E-Comm network is exponentially distributed [11], similar to the call inter-arrival time in PSTNs. Table 4 shows that both exponential and gamma distributions are adequate to model the call inter-arrival time. We use exponential distribution because of its simplicity.

Table 4. Distribution of call inter-arrival time in a sample busy hour in the 2002 dataset.

Agency 2	Distribution parameters and the K–S test
Exponential	β=1282.2244, p-value=0.1232
Lognormal	σ=6.6795, μ=1.1643, p-value=0.0009
Gamma	β=1079.9108,k=1.1874, p-value=0.7863
Agency 5	
Exponential	β=1738.2826, p-value=0.5093
Lognormal	σ= 6.8838, μ=1.2564, p-value=0.0007
Gamma	β=1737.6351, k=1.0004, p-value=0.509

6. Simulation and prediction

After validating the implementation of WarnSim, we use WarnSim to validate the proposed traffic model and to evaluate and predict E-Comm network performance. In the simulation experiments, we assume that the call coverage pattern remains unchanged.

Validation of WarnSim: To validate WarnSim, we compare WarnSim simulation results with the prediction results of Erlang B model. Call blocking probabilities shown in Table 5 match well.

Table 5. Comparison of Erlang B and WarnSim results.

Erlang B model	WarnSim simulation
10 phone lines	1 system with 10 channels
10 Erlangs call traffic: exponentially distributed call holding time and exponentially distributed call inter-arrival time	10 Erlangs call traffic: exponentially distributed call holding time with mean value of 180 sec and exponentially distributed call inter-arrival time with mean value of 18 sec
Blocked calls neither queued nor retried	Max queuing time = 0 Blocked calls not retried
Call blocking probability: 21.5%	Call blocking probability: 17%–27%; Avg.: 21.86% (10 simulation runs)

Validation of the proposed traffic model: We use WarnSim to generate traffic traces and compare them with the collected E-Comm traffic data. Systems and channels, shown in Table 6, reflect the configuration of the E-Comm network. WarnSim distribution parameters listed in Table 7 are used for the call generator to model busy hour traffic from the 2003 dataset. Simulation results shown in Table 8 indicate that the proposed traffic model performs adequately when used to evaluate call blocking probability and channel utilization in the E-Comm network.

Table 6. System IDs and number of channels.

System ID	1	2	3	4	5	6	7	8	9	10	11
Channels	10	7	4	5	3	7	8	4	7	6	3

Table 7. Distribution parameters for the WarnSim call generator.

	Agency 2	Agency 5	Other
Call holding time	lognormal $\sigma = 8.05$ $\mu = 0.55$	lognormal $\sigma = 8.09$ $\mu = 0.73$	lognormal $\sigma = 7.88$ $\mu = 0.82$
Call inter-arrival time	exponential $\beta = 1354$	exponential $\beta = 761$	exponential $\beta = 3480$

Table 8. Evaluation of network performance: using collected traffic (actual) vs. model generated traffic (simulated).

ID	Actual blocking probability (%)	Simulated blocking probability (%)	Actual channel utilization (%)	Simulated channel utilization (%)
1	1.9 – 3.5	2.9 – 3.9	57 – 65	53 – 56
2	0.0 – 0.6	0.8 – 1.1	29 – 48	34 – 37
3	0.0	0.0	11 – 14	11
4	0.0 – 0.4	0.4 – 1.3	21 – 23	21 – 26
5	0.0	0.0 – 1.1	4 – 17	10 – 11
6	0.0 – 0.3	0.1 – 0.3	19 – 42	27 – 29
7	0.0 – 0.4	0.0 – 0.2	25 – 34	25 – 27
8	0.0	0.0	8 – 11	9 – 10
9	0.3 – 0.5	1.1 – 2.0	37 – 43	36 – 39
10	0.0	0.1 – 0.2	16 – 26	20 – 22
11	0.0	0.0	6 – 10	6 – 8

Evaluation of E-Comm network performance: We analyze the relationship between channel utilization, call blocking probability, and the number of channels, as well as the relationship between call blocking probability and the maximum call queuing time. Table 6 shows the default number of channels in each system. Figs. 6 and 7 show the simulated call blocking probabilities in System 1 with busy hour traffic data (2003-05-15 02:00–03:00).

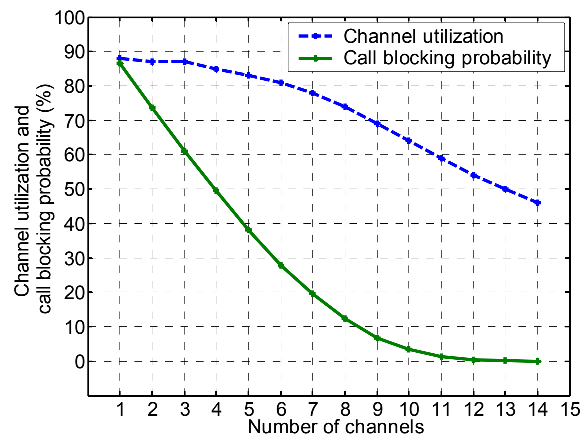

Fig. 6. Call blocking probability and channel utilization vs. the number of channels.

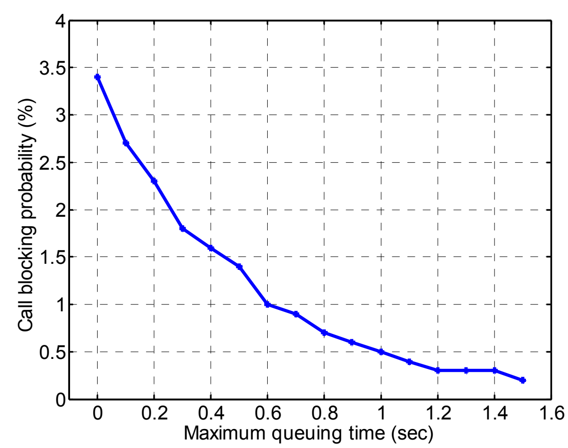

Fig. 7. Call blocking probability vs. the maximum call queuing time.

Prediction of E-Comm network performance: We predict performance of the E-Comm network by considering the case when the number of calls made by Agency 5 increases by 100% from the second busiest hour in 2003. Maximum queuing time is set to zero (blocked call are discarded). The number of channels for each system is shown in Table 6. WarnSim probability distribution parameters for the call generator are shown in Table 9.

Table 9. Probability distribution parameters for the WarnSim call generator.

	Agency 2	Agency 5	Other
Call holding time	lognormal $\sigma = 8.05$ $\mu = 0.55$	lognormal $\sigma = 8.09$ $\mu = 0.73$	lognormal $\sigma = 7.88$ $\mu = 0.82$
Call inter-arrival time	exponential $\beta = 1354$	exponential $\beta = 381$	exponential $\beta = 3480$

The simulation results shown in Table 10 indicate that the call blocking probabilities of four systems (IDs 1, 2, 4, and 9) visibly increase with the increase of call traffic. Further simulations revealed that in order to maintain call blocking probabilities of every system below the required 3%, Systems 1, 2, 4, and 9 require 4, 2, 1, and 3 additional channels, respectively.

Table 10. Evaluation of network performance: using collected traffic (original) vs. model generated traffic after the increase (predicted).

ID	Original blocking probability (%)	Predicted blocking probability (%)	Original channel utilization (%)	Predicted channel utilization (%)
1	1.9 – 3.5	12.1 – 12.6	57 – 65	71 – 72
2	0.0 – 0.6	5.1 – 7.0	29 – 48	54 – 55
3	0.0	0.1 – 0.4	11 – 14	16 – 17
4	0.0 – 0.4	1.5 – 3.7	21 – 23	35 – 39
5	0.0	1.0 – 1.3	4 – 17	16 – 18
6	0.0 – 0.3	2.1 – 2.7	19 – 42	44 – 45
7	0.0 – 0.4	0.6 – 0.8	25 – 34	38 – 40
8	0.0	0.0 – 0.3	8 – 11	16 – 18
9	0.3 – 0.5	9.0 – 10.1	37 – 43	60 – 62
10	0.0	1.3 – 1.5	16 – 26	35 – 38
11	0.0	0.3 – 0.9	6 – 10	11 – 13

7. Conclusions

In this paper, we described the structure of the E-Comm network and performed analysis of the E-Comm traffic data. We developed a model of call traffic on the agency level. The lognormal distribution proved appropriate to model the call holding time, while the exponential distribution was suitable to model the call inter-arrival time.

In order to evaluate and predict the performance of the E-Comm network, we developed a new simulation tool named WarnSim and used it to validate the proposed traffic models. We evaluated the performance of the E-Comm network and confirmed its capability to handle busy hour traffic. We also predicted performance of the E-Comm network by increasing the number of channels (network capacity) needed to accommodate the increased volume of call traffic.

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