Analysis of Public Safety Traffic on Trunked Land Mobile Radio Systems

Duncan S. Sharp, *Member, IEEE*, Nikola Cackov, Nenad Lasković, Qing Shao, and Ljiljana Trajković, *Senior Member, IEEE*

***Abstract*—Mobile radio systems for public safety and agencies engaged in emergency response and disaster recovery operations must support multicast voice traffic. In this paper, we analyze the distribution of call interarrival and call holding times for multicast voice (talk group) traffic on a transmission trunked mobile radio system. In such systems, the channel is held only while a user is making a call (while the push-to-talk key is pressed and the radio is transmitting). We find that the call interarrival time distributions are exponential and exhibit tendency toward long-range dependence. The call holding times best fit lognormal distributions and are not correlated. A potentially important implication of these findings is that performance estimation methods that assume memoryless Markov arrival and departure processes may not be viable approaches.**

***Index Terms*—Analysis of voice traffic, mobile communications, public safety networks, radio systems.**

I. Introduction

MOBILE communications for emergency response and disaster recovery are often cited as prime applications for mobile ad hoc networks. Today, land mobile radio systems provide communications for this application. The dominant form of communication is voice calling among a group of geographically distributed workers. In this paper, we analyze traffic from a shared land mobile radio system serving public safety agencies in the Lower Mainland of British Columbia. Our work was motivated by the need of researchers and system designers for traffic models in order to evaluate system performance.

We first introduce basic mobile radio concepts and terminology, discuss prior work, and identify our contribution.

A. Short Survey of Prior Traffic Analysis

Voice traffic on a land mobile radio system is often from short conversations or sessions (messages) where parties in the conversation exchange information. These sessions are usually a series of short voice transmissions from two or more users. Each individual contribution is often called a transmission or a call. A call consists of a push-to-talk (PTT) event to activate the radio transmitter, followed by a period of voice "calling." The call ends with release of the PTT key. The call is multicast to all other members of the talk group.

Analysis of talk group voice traffic from land mobile radio systems began in the early 1980s. This coincided with the introduction of trunked radio systems. Contributions by Hess [1]–[3] included characterization of message or session lengths and session interarrival times, use of Erlang-C model for message traffic, and analysis of traffic peaks. Treating a series of voice calls as one message is less valid today because most high efficiency trunked radio systems release the channel between voice call transmissions. Using Erlang-C model (M/M/s queues) has been advocated by several authors [3], [4]. Another study, by Hoang [5], [6], observed that each talk group in a mobile radio system behaves as a single source (rather than each mobile unit being an independent source). In many practical systems, this limits the number of sources and, hence, violates the infinite source assumptions that are implied by the use of Erlang-C model. Stevens [7] considers the issue of finite sources and derives equations for an M/M/s/K/K queueing model. The K/K term indicates that there are K sources and sufficient system capacity (servers and queue positions) for all K sources. Others have also contributed to the literature on traffic analysis for mobile radio talk group and dispatch traffic [8]–[10]. Stone's contributions [4] were submitted to the Public Safety Wireless Advisory Committee (PSWAC) on behalf of the U.S. Department of Justice and included user traffic profiles and grade of service recommendations.

In prior work [3], weekly and daily traffic distribution patterns have been explored. Our analysis of traffic patterns across time scales of several weeks supports these earlier findings. Prior literature on the distribution of call interarrival and call holding times during busy periods was predominantly based on message trunking. In message trunking, the channel is held for the duration of a session. Transmission trunking, where the channel is released between each call, is now more commonly used. It is more efficient because the channel resources are only held for the call durations (not the entire session duration). The busy period is of interest because it is often used as the design reference for provisioning a network with sufficient channel capacity to meet certain quality-of-service criteria (such as delay or blocking probability). Our analysis sought to address this gap by focusing on call interarrival and call holding times of transmission trunked systems during busy periods. An unexpected finding was that the call interarrival times of aggregated traffic from multiple talk groups, which is how a trunked system sees the traffic, shows evidence of long-range dependence.

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D. Sharp is with Planetworks Consulting Corporation, Vancouver, BC V6B 2M9, Canada (e-mail: dsharp@planetworks.ca).

N. Cackov, N. Lasković, Q. Shao, and Lj. Trajković are with the School of Engineering Science, Simon Fraser University, Burnaby, BC V5A 1S6, Canada (e-mail: ncackov@cs.sfu.ca; nlaskovi@cs.sfu.ca; qshao@cs.sfu.ca; ljilja@cs.sfu.ca).

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The paper is organized as follows. In Section II, we describe the mobile radio system that was the source of collected traffic. Section III describes the traffic measurement system, while Section IV outlines our analysis approach and notation. Traffic analysis and graphical presentation of results are given in Section V. Section VI contains conclusions and future work.

II. Public Safety Network

The geographically distributed and mobile talk groups or teams that characterize public safety operations need dependable communications. Voice communication on a common channel is an effective way of coordinating these talk groups. Users in a talk group use the channel to listen and talk. Talk groups can be classified by the type of carried traffic. For example, a dispatch talk group is used to assign tasks to field resources. Most traffic occurs between the dispatcher and one or more specific users or units. A specific task may require a separate talk group in order to coordinate group activities. Information talk groups may be used to disseminate information about an incident or situation and/or to serve information in response to queries from the field. Chat talk groups, as the name implies, are talk groups where users can congregate to exchange information without disturbing other talk groups. Talk group membership is flexible with users joining and exiting various talk groups as activities change. Priorities are usually assigned to talk groups depending on the urgency and operational importance of the communications carried, with higher priority traffic being given preferential treatment.

The potential of radio to support public safety operations, such as fire fighting and police work has long been recognized. The earliest land mobile radio systems were developed for public safety. A group of mobile and portable radios communicating directly on a common channel, as in Fig. 1(a), is a simple example of a single-hop ad hoc network. To extend the coverage area beyond the range of a single user's radio, one or more repeater sites can be added as shown in Fig. 1(b). This infrastructure extends coverage at the expense of higher capital and operational costs. To achieve economies of scale, several user groups may share this infrastructure. In order to handle the additional traffic, multiple channels may be added. As these types of mobile systems grew in size, *trunked* systems, where a number of user groups dynamically share a pool of radio channels, were developed to conserve spectrum. Fig. 1(c) shows the trunked concept.

We had access to traffic data from E-Comm, a large public safety mobile radio network operator. E-Comm serves many public safety agencies in the Southwest British Columbia with Enhanced Digital Access Communications System (EDACS) from M/A-COM (formerly Comnet–Ericsson). We briefly highlight the system architecture and operation, providing insight into the underlying process of traffic generation.

A. System Architecture

A trunked mobile radio system, such as the E-Comm system, consists of a central system controller, repeater sites, fixed user sites (dispatch locations), and mobile users, including both portable (hand-held) and mobile radios (vehicle-mounted radio units). The system elements are shown in Fig. 2.

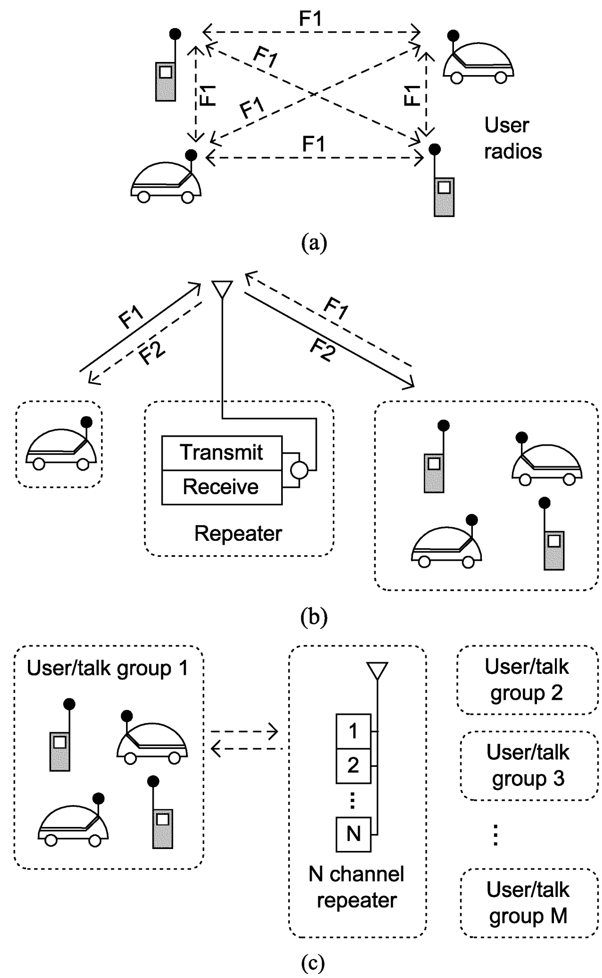

Fig. 1. Land mobile radio concepts. (a) Simplex operation: a group of radio units, all within radio range, communicate by sharing a single radio frequency. This is a simple, single-hop ad hoc network. (b) Repeater operation: coverage is extended by adding a fixed repeater site (infrastructure) and repeater operation requires use of two frequencies. (c) Trunked operation: a number of groups of users (M) share a smaller number of channels (N). Each user group is dynamically assigned a repeater channel. Delay depends on the traffic, the number of channels, and the multiple access scheme used.

Each repeater site has a control channel and several traffic (working) channels (typically up to 20 or 30 channels). The number of channels required depends on the traffic load and desired quality-of-service. Each repeater site covers a radius from one to over 25 km, depending on traffic, as well as terrain and propagation issues. To provide wide area coverage, additional repeater sites are used. Similar to other large-scale trunked radio systems, the E-Comm system is divided into several coverage subsystems. Although all subsystems belong to the overall system and are managed by a central controller, each subsystem forms a separate pool of channel resources for traffic purposes.

Users wishing to communicate with others in the same talk group must have their radios set to the appropriate "talk group." When the user presses the PTT key on their radio, a signal is sent over the control channel to the central controller. The central controller checks all other units that have selected the same

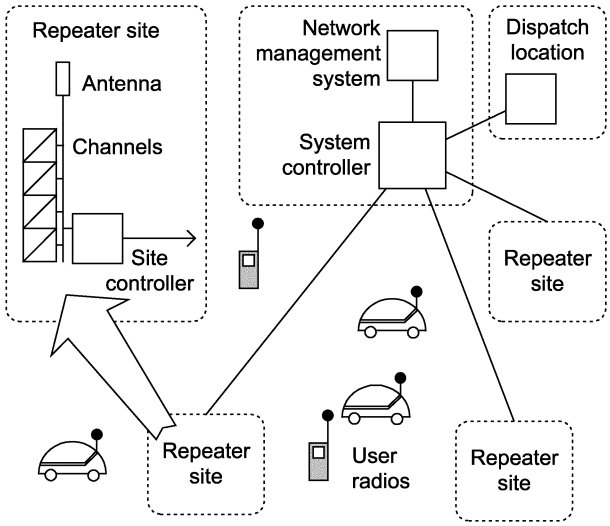

Fig. 2. Trunked mobile radio system concept diagram.

talk group and it verifies that there are channels available on all required repeater sites. The central controller then assigns a channel on each repeater site that is required for the call and signals every radio in the talk group to tune to the appropriate repeater frequency for the call. Assigning and setting up a channel takes typically 500 ms, after which the caller receives an audible signal and can begin talking. Any voice communication that precedes channel setup is lost. The call is received by all radios on the talk group that are within signal coverage. When the PTT key is released, the central controller releases the channel at each repeater site. If there are no channels available, then the PTT request is placed in a queue and served on a first-in–first-out (FIFO) basis within each priority level. In some systems, including E-Comm's, recent "talkers" may be given priority over new calls in order to ensure lower delay to existing call sequences during congestion.

B. Operational Arrangements

The system supports agencies, each with one or more user groups. Each user group may have one or more talk groups. A specific user group may range from a few units up to several hundred. Large user groups usually have several talk groups with distinct talk groups assigned for different functions. As noted earlier, talk groups may be used for dispatch, queries and information retrieval, chat, and for specific incidents and operations.

The system supports multiple priorities. The highest priority is reserved for emergencies. Priorities are assigned to give urgent and important traffic (dispatch and command talk groups) precedence over other traffic during periods of congestion.

III. Traffic Measurements

The system controller, which assigns channels and manages the system, is a software programmed real-time central processing unit. The controller maintains a call activity detail file that is a chronological list of all call related events. The system controller also provides summary reports that integrate and summarize the call activity events for specific systems (coverage areas), users, or talk groups. These data are initially written to a hard disk and then transferred to magnetic tapes for backup and storage. The data fields that are relevant to our analysis are summarized in Table I.

TABLE I
Relevant Traffic Data Fields From the Call Activity Detail and Summary Report Files

	Call Activity Detail file
Time	date time stamp (0.01-s resolution)
Type	call type, such as group, emergency, etc.
State	a state transition, such as assign or drop a channel
Caller	the identification of the radio unit originating the call
Callee	the talk group the call is destined to
Duration	call holding time in seconds (0.01-s resolution)
	Summary Report file (60-min integration time)
Start at	date time stamp of period start
Active talk groups	number of talk groups active during the period
PTTs	number of call attempts (push-to-talk events)
Granted calls	number of calls carried
Granted duration	call holding time sum total
Queued calls	number of call attempts queued
Queue duration	queue delay time sum total
Max queue depth	maximum queue depth
Max call delay	maximum call queue delay

TABLE II
Summary of Vancouver System User Count and Channel Capacity

Estimated number of users	
Police	1527
Fire	223
Ambulance	167
Transit	244
Total	2161
Number of traffic channels	12

The call activity detail file was used to extract traffic traces consisting of the call arrival times and call holding times (call durations). This processing removed all confidential information identifying specific user groups. These traffic traces provide detailed insight into the traffic processes. After reviewing a range of busy periods spread across several weekdays, two days of traffic from the Vancouver system were examined in detail. The system's key characteristics are summarized in Table II.

Our traffic analysis employed traces from the Vancouver system that handles a large traffic volume and has sufficient capacity so that congestion and queueing rarely occur. The summary reports were used to observe traffic patterns over a seven-week period during September, October, and November 2001. The number of agencies and users in the system did not change during the study period.

IV. Methodology

We considered only traffic within a single coverage system. This removed the issue of mobility patterns and each coverage area could be treated as a single traffic pool. By removing mobility, the traffic is reduced to a function of two random processes: a call arrival process and a call holding process. For voice calls, the Erlang is a convenient traffic unit. Traffic measured in Erlangs is dimensionless. In our case, an Erlang represents the average number of simultaneous voice calls in progress. Because calls arrive and depart randomly, the traffic is also a random process.

Traffic is measured across an integration period (60 min is common for mobile voice). Average traffic is a statistical value and to be meaningful the process must be sufficiently stationary during the integration period. We consider traffic (A) in Erlangs to be the sum of all call holding times (Tc) across an integration period (Tp) divided by the period. Traffic A can be calculated from the number of calls (Nc) during the period (Tp) and the average call holding time ($\mathrm{avg}\, Tc$) as

$$A = \frac{Nc \times \mathrm{avg}\, Tc}{Tp}. \quad (1)$$

The average call interarrival time ($\mathrm{avg}\, Ti$) is

$$\mathrm{avg}\, Ti = \frac{Tp}{Nc}. \quad (2)$$

Hence

$$A = \frac{\mathrm{avg}\, Tc}{\mathrm{avg}\, Ti}. \quad (3)$$

Inverting Tc and Ti gives the departure and arrival rates, respectively. This leads to the well-known expression that traffic is the ratio of the arrival rate and the departure rate.

Traffic traces consisting of call arrival times (Ta) and call holding times (Tc) for individual units and talk groups were extracted from the Call Activity Detail files using simple logic statements and sort functions. Call interarrival time (Ti) is the difference between successive call arrivals: $Ti = Ta[n+1] - Ta[n]$, where n denotes the nth arrival.

We analyzed system traffic (all talk groups) and selected individual talk groups. Time periods included various 1-h intervals. Our analysis included the distributions of call interarrival times (the arrival process) and call holding times (the departure process) with lag plots, probability density functions (PDF), cumulative distribution functions (CDF), and autocorrelation plots [11]. Various methods were used to test the data for long-range dependence.

Lag plots are graphs of the variable under study (X) obtained by plotting $x[n+1]$ versus $x[n]$. Although nonrigorous, they may provide a quick and simple indication of certain correlation structure.

Both probability density and cumulative distribution functions were calculated [12], [13]. Probability density functions plot the probability of occurrence of the variable under study. The cumulative distribution is the cumulative summation of the probability density function plotted to express the probability that the variable will not exceed specific values.

Autocorrelation is a measure of dependence among the instances of the variable under study. Autocorrelation is presented graphically by plotting the autocorrelation function for a range of lags. Correlation is present if the autocorrelation plot shows structure or does not decay rapidly. The value of the autocorrelation function for lag zero equals one. Our plots of the autocorrelation functions start with lag one in order to display small values.

Variance-time plot graphs the variance of the averages of different sized nonoverlapping blocks of the variable under study. They can be used to indicate long-range dependence [14]. On a logarithmic scale, a random variable with no long-range dependence has a linear variance-time plot with slope (B) of -1. Hurst parameter $\mathrm{H} = 1 + \mathrm{B}/2$ and, hence, $\mathrm{B} = -1$ implies $\mathrm{H} = 0.5$. A slope B between 0 and -1 $(0.5 < \mathrm{H} < 1)$ indicates self-similarity across various time scales, and we infer long-range dependence. Alternate tests for long-range dependence included R/S, periodogram, Whittle, and wavelet estimators [15], [16].

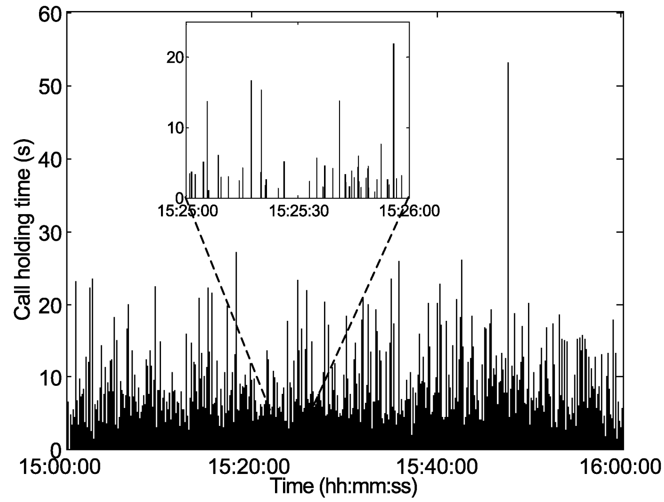

Fig. 3. Time series of aggregate traffic during busy period 15:00–16:00 on Thursday, 2001-11-01. The horizontal axis shows the timestamps of the calls and the vertical axis shows the call holding times in seconds. The inset graph is the 1-min interval between 15:25 and 15:26. Call interarrival times can be observed in the inset graph as time intervals between successive calls.

V. Traffic Analysis

We examined the three busiest hours during the two days of traffic data collected from the Vancouver system. The busiest hours were 14:00–15:00 and 15:00–16:00 on Thursday, 2001-11-01 and 21:00–22:00 on Friday, 2001-11-02. Our findings were similar for every period. The data used in this paper are taken from the busy period on Thursday, 15:00–16:00, when 248 radio units were active in 28 talk groups. A total of 3216 calls were made, generating 3.49 Erlangs of traffic during the hour.

The time series of the aggregate traffic trace is shown in Fig. 3. A visual inspection of the trace did not reveal any obvious visible tendencies that would imply nonstationarity. The trace was tested for second order or wide-sense stationarity by dividing it into equal blocks [17]. We examined the mean, variance, and Hurst parameter of each block employing various statistical tests [15], [17] and concluded that we could consider the call interarrival time and call holding time data to be wide-sense stationary.

A. Call Interarrival Times

Our findings for call interarrival times are shown in Figs. 4–9. Fig. 4 shows a lag plot for a single talk group. The "structure" in the plot demonstrates that individually some (but not all) talk groups have session behavior, i.e., that a series of calls form a conversation. The cluster on the bottom left-hand side corresponds to call interarrival times within sessions or conversations (intrasession call interarrival times). It indicates successive small call interarrival times. The distinct group of samples on the top left-hand side shows small call interarrival times followed

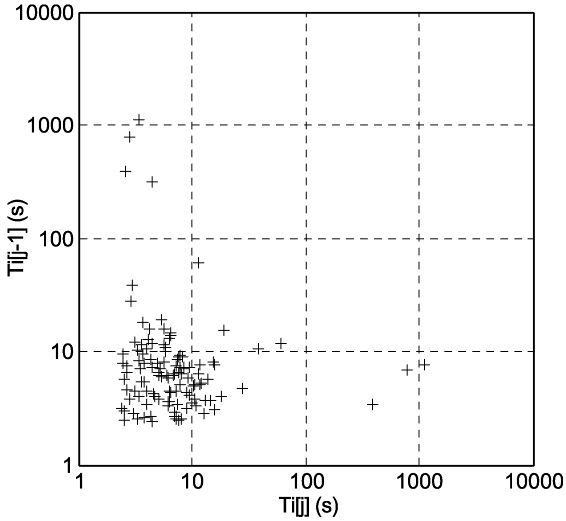

Fig. 4. Call interarrival time (Ti) lag plot for one chat talk group during busy period 15:00–16:00 on Thursday, 2001-11-01.

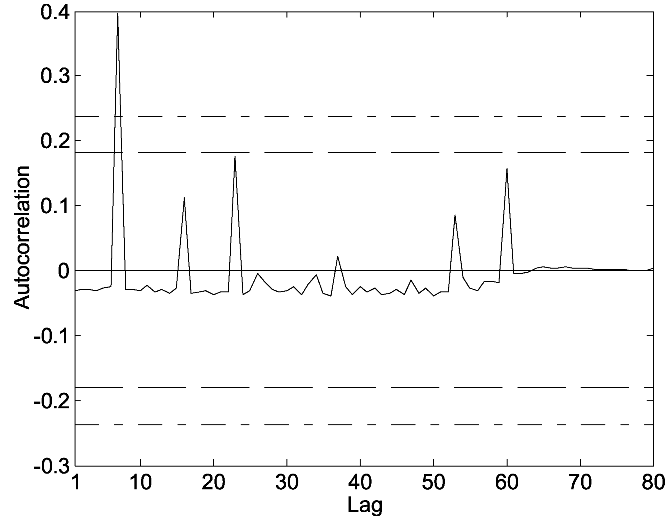

Fig. 6. Call interarrival time autocorrelation plot with 95% and 99% confidence intervals for one chat talk group during busy period 15:00–16:00 on Thursday, 2001-11-01. Dashed line: 95% confidence interval. Dash-dotted line: 99% confidence interval.

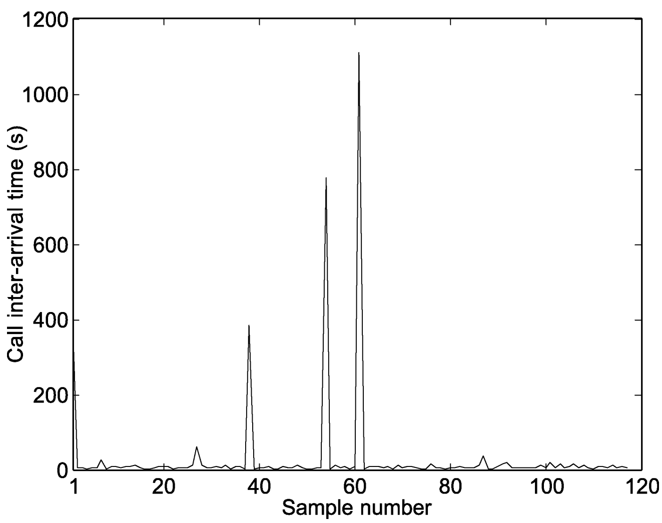

Fig. 5. Time series plot of call interarrival times for one chat talk group during busy period 15:00–16:00 on Thursday, 2001-11-01. The horizontal axis represents the sample number (index) of each sample and the vertical axis shows the corresponding value of the call interarrival time.

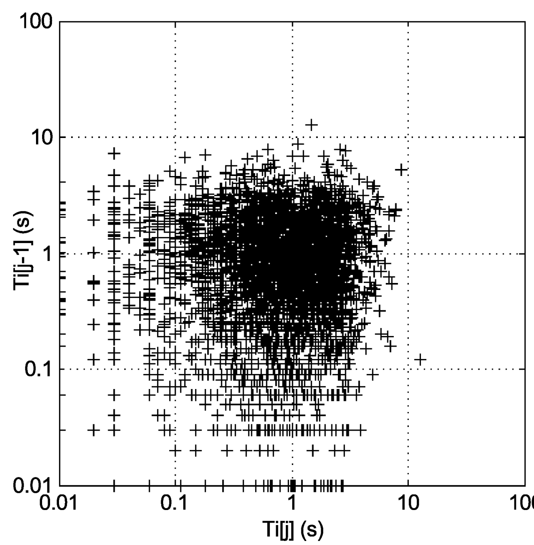

Fig. 7. Call interarrival time (Ti) lag plot for aggregate traffic during busy period 15:00–16:00 on Thursday, 2001-11-01. The 0.01-s resolution of the time stamp is evident below 0.1 s.

by large call interarrival times, indicating the end of sessions. A similar cluster may be observed on the bottom right-hand side of the graph: large call interarrival times followed by small call interarrival times, indicating the beginning of sessions. Both clusters correspond to call interarrival times between successive sessions (intersession call interarrival times). Fig. 5 shows call interarrival time versus the sample number. The peaks in the graph are due to the large values of the call interarrival time between two successive sessions. Call interarrival times within a session are significantly smaller and are shown in Fig. 5 as small values between two successive peaks. Fig. 6 shows the autocorrelation function of call interarrival times for the same talk group, with the 95% and 99% confidence intervals. Again, the peaks are a result of the session behavior of the users in the talk group. The peaks appear for lags equal to the distance (in number of samples) between two (not necessarily successive) peaks in Fig. 5.

Figs. 7–9 are representative results of the analysis for aggregate traffic. As talk groups are aggregated onto a communication system or traffic pool, the intersession call interarrival times are lost. The absence of session behavior in the aggregated call interarrival times can be observed in the lag plot shown in Fig. 7. There are no distinct clusters on the top left-hand or the bottom right-hand sides, which would correspond to intersession call interarrival times. We compared the call interarrival times with an exponential distribution. The results are shown in Fig. 8. Two commonly used tests for finding the goodness-of-fit are the Kolmogorov–Smirnov and Chi-square tests. The Chi-square test uses grouped (binned) data and, thus, implies certain loss of information. Hence, we employed the Kolmogorov–Smirnov test [18]. The difficulty associated with using goodness-of-fit tests

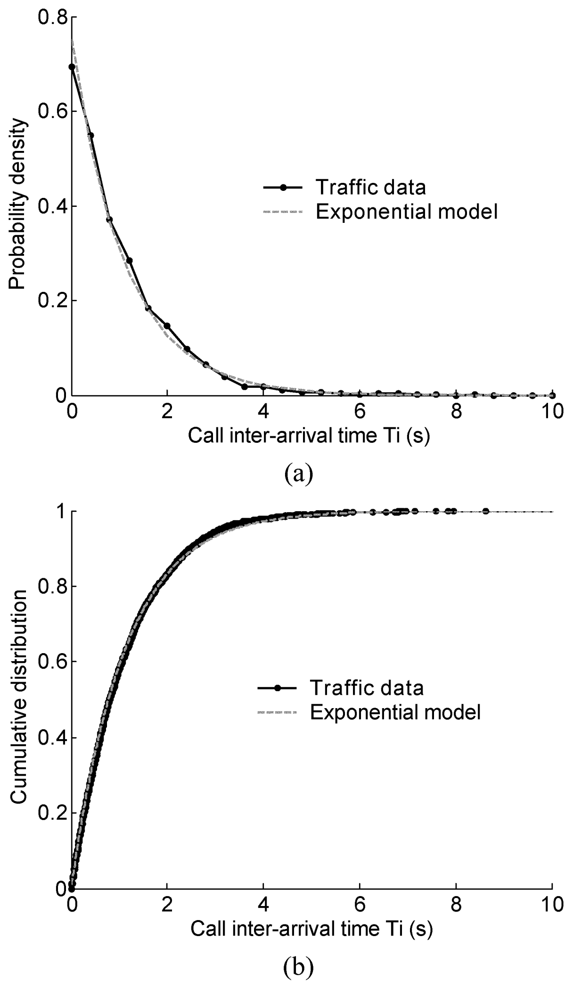

Fig. 8. Call interarrival time (Ti) distributions for all traffic during busy period 15:00–16:00 on Thursday, 2001-11-01. (a) PDF. (b) CDF. Ti statistics: average is 1.12 s and standard deviation is 1.08 s. One outlier (12.8 s) was omitted.

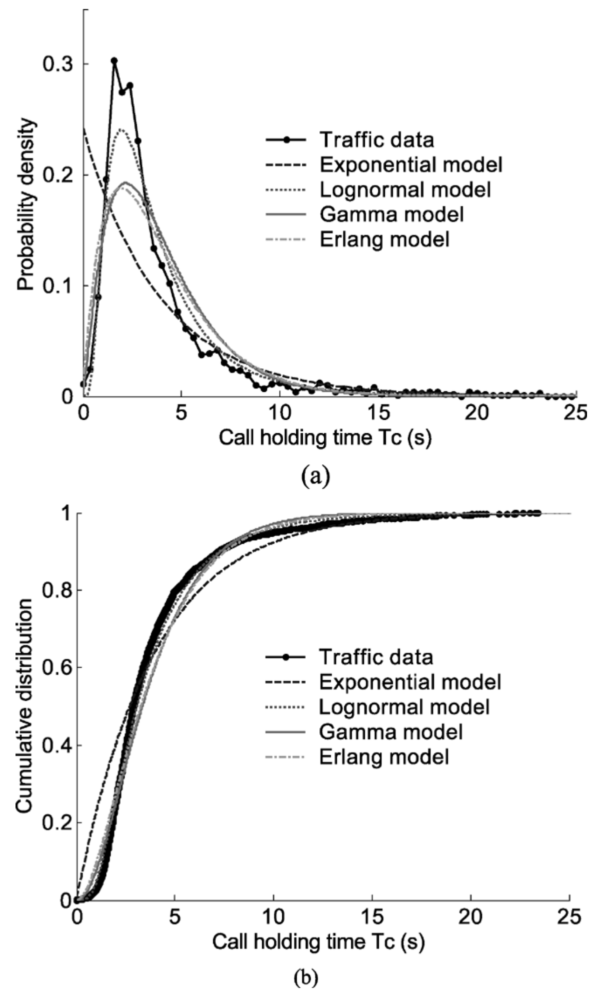

Fig. 10. Call holding time (Tc) distributions for aggregate traffic during busy period 15:00–16:00 on Thursday, 2001-11-01. (a) PDF. (b) CDF. Tc statistics: average is 3.91 s and standard deviation is 3.33 s. Four outliers, with values between 27 and 53 s were omitted.

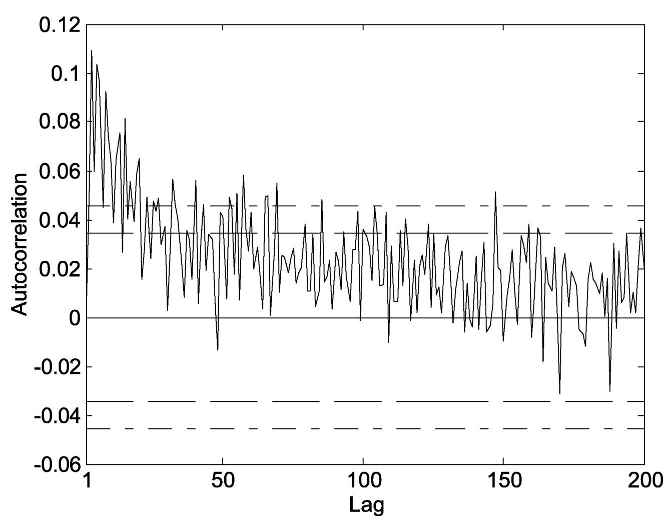

Fig. 9. Call interarrival time (Ti) autocorrelation plot (up to lag 200) with 95% and 99% confidence intervals for aggregate traffic during busy period 15:00–16:00 on Thursday, 2001-11-01. Dashed line: 95% confidence interval. Dash-dotted line: 99% confidence interval.

is that results depend on the sample size [11], [19], [20]. For large datasets such as ours, tests will often reject the hypothesis that samples of a dataset have a specific distribution. Hence, we applied the Kolmogorov–Smirnov test on ten randomly chosen subsets of the entire dataset [20]. Each subset consisted of 1000 samples (approximately 1/3 of the entire dataset). The tests indicated that call interarrival times fit the exponential distribution at the 0.1 significance level. The autocorrelation function, shown in Fig. 9, exhibits significant correlation between call interarrival times up to lag 70.

B. Call Holding Times

Our findings for call holding times are shown in Figs. 10 and 11. We compared the aggregate traffic with several candidate distributions: exponential, lognormal, gamma, and Erlang. Fig. 10 indicates that the lognormal distribution has the best fit. We used again the Kolmogorov–Smirnov test [18] to examine the distribution of call holding times. A series of ten tests on randomly chosen subsets with 1000 samples indicated that the lognormal distribution could be accepted for call holding times at the 0.01 significance level. Repeated tests with smaller subset of 300 samples produced higher significance level of 0.1. We also plotted the autocorrelation function for call holding times, as shown in Fig. 11. The plot shows no significant correlation

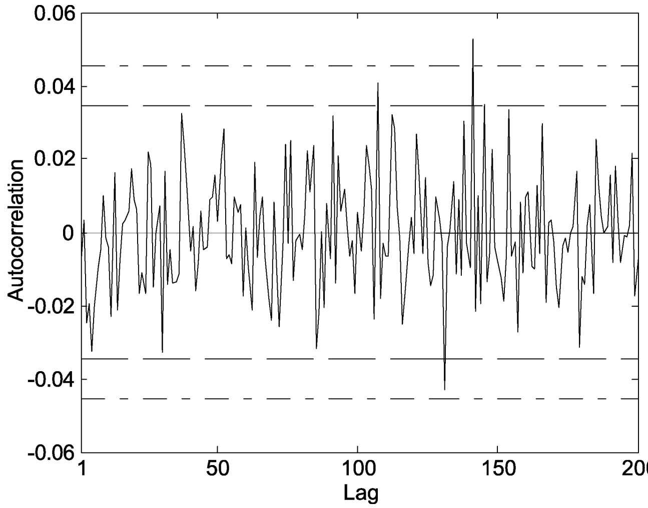

Fig. 11. Call holding time (Tc) autocorrelation plot (up to lag 200) with 95% and 99% confidence intervals for all traffic during busy period 15:00–16:00 on Thursday, 2001-11-01. Dashed line: 95% confidence interval. Dash-dotted line: 99% confidence interval.

TABLE III
HURST PARAMETER ESTIMATES

Estimator	Call interarrival time	Call holding time
Variance-time	0.76	0.49
R/S	0.61	0.59
Periodogram	0.63	0.50
Whittle	0.65	0.48
Wavelet	0.64	0.49

for any lag. All but a few values of the autocorrelation function fall within the 95% confidence interval around zero.

C. Long-Range Dependence

Identifying long-range dependence is a difficult task and estimators may often produce unreliable results [21]. Hence, we investigated long-range dependence for the call interarrival and call holding times by estimating the Hurst parameter using five estimation methods. The results are summarized in Table III and Fig. 12. The call interarrival times exhibit a tendency toward long-range dependence. For the call holding times, however, the majority of estimated Hurst parameter values lie near 0.5, which indicates absence of long-range dependence. These findings are consistent with the autocorrelation plots shown in Figs. 9 and 11.

Recently proposed Poisson cluster processes to model packet and flow arrivals in Internet protocol traffic [22] may provide a more insightful physical interpretation of the observed long-range dependence of call interarrival times. However, this approach would require identification of sessions and analysis of the distribution of calls within sessions. In trunked radio systems, finding a sufficiently accurate method to identify each session and its calls is difficult because multiple sessions can co-exist within a single talk group and gap duration may not be a good indicator of session separation, especially in busy (dispatch and information) talk groups. Furthermore, not every talk group exhibits a well-defined session behavior. Past studies [1] have shown that sessions could be identified only by listening

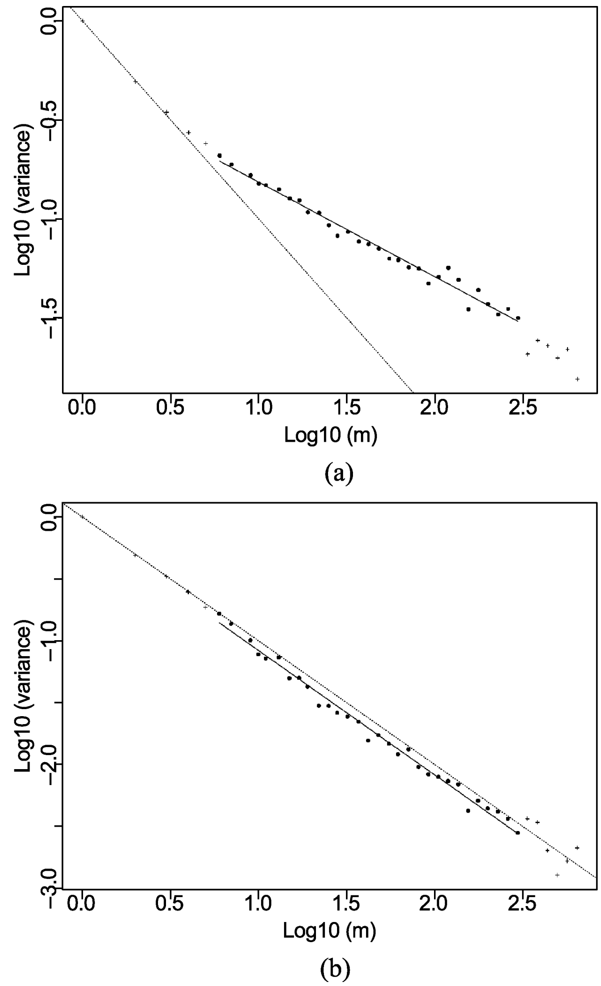

Fig. 12. Variance-time plot of the (a) call interarrival times (Ti) and (b) call holding times (Tc) for aggregate traffic during busy period 15:00–16:00 on Thursday, 2001-11-01. Hurst parameter estimates are (a) 0.76 and (b) 0.49.

to the actual conversations, which are not available from the E-Comm traffic measurement system.

VI. CONCLUSION

In this paper, we investigated busy period voice traffic on a transmission trunked mobile radio system. We considered an aggregate of multiple talk group traffic. Our analysis indicated that the interarrival times are exponentially distributed and exhibit certain degree of long-range dependence. The call holding times have a lognormal distribution and exhibit no significant correlation structure.

A potentially important implication of our findings is that performance estimation using methods that assume Markov arrival and departure processes, such as Erlang-C and finite source analysis, may not lead to reliable results. Future work may investigate performance estimation methods using traffic traces and traffic models. The results of such an investigation should be compared with system performance measurements under congestion because user behavior and, hence, traffic characteristics may change due to channel access delay and call queueing.

Understanding traffic characteristics and modeling group call voice traffic on a transmission trunked mobile radio system are necessary for research and development of next generation land mobile radio systems and mobile ad hoc networks for public safety agency use.

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Duncan S. Sharp (M'82) received the B.Sc. degree in electrical engineering from the University of Alberta, AB, Canada, in 1972 and the M.Eng. degree in communication networks from Simon Fraser University, Burnaby, BC, Canada, in 2003.

As a Consulting Engineer with a mid-size telecommunications engineering firm, Teleconsult Limited, Vancouver, BC, he was engaged in domestic and international projects from 1978 to 1997, rising to Chief Engineer. He continues to practice as a Project Engineer with Planetworks Consulting Corporation, Vancouver, BC. Mobile and ad hoc networks are his current research interests.

Mr. Sharp is a registered Professional Engineer in the Provinces of Alberta and British Columbia, Canada.

Nikola Cackov received the Dipl.Ing. degree in electrical engineering from Ss. Cyril and Methodius University, Skopje, Macedonia, in 2001. He is currently working toward the M.A.Sc. degree in the Communication Networks Laboratory, School of Engineering Science, Simon Fraser University, Burnaby, BC, Canada.

From 2001 to 2002, he worked as a System Engineer in the Networking Department, Pexim Computers, Skopje. His research interests include long-range dependence in network traffic and wavelet-based methods for traffic analysis.

Nenad Lasković received the Dipl.Ing. degree in electrical engineering from the University of Novi Sad, Serbia and Montenegro, in 1999. He is currently working toward the M.A.Sc. degree in the Communication Networks Laboratory, School of Engineering Science, Simon Fraser University, Burnaby, BC, Canada.

From 1999 to 2003, he was a Research and Teaching Assistant in the Department of Telecommunications and Signal Processing, University of Novi Sad. His research interests include traffic analysis and routing algorithms.

Qing Shao received the B.Sc. degree in electrical engineering from Beijing University of Posts and Telecommunications, Beijing, China, in 1993. He is currently working toward the M.A.Sc. degree in the Communication Networks Laboratory, School of Engineering Science, Simon Fraser University, Burnaby, BC, Canada.

He was with ChinaSat, Beijing, as a Field Engineer from 1993 to 1996 and as a Director of the Business Development Division from 1996 to 2000. His current research interests are traffic measurement and analysis of wired and wireless networks.

Ljiljana Trajković (S'78–M'86–SM'95) received the Dipl.Ing. degree from University of Pristina, Yugoslavia, in 1974, M.Sc. degrees in electrical engineering and computer engineering from Syracuse University, Syracuse, NY, in 1979 and 1981, respectively, and the Ph.D. degree in electrical engineering from University of California at Los Angeles (UCLA) in 1986.

She is currently a Professor in the School of Engineering Science, Simon Fraser University, Burnaby, BC, Canada. From 1995 to 1997, she was a National Science Foundation (NSF) Visiting Professor in the Electrical Engineering and Computer Sciences Department, University of California, Berkeley. She was a Research Scientist at Bell Communications Research, Morristown, NJ, from 1990 to 1997, and a Member of Technical Staff at AT&T Bell Laboratories, Murray Hill, NJ, from 1988 to 1990. Her research interests include high-performance communication networks, computer-aided circuit analysis and design, and theory of nonlinear circuits and dynamical systems.

Dr. Trajković is currently serving on the IEEE Circuits and Systems Society Board of Governors. She was Chair of the IEEE Technical Committee on Nonlinear Circuits and Systems (1998). She is currently a Chair of the IEEE Circuits and Systems Society Joint Chapter of the Vancouver/Victoria Sections. She also serves on various technical committees of IEEE conferences. She was Technical Program Chair and Vice General Co-Chair of ISCAS 2004. She is an Associate Editor of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS, PART I (2004–2006). She was an Associate Editor of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS, PART I (1993–1995), the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS, PART II (1999–2001 and 2002–2003), and the *IEEE Circuits and Systems Magazine* (2001–2003).