MODELING AND CHARACTERIZATION OF TRAFFIC IN A PUBLIC SAFETY WIRELESS NETWORK

Božidar Vujičić
bvujicic@cs.sfu.ca

Communication Networks Laboratory
http://www.ensc.sfu.ca/cnl
Simon Fraser University
Vancouver, BC

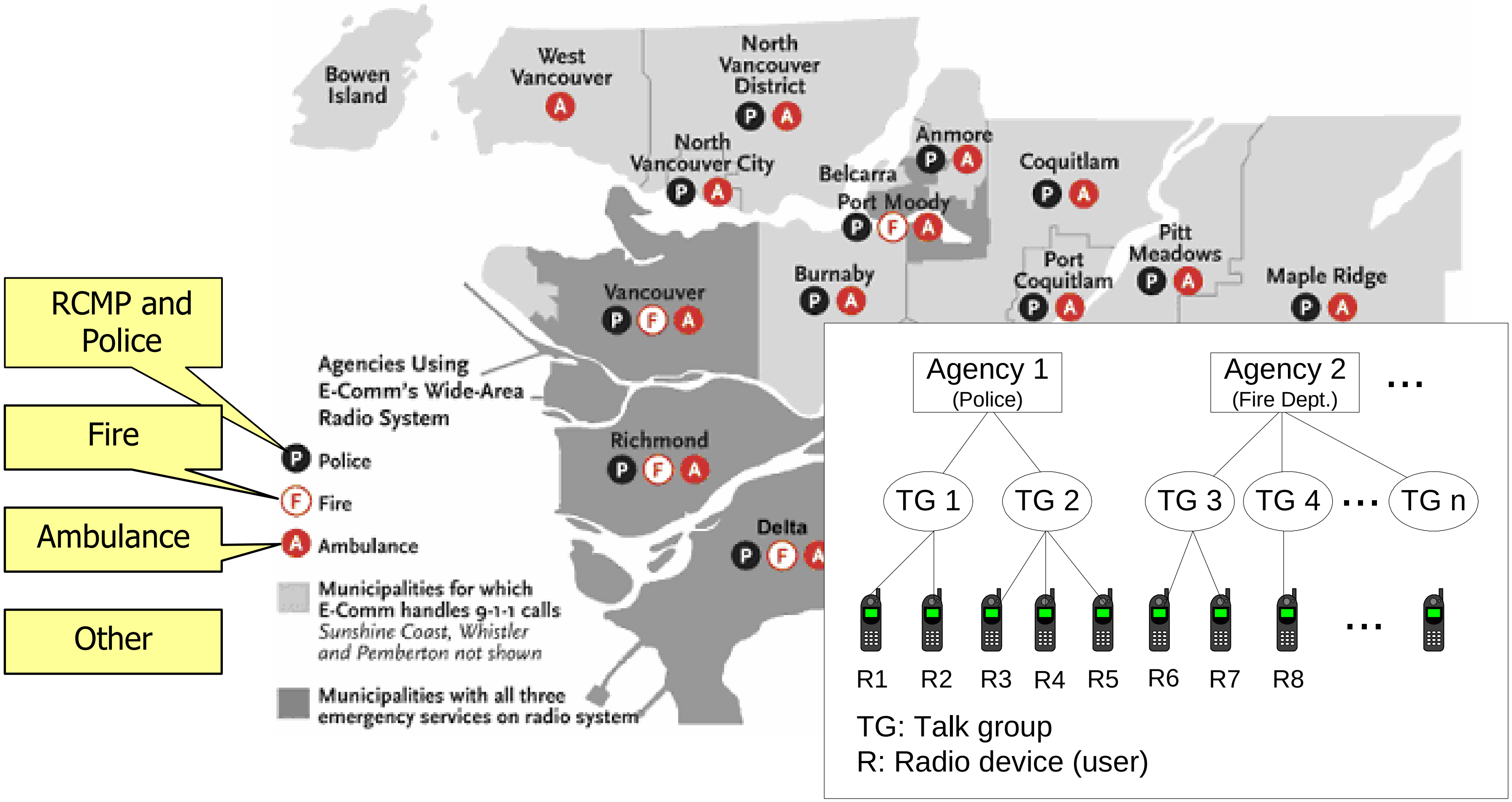
Roadmap

- Introduction
- Traffic data
- OPNET simulations and results
- Statistical concepts and analysis tools
- Statistical analysis of traffic data
- Conclusions and references

Roadmap

- Introduction
- Traffic data
- OPNET simulations and results
- Statistical concepts and analysis tools
- Statistical analysis of traffic data
- Conclusions and references

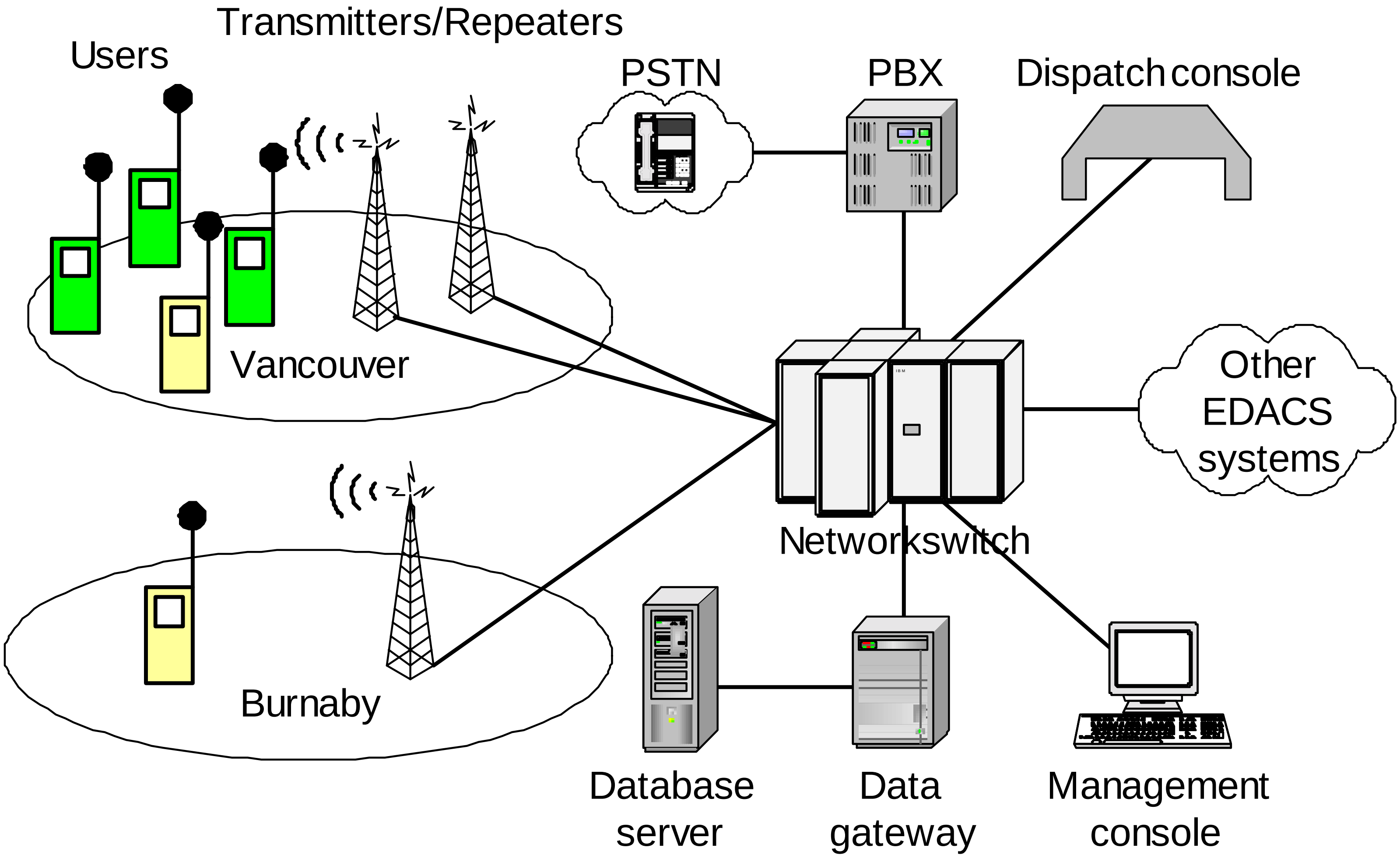
E-Comm network: coverage and user agencies



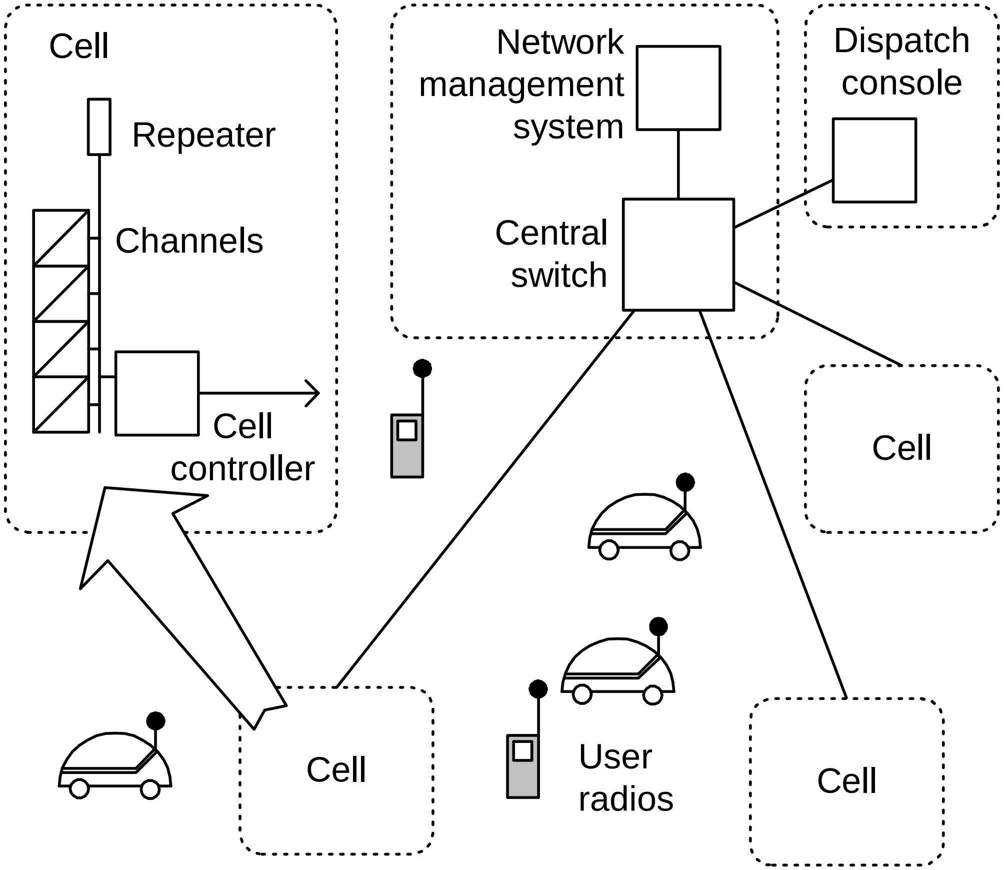
TG: Talk group

R: Radio device (user)

E-Comm network architecture



Structure of trunked radio systems



Network characteristics

- EDACS: Enhanced Digital Access Communications Systems
- Simulcast: repeaters covering one cell use identical frequencies
- Trunking: available frequencies in a cell are shared dynamically among mobile users
    - transmission trunking
    - message trunking
- Cell capacity (number of available frequencies in a cell):
    - one radio channel occupies one frequency
    - one call occupies one radio channel

Call establishment

- Users are organized in talk groups:
  - one-to-many type of conversations
- Push-to-talk (PTT) mechanism for network access:
  - user presses the PTT button
  - system locates other members of the talk group
  - system checks for availability of channels:
    - channel available: call established
    - all channels busy: call queued/dropped
  - user releases PTT:
    - call terminates

Erlang traffic models

Erlang B

$$P_B = \frac{\frac{A^N}{N!}}{\sum_{x=0}^{N} \frac{A^x}{x!}}$$

Erlang C

$$P_C = \frac{\frac{A^N}{N!}\frac{N}{N-A}}{\sum_{x=0}^{N-1} \frac{A^x}{x!} + \frac{A^N}{N!}\frac{N}{N-A}}$$

- P_B : probability of rejecting a call
- P_c : probability of delaying a call
- N : number of channels/lines
- A : total traffic volume

Erlang traffic models (2)

- Erlang B model assumes:
  - call holding time follows exponential distribution
  - blocked call will be rejected immediately
- Erlang C model assumes:
  - call holding time follows exponential distribution
  - blocked call will be put into a FIFO queue with infinite size

FIFO: first in first out

Roadmap

- Introduction
- Traffic data
- OPNET simulations and results
- Statistical concepts and analysis tools
- Statistical analysis of traffic data
- Conclusions and references

Traffic data

- 2001 data set:
    - 2 days of traffic data
        - 2001-11-1 to 2001-11-02 (110,348 calls)
- 2002 data set:
    - 28 days of continuous traffic data
        - 2002-02-10 to 2002-03-09 (1,916,943 calls)
- 2003 data set:
    - 92 days of continuous traffic data
        - 2003-03-01 to 2003-05-31 (8,756,930 calls)

Sample of processed data: 2003-03-01

No	Time (hh:mm:ss)(ms)	Call Duration (ms)	System Id	Channel Id	Caller	Callee
1	00:00:00 30	1340	1	12	A	B
6	00:00:00 489	1350	7	4	A	B
29	00:00:03 620	7550	2	7	C	D
31	00:00:03 760	7560	1	3	C	D
37	00:00:04 260	7560	7	6	C	D
38	00:00:04 340	7560	6	6	C	D

Traffic data for OPNET simulations

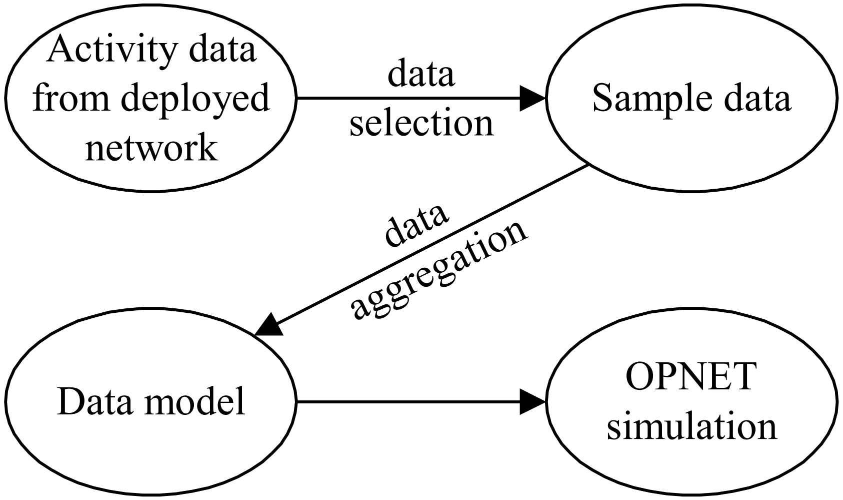
- Timestamps and durations corresponding to a single call differ due to discrepancies in records:
  - the smallest timestamp was chosen arbitrarily
  - the largest call duration (worst-case scenario) was used
- Original timestamp represents date and time of call start:
  - simulations: timestamp is the difference between the original timestamp and arbitrary reference time
  - reference times: 0:00 on February 25, 2002 and 0:00 on March 10, 2003

Trace (dataset)	Time span
2002	0:00, February 25, 2002 – 24:00, March 3, 2002
2003	0:00, March 10, 2003 – 24:00, March 16, 2003

Data processing for OPNET simulations

Timestamp	Duration (ms)	Caller	Callee	Cell
2003-03-20 0:00:10.639	4,870	A	B	4
2003-03-20 0:00:10.599	4,830	A	B	8
2003-03-20 0:00:10.529	4,860	A	B	9
2003-03-20 0:00:10.510	4,870	A	B	10

{10.510; 4,870; 4; 8; 9; 10}



Activity data from deployed network

data selection

Sample data

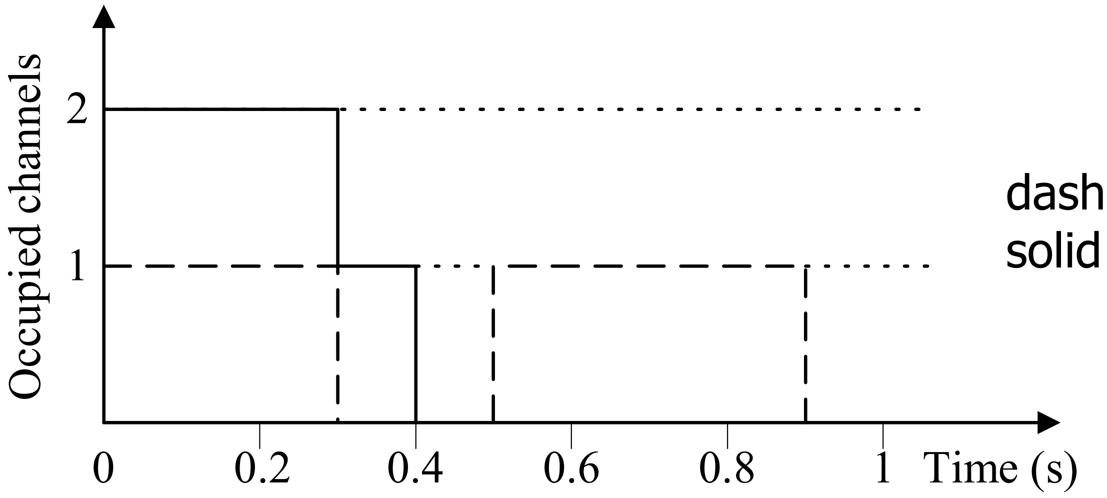
data aggregation

Data model

OPNET simulation

Data discrepancies

- Coarse resolution of the timestamp
  - activity data: 10 ms
  - data model: 1 s
- Example:



dashed: deployed network
solid: model

Data discrepancies: 2003

- Overlapping usage of channels

Timestamp	Duration (ms)	Cell	Channel
2003-03-20 0:00:33.370	9,420	10	4
…	…	…	…
2003-03-20 0:00:42.769	4,290	10	4

- 0:00:42.769 < 0:00:33.370 + 9.420
  - channel 4 in cell 10 is occupied by two calls at the same time!

Traffic data for statistical modeling

- Records of network events:
  - established, queued, and dropped calls in the Vancouver cell
- Traffic data span periods during:
  - 2001, 2002, and 2003
- We created traces of call holding times (call durations) and call inter-arrival times (differences between two successive timestamps)

Trace (dataset)	Time span	No. of established calls
2001	November 1–2, 2001	110,348
2002	March 1–7, 2002	370,510
2003	March 24–30, 2003	387,340

Hourly traces

- Call holding and call inter-arrival times from the five busiest hours in each dataset (2001, 2002, and 2003)

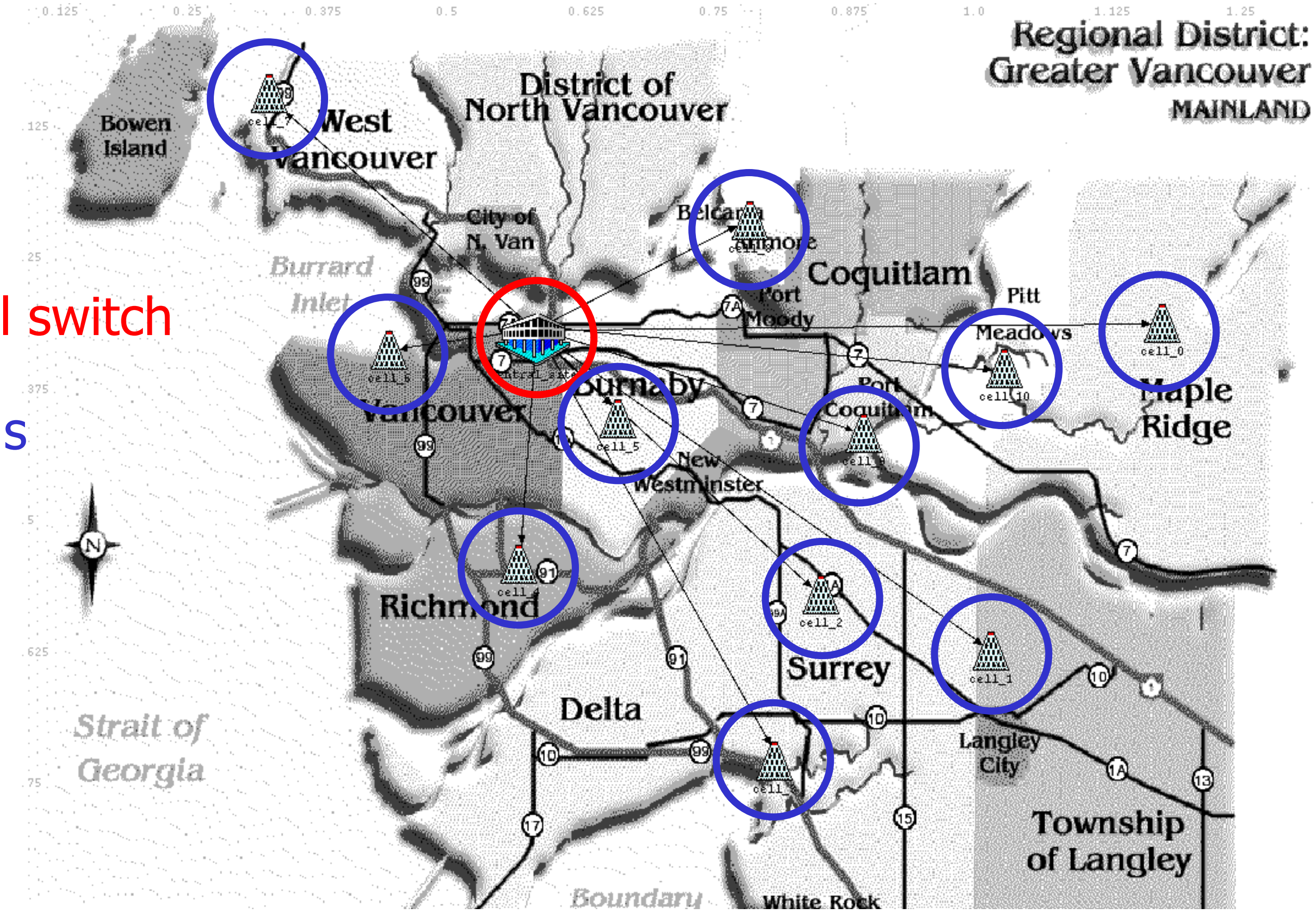
2001		2002		2003	
Day/hour	No.	Day/hour	No.	Day/hour	No.
02.11.2001 15:00–16:00	3,718	01.03.2002 04:00–05:00	4,436	26.03.2003 22:00–23:00	4,919
01.11.2001 00:00–01:00	3,707	01.03.2002 22:00–23:00	4,314	25.03.2003 23:00–24:00	4,249
02.11.2001 16:00–17:00	3,492	01.03.2002 23:00–24:00	4,179	26.03.2003 23:00–24:00	4,222
01.11.2001 19:00–20:00	3,312	01.03.2002 00:00–01:00	3,971	29.03.2003 02:00–03:00	4,150
02.11.2001 20:00–21:00	3,227	02.03.2002 00:00–01:00	3,939	29.03.2003 01:00–02:00	4,097

Roadmap

- Introduction
- Traffic data
- OPNET simulations and results
- Statistical concepts and analysis tools
- Statistical analysis of traffic data
- Conclusions and references

Network model

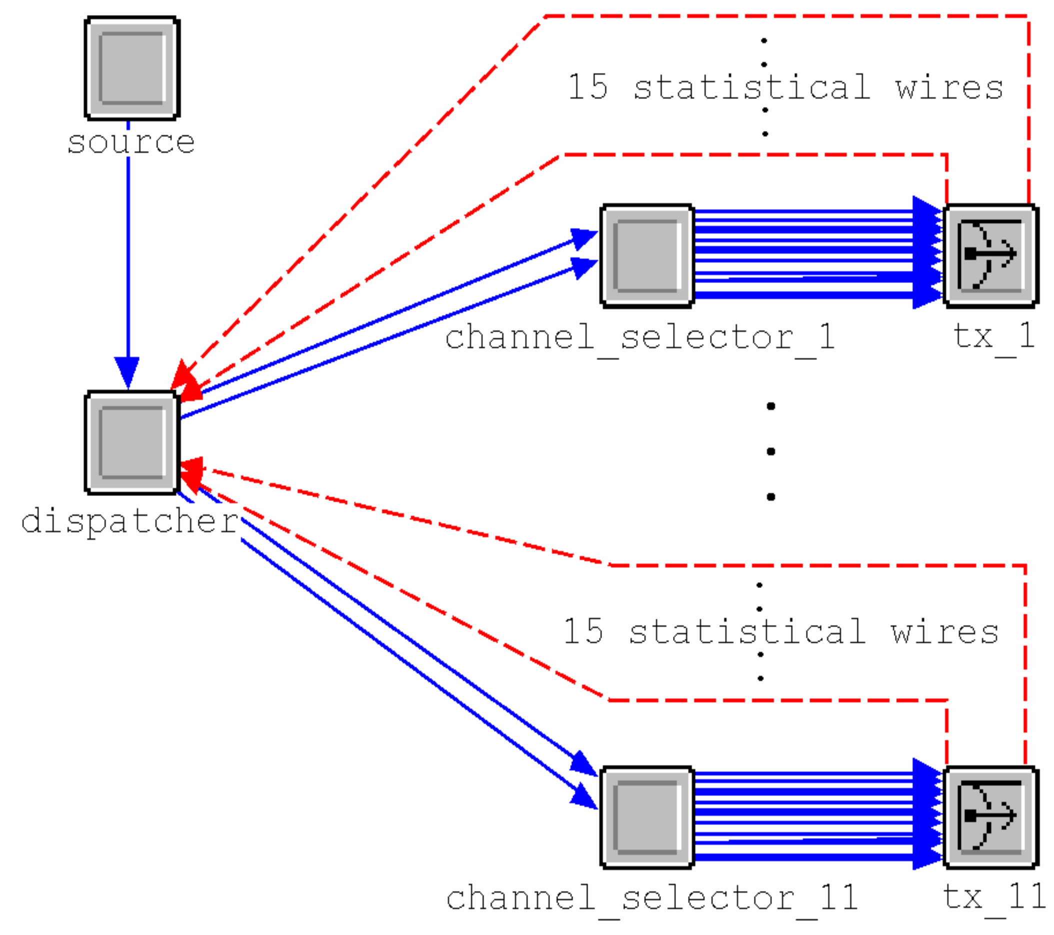
- central switch
- 11 cells



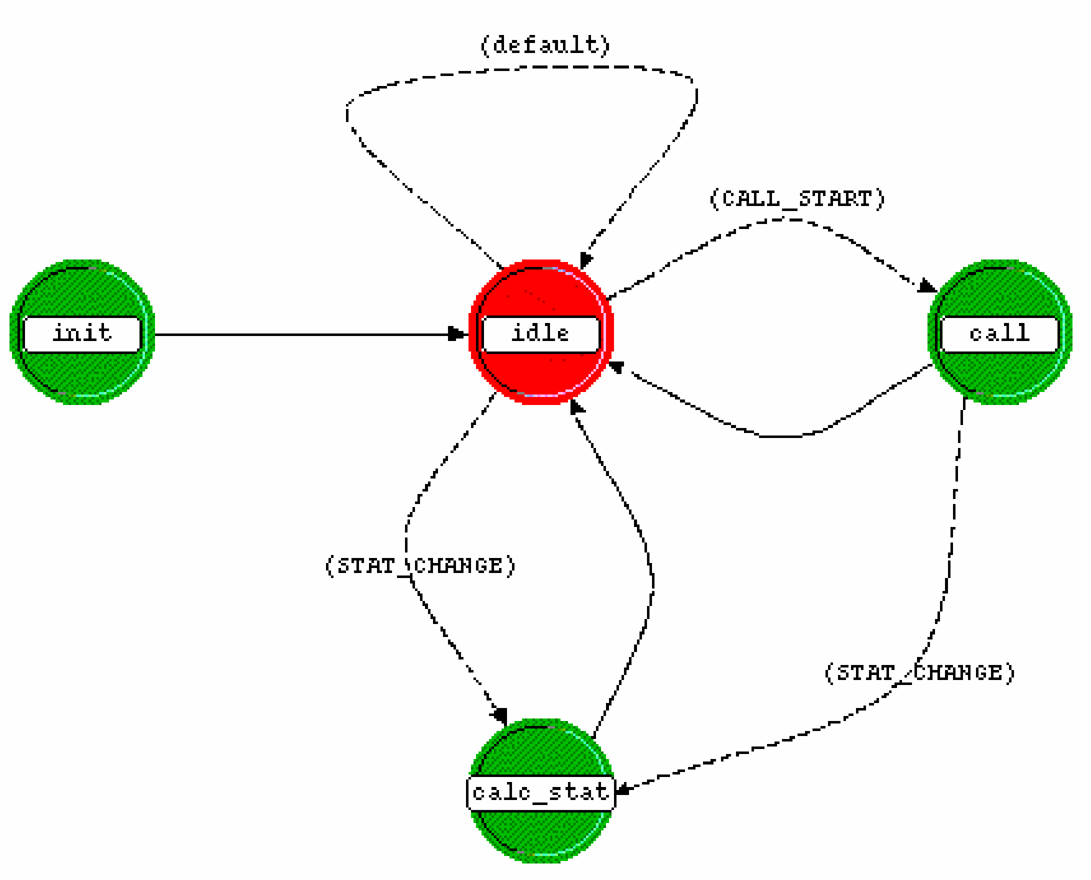
Central switch (site) model

- Reads the trace file
- Generates packets according to calls from trace file
  - one call = one packet
  - k: bit rate of channels (k=1,000 bps in simulations)
  - packet_size (bits) = k × call_duration (s)
- Checks for availability of channels in the cells and sending packets to appropriate cells
- Collects statistics

Central switch: OPNET node model

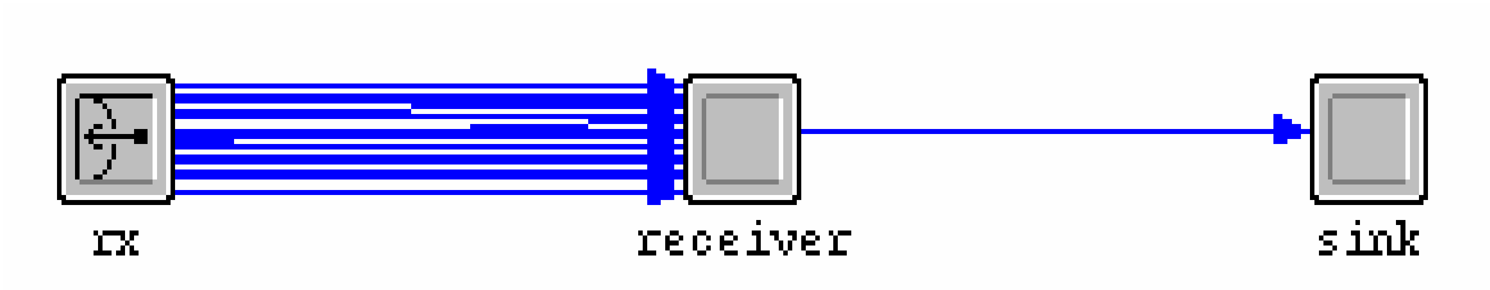


Dispatcher module in the central switch: OPNET process model



Cell: OPNET node model

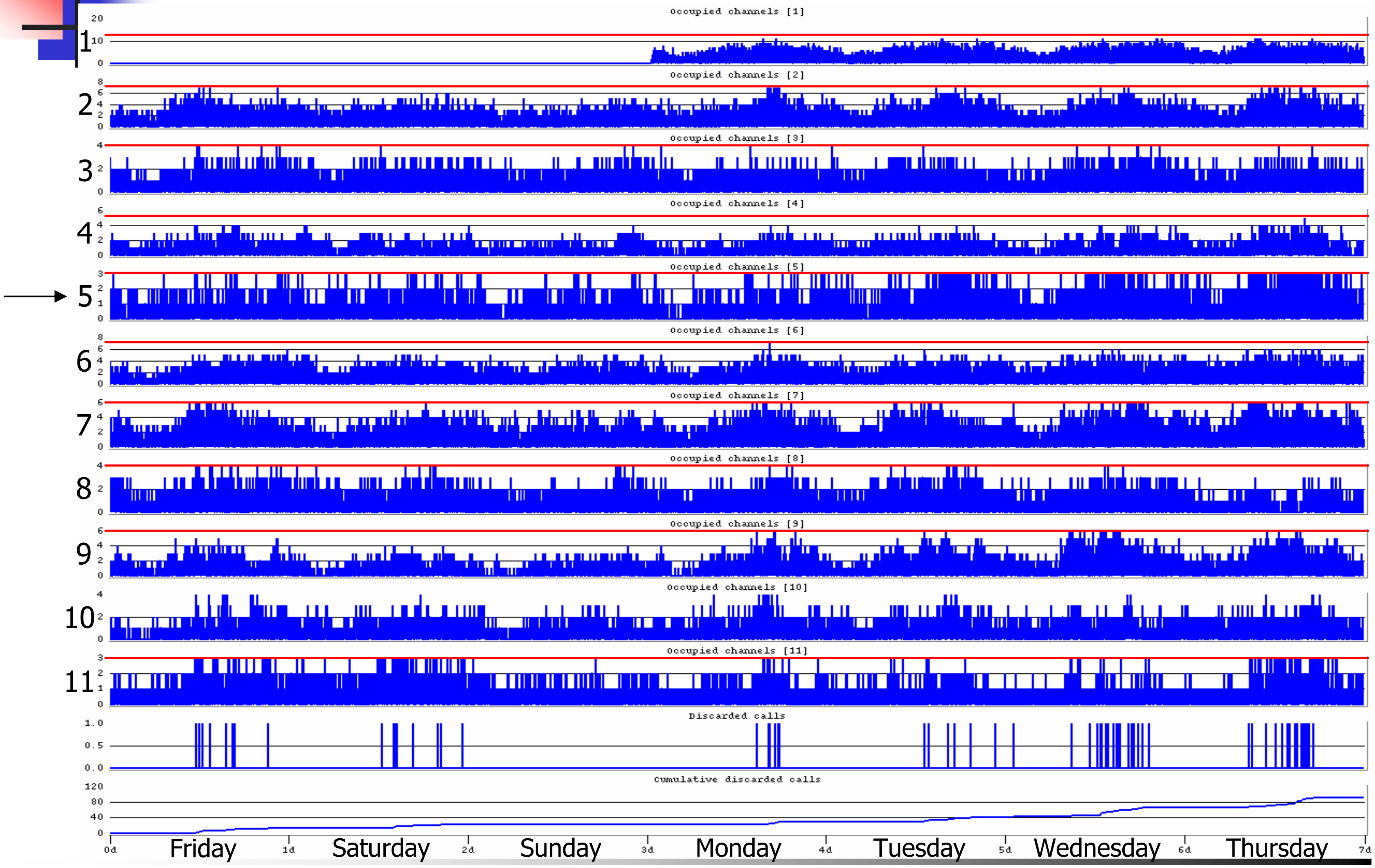
- Point-to-point receiver *rx*, a *receiver* module, and a *sink*
- When packet arrives, receiver module notifies corresponding channel_selector in central site of free channel in the link and sends packet to the sink



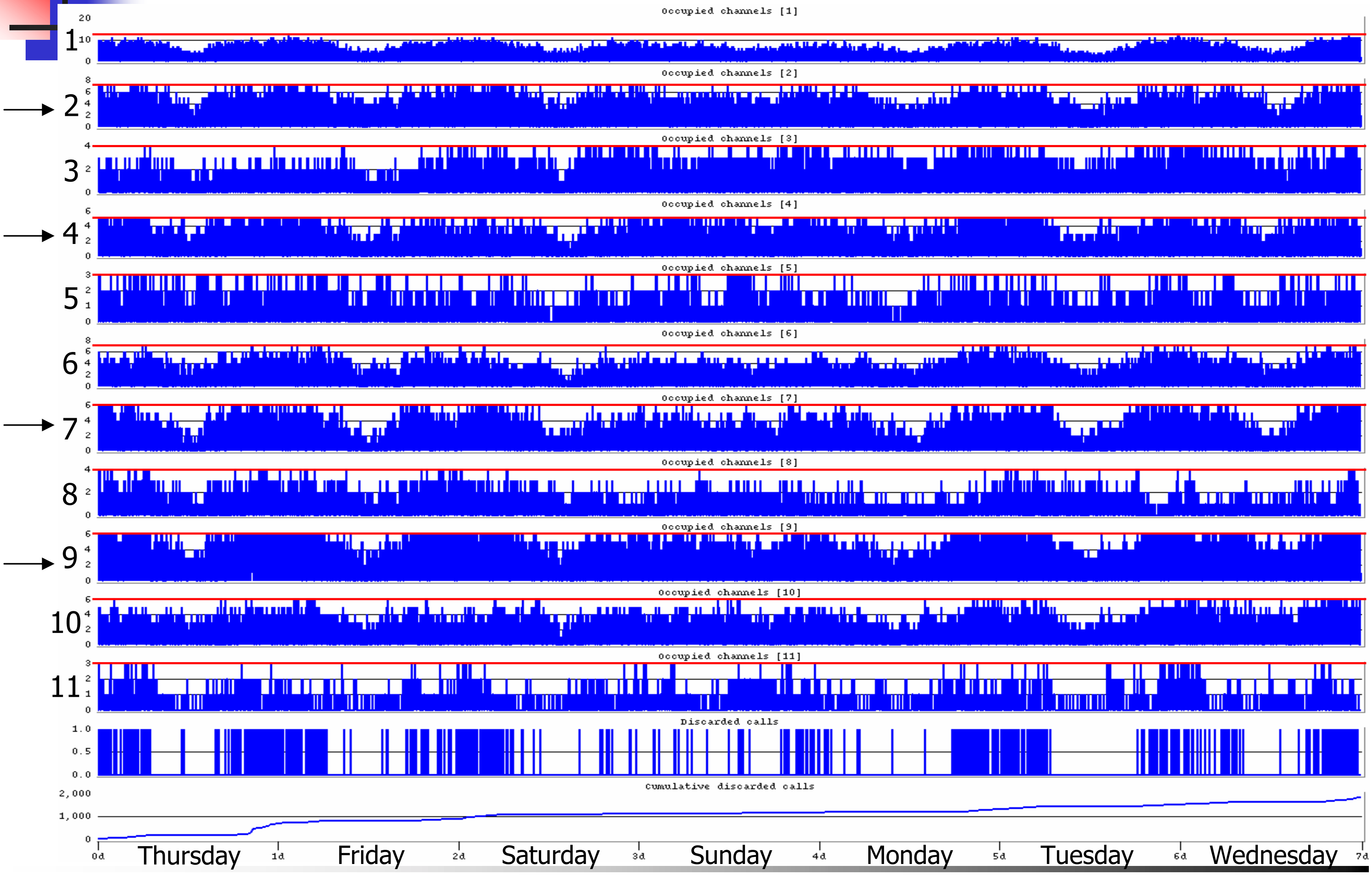
Roadmap

- Introduction
- Traffic data
- OPNET simulations and results
- Statistical concepts and analysis tools
- Statistical analysis of traffic data
- Conclusions and references

Channel occupancy and discarded calls: 2002



Channel occupancy and discarded calls: 2003



Observations

- Presence of daily cycles:
  - minimum utilization: ~ 2 PM
  - maximum utilization: 9 PM – 3 AM
- 2002 sample data:
  - cell 5 is the busiest
  - other cells seldom reach their capacities
- 2003 sample data:
  - several cells (2, 4, 7, and 9) have all channels occupied during busy hours

Observation of discarded calls

- Appear only in the OPNET simulation results (do not exist in the deployed network)
- Occur during busy hours
- May be used to identify possibly congested cells

Sample data	Cell no.	Capacity	No. of discarded calls
2002		original	91
2002	5	3 + 1	62
2003		original	1,812
2003	9	6 + 1	679
2003	4 9	5 + 1 6 + 1	521

original cap.	
cell	ch.
1	12
2	7
3	4
4	5
5	3
6	7
7	6
8	4
9	6
10	6
11	3

Maximum and average utilizations

		2002		2003	
Cell	Capacity	Maximum	Average	Maximum	Average
1	12	11	2.5	11	2.6
2	7	7	0.8	7	1.6
3	4	4	0.3	4	0.5
4	5	5	0.3	5	1.1
5	3	3	0.2	3	0.3
6	7	7	0.7	7	1.2
7	6	6	0.7	6	1.1
8	4	4	0.3	4	0.4
9	6	6	0.4	6	1.6
10	6	4	0.2	6	1.0
11	3	3	0.2	3	0.2

Roadmap

- Introduction
- Traffic data
- OPNET simulations and results
- Statistical concepts and analysis tools
- Statistical analysis of traffic data
- Conclusions and references

Statistical concepts

- Probability distribution:
  - probability that outcomes of a process are within a given range of values
  - expressed through probability density (pdf) and cumulative distribution (cdf) functions
- Autocorrelation:
  - measures the dependence between two outcomes of a process
  - wide-sense stationary processes: autocorrelation depends only on the difference (lag) between the time instances of the outcomes

Long-range dependence: definition

- LRD is defined as a non-summability of autocorrelation function $r(k)$ of a (wide-sense) stationary process $X(n)$:

$$\boxed{\sum_{k=-\infty}^{\infty} r(k) = \infty}$$

definition

$$\boxed{r(k) = c_r k^{-(2-2H)}, \;\; k \to \infty}$$

model

$$\boxed{f(\nu) = c_f \, |\nu|^{-\alpha}, \;\; \nu \to 0}$$

corollary

where $f(\nu)$ is the power spectral density of $X(n)$,
c_r and c_f are non-zero constants, and $0<\alpha<1$
H – Hurst parameter is used to quantify degree of LRD
0.5 < H < 1 implies LRD

LRD: long-range dependence

Wavelet coefficients

- Wavelet coefficients are given by the inner product:

$$d(j,k) = \int_{-\infty}^{\infty} X(t)\psi_{j,k}(t)dt$$

where

$$\psi_{j,k}(t) = 2^{-j/2}\psi\left(2^{-j}t - k\right)$$

- $\psi(t)$: mother wavelet
  - j : octave (logarithm of level of aggregation)
  - k : translation (time unit)
- Reconstruction formula:

$$X(t) = \sum_{j=0}^{\infty}\sum_{k} d(j,k)\psi_{j,k}(t)$$

LRD and wavelets

- Power spectral density (PSD):

$$f(\nu) \sim c_f \, |\nu|^{-\alpha}, \; \nu \to 0$$

- Power-law behavior of PSD implies following relationship between variance of wavelet coefficients and octave *j:*

$$\mathrm{E}\{d(j,k)^2\} = 2^{j\alpha} c_f C(\alpha,\psi)$$

where $C(\alpha,\psi) = \int |\nu|^{-\alpha} \left|\Psi(\nu)\right|^2 d\nu$ does not depend on j

D. Veitch and P. Abry, "A wavelet-based joint estimator of the parameters of long-range dependence," *IEEE Trans. on Information Theory*, vol. 45, no. 3, pp. 878–897, Apr. 1999.

LRD and wavelets

- Logarithm of mean square value of wavelet coefficients:

$$\log_2 \mathrm{E}\{d(j,k)^2\} = \alpha \times j + c$$

- Important property: for given j, $d(j,k)$ does not exhibit long-range dependence (with respect to k)
  - with appropriately chosen mother wavelet
- Hence:
  - simple estimator for E{$d(j,k)^2$} is a sample mean:

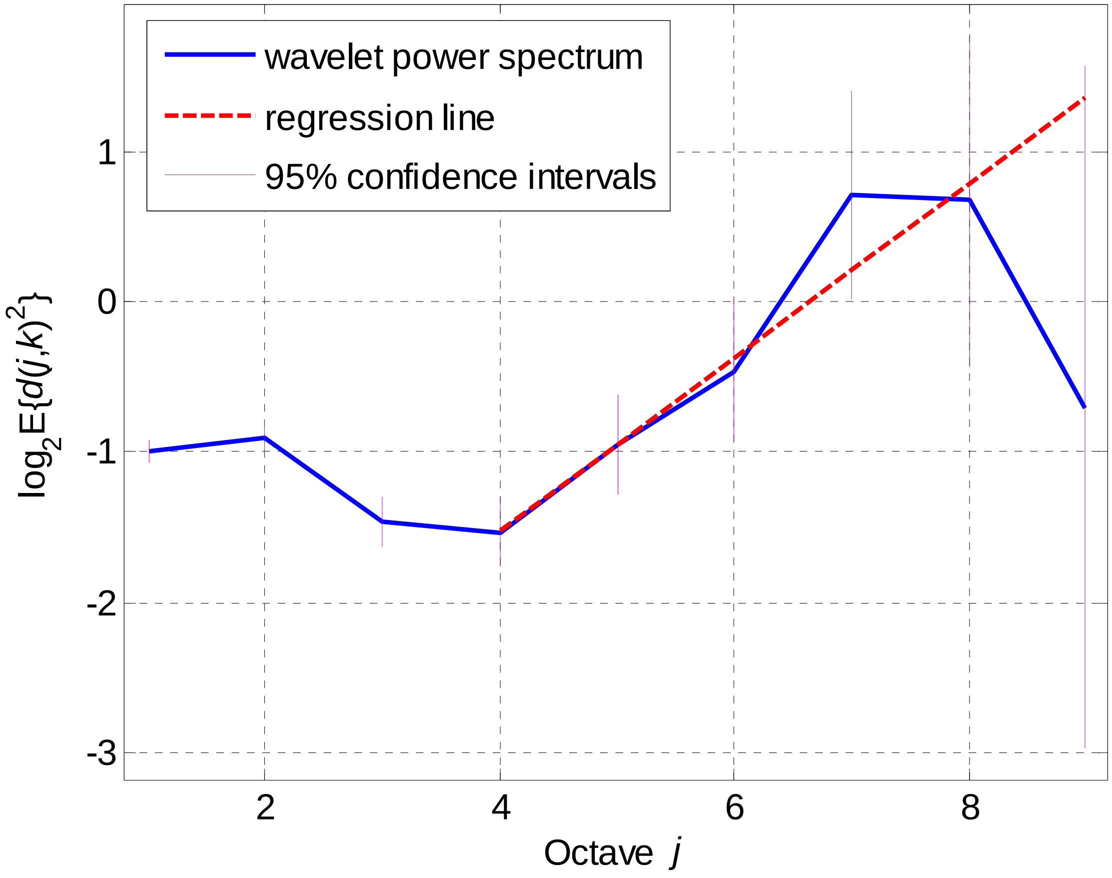
$$\mathrm{E}\{d(j,k)^2\} = \frac{1}{n_j} \sum_{k=1}^{n_j} d(j,k)^2$$

  - n_j: number of wavelet coefficients at octave j

Estimation of α and H

- Logscale diagram: plot of $\log_2 E\{d(j,k)^2\}$ vs. j (octave)
- Presence of LRD is illustrated by linear relationship between $\log_2 E\{d(j,k)^2\}$ and j on the coarsest octaves
- Estimation of α:
  - the slope of regression line $\log_2 E\{d(j,k)^2\}$ in the linear region of logscale diagram is the scaling exponent α
- $H = 0.5 (\alpha + 1)$
  - values of $H \approx 1$ imply strong LRD (strong correlations between outcomes of the process that are far apart)
  - for uncorrelated processes $H = 0.5$

Logscale diagram: example



- call inter-arrival times: 22:00–23:00, 26.03.2003
- α=0.576, H=0.788 (octaves 4–9)

Time constancy of α

- LRD processes are by definition wide-sense stationary processes (α does not depend on n)
  - high variability and relatively long on and off periods make LRD processes seem non-stationary
- An approach to determine whether a process is LRD or non-stationary is to test:
  - if the scaling exponent α is constant over the examined time series $X(n)$?
- The wavelet-based estimator of the Hurst parameter may produce unreliable estimates when applied to time series with variable α

Test for time constancy of α

- The test method for time constancy of the α:
  - divide time series $X(n)$ into m blocks of equal length
  - estimate α for each block
  - compare the estimates
- If α varies significantly, estimating α for the entire time series may not be meaningful
- In our examination: m$\in$\{3, 4, 5, 6, 7, 8, 10\}

Kolmogorov-Smirnov test

- Goodness-of-fit test: quantitative decision whether the empirical cumulative distribution function (ECDF) of a set of observations is consistent with a random sample from an assumed theoretical distribution
- ECDF is a step function (step size 1/N) of N ordered data points $Y_1, Y_2, \ldots, Y_N$:

$$E_N = \frac{n(i)}{N}$$

$n(i)$: the number of data samples with values smaller than Y_i

Parameters

- Hypothesis h (values 0 and 1):
  - null: the candidate distribution fits the empirical data
  - alternative (h is equal 1): the candidate distribution does not fit the empirical data
- Input parameters: significance level σ and tail
- Output parameters:
  - p-value
  - k: test statistic
  - cv: critical (cut-off) value

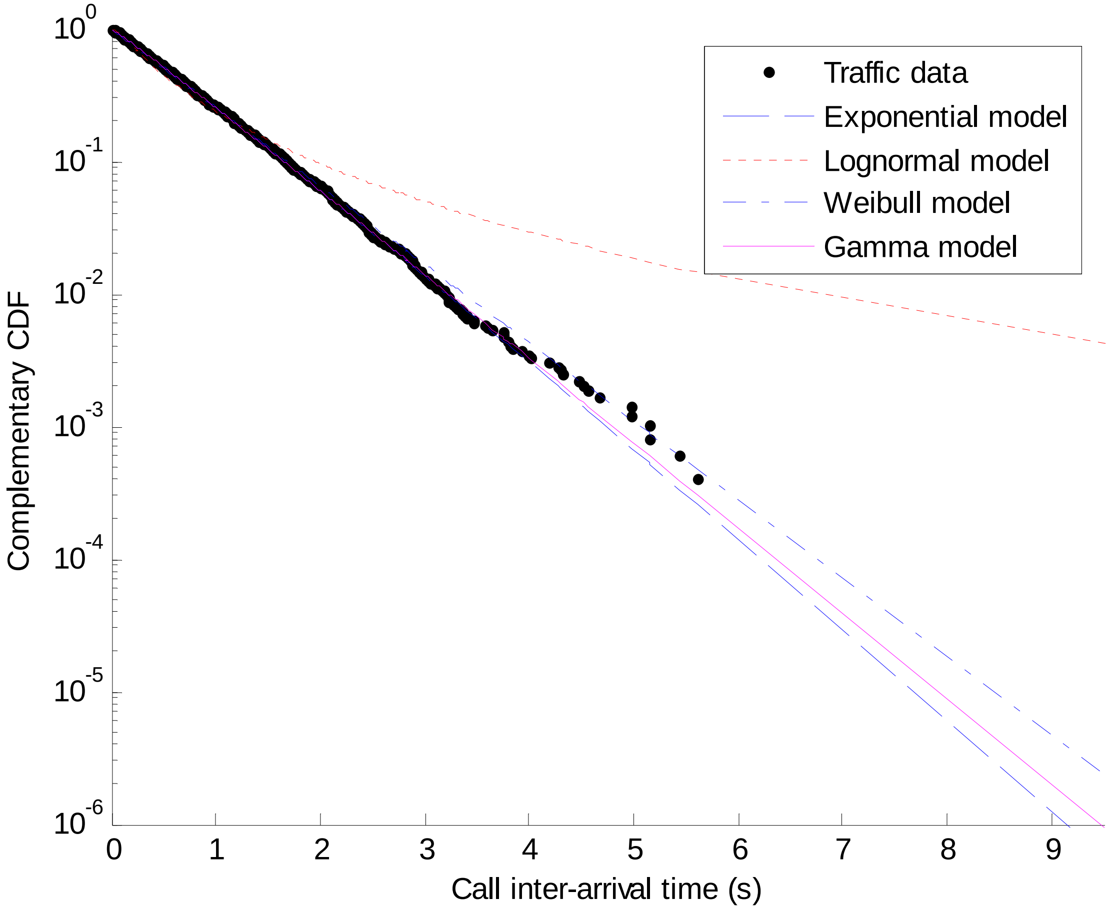
Input parameters

- Significance level σ: determines if the null hypothesis is wrongly rejected σ percent of times, if it is in fact true
  - default value σ = 0.05
- σ defines sensitivity of the test:
  - smaller σ implies larger critical value (larger tolerance)
  - critical value is the maximum allowable difference between distributions
- tail: specifies whether the K-S performs two sided test (default) or tests from one or other side of the candidate distribution

Output parameters

- Test statistic k is the maximum difference over all data points:
$$k = \max_{1 \le i \le N} \left| F(Y_i) - \frac{i}{N} \right|$$
where *F* is the CDF of the assumed distribution
- The null hypothesis is accepted if the value of the test statistic is smaller than the critical value
- p-value is probability level when the difference between distributions (test statistics) becomes significant:
  - if p-value $\leqslant \sigma$: test rejects the null hypothesis
- If test returns critical value = NaN, the decision to accept or reject null hypothesis is based only on p-value

Inter-arrival times: complementary cdf



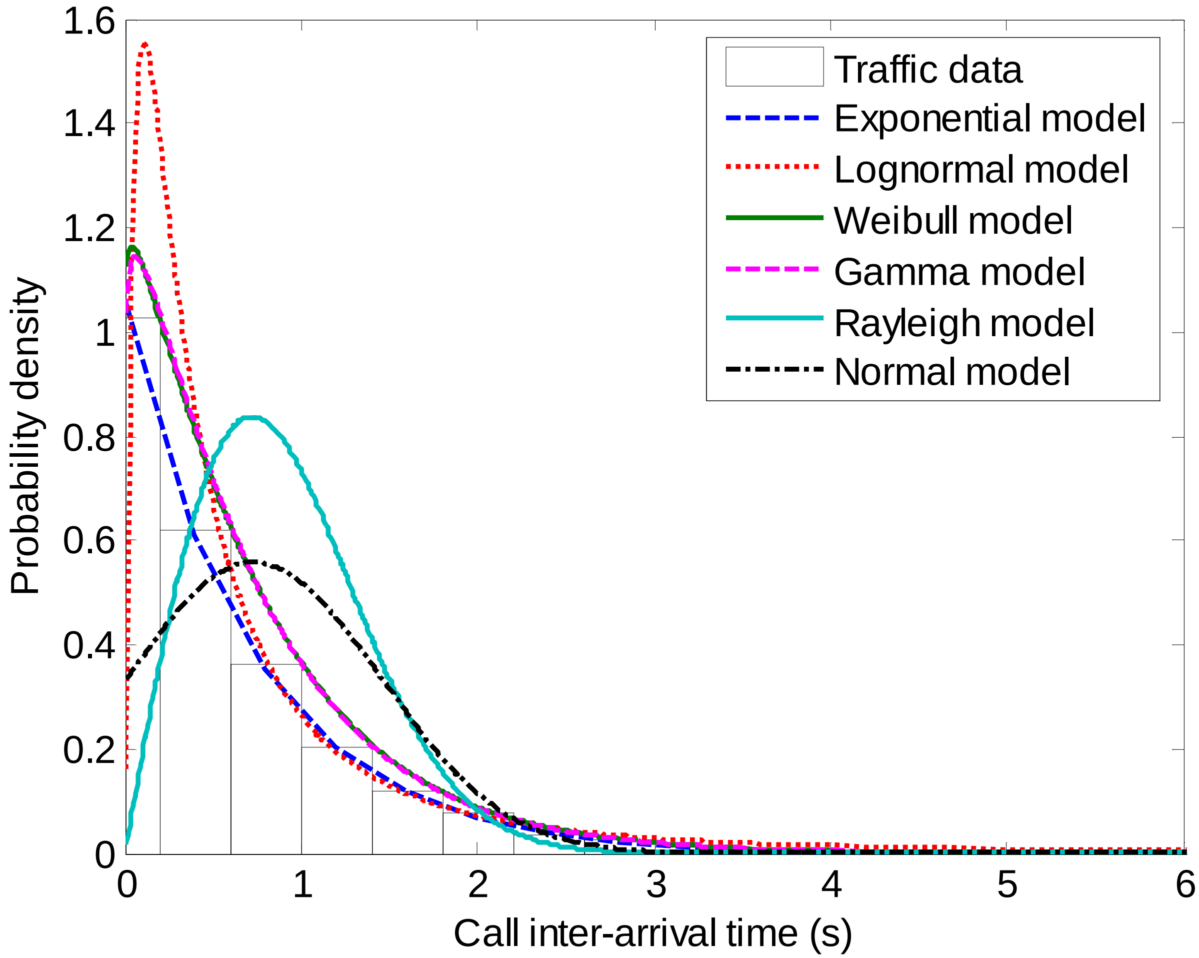
Roadmap

- Introduction
- Traffic data
- OPNET simulations and results
- Statistical concepts and analysis tools
- Statistical analysis of traffic data
- Conclusions and references

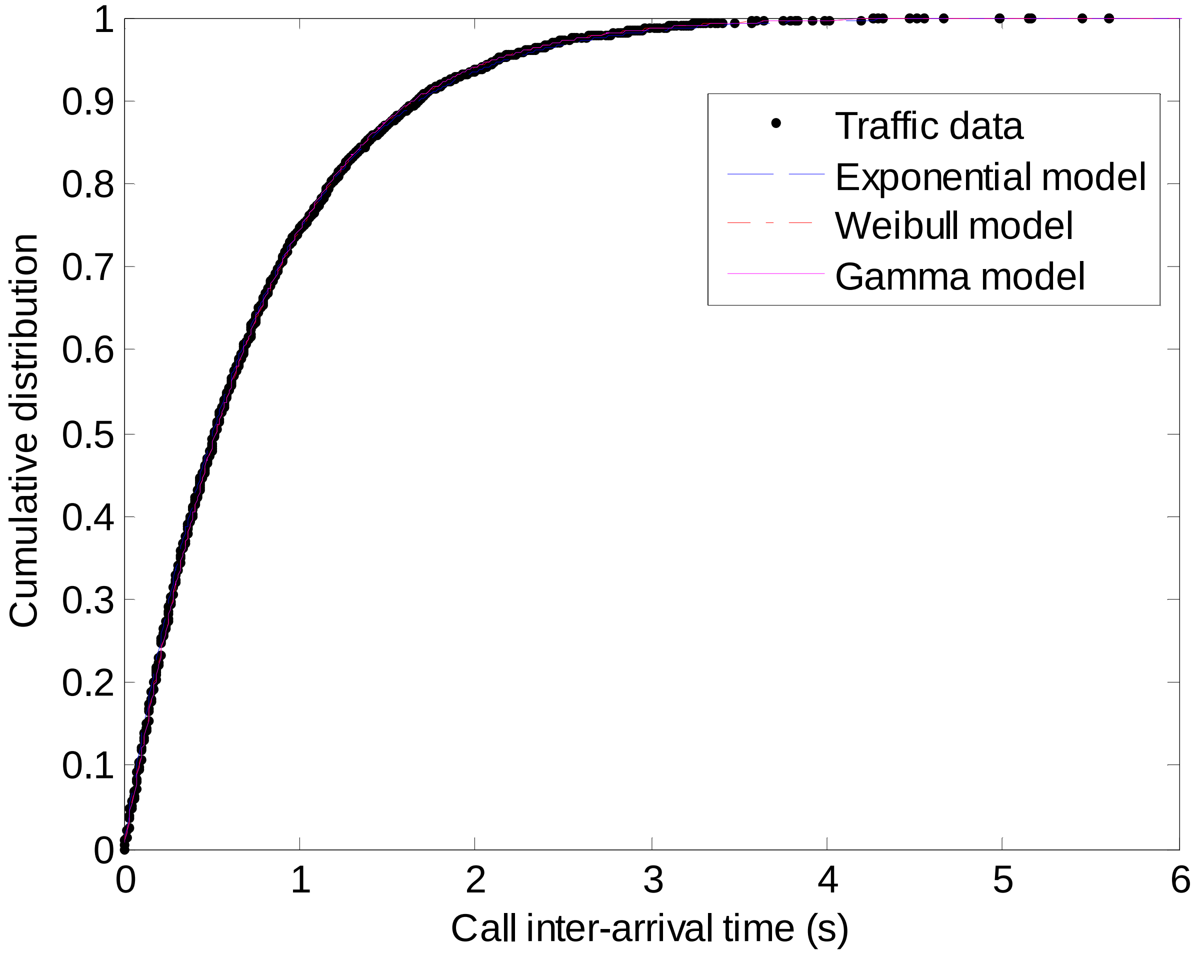
Statistical distributions

- Fourteen candidate distributions:
  - exponential, Weibull, gamma, normal, lognormal, logistic, log-logistic, Nakagami, Rayleigh, Rician, t-location scale, Birnbaum-Saunders, extreme value, inverse Gaussian
- Parameters of the distributions: calculated by performing maximum likelihood estimation
- Best fitting distributions are determined by:
  - visual inspection of the distribution of the trace and the candidate distributions
  - K-S test on potential candidates

Call inter-arrival times: pdf candidates



Call inter-arrival times: best-fitting distributions (cdf)



K-S test: call inter-arrival times 2001

Significance level σ = 0.1

Distribution	Parameter	02.11.2001, 20:00–21:00	02.11.2001, 16:00–17:00	02.11.2001, 15:00–16:00	01.11.2001, 19:00–20:00	01.11.2001, 00:00–01:00
exponential	h	1	1	0	1	1
	p	0.0384	0.0001	0.5416	0.0122	0.0135
	k	0.0247	0.0369	0.0131	0.0277	0.0259
Weibull	h	0	1	0	0	1
	p	0.3036	0.0409	0.4994	0.1574	0.0837
	k	0.0171	0.0236	0.0136	0.0195	0.0206
gamma	h	0	1	0	1	1
	p	0.3833	0.0062	0.3916	0.0644	0.0953
	k	0.0159	0.0287	0.0148	0.0227	0.0202

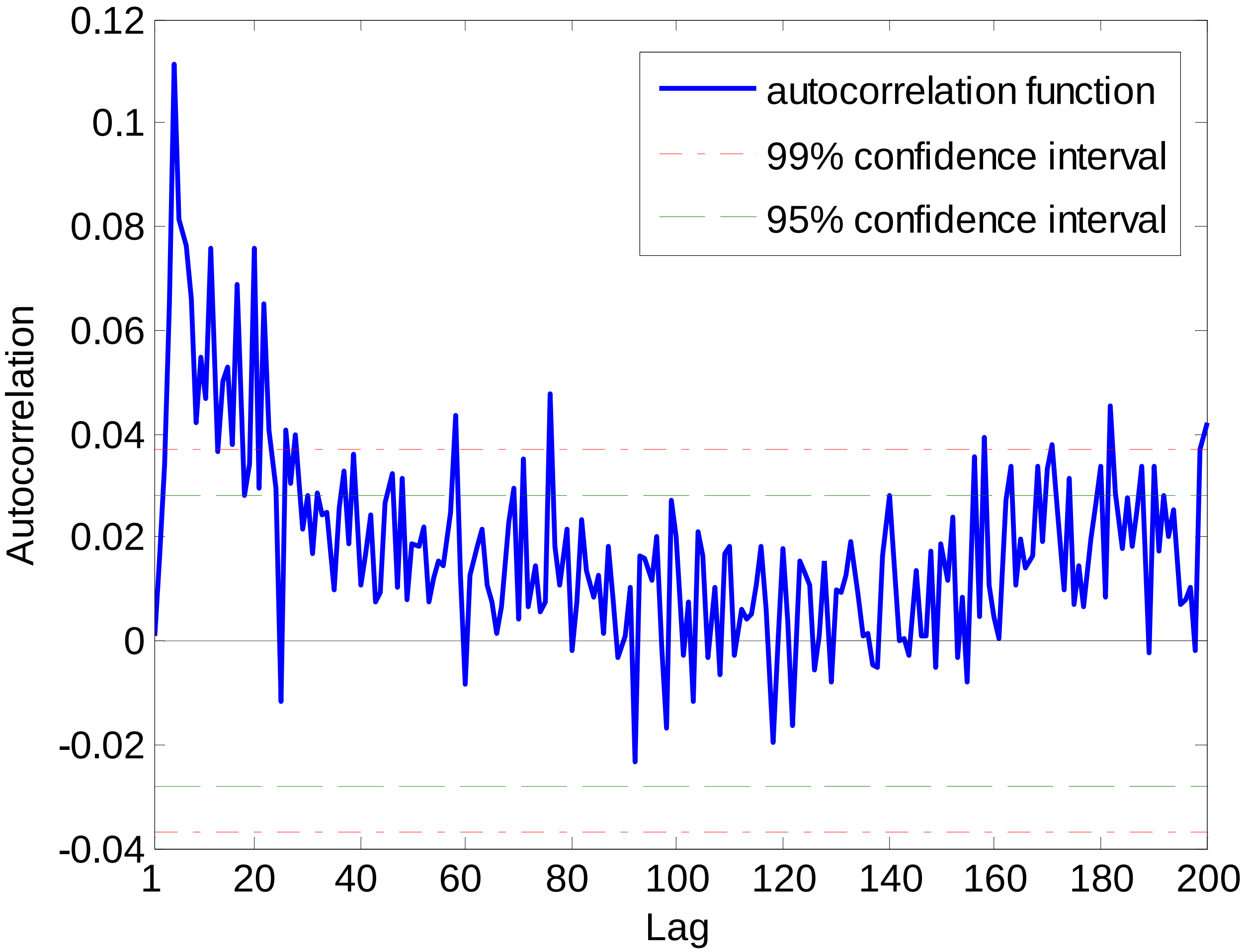
Significance level σ	0.01	0.04	0.05	0.08	0.09	0.1
02.11.2001, 16:00–17:00: cv	0.0275	0.0237	0.0230	0.0215	0.0211	0.0207
01.11.2001, 00:00–01:00: cv	0.0267	0.0229	0.0223	0.0208	0.0204	0.0201

K-S test: call inter-arrival times 2003

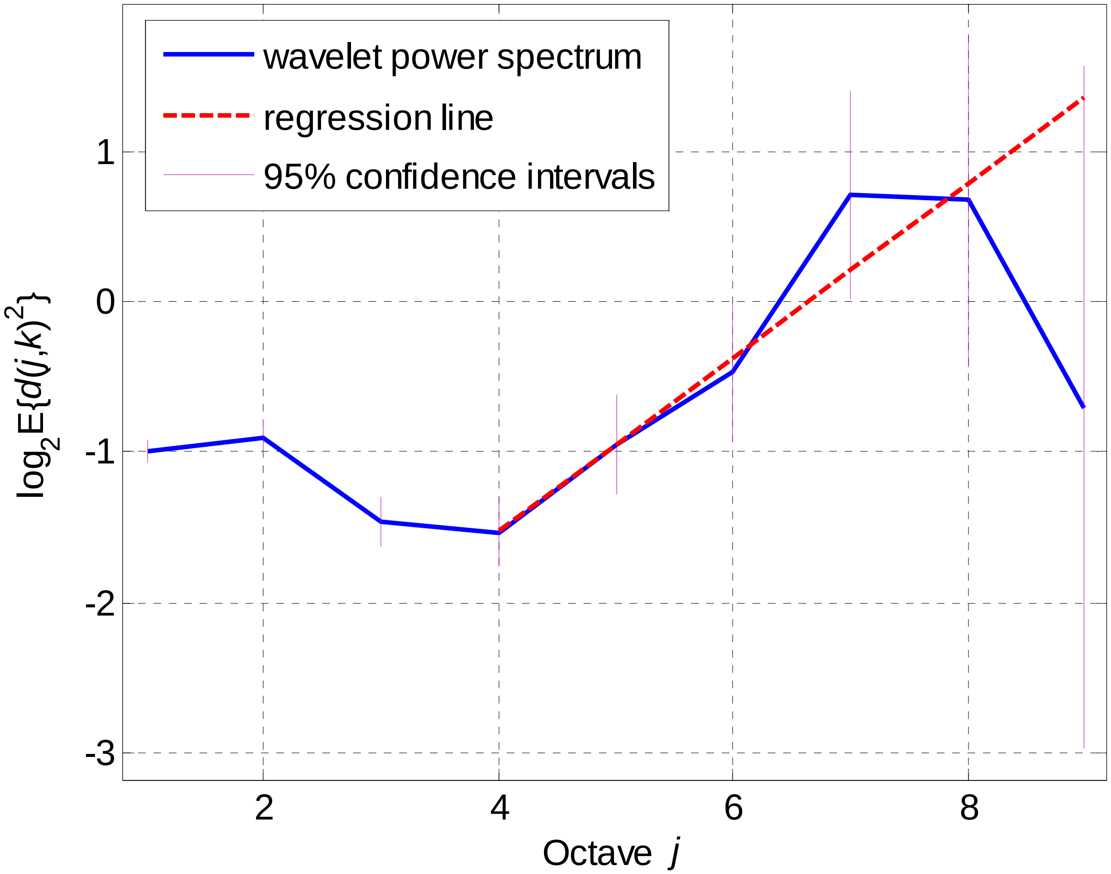
Significance level $\sigma = 0.1$

Distribution	Parameter	26.03.2003, 22:00–23:00	25.03.2003, 23:00–24:00	26.03.2003, 23:00–24:00	29.03.2003, 02:00–03:00	29.03.2003, 01:00–02:00
Exponential	h	1	1	0	1	1
	p	0.0027	0.0469	0.4049	0.0316	0.1101
	k	0.0283	0.0214	0.0137	0.0205	0.0185
Weibull	h	0	0	0	0	0
	p	0.4885	0.4662	0.2065	0.286	0.2337
	k	0.013	0.0133	0.0164	0.014	0.0159
Gamma	h	0	0	0	0	0
	p	0.3956	0.3458	0.127	0.145	0.1672
	k	0.0139	0.0146	0.0181	0.0163	0.0171
Lognormal	h	1	1	1	1	1
	p	1.015E-20	4.717E-15	2.97E-16	3.267E-23	4.851E-21
	k	0.0689	0.0629	0.0657	0.0795	0.0761

Call inter-arrival times: autocorrelation



Call inter-arrival times: 26.03.2003, 22:00–23:00



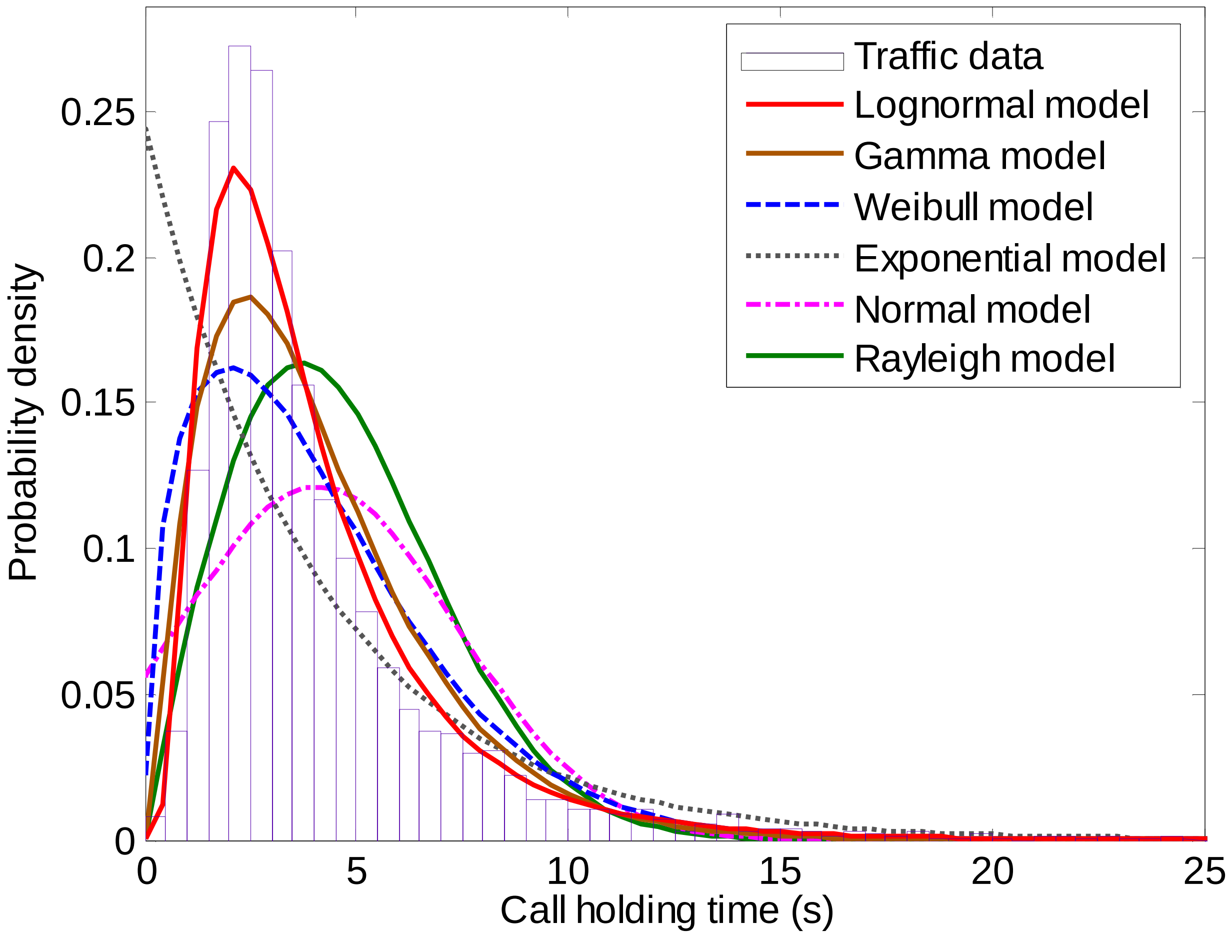
- LRD: $\alpha>0$ ($H>0.5$), $H = 0.5\,(\alpha + 1)$
- other traces have similar logscale diagrams

Call inter-arrival times: estimates of H

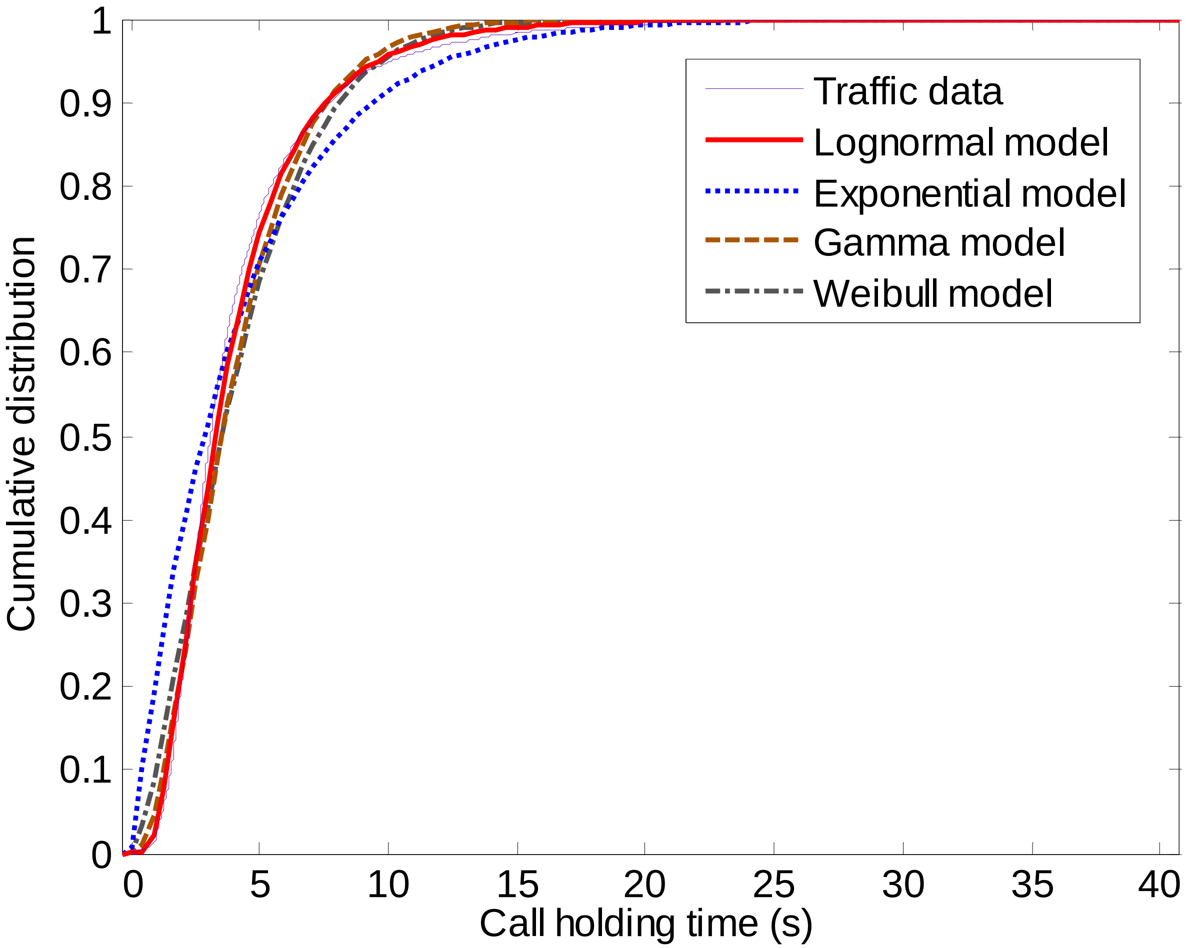
- Traces pass the test for time constancy of α: estimates of H are reliable

2001		2002		2003	
Day/hour	*H*	Day/hour	*H*	Day/hour	*H*
02.11.2001 15:00–16:00	0.907	01.03.2002 04:00–05:00	0.679	26.03.2003 22:00–23:00	0.788
01.11.2001 00:00–01:00	0.802	01.03.2002 22:00–23:00	0.757	25.03.2003 23:00–24:00	0.832
02.11.2001 16:00–17:00	0.770	01.03.2002 23:00–24:00	0.780	26.03.2003 23:00–24:00	0.699
01.11.2001 19:00–20:00	0.774	01.03.2002 00:00–01:00	0.741	29.03.2003 02:00–03:00	0.696
02.11.2001 20:00–21:00	0.663	02.03.2002 00:00–01:00	0.747	29.03.2003 01:00–02:00	0.705

Call holding times: pdf candidates



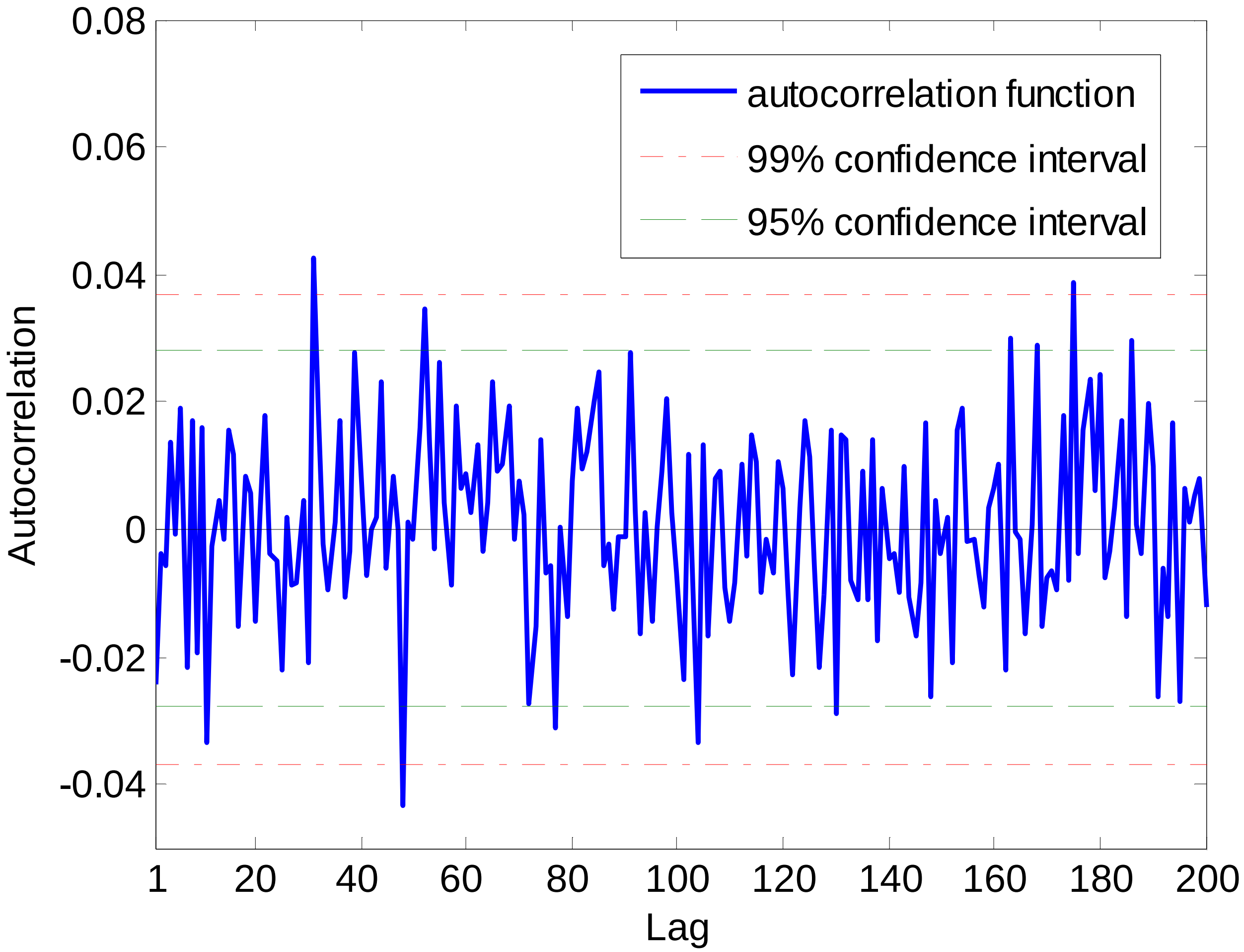
Call holding times: best-fitting distributions (cdf)



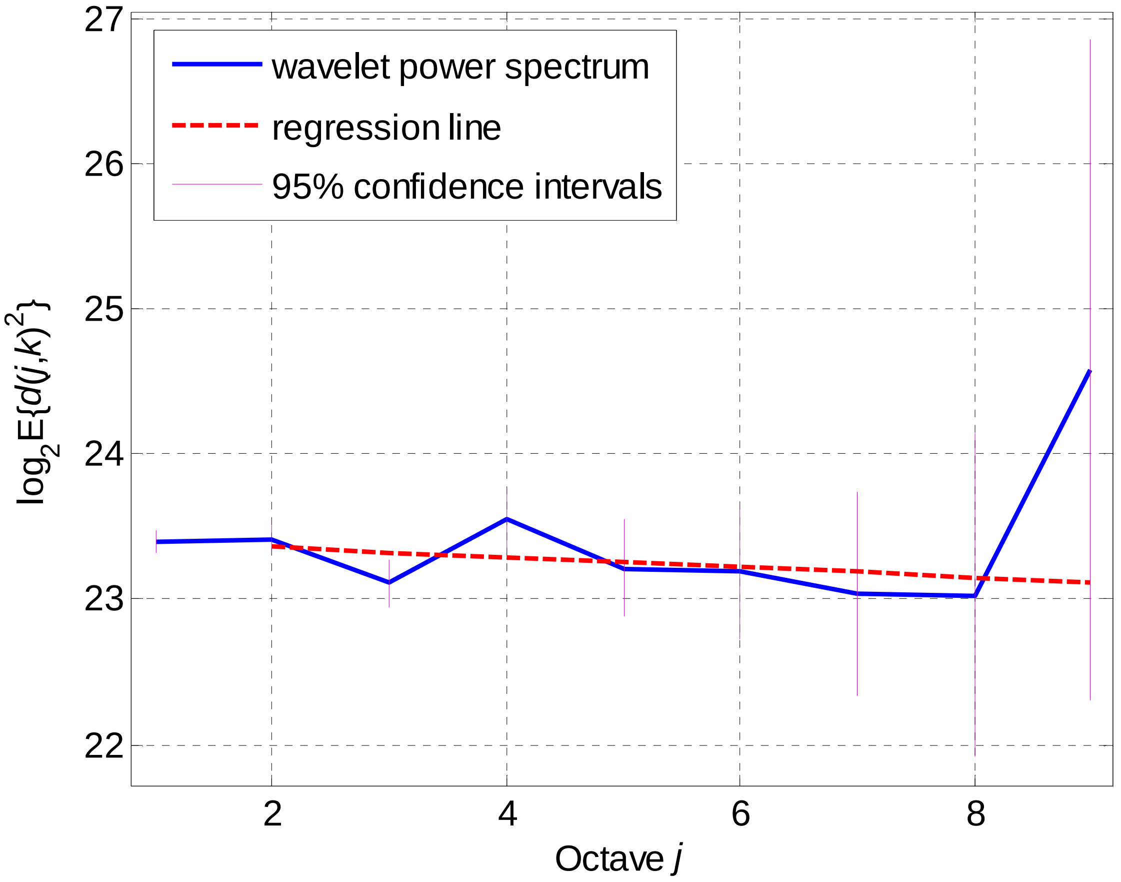
K-S test results: 2003

- No distribution passes the test when the entire trace is tested (significance levels = 0.1 and 0.01)
- Lognormal distribution passes test (significance level = 0.01) for:
  - 5-6 sub-traces from 15 randomly chosen 1,000-samples sub-traces
  - passes the test for almost all 500-samples sub-traces
- Test rejects null hypothesis when the sub-traces are compared with candidate distributions:
  - exponential
  - Weibull
  - gamma

Call holding times: autocorrelation



Logscale diagram, call holding times: 26.03.2003, 22:00–23:00



- independence: $\alpha \approx 0$ ($H \approx 0.5$)
- other traces have similar logscale diagrams

Call holding times: estimates of H

- All traces (except one) pass the test for constancy of α
- Only one unreliable estimate (*): consistent value

2001		2002		2003	
Day/hour	H	Day/hour	H	Day/hour	H
02.11.2001 15:00–16:00	0.493	01.03.2002 04:00–05:00	0.490	26.03.2003 22:00–23:00	0.483
01.11.2001 00:00–01:00	0.471	01.03.2002 22:00–23:00	0.460	25.03.2003 23:00–24:00	0.483
02.11.2001 16:00–17:00	0.462	01.03.2002 23:00–24:00	0.489	26.03.2003 23:00–24:00	0.463 *
01.11.2001 19:00–20:00	0.467	01.03.2002 00:00–01:00	0.508	29.03.2003 02:00–03:00	0.526
02.11.2001 20:00–21:00	0.479	02.03.2002 00:00–01:00	0.503	29.03.2003 01:00–02:00	0.466

Call inter-arrival and call holding times

	2001		2002		2003	
	Day/hour	Avg. (s)	Day/hour	Avg. (s)	Day/hour	Avg. (s)
inter-arrival	02.11.2001 15:00–16:00	0.97	01.03.2002 04:00–05:00	0.81	26.03.2003 22:00–23:00	0.73
holding		3.78		4.07		4.08
inter-arrival	01.11.2001 00:00–01:00	0.97	01.03.2002 22:00–23:00	0.83	25.03.2003 23:00–24:00	0.85
holding		3.95		3.84		4.12
inter-arrival	02.11.2001 16:00–17:00	1.03	01.03.2002 23:00–24:00	0.86	26.03.2003 23:00–24:00	0.85
holding		3.99		3.88		4.04
inter-arrival	01.11.2001 19:00–20:00	1.09	01.03.2002 00:00–01:00	0.91	29.03.2003 02:00–03:00	0.87
holding		3.97		3.95		4.14
inter-arrival	02.11.2001 20:00–21:00	1.12	02.03.2002 00:00–01:00	0.91	29.03.2003 01:00–02:00	0.88
holding		3.84		4.06		4.25

Avg. call inter-arrival times: 1.08 s (2001), 0.86 s (2002), 0.84 s (2003)

Avg. call holding times: 3.91 s (2001), 3.96 s (2002), 4.13 s (2003)

Distributions

Distribution	Expression	Remark
exponential	$f(x)=\frac{e^{-x/\mu}}{\mu}$	
Weibull	$f(x)=ba^{-b}x^{b-1}e^{-(x/a)^b}I_{(0,\infty)}(x)$	$I_{(0,\infty)}(x)$: incomplete beta function
gamma	$f(x)=\frac{x^{a-1}e^{-(x/b)}}{b^a\Gamma(a)}$	$\Gamma(a)$: gamma function
lognormal	$f(x)=\frac{e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}}{x\sigma\sqrt{2\pi}}$	

Best fitting distributions

Busy hour	Distribution					
	Call inter-arrival times				Call holding times	
	Weibull		Gamma		Lognormal	
	a	b	a	b	μ	σ
02.11.2001 15:00–16:00	0.9785	1.1075	1.0326	0.9407	1.0913	0.6910
01.11.2001 00:00–01:00	0.9907	1.0517	1.0818	0.8977	1.0801	0.7535
02.11.2001 16:00–17:00	1.0651	1.0826	1.1189	0.9238	1.1432	0.6803
01.03.2002 04:00–05:00	0.8313	1.0603	1.1096	0.7319	1.1746	0.6671
01.03.2002 22:00–23:00	0.8532	1.0542	1.0931	0.7643	1.1157	0.6565
01.03.2002 23:00–24:00	0.8877	1.0790	1.1308	0.7623	1.1096	0.6803
26.03.2003 22:00–23:00	0.7475	1.0475	1.0910	0.6724	1.1838	0.6553
25.03.2003 23:00–24:00	0.8622	1.0376	1.0762	0.7891	1.1737	0.6715
26.03.2003 23:00–24:00	0.8579	1.0092	1.0299	0.8292	1.1704	0.6696

Conclusions

- We used data from a deployed public safety wireless network in Vancouver: E-Comm
- We created an OPNET model and simulated network activity
- Network traffic exhibits daily cycles
- Between February 2002 and March 2003:
  - number of calls increased by ~60 %
  - average utilization increased non-uniformly across the network
- Several cells may become congested in future

Conclusions

- We analyzed five busy hours of voice traffic from 2001, 2002, and 2003:
  - call inter-arrival times
  - call holding times
- We examined statistical distribution functions of traffic traces:
  - Kolmogorov-Smirnov goodness-of-fit test
  - autocorrelation functions
  - wavelet-based estimation of the Hurst parameter

Conclusions

- Call inter-arrival times:
  - best fit: Weibull and gamma distributions
  - long-range dependent: $H \approx 0.7$–0.8
- Call holding times:
  - best fit: lognormal distribution
  - uncorrelated

References

- D. Sharp, N. Cackov, N. Lasković, Q. Shao, and Lj. Trajković, “Analysis of public safety traffic on trunked land mobile radio systems,” *IEEE J. Select. Areas Commun.*, vol. 22, no. 7, Sept. 2004, pp. 1197–1205.
- N. Cackov, B. Vujičić, S. Vujičić, and Lj. Trajković, “Using network activity data to model the utilization of a trunked radio system,” in *Proc. SPECTS*, San Jose, CA, July 2004, pp. 517–524.
- B. Vujičić, N. Cackov, S. Vujičić, and Lj. Trajković, “Modeling and characterization of traffic in public safety wireless networks,” in *Proc. SPECTS 2005*, Philadelphia, PA, July 2005, pp. 14–223.
- J. Song and Lj. Trajković, “Modeling and performance analysis of public safety wireless networks,” in *Proc. IEEE IPCCC*, Phoenix, AZ, Apr. 2005, pp. 567–572.
- N. Cackov, J. Song, B. Vujičić, S. Vujičić, and Lj. Trajković, “Simulation and performance evaluation of a public safety wireless network: case study," *Simulation*, vol. 81, no. 8, Aug. 2005, pp. 571–585.
- B Vujičić, H. Chen and Lj. Trajković, “Prediction of traffic in a Public Safety Network,” in *Proc. ISCAS 2006*, Island of Kos, Greece, May 2006, pp. 2637–2640.
- L. A. Andriantiatsaholiniaina and Lj. Trajković, “Analysis of user behavior from billing records of a CDPD wireless network,” in *Proc. Workshop on Wireless Local Networks 2002,* Tampa, FL, Nov. 2002, pp. 781-790.
- F. Barcelo and J. Jordan, “Channel holding time distribution in public telephony systems (PAMR and PCS),” *IEEE Trans. Vehicular Technology*, vol. 49, no. 5, Sept. 2000, pp. 1615–1625.

References

- D. Tang and M. Baker, “Analysis of a metropolitan-area wireless network,” in *Proc. of ACM Mobicom ’99,* Seattle, WA, Sept. 1999, pp. 13–23.
- W. Leland, M. Taqqu, W. Willinger, and D. Wilson, “On the self-similar nature of Ethernet traffic (extended version),” *IEEE/ACM Trans. Networking*, vol. 2, Feb. 1994, pp. 1–15.
- P. Abry, P. Flandrin, M. S. Taqqu, and D. Veitch, “Wavelets for the analysis, estimation, and synthesis of scaling data,” in *Self-similar Network Traffic and Performance Evaluation*, K. Park and W. Willinger, Eds. New York: Wiley, 2000, pp. 39–88.
- R. B. D'Agostino and M. A. Stephens, Eds., *Goodness-of-Fit Techniques*. New York: Marcel Dekker, 1986. pp. 63–93, pp. 97–145, pp. 421–457.
- R. J. Orsulak, R. R. Seach, J. P. Camacho, and R. J. Matheson. (2004, May). “Land mobile spectrum planning options,” National Telecommunications and Information Administration, Washington, DC, Spectrum Engineering Reports, Oct. 1995. [Online]. Available: http://www.ntia.doc.gov/osmhome/reports/slye_rpt/cover.html.
- E-Comm, Emergency Communications for SW British Columbia Incorporated. (2005, May). [Online]. Available: http://www.ecomm.bc.ca.
- EDACS Trunking Information. (2004, May). [Online]. Available: http://www.radioreference.com.
- *OPNET documentation V.9.0.A*, OPNET Technologies, Inc., Bethesda, MD, 2001.
- In Vancouver! Vancouver Travel Guide. (2004, May). [Online]. Available: http://www.vancouver-bc.com/maps-html.