MODELLING INTERNET PACKET TRAFFIC CONGESTION

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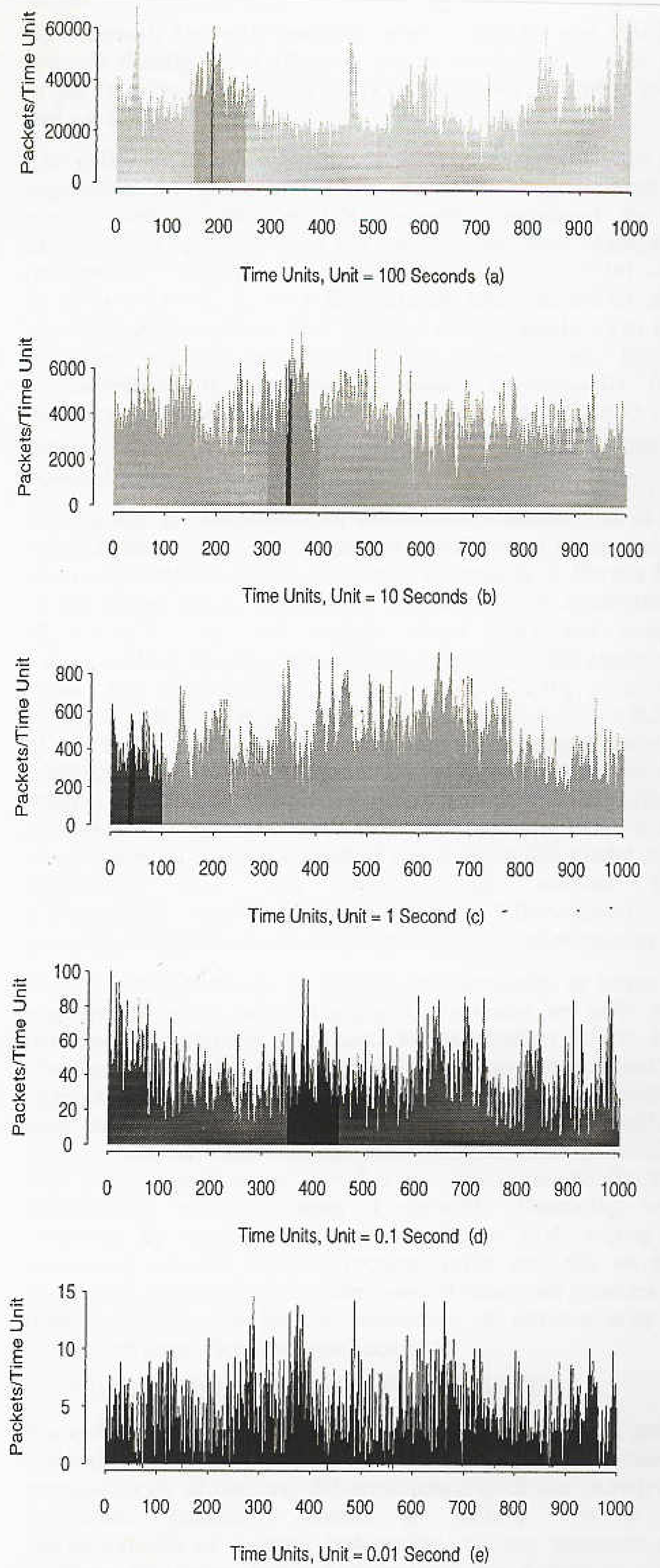


Figure 1 (a)—(e). Pictorial "proof" of self-similarity: Ethernet traffic (packets per time unit for the August '89 trace) on 5 different time scales. (Different gray levels are used to identify the same segments of traffic on the different time scales.)

Ethernet

packet rates

on different

time scales

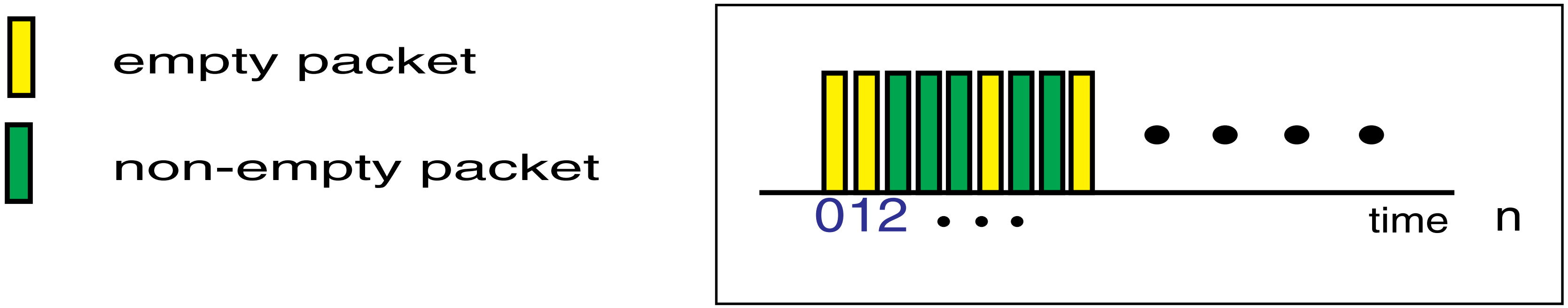
Leland *et al*

1995

"Pictorial proof

of self-similarity"

COMMUNICATIONS - PACKET TRAFFIC



1994 - "On the self-similar nature of Ethernet traffic", Leland *et al, Comp Comm Rev*

- "bursty activity" of packet rates over many time-scales
- conventional "Poisson" models for over optimistic on queue performance
- "Poisson-like" view of aggregated sources suggests smoother traffic

AUTOCORRELATION - nature of traffic streams

STATIONARY BINARY TIME SERIES:

$$X_t \in \{0,1\}, \quad t = 1,2,3,\ldots$$

BATCHED TIME SERIES- size N:

$$X_t^{(N)} = \frac{1}{N} \sum_{j=tN+1}^{(t+1)N} X_t$$

AUTO-CORRELATION FORMULA for X_t :

$$c(k) = \frac{E(X_t X_{t+k}) - E(X_t)E(X_{t+k})}{\sqrt{(\mathrm{Var}(X_t)\mathrm{Var}(X_{t+k}))}}$$

AUTO-CORRELATION FOR **LRD** TRAFFIC:

POWER LAW DECAY

$$c(k) \sim k^{-\beta}, \quad \beta \in (0,1)$$

AUTO-CORRELATION FOR **SRD** TRAFFIC:

EXP DECAY

$$c(k) \sim \alpha^{-k}, \quad \alpha > 1$$

SELF-SIMILARITY FOR **LRD** TRAFFIC :

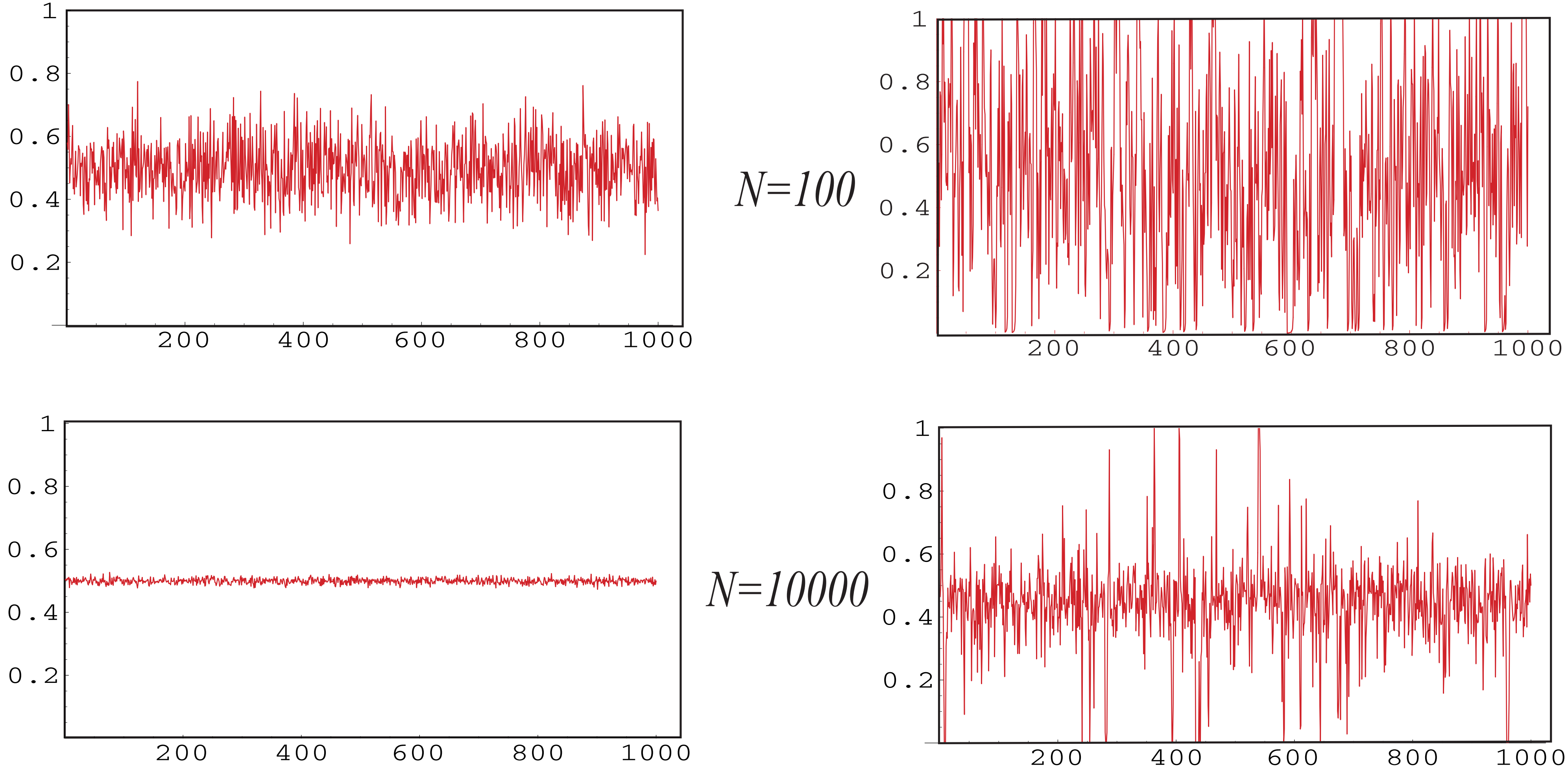
2nd ORDER statistics of X_t and $X_t^{(N)}$ are the same

SELF-SIMILARITY HURST PARAMETER H :

$$H = 1 - \beta/2$$

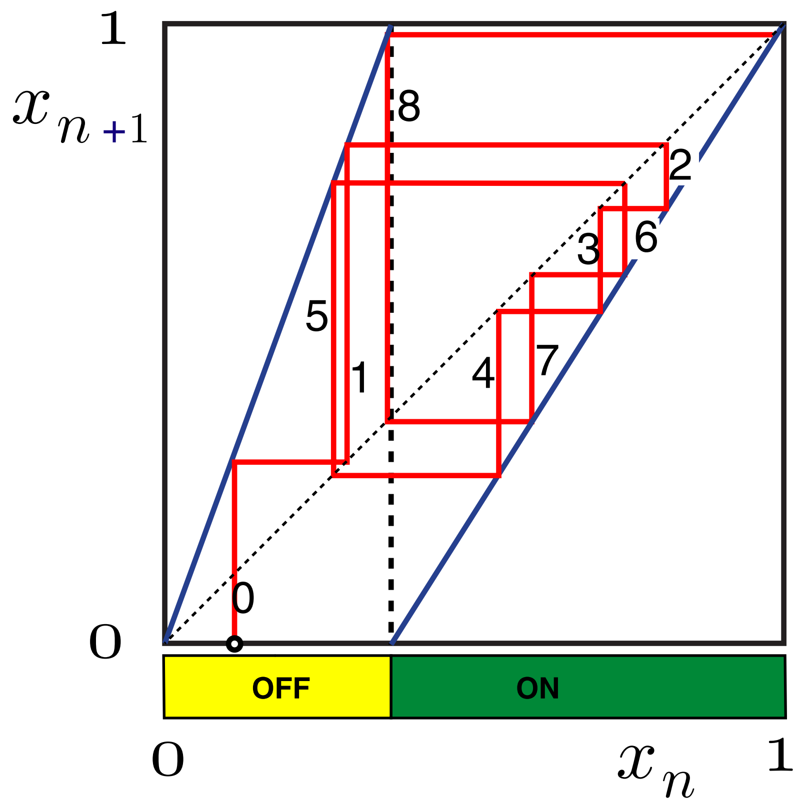
SRD and LRD OUTPUT

- N= *BATCH SIZE of AVERAGED DATA*

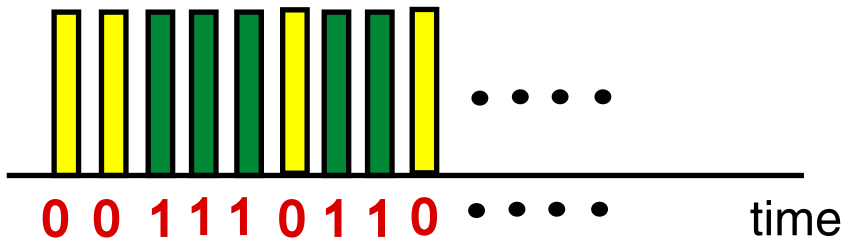


Short range dependent *Long range dependent*

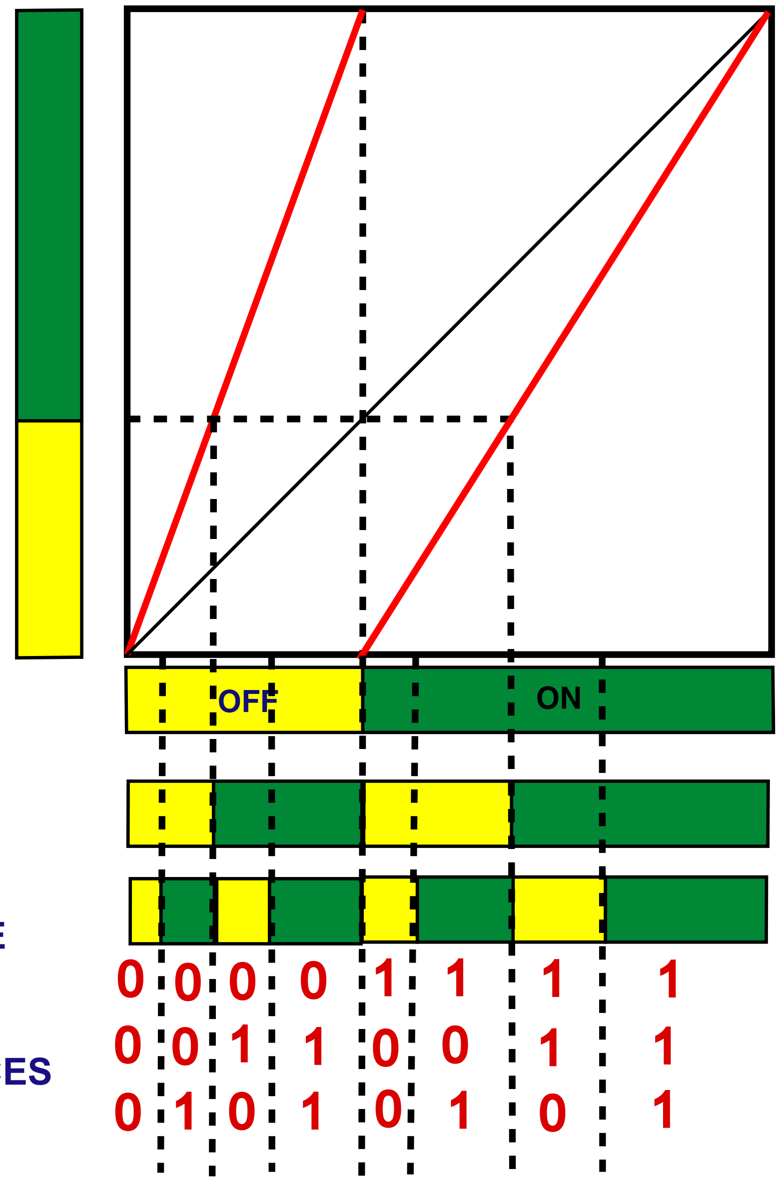
CHAOTIC MAPS *DIGITAL OUTPUT and CODING*



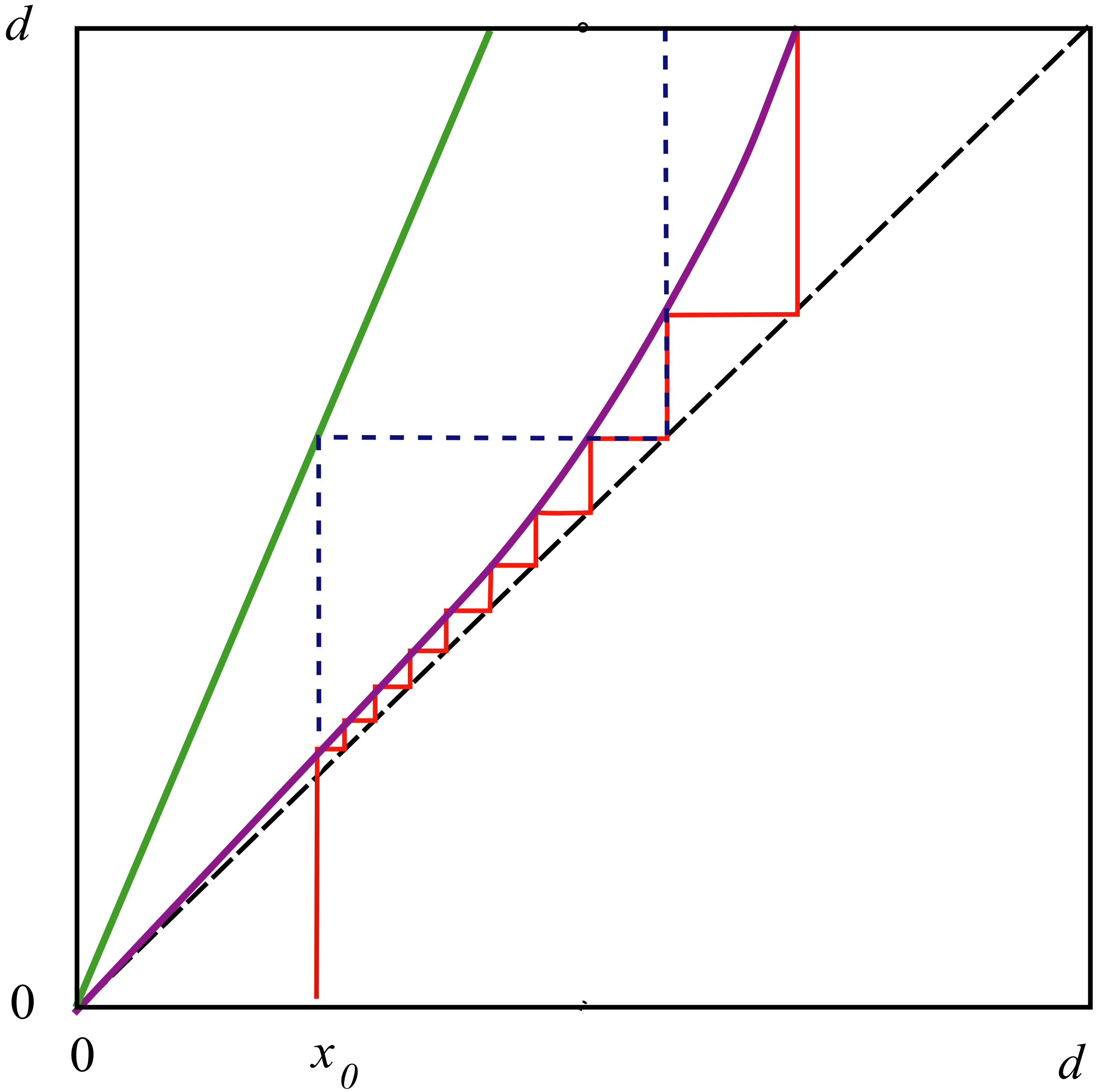
DIGITAL OUTPUT



ALL
POSSIBLE
DIGITAL
OUTPUT
SEQUENCES



INTERMITTENCY and LINEAR MAPS



intermittency map $f(x) = x + ax^m$

tangency with $y=x$ at $x=0$

implies intermittency at $x=0$

and small iterative changes
in the values of x

PROBABILITY of ESCAPE
to the region $x > d$ in more than n
iterations of the map f
is given by

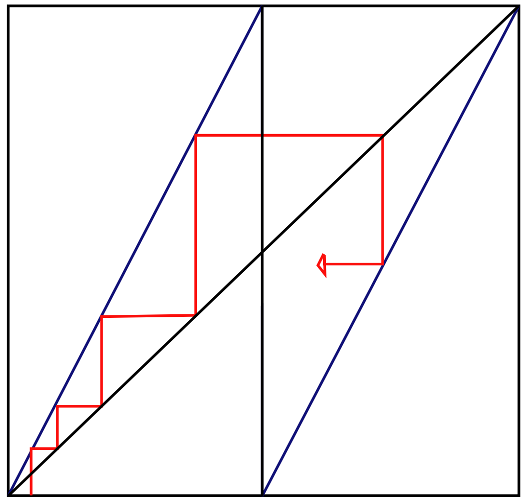
INTERMITTENCY(POWER LAW DECAY)

$\text{Prob}(n) \sim n^{-(2-m)/(m-1)}$

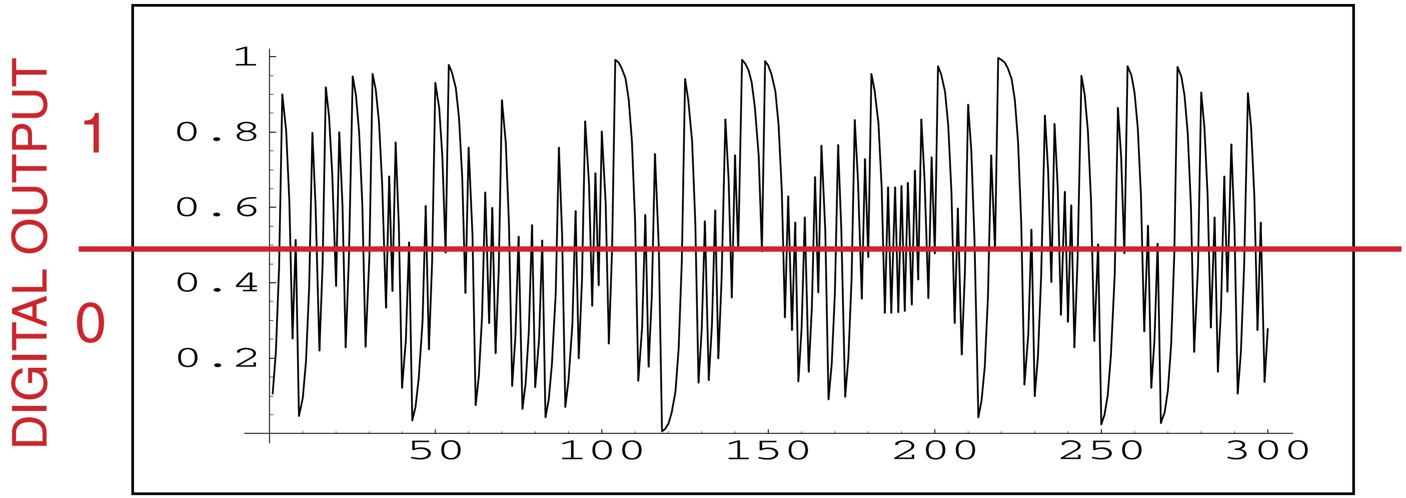
LINEAR(EXPONENTIAL DECAY)

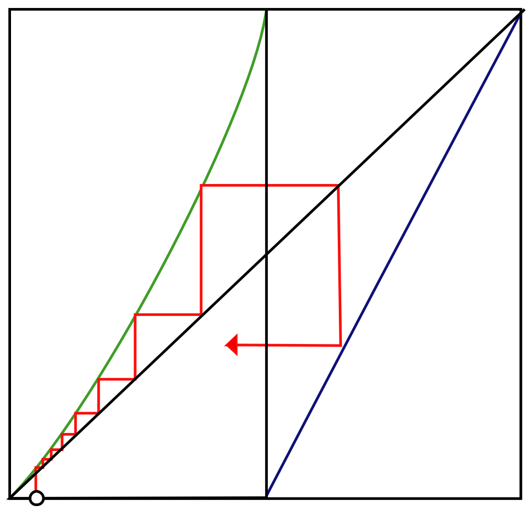
$\text{Prob}(n) \sim 2^{-n}$

OUTPUT COMPARISON OF MAPS

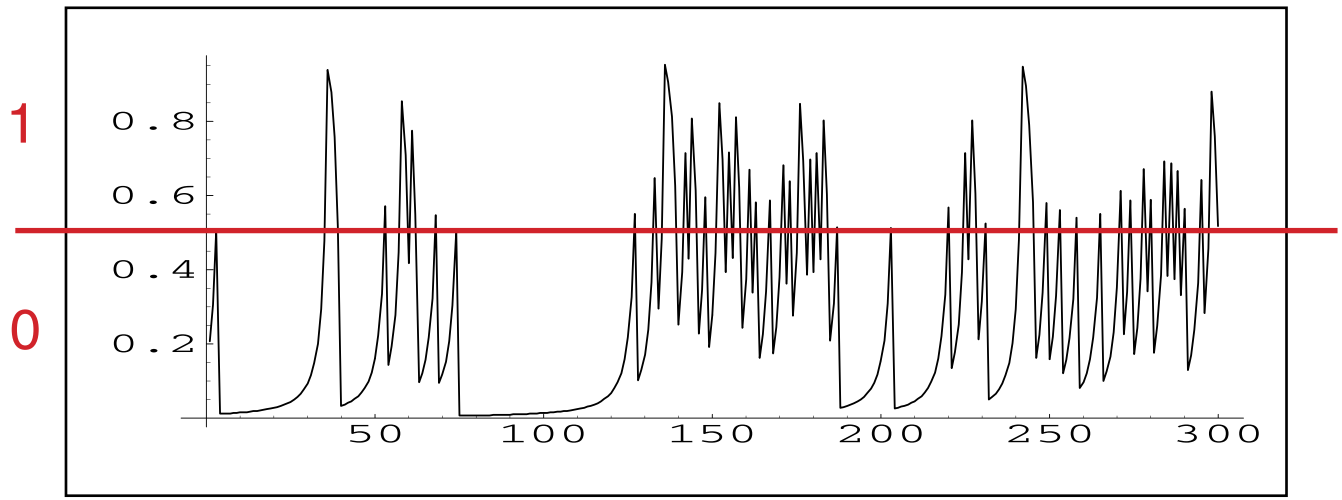


BURST





OFF | BURST

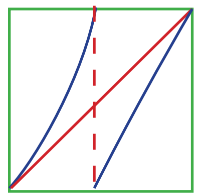


DYNAMICS - STATISTICS INTERFACE

- INTERMITTENCY IN DYNAMICS
  - - CORRELATION IN STATISTICS
    - - LONG RANGE DEPENDENCE IN APPLICATIONS

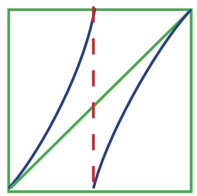
CONJECTURES ON AUTO-CORRELATION (Erramilli *et al* ('95), Giovanardi *et al* ('98,'00))

- SINGLE INTERMITTENCY MAPS (WANG, SCHUSTER)



ERRAMILLI MAPS

- DOUBLE INTERMITTENCY MAPS (BARENCO and A.)



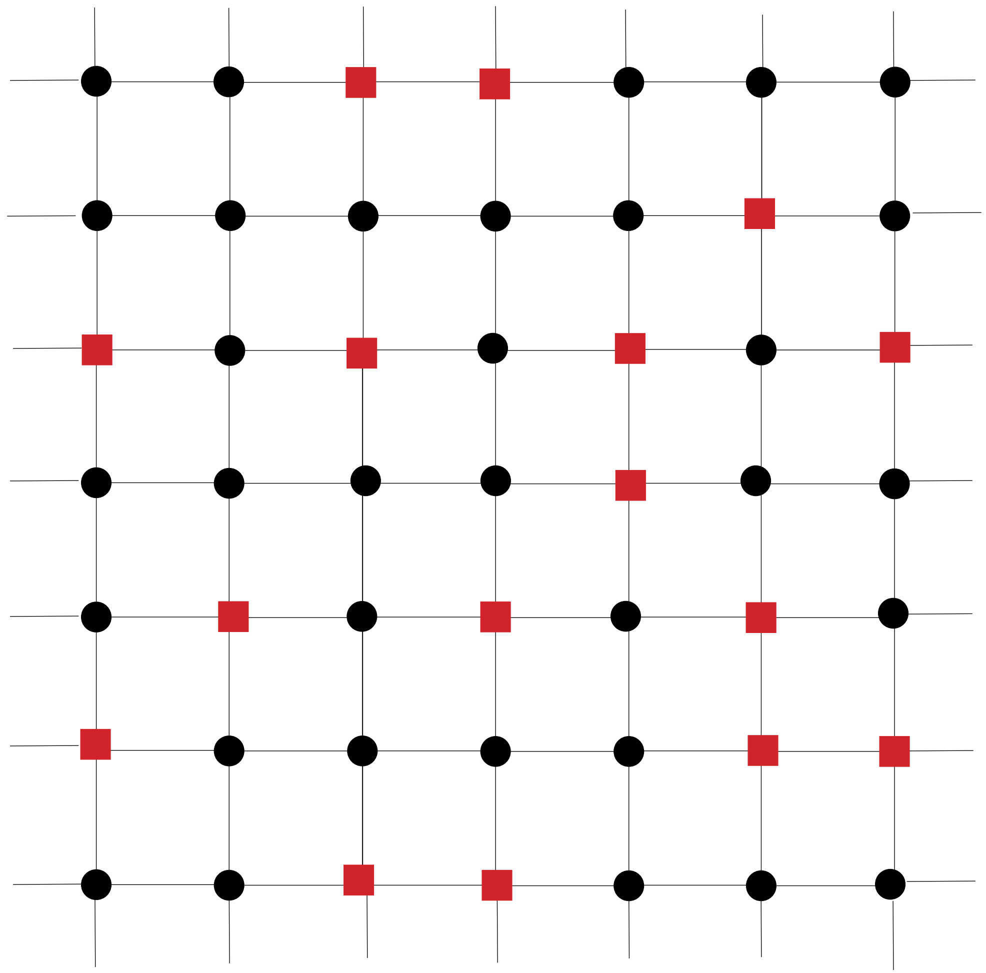
$$f_i(x) = \begin{cases} x + a x^{m_1}, & 0 < x < d \\ x - b(1 - x)^{m_2} & d \leq x < 1 \end{cases}$$

auto-correlation/intermittency property :

$$c(k) \sim k^{-\gamma} \qquad \gamma = (2-m)/(m-1), \;\; m = \mathrm{Max}\{m_i\}$$

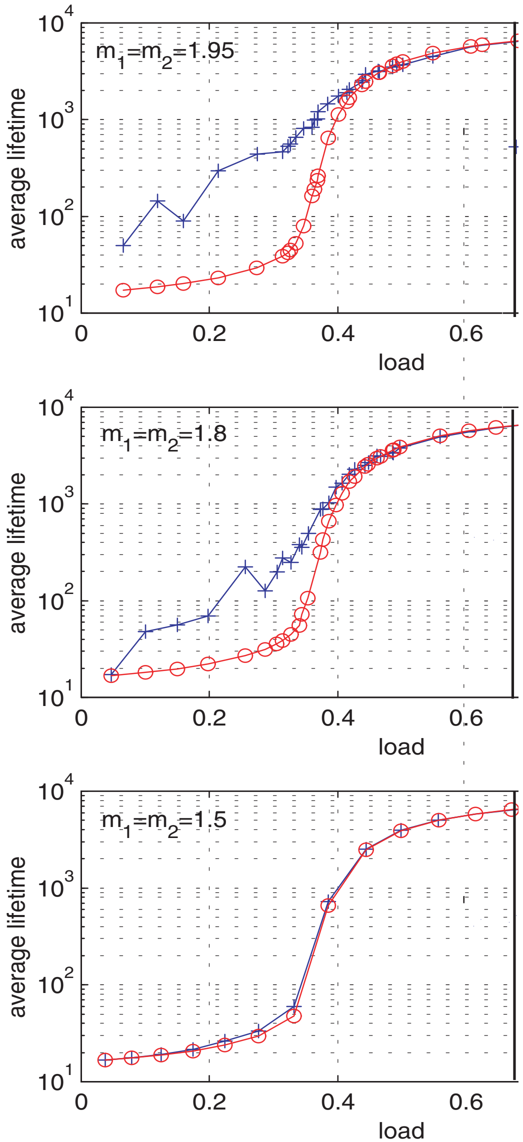
RECTANGULAR GRID *NETWORK MODEL*

- hosts ■ can source, transfer and receive packets
- random host destination
- routers ● can transfer packets
- every node has a buffer for queueing packets
- packets at head of queue move one step closer to destination for each time step



SRD ⟶ LRD

via intermittency



LRD/POISSON LOADS

below critical
$\lambda = 0.156$

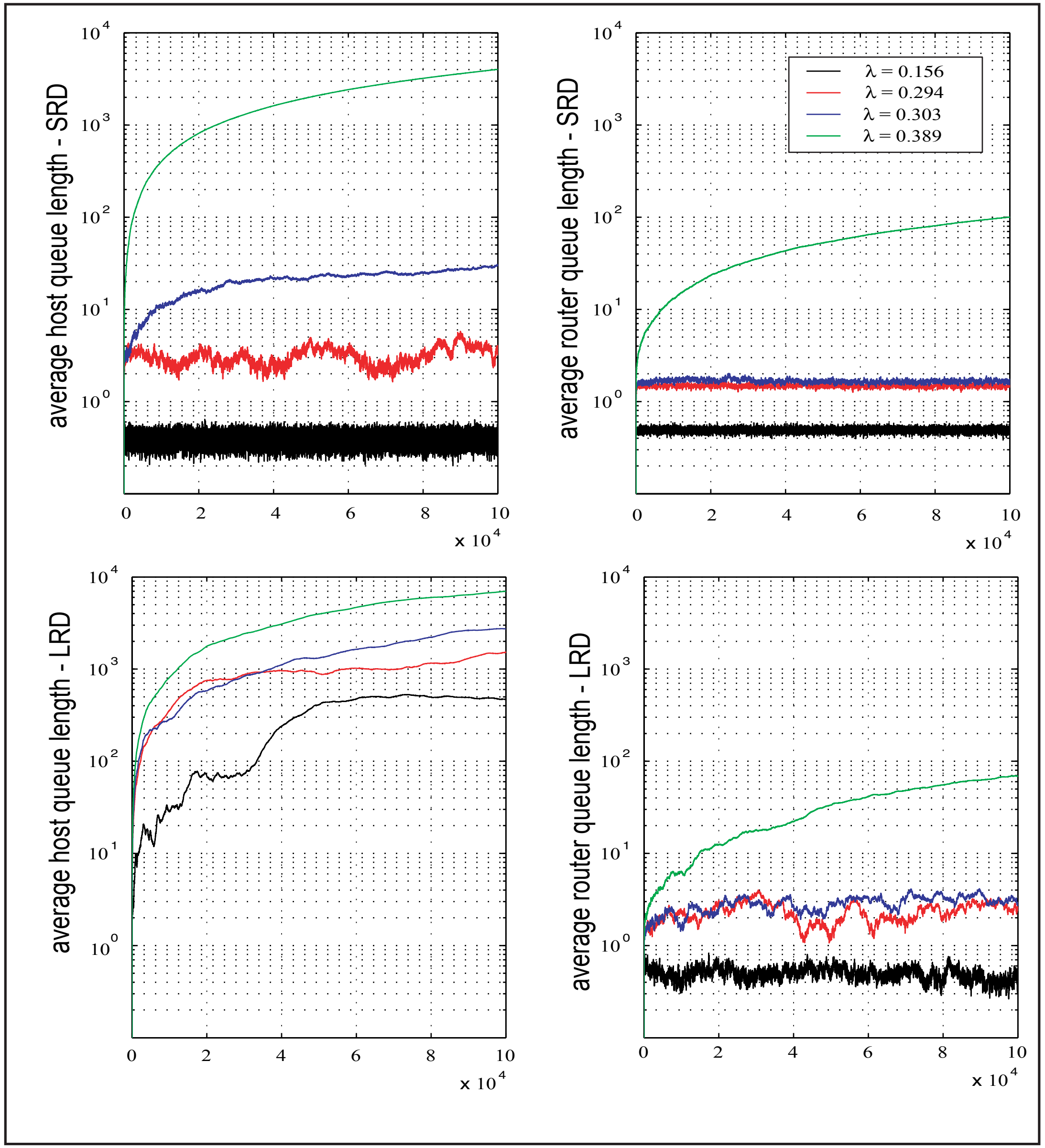
pre-critical
$\lambda = 0.294$

post-critical
$\lambda = 0.303$

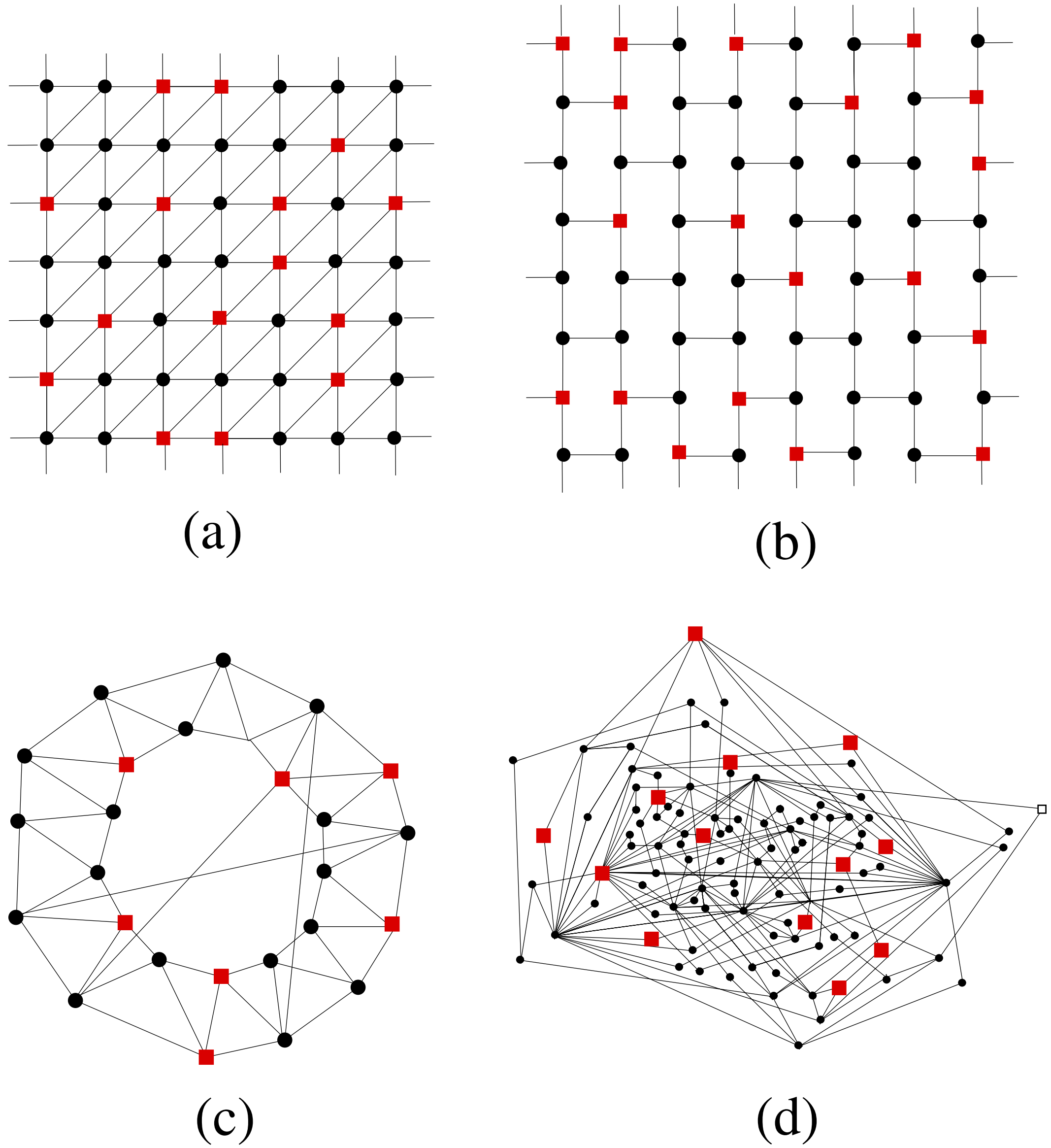
heavy congestion
$\lambda = 0.389$

Host density = 16 %

SRD ⟶ LRD *queue lengths*



NETWORK MODELS



different types of graph:

REGULAR:

(a) triangular

(b) hexagonal,

and

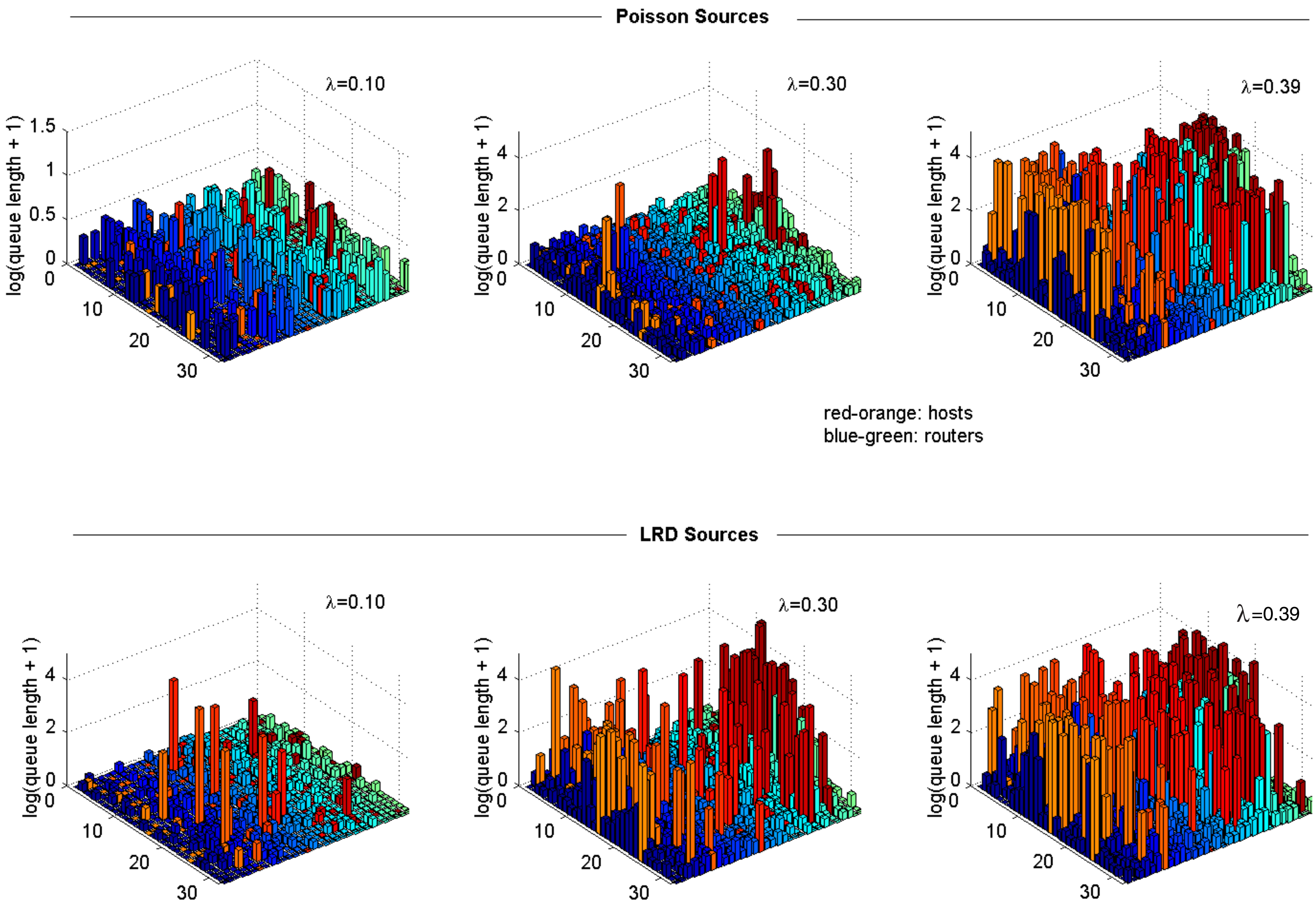
(c) SMALL-WORLD

random connections added to increase connectivity

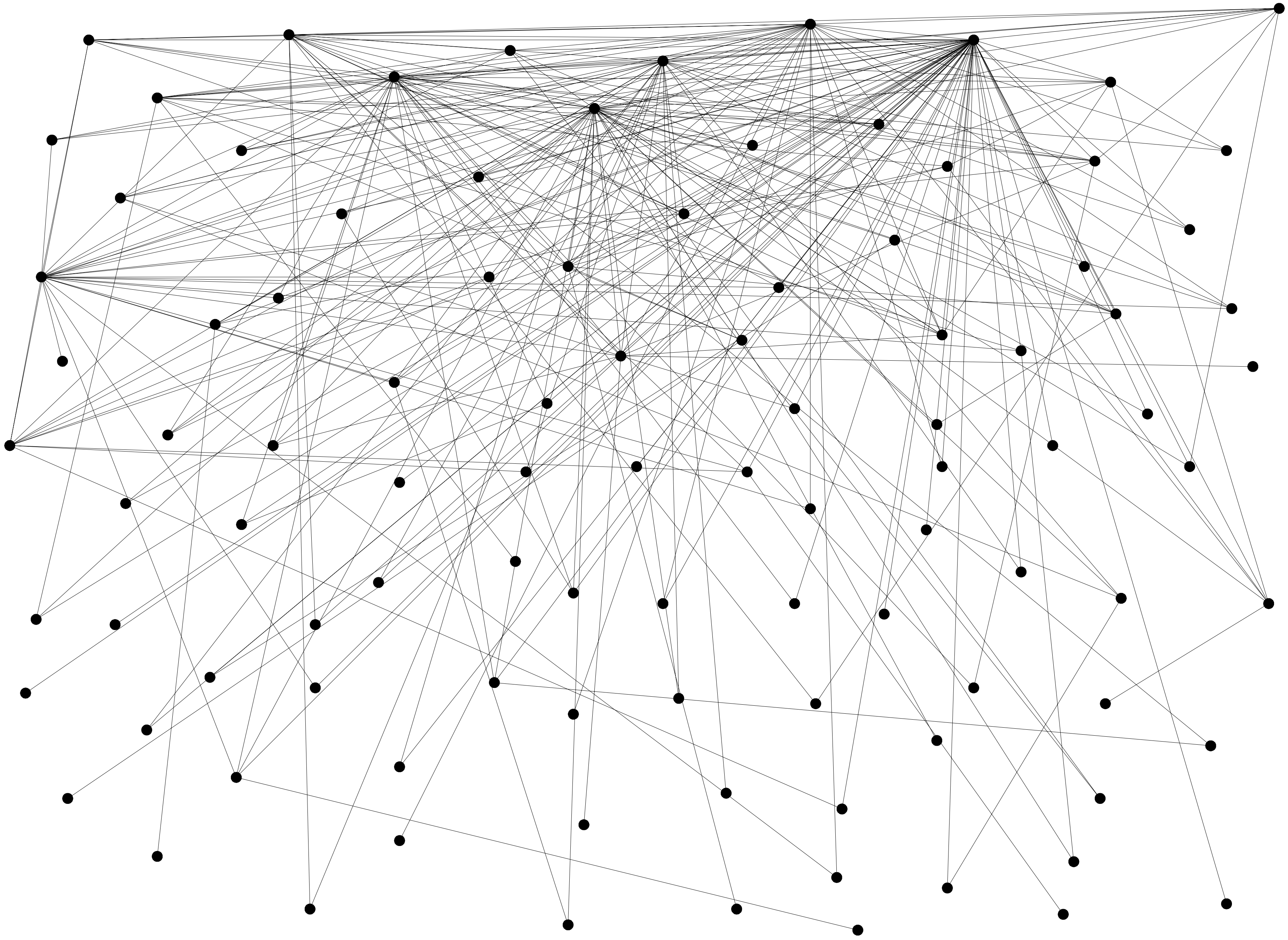
(d) SCALE-FREE

Prob(vertex valency =n) = $n^{-\gamma}$ with exponent $\gamma \in [2,3]$.

Manhattan network queues as load increases : Poisson vs. LRD



Comparing Queue Lengths for a Manhattan Network with Poisson and LRD sources

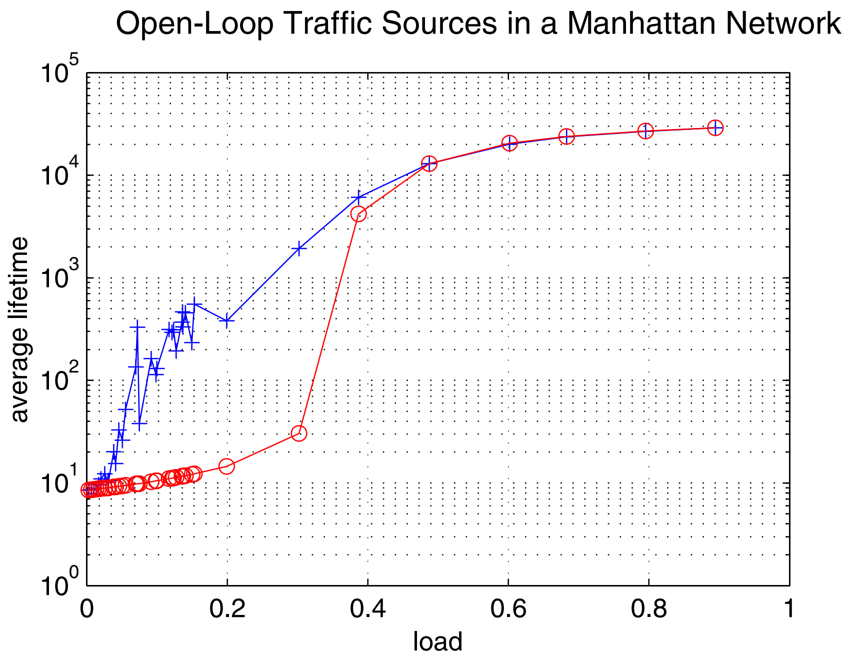


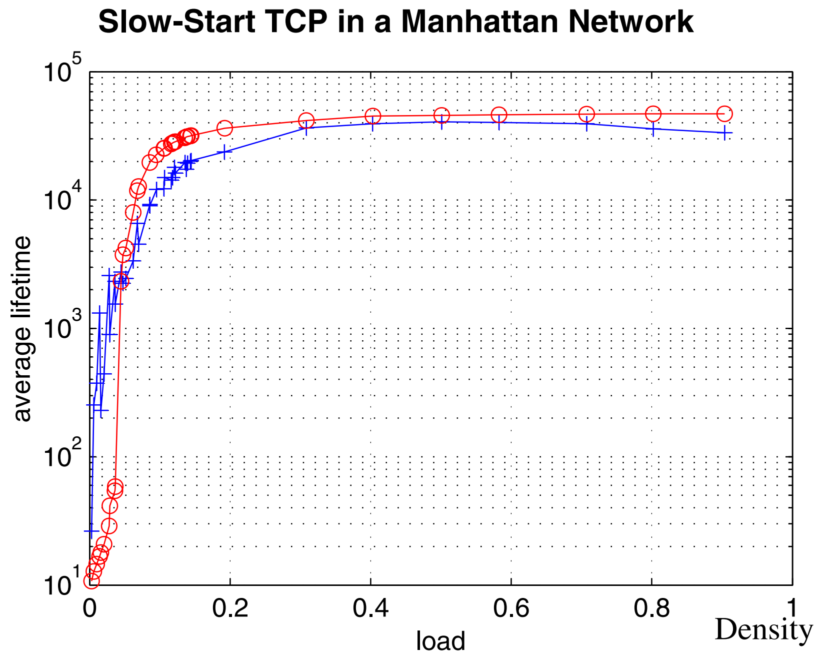
100 Node Scale-Free IG Network (Zhou, Mondragon: *ITC, Berlin 2003*)

TCP window dynamics

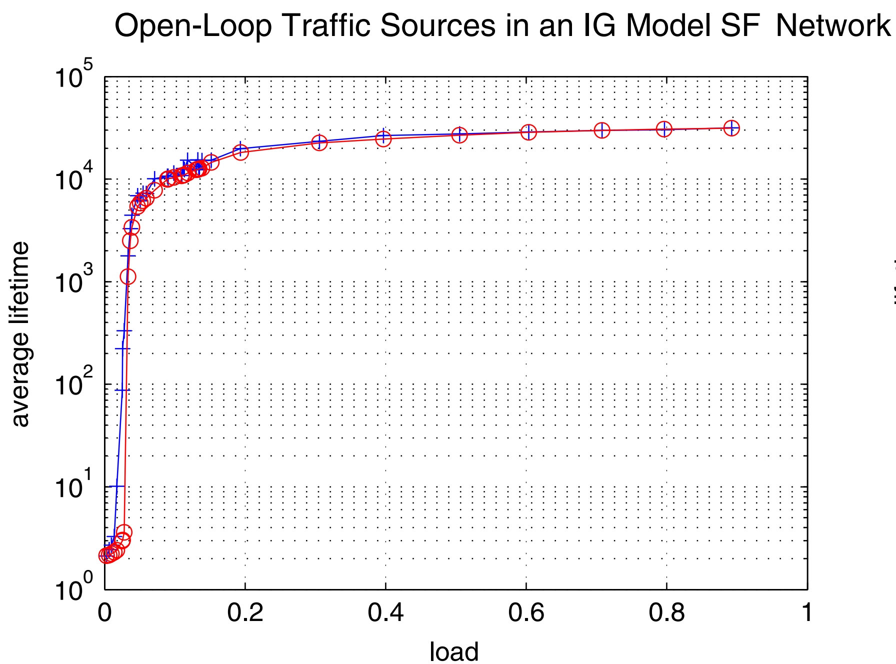
LRD sources
Poisson sources

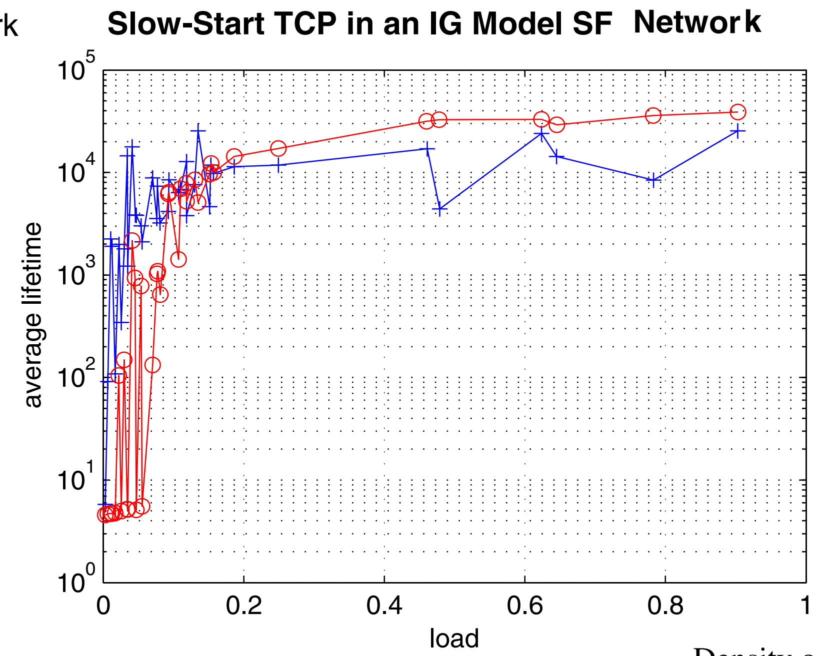
$m_1=m_2=1.95$





Density of hosts ρ =0.16





ρ =0.8

Density of hosts

ONGOING WORK

- Erratic onset of congestion is a robust feature of LRD modelling in various networks
- LRD can arise from various sources - data streams, network structures, aggregation, TCP
- comparative and hierarchical modelling to study relative LRD strengths for each of these features