

# Quantifying Failure Dependencies in Multi-layer Mobile Broadband Networks

Dong Zhou<sup>1</sup>, Džiugas Baltrūnas<sup>1</sup>, Ahmed Elmokashfi<sup>1</sup>

<sup>1</sup> Simula Research Laboratory, Lysaker, Norway

## ABSTRACT

Telecommunication networks tend to share infrastructure forming a complex temporal-spatial network of networks. This work investigates whether measurements from the end user perspective can help describing interdependencies between telecom networks. We use a correlation-based network formation method to investigate interdependencies between five mobile networks in Norway. This study builds on network performance measurements collected by hundreds of probes spread across Norway for a period of two years [1]. We generate multi-layer networks by correlating periods of degraded network performance across probes. These include periods where the probe has completely lost network connectivity and periods with patchy data transport, which we term downtime and loss respectively. Our results accurately match publicly available information about the interdependencies between the measured operators. Downtime correlation networks exhibit power-law degree distributions with a cut-off, while loss networks follow lognormal distributions. To better interpret these observations, we build a model that allows us to study the effects of failure events density and size as well as probe numbers and placement on the observed correlation networks. Our model shows that a power-law degree distribution can be obtained when failures are sparse and with a scale-free impact size. We also find that the number of probes and the geographical distance effects are not important for the observed power-law degrees. Moreover, a lognormal degree distribution is related to dense failures with weak spatial correlation. These findings provide insights into observability of interdependencies in communication networks in particular, and in multi-layer temporal-spatial systems in general such as climate systems and brain networks.

## DATASETS & METHODS

### NorNet Edge infrastructure

- Hundreds of measurement nodes in Norway
- Measuring 5 operators, mid-2013 to current
- Infrastructure sharing patterns

### Packet loss time series

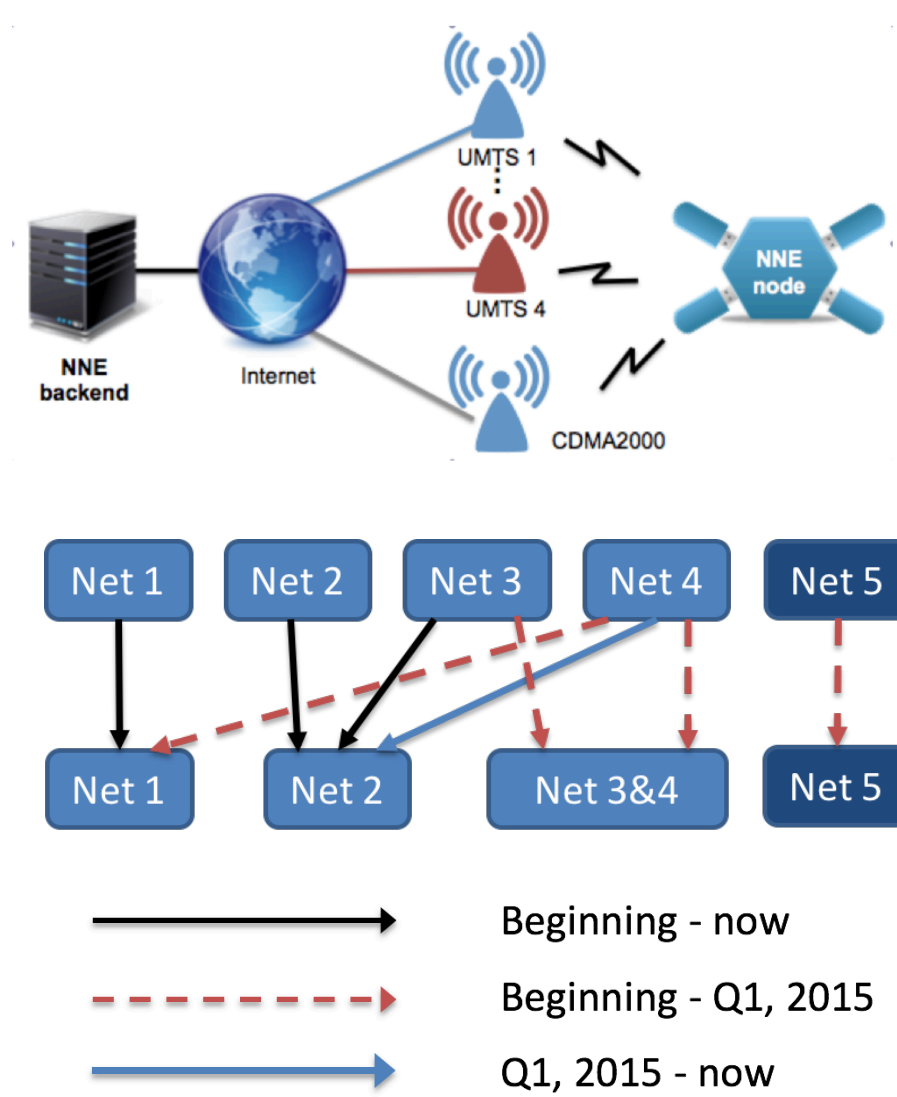
- Sending a 20-byte UDP packet per second
- Reply not received in 60s → **Packet lost!**
- Loss rates in 5-min bins through 3-month periods
- Considering only loss rates greater than 3%

### Downtime time series

- **Downtime events:** time periods without network connectivity
- 0-1 downtime time series in 5-min bins through 3-month periods
- Considering only events with lengths in [1min, 60min]

### Multi-layer correlation networks

- Pearson correlation coefficients:  $r_{i,j} = \frac{\sum_{t=1}^L (s_i(t) - \bar{s}_i)(s_j(t) - \bar{s}_j)}{\sqrt{\sum_{t=1}^L (s_i(t) - \bar{s}_i)^2} \cdot \sqrt{\sum_{t=1}^L (s_j(t) - \bar{s}_j)^2}}$
- $p$ -value of each correlation calculated
- Minimum shared time series length  $L_{\min}$
- Links: nodes  $i, j$  connected, if  $r_{i,j} \geq r_{\min}$ ,  $p_{i,j} < 0.05$ , and  $L_{i,j} \geq L_{\min}$
- Degree of node  $i$ ,  $k_i$



## OBSERVATIONS

### Inter- and intra-layer mean correlation

- Intra-layer (or diagonal) has higher correlation than inter-layer (or whole network)
- Reflecting infrastructure sharing variations
- Suggesting better choices for combining different operators

### Degree distribution

- Lognormal-like degrees in packet loss
- Power-law degrees with cut-off in downtime

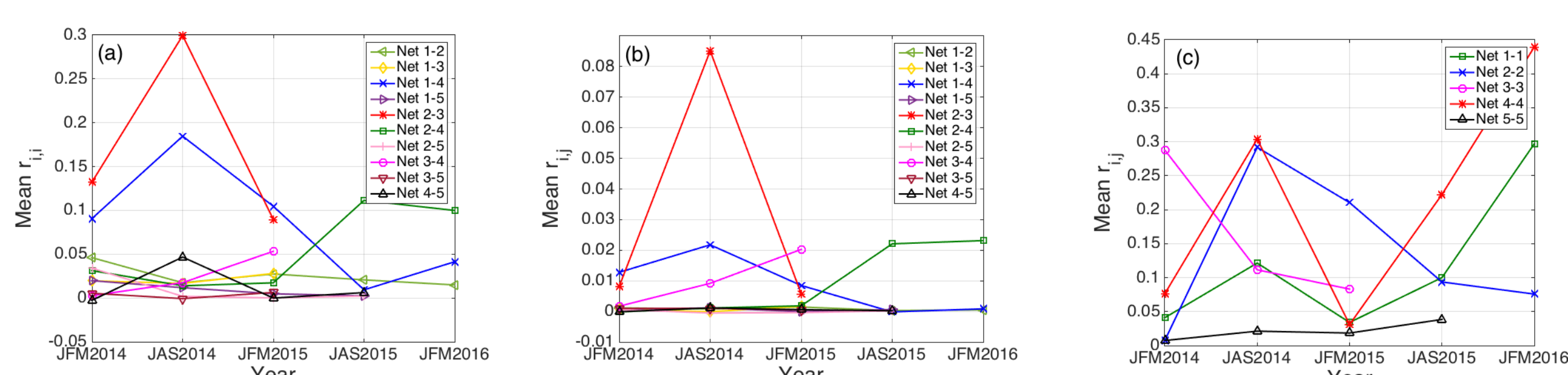


Fig. 1. (a) Average diagonal  $r_{i,i}$  of the common-node sub-matrix, inter-layer. (b) Average  $r_{i,j}$  over whole matrix, inter-layer. (c) Average  $r_{i,j}$  over whole matrix, intra-layer. Packet loss networks,  $L \geq L_{\min}$ , 5 stages.

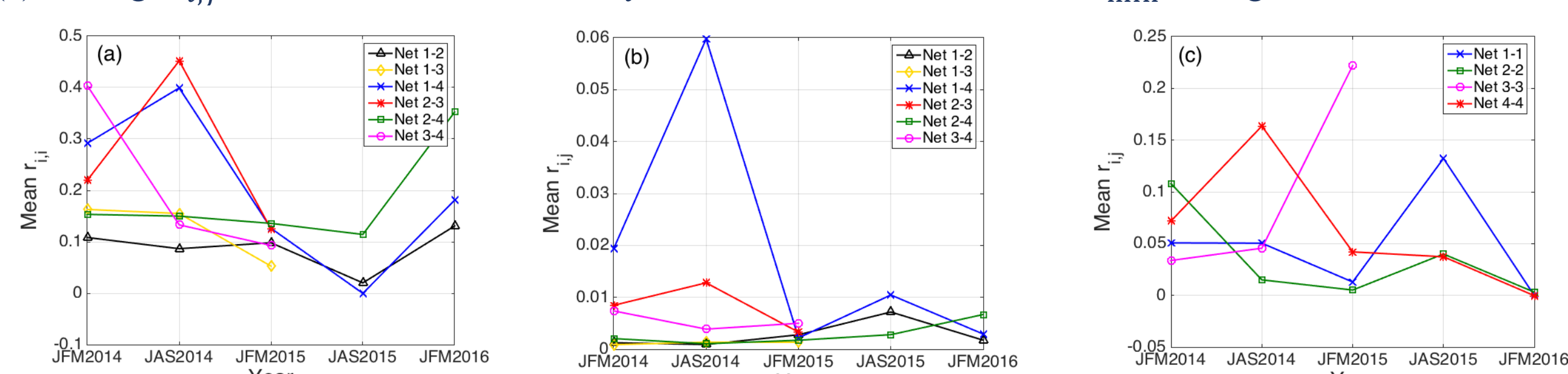


Fig. 2. (a) Average diagonal  $r_{i,i}$  of the common-node sub-matrix, inter-layer. (b) Average  $r_{i,j}$  over whole matrix, inter-layer. (c) Average  $r_{i,j}$  over whole matrix, intra-layer. Downtime networks,  $L \geq L_{\min}$ , 5 stages.

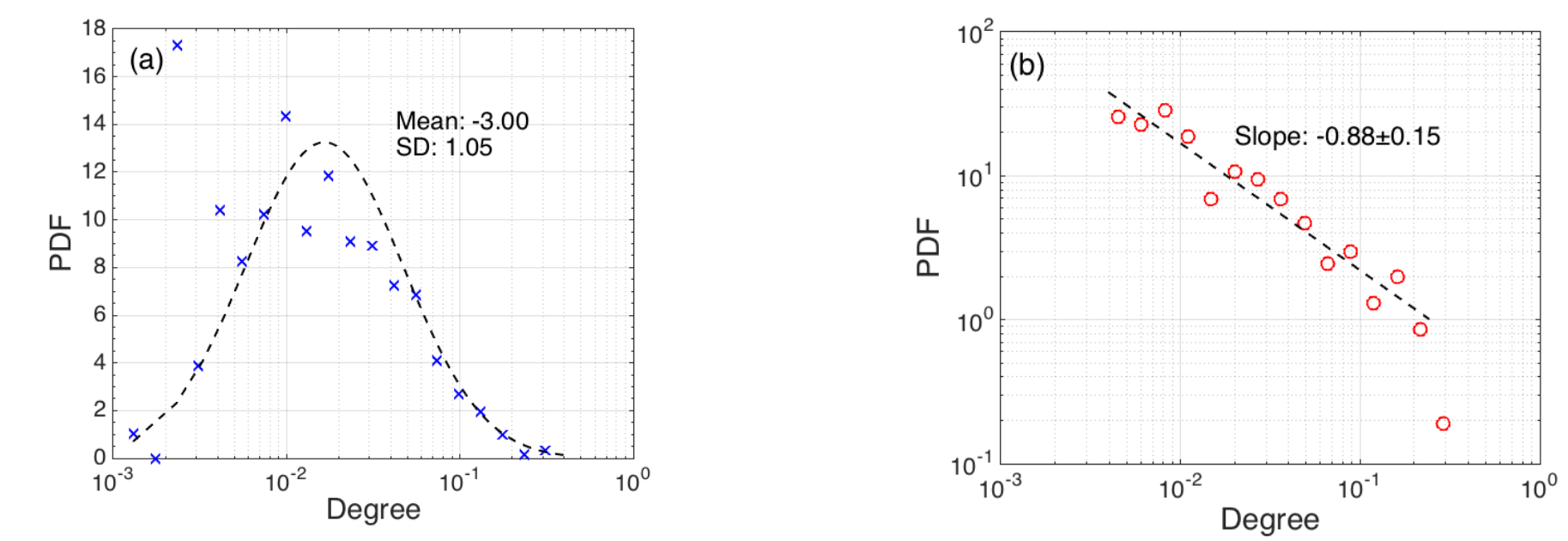


Fig. 3. PDF of normalized binary degrees. (a) Packet loss networks. (b) Downtime networks.  $r_{\min} = 0.05$ ,  $p_{i,j} \leq 0.05$ ,  $L_{i,j} \geq L_{\min}$ , 5 stages combined.

## MODEL RESULTS

### Assumptions

- Rectangular node space around Norway
- $N = 400$  nodes randomly located with 3 centers at Oslo, Bergen and Trondheim
- 0-1 failure time series of length  $L = 5000$  determined by event impact
- $M = \lfloor L/\mu \rfloor$  failure events randomly located from  $t = 1, \dots, L$ , each randomly affecting  $K_m$  node pairs
- Power-law event impact sizes:  $P\{K_m = n\} \propto n^{-\gamma}$ ,  $m = 1, \dots, M$
- Event impact probability:  $P_{i,j} \propto d_{i,j}^{-\alpha}$ ,  $i, j = 1, \dots, N$

### Model results

- Power-law degree behavior caused by sparser events and power-law event sizes
- Lognormal degree distribution caused by denser events and weaker distance effects
- Degree power-law exponent  $\beta$  increases, when  $1/\mu$  is smaller or  $\gamma$  is larger
- Peaks of mean degree VS  $1/\mu \rightarrow$

Two types of systems: “sparse enough” and “dense enough”

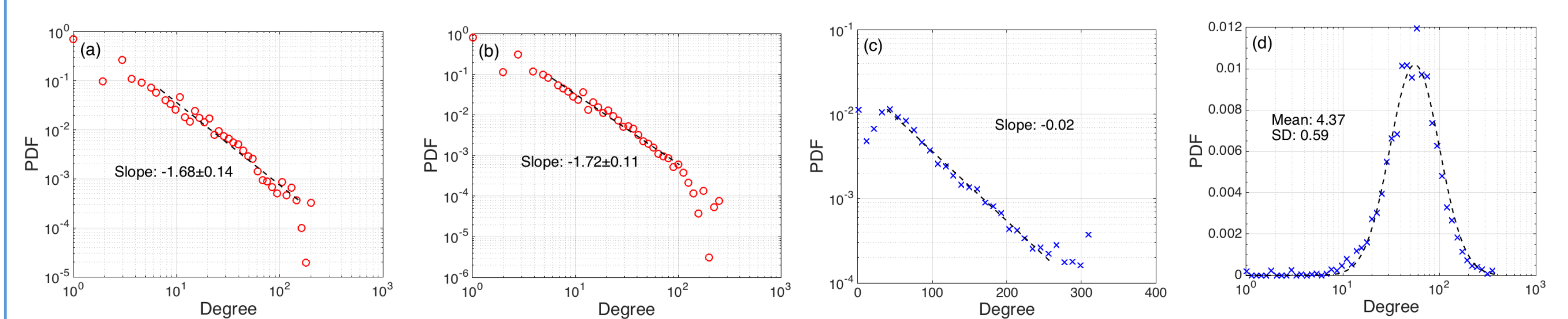


Fig. 4. PDF of degrees in the model.  $N = 400$ ,  $L = 5000$ ,  $r_{\min} = 0.05$ , combining 100 realizations. (a)  $1/\mu = 1/25$ ,  $\alpha = 1$ ,  $\gamma = 3$ . (b)  $1/\mu = 1/25$ ,  $\alpha = 0$ ,  $\gamma = 3$ . (c)  $1/\mu = 1/3$ ,  $\alpha = 1$ ,  $\gamma = 3$ . (d)  $1/\mu = 1/3$ ,  $\alpha = 0$ ,  $\gamma = 3$ .

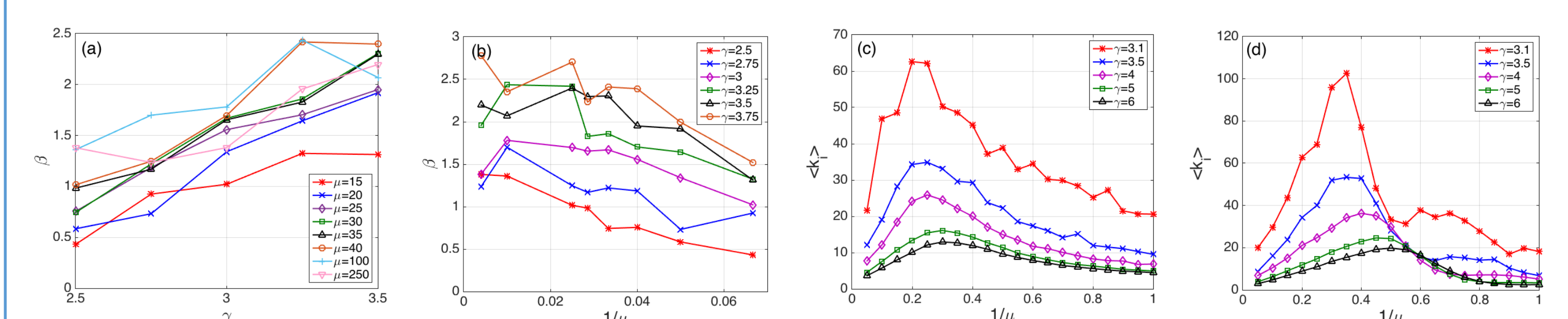


Fig. 5. (a) Power-law exponent  $\beta$  of the middle part degree distribution VS  $\gamma$  for different  $\mu$  values in the model.  $\alpha = 1$ ,  $N = 400$ ,  $L = 5000$ ,  $r_{\min} = 0.05$ . (b) Power-law exponent  $\beta$  of the middle part degree distribution VS  $1/\mu$  for different  $\gamma$  values in the model. (c) Mean degree  $\langle k_i \rangle$  VS  $1/\mu$ .  $\alpha = 1$ ,  $N = 400$ ,  $L = 5000$ ,  $r_{\min} = 0.05$ , averaged over 30 realizations. (d) The same with (c) but with  $\alpha = 0$ .

## SUMMARY & FUTURE WORKS

### Major conclusions

- Correlation network methods can be applied on loss/downtime time series in communication networks to measure the dominance of shared failure events
- Sparse events and heterogeneous event impact sizes cause power-law degree distribution in downtime networks
- Dense events and weak distance effects cause lognormal like degree distribution in loss networks
- Boundaries can be found between “sparse enough” and “dense enough” systems via the mean degree peaks

### Future works

- Establishing theories for the mean degree/weight and investigating the effects of parameters
- Exploring the system classification via more general event impact schemes
- Applying the model results to measure the resilience of more different real systems

## ACKNOWLEDGMENT

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[1] A. Kvalbein, D. Baltrūnas, J. Xiang, K. R. Evensen, A. Elmokash, and S. Ferlin-Oliveira. The NorNet Edge platform for mobile broadband measurements. Elsevier Computer Networks special issue on Future Internet Testbeds, 2014.

Contact: dong@simula.no