Finding Self-similarity in Opportunistic People Networks

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Motivation

- Investigate fundamental properties of opportunistic networks
- Better understand network connectivity
- Solve the long been ignored censorship issue

Contribution

- Point out and recover censorship within mobility traces of opportunistic networks
  - Propose **Censorship Removal Algorithm**
  - Recover censored measurements
- Prove the inter-contact time process as self-similar for future research on opportunistic networks

Outline

- Trace Description
- Censorship Issue
  - Survival Analysis
  - Censorship Removal Algorithm
- Self-similarity

Trace Description

- *UCSD campus trace**
  - 77 days, 275 nodes involved
  - Client-based trace
    - PDAs record Wi-Fi based APs nearby
- *Dartmouth College trace***
  - 1,777 days, 5148 nodes involved
  - Interface-based trace
    - APs maintain the association log for each wireless interface
  - 77 days extracted for comparison

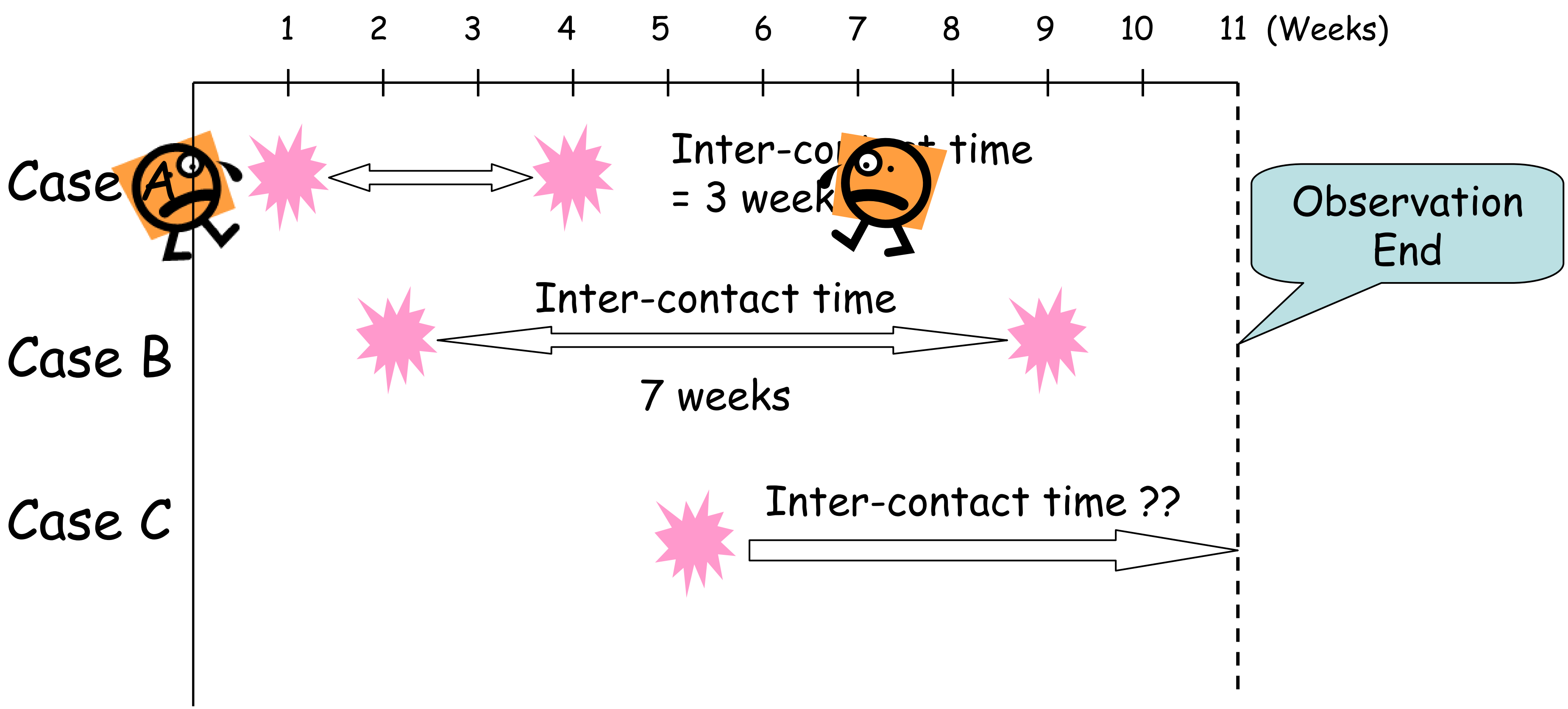
*UCSD: *Wireless Topology Discovery (WTD Project)*

**Dartmouth: *RAWDAD*

Basic Terms

- What is Contact ?
  - Two nodes are of their wireless radio range
  - Associated to the same AP at the same time
- What is Inter-contact Time ?
  - Period between two consecutive contacts
- Used to observe Network Connectivity
  - Distribution of inter-contact time
    - Disconnection duration
    - Reconnection frequency

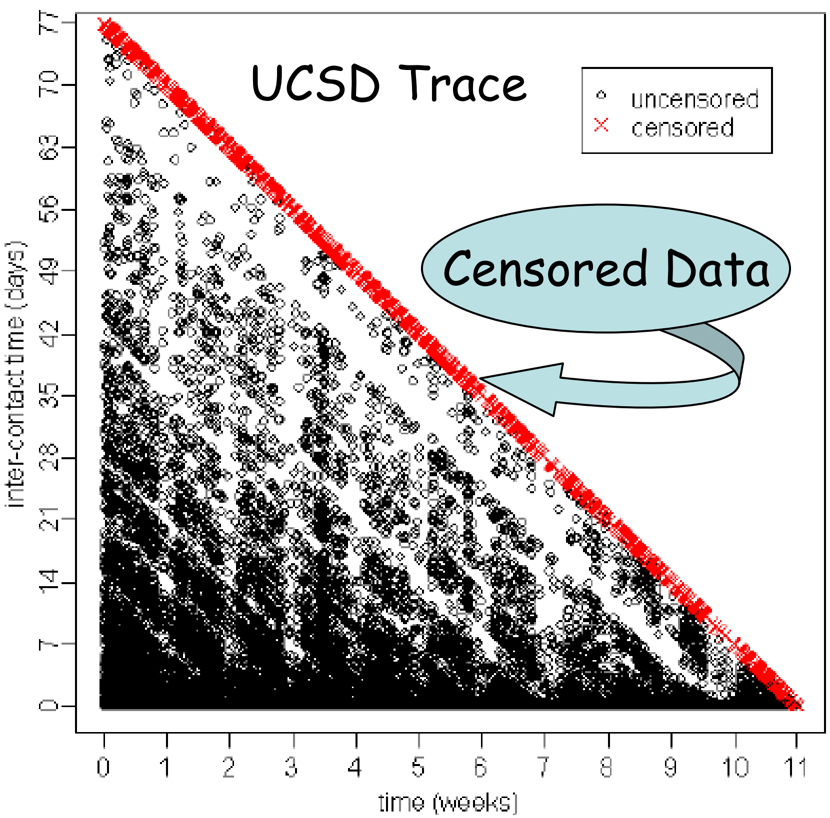
Basic Terms (Con't)

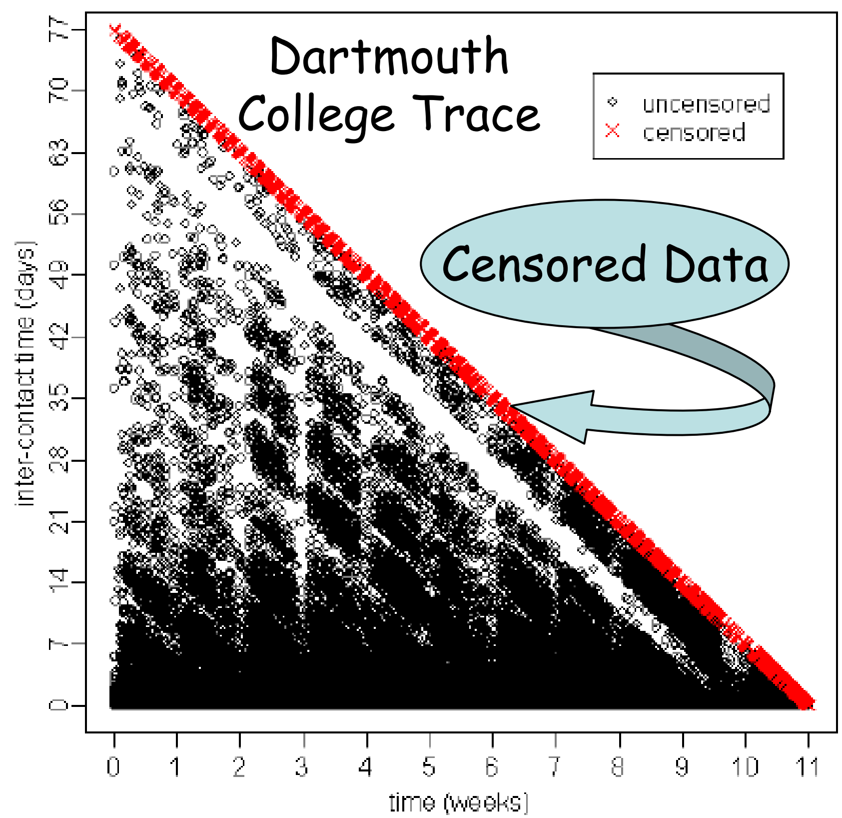


- In the last case, the inter-contact time has been censored as 6 weeks.

Censorship

- Inter-contact time samples end after the termination of the observation.
- Censored measurements are inevitable.





Survival Analysis

- Important in biostatistics, medicine, …
  - Estimate patients' time to live/death
  - Map to censored inter-contact time samples

- Censored samples should have the same likelihood distribution as the uncensored's.
  - ***Kaplan-Meier*** Estimator
    (a.k.a. *Survival Function* or *Product Limit Estimator*)

Kaplan-Meier Estimator

- Suppose there are N samples ($t_1 < t_2 < t_3 \ldots < t_N$)
- At time t_i :
  - d_i uncensored samples (complete samples)
  - n_i events (censored/uncensored)
- The survival function is:

$$\widehat{S}(t) = \prod_{t_i \le t} \Pr\left[t > t_i \,|t \ge t_i\right]$$
$$= \begin{cases} 1 \;;\; t_1 > t \\ \prod_{t_i \le t \le t_N} \left[\dfrac{n_i - d_i}{n_i}\right] \;;\; t_1 \le t \end{cases}$$

Kaplan-Meier Estimator – An Example

- 10 inter-contact time samples:
  1, 2+, 3+, 3.5+, 4, 5+,9, 9.5+, 10, 11+
  (in weeks, + for censorship)

i-c time interval	n_i	d_i (death)	c_i (censored)	Survival function S(t)
0	10	0	0	S(0)=1
(0,1]	10	1	0	S(1)= 1* 9/10=0.9
(1,4]	6	1	3	S(4)=0.9*5/6=0.75
(4,9]	4	1	1	S(9)=0.75*3/4=0.56
(9,10]	2	1	1	S(10)=0.56 *1/2=0.28
(10,11]	1	0	1	S(11)=0.28*1/1= 0.28

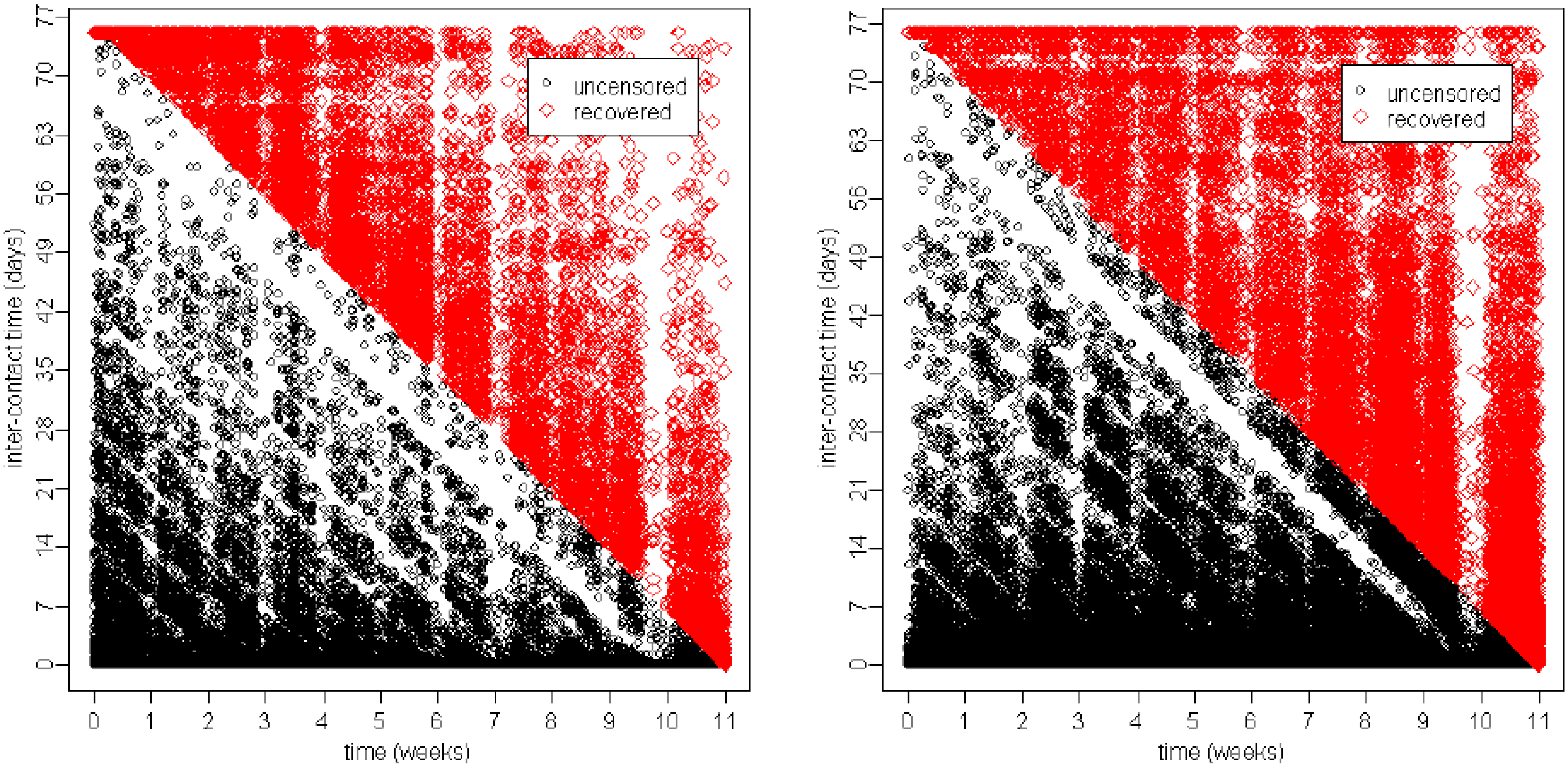
Censorship Removal Algorithm

- Based on the survival function S(t)
  - $t_1 < t_2 < t_3 \ldots < t_N$ (N : total sample number)
  - Death Ratio during $t_i \sim t_{i+1}$: $D(t_i) = \frac{S(t_{i-1}) - S(t_i)}{S(ti)}$
  - Ci: # of censored samples at t_i
  - Iteratively select Ci*D(t_i) samples from Ci
    - Uniformly distribute their estimated inter-contact time by S(t_i)
    - Mark them as uncensored samples
  - Terminate when all the censored samples are removed

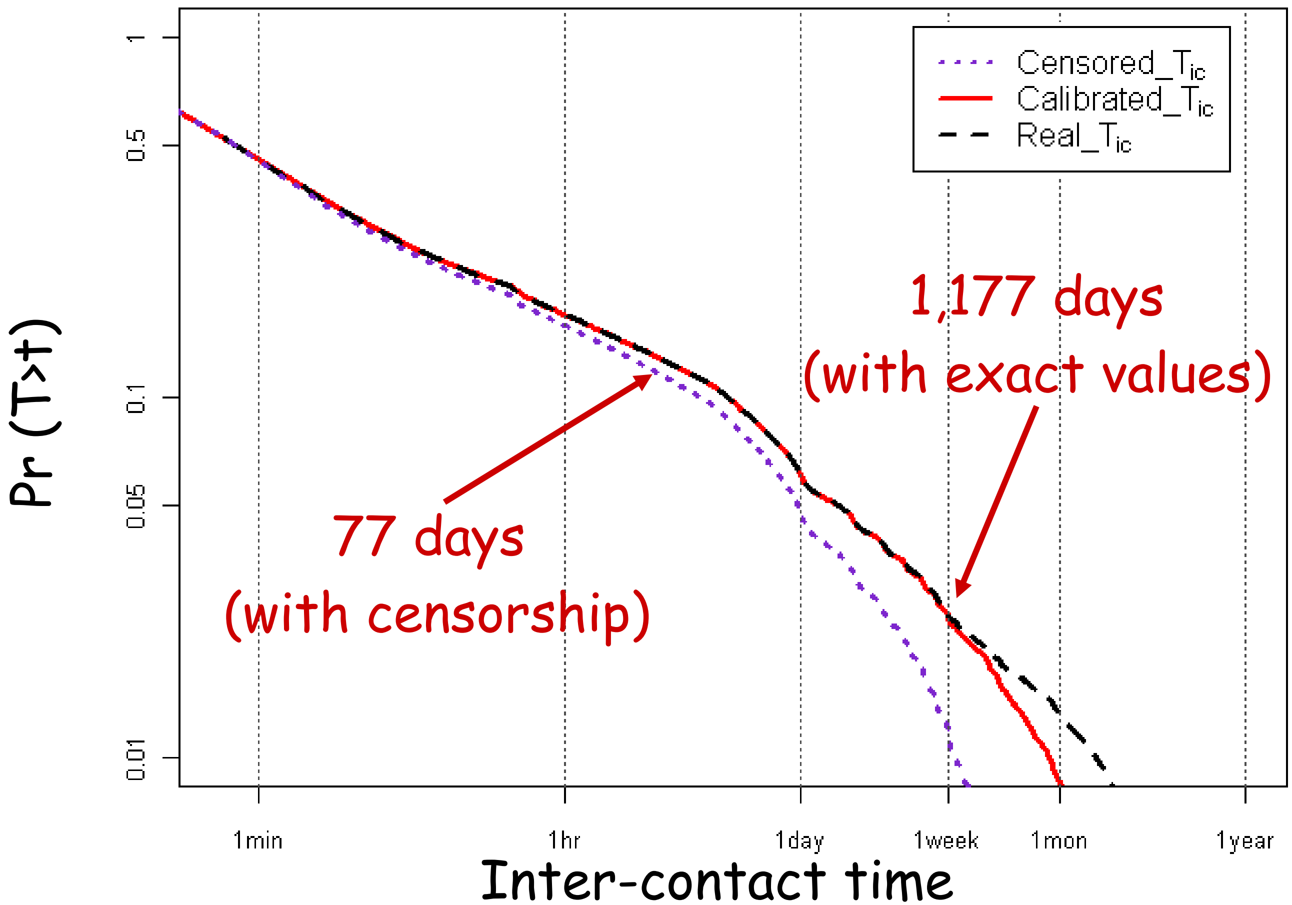
Censorship Removal Algorithm (Con't)

- Recovered inter-contact time measurements

UCSD Trace **Dartmouth Trace**



Censorship Removal Algorithm (Con't)



- Compare the recovered values to their exact values in original trace.
- 80.4% censored measurements are recovered.

Outline

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Self-Similarity

- What is self-similarity?
  - By definition, a self-similar object is exactly or approximately similar to part of itself.
- In opportunistic network, we focus on the network connectivity
- With recovered measurements, we prove inter-contact time series as a self-similar process
  - Reconnection/disconnection
  - Similar mobility pattern in people opp. networks

Self-Similarity

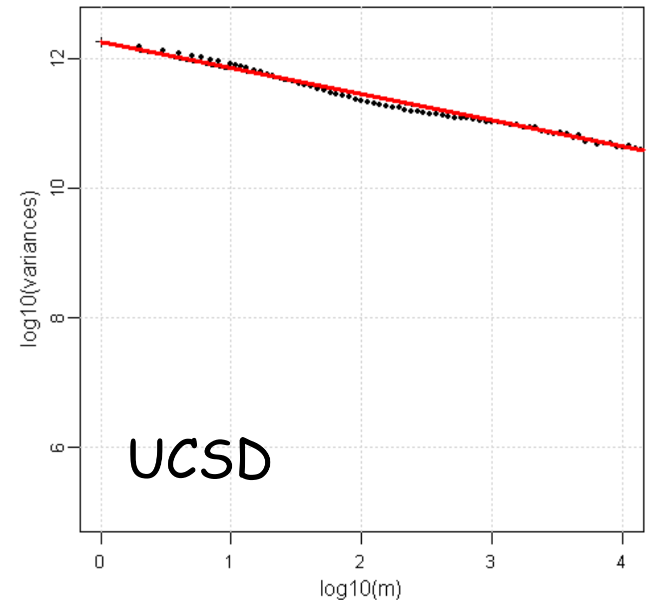
- A self-similar series
  - Distribution should be heavy-tailed
  - Examined by three statistical analyses
    - Variance-Time Plot, R/S Plot, Periodogram Plot
    - Estimated by a specific parameter : *Hurst*
    - *H* should be in the range of 0.5~1
  - Results of three methods should be in the 95% confidence interval of Whittle estimator

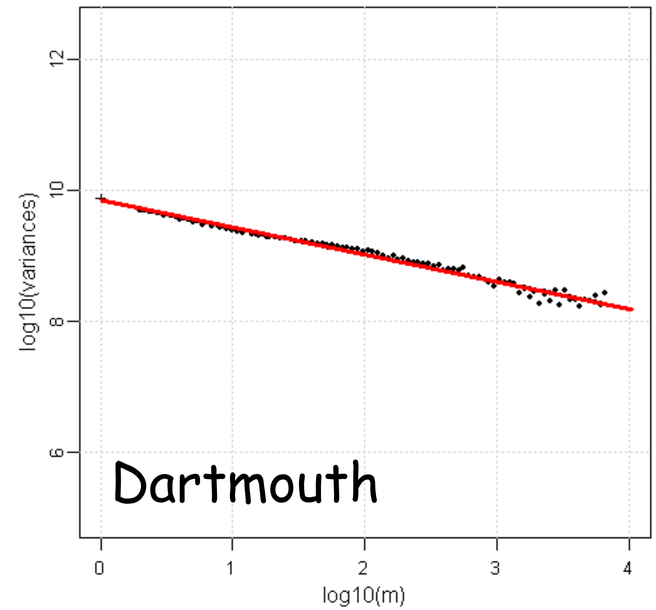
Self-Similarity (Con't)

- Previous works show inter-contact time dist. as power-law dist.
- A random variable X is called heavy-tailed:
  - If $P[X>x] \sim cx^{-\alpha}$, with $0<\alpha<2$ as $x \to \infty$
  - α can be found by log-log plot
  - Survival curves show the α for
    - UCSD: 0.26
    - Dartmouth: 0.47

Self-Similarity (Con't)

- ***Variance-Time Method***
  - Variance decreases very slowly, even when the size grows large
- The Hurst estimates are
  - UCSD: 0.801
  - Dartmouth: 0.7973

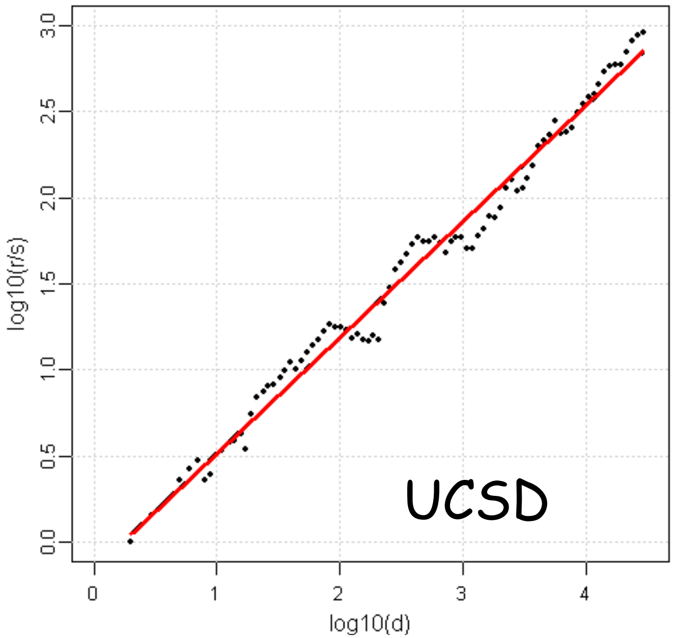


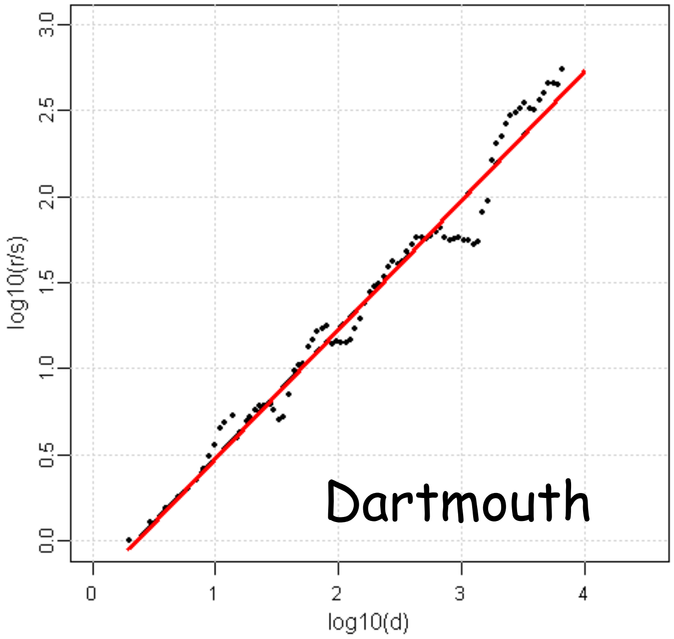


Self-Similarity (Con't)

- ***Rescaled Adjusted Range (R/S) method***
  - Keep similar properties when the dataset is divided into several sub-sets

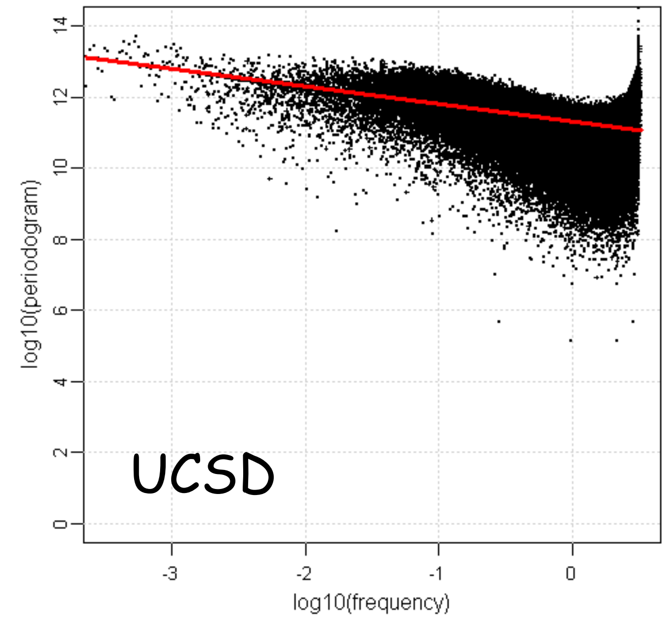
- The Hurst estimates are
  - UCSD:0.7472
  - Dartmouth:0.7493



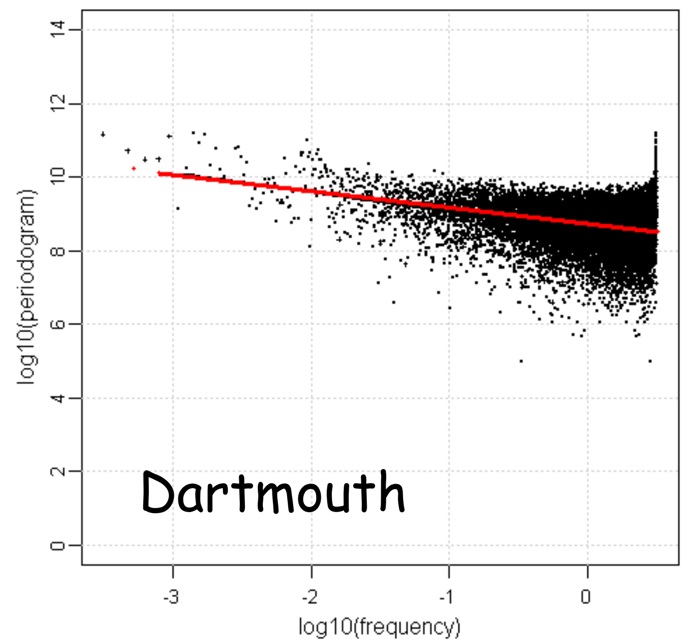


Self-Similarity (Con't)

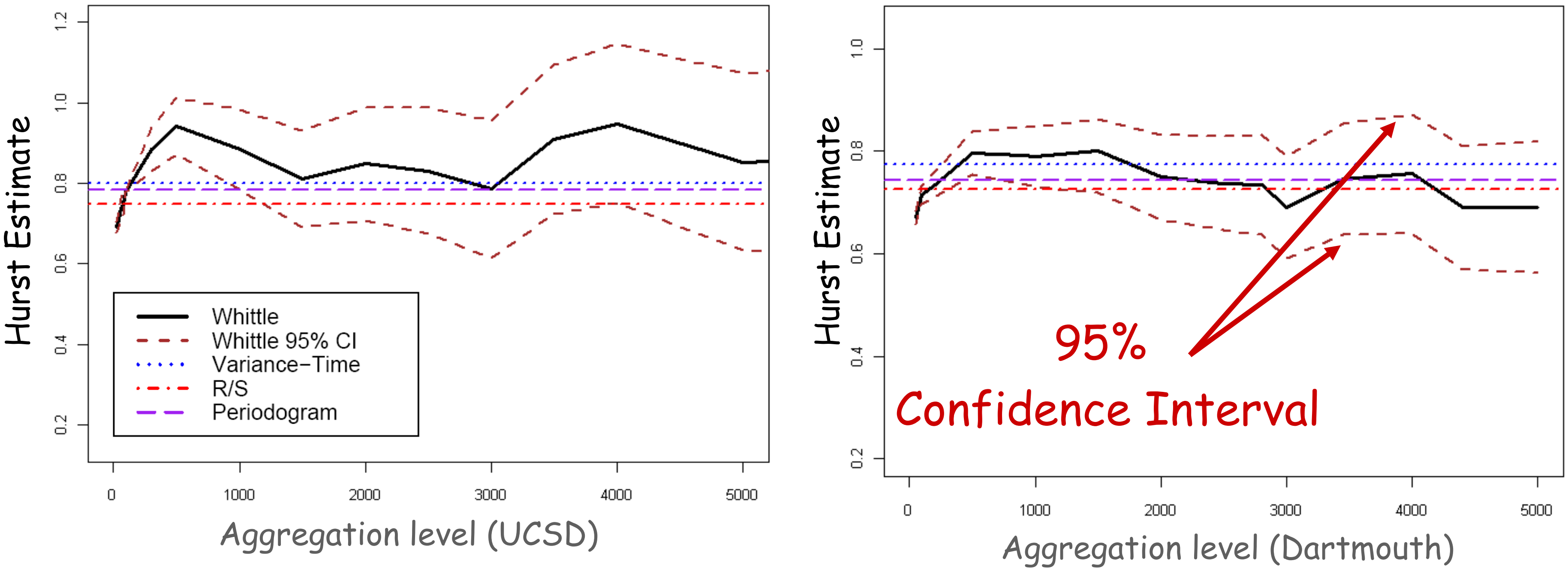
- ***Periodogram Method***
  - Use the slope of power spectrum of the series as frequency approaches zero



- The Hurst estimates are
  - UCSD: 0.7924
  - Dartmouth: 0.7655



Self-Similarity (Con't)



- ***Whittle Estimator***
  - Usually being considered as a more robust method
  - Provide a confidence interval
- Results of the three graphical methods are in the 95% confidence interval.

Conclusion

- Two major properties exists in modern opportunistic networks:
  - Censorship
  - Self-similarity
- Using CRA, we could recover censored inter-contact time to have more accurate datasets.
- With recovered datasets, we prove that inter-contact time series is self-similar.

Thank You !