Study of a Bus-Based Disruption Tolerant Network: Mobility Modeling and Impact on Routing

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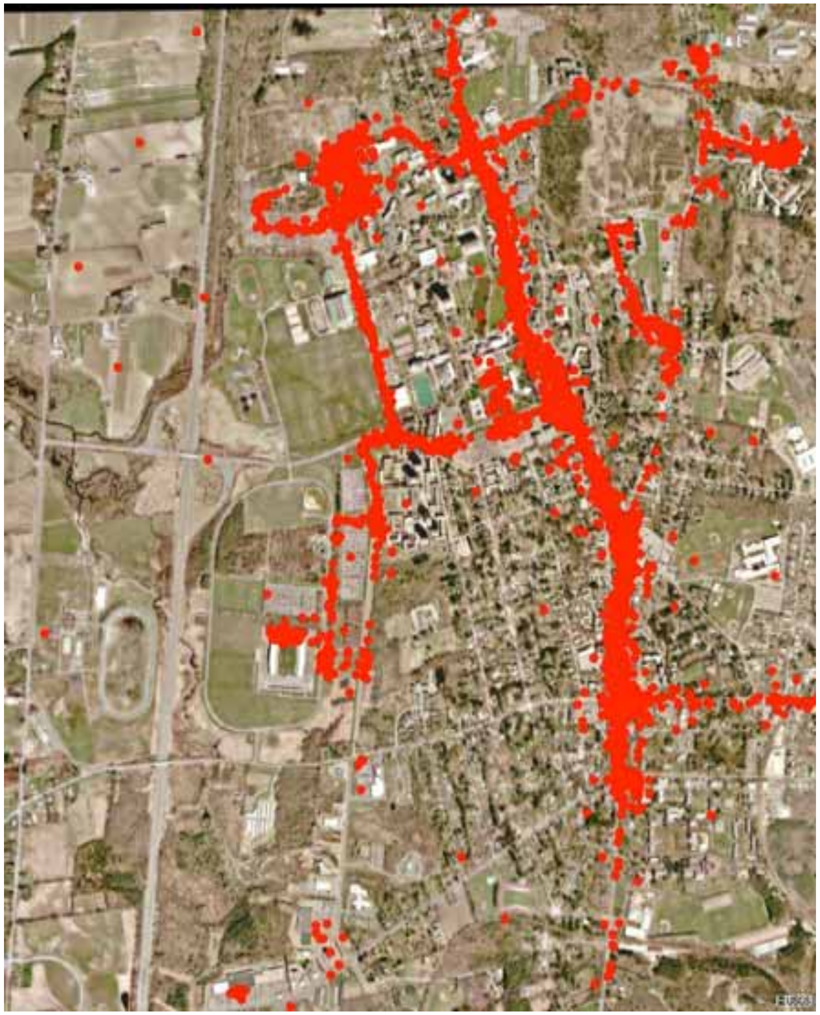
UMass DieselNet

- 10 routes span 150 square miles
- 40 buses installed with brick computer; GPS receiver; 802.11b AP and adapter
- Bus-to-bus transfer when within range
- Network formed by buses is disconnected
  - often no contemporaneous end-to-end path between a pair of buses at a given time
  - Disruption Tolerant Network



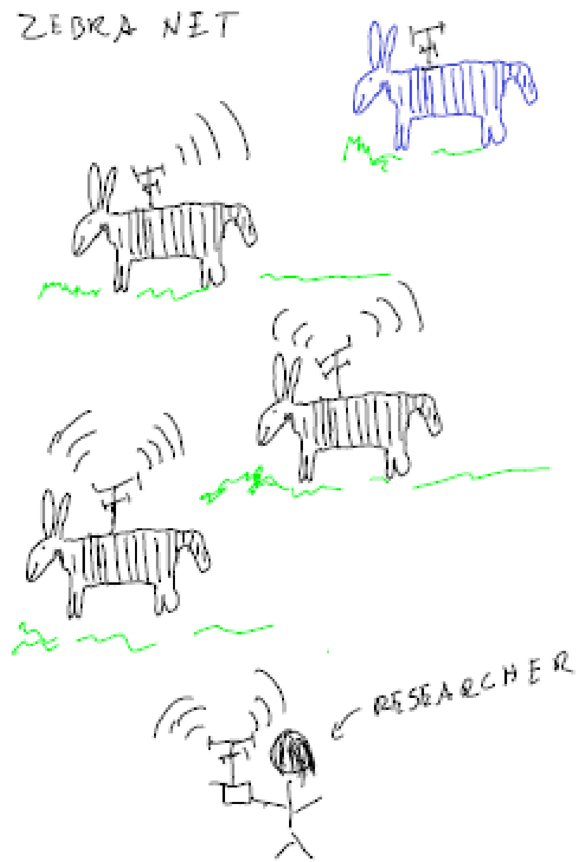
Bus-to-bus transfers during 3/23-4/24, 2005

Other DTN Scenarios

- Networks for remote areas
- Scientific applications
- Military networks, disaster recovery networks, etc.
- Pocket-switched network

Figure 5. The Internet Motoman project in Cambodia. (a) The main hospital, with its VSAT connection to the Internet, acts as the hub. (b) ...iods, MAP-enabled Honda motorcycles are used to connect schools to the hub. (c) For locations ... even a MAP-equipped ox cart.

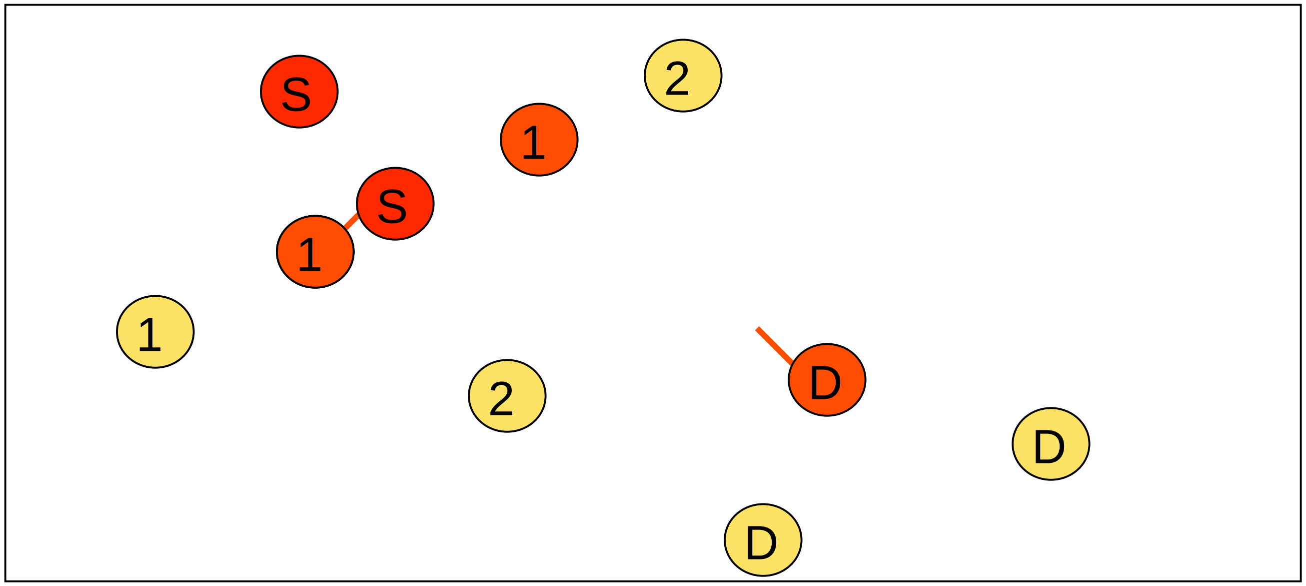
DakNet
(posta



Our focus: DTNs where disruptions are caused by random node mobility and sparse density

Store-Carry-Forward Routing

- Routing despite disconnection, also called mobility-assisted routing
- Epidemic routing [Vahdat and Becker,00]
  - packet propagation => disease spreading
  - recovery process on delivery to dest



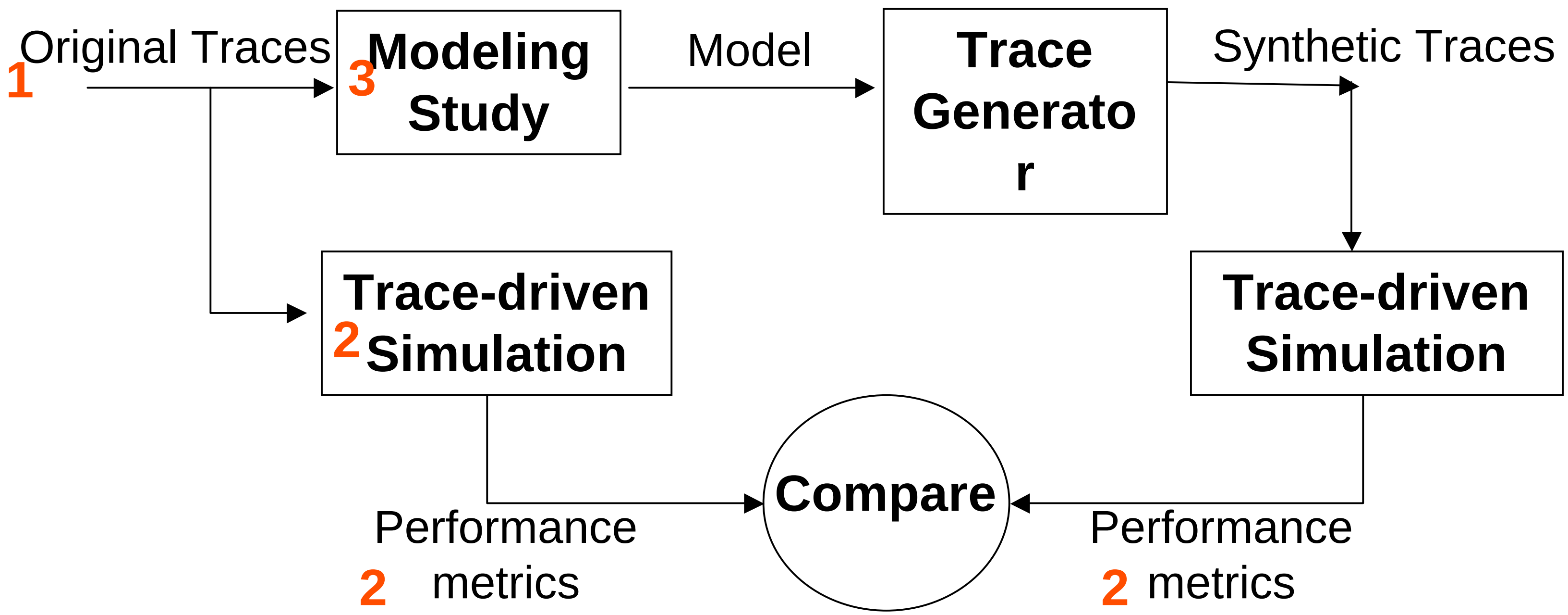
Node status:
infected,
susceptible,
recovered

Understanding DTN Mobility

- Mobility: important determinant of DTN routing performance
- Many works assume synthetic mobility models
- Real DTN mobility and implications to routing
  - trace collection: Haggle project, DieselNet, etc.
  - trace-driven simulation studies
  - trace characterization and modeling
    - power-law of aggregate inter-contact times [Chaintreau et al., 06, Chen et al.,06]
    - power law and exponential decay of aggregate inter-contact times [Karagiannis et al., 07]
    - pair-wise inter-contact times [Conan et al., 07]

Goal: a generative mobility model

- Our goal: a generative model based on real mobility traces that accurately predicts DTN routing performance

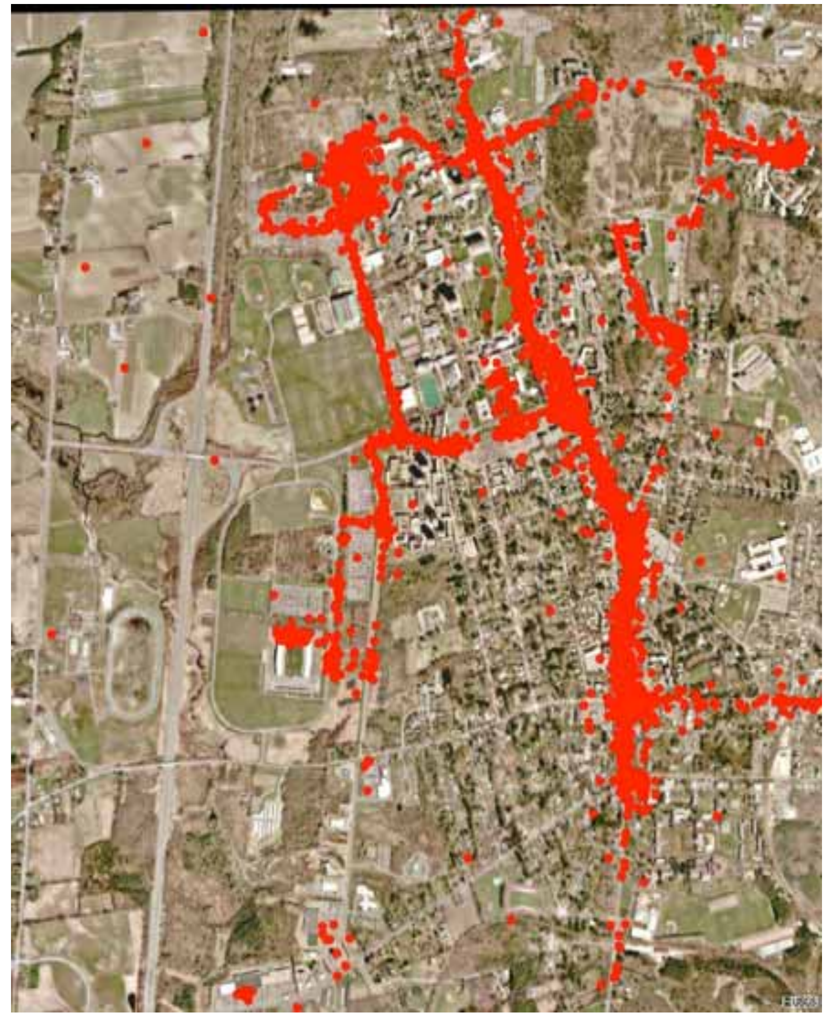


Outline

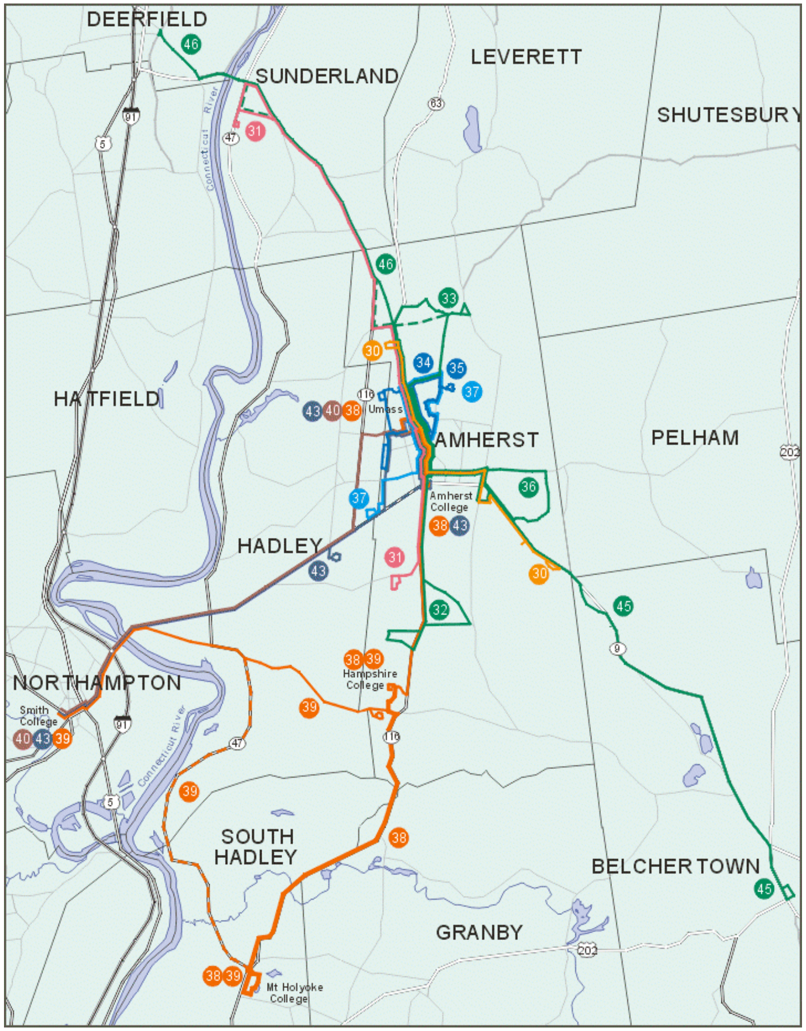
- Background and motivation
- Traces description, metrics of interest
- Modeling of inter-contact times
- Model comparison
- Summary and future directions

UMass DieselNet trace

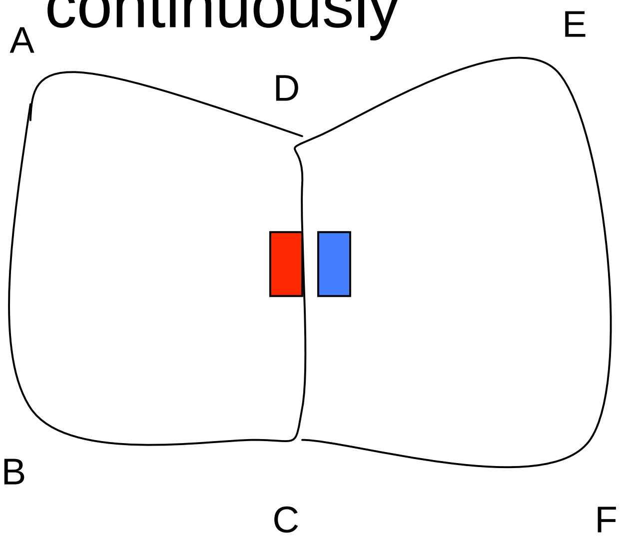
- 10 routes span 150 square miles
- 40 instrumented buses
  - – Linux computer; GPS receiver; 802.11b AP and adapter
- Bus-to-bus contact
  - – when within range: 802.11 affiliation, TCP connection, transfer max. amount of data
  - – <time, duration, amount of data transferred, GPS location>



UMass DieselNet: bus routes/schedules

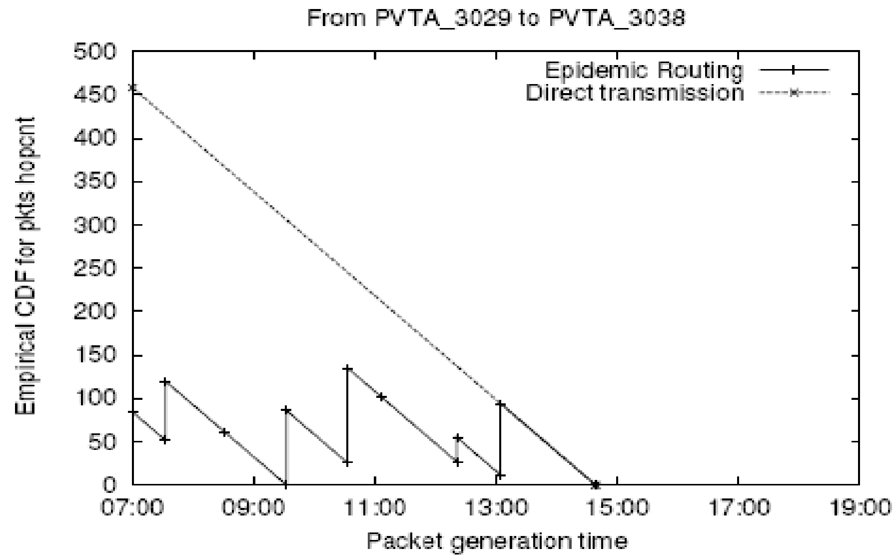


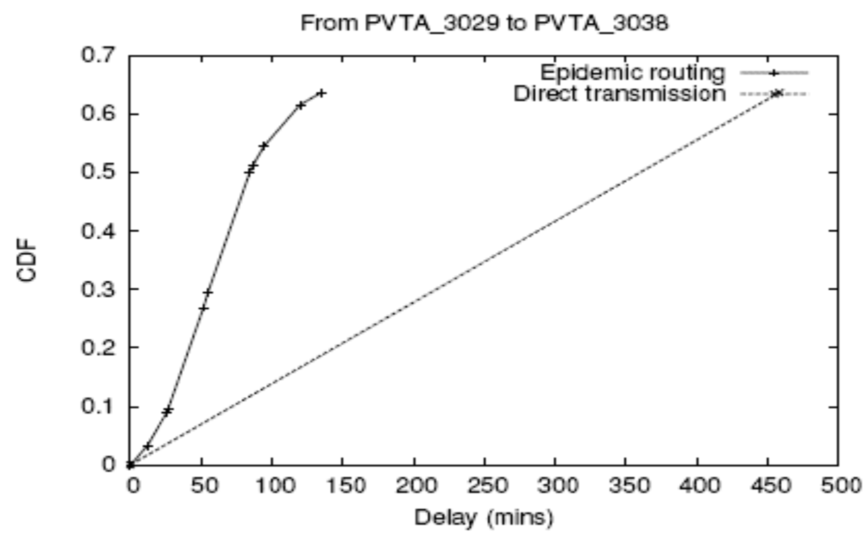
- 3 most popular routes
  - linear/butterfly route
  - during 7am to 7pm for non holiday weekdays
  - multiple shifts: each shift starts at different bus stops at different time, runs on route continuously



Performance Metrics of Interests

- *Performance metrics*:
  – best case delay, copies made hop count of epidemic path
- Trace-driven simulation
  – evaluate above metrics for pkt generated at any time [7am,7pm] between any (src,dest) pair
- *Aggregate distribution* of performance metrics, assuming:
  – src pkts arrive uniformly randomly to each unicast pair, at time uniformly randomly between [7 am, 7 pm]





(b) CDF for the delay

Outline

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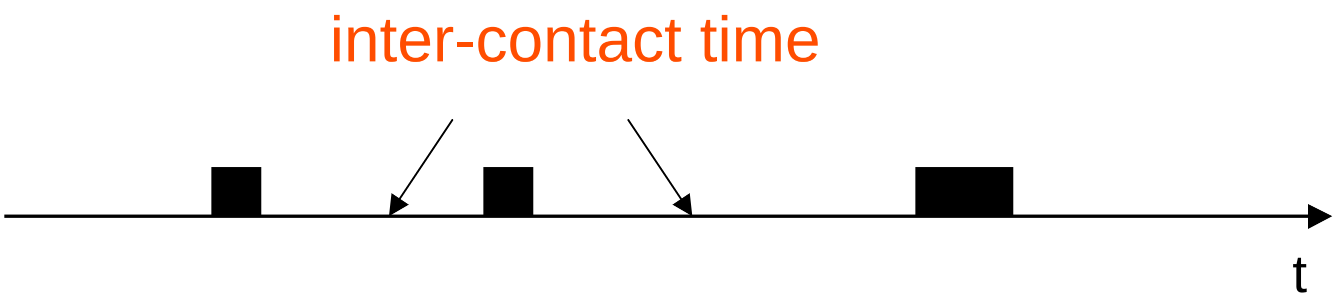
How to model the trace ?

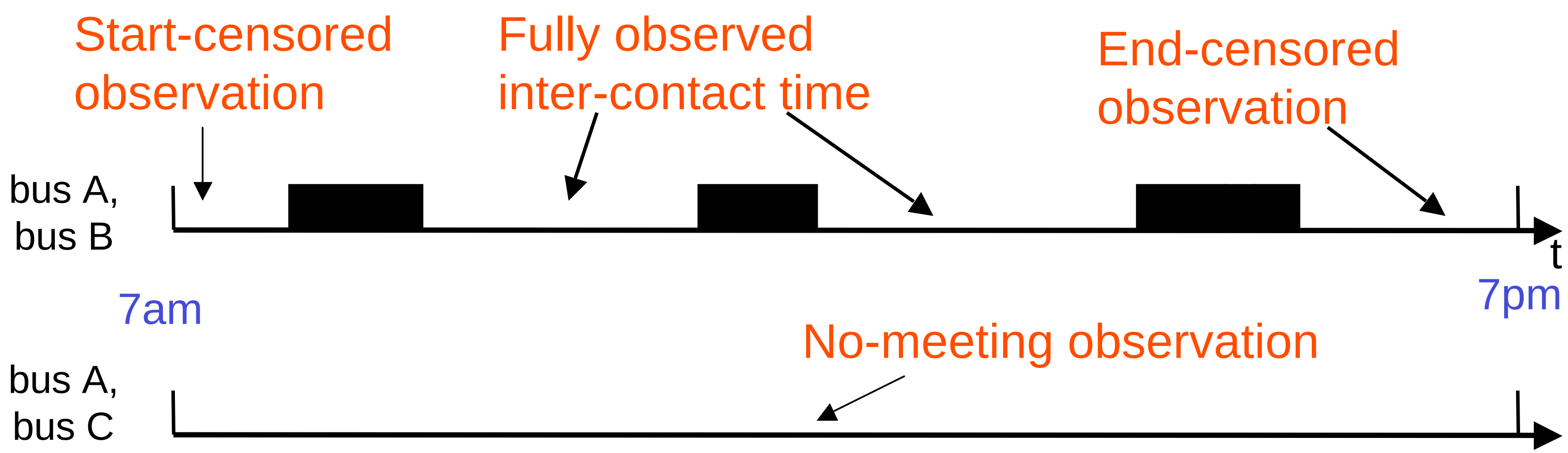
- Focus on inter-contact time: duration of time between two subsequent contacts for a bus pair



- Choose a modeling granularity
  – shift-level: buses running on given shift-pair
  – route-level: buses running on given route-pair
  – aggregate: all-bus-pair

Goal: A simple model with good prediction accuracy

Preliminary: artifacts of finite length measurements

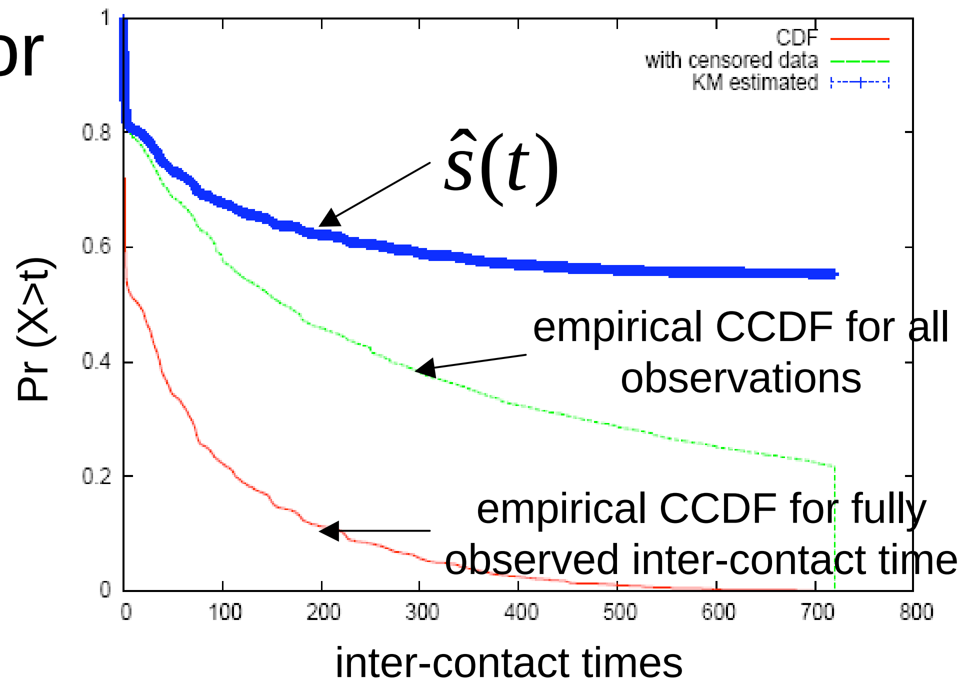


- Different observations:
  - fully observed, start-censored, end-censored, “no-meeting”

Preliminary: considering censored observations

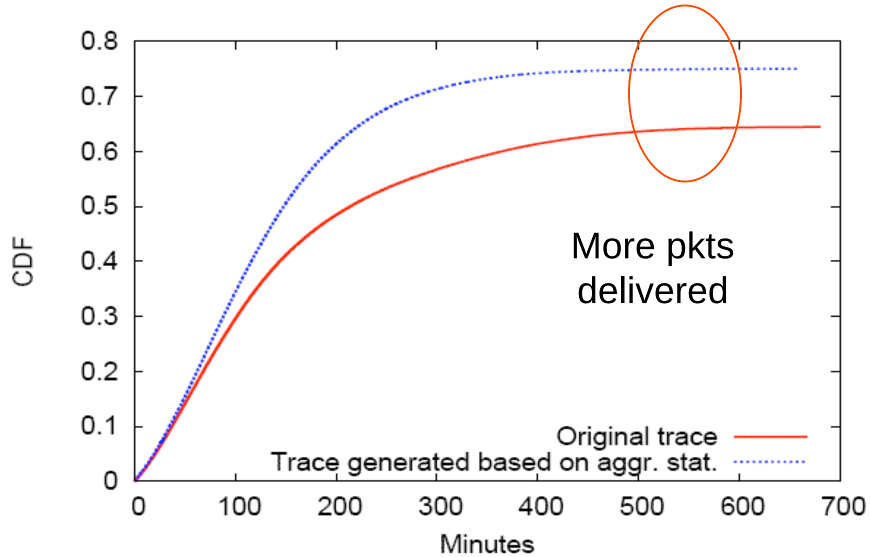
- Ignoring censored samples => under-estimation
  - long inter-contact time likely to be censored
  - empirical aggregate CDF gives larger weights to pairs with small avg. inter-contact time
- Kaplan-Meier estimator

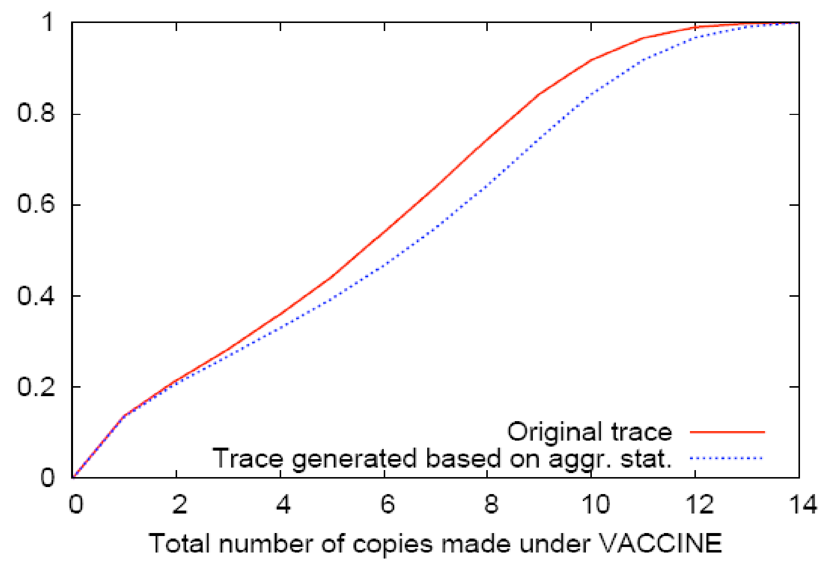
  $\hat{s}(t)$ for S(t):=Pr(X>t)
  - using all observations
  - Nonparametric maximum likelihood estimate



Evaluating Aggregate Model

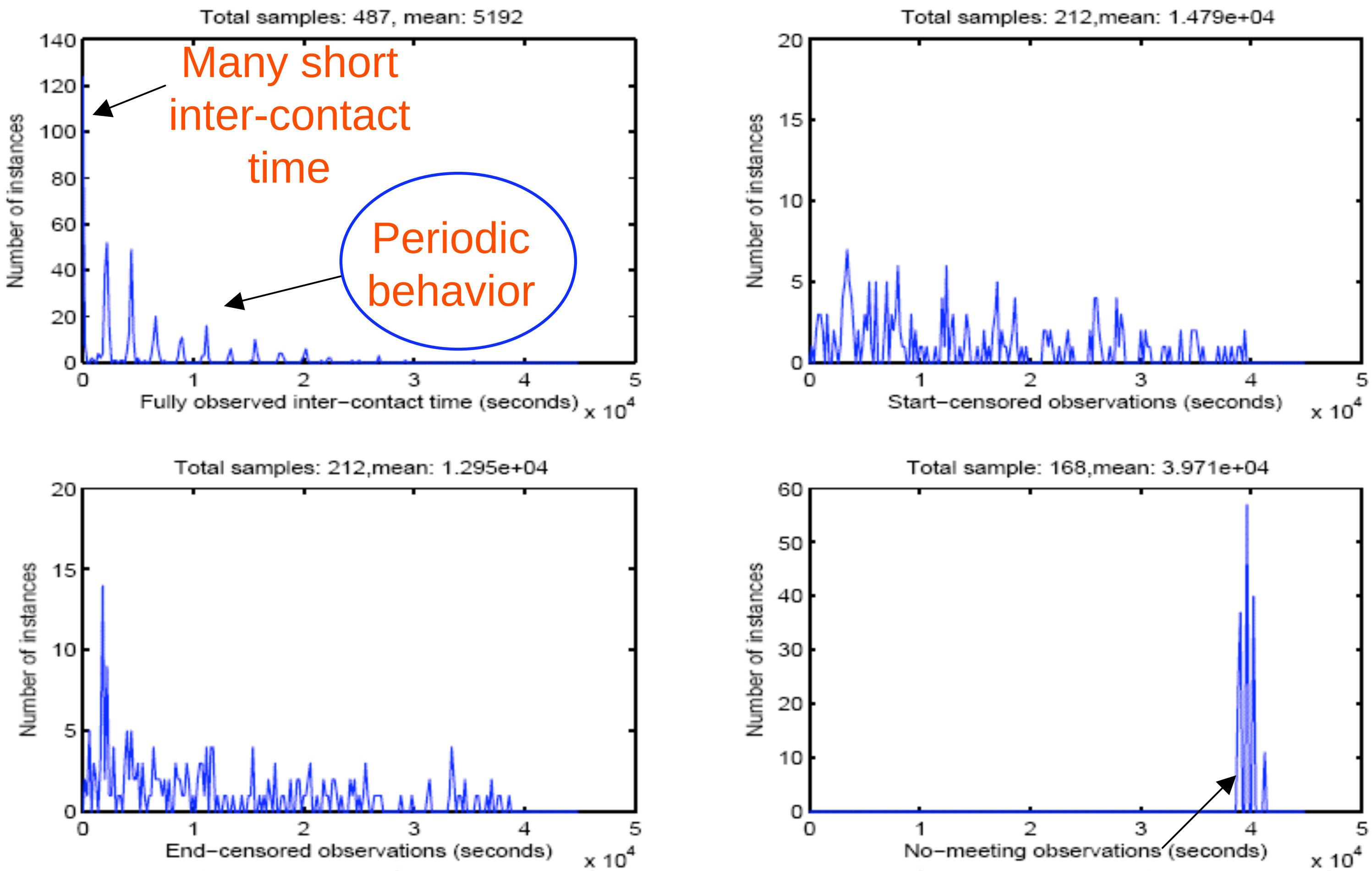
- Trace generated based on aggregate statistics
  - similar total no. of contacts, matching statistics
  - delivers more packets
  - fewer copies made, similar path hop count
  - insight: contacts equally distributed to all pairs





Need finer-grained model !
Route-level: aggregate inter-contact times for buses running on route-pair

Route-level inter-contact time



Same no. of start, end-censored inter-contact time

Many instances of no-meeting

Understand/Model the structure

- Two buses on same linear routes meet every half round trip time
- When within range, two buses may fail to set up connection => inter-contact time made up of several physical inter-meeting times
- A mixture normal model

$$f_{GEO\_1BM}(x) = \sum_{i=1}^{\infty} p^{i-1}(1-p)\, f_N(x \mid i\mu, \sigma^2)$$

p: prob. that two buses fail to set up connection in a meeting

μ : physical inter-meeting time

σ^2 : variance to account for random factors: traffic/road conditions..

Model Parameter Estimation

$$f_{GEO\_1BM}(x) = \sum_{i=1}^{\infty} p^{i-1}(1-p) f_N(x \mid i\mu, \sigma^2)$$

- *Expectation-Maximization Algorithm*: find maximum likelihood estimates for p,μσ from empirical data
  – hidden variables: # of physical meetings within inter-contact time, i.e., which component observation is drawn from
  – account for censored observations
- Estimated model generates similar fully-observed inter-contact time, censored observations as the original trace

Route-level Model

- **Linear routes**: some shift pairs have higher failure probability:

$$f_{GEO\_MP\_1BM}(x) = \sum_{i=1}^{2} w_i \sum_{l=1}^{\infty} p_i^{\,l-1}(1-p_i) f_N(x \mid i\mu, \sigma^2)$$

- **Butterfly shape route** (campus shuttle):
  - shifts pair on same direction: very rarely meet
  - shifts pair on opposite direction: meet either every half round trip time or every round trip time

$$f_{GEO\_2BM}(x) = \sum_{i=1}^{2} w_i \sum_{l=1}^{\infty} p_i^{\,l-1}(1-p_i) f_N(x \mid li\mu, \sigma^2)$$

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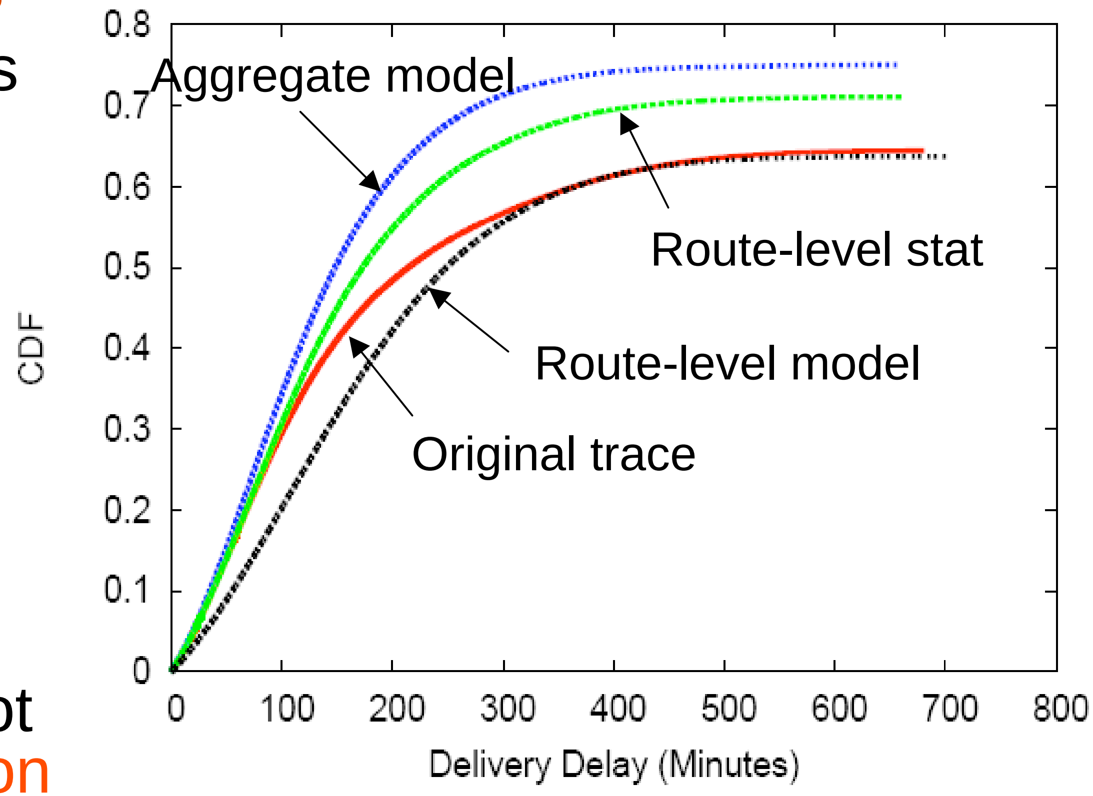
Model Comparison

- Compare different models in terms of performance prediction
  - aggregate model: sample from aggregate statistics, considering censorship
  - route-level statistics: sample from the route-level statistics, considering censorship
  - route-level model: derived based on route-level statistics, with additional consideration for Campus shuttle

Model Comparison: delivery delay

- ❑ Route-level statistics
  - – predicts delay, copies more accurately than aggregate model
- ❑ Route-level model
  - – better prediction: incorporate shift info
  - – matches tail
  - – predicts larger avg. delivery delay: small inter-contact times not considered; correlation between different bus pairs



Conclusion

- Generative model based on real mobility trace
  - importance of considering censorhip
  - aggregate model cannot capture aggregate performance statistics
  - finer-grained model predicts performance more accurately, and reveals structures within mobility
- Potentially applicable to other transport-based networks

Future Directions

- Understand and model short inter-contact times
- Model contact duration
- Model the correlation between diff shift-pairs
- Model validation: using a separate trace
- Impact of infrastructures: APs in garage, café
- Technique for identifying the structure without domain knowledge

Acknowledgement:

- DieselNet project: John Burgess, Mark Cornor, Brian Lynn, Adam Sherson, Glen Barrington (PVTA), Yuri Pyuro, et al.
- MobiCom reviewers and shepherd

Thanks!

Questions/Comments?

Backup slides

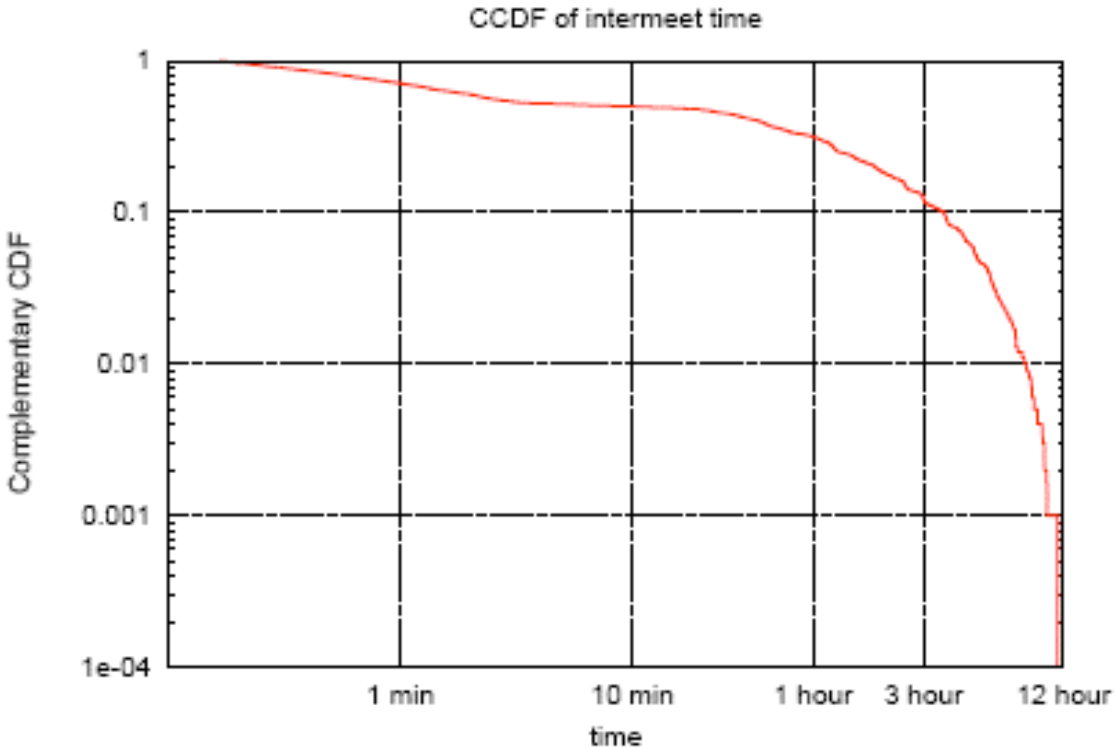
802.11b Trans. Range
[Anastasi et al. 03]

Table 3. Estimates of the transmission ranges at different data rates.

	11 Mbps	5.5 Mbps	2 Mbps	1 Mbps
Data *TX_range*	30 meters	70 meters	90-100 meters	110-130 meters
Control *TX_range*			90 meters	120 meters

Is Aggregate Model Sufficient ?

All-bus-pair-all-day aggregated inter-contact time



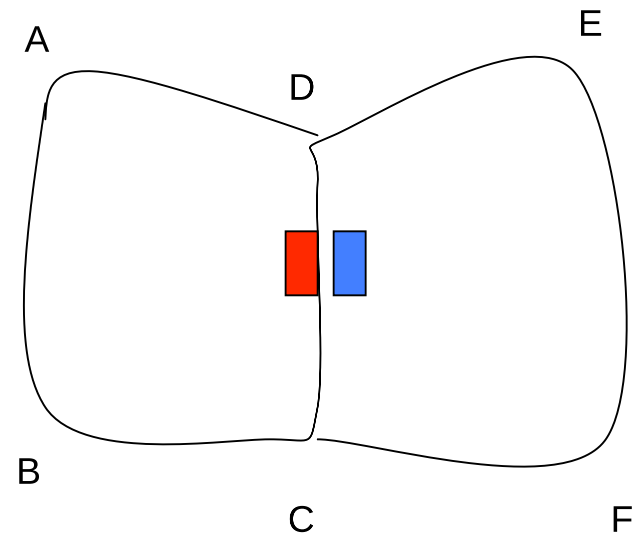
Kaplan-Meier Estimator (Product Limit Estimator)

- Suppose in $\{x_i\}$, there are n distinct inter-contact times, sorted as
  - $T_1 < T_2, \ldots, < T_n$
  - n_i: the no. of inter-contact times that are greater than T_i (including censored observations)
  - d_i: the no. of inter-contact times of length T_i
- Kaplan-Meier estimator for S(t):=Pr(X>t)

$$\hat{S}(t) = \prod_{t_i < t} \frac{n_i - d_i}{n_i}$$

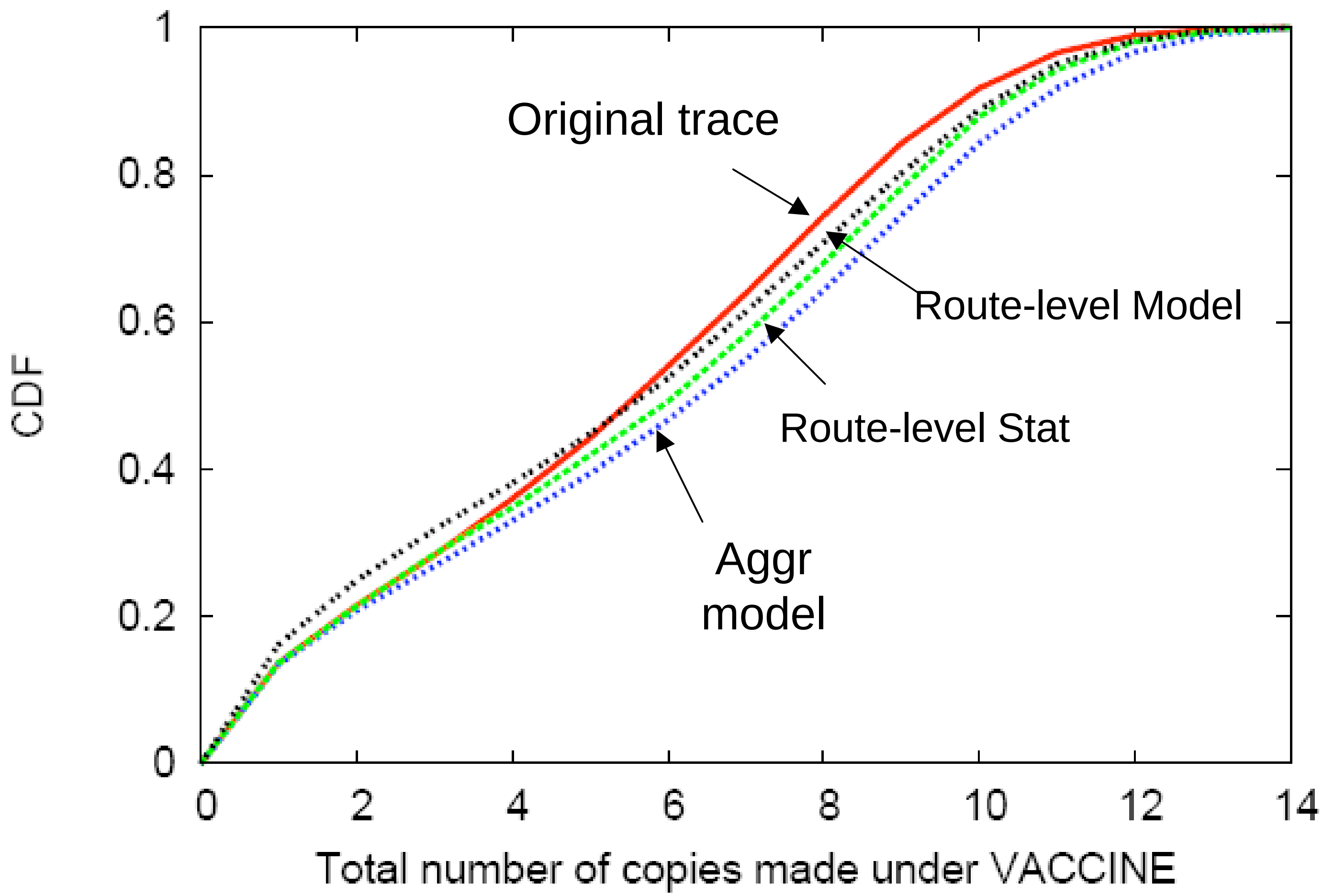
Bus Pairs on SHUTTLE Route

- T_1: time to traverse A-B-C-D-A
- T_2: time to traverse C-D-E-F-C
- Meeting sequence for buses on opposite directions: $T_1/2, T_1/2, T_2/2, T_2/2, T_1/2, T_1/2,$ …; or $T/2, T/2,$ …, where $T=T_1+T_2$ ($T_1 \approx T_2$ for SHUTTLE)
- Buses on same directions rarely meet



$$f_{GEO\_2BM}(x) = \sum_{i=1}^{2} w_i \sum_{l=1}^{\infty} p_i^{\,l-1}(1-p_i)\, f_n(x, il\mu, \sigma^2)$$

Model Validation: Copies Made

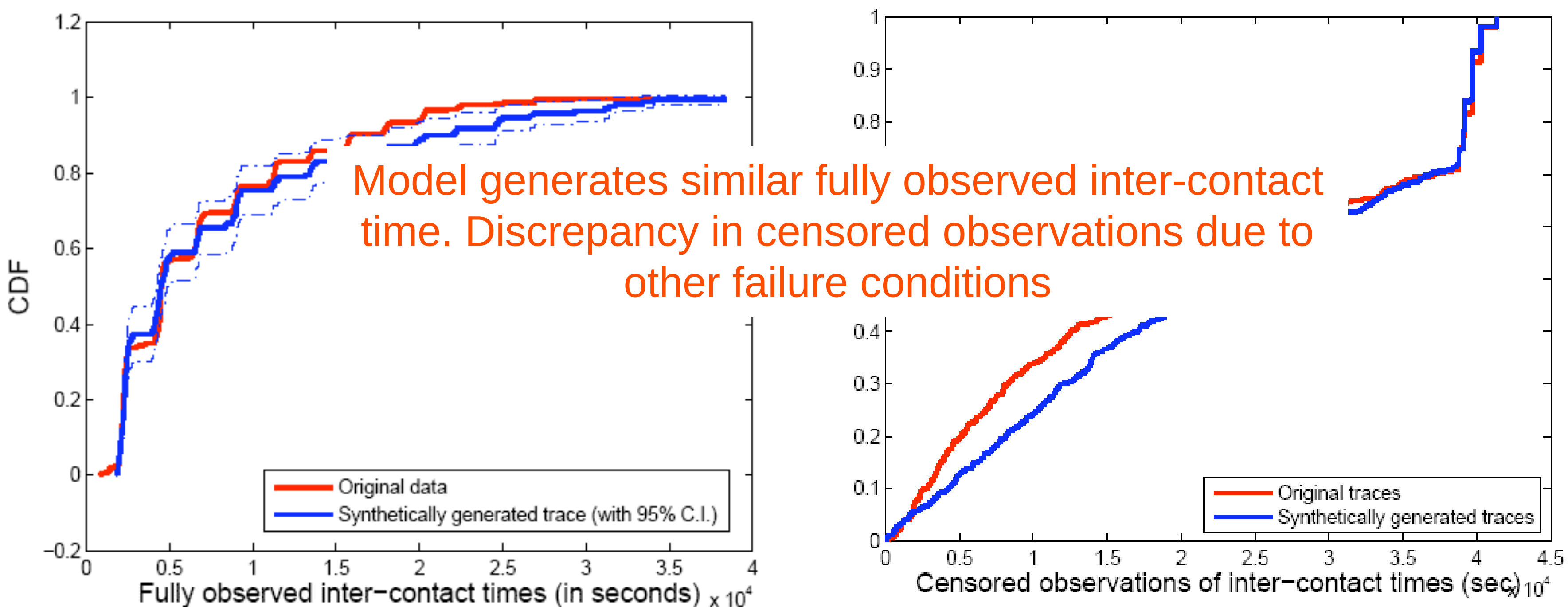


Relative accuracy of predictions by different models similar to delay performance

Parameter Estimation Results

- Some shift pairs have higher failure prob.

$$f_{GEO\_MP\_1BM}(x) = \sum_{i=1}^{2} w_i \sum_{l=1}^{\infty} p_i^{\,l-1}(1-p_i)\, f_N(x \mid i\mu, \sigma^2)$$



Model generates similar fully observed inter-contact time. Discrepancy in censored observations due to other failure conditions

Routing in DTNs

- *Challenges*
  - opportunistic contacts: need to search for paths
  - resource constraints: bandwidth, power, buffer space
  - local knowledge with delayed feedback
- *Objective*
  - resource efficient scheme to achieve good performance, e.g., high packet delivery ratio, small delay
- *Routing schemes*
  - single-copy or multiple-copy routing
  - stateless or stateful routing
  - resource constraints assumptions: packet scheduling, buffer management strategies