Understanding Human Mobility in Wireless Mobile Networks

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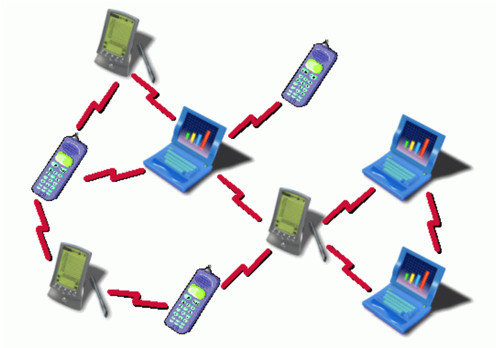
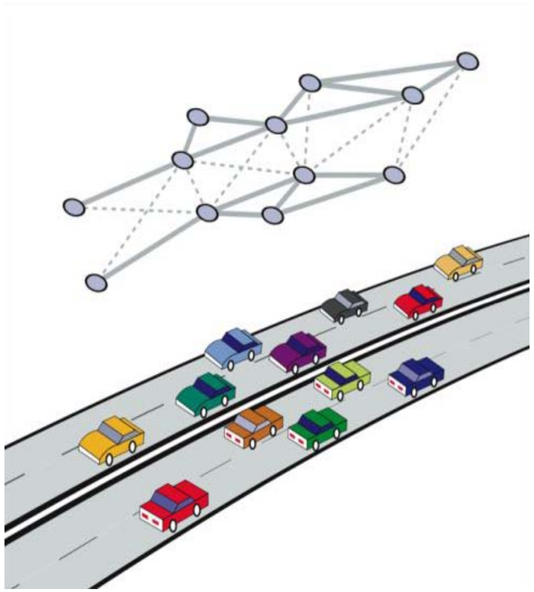
Presentation Outline

- **Introduction**
  - Wireless Mobile Networks
  - Understanding Mobility in Wireless Mobile Networks
  - Conventional Mobility Models
- **Human Mobility Models**
  - Theme I : Statistical Mobility Model based on Empirical Data (Levy-walk)
  - Theme II : Context-based Mobility Model (SLAW)
- **Conclusions**

Wireless Mobile Networks

- **Wireless Mobile Network**
  - A collection of wireless mobile devices interworking through multi-hop or movement without an infrastructure
  - E.g. Mobile Ad-hoc Networks(MANETs), Delay Tolerant Networks(DTNs)



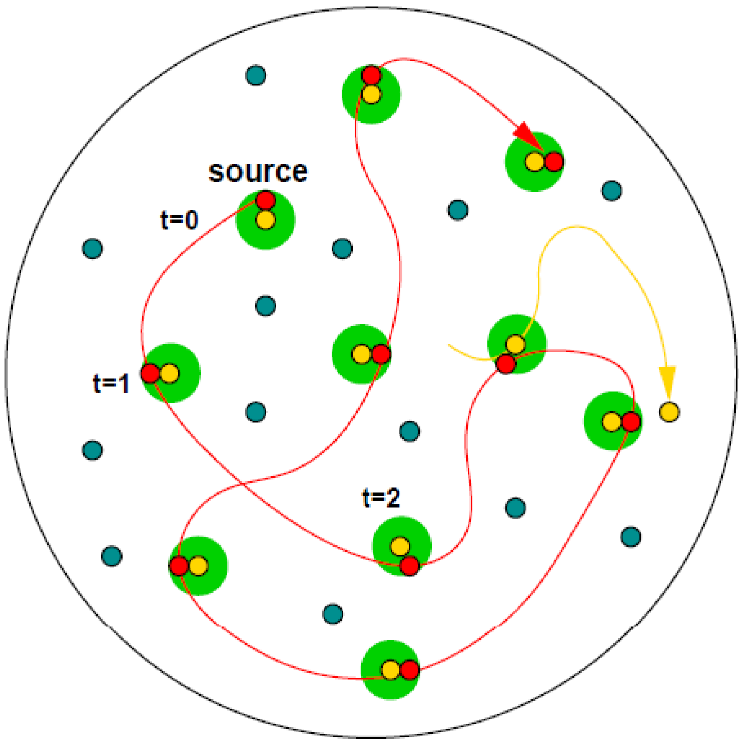


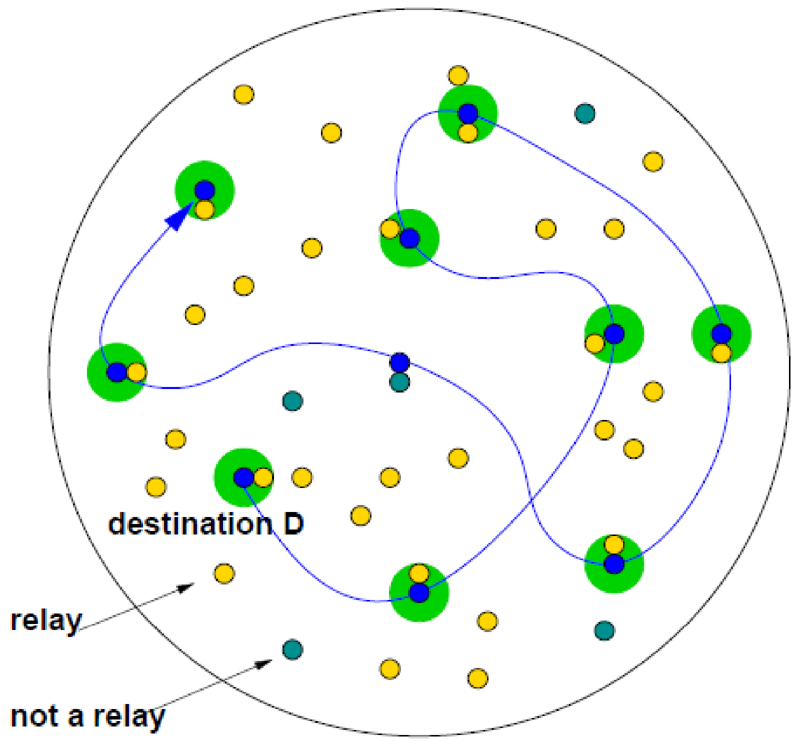
MANETs in Reality?

- **Excuses**
  - Premature mobile devices
  - Not-enough connectivity
  - Non-cooperative nature
  - Lack of killer applications
- **Gupta and Kumar ('00)**
  - Static Multi-hop Network
  - Per-node capacity : $\Theta(\frac{1}{\sqrt{n \log n}})$
- **Grossglauser and Tse ('01)**
  - Mobility-aided Network
  - Per-node capacity : $\Theta(1)$

How to Get Θ(1) in Wireless Mobile Networks

- **Grossglauser and Tse ('01)**
  - Exploiting mobility of nodes : Mobile Relay for a packet delivery



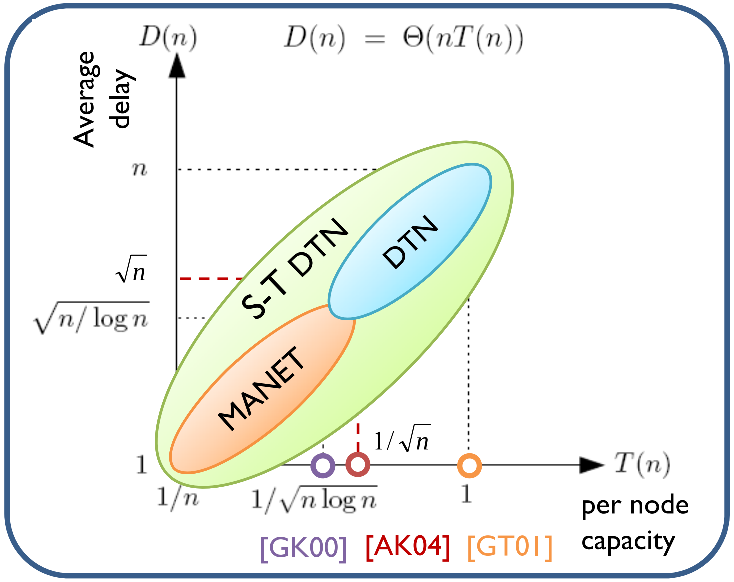


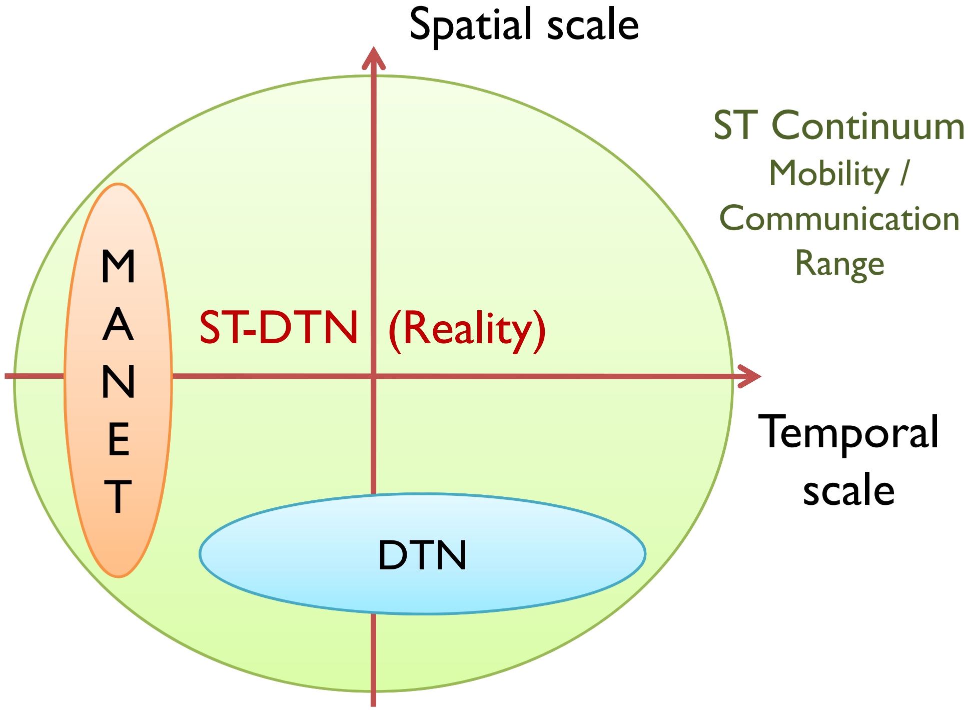
  - Delay : $O(n)$

Mobility-oriented Space Time DTN

- **ST-DTN : Superset of MANET & DTN**
- **Future Network Design should enable**
  - Any point in mobility-oriented "space-time continuum" of networks*

Delay-Capacity Tradeoff

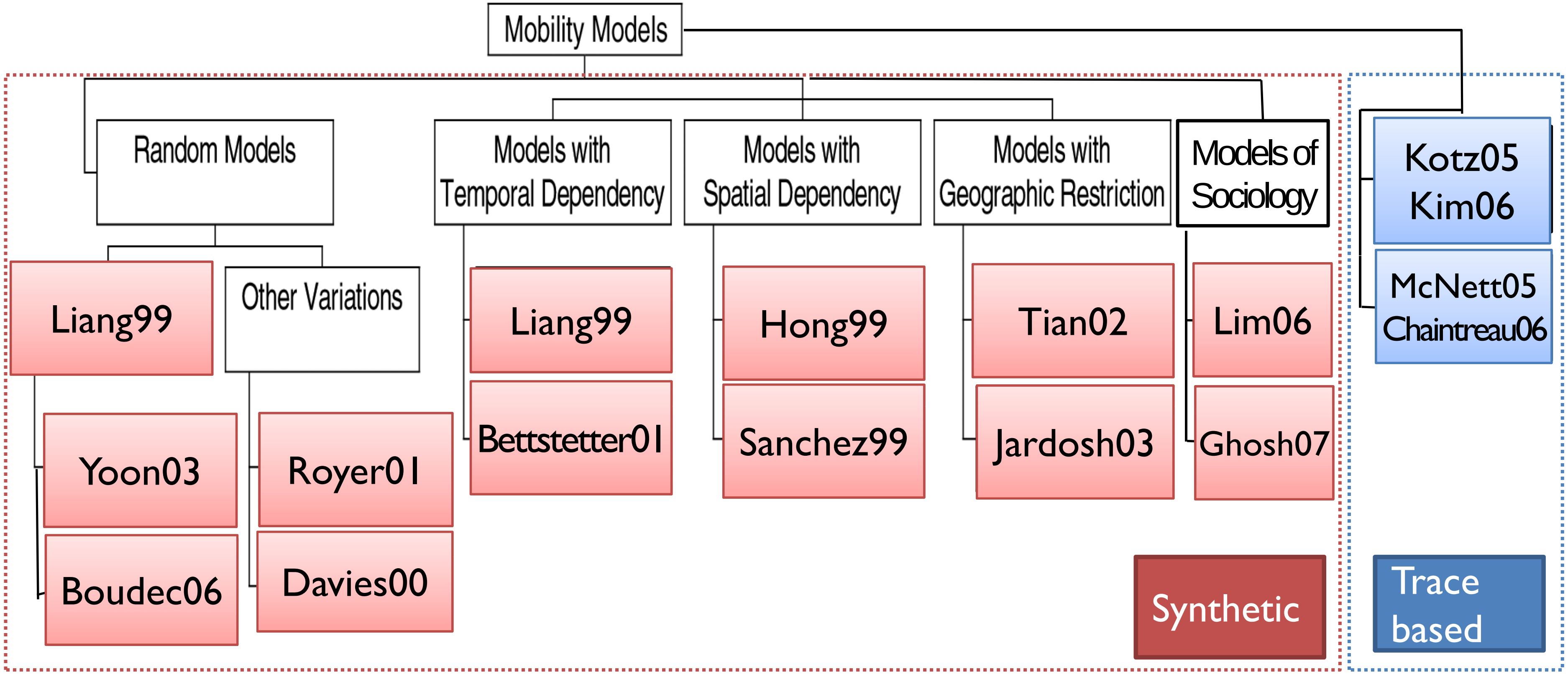




* S. Merugu, M. Ammar, and E. Zegura, "Routing in space and time in networks with predictable mobility," in Technical report: GIT-CC-04-07. College of Computing, Georgia Institute of Technology, 2004.
\# KH. Lee, Y. Yi, J. Jeong, H. Won, I. Rhee, S. Chong, "Max-Contribution : On Optimality Resource Allocation in Delay Tolerant Networks", submitted to INFOCOM 2010

Classification of Mobility Models

- **Classification of Remarkable Mobility Models**



- **Lack of Scalable, Reproducible and Realistic Model**

Theme I :
Statistical Mobility Model based on Empirical Data
(Levy-walk Nature of Human Mobility)

Joint work with NCSU

(Injong Rhee, Minsu Shin, Seongik Hong, Song Chong)

Motivation

- **Mobility models for mobile networks**
  - Many synthetic mobility models & even recent models : Lack of Reality !
  - Reality of a mobility models
    - In terms of Movement Trajectory
    - In terms of Inter-Contact Time (Especially meaningful measure for DTNs)

- **Do humans walk like animals?**
  - Statistical patterns of human mobility
  - Similar to commonly observed patterns in animals : *Levy walk* (flight)
    - (e.g. albatrosses[Viswanathan96], monkeys [Atkinson02], and jackals[Ramos04])

Our GPS Traces

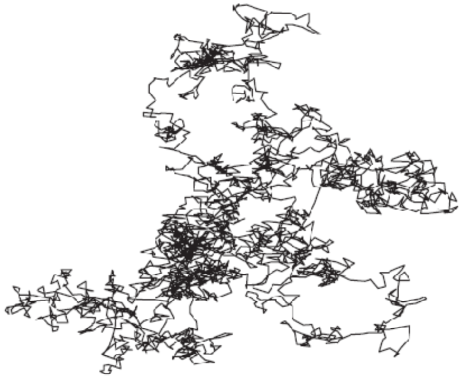
- **103 participants, 226 daily traces**
- **5 different sites**

Site (# of participants, # of daily traces)	# of flights # of samples	Duration (hour)			Radius (Km)		
		Min.	Avg.	Max.	Min.	Avg.	Max.
KAIST (32, 92)	9416 135055	4.21	12.22	23.33	0.27	1.62	13.51
NCSU (20, 35)	4286 42829	1.71	10.19	21.69	0.46	1.82	5.84
New York City (12, 39)	1161 39554	1.23	8.44	22.66	0.28	3.94	12.47
Disney World (18, 41)	4548 44386	2.18	9.01	14.28	0.19	2.53	9.37
State fair (19, 19)	685 5861	1.48	2.56	3.45	0.22	0.38	0.59

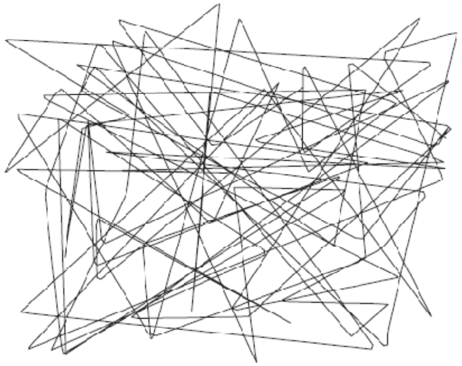
Garmin 60CSx
Accuracy < 3m
(at 95% of time)

Levy-walk Trajectory & GPS Traces

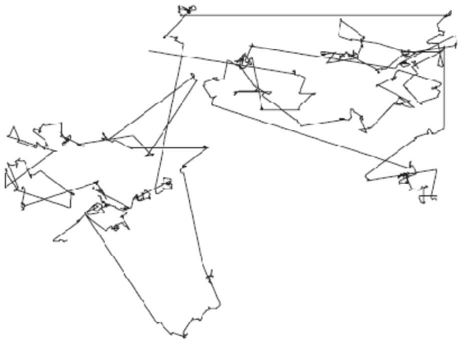
- **Sample trajectories**



Brownian motion

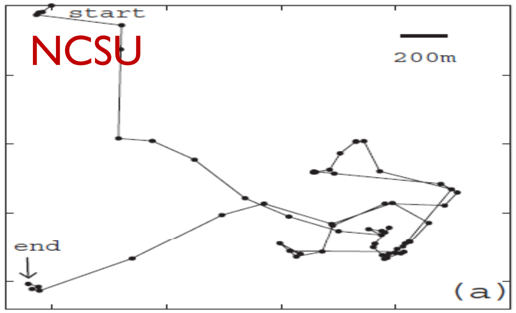


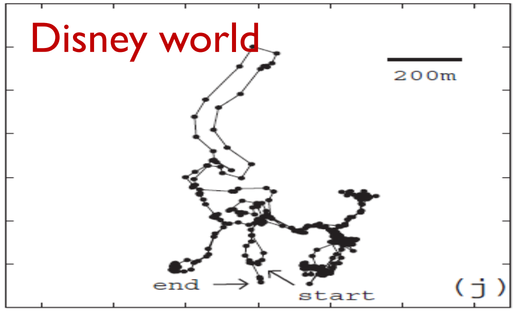
Random waypoint

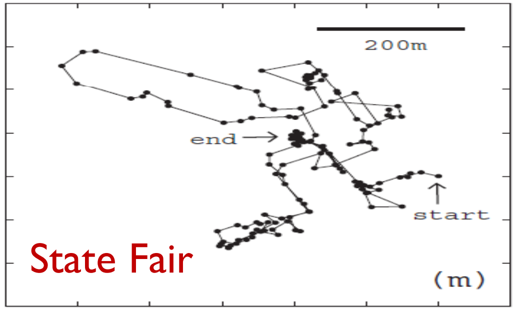


Levy walk

- **Real traces**

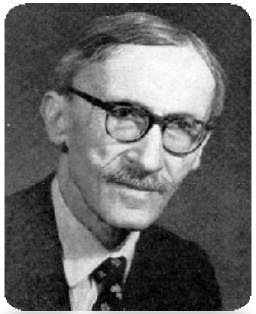






What Is the “Levy-walk”?

- **Levy Distribution (introduced to explain atypical particle diffusion)**

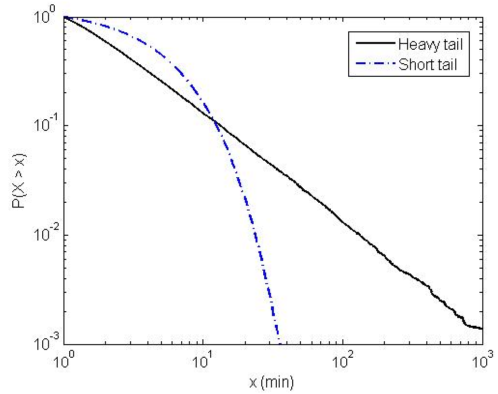


Paul Pierre Lévy
(1886~1971)

$$p(x) \sim x^{-(1+\alpha)}, 0 < \alpha < 2$$

$$p(x) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} e^{-itx - |ct|^{\alpha}} dt$$

$$\sim \frac{\alpha c^{\alpha} \sin(\pi\alpha)\Gamma(\alpha)/\pi}{x^{1+\alpha}}$$

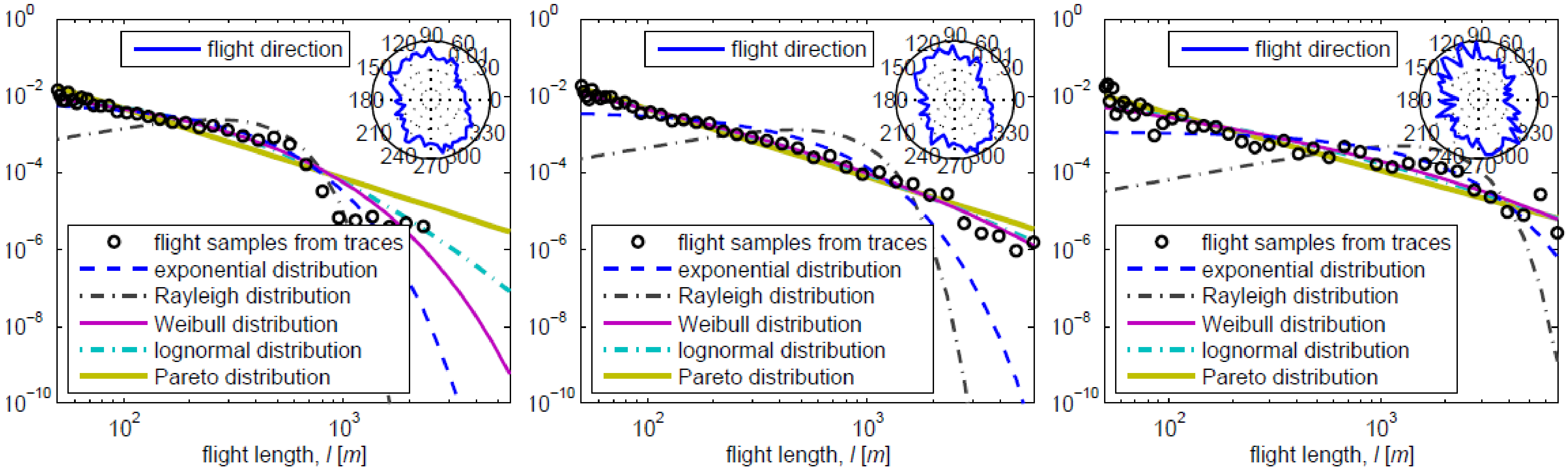


log-log scale

- **Position of a random walker after time t**
  - Brownian motion (Gaussian distribution)
    - Normal diffusion : Mean squared displacement grows linearly with time t. (i.e. $\mathrm{MSD} \sim t^{\gamma},\ \gamma = 1$)
  - Levy walk (Levy distribution)
    - Super-diffusion : $\mathrm{MSD} \sim t^{\gamma},\ \gamma > 1$

Flight Length Distribution

- **Identification of Best Describing Distribution of Flight Length**
  - Maximum Likelihood Estimation
  - Akaike Test (Evaluation method of Goodness of Fit)

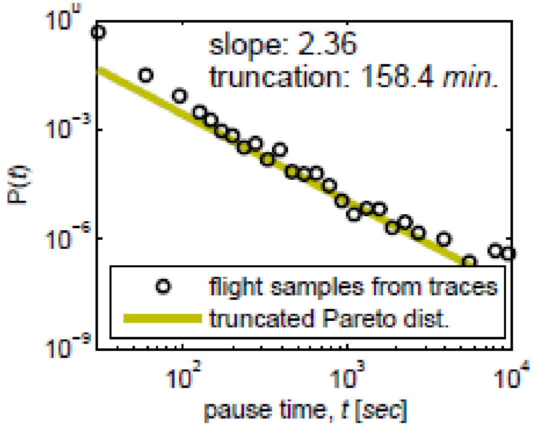


(a) Rectangular model (b) Angle model (c) Pause-based model

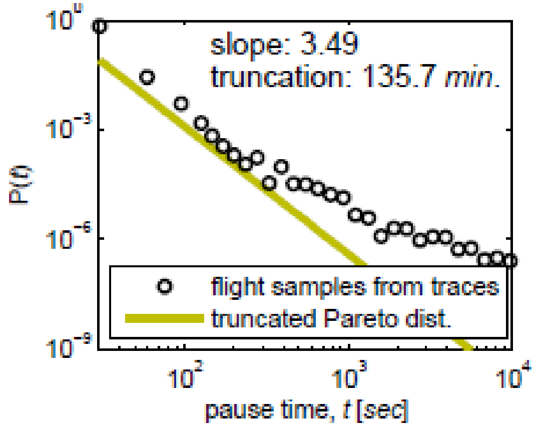
	Rectangular $a_\theta = 0°$	Angle	Pause-based $a_\theta = 360°$
Campus I	-1.53 (0.03)	-1.64 (0.03)	-1.22 (0.11)
Campus II	-2.27 (0.02)	-2.15 (0.04)	-1.63 (0.11)
NYC	-1.62 (0.02)	-1.57 (0.04)	-1.17 (0.10)
Disney World	-2.20 (0.04)	-2.16 (0.08)	-1.85 (0.09)
State fair	-2.81 (0.45)	-2.11 (0.18)	-1.76 (0.15)

Human Walk
~ Levy-walk of α = [0.53,1.81]

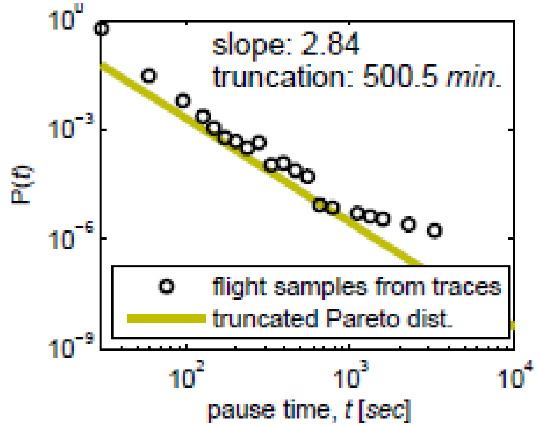
- **Maximum Likelihood Estimation on Pause Time**



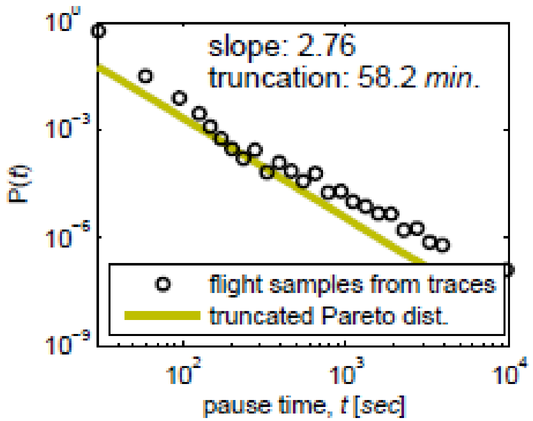
NCSU



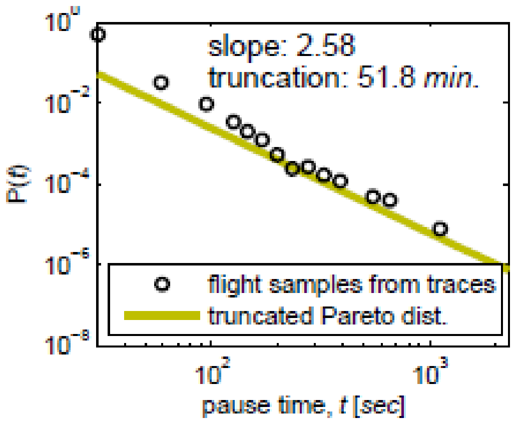
KAIST



New York City



Disney world



State Fair

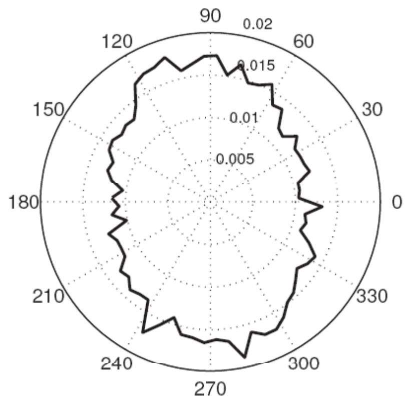
Pause Time
~ Power-law of β = [1.36,2.49]

Levy-walk Mobility Model

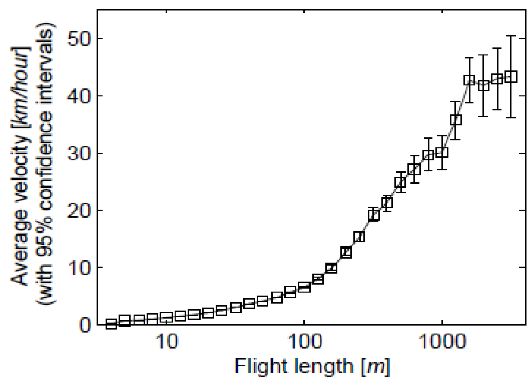
- **Model parameters**

Flight length	l	Direction	θ
Flight time	Δt_f	Pause time	Δt_p

- Flight length : follows the distribution $p(l) \sim l^{-(1+\alpha)}$
- Direction : uniform in [0 2pi]
- Flight time : function of flight length $\Delta t_f = kl^{1-\rho}, 0 \le \rho \le 1$
- Pause time : follows the distribution $\psi(\Delta t_p) \sim \Delta t_p^{-(1+\beta)}$



Turning Angle Distribution



Average Velocity over Flight Length

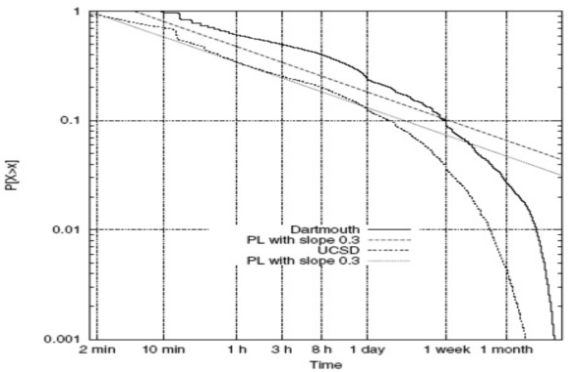
Velocity Model

$k = 30.55, \rho = 0.89$ for $l < 500m$

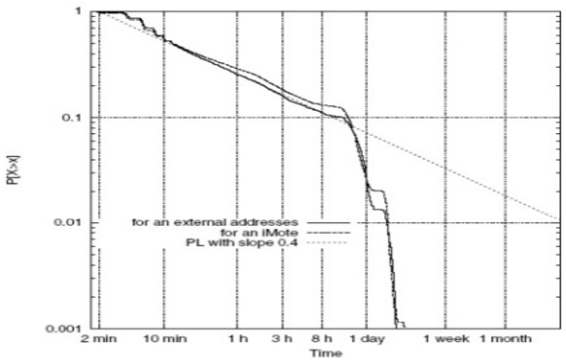
$k = 0.76, \rho = 0.28$ for $l \ge 500m$

Verification of Levy-walk Mobility Model

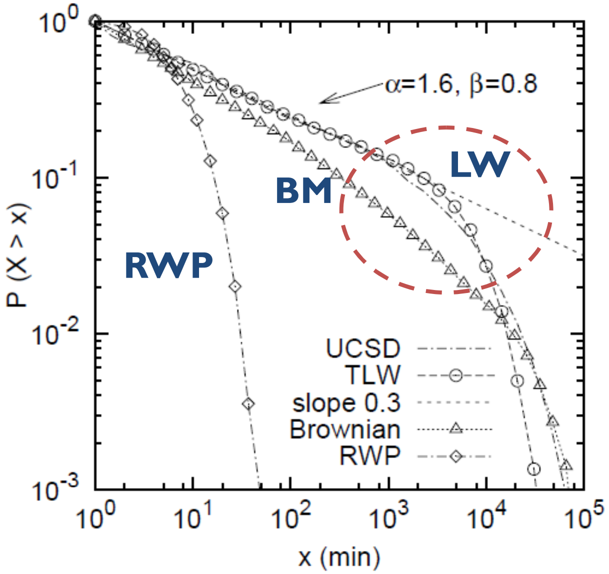
- **Recreation of Inter-Contact Time**



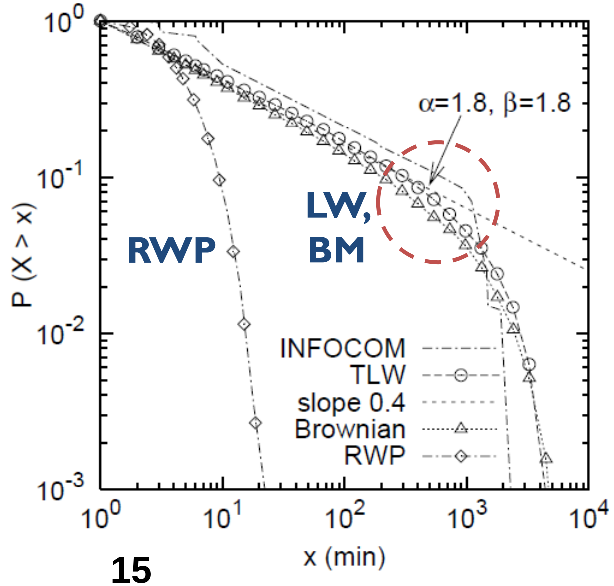
ICT (UCSD)



ICT (Infocom 2005)



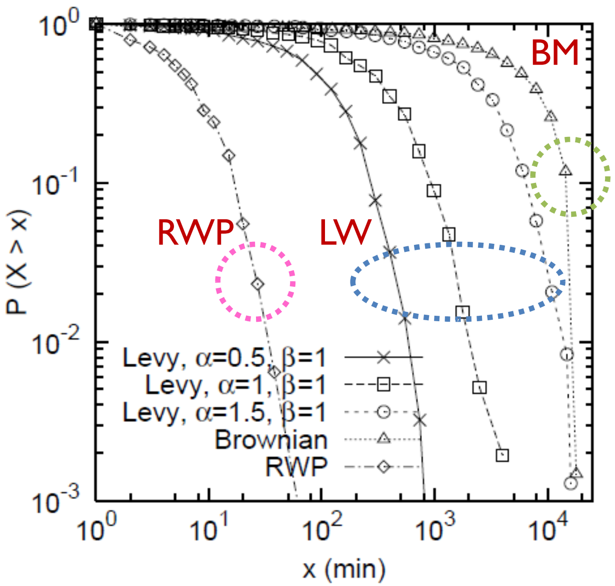
(a) UCSD



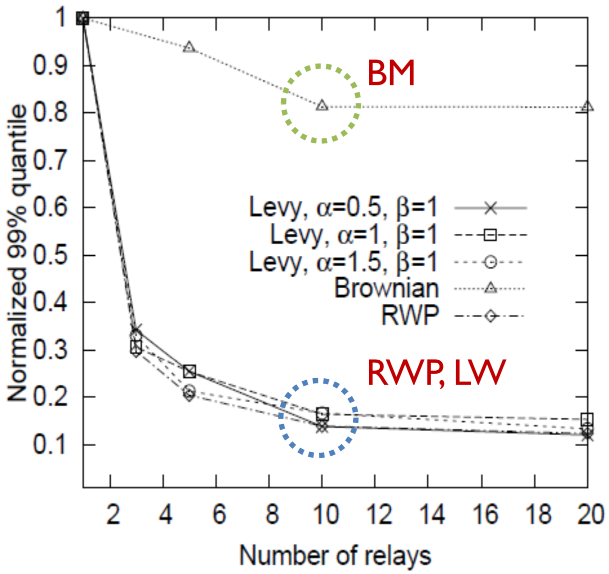
(b) INFOCOM

DTN Routing Performance

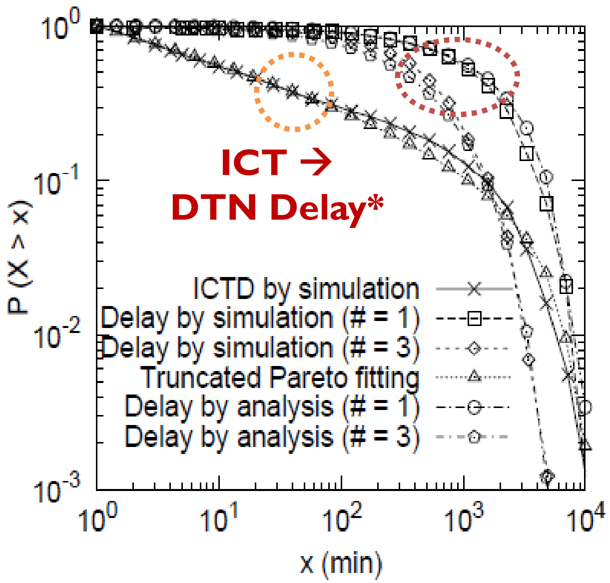
- **Simulation : 2-hop Relay Scheme / MATLAB Simulator**
- **Delay Performance**
  - Levy-walk spends much longer time for delivery (due to Power-law ICT)



(a) One relay



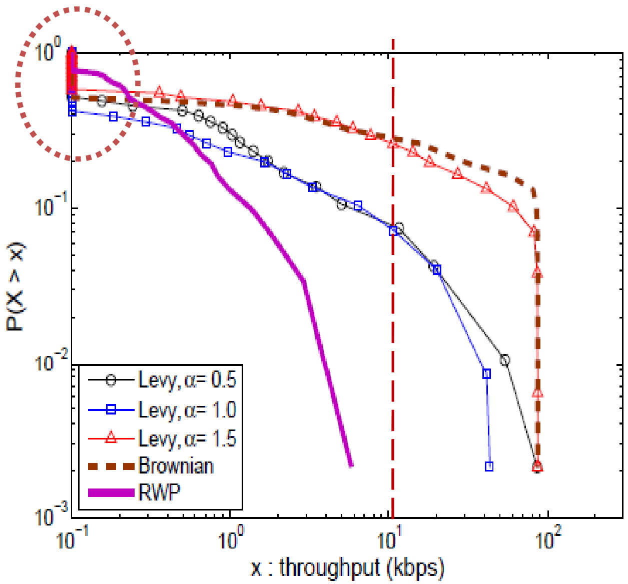
(b) Multiple relays

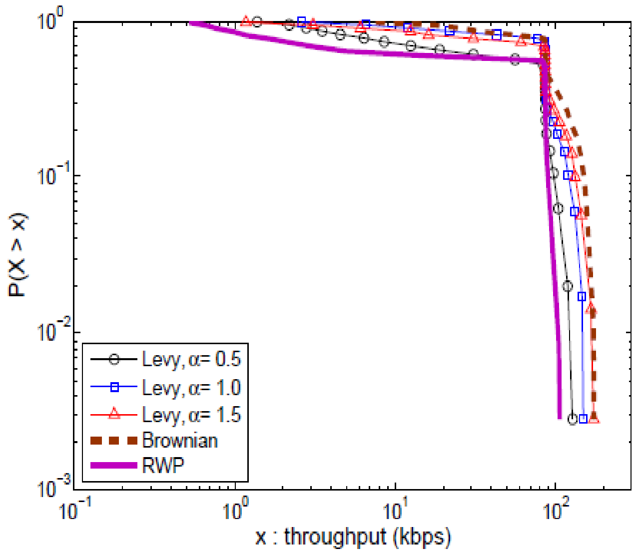


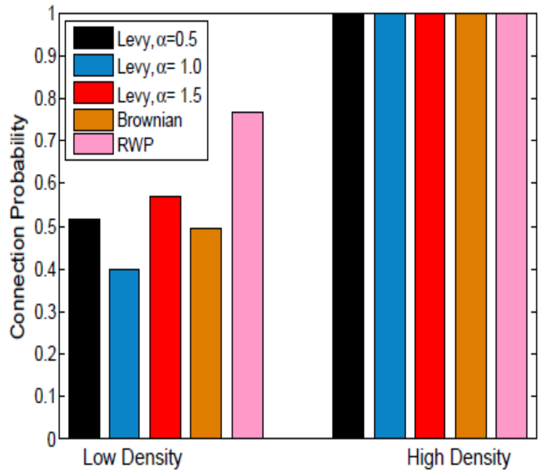
***Routing Performance Analysis of Human-Driven Delay Tolerant Networks using the Truncated Levy Walk Model,** *ACM SIGMOBILE Mobility Models 08 (Colocated with MobiHoc 08)*

MANET Routing Performance

- **Simulation : DSR (Reactive Routing Protocol) / GloMoSim Simulator**
- **Throughput**
  - Levy walk & BM provides more throughput than RWP
- **Connection Probability**
  - Levy walk & BM provides less connection probability than RWP







Theme II : Context-based Mobility Model (SLAW : Self-similar Least Action Walk)

Joint work with NCSU

(Seongik Hong, Seongjoon Kim, Injong Rhee, Song Chong)

Motivation

Fundamental Statistical Features in Human Mobility

(F1) *Levy-walk : Truncated power-law flights and pause-times.*

(F2) *Heterogeneously bounded mobility areas.*

(F3) *Truncated power-law inter-contact times (ICTs).*

(F4) *Fractal waypoints. From the analysis of the GPS.*

Comparison of Existing Models

Category	Features / Models	$F1$	$F2$	$F3$	$F4$
Random	RWP, RD	N	N	N	N
	BM(RW)	N	N	Y	N
	TLW [32]	Y	N	Y	N
Random Variants	MWP [21]	N	N	N	N
	GM [25]	N	N	?	N
	RPGM [20]	N	N	?	N
Geographic	Freeway [2]	N	N	?	N
	Manhattan [2]	N	N	?	N
	OM [22]	N	N	?	N
Social	Dartmouth [24]	N	N	?	N
	CMM [26]	N	N	?	N
	ORBIT [15]	N	Y	?	N

Challenge 1 : Demystifying the Interaction of 4 Features

Challenge 2 : A Realistic Mobility Model Satisfying 4 Features

Challenge 3 : A Realistic Model Implying Correlation of Humans

Levy-walk Reconstruction (Mobility Model)

- **Reconstruction methods of Levy-walk**
  - 1. Using flight lengths taken from the distribution
    - Reconstruction as a random walk : Truncated Levy-walk Mobility Model
  - 2. Demystifying and applying the underlying mechanism of Levy-walk
    - Fundamental approach but very complicated

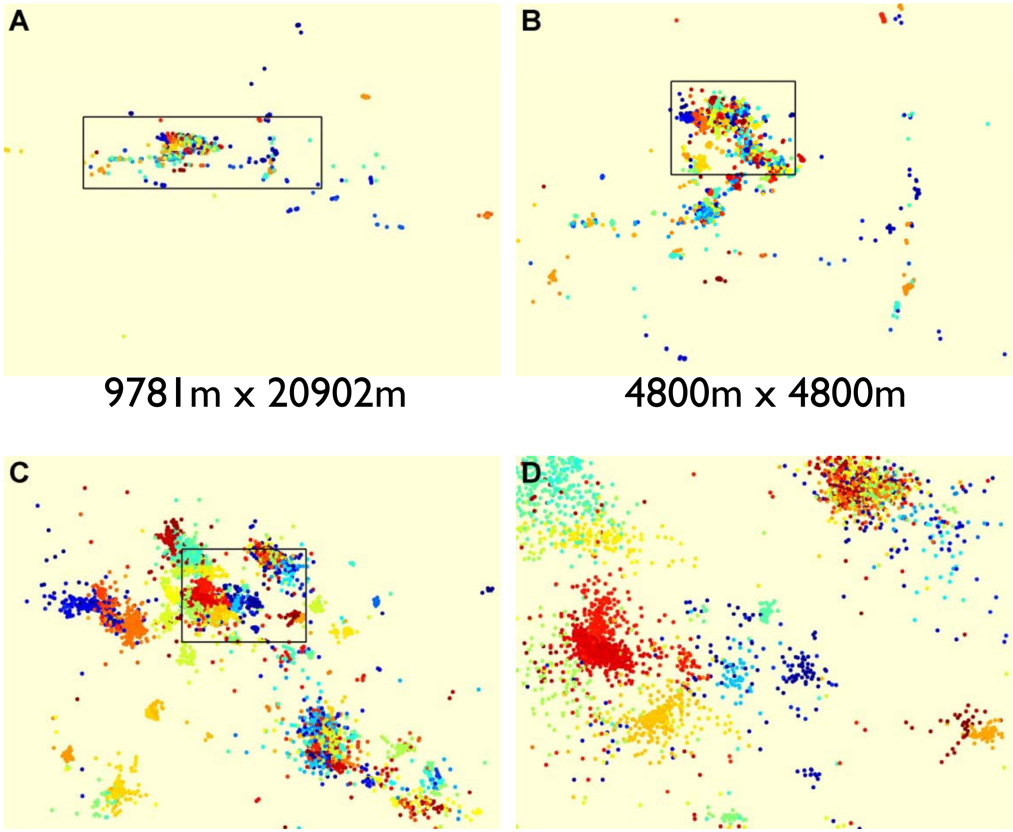
- **Hypothesis to demystify the mechanism of Levy-walk**
  - Levy-walk might be a result of sequential visit patterns of the locations of meaningful contexts.

- **We've tried so many algorithms to model the Hypothesis but failed.**

Successful Decomposition

1. Geographical distribution of locations of underlying contexts
2. Movement decision rule of humans over the given locations

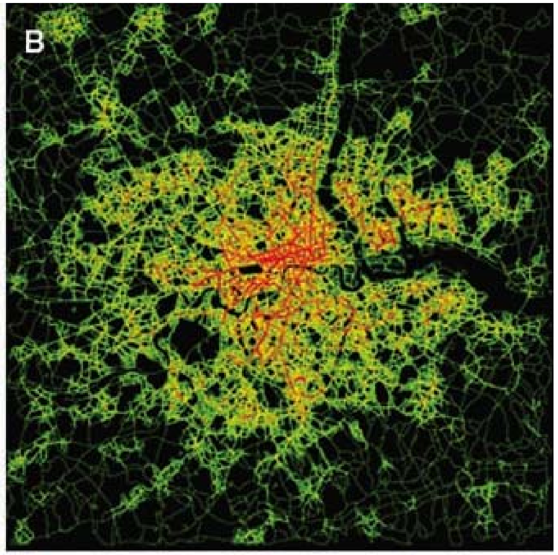
Geographical Distribution of Underlying Contexts



9781m x 20902m | 4800m x 4800m | 1200m x 1200m | 300m x 300m

Waypoint Distribution (KAIST)

(Aggregated from all walkers)



The road network in London (colored by level of connectivity)

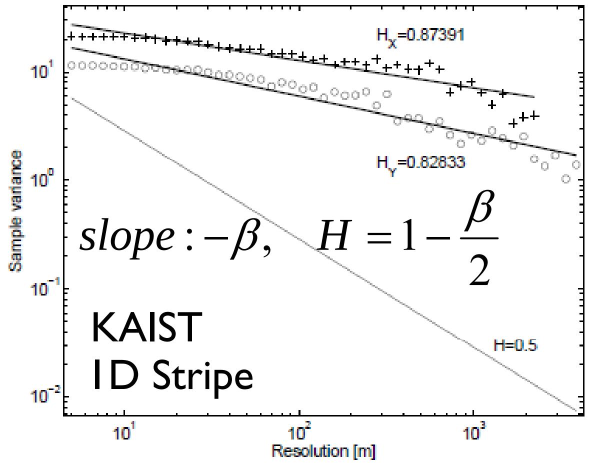
Related Finding :

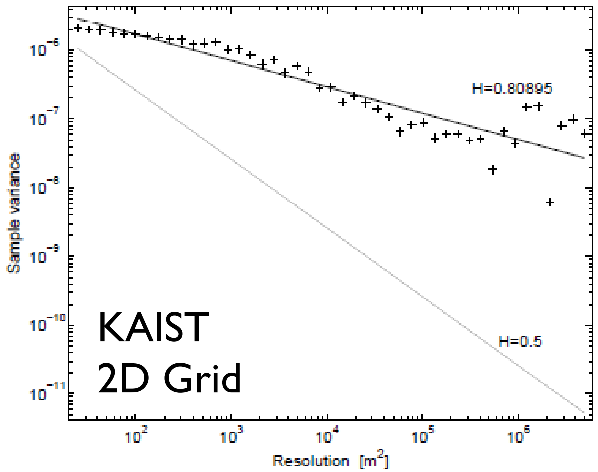
The shape of cities are also fractal

- Batty, M. The Size, Scale, and Shape of Cities. *Science 319, 769-771 (2008).*

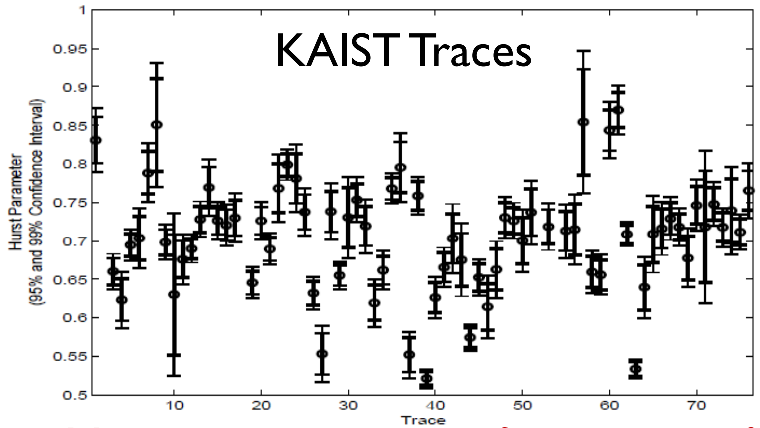
Fractal Waypoints

Hurst parameter Measurement (Aggregated Variance Method, R/S)

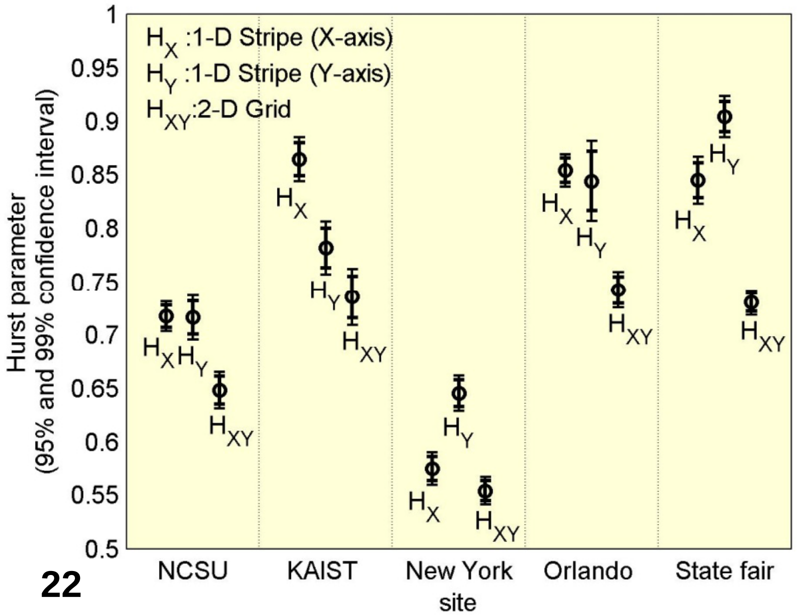




Hurst parameters of all traces > 0.5



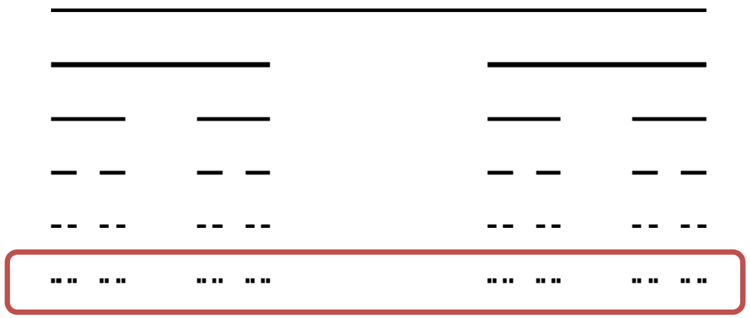
Hurst parameters of all sites > 0.5



Power-law Gaps over Fractal Points

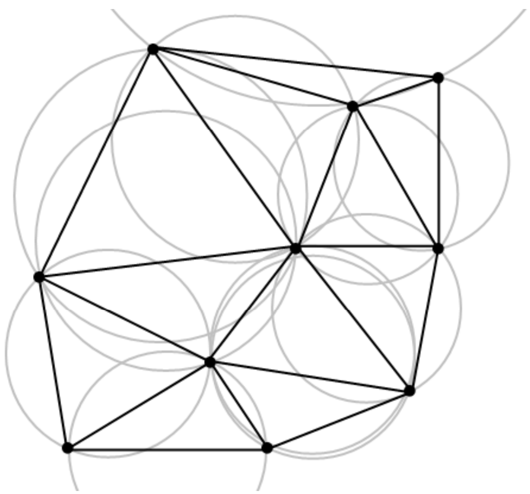
- **Fractal points in one-dimensional space**
  - Distances among neighboring points ➔ Power-law distribution

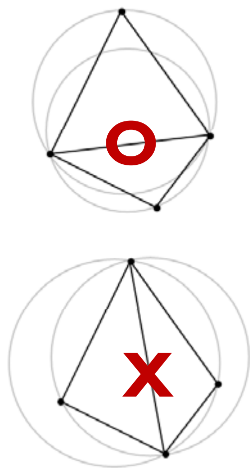
Cantor Set



Theorem :
Fractal points over one-dimensional space induce power-law gap.
(1-to-1: Hurst parameter, power-law slope)

- **Fractal points in two-dimensional space ?**
  - 2D gaps can be approximated by Delaunay Triangulation[1]



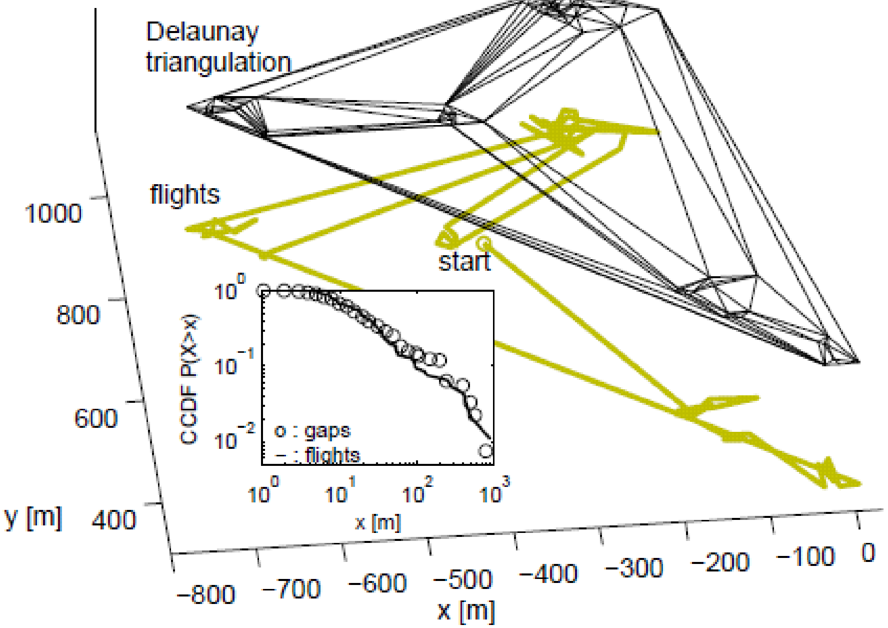


Related Reference

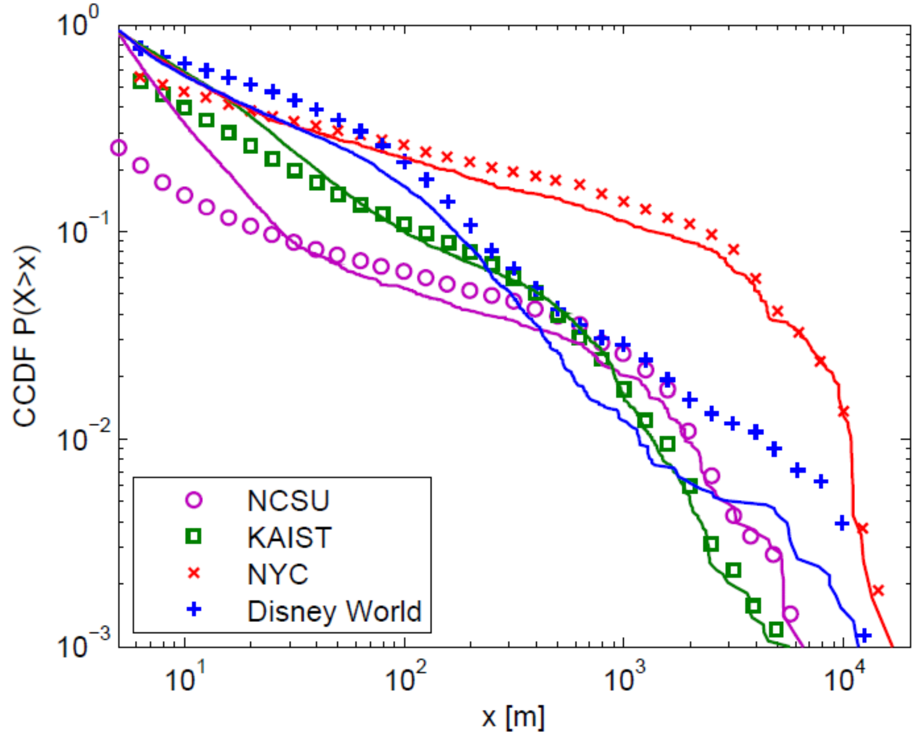
(Gaite, J. Zipf's law for fractal voids and a new void-finder. *Eur. Phys. J. B* ***47, 93-98 (2005).***)

Power-law Gaps over Fractal Points

Delaunay triangulation & real trace of a daily trace from KAIST



Delaunay triangulation & real traces



Lessons learned :

Humans basically visit neighboring waypoints

(Delaunay triangulation tends to avoid skinny triangles)

Least Action Trip Planning (LATP)

- **Trip planning algorithm based on a weight function of *1/d*$^{\alpha}$**
  - Destructive visit over given waypoints
  - *d* : distance from the current location to a candidate location
  - α : a positive constant (determines the distance weight)

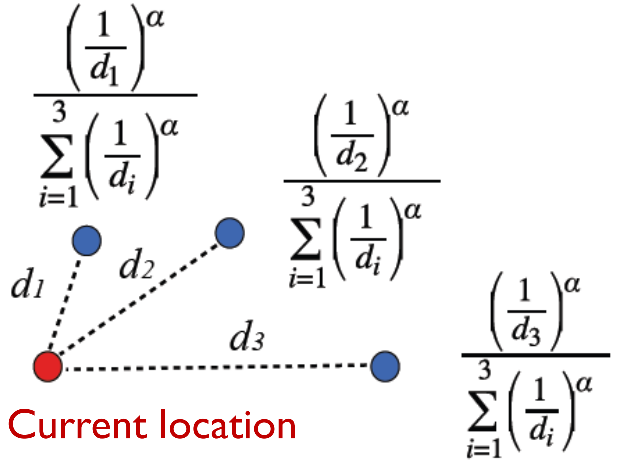
Algorithm 1 *Least action trip planning* (LATP) algorithm with a distance weight function $d^{-\alpha}$

V: set of all vertices (waypoints)
V': set of all visited vertices
$s \in V$: starting vertex
$c \in V$: current vertex
$c \Leftarrow s$
$V' \Leftarrow \{c\}$
while $V' \neq V$ **do**
  Calculate distances to all unvisited vertices, $d(c, v) = \|c - v\|_2$ for all $v \in V - V'$
  Calculate probability to move to all unvisited vertices,

$$P(c, v) = \frac{\left\{\frac{1}{d(c,v)}\right\}^{\alpha}}{\sum_v \left\{\frac{1}{d(c,v)}\right\}^{\alpha}} \text{ for all } v \in V - V'$$

  Choose a next vertex $v' \in V - V'$ according to the probabilities $P(c, v)$
  $c \Leftarrow v'$
  $V' \Leftarrow V' \cup \{c\}$
end while

LATP Example



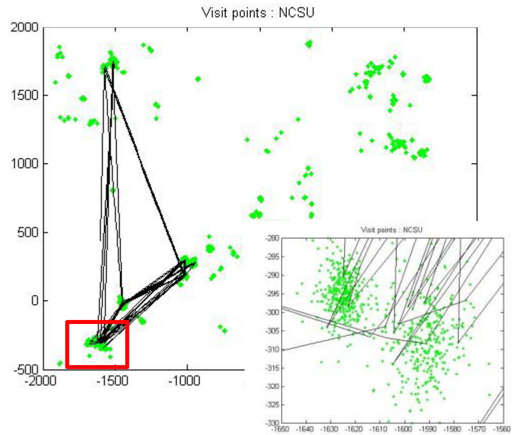
Interpretation of LATP

- **Selection of α has some meanings**
  - α is zero : random visit over given waypoints (no distance optimization)
  - α is infinite : always visit the nearest unvisited waypoint first
    - Approximation to the optimal traveling salesman (TSP) algorithm (NP-hard) : Nearest Neighbor First

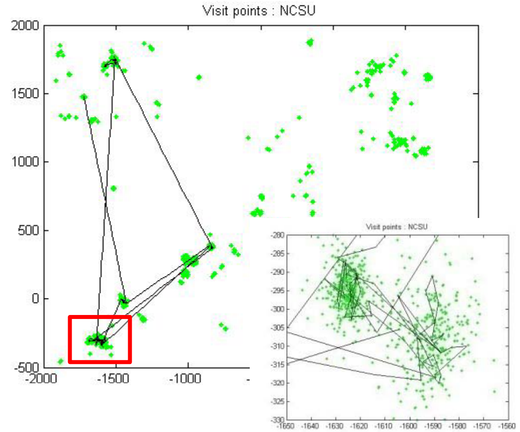
Small α **Large**

More Time-critical Events — More Planned Movement

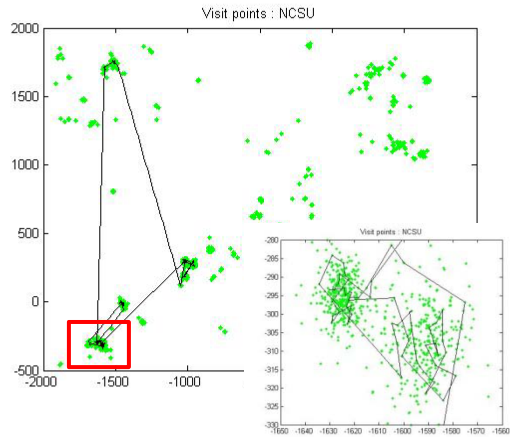
$\alpha = 0$



$\alpha = 1.5$

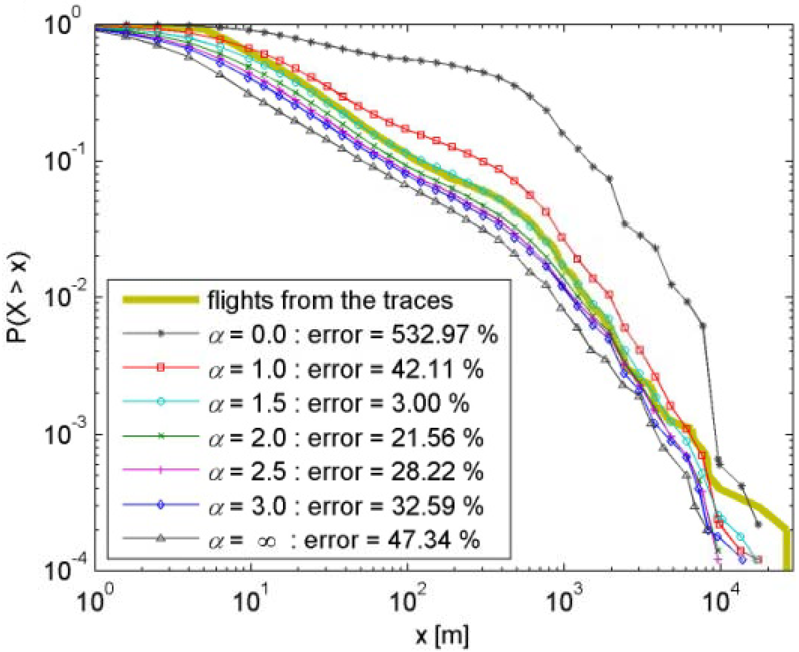


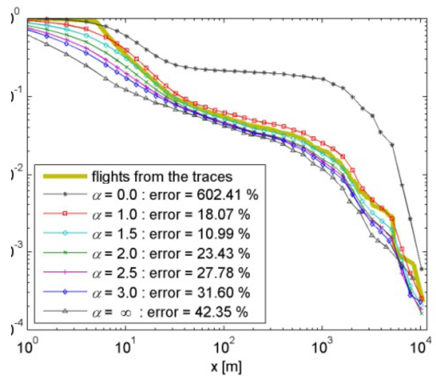
$\alpha = 3$



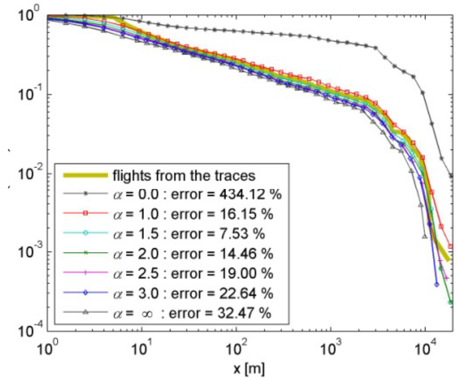
LATP Performed on Real Waypoints

KAIST
(3% Error in sum flights @ α=1.5)





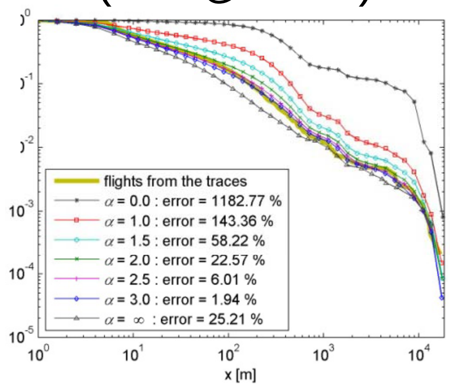
NCSU
(10%@α=1.5)



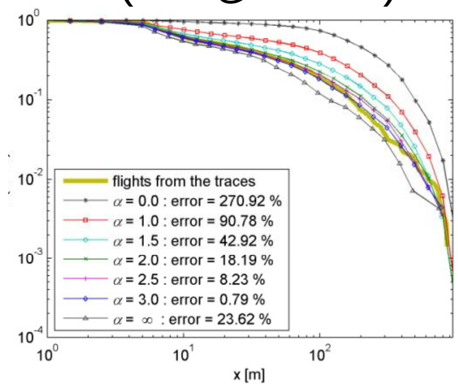
New York City
(7% @ α=1.5)

Campuses : smaller values of α (α=1.5)
➔ More likely to have time critical events

State Fair & Disney World :
larger values of α (α=3)
➔ **More likely to be distance greedy.**
(Planned movements are rarely violated)



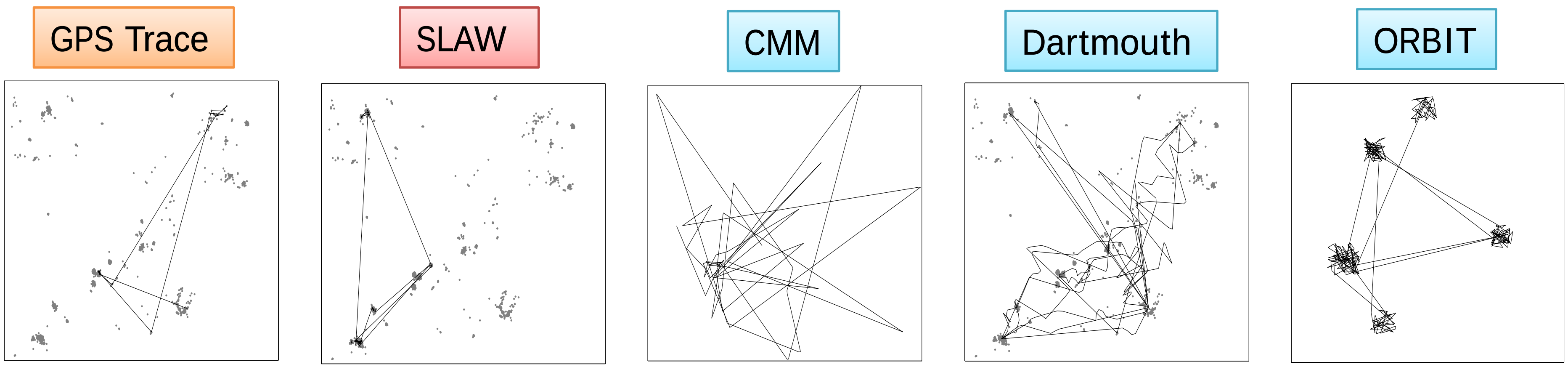
Disney World
(2% @ α=3.0)



NC State fair
(1% @ α=3.0)

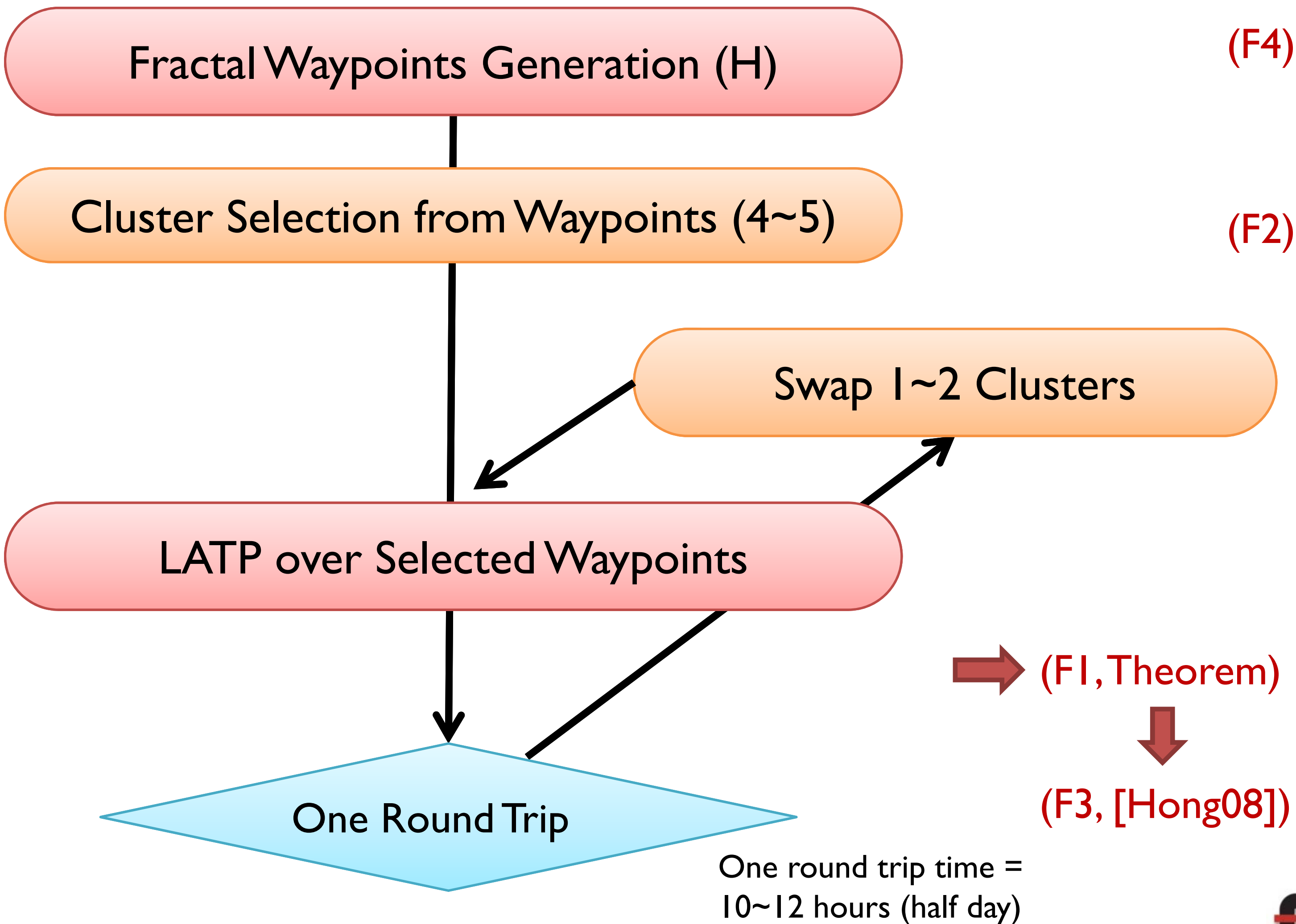
Comparison of Recent Mobility Models

- **Dartmouth**
  - Movement over given spots with probability obtained from real traces
- **CMM (Clustered Mobility Model)**
  - Movement over given regions with probability obtained from virtual preferential attachment procedure
- **ORBIT**
  - Planned movement over given clusters of way-points



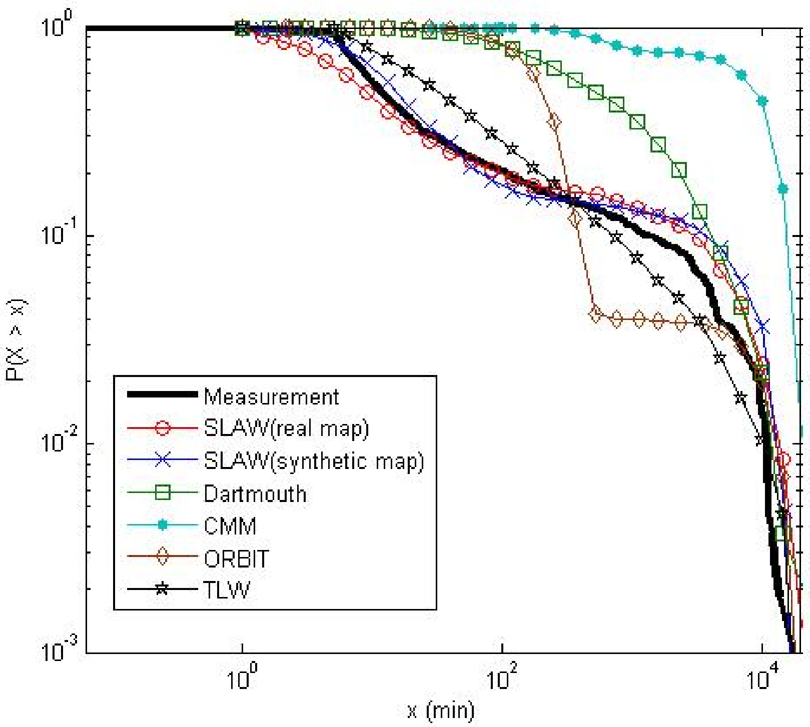
Self-similar Least Action Walk (SLAW)

- Synthesis of SLAW

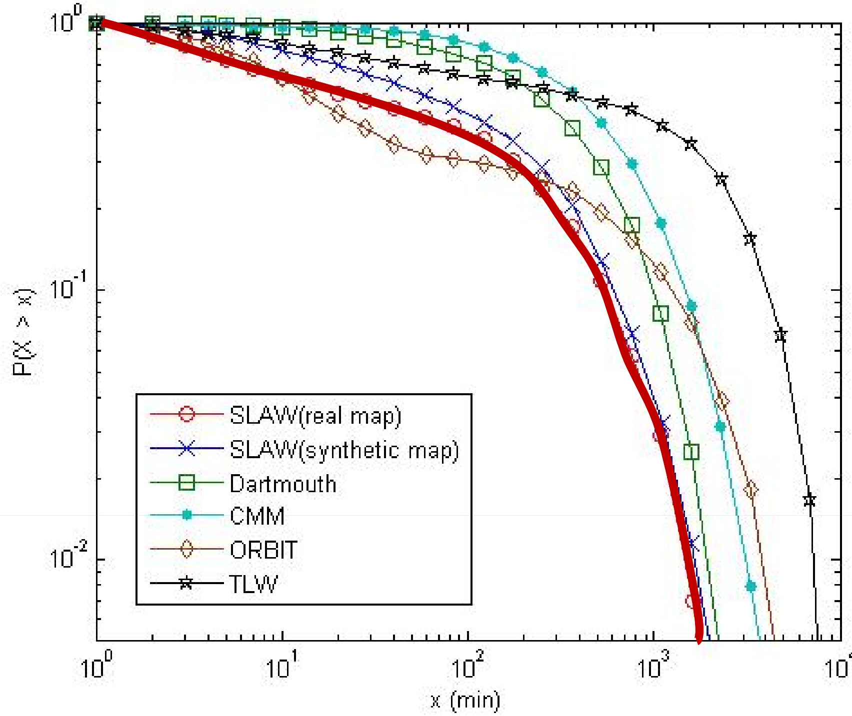


SLAW Verification :
Flight Length and ICT Distributions

Flight length



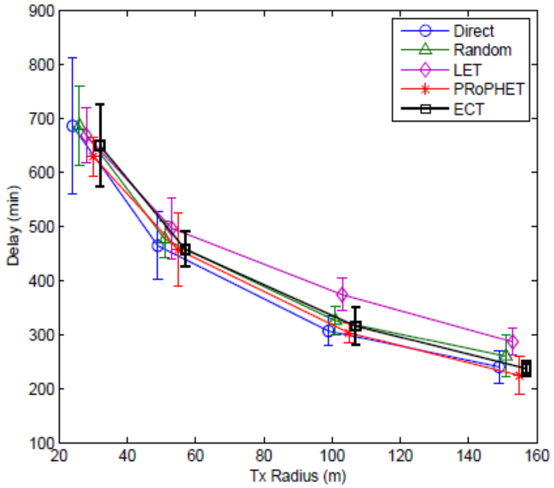
ICT



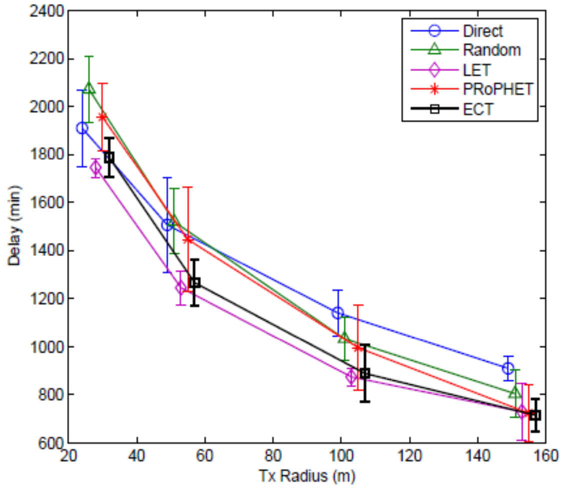
SLAW presents very realistic distributions of flight length and ICT

DTN Routing Performance

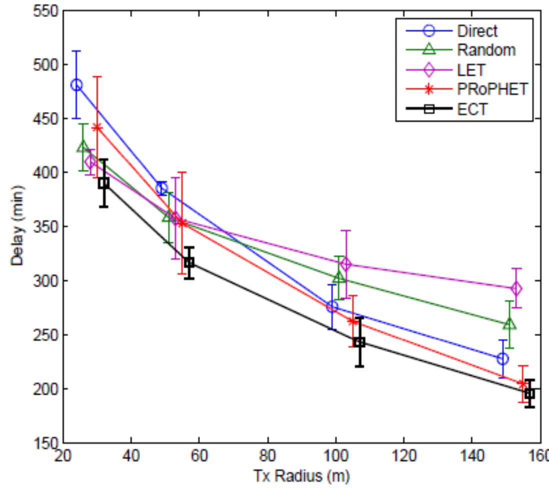
- **Comparison of average DTN routing delay**
  - New routing metric, ECT (Expected Contact Time) is suggested
  - 4 routing schemes are compared (Direct, Random, LET, PRoPHET)
  - Some routing metrics show bad performance in recent models
  - ECT shows best performance in SLAW
  - Movement over common contexts among users reduces the delay



(a) Dartmouth



(b) ORBIT



(c) SLAW

Applications of SLAW

- **Telecommunication**
  - Cell tower, Base Station Deployment Planning
  - Handoff Prediction
  - User Distribution Prediction (in a cell, in multi-cells)
- **Networking**
  - MANET Performance Evaluation
  - DTN Performance Evaluation
- **Civil Engineering**
  - City Planning, Pathway Planning
- **Disease and outbreak control**
  - Virus Spread Pattern Analysis
- **Sociology**
  - Human Social Network Study (modeling Familiar Stranger)
- **Marketing**
  - Optimal Marketing Location Planning