Levy walk nature of human mobility and its impact on DTN/MANET performance

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Outline

- **Introduction**
  - What is “Levy walk”?
- **Measurement methodology**
  - Data collection
  - Trace analysis
- **Human mobility patterns**
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  - Pause time distribution
  - Mean squared displacement
- **Levy walk mobility model**
  - Inter-contact time distrbution
  - Routing in Delay Tolerant Networks
  - Routing in MANETs
- **Conclusion**

Introduction

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

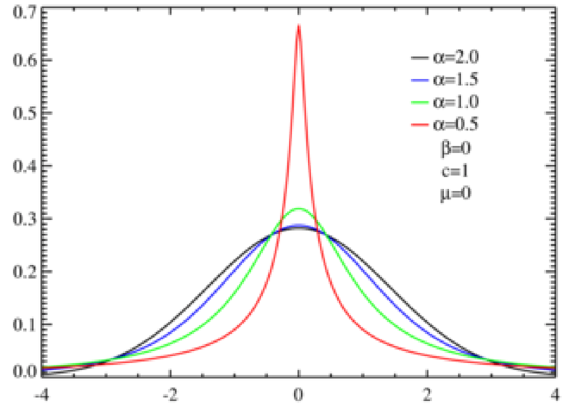
- **Mobility models for mobile networks**
  - Realistic mobility models are required for
    - Realistic network simulation
    - Accurate understanding of the protocol performance

What is the "Levy-walk"?

- **Consider random walk with flight length dist.** ***p(l)***

$$p(l) \sim l^{-(1+\alpha)}$$

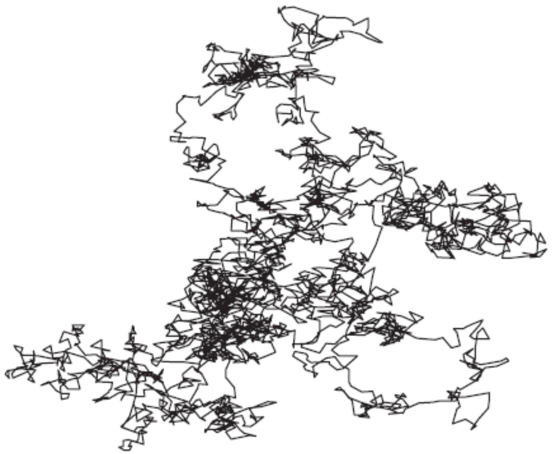
$\alpha \geq 2$	Finite variance, Brownian
$0 < \alpha < 2$	Infinite variance (scale-free), Levy walk

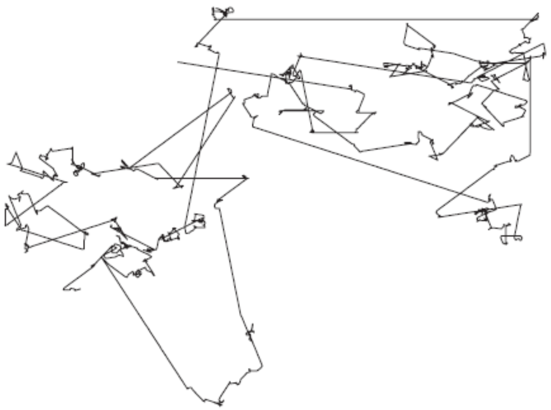


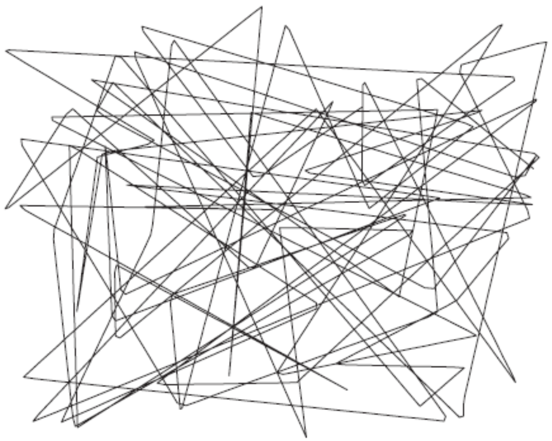
- **Position of a random walker after time t**
  - Brownian motion : Gaussian distribution
    - According to Central Limit Theorem
    - Normal diffusion : Mean squared displacement grows linearly with time t. (i.e. $\mathrm{MSD} \sim t^{\gamma},\ \gamma = 1$)
  - Levy walk: Levy stable distribution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

Levy-walk trajectory

- **Sample trajectories**







Brownian motion **Levy walk** **Random waypoint**

- Levy walk is the optimal way to find randomly dispersed objects in nature
- Animals perform Levy walks for survival!

GPS traces

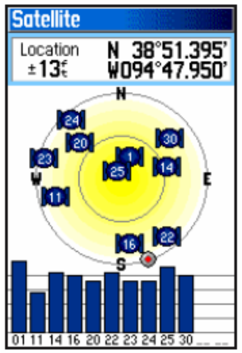
- **Data collection**
  - Handheld GPS receivers are used
  - Daily mobility traces are collected from five different sites
    - 44 participants and 134 daily traces

Site	# of participants	# of daily traces	Avg. duration (Hours)	Avg. maximum distance (Km)
KAIST	4	46	10.6	2.6
NCSU	20	35	10.2	3.6
New York City	8	30	9.3	8.4
Disney World	4	15	8.7	3.4
State fair	8	8	2.6	0.6

Sample traces in Disney world

GPS receiver

- **Garmin GPSMAP 60 CSx (Retail Price : $482 USD)**



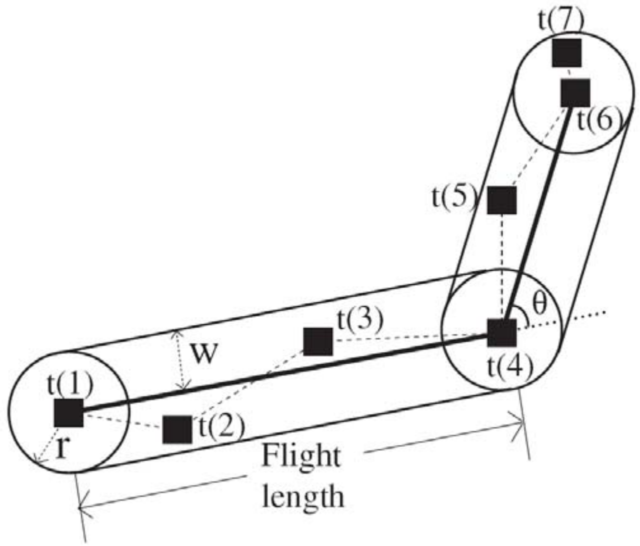
Physical & Performance:	
Unit dimensions, WxHxD:	2.4" x 6.1" x 1.3" (6.1 x 15.5 x 3.3 cm)
Display size, WxH:	1.5" x 2.2" (3.8 x 5.6 cm)
Display resolution, WxH:	160 x 240 pixels
Display type:	256 level color TFT
Weight:	7.5 oz (213 g) with batteries
Battery:	2 AA batteries (not included)
Battery life:	18 hours, typical

Accuracy	
GPS	< 3m 95% of time
Minimum Record Interval	10 seconds

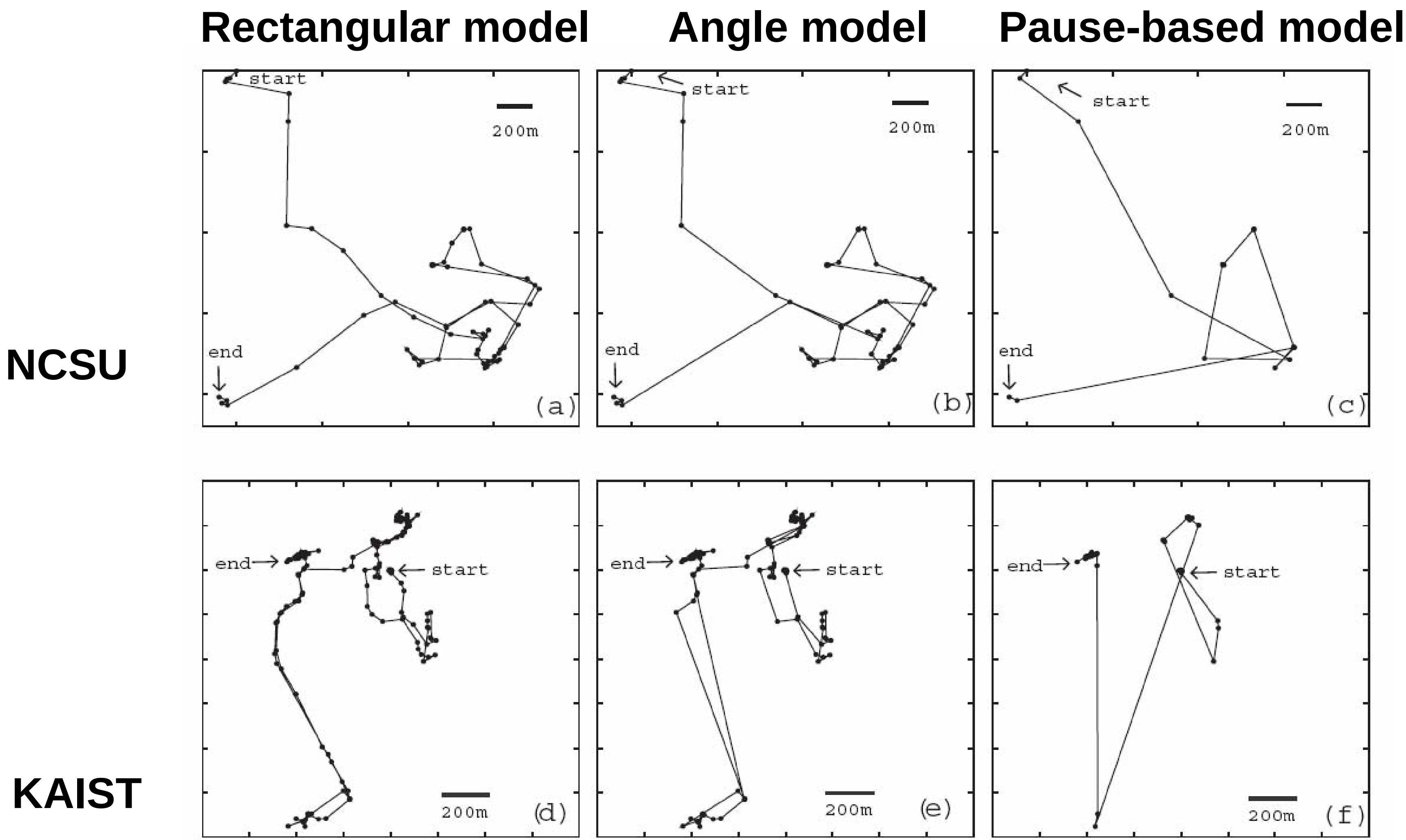
User Manual
http://www8.garmin.com/manuals/GPSMAP60CSx_OwnersManual.pdf

Trace analysis

- **Rectangular model**
  - Recompute a position at every 30 seconds.
  - Pause
    - Participant moves less than *r* meters during 3 second period.
  - Flight length
    - Non pause points
    - All sampled points are inside of the rectangul formed by two end points with width *w*
- **Angle model**
  - Merge consecutive flights 'ich have a_θ directional change less than
- **Pause-based model**
  - Extreme case of angle model
  - Represent human intention more faithfully

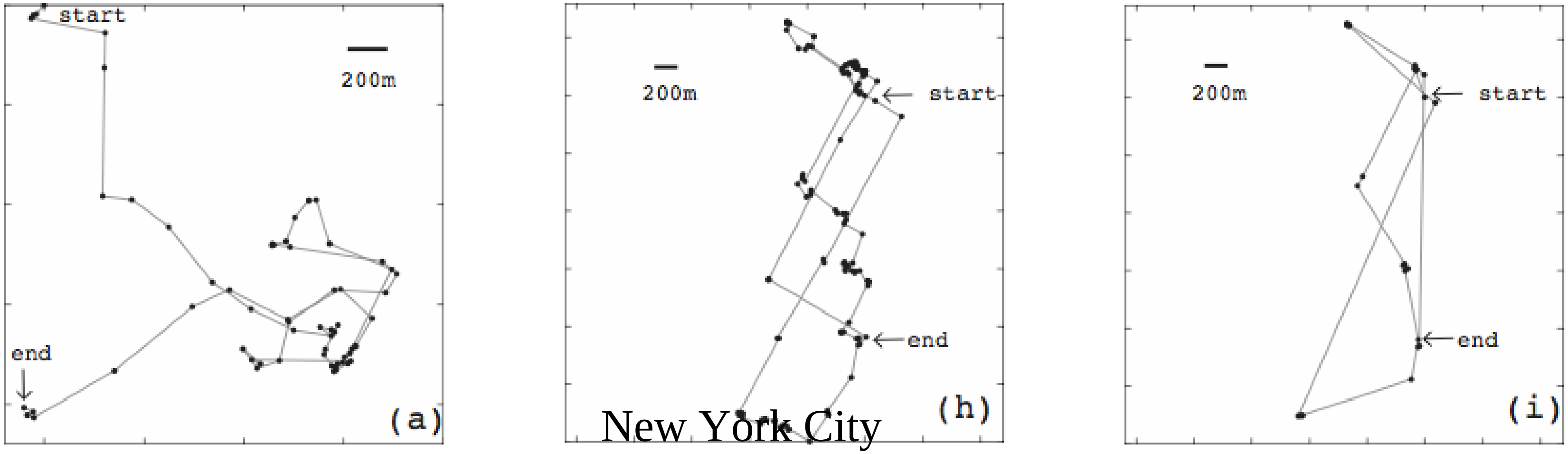


Sample traces

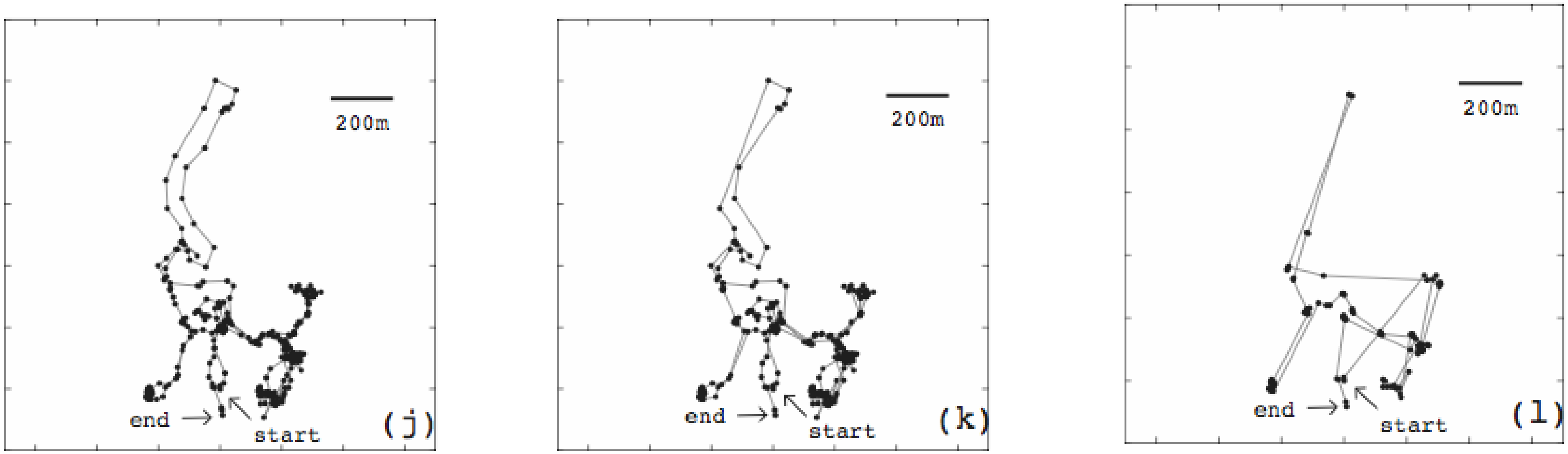


$r = w = 5$

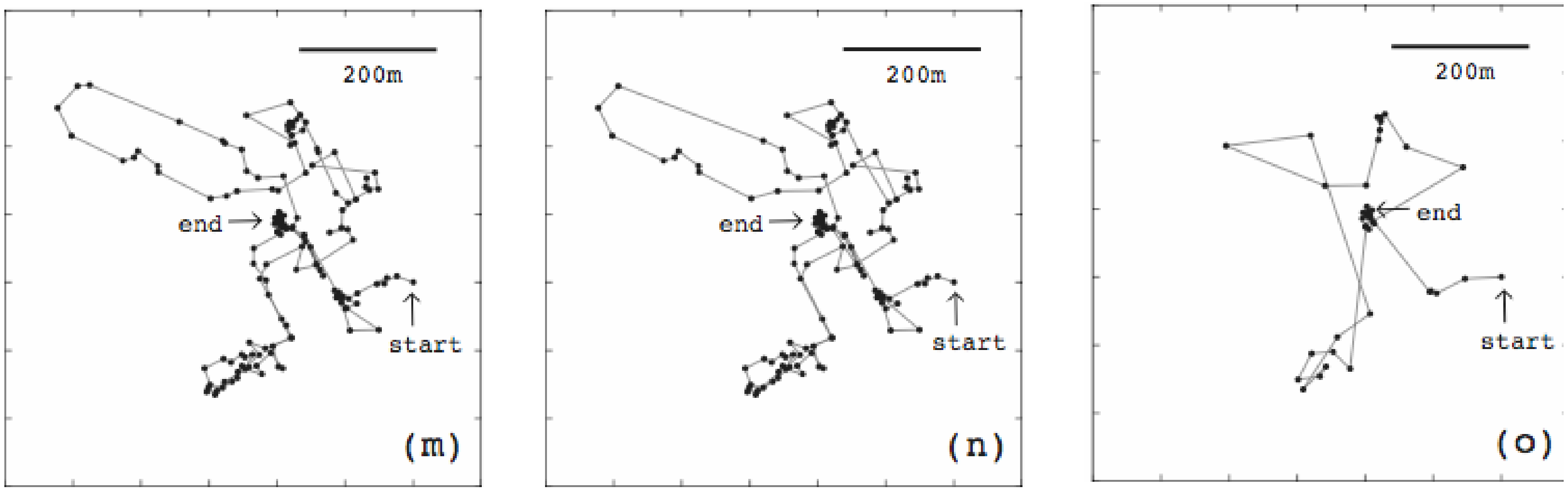
$a_\theta = 30$



New York City



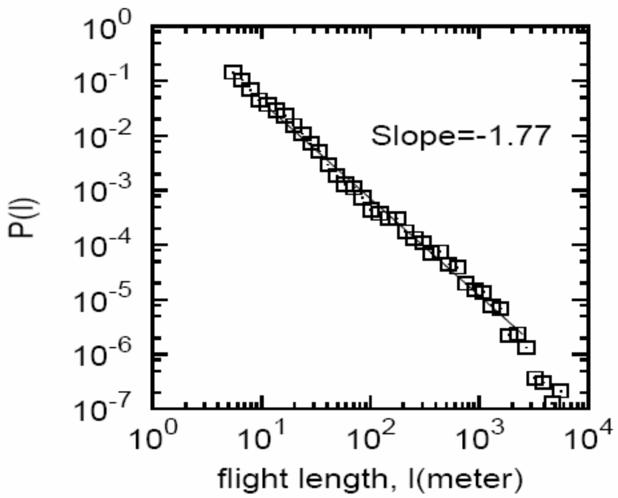
Disney World, Orlando



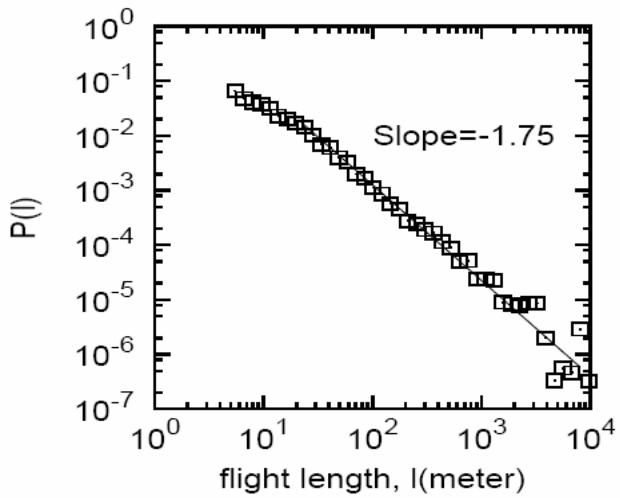
NC State Fair

Human mobility – Flight length distribution

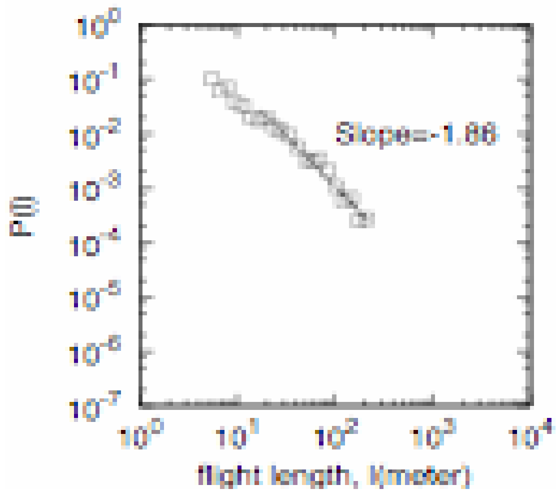
- **Hallmark of Levy walk**
  - All scenarios show power-law tendency of flight length distributions.
  - Heavy tails up to a few kilometers (truncation point)
    - Except State fair because of the small area



(a) Campus I



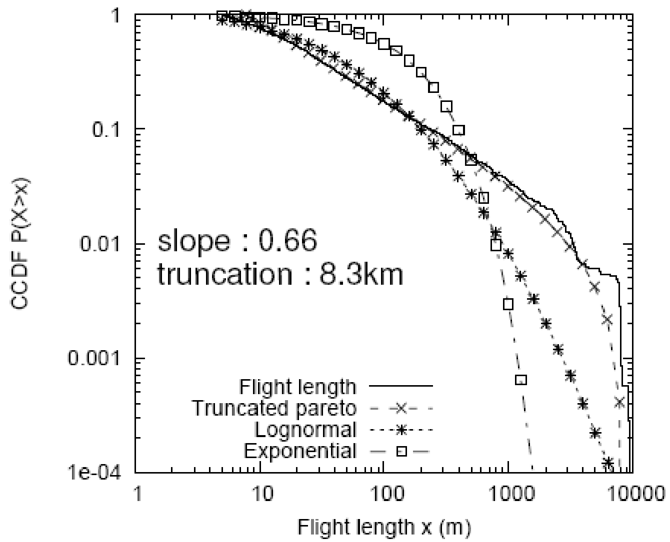
(b) New York City



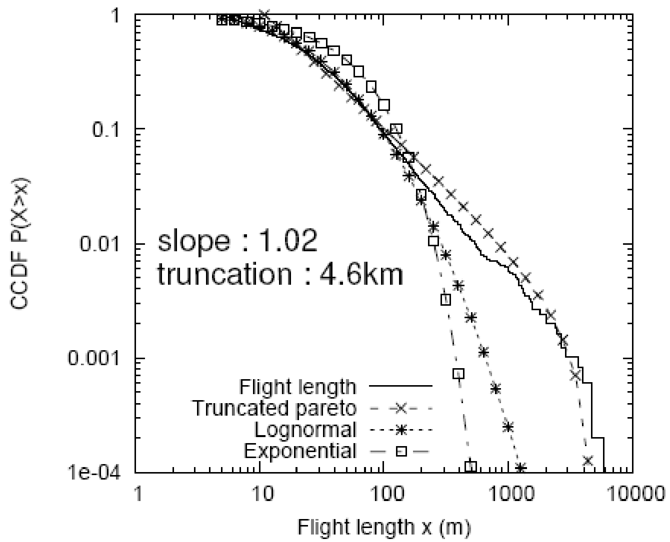
(c) State Fair

Maximum Likelihood Estimation (MLE)

- **MLE test to fit CCDF of the flight lengths**
  - Truncated pareto, exponential, lognormal distributions are tested.
  - Best fit with the truncated pareto distribution



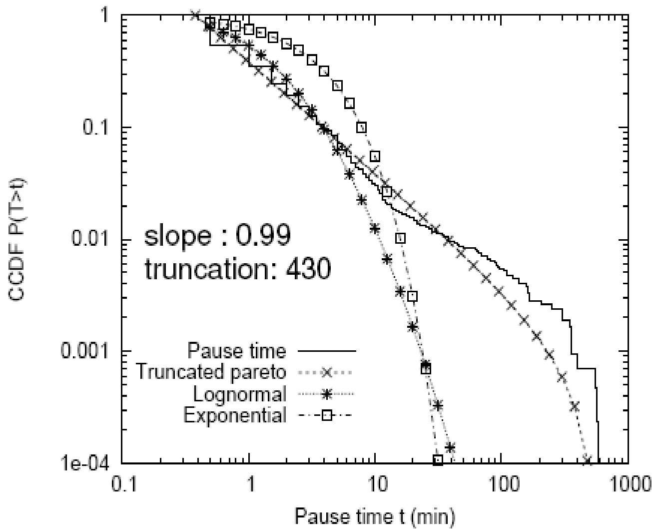
New York City



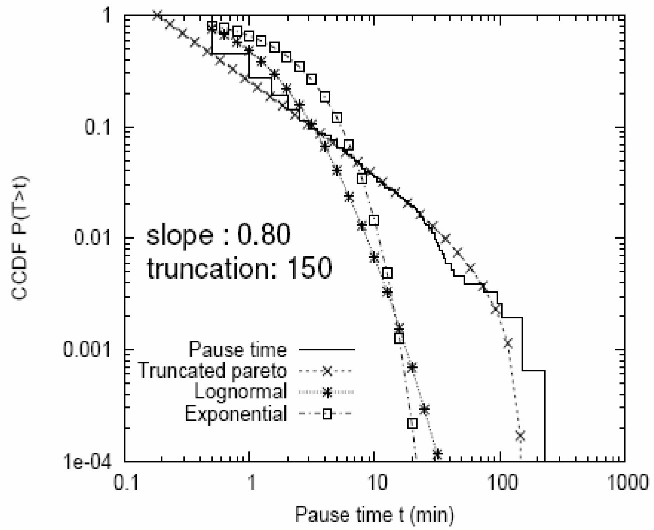
Disney World

Pause time distribution

- **Heavy-tail pause-time distribution**
  - Best fit with truncated pareto distribution
  - Long trapping makes the mobility less diffusive
    - Sometimes causing sub-diffusion, $\gamma < 1$



Campus I

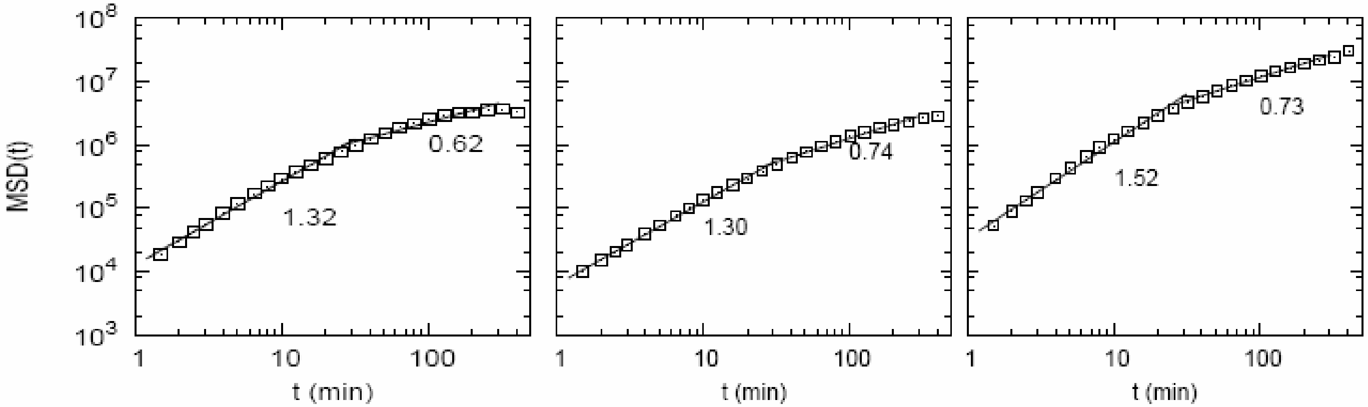


Disney World

Mean squared displacement

$$\mathrm{MSD}(t) = \frac{\sum_T \sum_{t_0} |\mathrm{pos}_T(t+t_0) - \mathrm{pos}_T(t_0)|^2}{N}$$

- **Scale-free mobility leads to abnormal diffusion**
  - Up to 30 min, our participants make super-diffusion $\gamma > 1.2$
  - After that, they make sub-diffusion $\gamma < 1.0$
- **Reasons**
  - Truncated flight lengths + power-law pause time => sub-diffusion
  - Home-coming tendency of humans



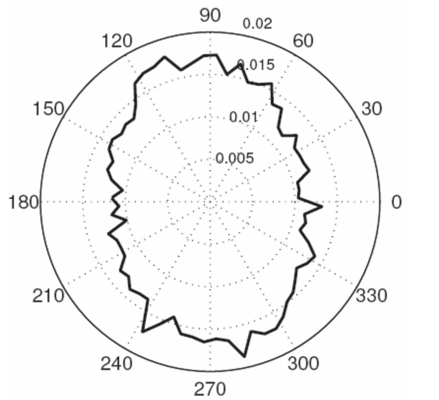
(a) NCSU (b) KAIST (c) New York City

Levy-walk mobility model

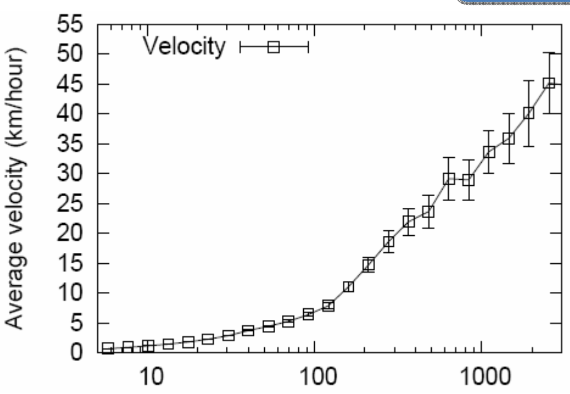
- **Model parameters**

Flight length	l	Direction	θ
Flight time	Δt_f	Pause time	Δt_p

- Flight length : power-law 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 : power-law distribution $\psi(\Delta t_p) \sim \Delta t_p^{-(1+\beta)}$



Turning Angle Distribution



Average Velocity over Flight Length

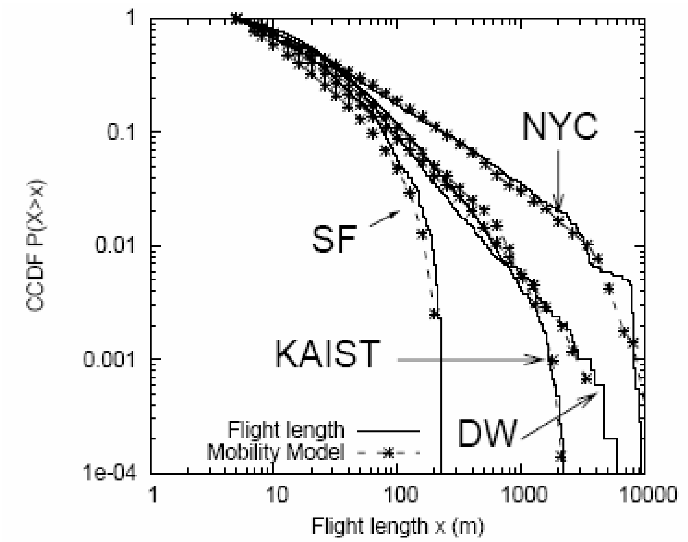
Velocity Model

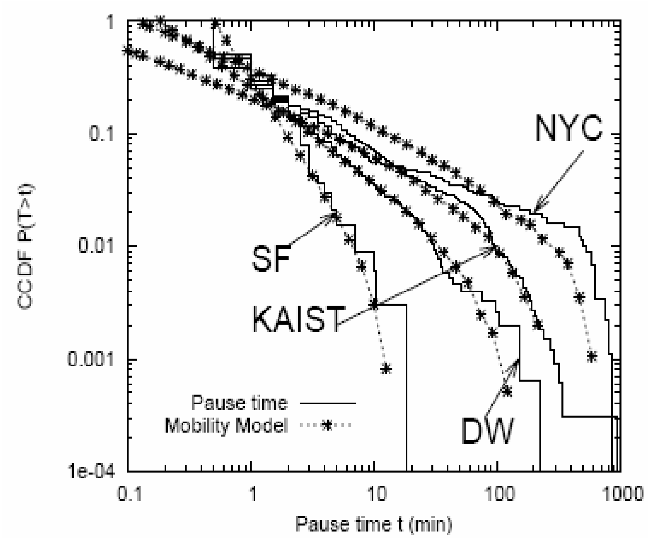
$k = 18.72, \rho = 0.79$ for $l < 500m$

$k = 1.37, \rho = 0.36$ for $l \ge 500m$

Levy-walk mobility model

- **Mobility models to be compared**
  - Flight length : Levy ($0<\alpha<2$), BM ($\alpha=2$), RWP (as defined)
  - Direction : Levy, BM (uniform), RWP (as defined)
  - Flight time : Levy, BM, RWP (velocity model in previous page)
  - Pause time : Levy ($0<\beta<2$), BM ($\beta=2$), RWP (uniform)
- **Generation steps**
  - Determine : flight length → direction → corresponding flight time and pause time
  - Repeat





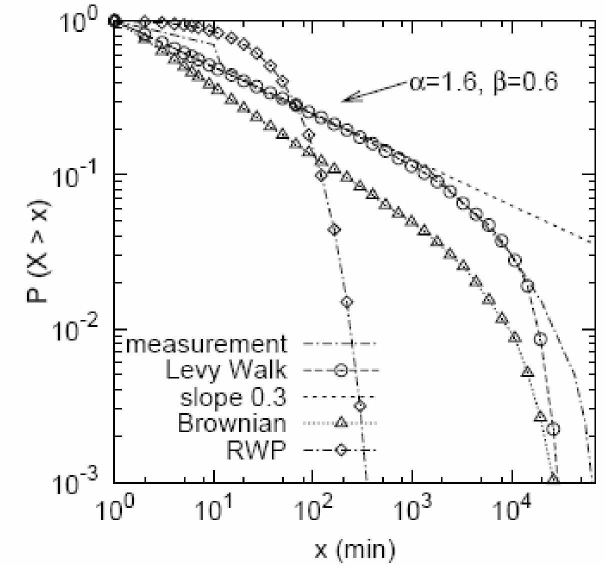
Inter-contact time distribution

- **Simulation results on the ICT**
  - RWP: Exponential
  - Levy & BM: Power-law

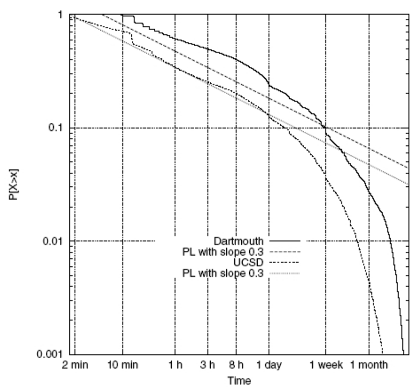
- **Simulation settings**
  - 40 nodes in square area
  - settings are from real data

	UCSD	Infocom 05
area	3.5x3.5 km^2	1.5x1.5km^2
max f.l.	3 km	200 m
max p.t.	28 hours	1 hour
tx range	250 m	100 m

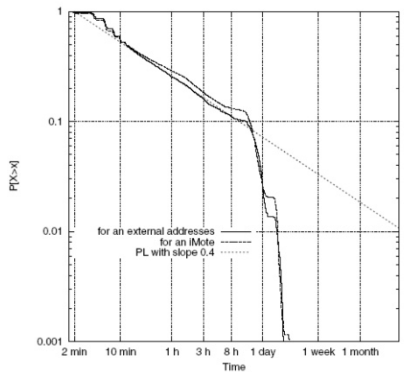
- **Levy mobility model reflects the characteristics of human mobility well in the viewpoint of ICT**



CCDF of ICT (simulation results)



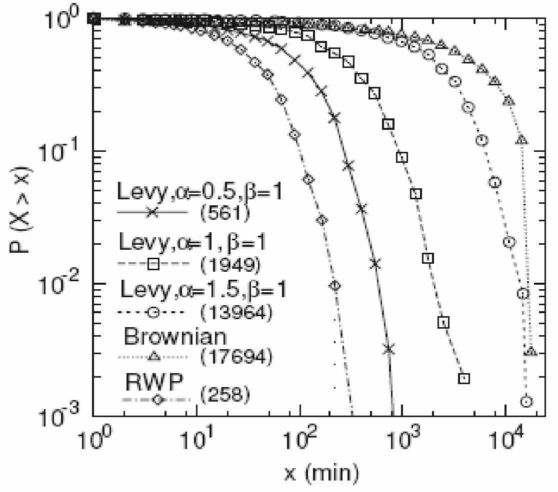
ICT (UCSD)



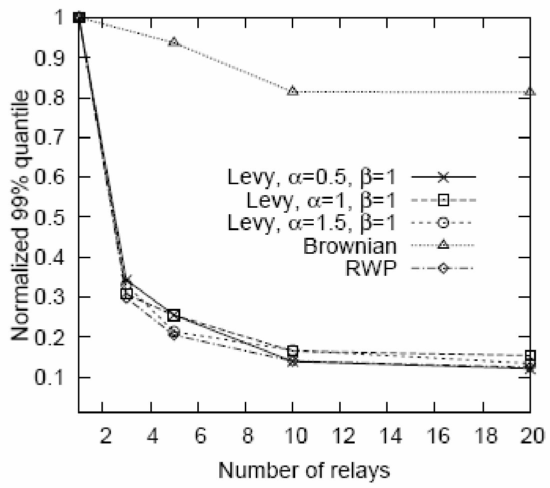
ICT (Infocom 2005)

Impact on DTN

- **In BM, delay does not improve much with multiple relays**
  - Since still many relays take long time to meet the destination
- **RWP and Levy walk models show the same ratio of improvement**
  - In RWP, most nodes travel long distances frequently
  - In Levy walks, there are some nodes that make such long trips with high probability
- **Great reduction of the delays even with a small number of relays in RWP and Levy walk**



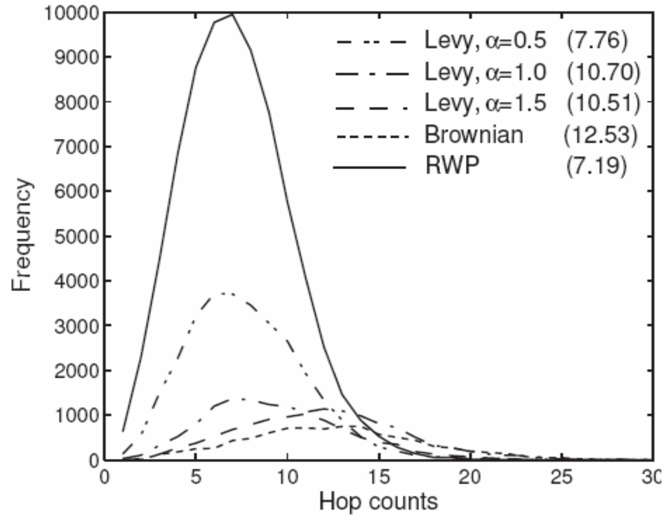
DTN delay using one relay

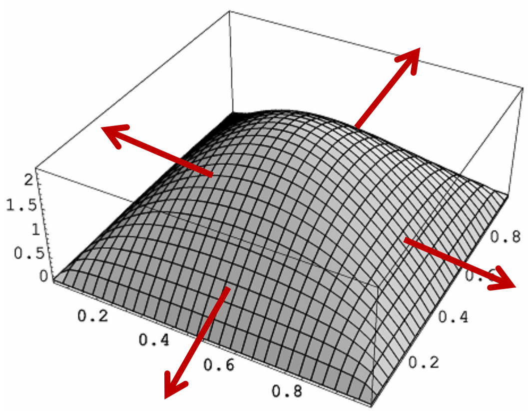


Normalized DTN delay using multiple relays

Preliminaries in routing

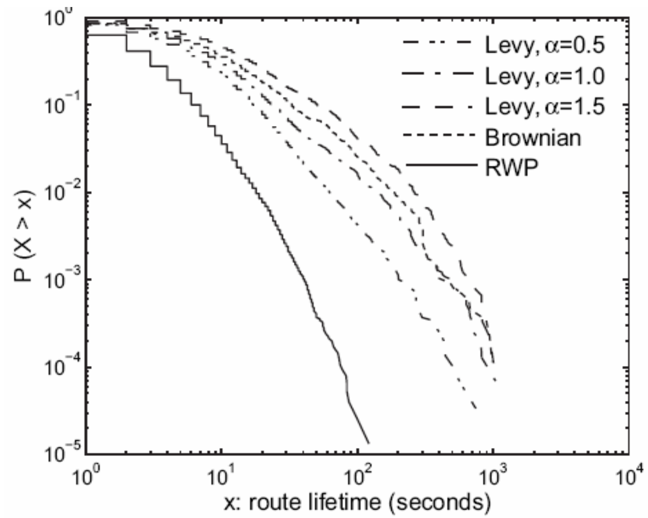
- **Observations**
  - Levy walk has longer hops than RWP
    - Nodes in Levy walk are more spread out in the area since they are less diffusive
  - Levy walk has longer path duration than RWP
    - Effect of short flights and heavy tailed pause time





Node distributions are flatter in BM and Levy-walk

Node Distribution of RWP
C. Bettstetter, G. Resta, P. Santi, “The Node Distribution of the Random Waypoint Mobility Model for Wireless Ad Hoc Networks”, IEEE TMC 2003



MANET performance comparison

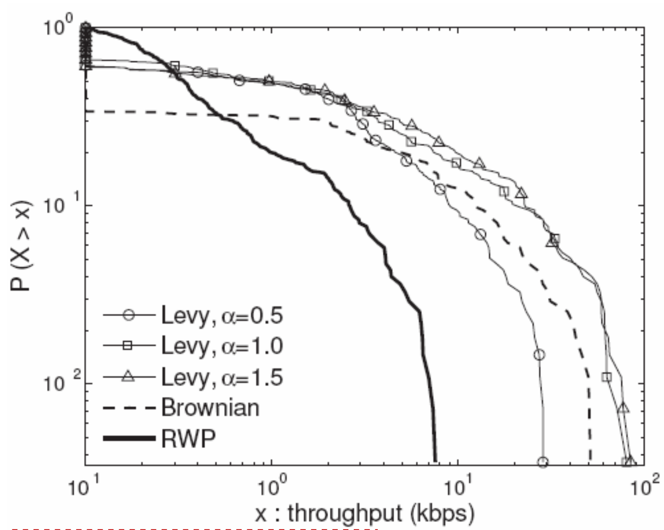
- **DSR Routing Performance Comparison**

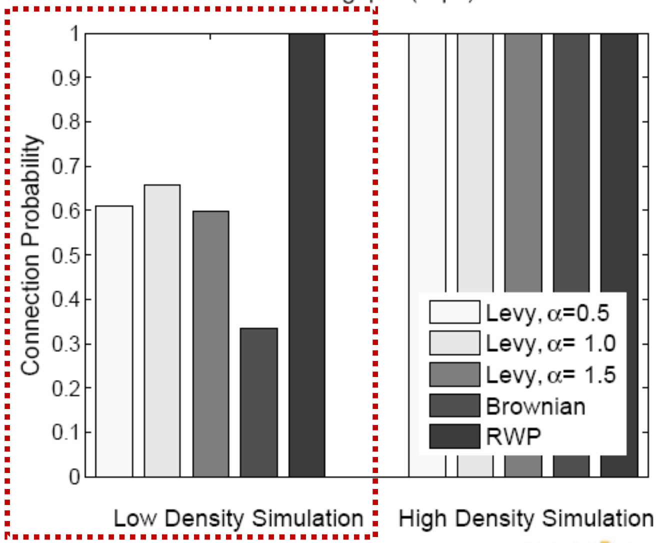
Parameter	Value
Simulation Tool	GloMoSim v2.03 (UCLA)
Radio Range	250m
Number of nodes	100
Data Rate	2 Mbps
Simulation Time	2000 seconds
Simulation Area	2 km x 2 km (Low density) 1 km x 1 km (High density)
Max Flight	1 km (Low density) 500 m (High density)
Max Pause	1000 seconds (Levy, BM) 60 seconds (RWP)

Parameter	Value
Pause Time Distribution	Levy (Levy) BM (BM) Uniform (RWP)
Velocity	Developed Velocity Model

MANET routing (Low density)

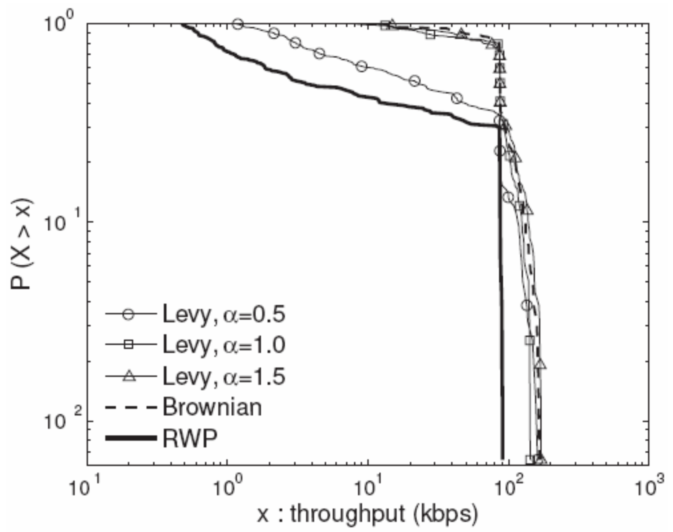
- **Levy walk has much more throughput in tail part than RWP**
  - Shorter flight and longer pause time
  - Long path duration
- **BM has less throughput in tail than some Levy walk**
  - Shorter flight but shorter pause time than Levy walk
- **RWP accomplishes 100% connection due to its busy movement**

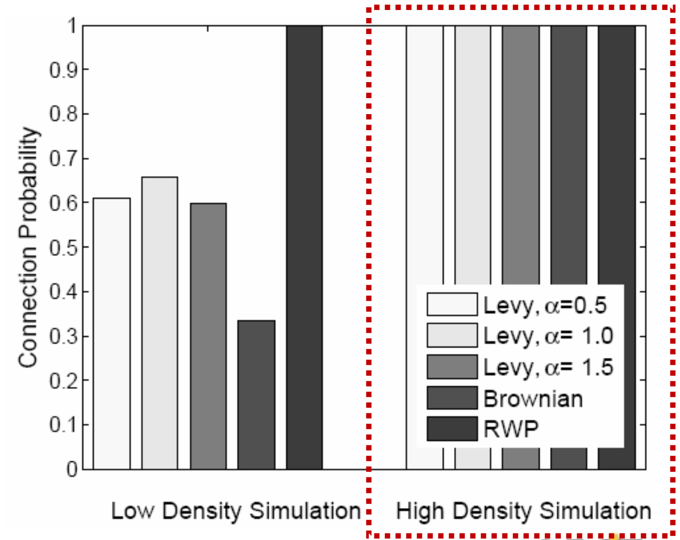




MANET routing (High density)

- **Levy walk & BM still provides more throughput in tail part than RWP**
- **All mobility model show 100% connection**
- **In MANET routing,**
  - Higher α ➔ More throughput, Lower connection probability
  - Higher β ➔ Less throughput, Higher connection probability





Conclusion

- **Human mobility at outdoor setting**
  - Statistically resembles Levy walk
  - Power-law tendency of flight lengths and pause time
  - Super-diffusive characteristic
- **Simple Levy walk mobility model**
  - Recreating power-law distribution of inter-contact times
  - Routing performance with Levy walk mobility model shows distinctive features
- **Future work**
  - Exploring the cause of scale-free human mobility
  - Inter-dependency of humans such as grouping
  - Throughput-delay trade off caused by Levy walk
  - Characterizing inter-contact time analytically using Levy parameters