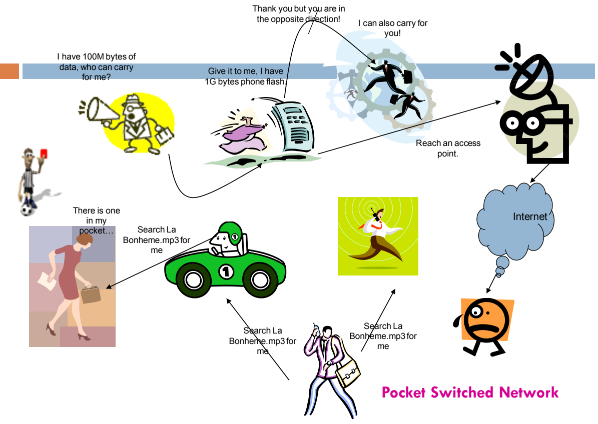
LECTURE 14 : MOBILITY AND OPPORTUNISTIC NETWORKING

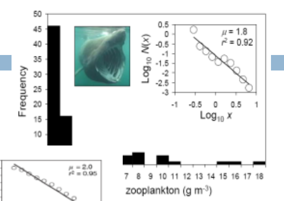


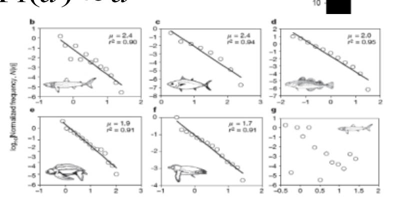
People Are the Network

Mobility Pattern

Pattern: most of the studies on animal mobility pattern including experimental data and theoretic analysis found that their mobility pattern follow the Levy flight:

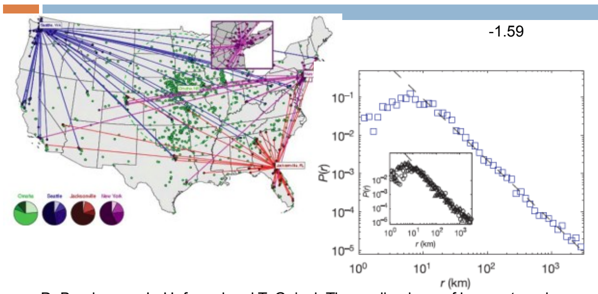
$$\Pr(d) \propto d^{-2}$$





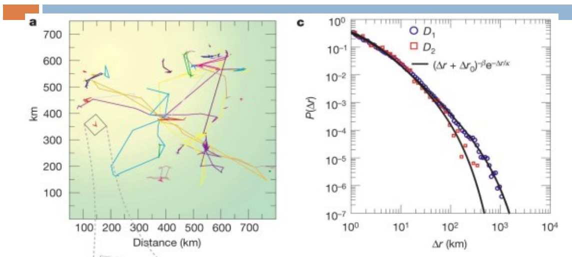
Levy flight search patterns of wandering albatrosses, Nature 381, (1996)
Revisiting Le´vy flight search patterns of wandering albatrosses, bumblebees and deer, NATURE| Vol 449|25 October 2007
Scaling laws of marine predator search behaviour, Nature (2008)

Human Mobility



D. Brockmann, L. Hufnagel and T. Geisel, The scaling laws of human travel, Nature, 439, 462-465, (2006).

Human Mobility

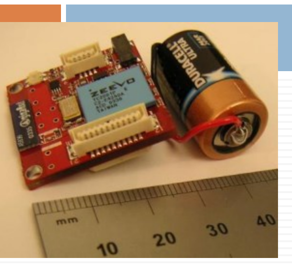


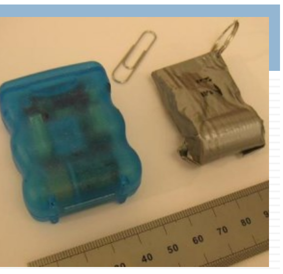
Understanding individual human mobility patterns
Marta C. Gonza´lez, Ce´sar A. Hidalgo & Albert-La´szlo´ Baraba´si, NATURE| Vol 453|5 June 2008

EXPERIMENTAL SETUP

- iMotes
  - ARM processor
  - Bluetooth radio
  - 64k flash memory
- Bluetooth Inquiries
  - 5 seconds every 2 minutes
  - Log {MAC address, start time, end time} tuple of each contact

Experimental devices

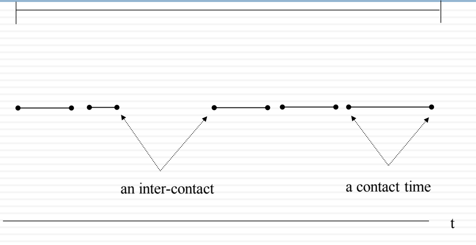




Experimental data set	Cambridge04	Infocom05	Hong Kong	Cambridge05	Infocom06
Device	iMote	iMote	iMote	iMote	iMote
Network type	Bluetooth	Bluetooth	Bluetooth	Bluetooth	Bluetooth
Duration (days)	3	3	5	11	3
Granularity (seconds)	120	120	120	600	120
Number of Experimental Devices	12	41	37	54	98
Number of internal contacts	4,229	22,459	560	10,873	191,336
Average # Contacts/pair/day	10	4.6	0.084	0.345	6.7
Number of External Devices	148	264	868	11,357	14,036
Number of external contacts	2,441	1,173	2,507	30,714	63,244

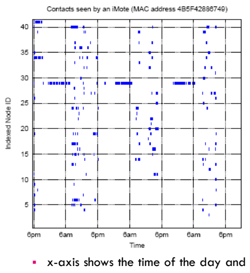
User Population	Toronto	UCSD	Dartmouth	MIT BT	MIT GSM
Device	PDA	PDA	Laptop/PDA	Cell Phone	Cell Phone
Network type	Bluetooth	WiFi	WiFi	BT	GSM
Duration (days)	16	77	114	246	246
Granularity (seconds)	120	120	300	300	10
Devices participating	23	273	6648	100	100
Number of internal contacts	2,802	195,364	4,058,284	54,667	572,190
Average # Contacts/pair/day	0.35	0.034	0.00080	0.022	0.23
Recorded external devices	N/A	N/A	N/A	N/A	N/A
Number of external contacts	N/A	N/A	N/A	N/A	N/A

PAIR WISE RELATIONSHIP

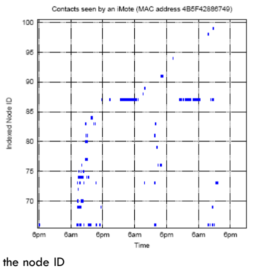


Contacts seen by an iMote

iMotes



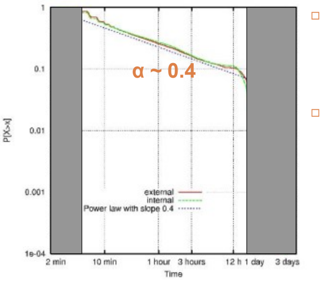
External Devices



- x-axis shows the time of the day and the y-axis shows the node ID
- Contacts are sparse
- iMote sees node 28 every night and they stay together the whole night ☺

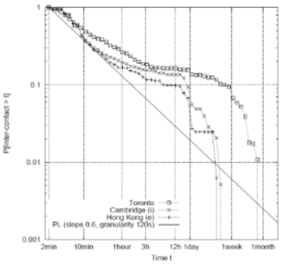
Heavy Tailed Distributions

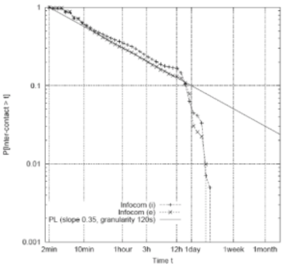
- Inter-contact time distribution



- It compares with a Power law on range [5mn;1day] slope α ~ 0.4 .
- Internal and external contacts have almost the same law.

OTHER EXAMPLES





Implication on Opportunistic Forwarding:

- For $\alpha > 2$
  - Any stateless algorithm achieves a finite expected delay.
- For $\alpha \ge \frac{m+1}{m}$ and $\#\{\text{ nodes }\} \ge 2m$
  - There exist a forwarding algorithm with m copies and a finite expected delay.
- For $\alpha < 1$
  - No stateless algorithm (even flooding) achieve a bounded delay (Orey's theorem).

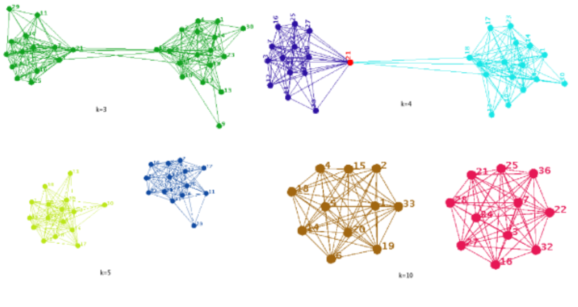
Social Structures Vs Network Structures

- **Community structures**
  - Social communities, i.e. affiliations
  - Topological cohesive groups or modules
- **Centralities**
  - Social hubs, celebrities and postman
  - Betweenness, closeness, inference power centrality

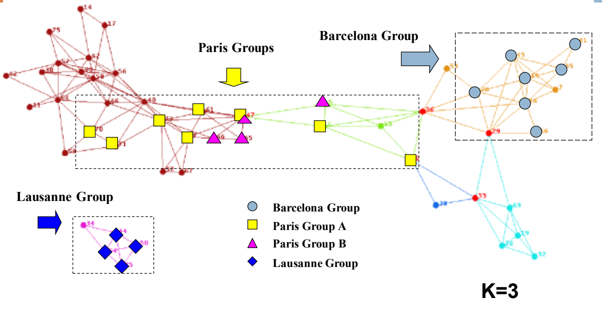
K-clique Community Definition

- **Union of k-cliques reachable through a series of adjacent k-cliques [Palla et al]**
- **Adjacent k-cliques share k-1 nodes**
- **Members in a community reachable through well-connected well subsets**
- **Examples**
  - 2-clique (connected components)
  - 3-clique (overlapping triangles)
  - Overlapping feature

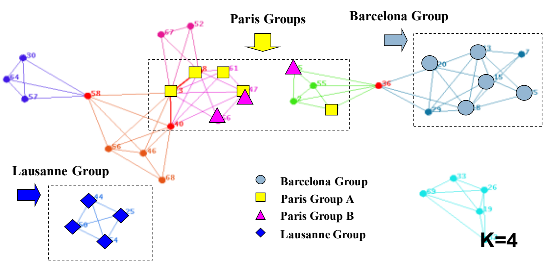
K-clique Communities in Cambridge Dataset



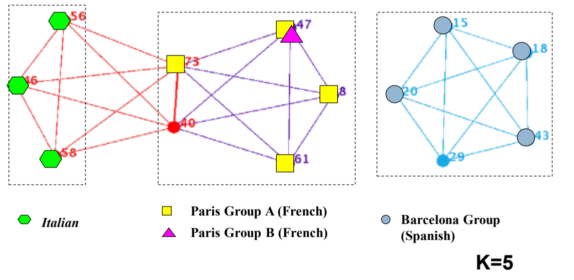
K-clique Communities in Infocom06 Dataset



K-clique Communities in Infocom06 Dataset



K-clique Communities in Infocom06 Dataset



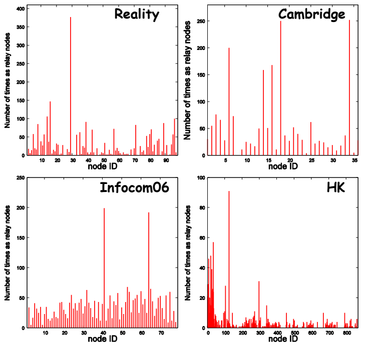
Other Community Detection Methods

- Betweenness [Newman04]
- Modularity [Newman06]
- Information theory[Rosvall06]
- Statistical mechanics[Reichardt]
- Weighted Network Analysis[Newman05]
- Survey Papers[Danon05][Newman04]

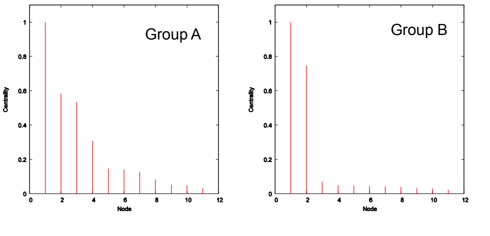
Centrality in Temporal Network

- Large number of unlimited flooding
- Uniform sourced and temporal traffic distribution
- Number of times on shortest delay deliveries
- Analogue to Freeman centrality [Freeman]

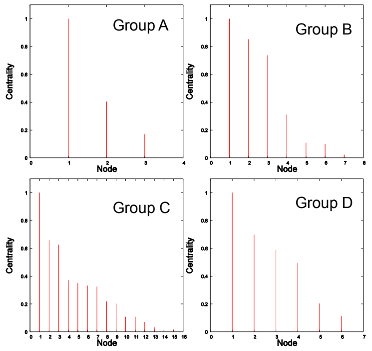
Homogenous Centrality



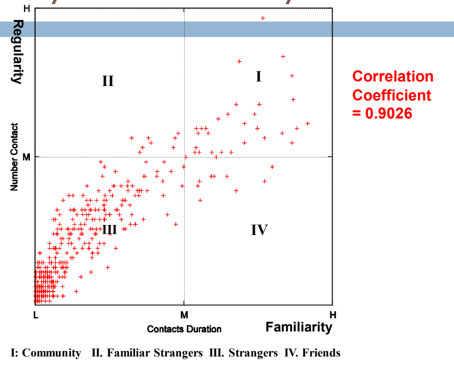
Within Group Centrality Cambridge Dataset

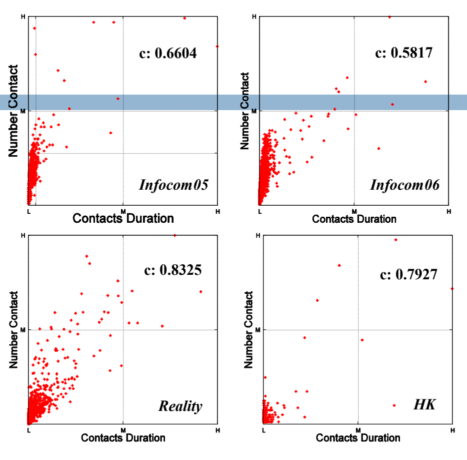


Within Group Centrality Reality Dataset



Regularity and Familiarity





Interaction and Forwarding

Third generation human interaction model

- Categories of human contact patterns
- Clique and community
- Popularity/Centrality

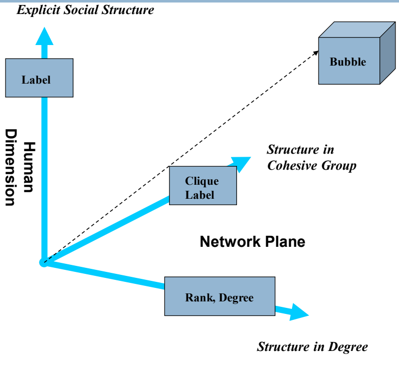
Dual natures of mobile network

- Social network
- Physical network

Benchmark Forwarding strategies

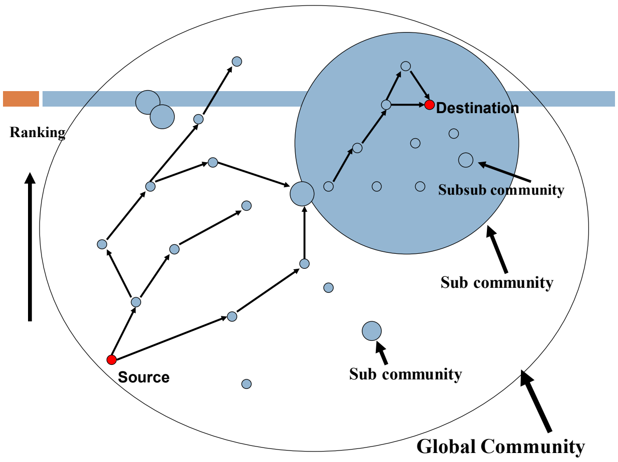
- Flooding, Wait, and Multiple-copy-multiple-hop (MCP), PROPHET

Design Space

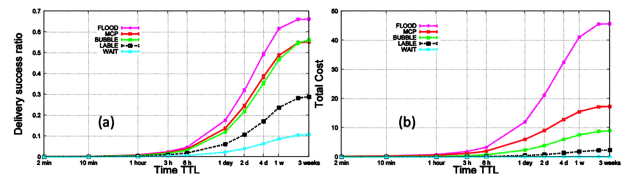


Centrality meets Community

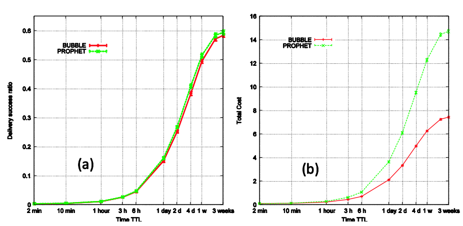
- Population divided into communities
- Node has a global and local ranking
- Global popular node like a postman, or politician in a city
- Local popular node
- BUBBLE



Centrality meets Community



Centrality meets Community

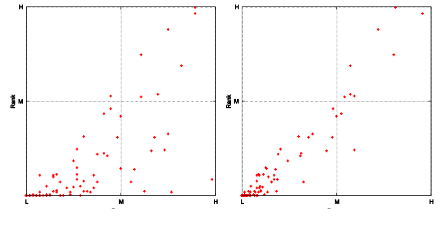


Making Centrality Practical

How can each node know its own centrality in decentralised way?

How well does past centrality predict the future?

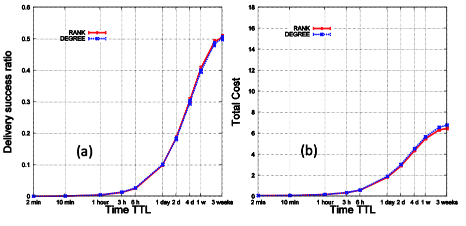
Approximating Centrality



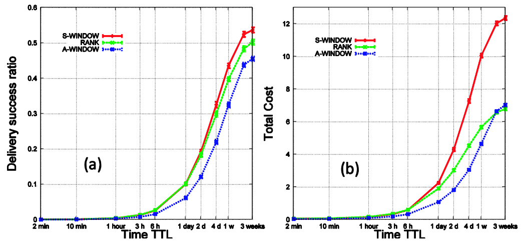
- Total degree, per-6-hour degree
- Correlation coefficients, 0.7401 and 0.9511

Approximating Centrality

- DEGREE
- S-Window
- A-Window (Exponential Smoothing)



Approximating Centrality

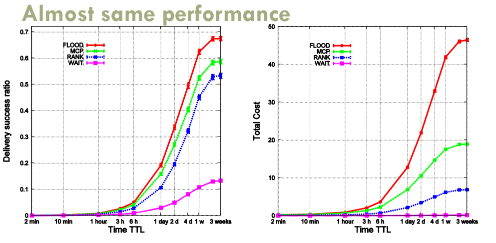


Predictability of Human Mobility

Three sessions of Reality dataset

Two sessions using the ranking calculated from the first session

Almost same performance



Distributed Community Detection

SIMPLE, *K-CLIQUE*, *MODULARITY*

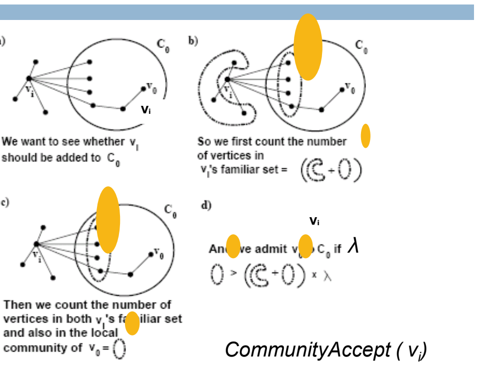
Terminology : Familiar Set (*F*), Local Community (*C*)

Update and exchange local information during encounter

Build up Familiar Set and Local Community

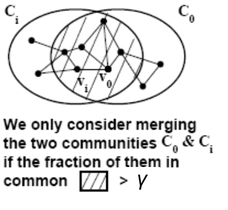
☐*CommunityAccept*( ), *MergeCommunities*( )

SIMPLE



CommunityAccept (v_i)

SIMPLE



MergeCommunities (C_o, C_i)

Results and Evaluations

Data Set	SIMPLE	K-CLIQUE	MODULARITY
Reality	0.79/0.76	0.87	0.82
UCSD	0.47/0.56	0.55	0.40
Cambridge	0.85/0.85	0.85	0.87
Complexity	O(n)	O(n^2)	O(n^4)/O(n^2k^2)

Newman weighted analysis

Palla et al, k-Clique

$$\sigma_{Jaccard} = \frac{|\Gamma_i \bigcap \Gamma_j|}{|\Gamma_i \bigcup \Gamma_j|}$$

Distributed BUBBLE RAP (DiBuBB)