Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

UPMC PARIS UNIVERSITAS

Mobility Modeling

Dr. Franck Legendre

Master RES – Nouveaux Réseaux et Services

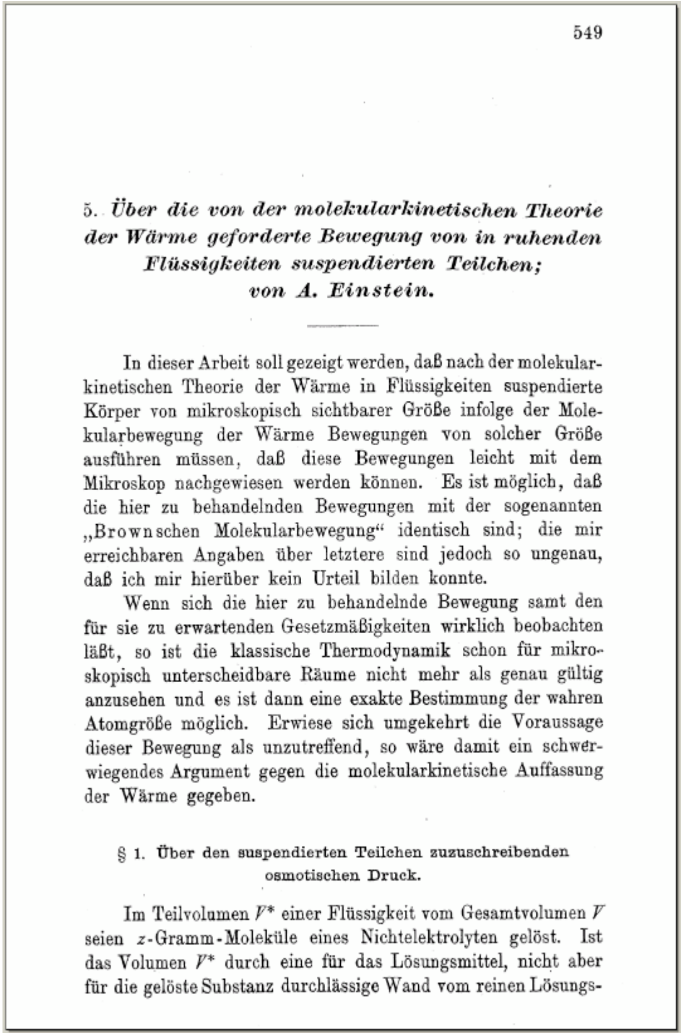
Outline

- Introduction
  - Rationale, Classification, State-of-art
- Mobility Models
  - From random to more realistic models
- Performance evaluation
  - Analytical vs. Simulations vs. Traces vs. Experiments
- System design
  - Designing better communication systems
- Outlook, demos and conclusion

Outline

- Introduction
  - Rationale, Classification, State-of-art
- Mobility Models
  - From random to more realistic models
- Performance evaluation
  - Analytical vs. Simulations vs. Traces vs. Experiments
- System design
  - Designing better communication systems
- Outlook, demos and conclusion

It all started with Einstein's Brownian motion



549

5. *Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen;*
von A. Einstein.

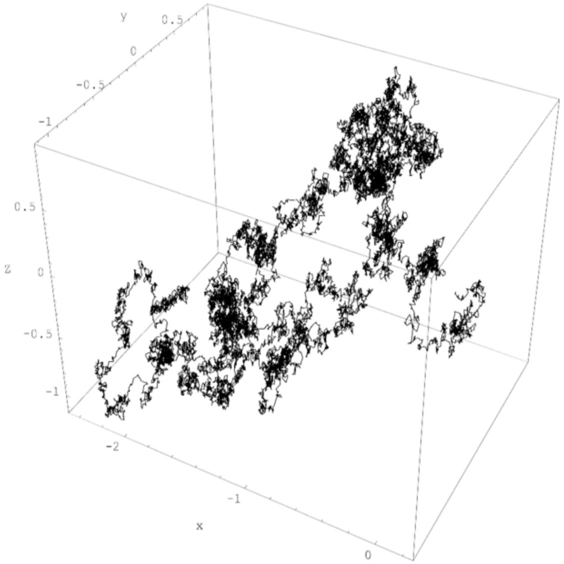
In dieser Arbeit soll gezeigt werden, daß nach der molekularkinetischen Theorie der Wärme in Flüssigkeiten suspendierte Körper von mikroskopisch sichtbarer Größe infolge der Molekularbewegung der Wärme Bewegungen von solcher Größe ausführen müssen, daß diese Bewegungen leicht mit dem Mikroskop nachgewiesen werden können. Es ist möglich, daß die hier zu behandelnden Bewegungen mit der sogenannten „Brownschen Molekularbewegung" identisch sind; die mir erreichbaren Angaben über letztere sind jedoch so ungenau, daß ich mir hierüber kein Urteil bilden konnte.

Wenn sich die hier zu behandelnde Bewegung samt den für sie zu erwartenden Gesetzmäßigkeiten wirklich beobachten läßt, so ist die klassische Thermodynamik schon für mikroskopisch unterscheidbare Räume nicht mehr als genau gültig anzusehen und es ist dann eine exakte Bestimmung der wahren Atomgröße möglich. Erwiese sich umgekehrt die Voraussage dieser Bewegung als unzutreffend, so wäre damit ein schwerwiegendes Argument gegen die molekularkinetische Auffassung der Wärme gegeben.

§ 1. Über den suspendierten Teilchen zuzuschreibenden osmotischen Druck.

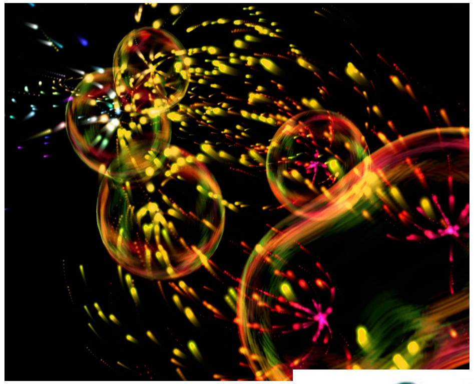
Im Teilvolumen V^* einer Flüssigkeit vom Gesamtvolumen V seien z-Gramm-Moleküle eines Nichtelektrolyten gelöst. Ist das Volumen V^* durch eine für das Lösungsmittel, nicht aber für die gelöste Substanz durchlässige Wand vom reinen Lösungs-

- "Investigations on the theory of Brownian movement"
  - To indirectly confirm the existence of atoms and molecules

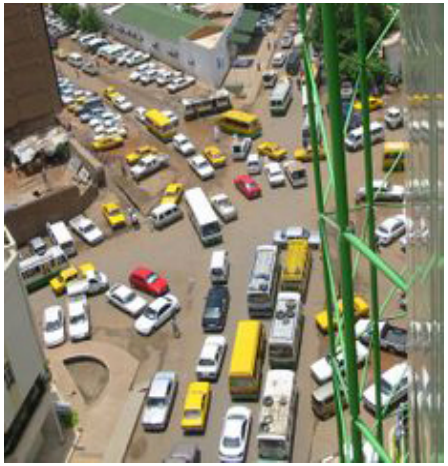


Many domains

Physics

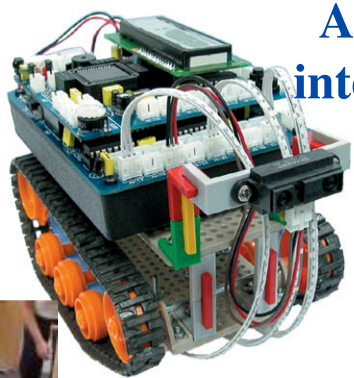


Transportation systems

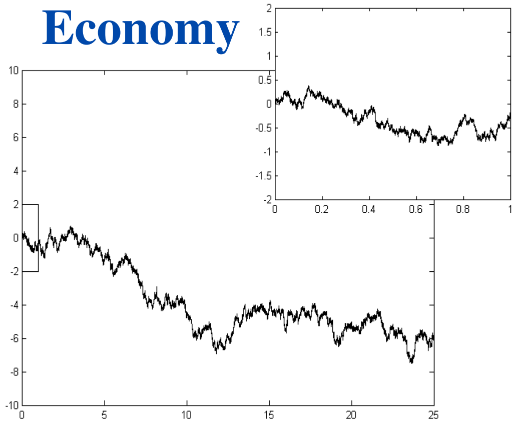


Biology

Artificial intelligence



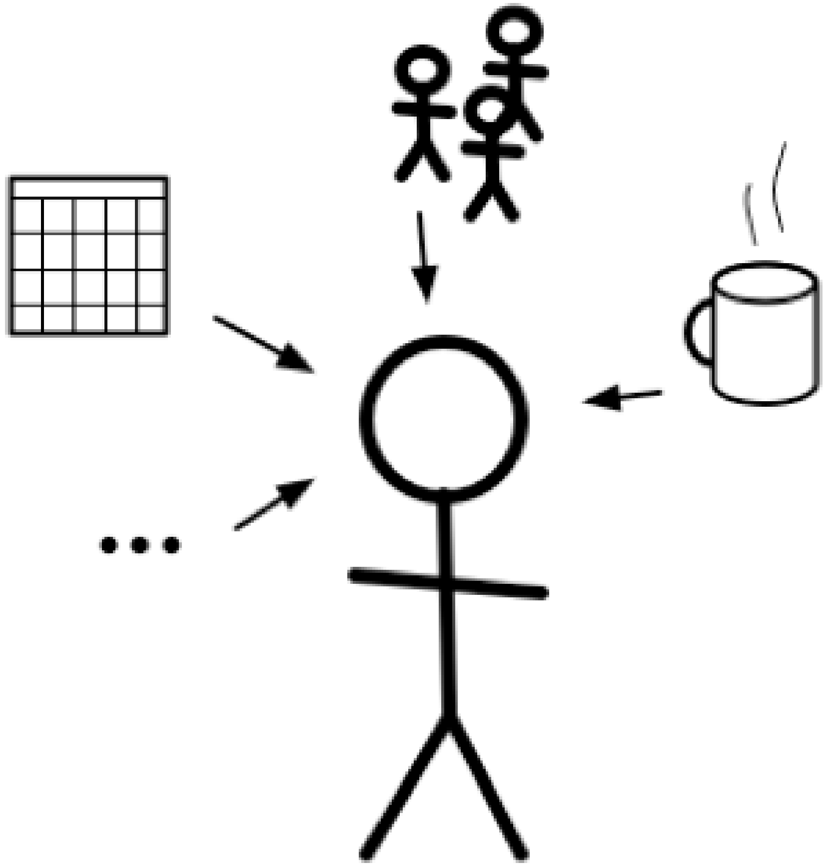
Economy



Architecture

Gaming

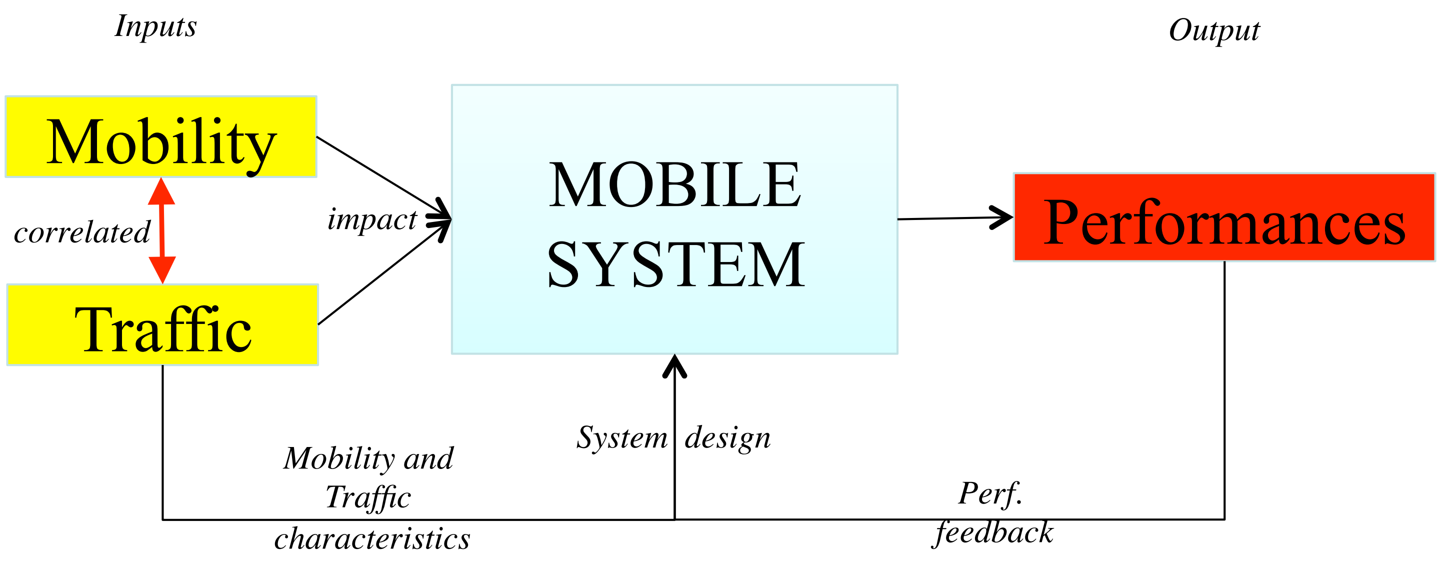
Understanding mobility is complex



Rationale for Mobility Models

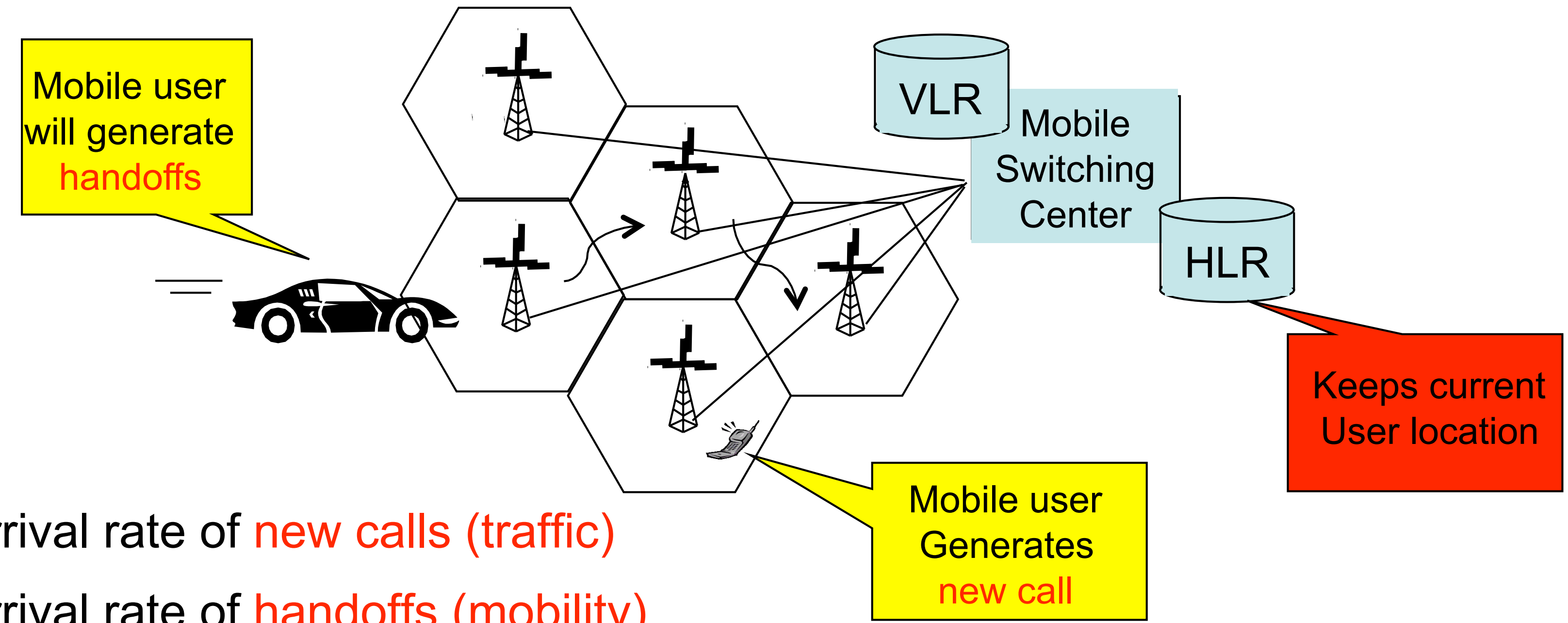
- Mobility Models are required for
  - Performance evaluation
    - Analytical
      - A system dynamics must be tractable in order to derive characteristics of interest
    - Simulations
      - Often used as an alternative when models are too complex (no analytical derivation)
      - But still complementary to the analytical approach
    - Trace-replaying and experiments
  - Solution design
    - Networking solutions should be designed according to their *in situ* environment (i.e., mobility context and characteristics)

Rationale for Mobility Models (cont'd)



Evaluation of Cellular Networks

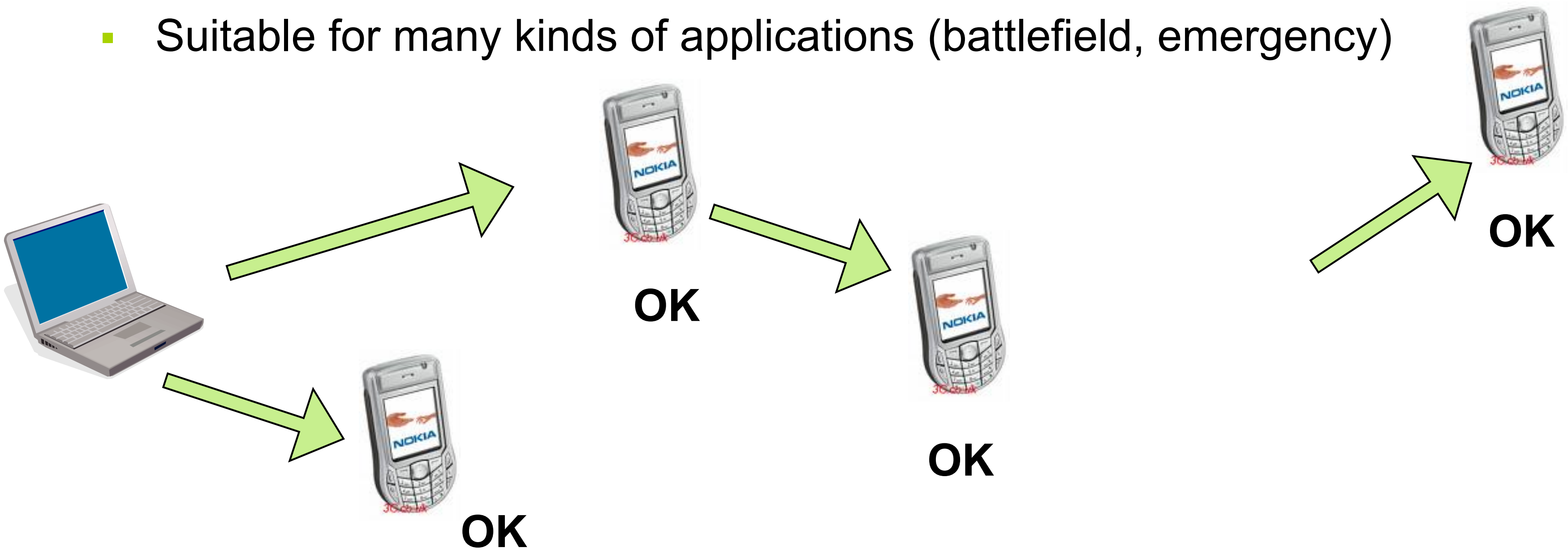
- Aim at providing integrated communications (i.e., voice, video, and data) between nomadic subscribers in a seamless fashion



- Input
  - Arrival rate of new calls (traffic)
  - Arrival rate of handoffs (mobility)
- Output
  - HLR load, probability of call rejection

Evaluation of Ad Hoc and Delay Tolerant Networks

- A wireless ad hoc network is a decentralized wireless network
  - Suitable for many kinds of applications (battlefield, emergency)



- Input
  - Both ends can move: mobility highly impacts the performances
- Output
  - Path duration from source to destination? Delay?

Classification of Mobility Models

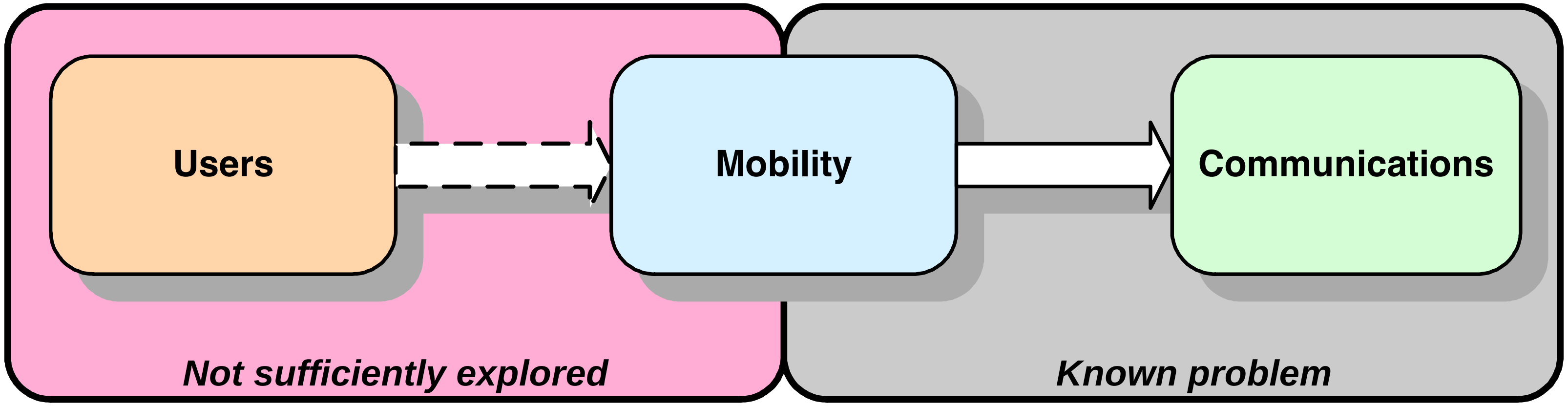
- Scale
  - Microscopic
    - accurately describes the motion of mobile individuals
  - Macroscopic
    - considers the displacement of mobile entities (e.g., pedestrians, vehicles, animals) at a coarse grain, for example in the context of large geographic areas such as adjacent regions or cells

- Formalism
  - Flow
  - Fluid (fluid-like PDE)
  - Stochastic (Markov, ODEs, Queuing)
  - Behavioral (non-linear)

Classification vs. Applications

	Macro	Micro-Macro		Micro
Applications	Cellular networks (e.g., PCS, 3G/4G)	Self-organizing networks (e.g., ad hoc, delay-tolerant, sensor, mesh)		
Level-of-detail	Low	Medium		High
Approaches (examples)	Markovian Fluid Gravity	*Synthetic*: RWP, RPGM City Section	*More Realistic*: Campus, Vehicular	Smooth RWP, Behavioral

The current situation in networking



Courtesy of Prof. Ammar

Outline

- Introduction
  - Rationale, Classification, State-of-art
- Mobility Models
  - From random to more realistic models
- Performance evaluation
  - Analytical vs. Simulations vs. Traces vs. Experiments
- System design
  - Designing better communication systems
- Outlook, demos and conclusion

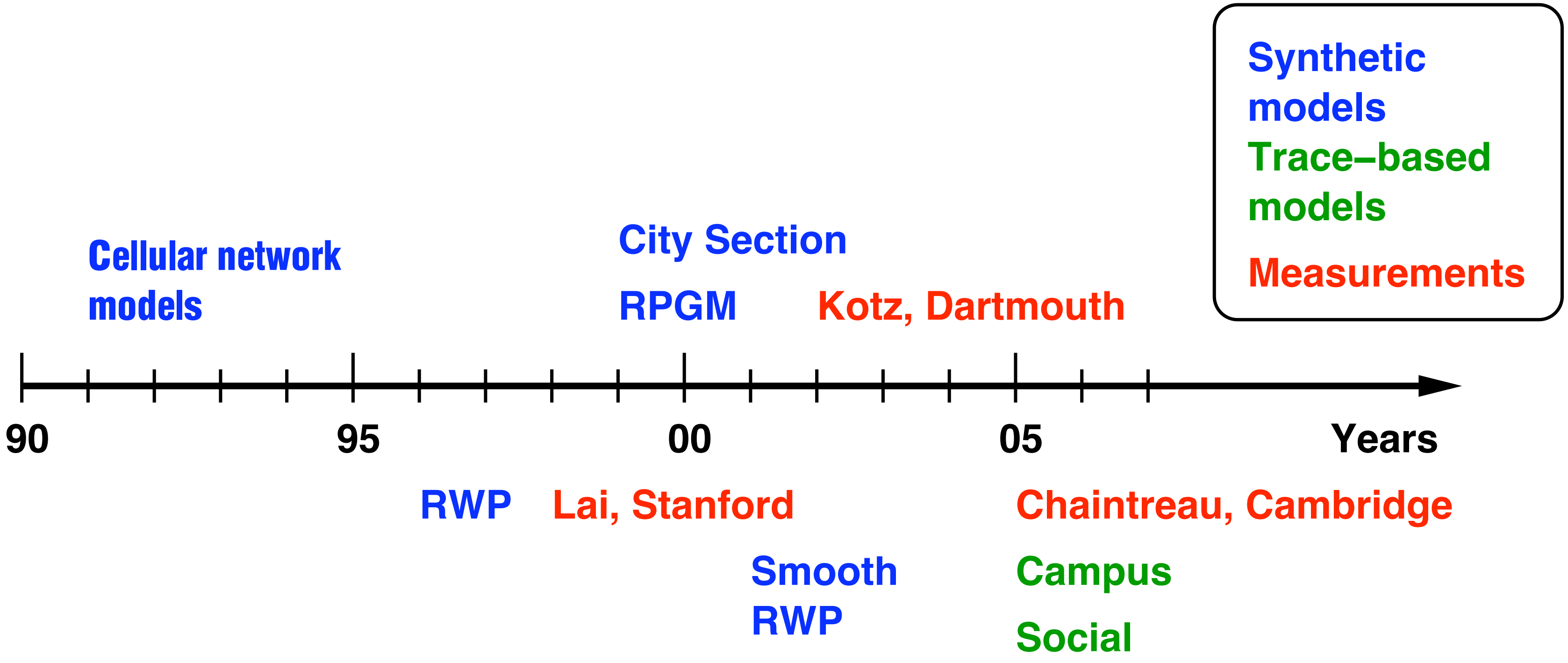
Mobility Models – From Random to more Realistic

- Cellular models

- Random Mobility models (synthetic) [**Camp02Survey**]
  - Ad Hoc
  - Vehicular

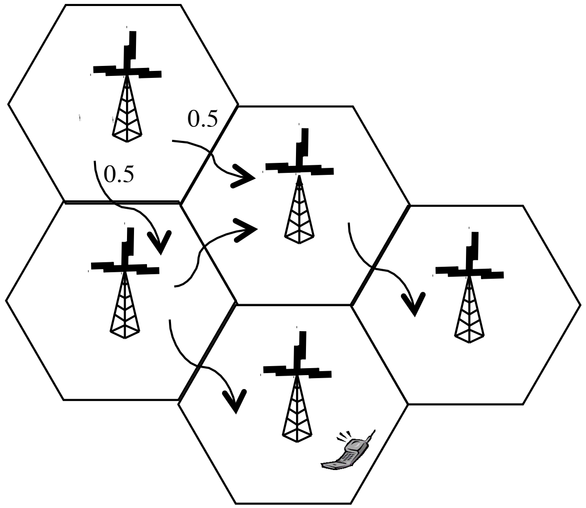
- More realistic mobility models
  - Extension of random models
  - Behavioral models: Ad Hoc, Vehicular **[Haerri06Survey]**, Social
  - Survey and Trace-based models

Mobility Models – Review



Cellular model – Markovian

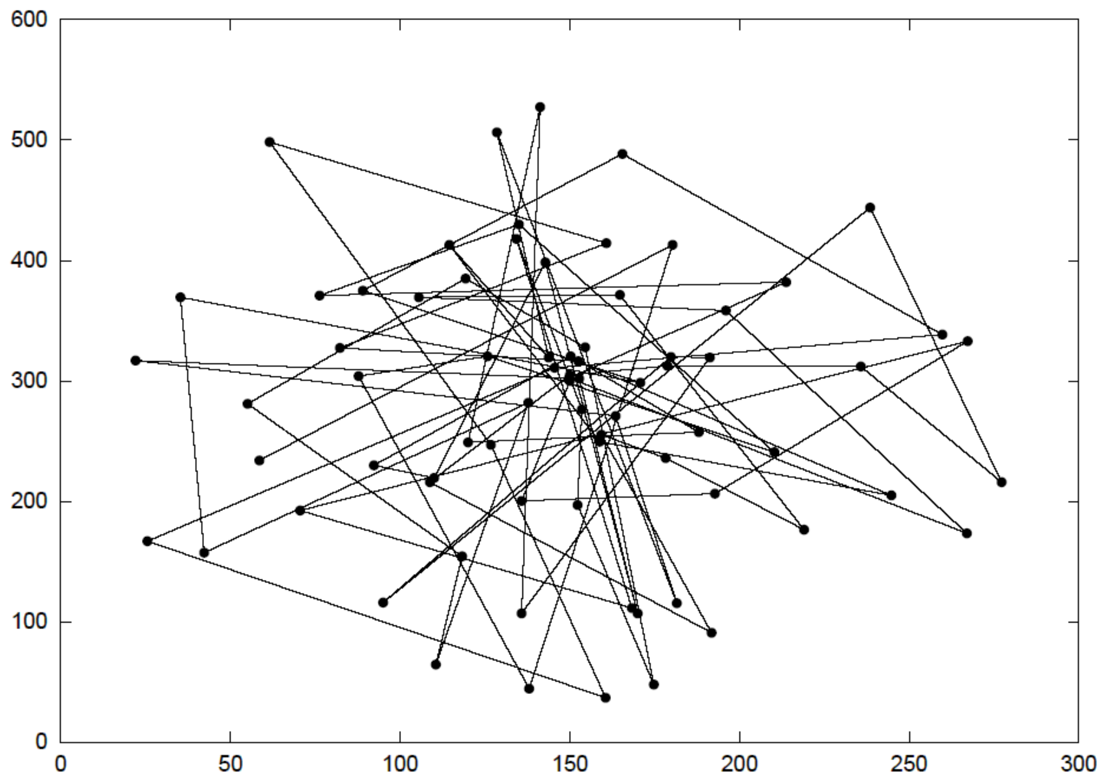
- Each transition from a cell *i* to *j* has a defined probability



Synthetic model – Random Walk

- Based on Einstein Brownian Motion
- A mobile node moves from its current location to a new location by randomly choosing a direction and speed in which to travel
  - The new speed and direction are both chosen from pre-defined ranges, [*speedmin*; *speedmax*] and [0;2π] respectively
  - Each movement in the Random Walk Mobility Model occurs in either a constant time interval *t* or a constant distance traveled *d*
  - At the end of a move, a new direction and speed are calculated
  - If an MN which moves according to this model reaches a simulation boundary, it “bounces” off the simulation border with an angle determined by the incoming direction

Synthetic model – Random Walk (cont'd)

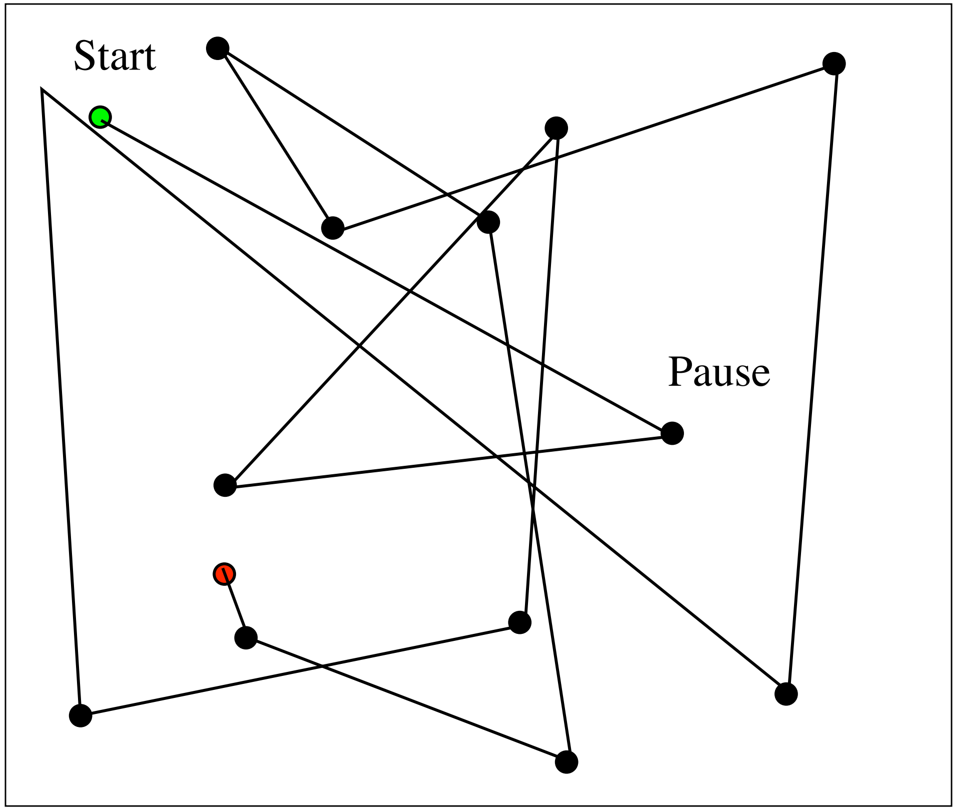


Trajectory of one MN under Random Walk

Synthetic model – Random Waypoint (RWP)

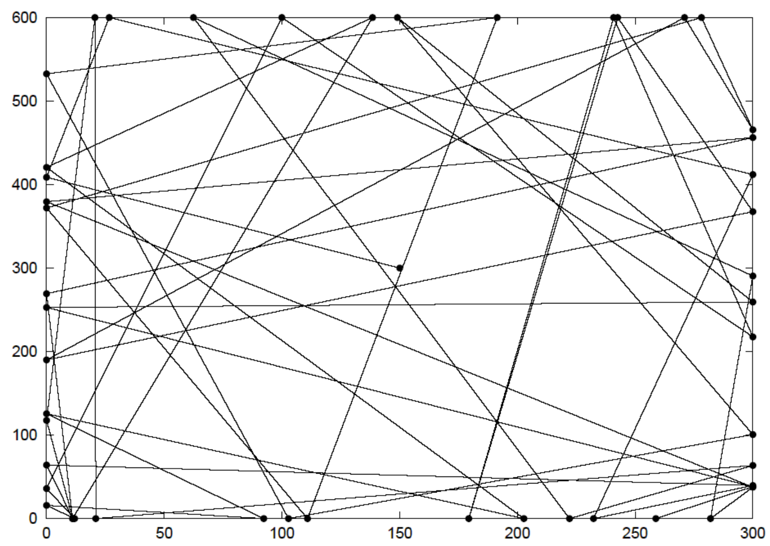
- An MN begins by staying in one location for a certain period of time (i.e., a pause time)
- Once this time expires, the MN chooses a random destination in the simulation area and a speed that is uniformly distributed between *[minspeed, maxspeed]*
- The MN then travels toward the newly chosen destination at the selected speed
- Upon arrival, the MN pauses for a specified time period (uniformly distributed between *[minpause, maxpause]*) before starting the process again

Synthetic model – Random Waypoint (RWP) (cont’d)



Synthetic model – Random Direction (RD)

- A mobile node chooses a random direction in which to travel similar to the Random Walk Mobility Model. The node then travels to the border of the simulation area in that direction
- Once the simulation boundary is reached, the node pauses for a specified time, chooses another angular direction (between 0 and 180 degrees) and continues the process



Trajectory of one MN under Random Direction

Synthetic model – Characteristics of Random models

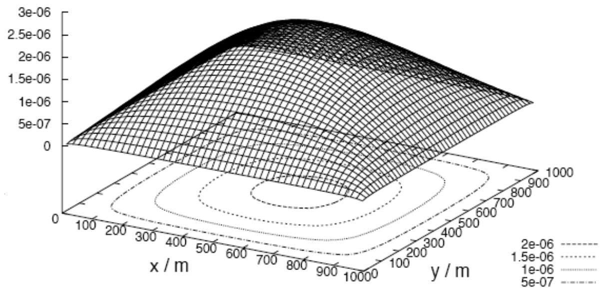
- All are derived from Einstein's Brownian Motion
  - Mathematically tractable
  - Memory-less

- Problems of simple random models
  - No preferred locations in space domain (uniform nodal distribution across space)
  - No structure in time domain (homogeneous behavior across time)
  - No collective behavior (i.e., group mobility, gatherings)

Mobility Models – Analytical derivation

- The case of RWP [**Bettstetter02Spatial**]
  - Theorem: A node moves on a line $[-x_m, x_m]$ *according to a one–dimensional RWP* model with constant speed and uniformly distributed destination points. The probability density function $f_x(x)$ of *its location given by*

$$f_x(x) = -\frac{3}{4x_m^3}x^2 + \frac{3}{4x_m}, \quad -x_m \le x \le x_m$$

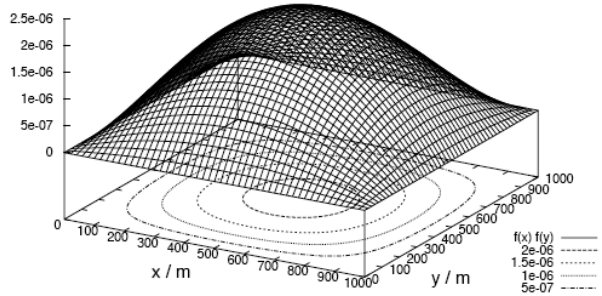


a. Square simulation area

Simulations (up) vs. analytic (down)

  - Assuming a 2D RWP movement in a square area consisting of two independent one–dimensional movement processes along the *x and y axes, we have:*

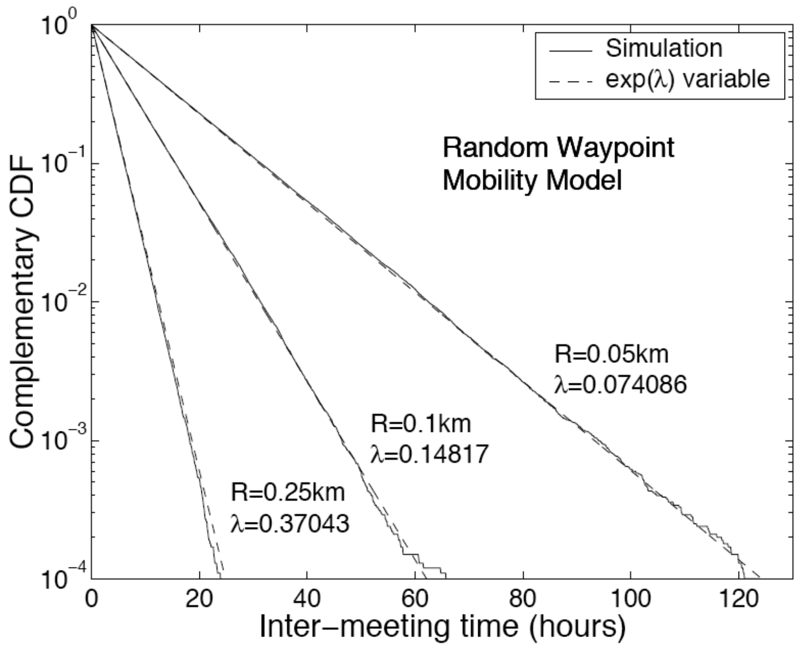
$$f(x)f(y) = -\frac{9}{16x_m^3 y_m^3}(x^2 - x_m^2)(y^2 - y_m^2)$$



a. Square simulation area: $f(x)\, f(y)$

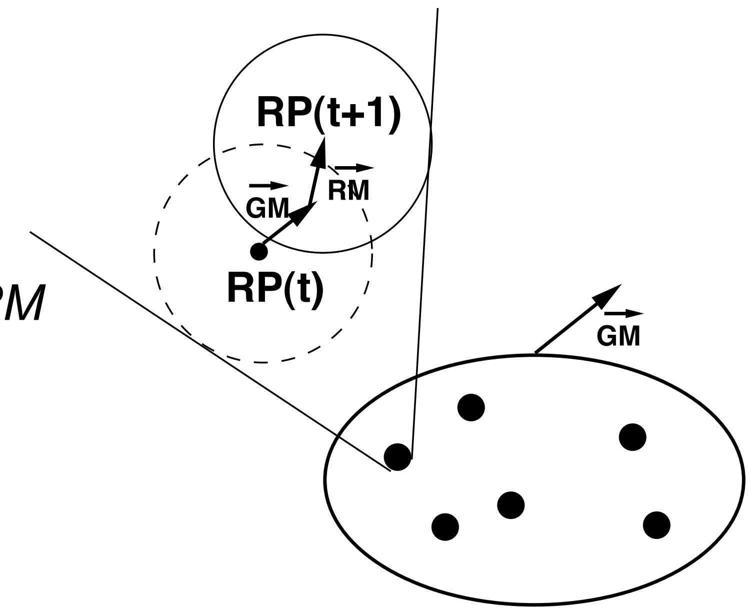
Mobility Models – Analytical derivation

- The case of RWP and Random Direction **[Groenvelt05Message]**
  - The inter-contact rate is approximated by $\lambda \approx \dfrac{2\,\omega\, r\, E[V^*]}{L^2}$
    - ω is a constant specific to the mobility model
      - $\omega = 1.3683$ for RWP
      - $\omega = 1$ for RD
    - r communication range
    - $E[V^*]$ is the average relative speed between two nodes
    - L length of square area
  - See also **[Sharma04Scaling]**

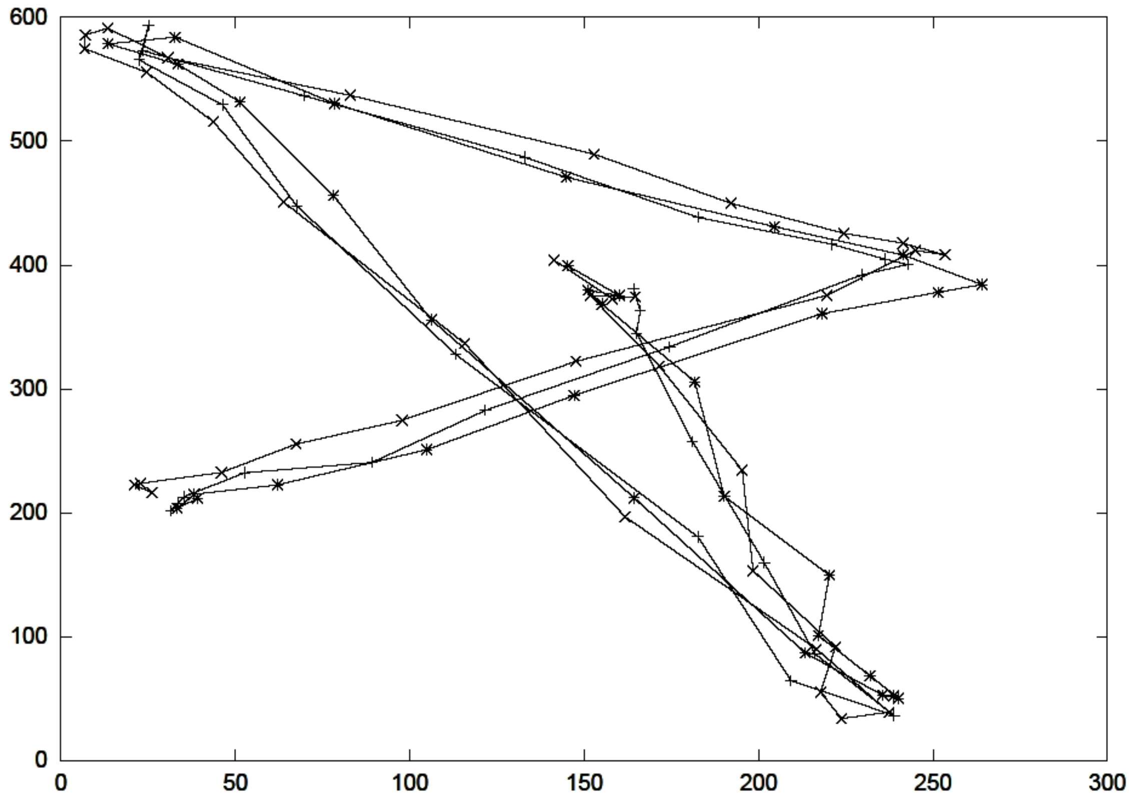


Synthetic model – Reference Point Group Mobility

- The Reference Point Group Mobility (RPGM) model represents the random motion of a group of nodes as well as the random motion of each individual MN within the group
  - A logical center for the group is used to calculate group motion via a group motion vector, *GM*
  - This logical center follows RWP
  - Individual nodes randomly move about their own pre-defined reference points combined with a random motion vector, *RM*



Synthetic model – Reference Point Group Mobility

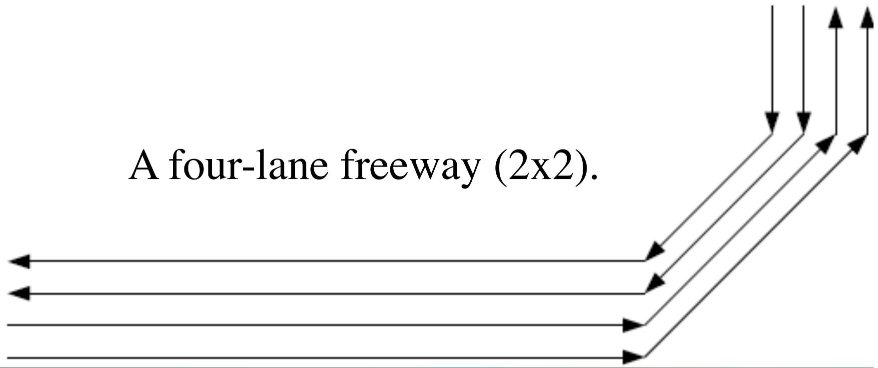


Trajectory of one group (three MN) under RPGM

Synthetic vehicular model – Freeway [Bai03Important]

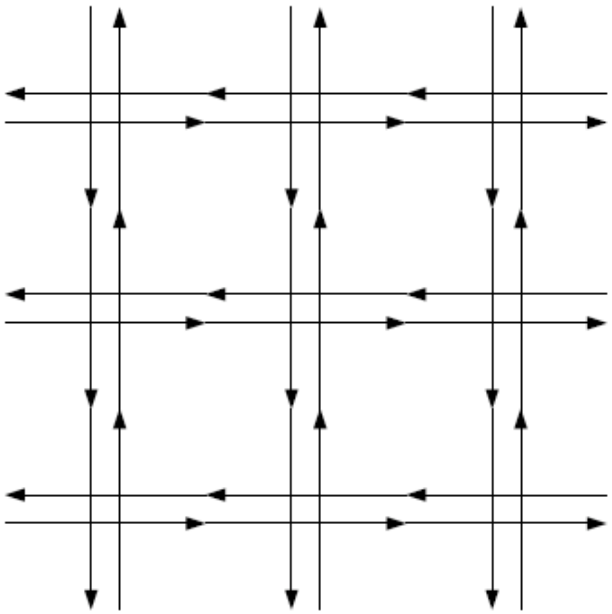
- Models the behavior of vehicles traveling on a freeway **[Bai03Important]**. The movement of a node is restricted to a lane of a freeway and is temporally dependent on the previous speed and other vehicles travelling in front on the same lane
  - Speed update: $v_i(t+1) = v_i(t) + random() * a_i(t)$
    - where a_i is the acceleration of node *i*
    - $random() \sim U[-1,1]$ adds some noise
  - Speed of *i* is limited by *j* in front: $d(i,j) \le d_{safety} \Rightarrow v_i(t) \le v_j(t)$
    - where d_{safety} is the safety distance

A four-lane freeway (2x2).



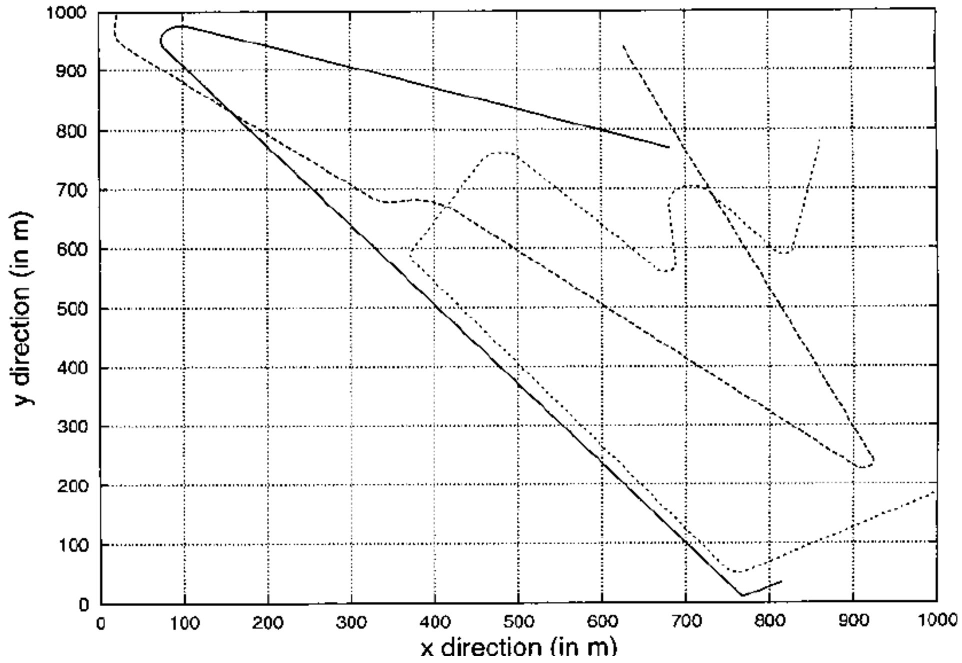
Synthetic vehicular model – Manhattan [Bai03Important]

- Nodes move on a grid
  - At each intersection, it randomly selects the street it will follow
    - 0.5 straight, 0.25 right, 0.25 left
  - Nodes behave similarly to the freeway model
  - Nodes *can* pause at intersections



More Realistic – Extension of Random models

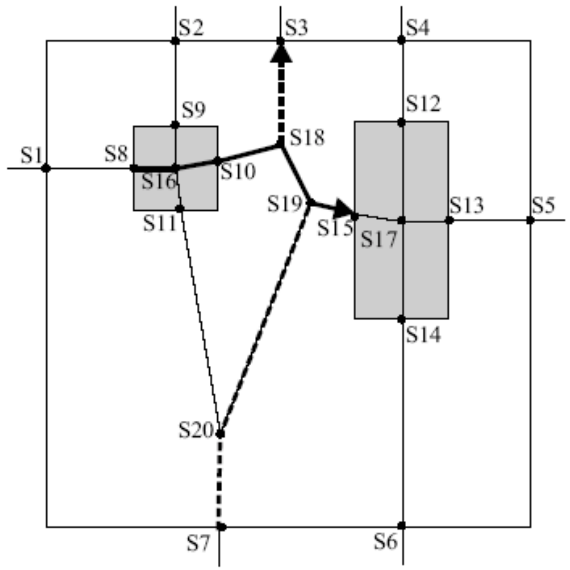
- Smooth RWP [**Bettstetter00Modeling**]
  - RWP with smooth turning
  - Slowdown when turning
  - Accounts for car behavior in cities



Three Smooth RWP traces

More Realistic – Campus

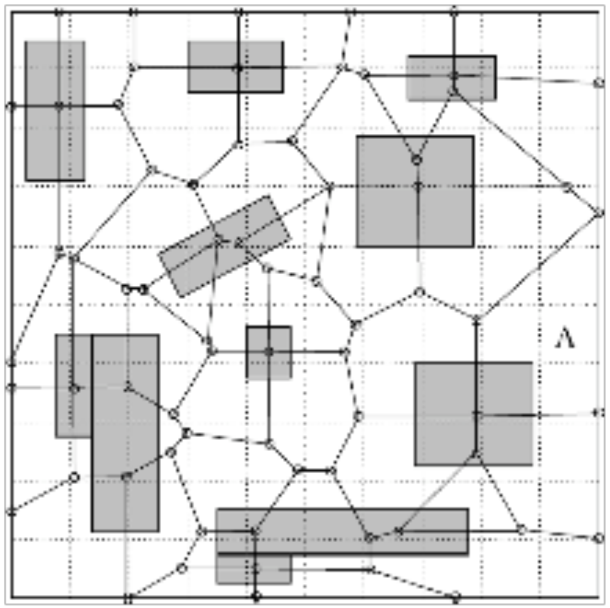
- Campus Model with obstacles [**Jardosh05Real**]
  - Voronoi diagram is used to determine the path of mobile nodes
    - Planar graph whose edges are line segments that are equidistant from two obstacle corners
  - A variation of RWP
    - The environment limits the trajectories of mobile nodes to the Voronoi graph
    - Shortest-path is computed on this graph between S-D



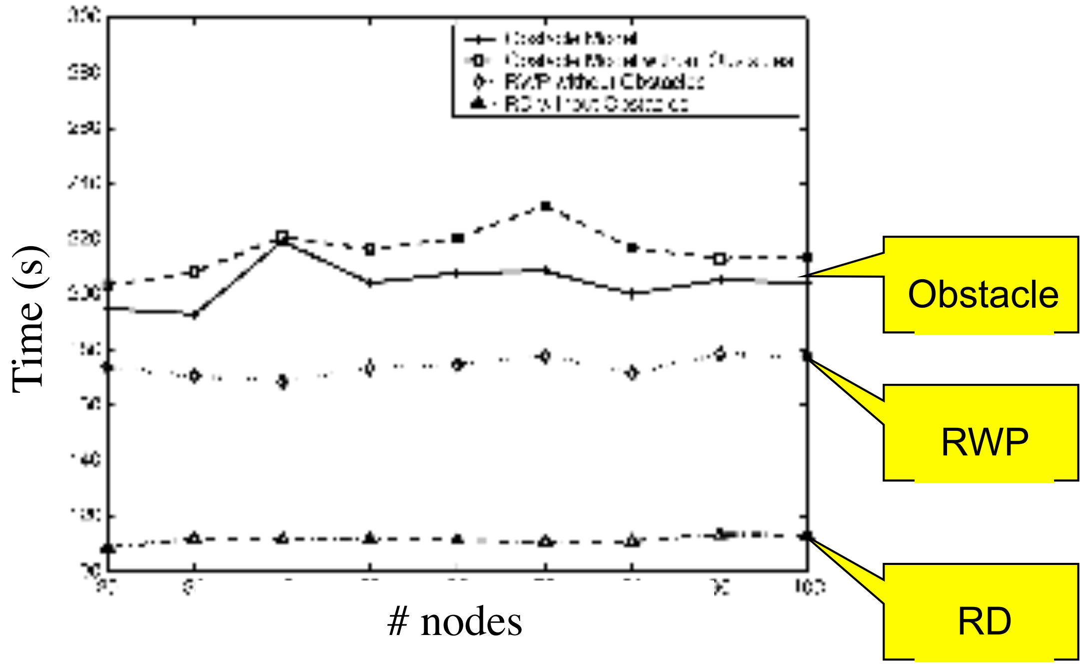
Example of trajectories S8->S15 and S7->S3.

More Realistic – Campus (Cont'd)

- Radio propagation model accounts for obstacles
  - Signal fading model with factor depending on the relative node position and type of obstacle that lie in the path between the two nodes



Simulated terrain



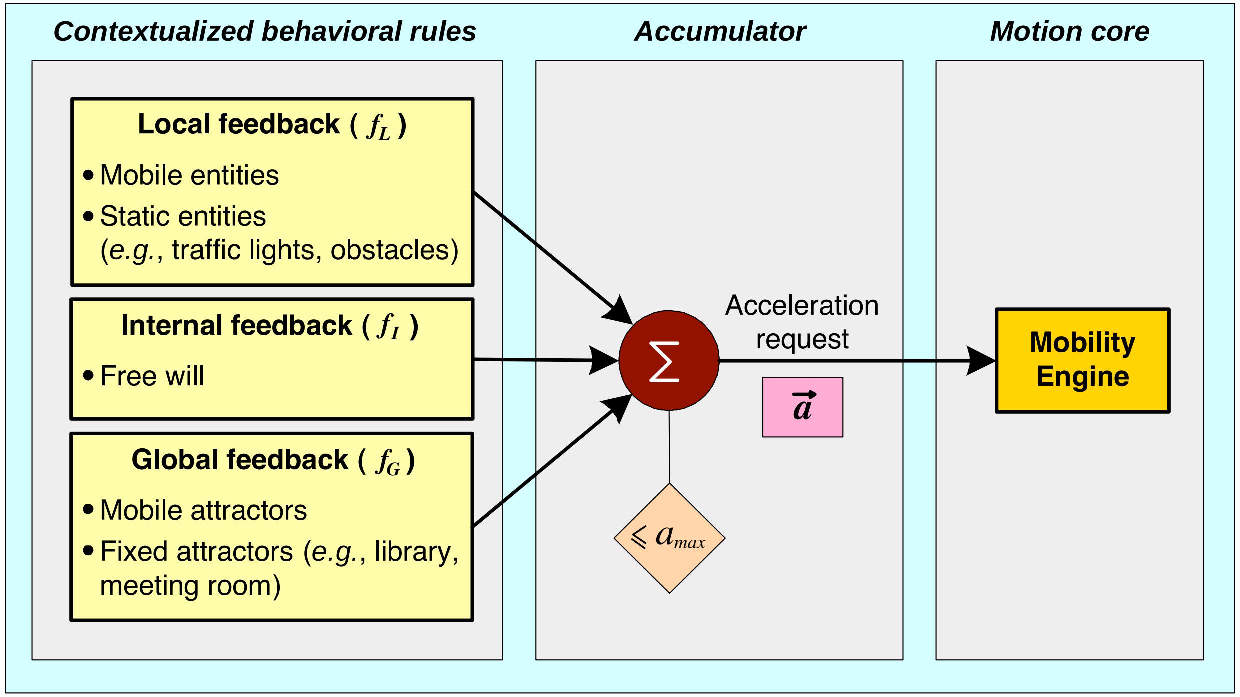
Average link duration

More Realistic – Behavioral Models (BM)

- Behavioral models: decompose mobility into atomic rules
  - At the local scale: avoid obstacles, walls, other peers (pedestrian, vehicle), **stay in group** (e.g., fish/bird flocks **[Reynolds87Flocks]**)
  - At the global scale: take the shortest path, join group of friends
- Main characteristics
  - Accounts for interactions (non-linear)
  - Emergent behaviors (trait of complex BM models)
- Three examples
  - At the micro-scale: vehicular, pedestrians
  - At the macro-scale: social model of crowd motion

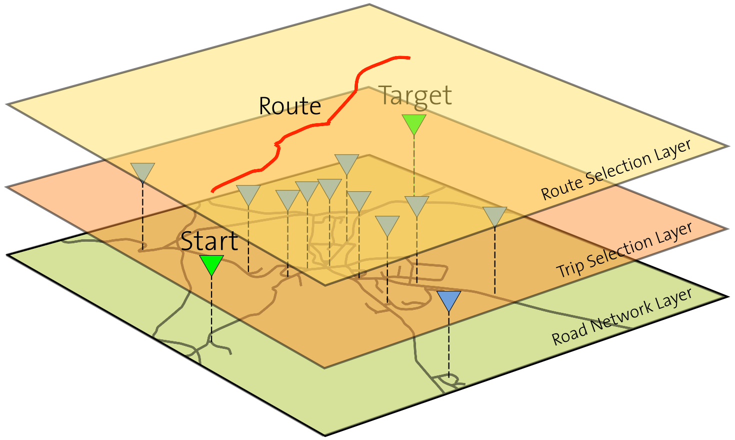
More Realistic – Behavioral Models (cont'd)

- From behavioral rules to motion
  - Behavioral rules: output acceleration requests
  - Accumulator: combines rules
  - Motion core: $\vec{v}(t+\Delta t) = \vec{v}(t) + \vec{a}\Delta t$

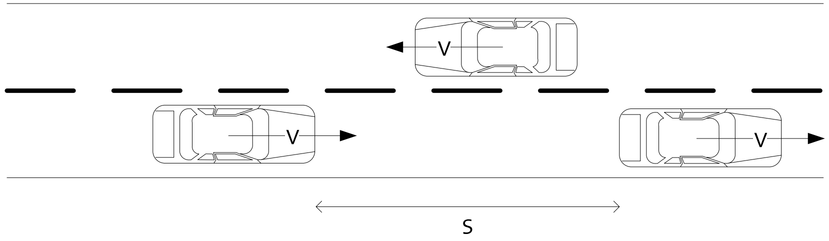


More Realistic – Vehicular behavioral Models

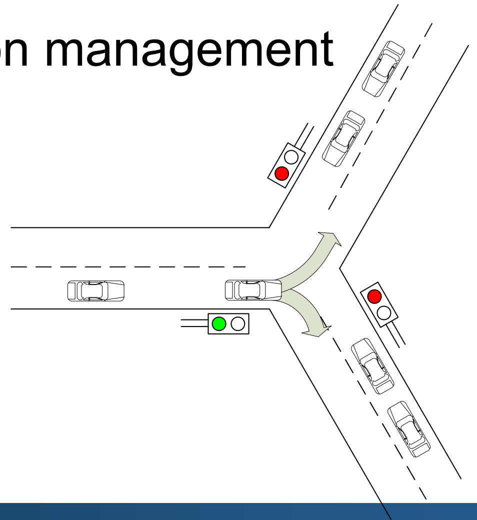
- Global behavioral rule (*global feedback*)
  - Pre-trip: RWP but constraint to road network



- Local behavioral rules (*local feedback*)
  - Speed adjustement and Car-following

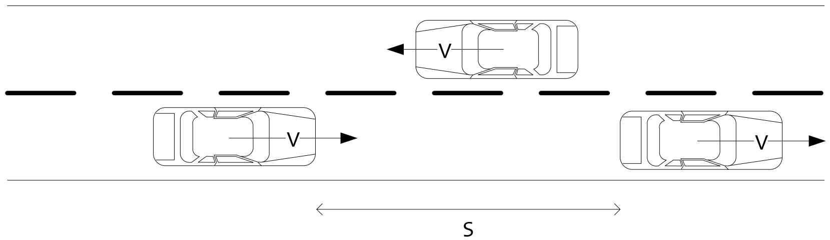


  - Intersection management



More Realistic – Vehicular behavioral Models

- Intelligent Driver Model (IDM) [**Helbing00Congested**]
  - The speed of vehicle depends on the current speed v, the desired speed v_0, the distance to the front vehicle s, and desired safety distance s^*



$$\frac{dv}{dt} = a\left[1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*}{s}\right)^2\right]$$

(1) (2)

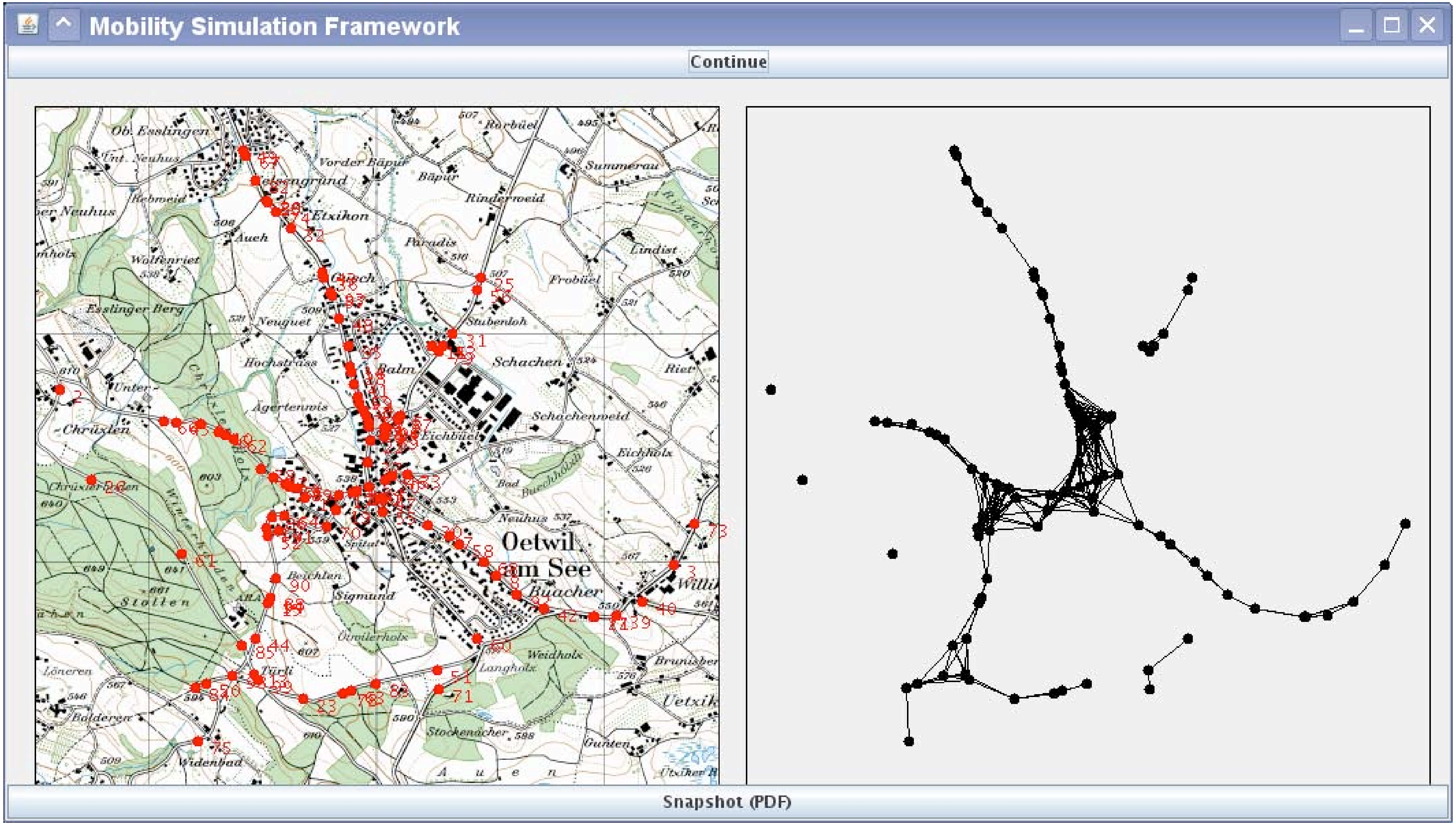
- with $s^* = s_0 + \left(vT + \frac{v\Delta v}{2\sqrt{ab}}\right)$

Parameter	Description	Value
v_0	Desired speed	speed limit
a	Acceleration constant	0.6
b	Deceleration constant	0.9
T	Reaction time	0.5 s
s_0	Minimal gap between vehicles	1 m

Table 2: Local behavioral rules parameters.

  - (1) Free-road term (accelerates until speed limit is reached)
  - (2) Breaking term (is *0* when no vehicle ahead)

More Realistic – Vehicular behavioral Models

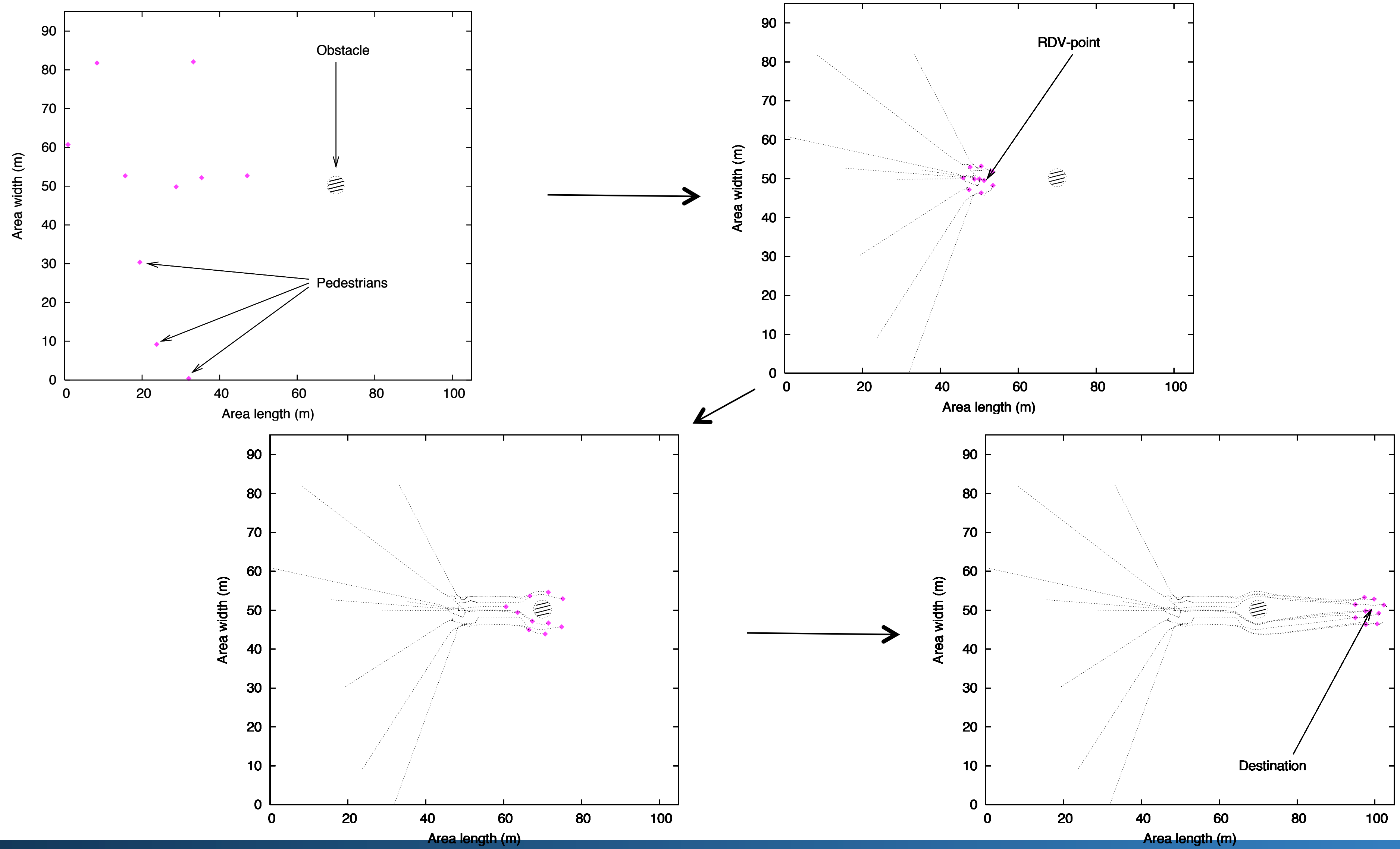


More Realistic – Behavioral pedestrian motion [Helbing00Escape,Legendre06Reconsidering]

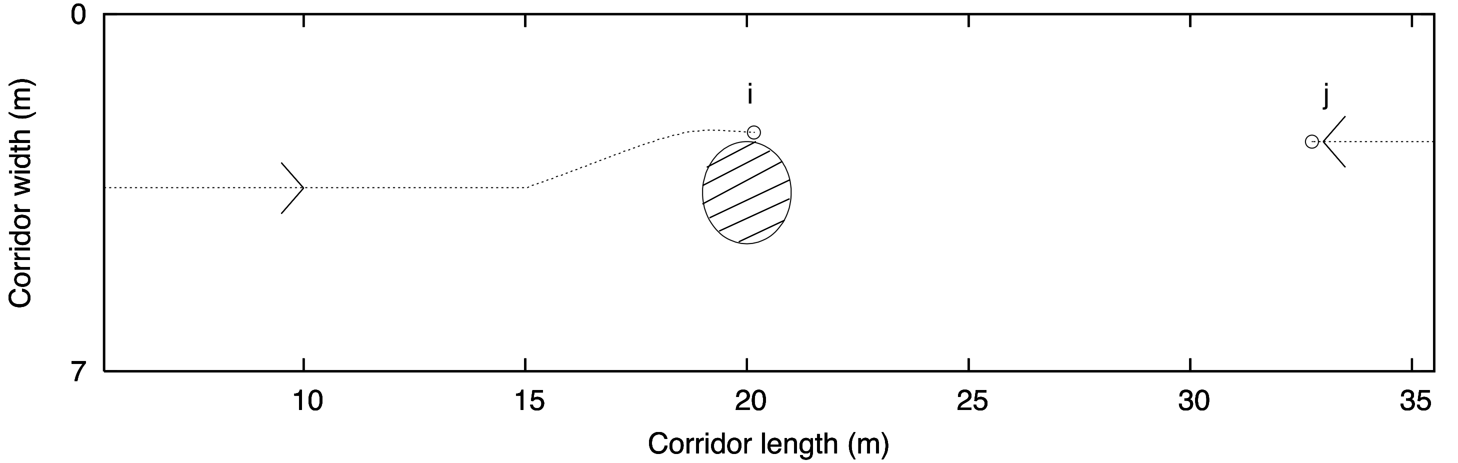
- Global behavioral rule (*global feedback*)
  - Take shortest path

- Local behavioral rules (*local feedback*)
  - *Avoid walls*: repulsive force (normal to wall) $\vec{a}_{avoidWall} = \gamma(p\vec{o}s_i(t) - p\vec{o}s_{w_i}(t))$
  - *Avoid obstacles*: pass by nearest obstacle edge minimizing detour to avoid obstacle $\vec{a}_{avoidObstacle} = \gamma(p\vec{o}s_{S_i}(t) - p\vec{o}s_i(t))$
  - *Mutual avoidance*: keep safety distance $\vec{a}_{mutualAvoidance} = \sum_{j \in Ti(t)} \gamma(pdv(x,t))$
  - Group mobility
    - *Mutual avoidance*: same as previous
    - *Velocity matching*: match velocity of group $\vec{a}_{L_{velocityMatching}} = \beta\left(\frac{1}{|N_G|}\sum_{x \in G} \vec{v_x}(t)\right) - \vec{v_i}(t)$
    - *Group Centering*: head to center of group $\vec{a}_{L_{groupCentering}} = \gamma\left(\frac{1}{|N_G|}\sum_{x \in G} p\vec{o}s_x(t)\right) - p\vec{o}s_i(t)$

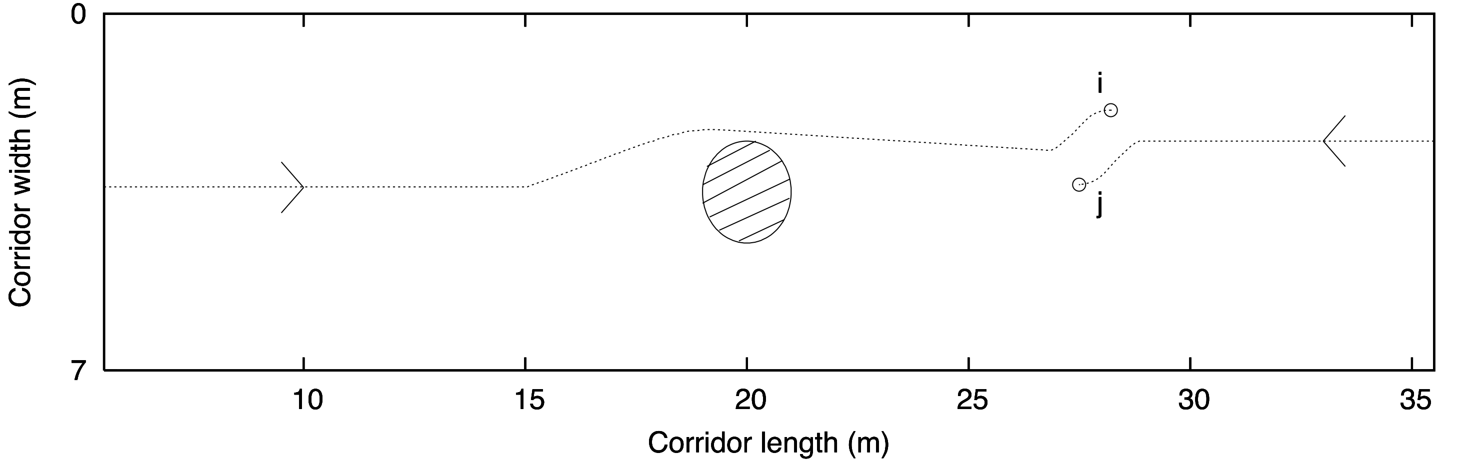
More Realistic – Behavioral pedestrian motion



More Realistic – Behavioral pedestrian motion (cont'd)



(a) At t=18 s: obstacle avoidance of pedestrian i.

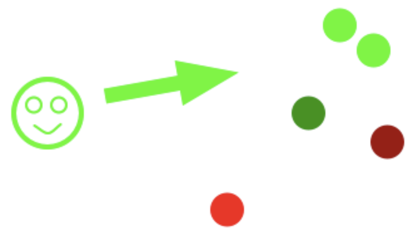


(b) At t=24.5 s: mutual avoidance of pedestrians i and j.

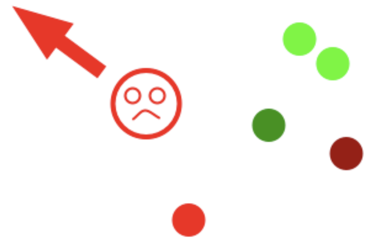
More Realistic – Social

- Aim at modeling the roots behind mobility [**Mascolo06**]
  - Human-beings are predominantly sociable

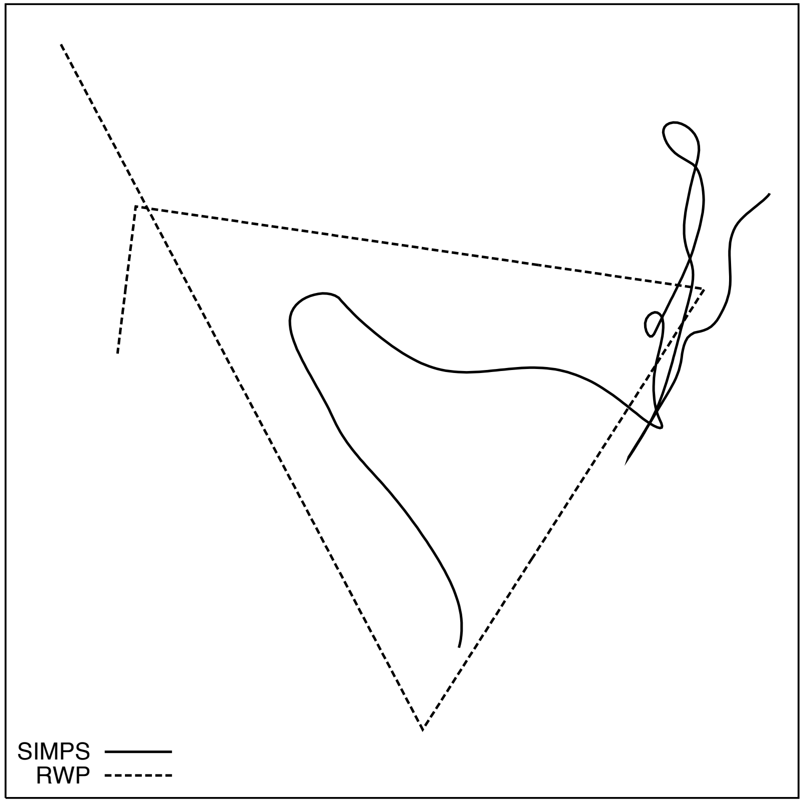
- Example of SIMPS [**Borrel08Simps**]
  - Translates *sociostation* in the mobility domain. Two behavioral rules:
    - Socialize: when under-socialized a an individual is attracted toward each of his acquaintances



    - Isolate: when over-socialized (bored), the individual is repulsed by each stranger



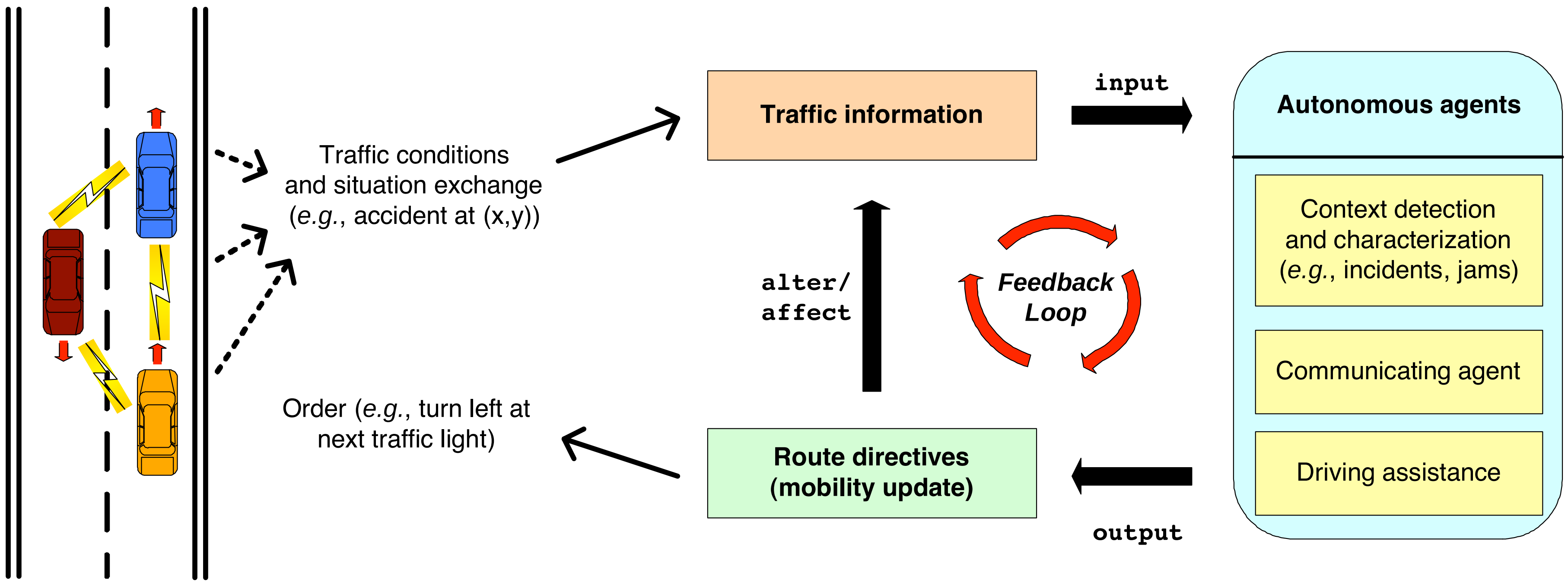
More Realistic – Social



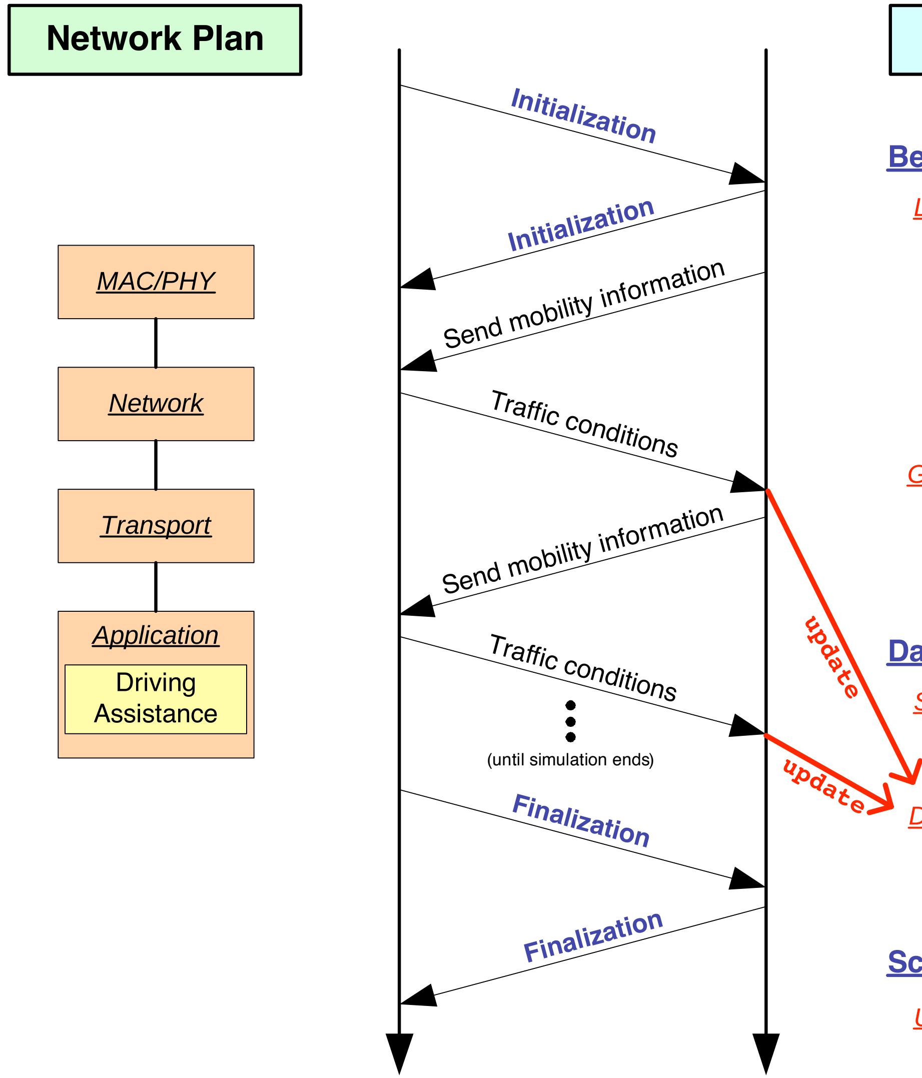
Comparative trajectories of RWP and SIMPS.

More Realistic – Joint Simulations

- Binding a network simulator and mobility generator is required when a feedback loop exists
  - Mobility traces can no more be loaded at the start of the simulation



More Realistic – Joint Simulations (cont'd)



Traffic Plan

Behaviors

Local behaviors

Basic motion

Car following

Speed adjustment

Intersections

Traffic light management

Turning behavior

Global behaviors

Route choice

Pre-trip

En-route

Data

Static street network database

Position, length,
# of lanes, speed limit

Dynamic street network database

Street load

Scenario

User-defined events

Incidents

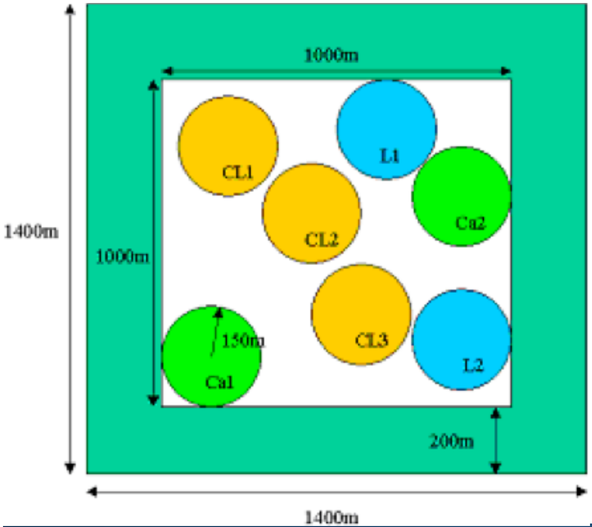
More Realistic – Surveys and Trace-based

- Surveys
  - Observe or survey people
  - E.g.,
    - Brown with its microscope: Brownian motion (1827)
    - People overlooking pedestrians from top of buildings

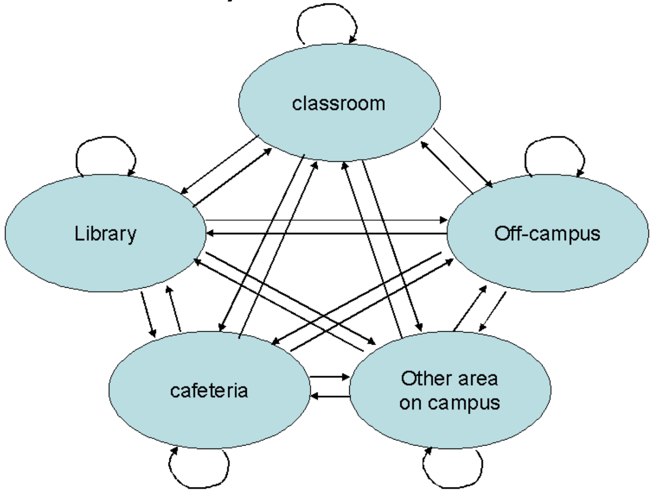
- Trace-based models
  - Traffic sensors on roads
  - GPS recordings
    - Students on Campus [Dartmouth], Buses [Seattle], Taxis
  - Radio contacts (RFID, Bluetooth, Wifi) **[Crawdad]**
    - MIT, UCSD, Cambridge, ETH

More Realistic – Surveys

- Weighted Waypoint **[Hsu05Weighted]**
  - Based on surveys from sampled respondents on USC campus during 4 weeks
  - Destinations are not randomly picked with the same weight across the simulation area
  - The parameters of a mobility model (e.g. pause time) are location-dependent and time-dependent



Map of virtual campus with categorized places:
- CL=classroom
- L=library
- Ca=cafeteria



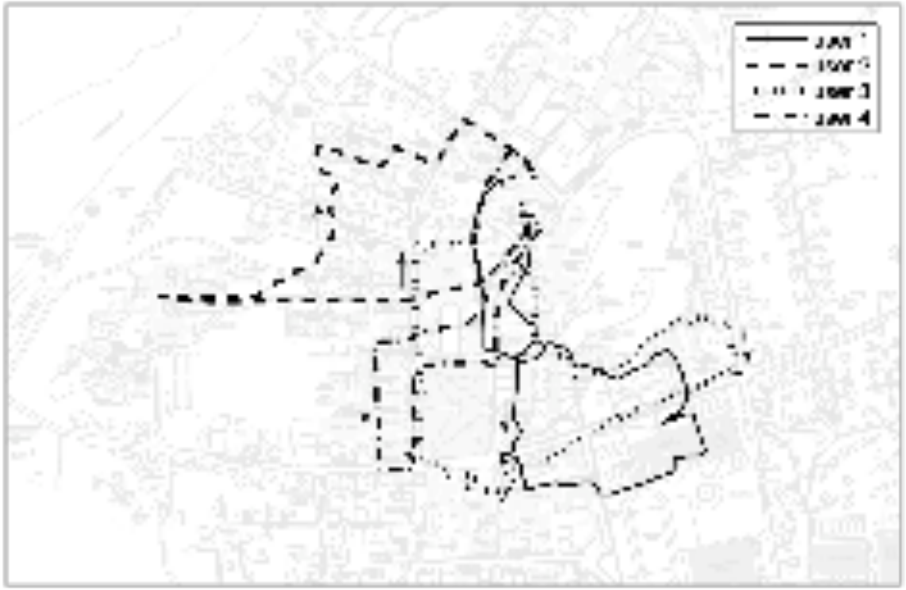
5-state Markov model with transitions between categorized places

More Realistic - Traces

- Use of traces
  - Being replayed instead of using traces from a mobility model
  - Used to calibrate a model
    - Extract a mobility metric and try to match its distribution
  - Trace analysis (see next lectures on DTN)
    - Pluridisciplinary: time-series, graph theory, datamining

More Realistic – GPS traces-based models

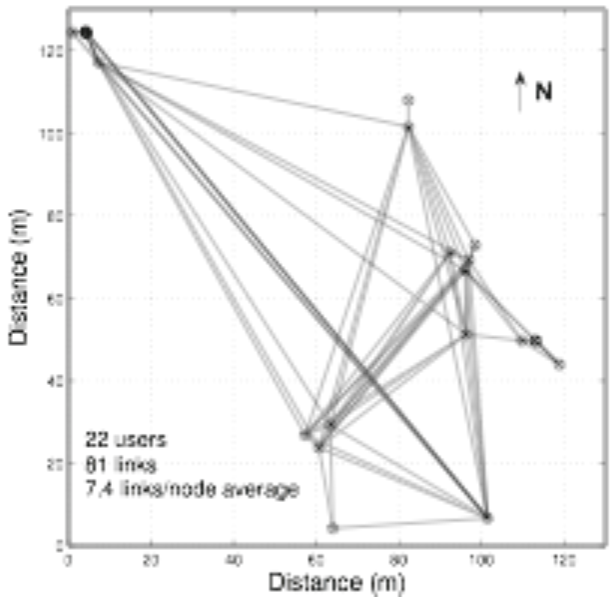
- Example of traces are Dartmouth campus **[Kim06Extracting]**
  - Student traced for several weeks with GPS-enabled devices



GPS tracks of four walks on Dartmouth campus

More Realistic – Calibrated Campus Mobility Model

- Markovian model of AP cell displacements calibrated with ETH AP client associations **[Gross05Mobility]**
- Evolutionary topology model based on AP bindings **[McNett05Access]**
    - Extrapolation of user walk between AP



Mobility Models – Complexity comparison

- Complexity of behavioral models
  - Search for neighboring entities and obstacles: $O((n+o).\log(n+o))$
    - n : number of mobile entities
    - o : number of obstacles
  - Application of rules to each entity: $O(m.n)$
    - m: number of rules combined simultaneously
  - Since $(n+o) >> m$ overall complexity is $O((n+o).\log(n+o))$

- Complexity of synthetic models
  - O(n.m) (if implemented with a rule-based approach)
  - Eg., RWP can be modeled with two rules used alternatively, {*pause*| *moving*} => $O(n)$

Mobility Models – Complexity comparison (cont'd)

- Complexity of trace-replaying
  - $O(1)$
- Complexity of trace analysis
  - Can rapidly become *NP*-hard

Mobility Models – Metric comparison

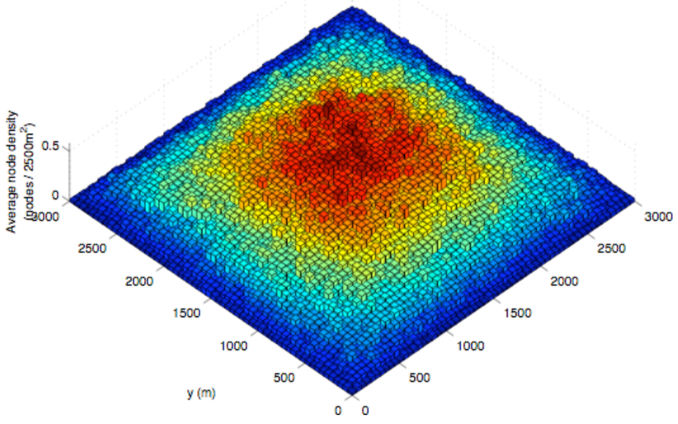
- Important Metrics [**Bai03Important**]
  - Node density
  - Relative movement direction

  - Number of Neighbors
  - Link lifetime (contact duration)

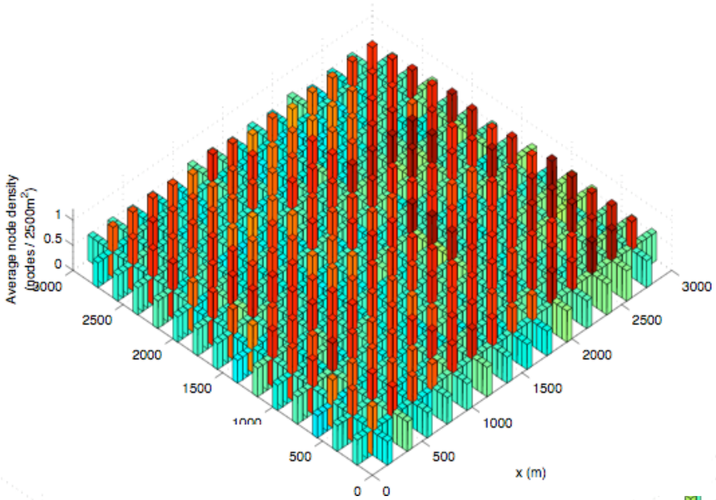
  - Network graph

Mobility Models – Metric comparison

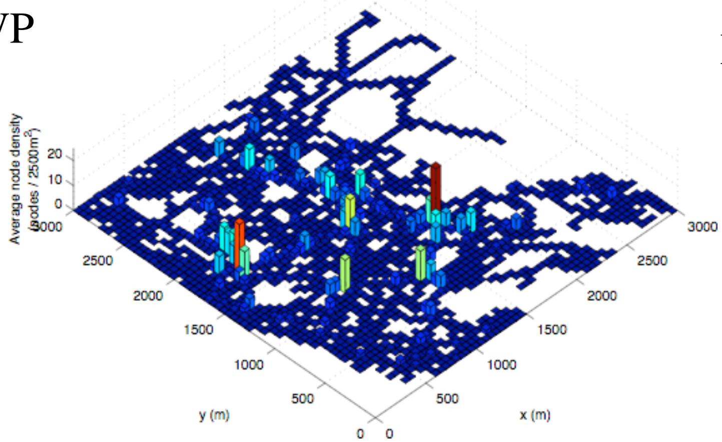
- Node Density



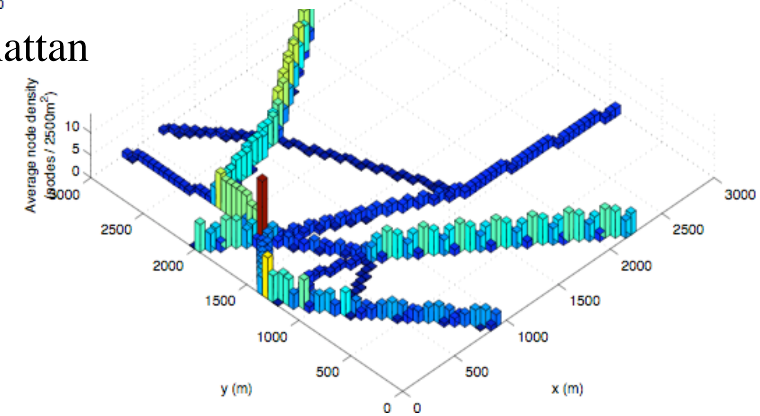
RWP



Manhattan



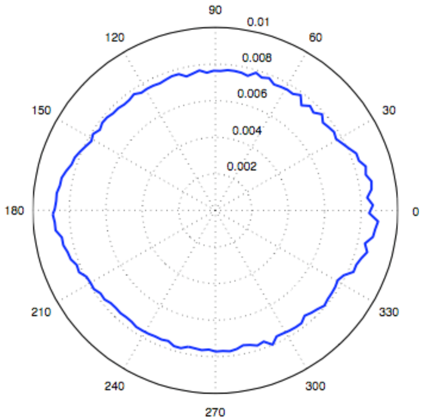
Vehicular BM



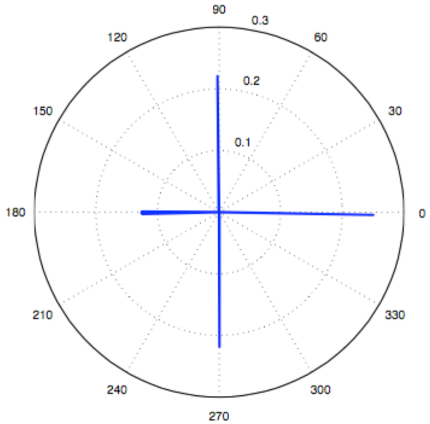
Vehicular traces
(ETH ITS group)

Mobility Models – Metric comparison

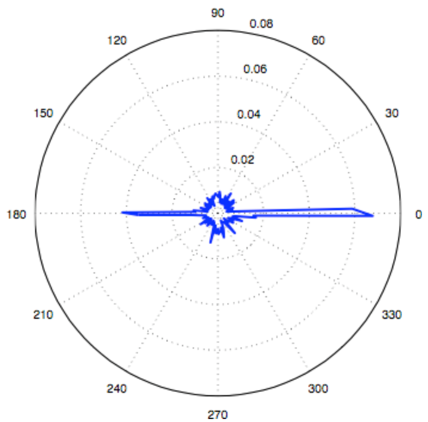
- Relative Movement Direction



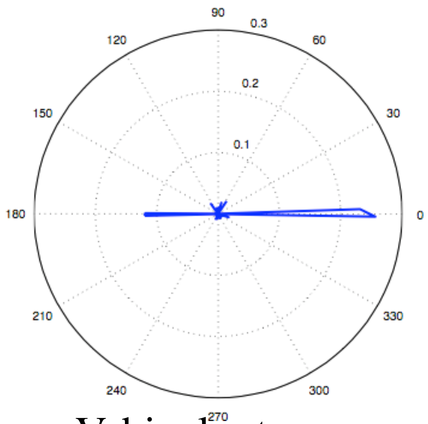
RWP



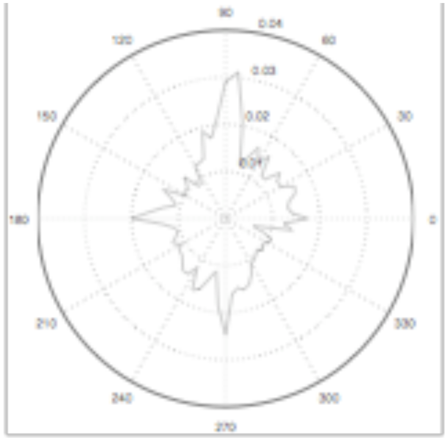
Manhattan



Vehicular BM



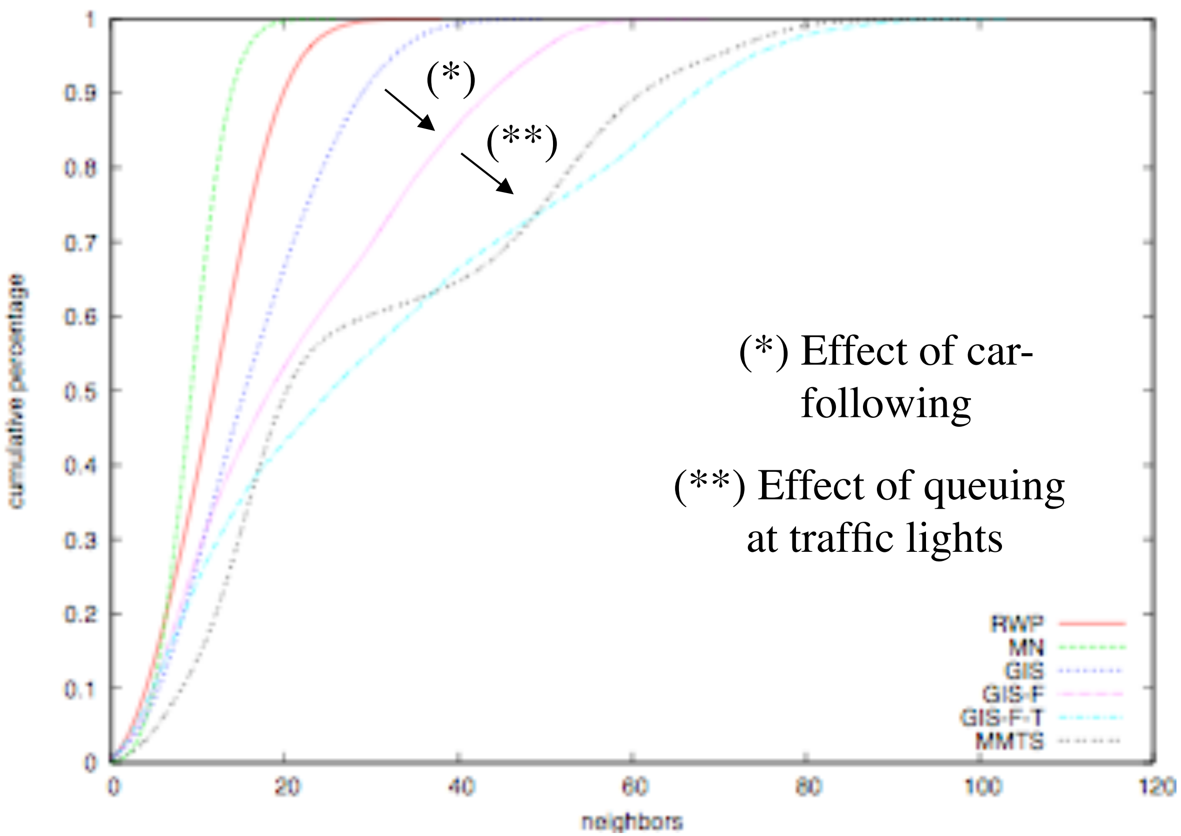
Vehicular traces
(ETH ITS group)



From GPS traces
of students on
Campus
(Dartmouth)

Mobility Models – Metric comparison

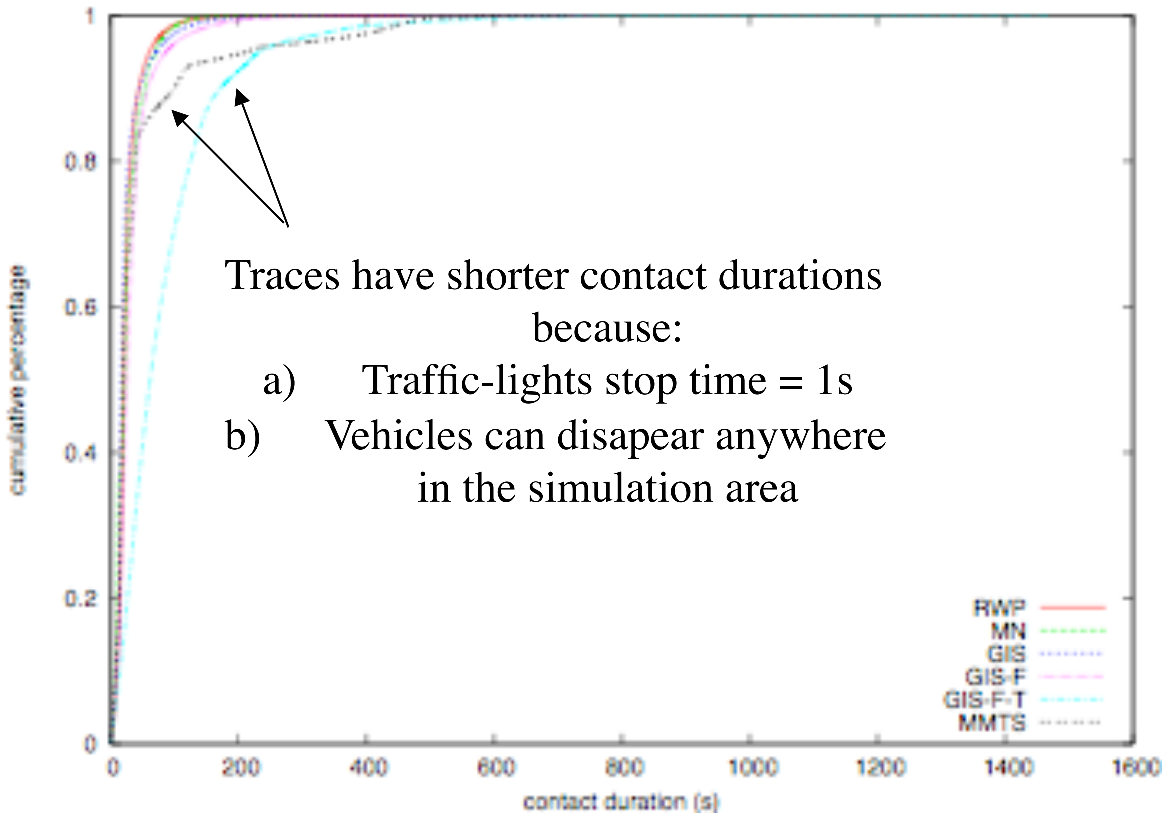
- Node degree CDF



RWP vs. MN vs. Vehicular BM vs. Traces

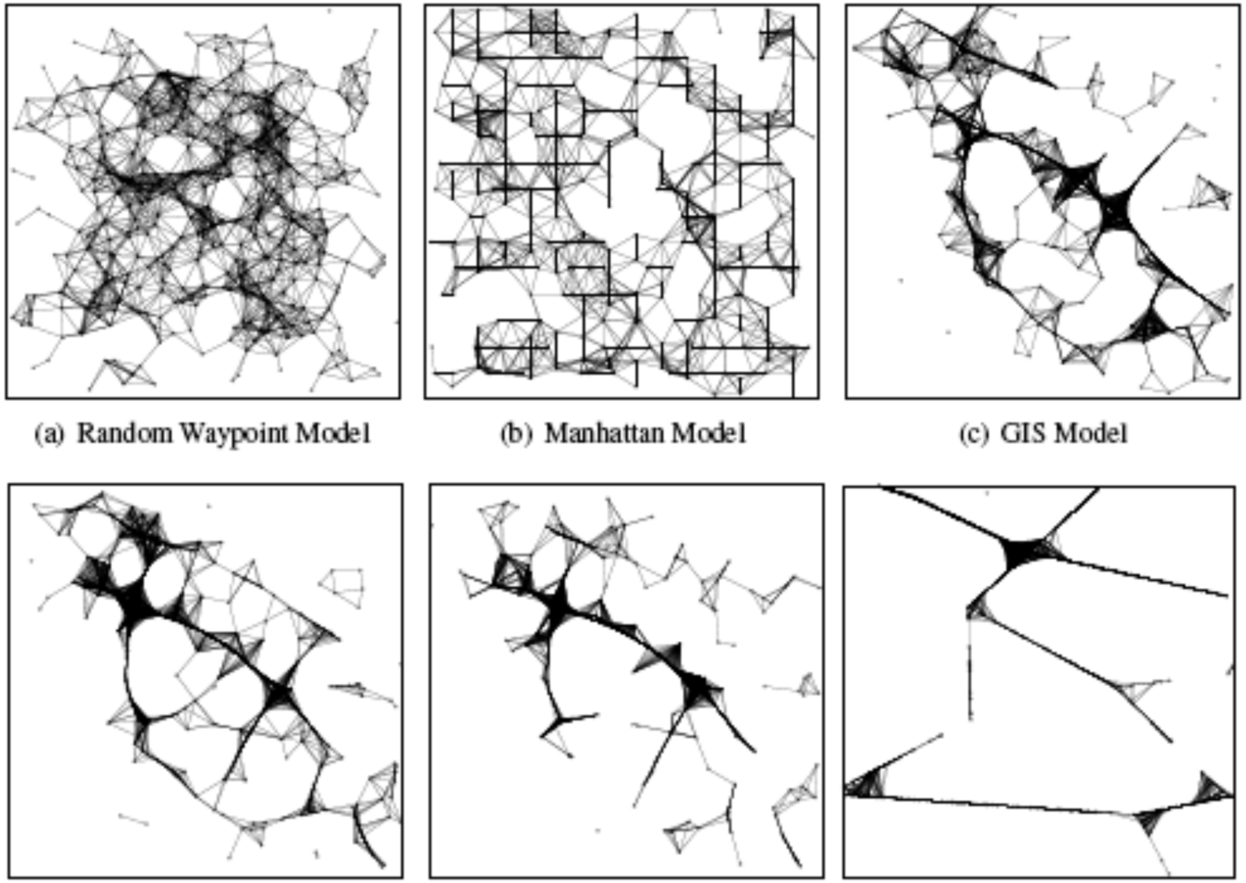
Mobility Models – Metric comparison

- Contact duration CDF (link lifetime)



Mobility Models – Metric comparison

- Network Graph (snapshots)



(a) Random Waypoint Model (b) Manhattan Model (c) GIS Model

(d) GIS Model with car-following (e) GIS Model with car-following and traffic lights (f) MMTS Model

Mobility Models – Mobilty generators and Frameworks

- Plenty of mobility generators
  - Pedestrians: GEMM **[Feeley04Realistic]**
  - Vehicles **[Choffnes05Traffic,CanuMobiSim,VanetMobiSim]**
  - Urban: Udel **[Kim05Survey,Kim05Realistic]**, GMSF **[Baumann08GMSF]**

- As well as simulators
  - Ns-2 **[Ns2]**
  - Qualnet **[Qualnet]**
  - GloMoSim **[GlomoSim]**
  - Opnet **[Opnet]**
  - Omnet, …

Mobility Models - Conclusion

	Realistic	Tractable	Flexibility	Param. space	Comp. Complex-ity	Calibra-ted
Synthetic	+	Yes	++	Low	Low	Most not
Behavioral	++	No	++	High	High	Yes
Traces	++	/	-	/	Very Low	/

A good model is a tractable model (analytically) still representative of real-world mobility

It's a Tradeoff!

References

RANDOM MOBILITY MODELS and ANALYTICAL DERIVATION

- **[Camp02Survey]** Tracy Camp and Jeff Boleng and Vanessa Davies, "**A Survey of Mobility Models for Ad Hoc Network Research,**" WCMC: Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications, 2002
- **[Haerri06Survey]** J. Haerri, F. Filali, and C. Bonnet, "**Mobility models for vehicular ad hoc networks: a survey and taxonomy**," Tech. Rep. EURECOM+1951, Institut Eurecom, France, Mar 2006.
- **[Bettstetter02Spatial]** Christian Bettstetter and Christian Wagner, **The Spatial Node Distribution of the Random Waypoint Mobility Model**," Mobile Ad-Hoc Netzwerke, 1. deutscher Workshop \"{u}ber Mobile Ad-Hoc Netzwerke WMAN 2002
- **[Groenvelt05Message]** Robin Groenevelt, Philippe Nain and Ger Koole, **The message delay in mobile ad hoc networks**," Perf. Evaluation, 2005
- **[Sharma04Scaling]** G. Sharma and R. Mazumdar, **Scaling Laws for Capacity and Delay in Wireless Ad hoc Networks with Random Mobility**," in Proc. IEEE ICC, (Paris, France), June 2004.
- **[Navidi04Stationary]** William Navidi and Tracy Camp, **Stationary distributions for the random waypoint mobility model**," IEEE Transactions on Mobile Computing, 3(1):99–108, 2004.

MORE REALISTIC MOBILITY MODELS

- **[Bai03Important]** Fan Bai, Narayanan Sadagopan, and Ahmed Helmy, **IMPORTANT: A framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks**," In INFOCOM, 2003
- **[Bettstetter00Modeling]** Christian Bettstetter, **Mobility Modeling in Wireless Networks: Categorization, Smooth Movement, and Border effects**," Mobile Computing and Communications Review
- **[Jardosh05Real]** Amit P. Jardosh, Elizabeth M. Belding-Royer, Kevin C. Almeroth, and Subhash Suri, "**Real-World Environment Models for Mobile Network Evaluation**," JSAC, 2005
- **[Reynolds87Flocks]** C. W. Reynolds, "**Flocks, Herds and Schools: A Distributed Behavioral Model**," in Proc. ACM SIGGRAPH, (Anaheim, CA), July 1987.
- **[Helbing00Congested]** Martin Treiber, Ansgar Hennecke, and Dirk Helbing, "**Congested traffic states in empirical observations and microscopic simulations**," Physical Review, 62:1805, 2000.
- **[Helbing00Escape]** D.Helbing, "**Simulating dynamical features of escape panic**," Nature 2000
- **[Legendre06Reconsidering]** F. Legendre, V. Borrel, M. D. de Amorim, and S. Fdida, "**Reconsidering microscopic mobility modeling for self-organizing networks**," IEEE Network Magazine, Nov. 2006.

References

MORE REALISTIC MOBILITY MODELS (cont'd)

- **[Musolesi06Community]** M. Musolesi and C. Mascolo, "**A Community based Mobility Model for Ad Hoc Network Research**," in Proc. ACM Realman, (Florence, Italy), May 2006.
- **[Borrel08Simps]** V. Borrel, F. Legendre, M. D. de Amorim, and S. Fdida, "**Simps: Modeling mobility by its causes not consequences**," To Appean in IEE/ACM Transactions on Networking, 2008.
- **[Legendre06Emergency]** F. Legendre, V. Borrel, M. D. de Amorim, and S. Fdida, "**Modeling mobility with behavioral rules: the case of incident and emergency situations**," in Proc. AINTEC, (Bangkok, Thailand), Dec. 2006

MORE REALISTIC SURVEYS and TRACE-BASED MODELS

- **[Crawdad]** The CRAWDAD Pro ject, "**A Community Resource for Archiving Wireless Data At Dartmouth**"
- **[Hsu05Weighted]** Wei-jen Hsu, Kashyap Merchantd, Haw-wei Shu, Chih-hsin Hsu, and Ahmed Helmy,"**Weighted waypoint mobility model and its impact on ad hoc networks**," SIGMOBILE Mob. Comput. Commun. Rev., 2005
- **[Kim06Extracting]** Minkyong Kim, David Kotz, and Songkuk Kim, "**Extracting a mobility model from real user traces**," IEEE Infocom 2006
- **[Gross05Mobility]** Cristian Tuduce and Thomas Gross, "**A Mobility Model Based on WLAN Traces and its Validation**," Infocom 2005
- **[McNett05Access]** Marvin McNett and Geoffrey M. Voelker, "**Access and mobility of wireless pda users**," SIGMOBILE Mob. Comput. Commun. Rev., 9(2):40–55, 2005.
- **[Bai03Important]** Fan Bai, Narayanan Sadagopan, and Ahmed Helmy, **IMPORTANT: A framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks**," In INFOCOM, 2003

MORE not REFERENCED

- **[Bar-Nov95Mobile]** A. Bar-Noy, I. Kessler, and M. Sidi, "**Mobile users: To update or not to update?**," ACM Wireless Networks, vol. 1, no. 2, pp. 175–185, June 1995.
- **[Leung94Traffic]** K. Leung, W. Massey, and W. Whitt, "**Traffic models for wireless communication networks**," IEEE Journal on Selected Areas in Communications, vol. 12, no. 8, pp. 1353–1364, Oct. 1994.
- **[Slater93International]** P. Slater, "**International migration and air travel: global smoothing and estimation**," Journal of Applied Mathematics and Computation, vol. 53, no. 2, pp. 225–234, Feb. 1993.
- **[Helbing01Traffic]** Dirk Helbing. "**Traffic and related self-driven many-particle systems**," Reviews of Modern Physics, 73:1067, 2001.
- **[Saha04Vehicular]** Amit Kumar Saha and David B. Johnson. "**Modeling mobility for vehicular ad-hoc networks**," In VANET '04: Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks, pages 91–92, New York, NY, USA, 2004. ACM Press.
- **[Lelescu06ModelT++]** D. Lelescu, U. C. Kozat, R. Jain, and M. Balakrishnan, "**Model T++:: an empirical joint space-time registration model**," in Proc. ACM MobiHoc'06, (Florence, Italy), ACM Press, May 2006.
- **[Hsu07Time]** Hsu, Spyropoulos, T, Psounis, K., and Helmy, A, "**Modeling Time-Variant User Mobility in Wireless Mobile Networks Modeling Time-Variant User Mobility in Wireless Mobile Networks**," IEEE INFOCOM 2007

References

NETWORK SIMULATORS

- **[Ns2]** The Network Simulator - ns-2, Information Sciences Institute - The University of Southern California.
- **[Qualnet]** Qualnet 4.0 network simulator, Scalable Network Technologies, Inc.
- **[GlomoSim]** Xiang Zeng, Rajive Bagrodia, and Mario Gerla. Glomosim: a library for parallel simulation of large-scale wireless networks. SIGSIM Simul. Dig., 28(1):154–161, 1998.
- **[Opnet]** OPNET, OPNET Technologies, Inc.

MOBILITY GENERATORS

- **[CanuMobiSim]** CANU Mobility Simulation Environment (CanuMobiSim), University of Stuttgart. Web- site.
- **[VanetMobiSim]** VanetMobiSim, Insitut Eurecom, Sopia Antipolis, France.
- **[Feeley04Realistic]** Michael Feeley, Norman Hutchinson and Suprio Ray, "**Realistic Mobility for Mobile Ad Hoc Network Simulation**," LNCS 2004
- **[Choffnes05Traffic]** David R. Choffnes and Fabian E. Bustamante, "**An integrated mobility and traffic model for vehicular wireless networks**," In VANET '05: Proceedings of the 2nd ACM international
- **[Kim05Survey]** Jonghyun Kim and Stephan Bohacek, "**A survey-based mobility model of people for simulation of urban mesh networks**", 2005
- **[Kim05Realistic]** Jonghyun Kim, A. Ilic, and S. Bohacek, "**Realistic simulation of urban mesh networks - part I: Urban mobility**," in Technical Report, (University of Delaware), 2006
- **[Baumann08GMSF]** Rainer Baumann, Franck Legendre, Philipp Sommer, "**Generic Mobility Simulation Framework (GMSF)**," ACM SIGMOBILE MobiHoc'08 Mobility Models Workshop, Hong Kong, May 2008

Outline

- Introduction
  - Rationale, Classification, State-of-art
- Mobility Models
  - From random to more realistic models
- Performance evaluation
  - Analytical vs. Simulations vs. Traces vs. Experiments
- System design
  - Designing better communication systems
- Outlook, demos and conclusion

Performance Evaluation

- Introduction
- Performance Evaluation - Example of Content Dissemination
  - System formulation, derivation, and resolution
  - Experimentations

Perf. Evaluation - Introduction

- So know that I'm a bit more acquainted with mobility, what can I do with it?

- Evaluate your system! (e.g., ad hoc routing protocol)
  - How?
    - 1) Analytically
    - 2) By simulation
    - 3) Trace-replaying
  - First, formalize your system with key parameters
    - Mobility-wise, what most impacts your system? E.g,
      - handoff in cellular networks
      - link-duration in ad hoc networks
      - inter-contacts in delay-tolerant applications

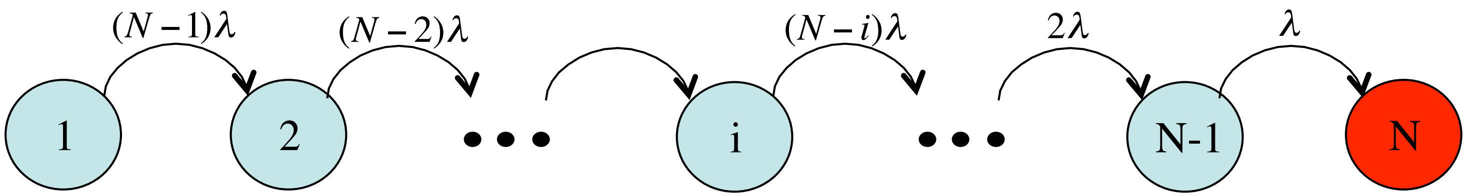
Perf. Evaluation – Example of System to evaluate

- Example of Content Dissemination
  - Consider a DTN network of *N-1* mobile nodes and an AP
  - Goal is to disseminate a given content to all nodes
  - Two strategies
    - *No cooperation*: content is provided only by AP
    - *Unlimited cooperation*: nodes store-and-forward content
  - Formalization – Key parameters
    - Number of nodes N
    - Inter-contact rate λ (rate of inter-node encounters)
  - Performance evaluation
    - What is the delay until all nodes get the content?

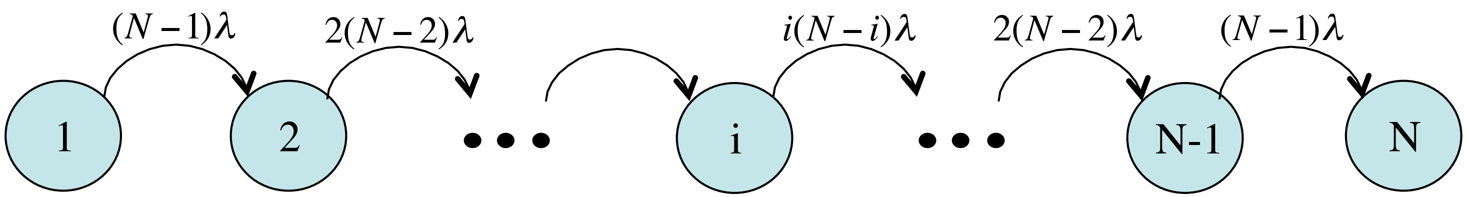
Perf. Evaluation – System formalization

- Example with Continuous Time Markov Chains (CTMC) **[Bremaud]**
  - Each state represents the number of nodes having content
  - Sequence of inter-contact times are *iid* and exponentially distributed

- No-cooperation strategy



- Unlimited cooperation



Perf. Evaluation – System derivation

- Overall delivery time $E[T_{odt}]$ = time to absorption (state N)

- No-cooperation strategy

$$E[T_{odt}] = \sum_{i=1}^{N-1} \frac{1}{\lambda_i} = \frac{1}{\lambda} \sum_{i=1}^{N-1} \frac{1}{N-i} = \frac{1}{\lambda} \sum_{j=1}^{N-1} \frac{1}{j} = \frac{1}{\lambda} H_{N-1}$$

$$\Leftrightarrow E[T_{odt}] = \frac{1}{\lambda}\left(\gamma + \ln(N-1) + O\left(\frac{1}{N-1}\right)\right)$$

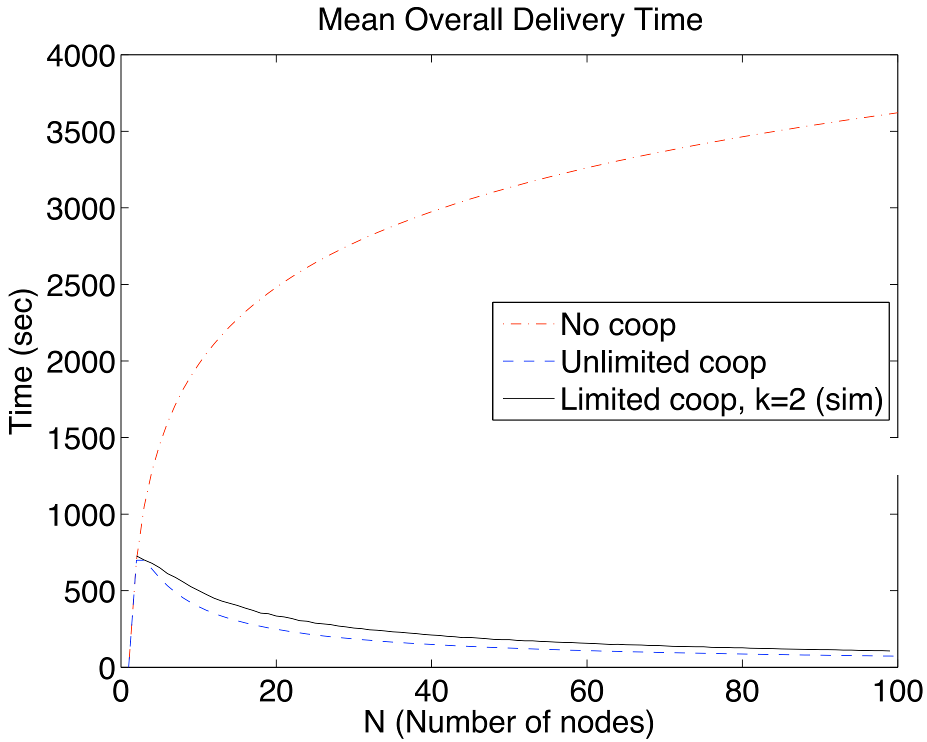
- Unlimited cooperation

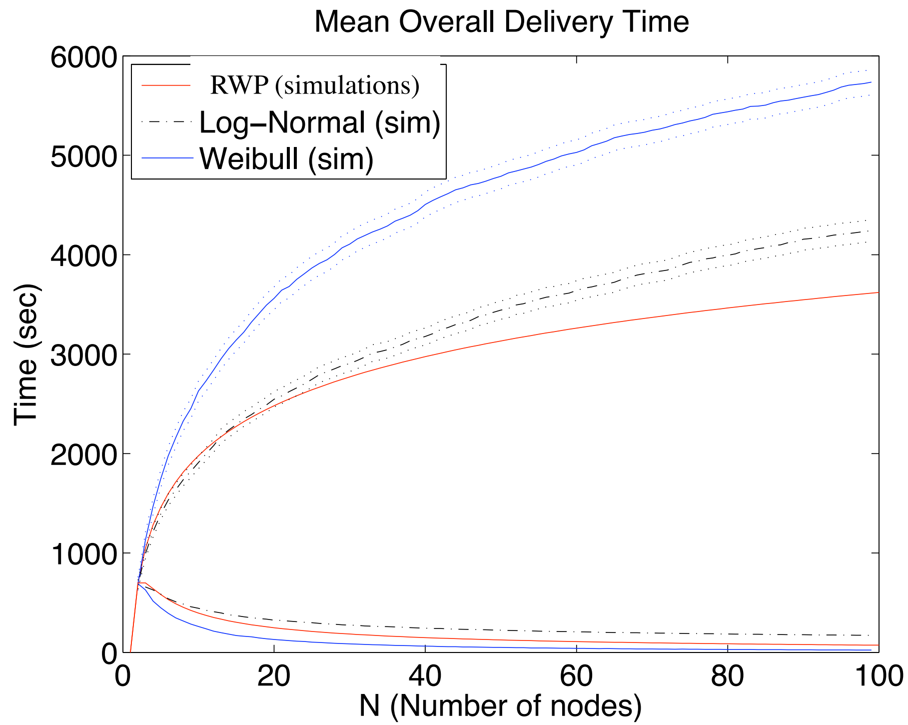
$$E[T_{odt}] = \frac{2}{\lambda N}\left(\gamma + \ln(N-1) + O\left(\frac{1}{N-1}\right)\right)$$

- *Note*
  - More complex strategies have non closed-form expressions (e.g., 3D CTMC) and requires to resort to numerical evaluation

Perf. Evaluation – System resolution

- Numerical evaluation of closed-form equations (l.) vs. simulations (r.)

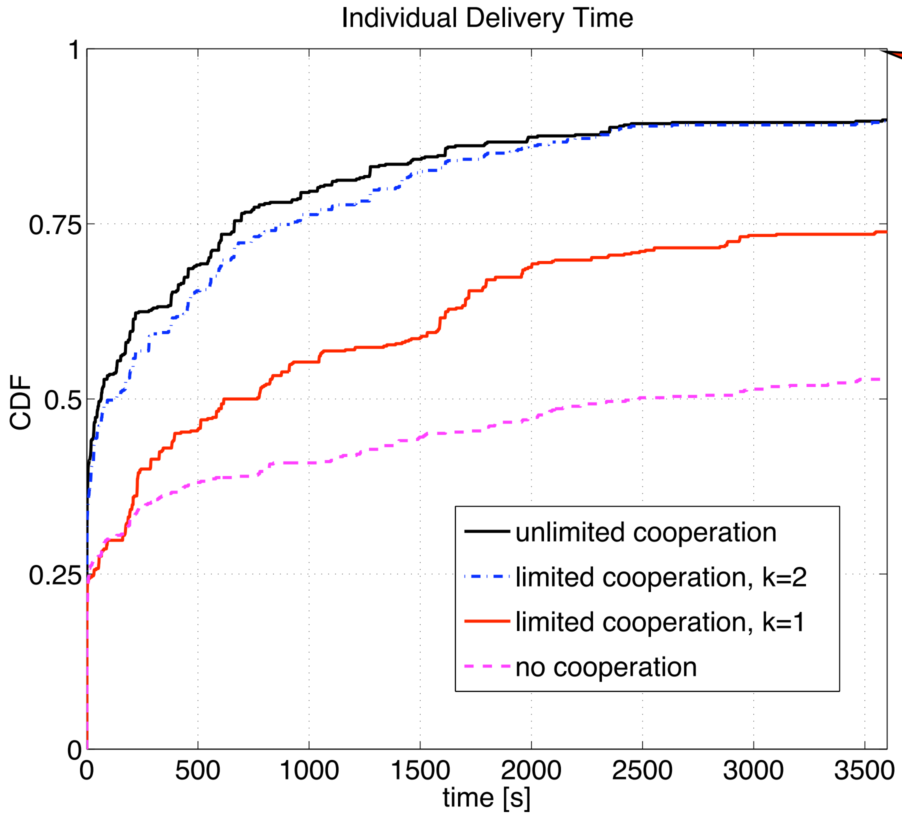




  - Simulations with RWP (left red) confirms the relevance of our model
  - Simulations with other inter-contact distributions confirms the qualitative behavior of our model

Perf. Evaluation – System resolution with traces

- Replaying traces also confirms the analytical results (black vs. pink)

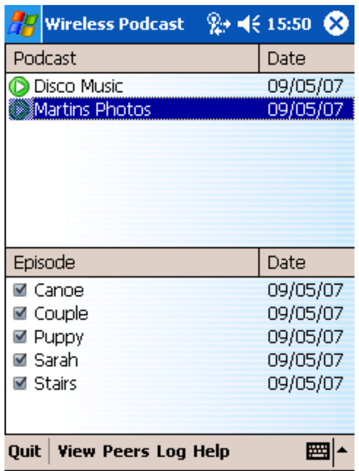


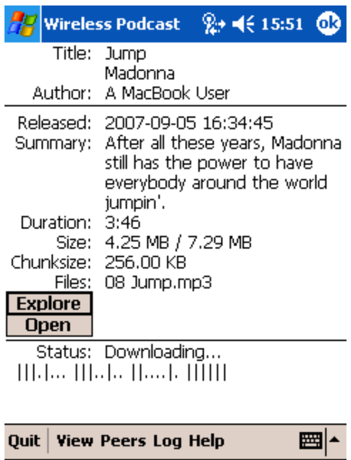
CDF does not converge to 1 because the empirical inter-contact distribution has infinite mean (see next lectures)

Perf. Evaluation – System experimentation

- Don’t have results from content dissemination experiment yet (soon)

- But be aware that
  - Home-made simulator required 2 days of code development
  - Trace collection at ETH CSG required 2 months (SA)
  - Software development required 6 months for having first prototype! (MA)





References

COMMUNICATION SYSTEM MODELING

- **[Bremaud]** Pierre Brémaud, "**Markov chains : Gibbs fields, Monte Carlo simulation, and queues**".

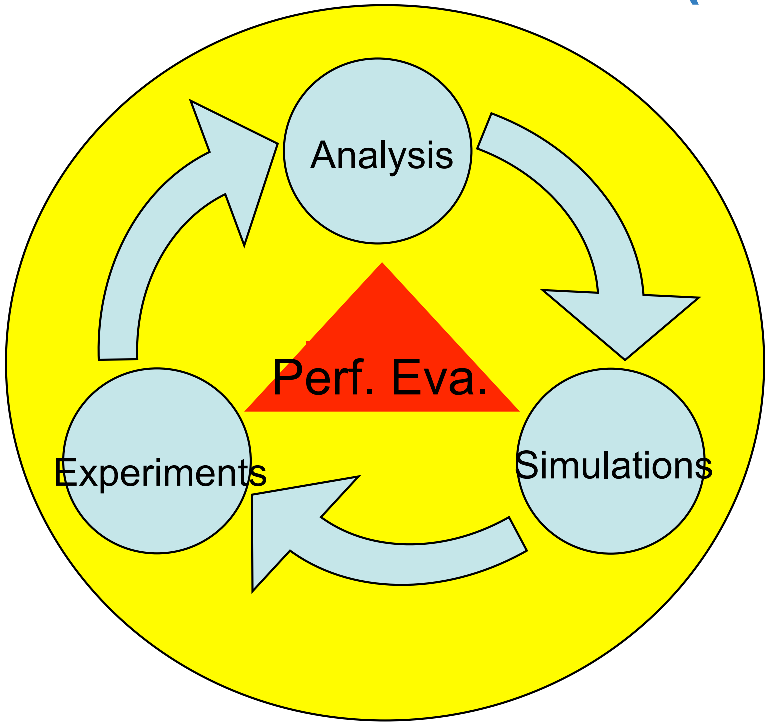
EXPERIMENTATIONS, TESTBEDS, and PROTOTYPING

- **[Kawadia03Asl]** V. Kawadia, Y. Zhang, and B. Gupta "**System services for ad-hoc routing: Architecture, implementation and experiences**," In MOBISYS, San Francisco, CA, May 2003
- **[Lundgren02Ape]** Henrik Lundgren, David Lundberg, Johan Nielsen, Erik Nordström, Christian Tschudin, "**A Large-scale Testbed for Reproducible Ad hoc Protocol Evaluations**", WCNC 2002.
- **[Kohler03Click]** Kohler, R. Morris, B. Chen, J. Jannotti, and M. F. Kaashoek, "**The Click modular router**," *ACM Transactions on Computer Systems, 18(3):263–297, Aug. 2000.Sep. 2003.*
- **[Neufeld02NsClick]** M. Neufeld, A. Jain, and D. Grunwald, "**Nsclick: Bridging network simulation and deployment**," In Proc. of MSWiM, Atlanta, Georgia, Sep. 2002.
- **[Gray04Outdoor]** R. S. Gray, D. Kotz, C. Newport, N. Dubrovsky, A. Fiske, J. Liu, C. Masone, S. McGrath, and Y. Yuan, "**Outdoor Experimental Comparison of Four Ad Hoc Routing Algorithms**," In Proc. of MSWiM 2004, Venice, Italy, October 2004.
- **[Gray04Experimental]** R. S. Gray, D. Kotz, C. Newport, J. Liu, Y. Yuan, and C. Elliott. "**Experimental Evaluation of Wireless Simulation Assumptions**", In Proc. of MSWiM 2004, Venice, Italy, October 2004.
- **[Tschudin04Lessons]** C. Tschudin, P. Gunningberg, H. Lundgren, and E. Nordstrom, "**Lessons from Experimental MANET Research**," Ad Hoc Networks Journal, special issue on "**Ad Hoc Networking for Pervasive Systems**," M.Conti, E.Gregori (Editors).

SHORTCOMINGS OF SIMULATIONS, TRACES, and SOLUTIONS

- **[Yoon03Harmful]** Jungkeun Yoon, Mingyan Liu, Brian Noble, "**Random Waypoint Considered Harmful**," Infocom, 2003
- **[Lin04Mobility]** Guolong Lin, Guevara Noubir, and Rajmohan Rajaraman, "**Mobility Models for Ad hoc Network Simulation**", Infocom 2004
- **[LeBoudec06Perfect]** Jean-Yves Le Boudec and Milan Vojnovic, "**The Random Trip Model: Stability, Stationary Regime, and Perfect Simulation The Random Trip Model: Stability, Stationary Regime, and Perfect Simulation**," IEEE/ACM TON, 2006
- **[Baumann06Realistic]** Rainer Baumann, Simon Heimlicher, and Martin May, "**Towards Realistic Mobility Models for Vehicular Ad-hoc Networks**," IEEE INFOCOM MOVE (Networks for Vehicular Environments), 2007
- **[Kurkowski05Incredibles]** S. Kurkowski, T. Camp, and M. Colagrosso, "**Manet simulation studies: the incredibles**," ACM Mobile Computing and Communications Review, vol. 9, no. 4, pp. 50–61, Apr. 2005.
- **[Swedish]** To complete.
- **[Lee06Modeling]** Jong-Kwon Lee and Jennifer C. Hou, "**Modeling steady-state and transient behaviors of user mobility: formulation, analysis, and application**", MobiHoc, 2006
- **[Lenders06Impact]** V. Lenders, J. Wagner, and M. May, "**Analyzing the impact of mobility in ad hoc networks**," in Proc. ACM Realman, (Florence, Italy), ACM Press, May 2006.

Performance Evaluation – Conclusion (cont'd)



A good researcher should carry analytical performance evaluation, simulations, and possibly real-world experiments.

Papers you should definitely read

- **[Camp02Survey]** Tracy Camp and Jeff Boleng and Vanessa Davies, "**A Survey of Mobility Models for Ad Hoc Network Research,**" WCMC: Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications, 2002
- **[Bai03Important]** Fan Bai, Narayanan Sadagopan, and Ahmed Helmy, **IMPORTANT: A framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks**," In IEEE INFOCOM, 2003
- **[Chaintreau06Impact]** Augustin Chaintreau, Pan Hui, Jon Crowcroft, Christophe Diot, Richard Gass and James Scott, **Impact of Human Mobility on the Design of Opportunistic Forwarding Algorithms**" In IEEE INFOCOM, 2006.
- **[Kim06Extracting]** Minkyong Kim, David Kotz, and Songkuk Kim, "**Extracting a mobility model from real user traces**," IEEE Infocom 2006

Papers you should read

- **[Kim06Extracting]** Minkyong Kim, David Kotz, and Songkuk Kim, "**Extracting a mobility model from real user traces**," IEEE Infocom 2006

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

UPMC
PARIS UNIVERSITAS

Questions? Discussion …