Mobility Management

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Mobility Models for Systems Evaluation - A Survey

By Musolesi and Mascolo

Mobility Patterns Categories

+ Trace Models
  - Obtained by measurements of deployed systems
  - Consists of logs of connectivity or location information
  - Related to a specific scenario
  - Publicly available traces are limited
+ Synthetic Models
  - Mathematical models - sets of equations that try to capture the movement of the devices
+ Design Synthetic Models from Real Traces
  - Capture and model key statistical properties of the traces
  - Reproduce and generalize them into simulators' input data
+ Social Network Theories
  - Mobile devices are carried by humans

Purely Synthetic Mobility Models

Represent movements of a single node

+ Random Walk Mobility Model
  - Purely random movement
  - Not suitable for wireless environment
+ Random Waypoint Mobility Model
  - Addition of pauses to the Random Walk
  - Not realistic
    - Initial placement of nodes
    - Nodes concentrate in the middle of a bounded area
    - Speed decay over time
  - Random Trip Mobility Model
    - Generalization of Random Walk and Random Waypoint
    - Sample the initial simulation state from the stationary regime to solve the problem of reaching time-stationary

Synthetic Group Mobility Model

Model behavior of groups that move together, i.e. platoon of soldiers, groups of students or colleagues.

+ Structured Group Mobility Model
  - Link movements of node to the position of a subset of the other nodes of the network
  - Not realistic
    - Groups move randomly
    - Memberships are hard-wired: nodes cannot join other groups during simulation

+ Heterogeneous Random Walk Model
  - Reproduce the presence of clusters that are observed in real-world traces to study the emergence of clustered networks

Trace-based Mobility Model

Exploit available measurements to generate synthetic traces characterized by the same statistical properties of the real ones

+ WLAN Campus Usage Traces
  - Movements between areas of campus represented by means of Markov model
  - Session duration data follow power-law distribution
  - Pause time and speed follow log-normal distribution

+ Movements inside downtown Osaka
  - No reliance on any wireless measurements
  - Empirical methodology to analyze characteristics of crowds in instants of time and maps of the city

Characterization and Analytical Models of Human Connectivity

+ Power-law distributions to represent contacts duration and inter-contacts time
+ Beyond characteristic time of 12 hours, the CCDF exhibits exponential decay

⇒ *Do not abandon Random Waypoint Model yet!*

+ User registration patterns exhibit a distinct hierarchy and WLAN APs can be clustered based on registration patterns
+ Heavy-tailed Wei-bull distribution to model cluster size distributions, intra-cluster transition probabilities, and trace lengths
+ Modeling of animal movements such as animal foraging behavior

Social Network-Based Mobility Models

+ Devices are carried by humans, so the movement of such devices is based on human decisions and social behavior

+ Presence of clusters dependent on the relationships among members of the social group

+ Fundamentally different from other types of networked systems - clustering is far greater than in networks based on the stochastic models

Social Network Based Mobility Models - Community Based Mobility Model

+ Hosts grouped together based on social relationships among individuals
+ Grouping mapped to a topographical space, with topography biased by the strength of social ties
+ Movements of hosts are driven by social relationships among them
+ Fundamental parameters, such as distribution of contacts duration and inter-contacts time, provide good approximation of real movements
+ Approximate power law holds over a large range of values for inter-contacts time
+ Contacts duration distribution follows a power law for a more limited range of values

Social Network Based Mobility Models - Community Based Mobility Model, Cont.

+ Weighted graph to present social networks [0,1]. 0 = no interactions between nodes/person. 1= strong social interaction.
+ Network represented by interaction matrix M: m_{ij} = interaction between individual i and j. m_{ij} = 1 where i=j.
+ Interaction matrix to generate connectivity mtrix C: c_{ij} = 1 if m_{ij} > specific threshold.
+ A host is initially positioned in a certain square in the grid. A goal is assigned to host to drive movement. Host i is associated to square S_{pq} if its goal is inside S_{pq}.
+ Each S_{pq} exerts a certain social attractivity to a certain host. The social attractivity of a square is a measure of its importance to host in terms of the social relationships.

Social Network Based Mobility Models - Community Based Mobility Model, Cont.

Social attractivity of square S_{pq} towards host i = $SA_{pq(i)}$:

$$SA_{p,q_i} = \frac{\sum_{j \in C_{S_{p,q}}} m_{i,j}}{w}$$

w = the cardinality of C_{Spq} (i.e. the # of hosts associated to the square S_{pq})

2 mechanisms for selection of next goal:

+ Deterministic: based on selection of square that exerts the highest attractivity. goals are chosen only inside squares associated to their community.

+ Probabilistic: based on probability of selection of a goal in a certain square proportional to their attractivities.

Social Network Based Mobility Models - Community Based Mobility Model, Cont.

Probabilistic mechanism: hosts randomly select next goals in other squares of the simulation area, with a certain non-zero probability

+ New goals are chosen inside the same area when the input social network is composed by loosely connected communities
+ Host may also be attracted to a different square when it has strong relationships with both communities.
+ Probability of selecting square $S_{pq(i)}$:

$$P(s = S_{p,q_i}) = \frac{SA_{p,q_i} + d}{\sum_{j=1}^{p \times q} (SA_{p,q_j} + d)}$$

d = random value greater than 1

Connectivity Models

Focuses on the evolution of the emergent connectivity graph that is changing over time as nodes move.

+ Connectivity Trace Generator (CTG)

- Probability distributions describing the patterns of collocation of mobile users (i.e. contact duration and inter-contacts time) are direct inputs of a synthetic traces generation tool
  - Input of CTG is a set of real traces - processed by a trace analyzer to generate parameters describing user connectivity
  - Parameters are the coefficients of the curves used to approximate the distributions of:
    - Inter-contacts time
    - Contract durations
    - Link degrees characterizing the social graph of the contacts among the users.
- Connectivity graph as basis for time-varying graph of instant connectivity for each instant t

Testing Tools and Mobility Modeling

+ Most popular are NS-3, Glomosim, Opnet
+ Discrete-event simulators: OMNeT++, Parsec
+ Different simulators show significant differences
  - Various modeling techniques and assumptions
  - Different methodologies followed by researchers.
+ Use of unrealistic mobility models
+ Absence of a meaningful number of runs to achieve a sufficient statistical validity of the results

⇒ Lack of confidence in simulation results to evaluate the performance of protocols and systems!

Outlook

+ Identify common features of human mobility
  - Increase availability of mobility traces extracted from heterogeneous environments

+ Connectivity Models and Mobility Models are complementary, not alternative
  - Integrate the use of connectivity and mobility models to characterize human mobility

+ Benchmarks for Protocol and System Evaluation: Choice of values for parameters of simulations are extremely variable

+ Limited number of available tools for academic and industrial testing of mobile applications

+ Available traces do not follow common standard

The Random Trip Model: Stability, Stationary Regime, and Perfect Simulation

By Boudec and Vojnovic

Overview

+ Provide a class of "stable" mobility models to accommodate a large variety of examples
+ Provide an algorithm to run “perfect simulation” of these models
+ Model of random with independent node movements.

- Independent node movements are defined by specifying a random process of movement for a single node
- Does not accommodate group movements

+ Guarantee existence of a time-stationary regime of node mobility state or its non existence.
+ Guarantee convergence of node mobility state to a time-stationary regime, starting a node movement from origin of a trip.

Overview, Cont.

+ Problems on stability of random processes
  - Speed decays to 0 as simulation progresses
  - Conditions for existence of stationary regime or its non existence
  - Conditions for guarantee of convergence to a stationary regime

+ Random trip examples: city driving, circulation models, special purpose models.

+ Perfect Simulation: When condition for stability is satisfied, simulation runs go through a transient period and converge to the stationary regime.

+ Palm Calculus Framework: a set of formulae that relates time averages to event averages. Utilize to derive simple sampling algorithms for the generic random trip model.

Model Definition

+ Domain A is a subset of Rd for integer d ≥ 1

+ Phase I is a set of phases on Rd. A phase describes some state of the mobile, specific to the model (i.e. move/pause at time t)

+ Path P is a set of paths on A. A path is a continuous mapping from [0,1] to A that has a continuous derivative

- For p ∈ P, p(0) is the origin of p, p(1) is its destination, p(u) is the point on p attained when u ∈ [0,1] of the path is traversed

Model Definition, Cont.

+ Trip is specified by path P_n and a duration S_n:

- $T_n \in R+$, $n \in Z+$ of transition instants such that $T_0 \leq 0 < T_1 < T_2 < \ldots$. At time T_n, a phase $I_n \in I$, a path $P_n \in P$, and a trip duration $S_n \in R+$ are drawn according to some specified trip selection rule, specific to the model.
- The next transition instant: $T_{n+1} = T_n + S_n$
- The position of the mobile: $X(t) = P_n[(t-T_n)/S_n]$ for $T_n \leq t \leq T_{n+1}$

+ Trip selection rule is constrained to choose a path P_n such that $P_n(0) = P_{n-1}(1)$

+ Default Initialization Rule: at time t = 0, a phase, path, position on the path, and remaining time are drawn according to some specified initialization rule.

Conditions on Phase and Path

(1) $Y \equiv (Y_n)$, $n = [0, +\infty)$ with $Y_n := (I_n, P_n)$ defined as a couple of phase and path is a Markov chain on I x P

(2) The chain Y is Harris recurrent: Ensures that chain Y has unique stationary measure π^0:

$$\pi^0(A) = \int_{I \times \mathcal{P}} P(y, A)\pi^0(dy)$$

(3) The chain Y is positive Harry recurrent: invariant measure π^0 is such that it can be normalized to a probability distribution

Conditions on Trip Duration

(1) The distribution of a trip duration S_n, given the phase I_n and path P_n is independent of any other past and n

(2) Each trip takes a strictly positive time

(3) The Markov renewal process is non arithmetic

Random Trip Examples

+ Random Waypoint with pauses:
  - A is convex (rectangle or a disk)
  - Paths are straight line segments: $p(u) = (1-u)m_0+um_1$ for the segment with endpoints m_0 and m_1
  - Pauses are special cases of paths when endpoints are equal $p(u) = m_0$
  - 2 phases I= {pause, move}
  - At a transition instant, the trip selection rule alternates the phase from pause to move or vice versa.
    - If the new phase is pause, trip duration S_n is drawn from distribution $F0_{pause}(s)$.
    - If the new phase is move, the trip selection rules pick a point M_{n+1} at random uniformly in A, and a numerical speed V_n according to the density $F0_V(v)$.
  - The default initialization rule starts the model at the beginning of a pause, at a location uniformly chosen in A.

+ If M is a random trip model, then M', a model of M with added pauses, is also a random trip model.

Random Trip Examples, Cont.

+ Random Waypoint on General Connected Domain: Variant of the classical random waypoint.

- A is assumed to be a connected domain over which a uniform distribution is well defined (instead of a convex).
- Examples: Swiss Flag, City Section where the domain is the union of segments defined by the edges of space graph.

+ Random Waypoint on Sphere: is a random waypoint on connected, non convex domain.

- Stationary location is uniform.

Random Trip Examples, Cont.

+ Restricted Random Waypoint
  - Trip endpoints are selected on a finite set of subdomain $A_i \in R_d$, i $\in$ L. A is a convex closure of the subdomains A_i.
  - Let node X starts from a point M_n chosen uniformly at random on a subdomain i. X picks the number of trips r to undergo with trip endpoints in the subdomain i from distribution F(i).
  - The next subdomain is drawn from the distribution Q(i).
  - Assume that Q is an irreducible transition matrix and the number of trips within a subdomain has a finite expectation,

⇒ Restricted random waypoint is a random trip model.
  - Examples
    - Fish in a bowl - Domain defined by the volume of the bowl.
    - Space graph - a special case with A = the space graph and Ai = the set of vertices

Random Trip Examples, Cont.

+ Random Walk on Torus
  - Distribution of location and speed at a random instant are the same as at a transition instant.
  - Domain A is the rectangle $[0,a_1] \times [0,a_2]$.
  - Paths are wrapped segments - the mobile moves from endpoint M_n in the direction and speed given by the speed vector (according to some fixed distribution) until it hits boundary of A at (x_0, a_2). Then it is wrapped around to $(x_0, 0)$ where it continues the trip. Wrapping does not modify the speed vector.
  - After a trip, a pause time is drawn independent of all past from some fixed distribution. If there is no pause, then it is a random walk on the torus.

+ Assume that the distribution of the speed vector chosen by the trip selection rule has a density. Assume that either the distribution of trip durations or distribution of pause times have a density.

⇒ The random walk on torus satisfies the random trip assumption.

Random Trip Examples, Cont.

+ Billard
  - Wrapping function is replaced by billiard function.
  - The billiard reflection may alter the speed vector.

+ Assume that the distribution of the speed vector chosen by the trip selection rule has a density and is completely symmetric. Assume that either the distribution of trip durations or distribution of pause times have a density.

⇒The billiard satisfies the random trip assumption.

Time Stationarity and Convergence

The state of a mobile node at time t is described by the continuous-time Markov process:

$$\Phi(t) := (Y(t), S(t), S^{-}(t))$$

S(t) is the duration of the trip at time t. $S^{-}(t)$ is the elapsed time on the trip at t.

There exists a time-stationarity distribution π for Φ(t) if and only if $\mathbb{E}^0(S_0)$ is finite.

$$\pi(B) = \frac{\mathbb{E}^0\left(\int_0^{T_1} 1_{\Phi(s)\in B} ds\right)}{\mathbb{E}^0(S_0)}, \; B \in I \times \mathcal{P} \times \mathbb{R}_+^2$$

$\mathbb{E}^o(Z)$ is the Palm Expectation - the expectation, conditional to the event that a transition occur at time 0, when the system has a stationary regime. $\mathbb{E}^o(S_o)$ = Average trip duration.

Time Stationary Distribution

+ Perfect Simulation: Sample from the time stationary distribution of the process state - Phase I(t), path P(t), trip duration S(t), where on trip U(t). The time stationary distribution of the process state at an arbitrary time t:

1) *Phase and Path: Let* $Y(t) = (I(t), P(t))$.

$$d\mathbb{P}(Y(t) = y) = \frac{\bar{\tau}(y)}{\int_{\mathcal{Y}} \bar{\tau}(x)\pi^0(dx)}\pi^0(dy).$$

2) *Trip duration, given phase and path:*

$$d\mathbb{P}(S(t) = s | Y(t) = y) = \frac{s}{\bar{\tau}(y)} F(y, ds).$$

3) *Fraction of time elapsed on the trip:* $U(t)$ *is independent of* $(I(t), P(t), S(t))$ *and is uniform on* $[0, 1]$.

Apply the Perfect Sampling Algorithm

+ Random Waypoint on Sphere
+ Random Walk on Torus
+ Billiards

For further details, please read the paper.

Thank you for your attention!