First AETOS Conference

Network

A SMOOTH-TURN MOBILITY MODEL FOR AIRBORNE NETWORKS

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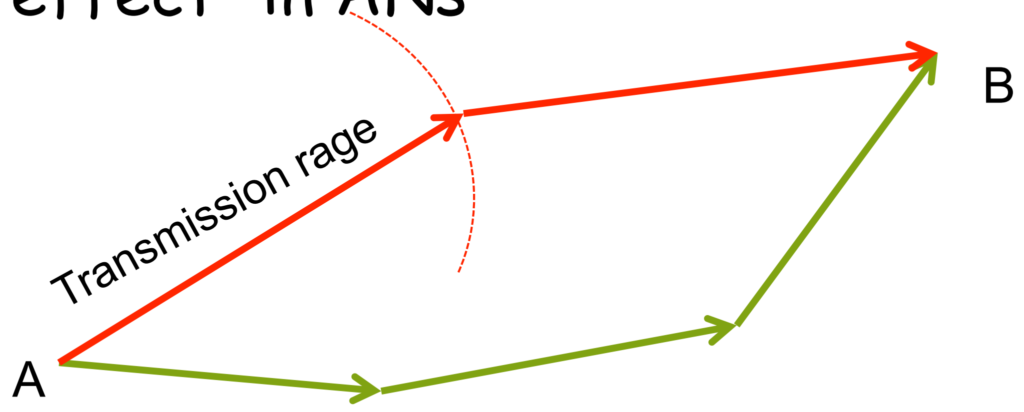
Outline

- Motivation
- Model Description
- Model Properties
- Randomness
- Conclusions

Motivation: Need for AN Mobility Models

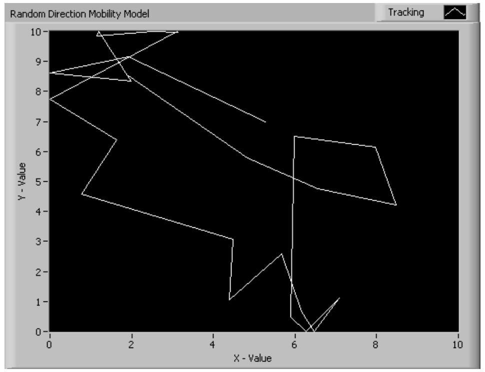
- Need for mobility models for airborne networks
  - ``Edge effect" in ANs

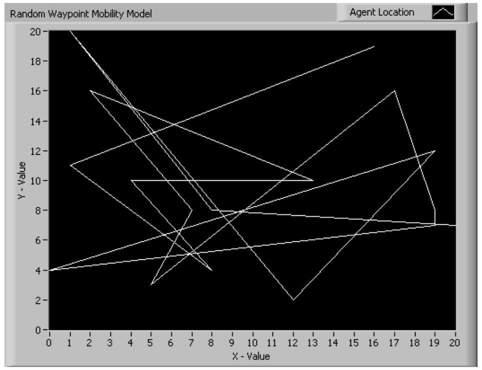


  - Philosophy
    - Routing protocol design should take into account the knowledge of the dynamic structure of ANs.
    - Mobility model captures the random movement patterns of nodes.
    - Mobility model serves as the fundamental mathematical framework for network connectivity analysis, network performance evaluation, and eventually the design of reliable routing protocols.

Motivation: Research Gap

- Existing mobility models
  - Random Direction (RD) Random Waypoint (RWP)





- Fail to capture "smooth trajectory" of airborne vehicles
  - Tend to maintain the same heading speed
  - Change direction through making large turns
  - Mechanical and aero-dynamical constraints
- The correlation along temporal and spatial dimensions created by the smooth trajectory can be useful to design routing protocols.

Motivation: Our Aim

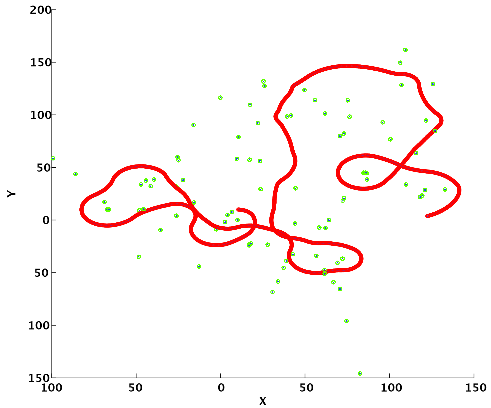
- Aim
  - Construct realistic AN mobility models that capture the features unique to ANs, yet simple and tractable enough to serve as analytical frameworks for connectivity analysis.
    - Capture the smooth-turn behavior
    - Take into account the correlation in acceleration along spatial and temporal dimensions caused by physical laws
  - Connectivity properties of the model
    - Node distribution
    - Number of neighbors, etc.
  - A comprehensive investigation of AN mobility models
    - Classification according to applications
    - Classification according to randomness levels
    - Quantifying randomness

Model: Description

Idea of the Model

- Select a point perpendicular to its heading direction and circle around it → smooth trajectory
- Duration between the changes of circling centers to be memoryless → makes the analysis tractable
- Inverse length of the circling radius to be Gaussian distributed → straight trajectories and slight turns are preferable

Model Details



$$
\begin{aligned}
a_t(t) &= 0 \\
a_n(t) &= \frac{V^2}{r(T_i)} \\
\dot{\Phi}(t) &= -w(t) = -\frac{V}{r(T_i)} \\
\dot{l_x}(t) &= v_x(t) = V cos(\Phi(t)) \\
\dot{l_y}(t) &= v_y(t) = V sin(\Phi(t))
\end{aligned}
$$

- Wrap-around and reflection boundary models

Properties: Node Distribution

- Theorem 1: initial distribution is uniform

THEOREM 1. *N airborne vehicles move independently in the space $[0, L) \times [0, W)$ according to the ST mobility model associated with wrap-around boundary model. If the initial locations of these vehicles are uniformly distributed in $[0, L] \times [0, W]$, and the heading angles are also initially uniformly distributed in $[0, 2\pi)$, then the node locations and heading angles remain uniformly distributed at all times $t > 0$.*

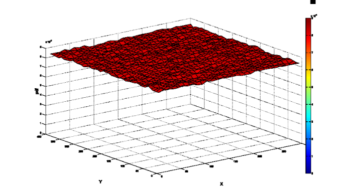
- Theorem 2: arbitrary initial distribution

THEOREM 2. *N airborne vehicles move independently in the space $[0, L] \times [0, W]$ according to the ST mobility model associated with wrap-around boundary model. Assuming that λ is finite and $\sigma \neq 0$, the distributions of node locations and heading angles are uniform in $[0, L) \times [0, W)$ and $[0, 2\pi)$, respectively, in the limit of large time, regardless of the distribution at the initial time.*

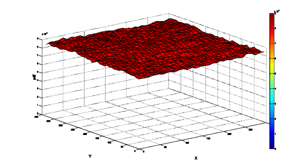
- The results resemble those of the RD model.

Properties: Simulations

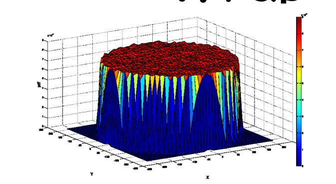
- Rectangular regions
  - Wrap-around



Mirror



- Circular regions
  - Wrap-around



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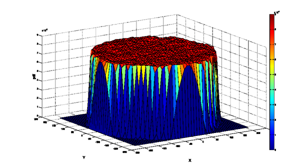


Properties: Connectivity

Network

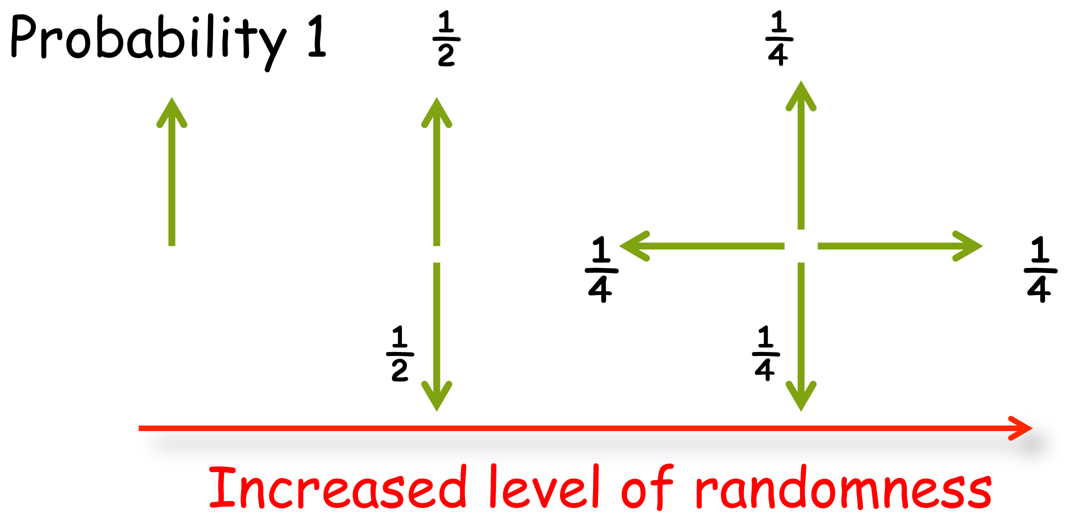
- Uniform distribution of node locations facilitates tractable network connectivity analysis
  - For individual nodes
    - Expected number of neighbors $E(M) = \frac{\pi N d^2}{A}$
    - Probability of the number of neighbors

$$P(M = m) = \frac{e^{-E(M)} E(M)^m}{m!}$$

  - At a network level
    - P(connected) <= $P(No\ isolated\ Node) = (1 - P(M = 0))^n$
    - $P(k - connected) \leq (1 - P(M \leq k - 1))^n$
    - In a circular region with boundary, if the transmission range is $\sqrt{\frac{logn + c(n)}{n\pi}}$, then P(connected)→1 as n→infty, iff c(n)→ infty

Randomness: Quantification

- Important information for routing design

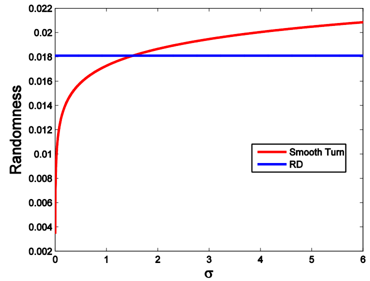


- Randomness: Conditional entropy about the prediction of location and direction at a future time.
- Immediate entropy measure: entropy rate defined on the Markov chain

$$H = -\int_{i,j} p_i Q_{ij} ln Q_{ij}$$

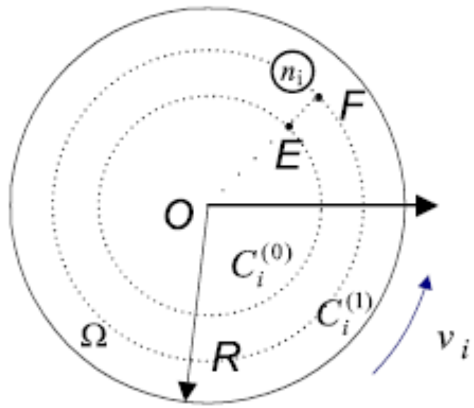
Randomness: Comparison

- Randomness for RD and ST models
  - RD: $$-(1-\lambda\Delta t)ln(1-\lambda\Delta t)-\lambda\Delta t ln\frac{\lambda\Delta t}{2\pi}$$
  - ST: $$-(1-\lambda\Delta t)ln(1-\lambda\Delta t)-\lambda\Delta t ln\frac{\lambda\Delta t}{\sqrt{2\pi e\sigma}}$$



- Comparison of AN models

Mobility models	Application	Randomness
Flight plan (FP)	Cargo and Commercial	Low
Semi-Circular Random Mobility (SCRM)	Search and rescue	Medium
Smooth-Turn (ST)	Patrolling	High

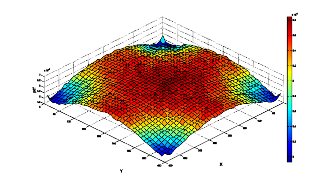


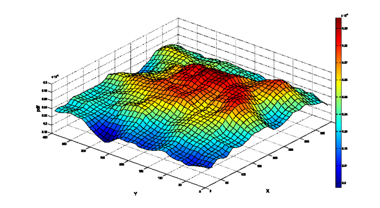
Conclusions: Summary

- Contributions
  - A novel AN mobility model that captures smooth turns
  - Stationary analysis and preliminary connectivity analysis of the model
  - An entropy measure that characterizes the randomness of mobility models
  - Classification and comparison of different types of AN mobility models
- Future Works
  - Enhance the basic model
  - Further connectivity studies
  - Use of randomness in routing design

Conclusions: Model Enhancement

- Enhance the model parameters
  - Varying speed
  - 3-D movement
  - Realistic range of turning radius
- Collision Avoidance
  - Easy to extend because of the incorporation of physical laws
- RWP-like Smooth-turn Mobility Models
  - Randomly select a center uniformly distributed in the space
  - Randomly select a destination uniformly distributed in the space



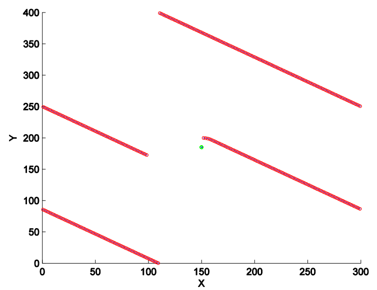


Thank You !

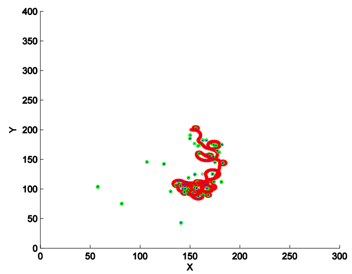
- We thank National Science Foundation for the support.

Model: Further Discussion

- Impact of parameters on the mobility model
  - Heading speed: constant
  - Mean duration: how frequently is the change of direction
  - Variance of Gaussian variable: preference between straight trajectory versus turns.



σ is close to 0

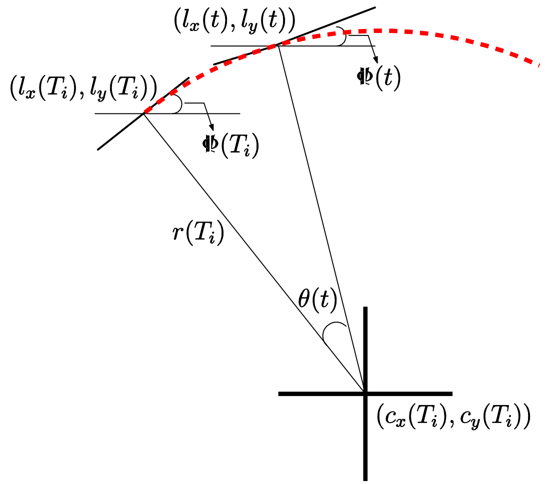


σ is large

- Connection to existing literature
  - RD model equipped with smooth trajectory
  - Built upon the coordinated-turn models for target tracking

Model: Basic Analysis and Boundary Models

- Basic Analysis



- Boundary models
  - Wrap-around
  - Reflection
  - Captured by floor functions