Evaluation of Measurement Techniques for the Validation of Agent-Based Simulations Against Streaming Data

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Problem Domain

- Disasters, crises, emergencies, civil disorders, humanitarian relief efforts, transportation disruptions, ... events involving large numbers of people.
  - Natural origins: hurricanes, tornados, earthquakes, tsunami, snow storms, floods, volcanoes, epidemics, ... 
  - Human origins: terrorists attacks, political unrest, civil unrest / disorder, industrial accidents, transportation accidents, ...
Emergency Response Management

- **Problems**
  - Communication
  - Co-ordination
  - Situation Awareness (SA)
  - Sharing SA

- **Information Needs**
  - Alerts - Has something happened?
  - Location - Where, extent?
  - Numbers - How many people?
  - Movement - Stationary, moving?
  - What is nature of the event?
  - How should we respond?

- Enhanced Situational Awareness: Calling activity and cell phone locations can help with these information needs
Cell Phones: An In-Place Mobile Sensor Network

- Increasing ubiquity in urban areas
- Approaching +100% in some regions
- Often more popular than wired systems, especially in developing economies
- Cell tower and handset continually exchange “signal strength” info
- Location data
  - Closest cell-tower cells, distance estimates possible
  - Ability to triangulate
  - Growing availability of GPS data
- Collective knowledge of the location, numbers, calling activity and movement of a large sample of population in a region is potentially available
Animation
Animation
WIPER

- Wireless Integrated Phone-Based Emergency Response System
- Ties into the existing cellular phone infrastructure to detect, monitor, predict anomalies
  - Fact: people make cell phone calls during a disaster
  - Family, friends, E911
  - New calling patterns
  - Increased numbers of calls placed
- Streaming data
  - Calls placed per cell tower
  - Calling patterns & volume
WIPER/DDDAS
Distributed System Structure

- Real Time Data Source
  - Historic data from cellular service provider
  - Eventually will use live data streams
- DAS - Detection and Alert System
- SPS - Simulation and Prediction System
- DSS - Decision Support System
WIPER - Data Source

- Data collection occurs at the cellular service provider
- WIPER receives anonymized, pre-processed, encrypted data
- No personally identifiable information leaves the service provider’s network
WIPER - Detection and Alert

Location and Activity View

Real World

Social Network View
Simulation Prediction System

- For all alerts, WIPER generates an ensemble of Agent-Based Simulations
- Simulations used to determine nature of anomaly, predict evolution of event
- Simulations use direct stream of information to monitor real world and dynamically validate/update simulations
Simulation Prediction System

- Agent-Based/GIS-Based Simulations used to test hypotheses about real-world phenomena
- Geo-spatial constraints embodied in the simulations
  - Rivers, roads, coast-lines
  - Accurate cell-tower coordinates
  - Overlaid on maps to support emergency response managers
Modeling & Simulation

- “All models are wrong, some models are useful” … Box

- Verification, calibration and validation
  - Verification: is the model right (debugging)?
  - Calibration: does the model fit the data (parameterization)?
  - Validation: is it the right model (solving the wrong problem)?
DDDAS Adaptation Techniques

- Update the Model
- Replace the Model

Diagram:
- Verification
- Calibration
- Validation
- DDDAS
Online Validation: Approach

How do we validate simulations against streaming data?
- Treat validation as model selection process. Create ensemble of models, rank simulations based on distance measure.

How do we rank models?
- Simulations generate output as a vector of towers, with agents in tower as the value at each position
- Rank simulation output by measuring distance from simulation output vector to target
Animation

Real Time Streaming Data

Sim 1 => Sim 2

Sim 3 => Sim 4
Figure: Cell Phone activity aggregated at tower level and overlaid on a satellite image. Satellite imagery courtesy Google Earth.

Figure: Call activity in 3D. Calling activity represented by cell height.
Online Validation

Validation on Movement Models

- Treat the output from simulation, list of towers with numbers of active agents, as a vector
- Use distance measure to choose closest match
- Validation work demonstrates this approach, evaluates measures for their applicability
- This approach is related to Input-Output Validation [Balci 98]

Figure: Validation on agent movement models. Target Flee, metric $L_\infty$
Distance Measures

We consider the following distance measures for their applicability to online model validation. For each measure, \( \bar{p} = (p_1, p_2, \cdots p_n), \bar{q} = (q_1, q_2, \cdots q_n) \):

- **Euclidean**
  \[
  d(\bar{p}, \bar{q}) = \sqrt{\sum_{i=1}^{n}(p_i - q_i)^2}
  \]

- **Manhattan**
  \[
  d(\bar{p}, \bar{q}) = \sum_{i=1}^{n}|p_i - q_i|
  \]

- **Chebyshev**
  \[
  d(\bar{p}, \bar{q}) = \max_{i}(|p_i - q_i|) = \lim_{k \to \infty} \left( \sum_{i=1}^{n}|p_i - q_i|^k \right)^{1/k}
  \]

- **Binary**
  \[
  d(\bar{p}, \bar{q}) = \frac{\sum_{i=1}^{n}p_i \oplus q_i}{\sum_{i=1}^{n}p_i \lor q_i} \quad \text{where} \quad p_i = \begin{cases} 0 & \text{if } p_i = 0 \\ 1 & \text{otherwise} \end{cases}
  \]

- **Canberra**
  \[
  d(\bar{p}, \bar{q}) = \sum_{i=1}^{n} \frac{|p_i - q_i|}{|p_i + q_i|}
  \]
Experiments

- Nine hundred agents (cell phones)
- Twenty Voronoi cells (cell towers)
- Five movement models (human behavior)
- Five distance metrics

Experiment 1
- One target data stream for each movement model
- One hundred random simulations for each model

Experiment 2
- Five hundred replications (random seeds)
- 500x500 matrix of distances
Validating ABM

**Figure:** Plot of the distances of multiple simulation runs of various models on a Flee target using the Euclidean Distance metric, 10 minute intervals.
Validating ABM

Comparison of Models on First Iteration of Simulation Output, Euclidean Metric

Figure: Plot of distance values between simulation instances.
Use distance measures for ranking simulations
Evaluate the effectiveness: CMC curve
CMC Curves

- Used in vision and biometrics research
- Cumulative Match Characteristic curves
  - Y-axis is the true positive rate
  - X-axis is the cumulative rate

(Bowyer, 2004)
Figure: CMC Curve displaying Rank 1-25 matches for all of the 5 distance metrics.
Table: Summary of average distances to first true and false matches, showing value of measures for classification. All of the measures from the $L$ family display good characteristics.
Online Validation Contributions

- Method: Online Validation as Model Selection
- Demonstrate 100% Accuracy on Matching Model Type
- Several measures in $L$ family work well
Discussion

- Multiple online model validation metrics evaluated
  - Euclidean, Manhattan & Chebyshev metrics all work well
  - But … additional testing needed on more realistic scenarios

- WIPER System provides complimentary tools for monitoring and predicting crisis events - improved Situation Awareness

- Connection to cellular service provider allows multi-modal monitoring of real time events without need for new sensor infrastructure

- Architecture protects privacy while providing access to information, but potential for privacy concerns

- Limitations of cell phones during prolonged power outage
Summary

- WIPER is a demonstration project using existing cell phone system in a mobile sensor network
- Employs DDDAS principles
  - Simulation prediction system
  - Large amounts of streaming data
  - Simulation system adapts to new data by using online validation to select best fit model
- Euclidean, Manhattan & Chebyshev metrics all work well
- But … additional testing needed on more realistic scenarios
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Questions?

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