Task 5:
Large, High-Fidelity Simulations

Rajive Bagrodia,
Jennifer Hou
Scalable Simulation of Mobile Ad Hoc Networks

Rajive L. Bagrodia
Professor
Computer Science Dept
UCLA
rajive@cs.ucla.edu
Motivation

• **Net-centricity** is a force multiplier for the US military
• The next generation wireless communication technology being developed for this purpose will be **adaptive** (software-defined radios, smart antennas, programmable networks, …)
• There is substantial ‘**cross-layer interaction**’ among the technology solutions at multiple layers of the protocol stack (e.g., medium access, routing, and transport) to provision **dynamic Quality of Service** among the voice, video, and data traffics that must be carried by such networks
• There is **limited experience**, in the commercial or military arena, with large scale deployments and use of such on-the-move communication technology
• **Static analysis** and planning may not be adequate to achieve the dynamically varying **Quality of Service** requirements for the diverse applications
• Real-time network simulations can play a critical role in assessing the **dynamic impact of net-centricity** in the design and operation of such networks
Adequate feedback from PHY is one of the key requirements to success.
Simulator Performance: State of the Art

- Selected data points on simulation performance:
  - wireless networks at 10,000+ nodes with models of the complete protocol stack and terrain and mobility running about 100x slower than RT on standard desktop and 32-processor Sun Enterprise 10000 (GloMoSim 2000)
  - wireless networks at ~750 nodes with complete protocol stack model, mobility, and terrain in real-time on standard desktops with dual processors (QualNet 2004)
  - **Challenge**: Accurate models of many thousands of MANET nodes running on software-defined radios (SDR) in real-time or substantially faster than real-time for real-time network planning & control
Simulator Performance

Model Fidelity (expressed as event time granularity)

- Nanosecond
- Microsecond
- Millisecond
- Second
- 00s of sec

Speed

- 10x faster RT
- 100x slower RT

Scalability

- 10,000s
- 1,000s
- 100s

RT
An Example Scenario

- Assesses the impact of network dynamics on the performance of distributed applications across large scale networks
- Fast execution to accommodate real-time constraints
- High fidelity: in resembling the target network as closely as possible (accuracy)
- Scalable: in evaluation of distributed applications on large scale networks
Where is the overhead in wireless network simulation?

- Propagation model
  - Signal has long distance of reachability
  - Multiple interferences
  - Accumulation of weak signals
- Physical device model (802.11)
  - CSMA/CA
  - BO timer
  - SINR
- Common approach is to drop signals weaker than carrier sensing threshold (CST), i.e. to limit signal’s reachability
Cost of Wireless Network Simulation (1)

- **Accuracy Vs Efficiency in Simulators:**
  - Consider simple Carrier Sense (CS) protocol
Cost of Wireless Network Simulation (2)

- Overhead of computing interference power:
- $O(N)$ events per transmission for network of size $N$!!
  - Common approach to reduce number of events is to drop signals weaker than carrier sensing threshold (CST), i.e. to limit signal’s reachability

Use propagation Limit
Simulation of Wireless Networks

- Where does the time go?

<table>
<thead>
<tr>
<th>Layer type</th>
<th>Number of events $[\times 10^3]$</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 node network simulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio PHY and Propagation</td>
<td>29,863</td>
<td>95.5</td>
</tr>
<tr>
<td>Radio MAC</td>
<td>1,344</td>
<td>4.3</td>
</tr>
<tr>
<td>All the models above radio</td>
<td>48</td>
<td>0.2</td>
</tr>
<tr>
<td>1,000 node network simulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio PHY and Propagation</td>
<td>2,376,729</td>
<td>99.41</td>
</tr>
<tr>
<td>Radio MAC</td>
<td>13,475</td>
<td>0.56</td>
</tr>
<tr>
<td>All the models above radio</td>
<td>535</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Misleading results of CST propagation limit

* In worst case, CST limit introduces relative error > 100%

Experiment setup:

100 nodes
2000x2000m²
AODV
30 random CBR sessions
512-byte pkts; 2~10 pkts/sec
Same traffic load for all sessions
Our Observation

- Upper bound on aggregated power \( \bar{P} \) of interferences outside distance \( D \):

Approximate with continuous function

\[
\bar{P} = \sum_{s: d_s > D} \frac{P_s}{PL(d_s)} = \sum_{s: d_s > D} \frac{P_s}{PL(d_0)} \left( \frac{d_0}{d_s} \right)^\alpha \leq P_{\text{max}} d_0^\alpha \sum_{s: d_s > D} \frac{1}{d_s^\alpha}
\]

\[
\bar{P} \leq \frac{P_{\text{max}} d_0^\alpha}{PL(d_0)} \int_D ^{\xi} \frac{2\pi \lambda x \xi^\alpha}{x^\alpha} dx = \begin{cases} 
\frac{2\pi \lambda P_{\text{max}} d_0^\alpha}{PL(d_0)} (\ln \xi - \ln D) & \alpha = 2 \\
\frac{2\pi \lambda P_{\text{max}} d_0^\alpha}{(2 - \alpha)PL(d_0)} (\xi^{2-\alpha} - D^{2-\alpha}) & \alpha \neq 2 
\end{cases}
\]

\( s \): transmitter \hspace{1cm} \( PL \): path loss \hspace{1cm} \( d_s \): distance from \( s \) to receiver
\( P_s \): tx power \hspace{1cm} \( d_0 \): reference distance \hspace{1cm} \( P_{\text{max}} \): max tx power
\( \alpha \): exponent \hspace{1cm} \( \lambda \): max density of concurrently tx nodes
\( \xi \): network radius
Our Approach

- Parameterize distance limit $D$ as a function of desired level accuracy (ignored interference power)
  - Deriving better distance limit $D$

$$ P \leq \sigma_n^2 \Rightarrow D \geq \left( \frac{\xi^{2-\alpha} - \frac{(2-\alpha)\sigma_n^2 PL(d_0)}{2\pi \lambda P_{max} d_0^\alpha}}{1} \right)^{2-\alpha}$$

$D \approx 2500\text{m}$ with these parameters

Table. Common experiment parameters

<table>
<thead>
<tr>
<th>Propagation Model</th>
<th>TWO-RAY</th>
<th>Physical Data Rate</th>
<th>2Mbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Frequency</td>
<td>2.4GHz</td>
<td>Antenna Height</td>
<td>1.5m</td>
</tr>
<tr>
<td>Physical Model</td>
<td>802.11b DSSS</td>
<td>Transmission Power</td>
<td>15dBm</td>
</tr>
<tr>
<td>Modulation Scheme</td>
<td>DPSK</td>
<td>Receiving Threshold</td>
<td>-81dBm</td>
</tr>
<tr>
<td>MAC Model</td>
<td>802.11 DCF</td>
<td>Receiver Sensitivity</td>
<td>-91dBm</td>
</tr>
</tbody>
</table>
Validation of $D$

- **Experiment setup**
  - 400 nodes uniformly distributed
  - 4000x4000m$^2$ terrain
  - AODV
  - 120 CBR sessions between random pair of nodes and 8 pkts/sec each
  - 512 bytes / packet
  - Portion (%) of sessions are one hop traffic
Validation of $D$ (cont’)

In worst case, CST limit can produce 150% relative error
Performance Evaluation of $D$

- **Experiment setup**
  - Nodes are uniformly distributed
  - 30% of nodes have a CBR session to another node within two hop distance
  - 10 pkts/sec; 512 bytes/pkt
  - Varying network size
  - Varying node density
  - Varying traffic load
Varying network size

![Graph showing the relationship between average execution time and number of nodes for different distance limits.]

- Red squares: no distance limit
- Blue diamonds: distance limit

![Graph showing speedup as a function of number of nodes with distance limit.]

- Blue diamonds: distance limit

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Accurate Network Simulation

- Use of state-based discrete-event simulation to model next generation on-the-move technology:
  - software-defined radios (JTRS), MANET routing protocols, Quality-of-service, smart antennas (directional communication), dynamic hierarchy
- Simulator structure can emulate network protocols.
- Simulator models dynamic changes in environmental conditions (terrain, weather, urban, mobility)
- Model wireless transmission effects: interference, multi-path, shadowing, fading, jamming, active nulling, …
- Directly incorporate real video/audio or data traffic from corresponding applications
Accurate Physical Layer Overview

PHY components

MAC sub-layer

Tx
Data rate
Channel coding
Spreading
Modulation
Channel
Power

Rx
SINR computation
BER (demodulation)
DBPSK  DQPSK
BPSK/QPSK  GMSK
BER (channel decoding)
Block Convolutional Turbo
Carrier sensing

Air interface (antenna)
Accurate Physical Layer Overview

Antenna models

- Omni-directional uniform gain
- Switched beam multiple patterns
  (circular array with 8 patterns)
- Steerable multiple steerable patterns
  (triangular array with 4 different beamwidths)
- Adaptive patterns on the fly plus nulling

The use of directional antenna models is currently receiver side only due to (omni-directional) MAC.
Detailed SINR Computation

- Detailed noise consideration
  - Accumulated noise for SNR calculation
  - SNR is calculated every time the noise level is changed

![Diagram showing Radio Power vs. Time with Noise Components and SNR Threshold]
Accurate Phy Modeling

- Propagation models (inputs to the physical layer) can substantially affect higher layer performance
  - Fading model (none, Ricean and Rayleigh)
  - Packet reception model (SNRT and BER)
- Depending on the physical channel model, predicted packet delivery ratios (PDR) may differ by 300% & also invert protocol rankings!
BER / PER Computation

• BER is changed every time a signal (even if it is too small to receive or sense) arrives at the node, thus table lookup is done very frequently.

• N signal arrivals = 2N interference power changes

Example: 8 changes in the interference power level by 4 signals
Improving Scalability of Wireless Network Simulation

Objectives

– Preserve accuracy
– Improve network simulation efficiency
– As a foundation for integration of detailed radio and channel models
– hybrid simulation testbed
Scalable Wireless Network Simulation

- Real-time for virtual simulations with human-in-the-loop (e.g., training) and hw-in-the-loop
- Faster than real-time for constructive simulations for trade space analysis, Force Effectiveness Analysis, ...
- Scalability to achieve simulation of Unit of Action/UoE/Joint assets with 10,000+ communicating entities
FCS Communication Effects Server

• Technology transitioned into COTS simulator – QualNet

• QualNet is being used to develop a Communication Effects Server (CES) for the FCS Program
  – A discrete-event simulation based CES to incorporate realistic communication effects into virtual and constructive wargaming software environments.

• FY2004-2006 Objectives
  – Accurate representation of FCS communication architecture & its interaction with external networks
  – Integration into constructive & virtual simulation frameworks
  – Accurate, real-time simulation of an FCS Unit of Action with 10,000 communicating devices

Tech Xfer from DARPA GloMo/Maya programs ’95-’00
Urban System Analysis

JS AF

Building and terrain data extracted from JS AF

JS AF plus bit error tables are fed into Qualnet

Qualnet

Real data flows through simulated network with all mobility and terrain data accounted for

Wireless Insight

Data processed to find signal paths and loss rates in study area

OFDM radio model incorporated to calculate bit error rates

BER Curve Generated with OFDM Radio and Exponential Decay Channel Model

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Communication in Joint Urban Operations

Existing Analysis

- Free space channel model
- Link budget model
- Ground UGSs keep direct connection to the OAV/UAV

Detailed Analysis

- Ray-tracing based accurate channel characterization
- High-fidelity interference model
- Ground UGSs might use multi-hop paths to improve comm.
Application to JFCOM/JUO -- network performance in Jakarta Scenario

Impact of detailed QualNet simulations:
- Ray-tracing based accurate channel characterization
- High-fidelity interference model
- Multi-hop ad hoc routing algorithms to improve comm.

Region of detailed comm. analysis
- South West (106.6543741, -6.2086831)
- North East (106.6647400, -6.1950786)

Entities involved
- 33 UGS, 22 OAVs

Tech Xfer from DARPA NMS program – MAYA 2000-'04
A hybrid testbed for heterogeneous, wireless networking

- **Heterogeneity** in wireless technologies: MANET, wireless LAN, 3G cellular, sensors, narrowband, wideband, UWB, …
- **Hybrid testbed** that combines realism of physical testing with scalability, flexibility and repeatability of simulations (Zhou et al TOMACS, April 2004)
  - Smooth transition from design to deployment

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**WHYNET**: Scalable Testbed for Next Generation Mobile Wireless Networking Technologies

**Distributed Simulation Testbed**

**Physical Realism**

**Simulation**
- Repeatability, controllability, scalability

**Emulation**
- Real applications & network protocols

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**NSF NRT Project (UCLA, UCSD, USC, UCR, UCSB, UCD, Univ. Delaware)**  PM: Joe Evans

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Hybrid Testbed: Architecture

**Emulation Node**
- Emulates multiple wireless hosts

**Simulation Node**
- Parallel simulation for high-fidelity modeling of a wireless subnet

**Physical Node**
- Executes operational protocol stack

**Gateway**
- Inter-connects physical networks with simulated and emulated networks

**Master node**
- Provides global reference time
Hybrid Testbed

• Advantages
  – The integration of simulated, emulated, and physical networks allows for user-in-the loop evaluation of real applications and network protocols
  – Achieve combined benefits of different modeling paradigms, such as scalability, realism, controllability.
  – Online network simulation and control

• Challenges addressed
  – Inter-operability among heterogeneous network modeling paradigms
  – Satisfy real time constraints
sQualnet Simulation Framework

- Scalable framework as extension to Qualnet
- Rich set of sensor network specific models
  - Sensing and radio channels,
  - MAC (S-MAC, T-MAC) and routing (diffusion, DTN, tree) protocol
  - Battery and power consumption models
- Formal release of version 1.0
  - Source code for Qualnet licensees
  - Free Linux binary executable
- Adoption by growing user base
  - UCLA projects: SOS Dynamic Sensor OS, Ragobot, Ad hoc Distributed Control Systems (ADCS), and Helimote Energy Harvesting Aware Sensor Nets
  - External academic users: UCSB, USC, University of Bristol, University of Missouri-Rolla, Iowa State, Nanjing University, City University of Hong Long...
  - Industry users: SDRC, Boeing, HRL

Joint work with M. Srivastava
New and Emerging sQualnet Capabilities

- Modeling of multitiered heterogeneous sensor networks
  - Field of motes (non-IP) with backbone of microservers (IP)
- Real-code simulation for motes
  - Run unmodified SOS and TinyOS code for motes in sQualnet
  - Makes larger set of protocols available, reduces debugging effort
- (in progress) Hybrid simulation: mix of simulated and real nodes
  - Wireless channel emulation, sensor channel emulation, actuator emulation and application emulation,
MURI Simulation Objectives

- **Period 1:** Develop kernel optimizations in the scalable simulation environment that can support scalable simulation of high-fidelity physical layer models.

- **Period 2:** Develop a set of *caching techniques* that reuse intermediate states and computations in the high fidelity simulation models to improve scalability of models with relatively low impact on accuracy.

- **Period 3:** Develop a set of model aggregation techniques in both spatial and temporal domains that allow a few orders of magnitude reduction in computation complexity by limiting the prediction accuracy to specific target performance metrics.

- **Period 4:** Demonstrate the applicability of the preceding techniques in real-time simulation of networks with many thousands of radios.

  Expand capability for accurate evaluation of large, adaptive net-centric services & applications
Higher Fidelity Simulation Testbed

- PHY models in common network simulators: average radio performance under average channel conditions
  - MATLAB / Simulink
  - Detailed channel + PHY layer models
  - Offline handoff
  - Network simulator
  - BER – SNR performance

- New PHY technologies very sensitive to channel (large difference between peak and average)
  - High degree of inaccuracy in predicting the performance
  - Adaptivity for given channel conditions not considered

- Need for high fidelity channel and PHY models in network simulation
Direct Integration of Highly Detailed PHY Models

- **Efficient integration**
  - Time granularity: MAC ~10us, PHY (baseband) ~0.01us
  - Discrete event vs. discrete time (time stepped) simulation

- **Need for good and precise propagation models**
  - Incorrect channel inputs = inaccurate results
  - Channel models used in link level simulation insufficient:
    - Geographical information of the network
    - Differentiation of noise and interference
  - Integration of deterministic propagation model
Validation of Propagation Model With Field Measurements

- After being validated: **non-repeatable** (measurement) to **repeatable** (prediction) data
  - Example: validation of propagation path loss at 910MHz for urban microcell environment in Ottawa, Canada