Modeling Time Varying Behavior of Mobile Ad Hoc Networks

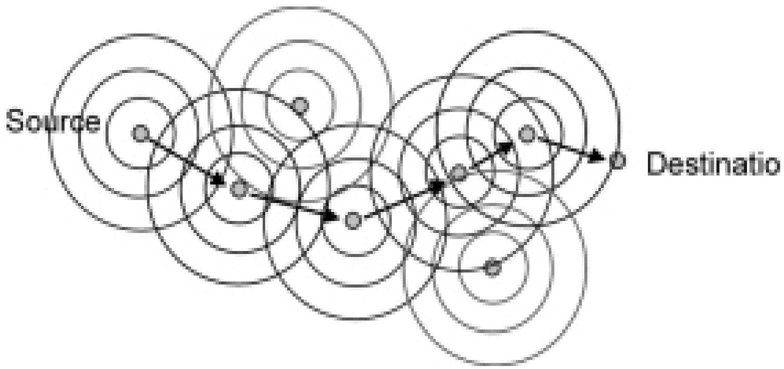
Yi Qian
Deptartment of Electrical and Computer Engineering
University of Puerto Rico
Mayaguez, PR

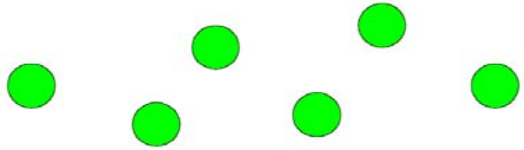
A joint research with

David Tipper
School of Information Science and Telecommunications
University of Pittsburgh
Pittsburgh, PA

Mobile Ad Hoc Networks

- Ad Hoc literally means “for this purpose only”
- Mobile Ad Hoc Network (MANET)
  - No fixed infrastructure
  - Nodes connect via wireless links
  - Network devices are part of the network –
    - act as routers for traffic without a direct wireless link (Mulit-hop connections)
  - Nodes are mobile and can move in arbitrary fashion
    - Topology and connections change frequently





Performance Evaluation

- Mobile Ad-hoc Network (MANET):

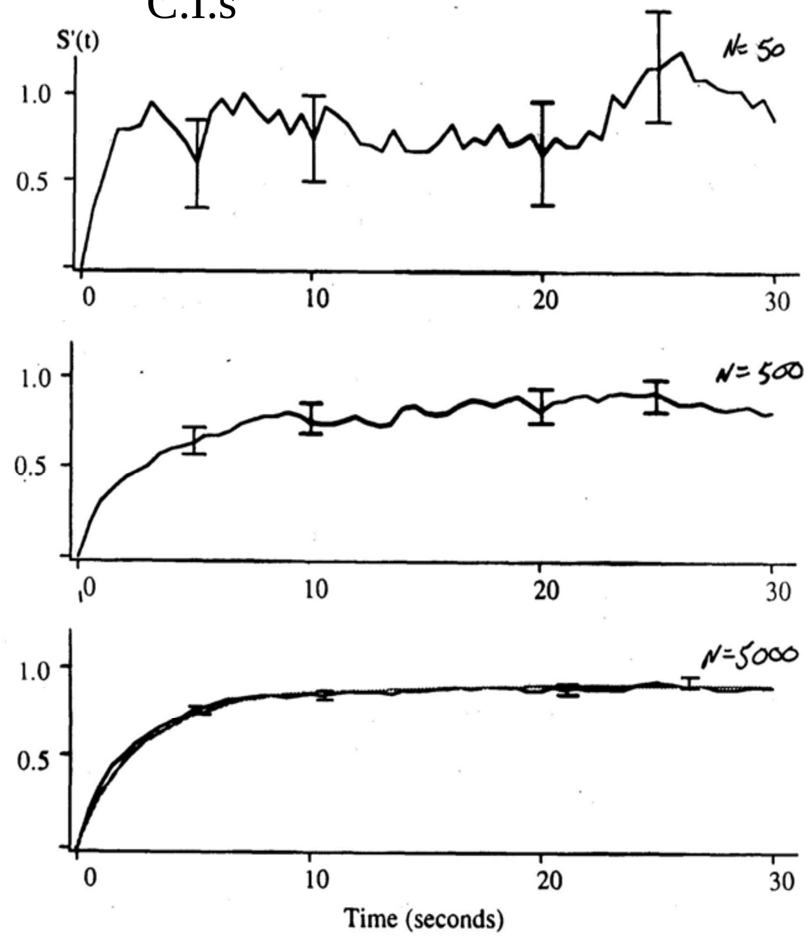
  No fixed infrastructure, nodes connect via wireless links, network devices are part of the network, nodes are mobile

- Performance of Mobile Ad Hoc Networks
  - Typically evaluated using discrete event simulation
    - NS-2, GlomoSim, Qualnet, etc.
  - Basic approach fix a scenario:
    - number of nodes, mobility model, transmission range, routing scheme - parameterize simulation model
    - Execute simulation model
  - Steady state type of simulation analysis used
    - Simulate over a fixed time horizon, multiple independent runs
    - Delete initial transient in each run, calculate confidence intervals
  - Accuracy and model details are issues
    - Number of nodes modeled, propagation models, battery life, topology of area, mobility pattern, etc.

Mobile Ad-Hoc Performance Evaluation

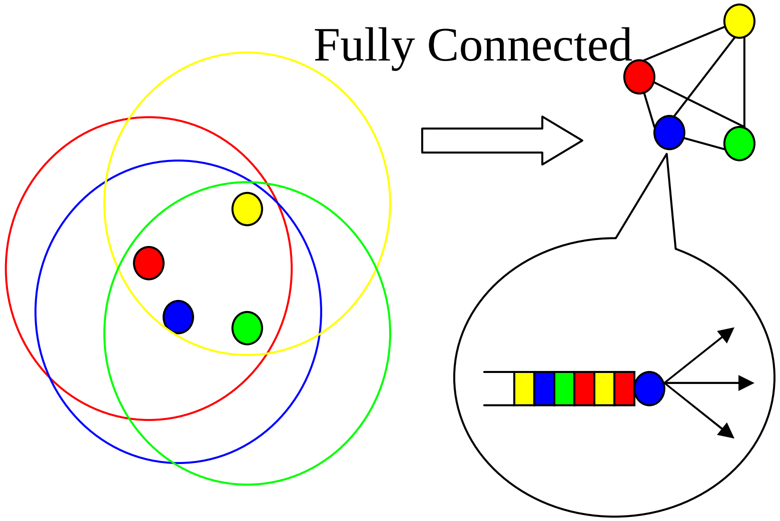
- Limitations
  - Mobile Ad-Hoc Networks have dynamically changing topologies, routes, and traffic
  - Transient/time varying behavior important
- Modeling time varying behavior via simulation
  - Simulation scenario set up same as steady state case
  - Create an ensemble of independent runs
  - Average the performance metrics over ensemble at various time points
  - Need a **large** number of runs to achieve accuracy
- Scalability a problem

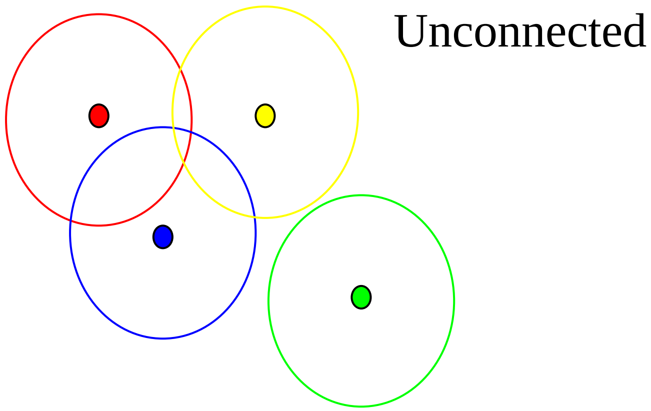
M/M/1/5 system with $\rho = .5$, 95% C.I.s



Mobile Ad Hoc Network Modeling

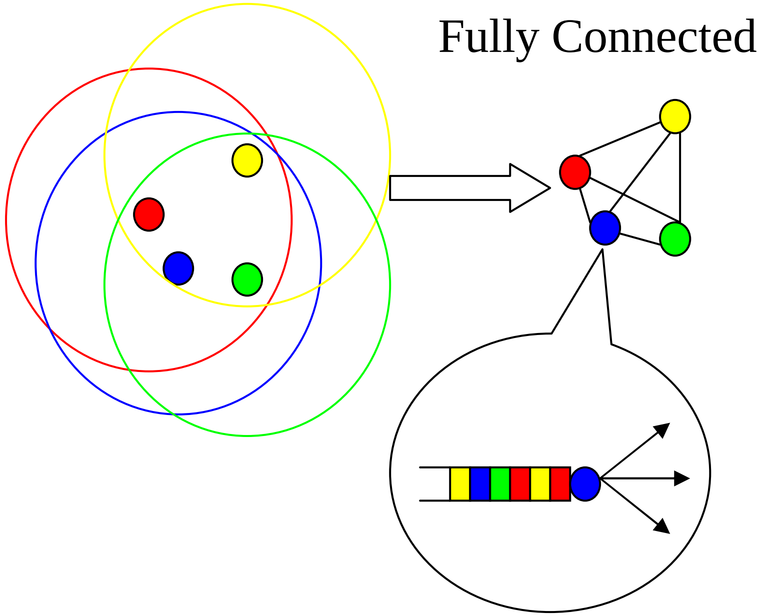
- Consider an ad-hoc network
- Note the network topology changes with time as nodes move around – ranging from fully connected network as shown to a unconnected network
- In the fully connected case a node has the potential of n–1 links to neighbor nodes
- The time duration of the links depend on the mobility model
- Represent topology with Adjacency Matrix
- Represent Node Performance with a fluid flow model of multi-traffic class queue
- Hybrid modeling approach
  - Simulation + analytical model

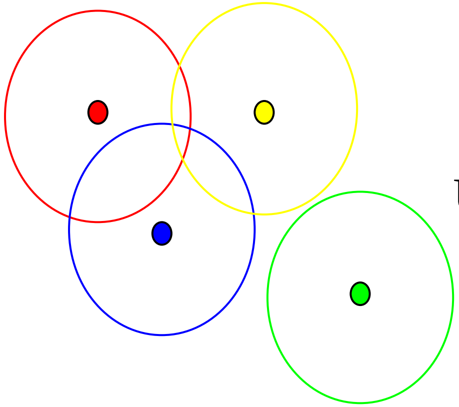




Modeling Time Varying Behavior

- How can we model dynamic network behavior?
- Network topology changes with time as nodes move around, routes change, and load maybe dynamic as well
  - Node Mobility
    - Adjacency matrix model
      - Discrete event simulation
      - Manipulate adjacency matrix elements directly
  - Network Queueing Performance
    - Multi-traffic class fluid flow model
    - Solve using numerical integration techniques
- Hybrid modeling approach
  - Combine simulation with analytical model





Unconnected

Modeling Topology Change

- Consider *M* nodes that are free to move in any direction at any time
- Represent topology with an adjacency matrix.

$$A(t) = \begin{bmatrix} a_{11}(t) & a_{12}(t) & \cdots & a_{1M}(t) \\ a_{21}(t) & a_{22}(t) & \cdots & a_{2M}(t) \\ \vdots & \vdots & & \vdots \\ a_{M1}(t) & a_{M1}(t) & \cdots & a_{MM}(t) \end{bmatrix}$$

$$a_{ij}(t) = \begin{cases} 1, & if \ \ node \ \ i \ and \ \ j \ are \ \ directly \ \ connected \ \ at \ \ time \ \ t \\ 0, & otherwise \end{cases}$$

- Connectivity $a_{ij}(t)$ determined by
  radio range, antenna pattern, power level, geographic terrain, distance between nodes, etc.
- Simple model based on distance

$$a_{ij}(t) = \begin{cases} 1, & d_{ij} \le R \quad at \ \ time \ \ t \\ 0, & otherwise \end{cases}$$

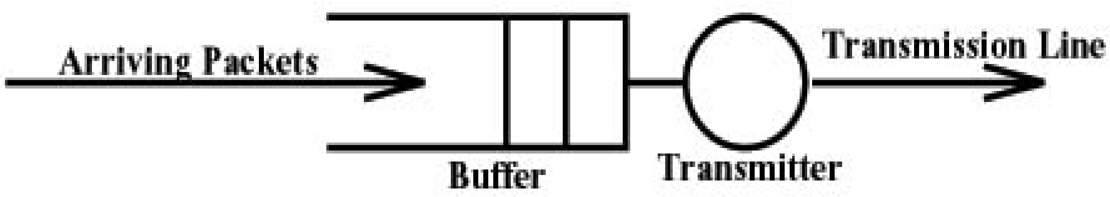
Modeling Topology Change

- Can determine adjacency matrix *A(t)* at time *t* from simulation
- Events:
  - Change in topology (link added/deleted as nodes come in or out of range)
  - Change in speed or direction of node
  - Change in characteristics of node (power level, battery charge, etc.)
- Given initial placement of nodes, their characteristics, and mobility pattern.
  - Conduct discrete event simulation to determine A(t) (e.g, using NS-2)
- Alternatively can manipulate A(t) elements directly
  - For example two state MMPP - link up or down

    (Refer to: T. Lin and S. Midkiff, ``Mobility versus Link Stability in the Simulation of Mobile Ad Hoc Networks Using DSR", *Proceedings of Communication Networks and Distributed Systems Modeling and Simulation Conference (CNDS)*, January, 2003, Orlando, FL)

Fluid Flow modeling

- Consider a single transmission link



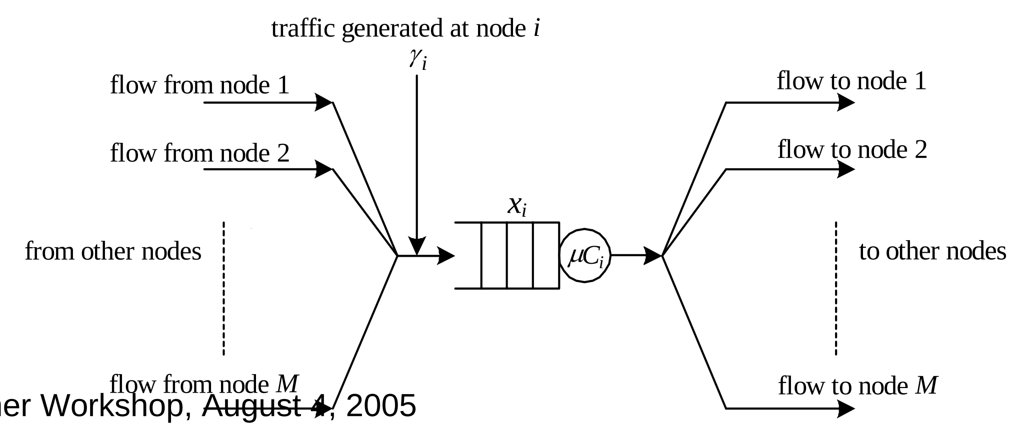
- $\lambda(t)$ = mean arrival rate of packets
- *x(t)* = mean number of packets at node at time *t*
- *C* = capacity of link
- G(x) = time varying utilization of server as function of number in system

$$\dot{x}(t) = -CG(x(t)) + \lambda$$

Find G by matching equilibrium with equivalent queueing model
For M/M/1 G(x) = μ x/(1+x)
See Tipper et.al., IEEE JSAC Jan. 90, IEEE Infoccom 95

Ad-Hoc Network Fluid Model

- Consider ad hoc network of *M* nodes connected in an arbitrary topology.
  - $x_i^j(t)$ mean number of packets at node i for node j at time t.
  - $\gamma_i^j(t)$ mean rate of traffic for node j arriving at node i.
  - r_{ik}^j routing variable from node i to node k of traffic destined for node j.
  - a_{ik} adjacency matrix variable, is one if node i and k are within range
  - C_i the transmission capacity of node i,
  - μ mean packet length.



Assumptions

- Assuming Poisson packet arrivals and exponential packet lengths.
- We can show that for each node i the fluid flow model for traffic class j is:

$$\dot{x}_i^j(t) = -\mu C_i \left(\frac{x_i^j(t)}{1 + \sum_{\substack{l=1 \\ l \neq i}}^{M} x_i^l(t)} \right) \left(\sum_{\substack{k=1 \\ k \neq i}}^{M} a_{ik}(t) r_{ik}^j \right) + \gamma_i^j(t) + \sum_{\substack{l=1 \\ l \neq i \\ l \neq j}}^{M} \mu C_l \left(\frac{x_l^j(t)}{1 + \sum_{\substack{k=1 \\ k \neq l}}^{M} x_l^k(t)} \right) (a_{li}(t) r_{li}^k)$$

Flow Out of node *i*

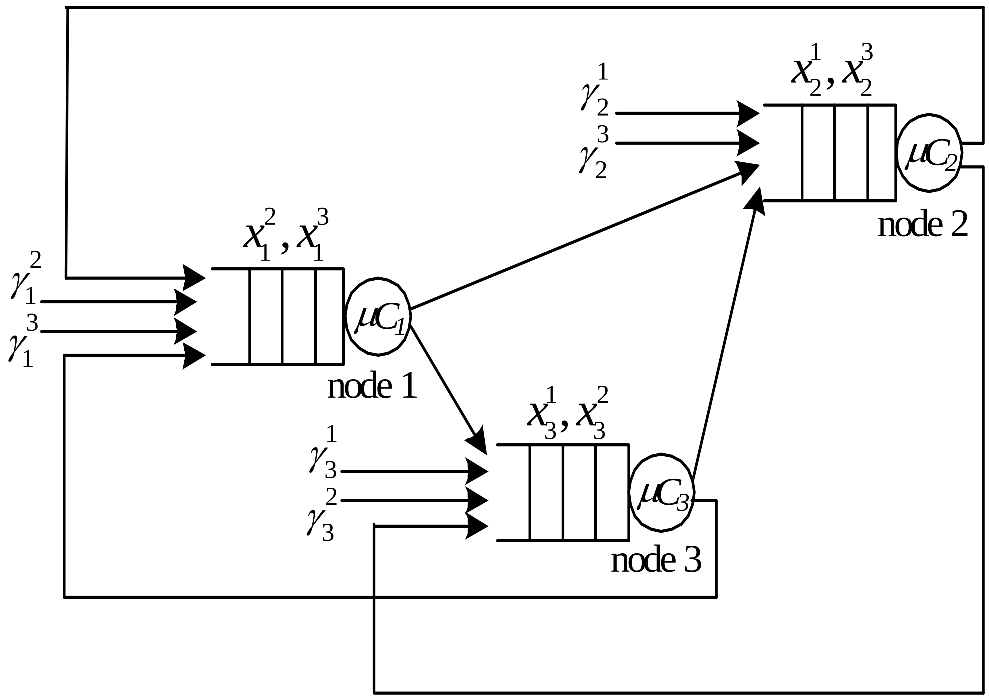
traffic generated at node i

Flow In to node *i*

Set of *M x M-1* equations

Three Node Network Model

- Consider a simple 3 node network model



Three Node Network Model

- We have the following 6 equations:

$$\dot{x}_1^2(t) = -\mu C_1 \frac{x_1^2}{1+x_1^2+x_1^3}(a_{12} r_{12}^2 + a_{13} r_{13}^2) + \gamma_1^2 + \mu C_3 \frac{x_3^2}{1+x_3^1+x_3^2} a_{31} r_{31}^2$$

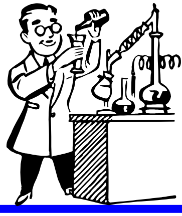
$$\dot{x}_1^3(t) = -\mu C_1 \frac{x_1^3}{1+x_1^2+x_1^3}(a_{12} r_{12}^3 + a_{13} r_{13}^3) + \gamma_1^3 + \mu C_2 \frac{x_2^3}{1+x_2^1+x_2^3} a_{21} r_{23}^3$$

$$\dot{x}_2^1(t) = -\mu C_2 \frac{x_2^1}{1+x_2^1+x_2^3}(a_{21} r_{21}^1 + a_{23} r_{23}^1) + \gamma_2^1 + \mu C_3 \frac{x_3^1}{1+x_3^1+x_3^2} a_{32} r_{32}^1$$

$$\dot{x}_2^3(t) = -\mu C_2 \frac{x_2^3}{1+x_2^1+x_2^3}(a_{21} r_{21}^3 + a_{23} r_{23}^3) + \gamma_2^3 + \mu C_1 \frac{x_1^3}{1+x_1^2+x_1^3} a_{12} r_{12}^3$$

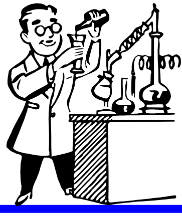
$$\dot{x}_3^1(t) = -\mu C_3 \frac{x_3^1}{1+x_3^1+x_3^2}(a_{31} r_{31}^1 + a_{32} r_{32}^1) + \gamma_3^1 + \mu C_2 \frac{x_2^1}{1+x_2^1+x_2^3} a_{23} r_{23}^1$$

$$\dot{x}_3^2(t) = -\mu C_3 \frac{x_3^2}{1+x_3^1+x_3^2}(a_{31} r_{31}^2 + a_{32} r_{32}^2) + \gamma_3^2 + \mu C_1 \frac{x_1^2}{1+x_1^2+x_1^3} a_{13} r_{13}^2$$



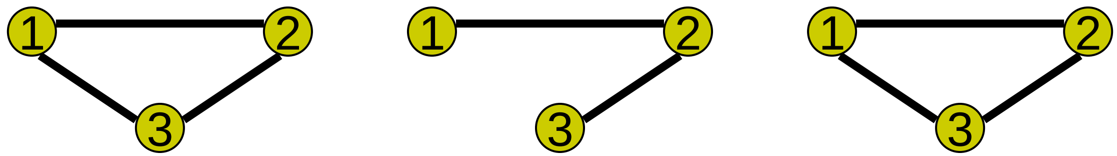
Numerical Experiments

- Numerically solve fluid flow model using standard numerical integration techniques (e.g. Runge Kutta in MATLAB)
  - Note can run separate from mobility simulation
- Examine behavior of ad-hoc network for variety of parameter values for small networks
- Evaluate baseline case of three nodes
  - Varied
    - Traffic Demand
    - Mobility Rate (frequency of link rearrangments)
    - Connection Duration
  - Accuracy with full simulation
- Vary Network size and routing algorithms

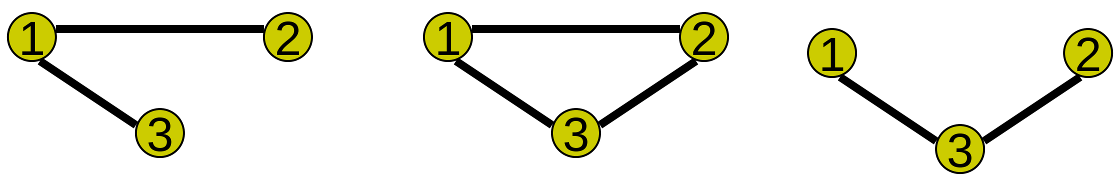


Numerical Experiments

- Baseline case
  - Light load (link utilization 40%), slow mobility

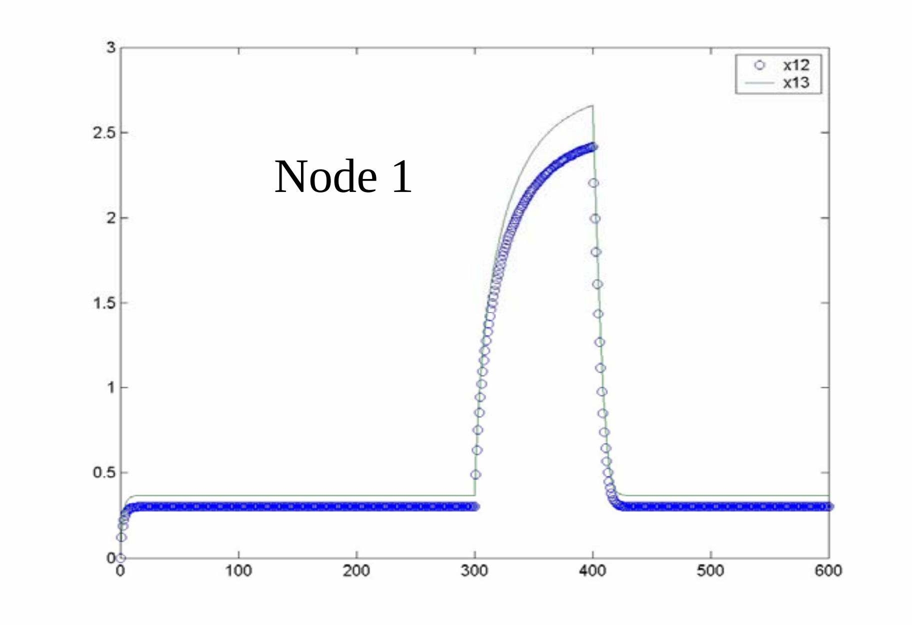


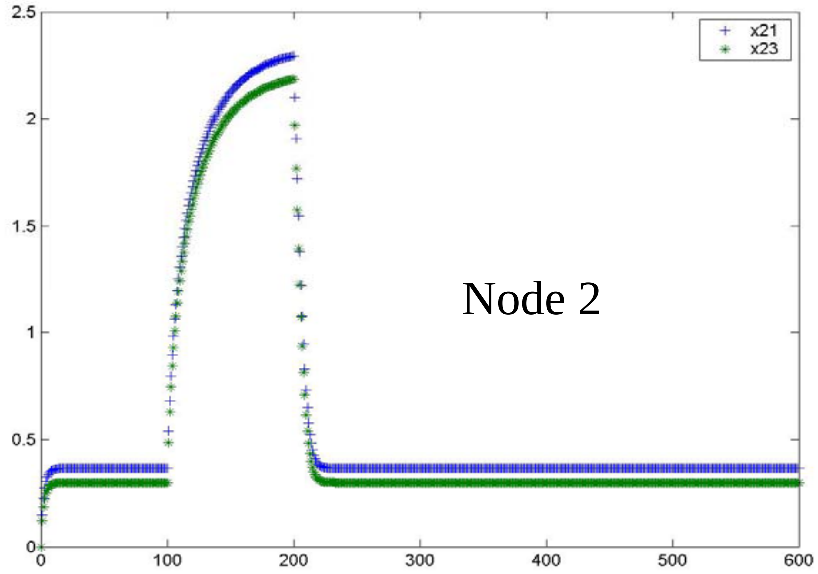
(a) t < 100 (b) 100 <= t < 200 (c) 200 <= t < 300



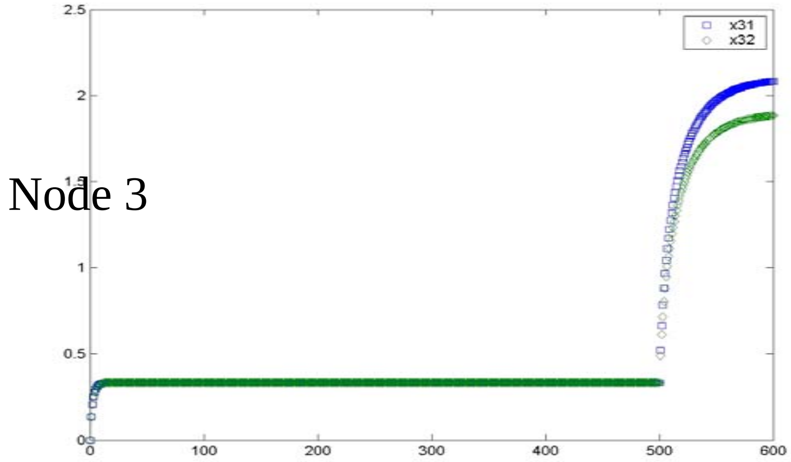
(d) 300 <= t < 400 (e) 400 <= t < 500 (f) 500 <= t

Light Load Case

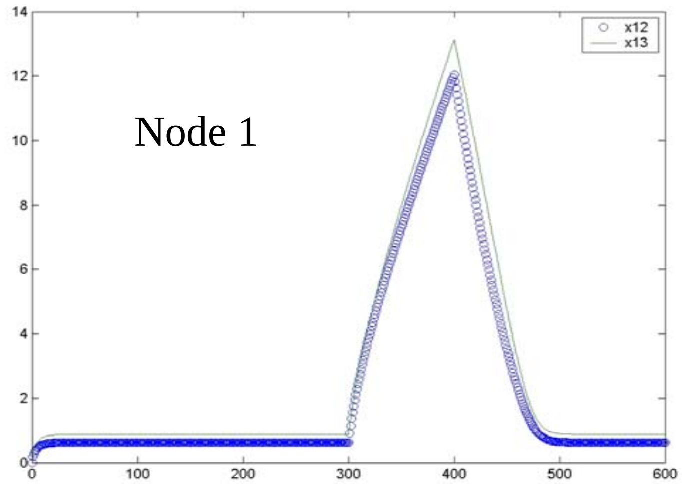


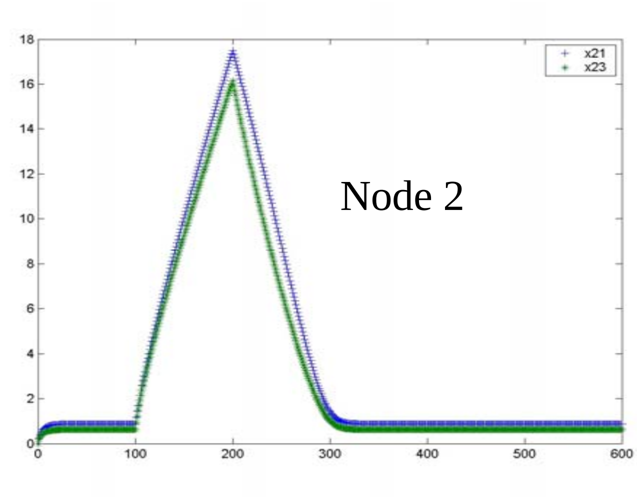


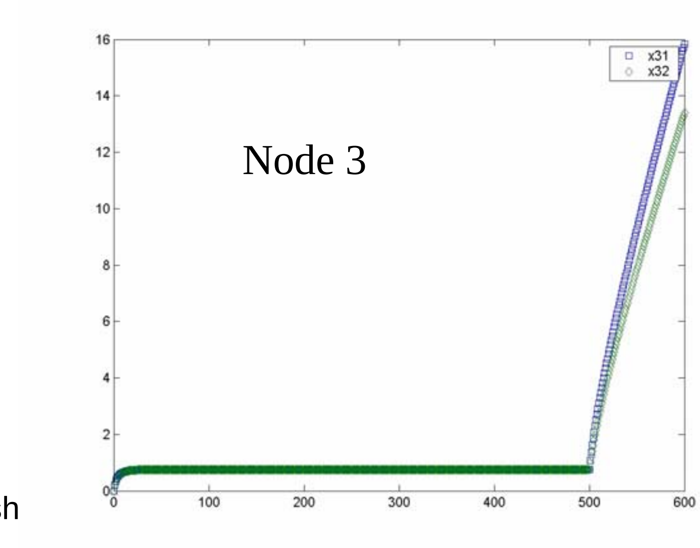
Notice node gets higher queue when it acts as relay node



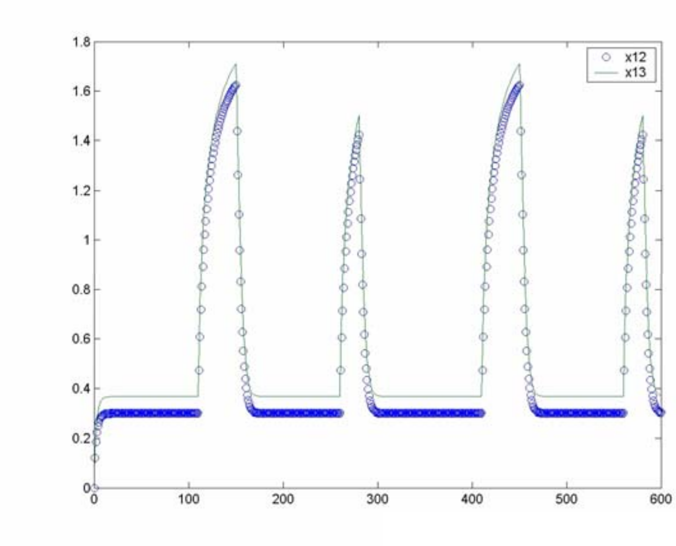
Moderate Load Case

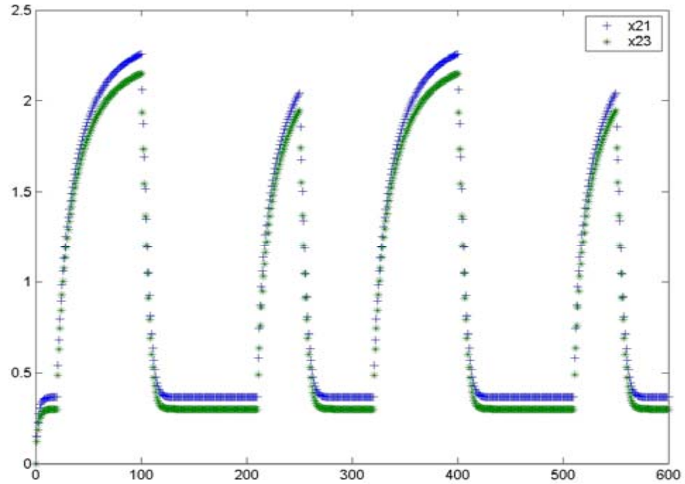


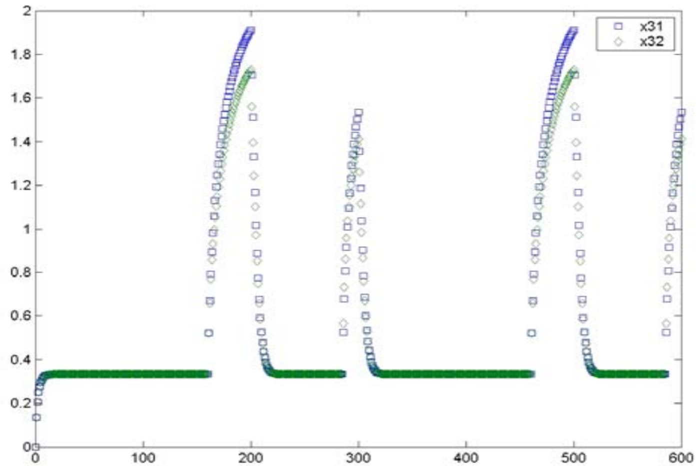




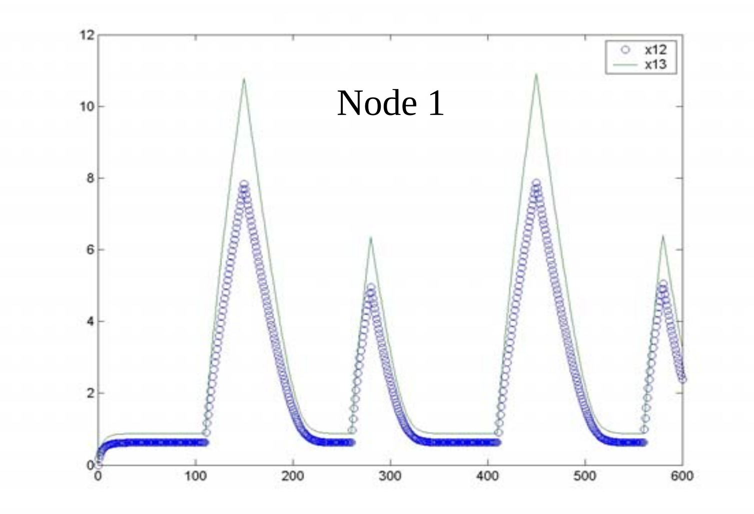
Light Load Moderate Mobility

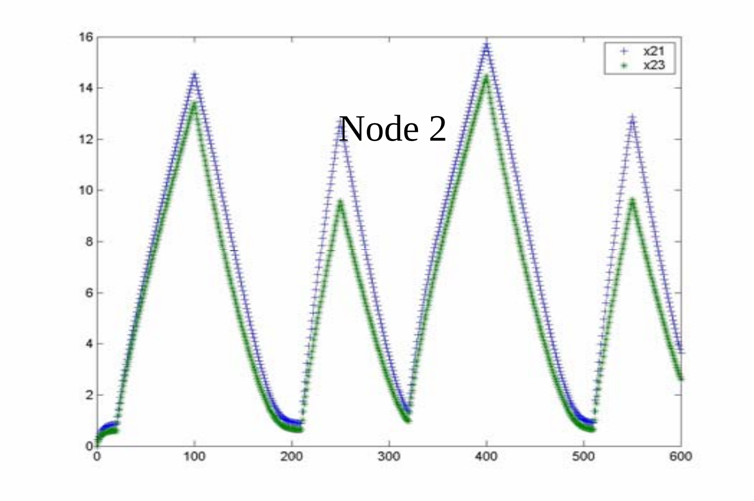




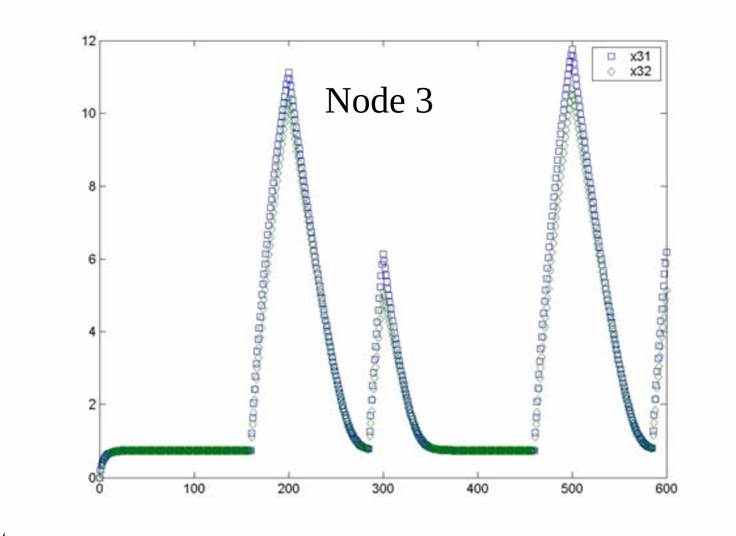


Moderate Load and Mobility

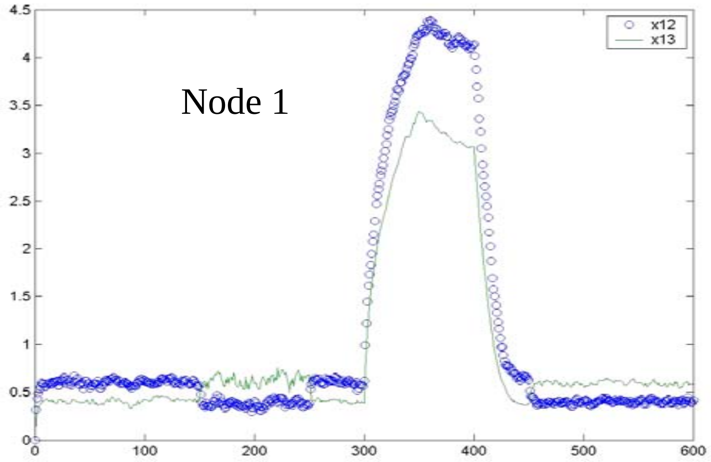


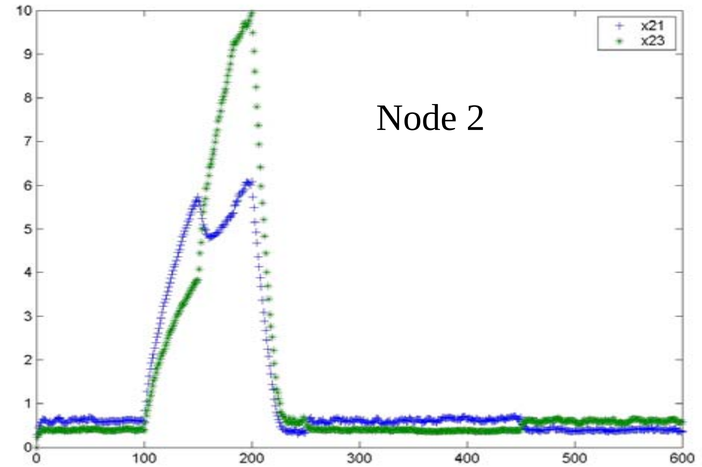


Increased mobility results in more time in transient state

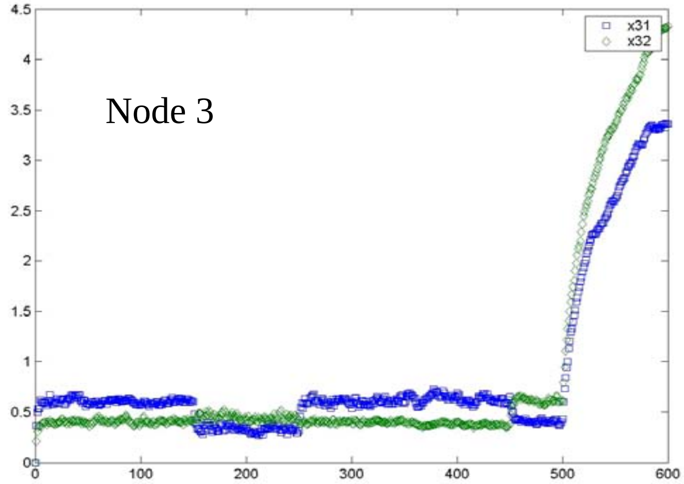


Light Load, Dynamic Load, Low Mobility





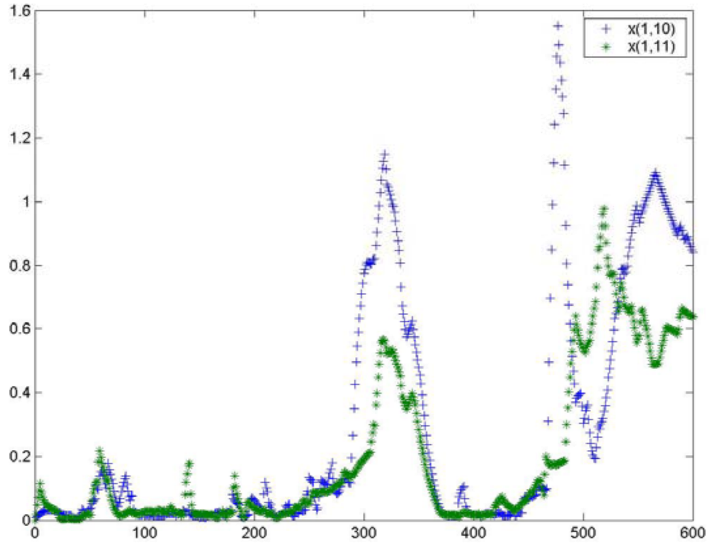
Load consists of a number of Small flows that come and go With time

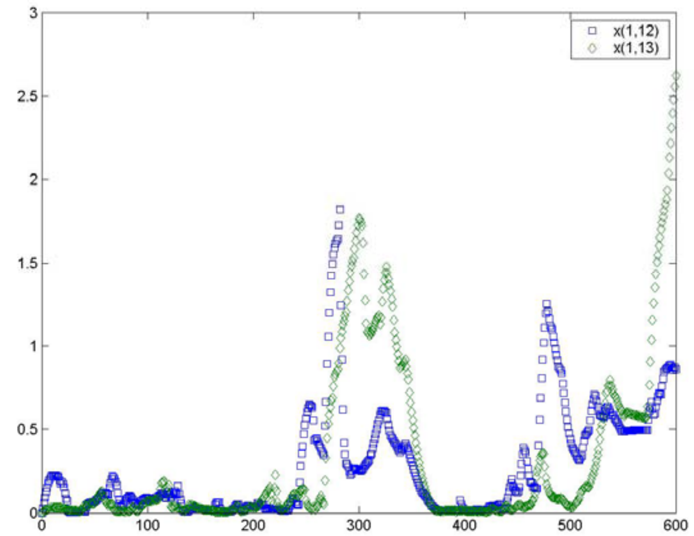


Larger Network Case

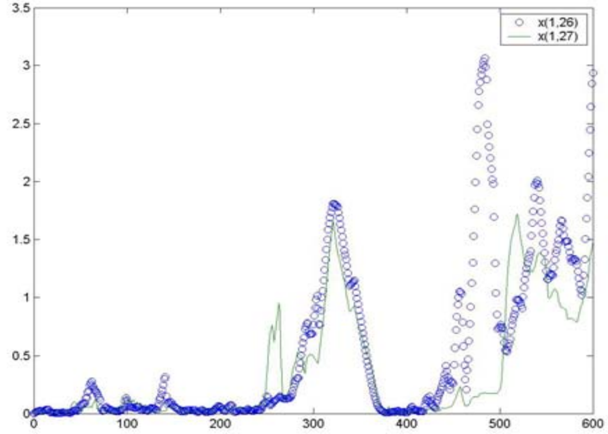
- Consider a 30 node network (M = 30)
- Fixed Load between every node pair
  - $\gamma_i^j(t) = 0.01$ for i = 1, 2, …, 30; j = 1, 2, …, 30.
- Mean packet length $\mu = 0.05$
- $C_i = 20$, for i = 1, 2, …, 30. (average utilization = 30%)
- Use Random Mobility Model
- Use the Shortest Path Routing Algorithm to determine the routing variables r_{ik}^j, where the "shortest path" means "least number of hops" here.
- Route recomputed after each topology change
- Typical results for traffic at a node (in this case node 1)

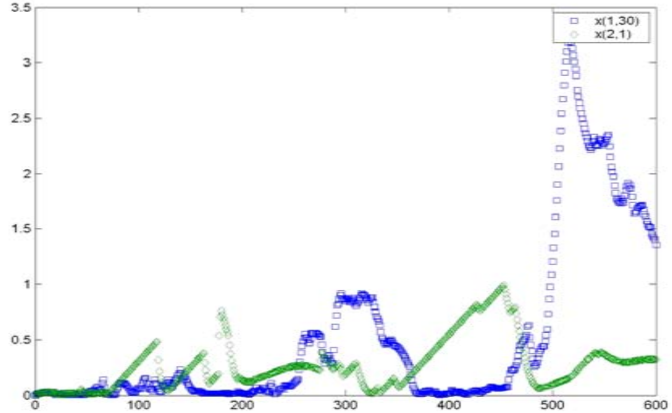
Some Results for 30-Node Case at Node 1





Notice that traffic is rarely in steady state!





Summary

- Because
  - Time Varying Behavior of mobile ad-hoc networks maybe as important as steady-state;
  - & Straightforward simulation of time varying behavior computationally difficult
- We propose a Hybrid approach to model time varying behavior of ad-hoc networks.
  - Adjacency matrix model of node mobility
  - Fluid flow model of node queuing behavior

  Preliminary work shows that: Numerical results illustrating application to small network
    - Observe small amounts of mobility => big transients!
    - Our approach is much faster than pure simulation of time varying behavior
- We propose to investigate several avenues of research with the hybrid modeling approach as discussed below
  - Develop a set of fluid flow models similar to one above for a variety of common traffic models found in the MANET literature
  - For each model, evaluate it's accuracy against simulation results (using Qualnet and NS-2) for small networks
  - Extensions to the model to incorporate additional MANET effects such as, energy consumption, capacity reduction due to interference and traffic contention effects will be investigated
    - For example, the capacity of a node can be reduced based on the number of neighbor nodes within interference radio range
  - Once a model with enough fidelity has been developed, extensive numerical experiments will be conducted to determine the effects of parameters on the performance metrics