MAC Protocols in MANETs: Modeling and Simulation

Presented at Mobihoc 2002

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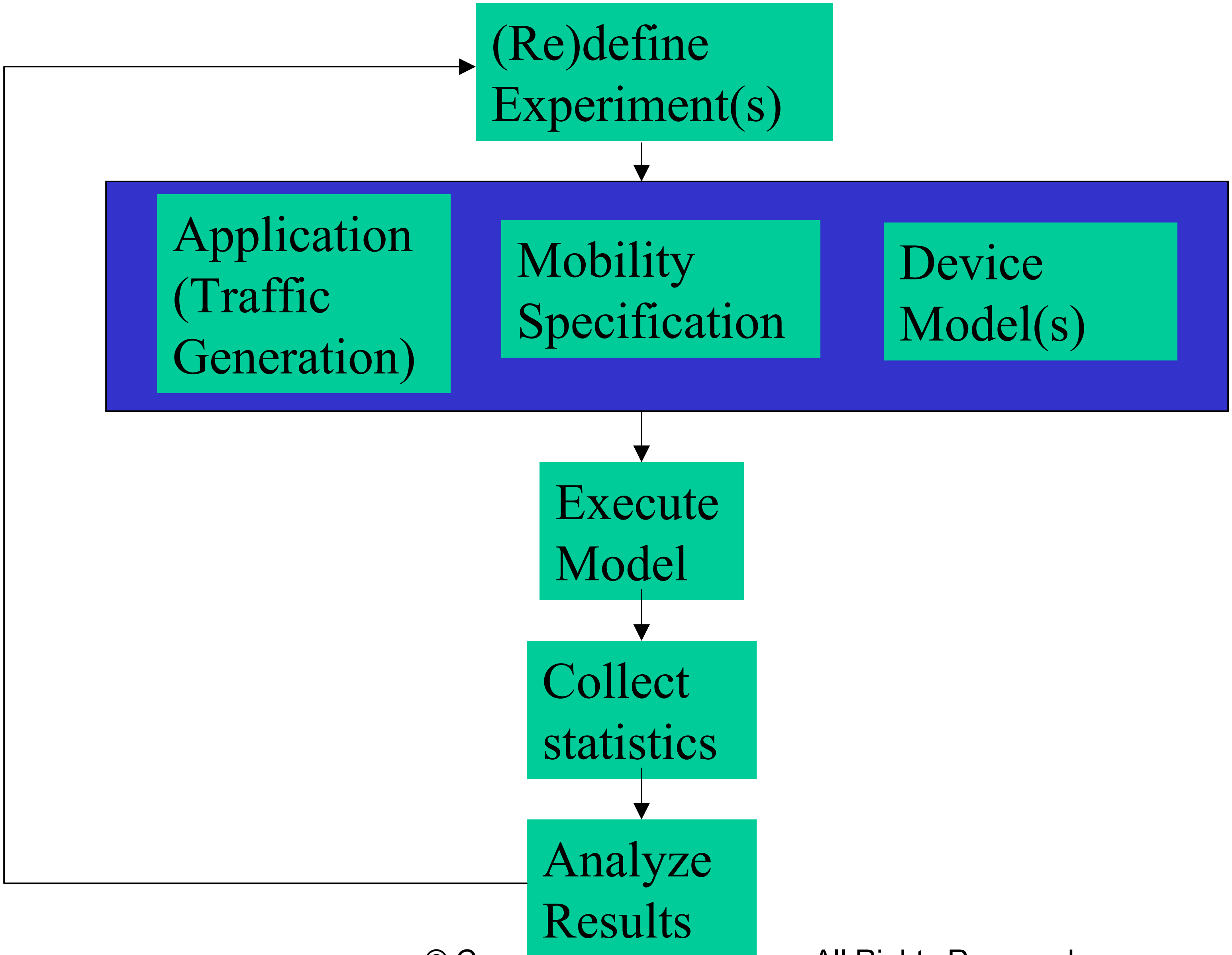
Simulation Life Cycle (for Network Models)



MANET Simulation: Level of Details

- MANET simulation in protocol design and development
  - easy prototyping, good repeatability...
- Protocol verification
  - Write detailed protocol models
  - Sufficient to use abstract models at other layers
    - Abstract (probabilistic) models can create sequences of events that can possibly but rarely happen in real networks
- Protocol performance evaluation
  - Write detailed protocol models
  - Important to use detailed models at other layers
    - Effects of multiple layer interactions cannot be ignored for the performance evaluation

MANET Simulation: Protocol Performance Evaluation

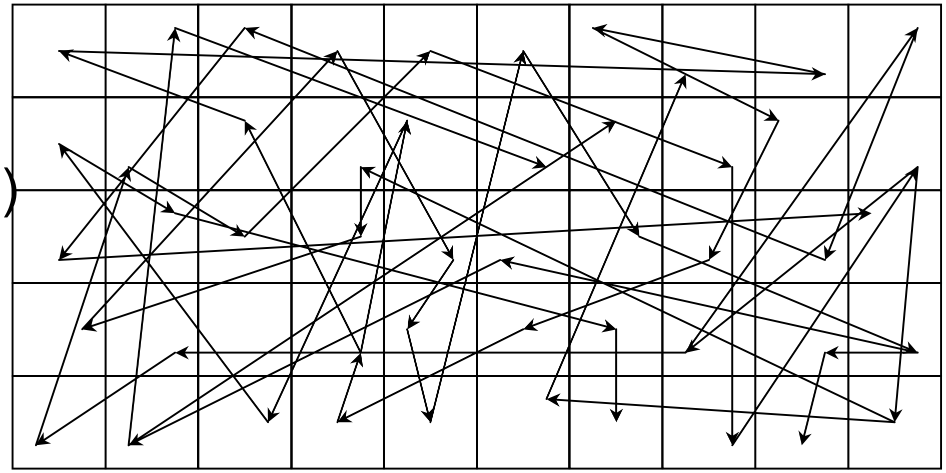
- Validity of simulation results depends on how properly the system is modeled
  - When an important aspect is missing, performance results could be misleading
- Physical layer modeling in wireless network simulation
  - From bits to waves: very different from protocol modeling
  - Not carefully verified even in commonly used network simulators
  - Effects of physical layer modeling are often underestimated in higher layer protocol studies
- Impact of physical layer modeling in two commonly used simulators: *ns*-2 (2.1b8) and GloMoSim (2.02)

Comparisons of Physical Layer Models in Different Simulation Tools (1)

- *ns-2* (2.1b8) and GloMoSim (2.02)
  - Share a common set of models, but they are developed independently by different groups of people
  - Path loss: two-ray
  - Physical layer: IEEE 802.11 DSSS PHY
  - MAC sub-layer: IEEE 802.11 DCF MAC
  - Network layer: static routing
  - Application layer: CBR
- Parameter adjustment (GloMoSim set to *ns-2*)
  - Radio frequency: 914 MHz in *ns-2*, 2.4 GHz in GloMoSim
  - Transmit power: 24.5 dBm in *ns-2*, 15 dBm in GloMoSim
  - Network and transport header sizes: none in *ns-2*, IP+UDP in GloMoSim

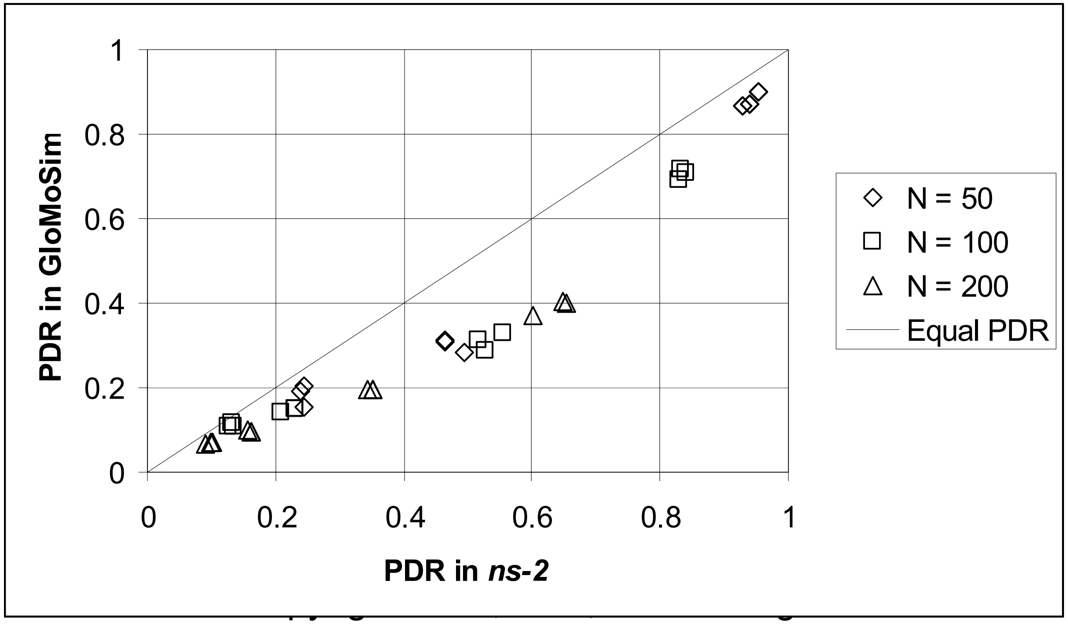
Comparisons of Physical Layer Models in Different Simulation Tools (2)

- Running the simplest wireless scenario
  - N (= 50, 100, 200) nodes randomly placed in 10 x N / 10 cells
  - N CBR sessions at P (= 1, 2, 5, 10) 512 byte packets per second
  - Static routes generated by DSDV prior to the comparison
  - No mobility
  - Three cases for each pair of N and P (36 cases total)
  - Minimal use of random number generation (MAC DCF)



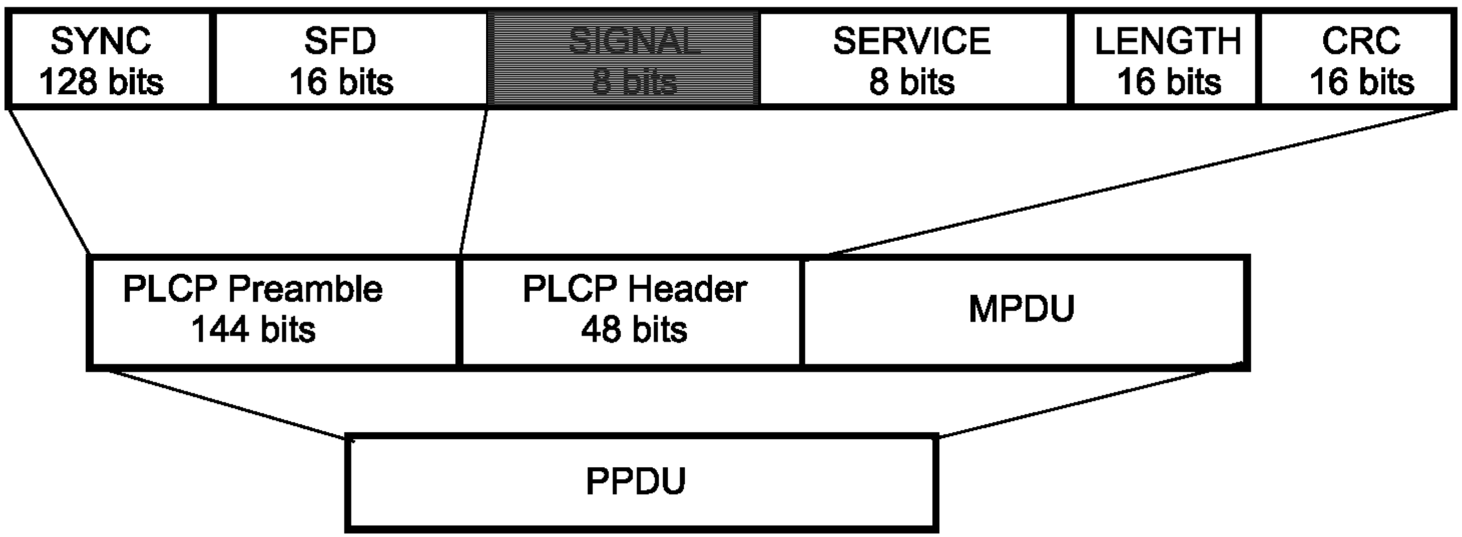
Comparisons of Physical Layer Models in Different Simulation Tools (3)

- PDRs (Packet Delivery Ratio) from *ns-2* and GloMoSim
- The differences are significant under non-extreme network conditions
- Two major causes of PDR differences:
  - Physical layer preamble and header lengths
  - Noise and interference computation



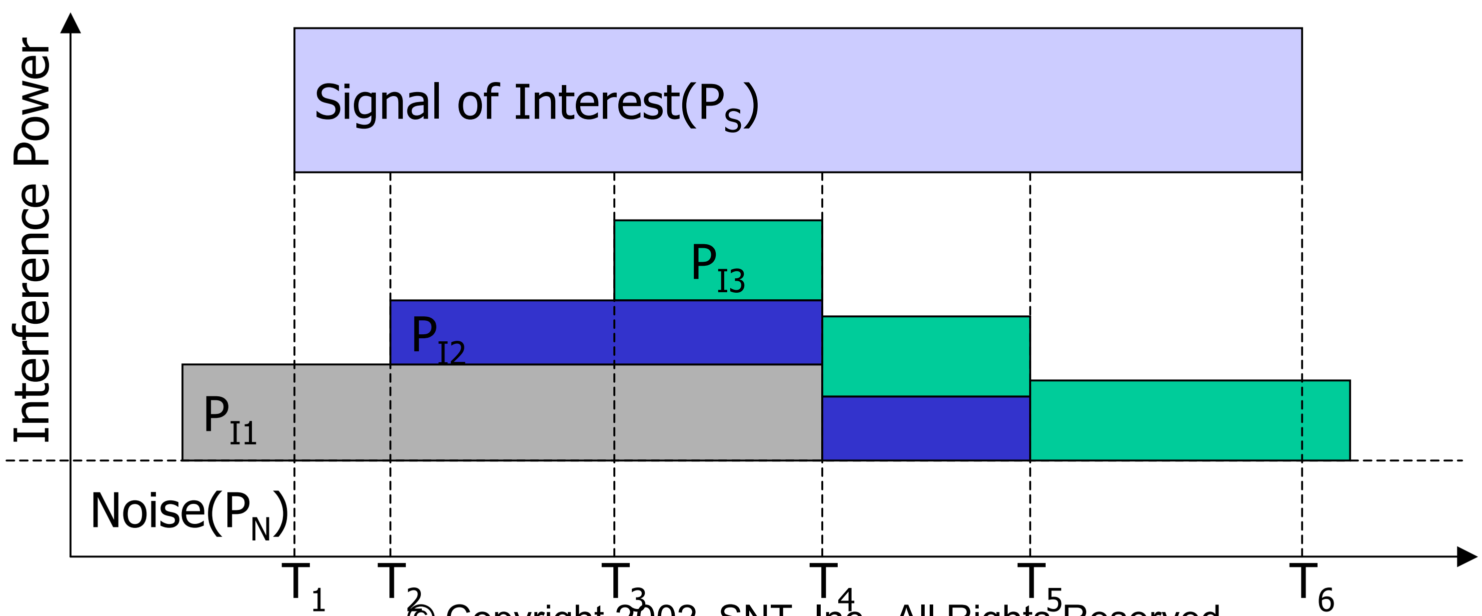
Physical Layer Preamble Lengths

- IEEE 802.11 physical layer preamble and header
  - "SIGNAL" indicates the type of modulation to be used for MPDU
  - DBPSK (1 Mbps) is used for modulating PLCP regardless of the data rate
  - 144 + 48 = 192 bits = 192 us (at 1 Mbps) in GloMoSim
  - 144 + 48 = 192 bits = 96 us (at 2 Mbps) in *ns-2* (fixed in 2.1b9)



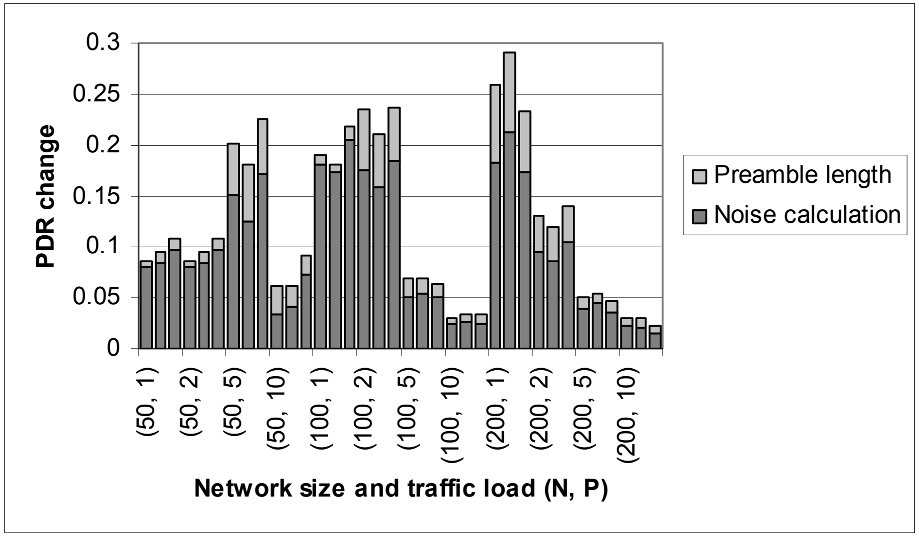
Noise and Interference Computation

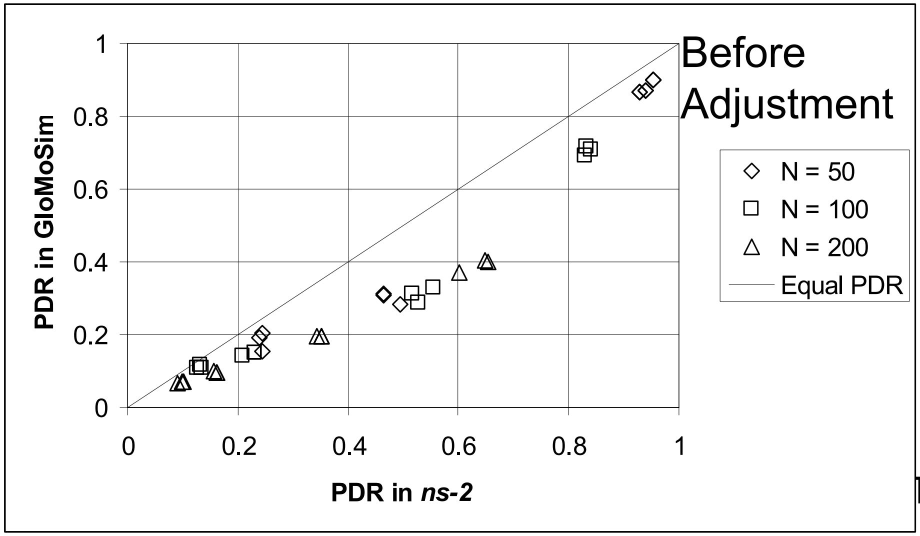
- Power of interfering signals is cumulative
- Example: SINR at T_3
  - $P_S / (P_{I1} + P_{I2} + P_{I3} + P_N)$ in GloMoSim
  - P_S / P_{I3} in ns-2

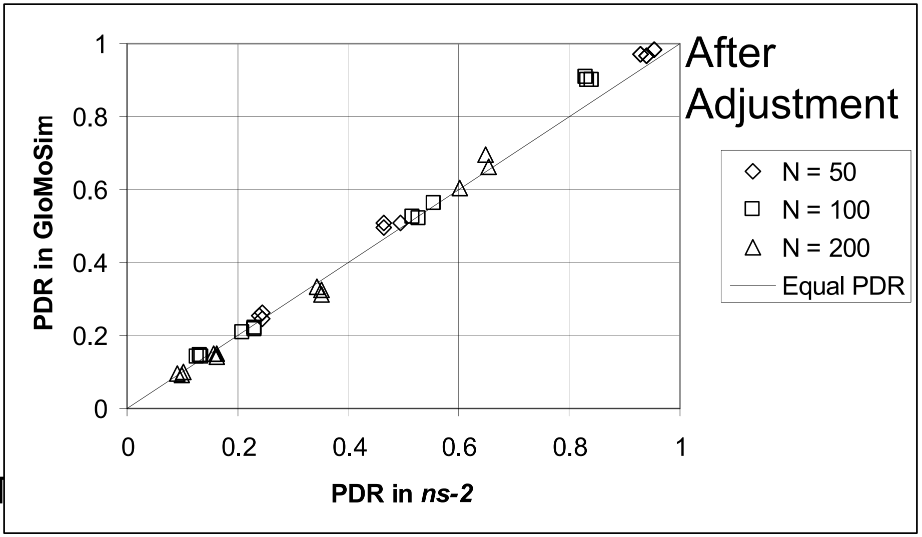


Comparisons of Physical Layer Models in Different Simulation Tools (4)

- Further adjustments made to GloMoSim models:
  - 96 us preamble
  - No interference power accumulation
- Interference modeling made larger difference



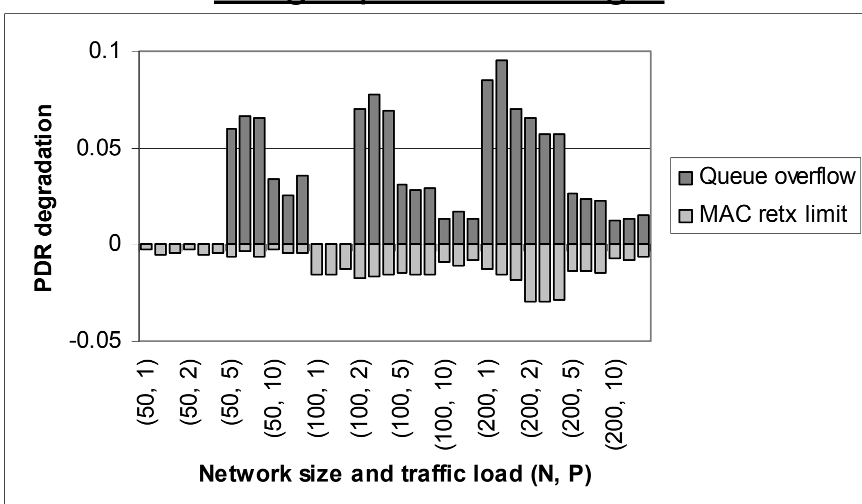




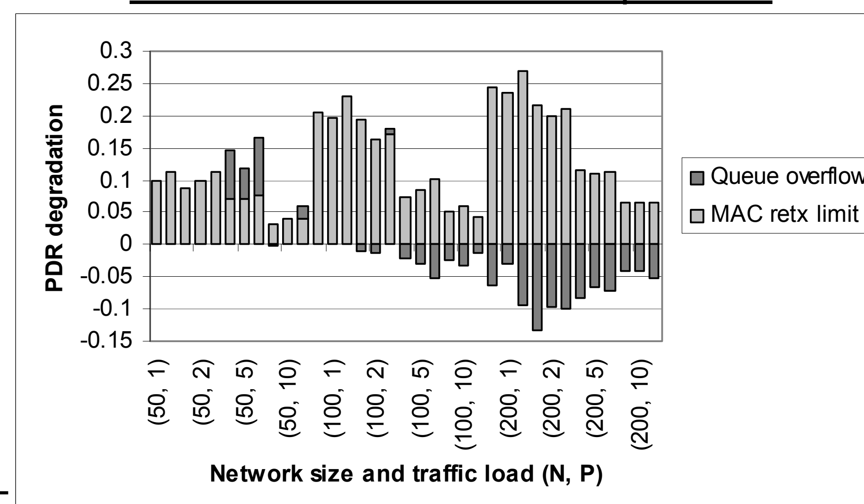
Effects of Physical Layer Modeling in Multiple Layer Interactions

- Both differences make PDR predicted by *ns-2* higher
- Their contributions are quite different:
  - Longer preamble length reduces the effective link capacity: more queue overflow, less MAC drops
  - More realistic interference computation causes many collisions: more MAC drops, less queue overflow

Longer preamble length

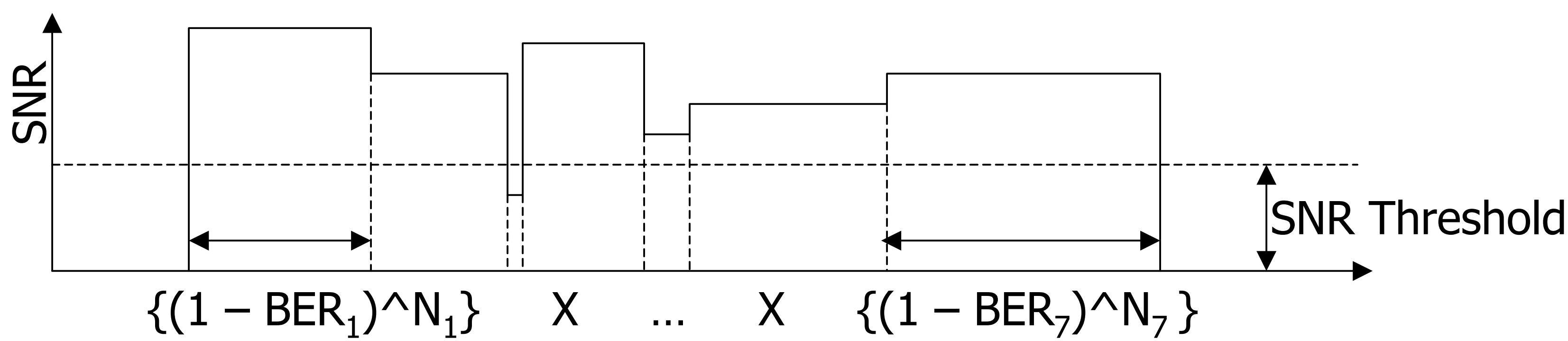


Realistic interference computation



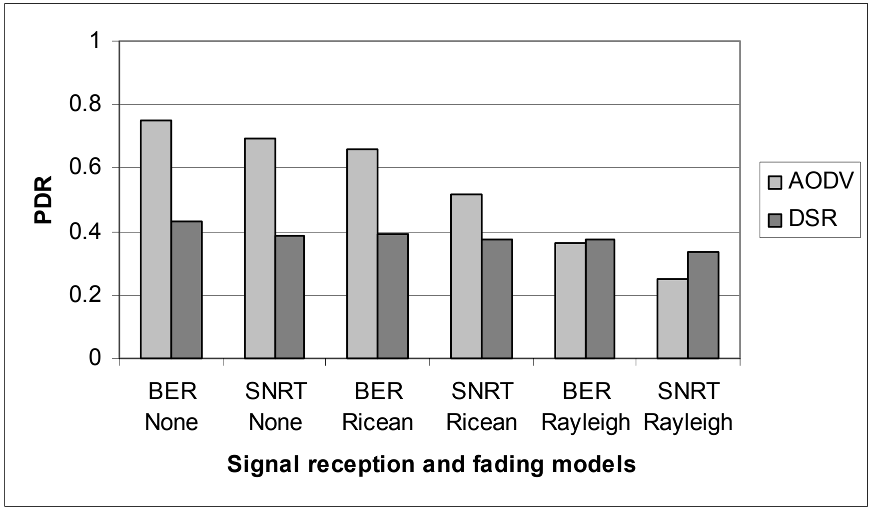
Impact of Physical Layer Modeling on Higher Layer Protocol Performance (1)

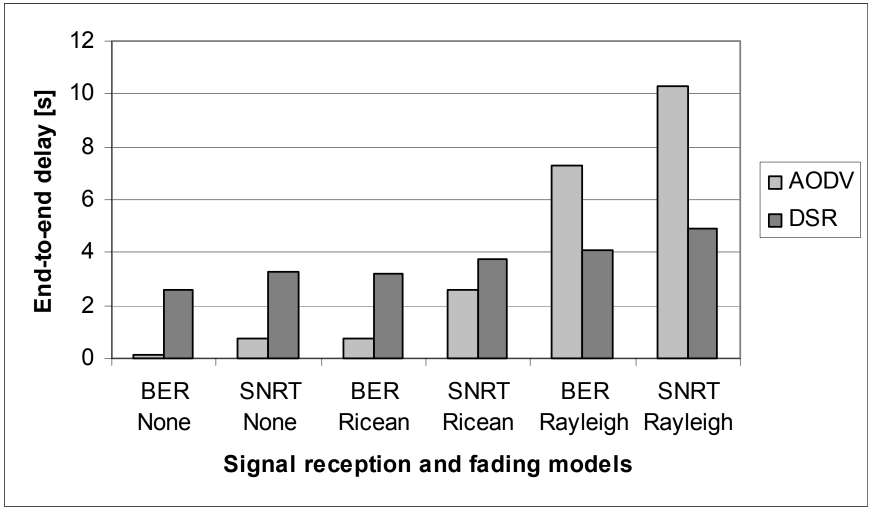
- 100 node scenario (Das et al INFOCOM 2000)
  - Mobility: Random waypoint model (0-20 m/s with 100s pause)
  - Propagation: two-ray with Rayleigh, Ricean (K = 5) and no fading
  - Physical layer: IEEE 802.11 DSSS PHY with BER and SNRT
  - MAC sub-layer: IEEE 802.11 DCF MAC
  - Network layer: IP with FIFO queue (100 packets max)
  - Routing: AODV and DSR
  - Application layer: CBR (40 sessions, 512 byte packets, 2.666 pps)



Impact of Physical Layer Modeling on Higher Layer Protocol Performance (2)

- Result for the SNRT and No fading case consistent with the corresponding data point in the INFOCOM paper
- AODV decimates its performance as predicted channel conditions become severe
- DSR degrades its performance, but not as dramatically as AODV





QualNet

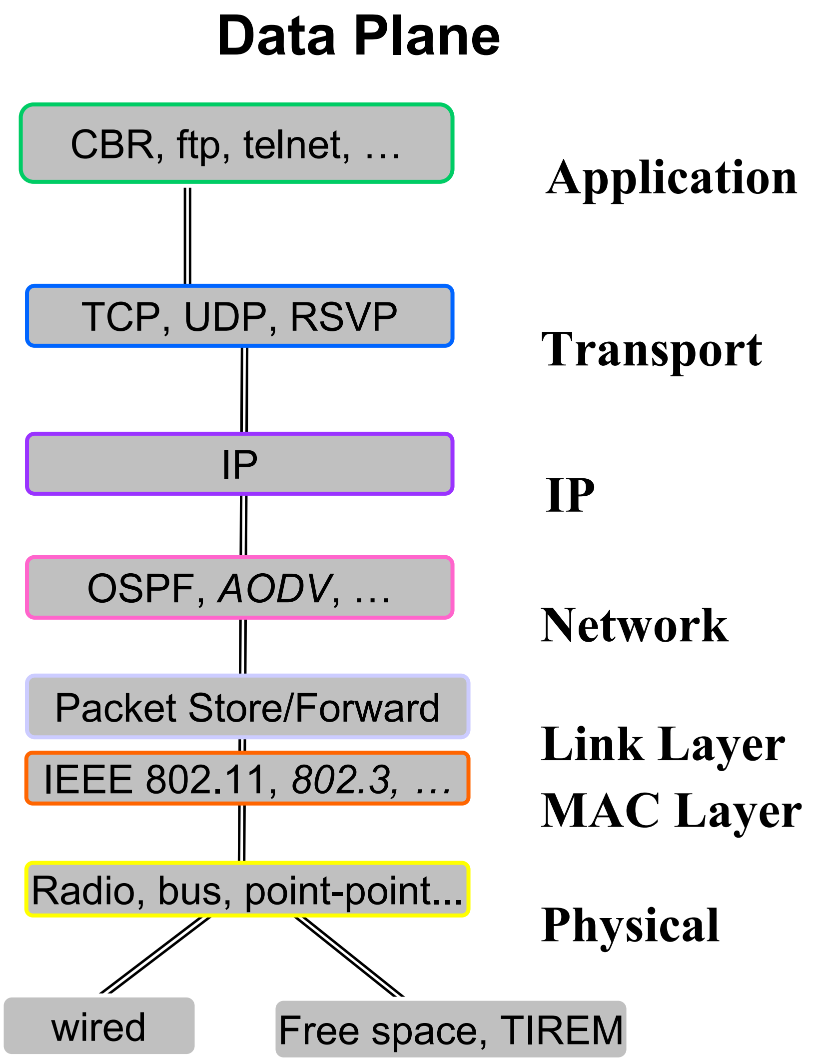
- Commercial derivative of GloMoSim
  - Substantially expanded MANET models:
    - AODV, DSR, OLSR, TBRPF, 802.11 DCF, 802.11 PCF, 802.11a, directional antennas, …
  - GUI-based model design, animation, & analysis
  - Commercial protocol & device models
  - Military comm models
  - Training, support, custom services

- SNT Focus: accurate, real-time network simulation & management
  - Accuracy via high-fidelity models (incorporating production code to model protocols) & detailed validation
  - Speed and scalability via research into efficient scheduling and (parallel) simulation algorithms

Accuracy

- Use an architecture that is similar to one used in physical networks with well-defined APIs between neighboring layers

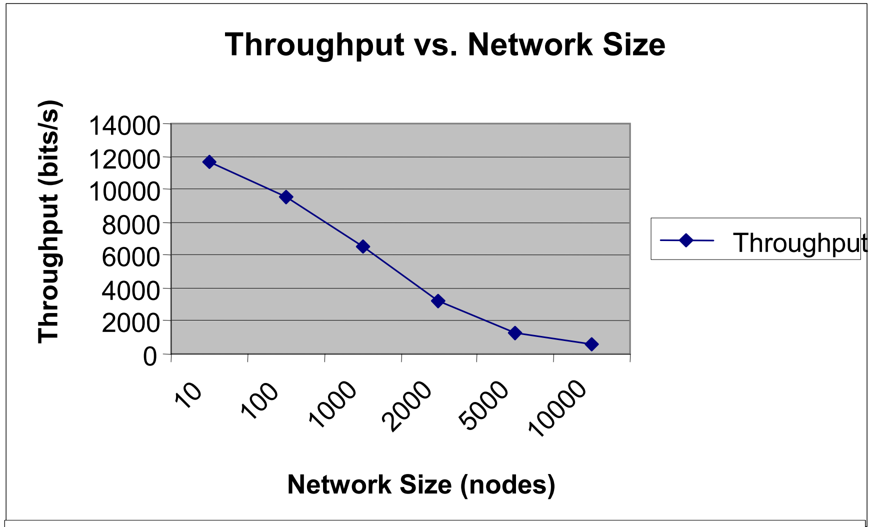
- Provide capability for network emulation by supporting direct code migration between the model and operational networks.

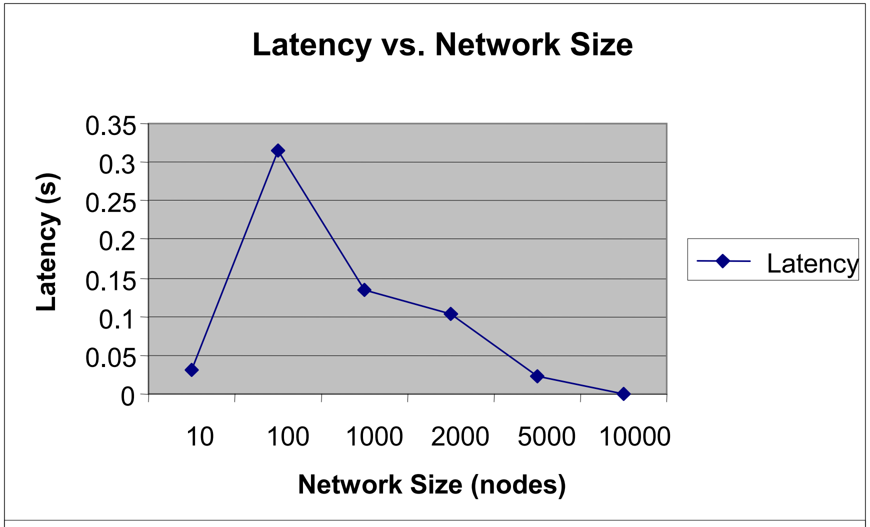


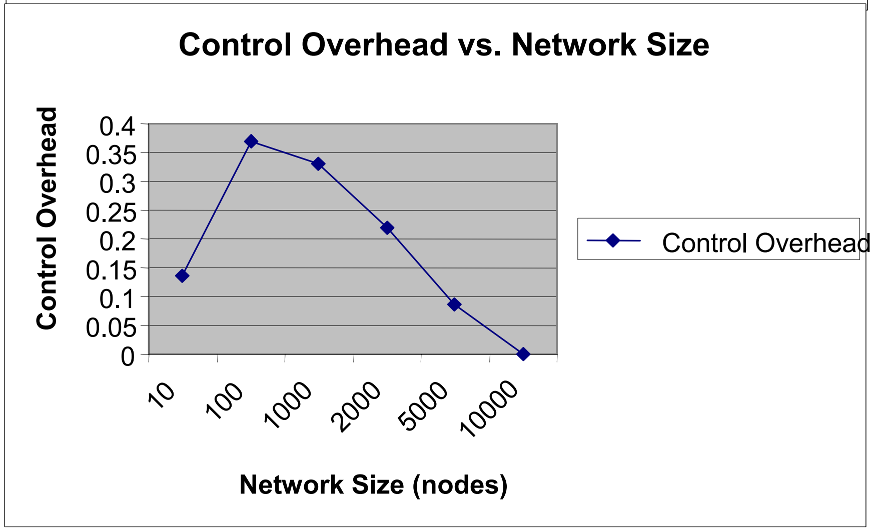
Accuracy & Scalability

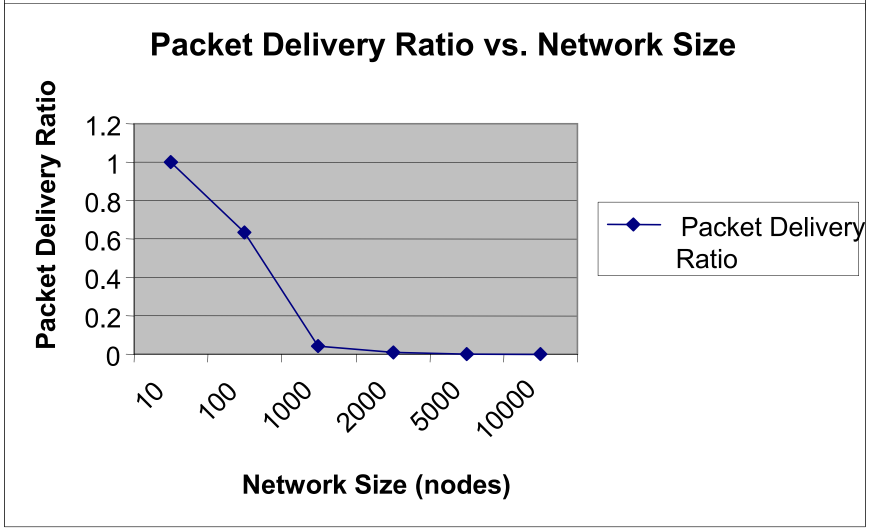
- Evaluate scalability of ad hoc networks
  - Constant Bit Rate (CBR) application traffic using UDP
  - Each flow generates 1460 B(ytes)ps
  - Wireless ad hoc routing protocol
  - MAC Layer: IEEE 802.11 DCF with a channel bandwidth of 2Mbps
  - Two-ray propagation path loss
  - Radio range is approximately 375 meters
- Varied network sizes:10, 100, 1000, 2000, 5000, and 10000 nodes
- Node placement: uniform in square terrain with node density 253 meters squared per node
- Number of randomly selected CBR sources and destinations: one third that of the total network size
- Simulated time: proportionate to number of nodes from 900 seconds to 90000 seconds
- Stabilized network load: proportionate to the number of nodes from 4380bytes/s to 4866180 bytes/s

Accuracy & Scalability









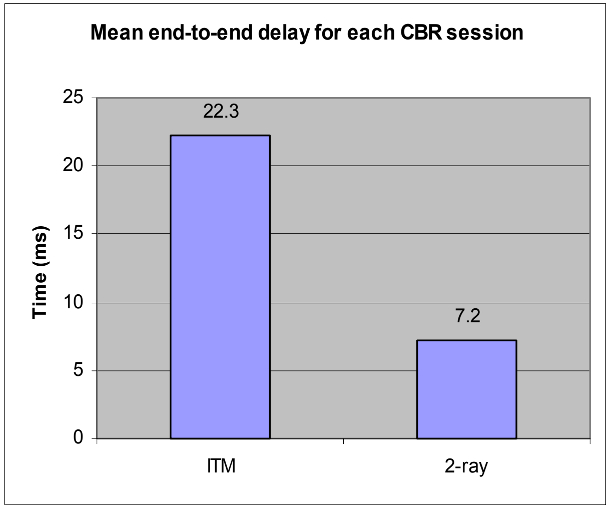
(http://www.msiac.dmso.mil/journal/wong32.html)

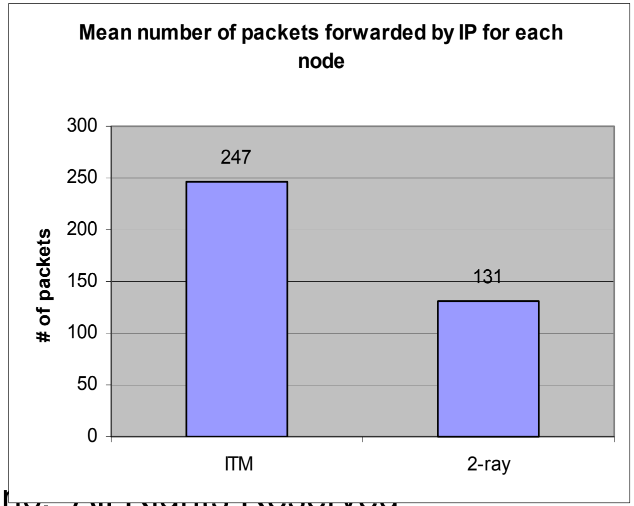
Accuracy & Speed

- Successfully parallelized ITM; incorporated into QualNet
- Preliminary performance study
  - Node density ~ 100 nodes / $(km)^2$
    - Neighboring nodes about 100m apart
  - Uniform distribution
  - ITM (Longley-Rice) using a terrain map ~ 50 mi. north of Santa Barbara in DTED format
  - 802.11b radios; AODV routing
  - 8kbps voice traffic: every node has a 10% chance of transmitting for 0-15 seconds to a random destination, per 60 second period since the last transmission; 50B payload/pkt
- Two Experiments
  - Varied signal propagation models: ITM & plane earth
  - varied number of nodes

Comparison of ITM and Two Ray results

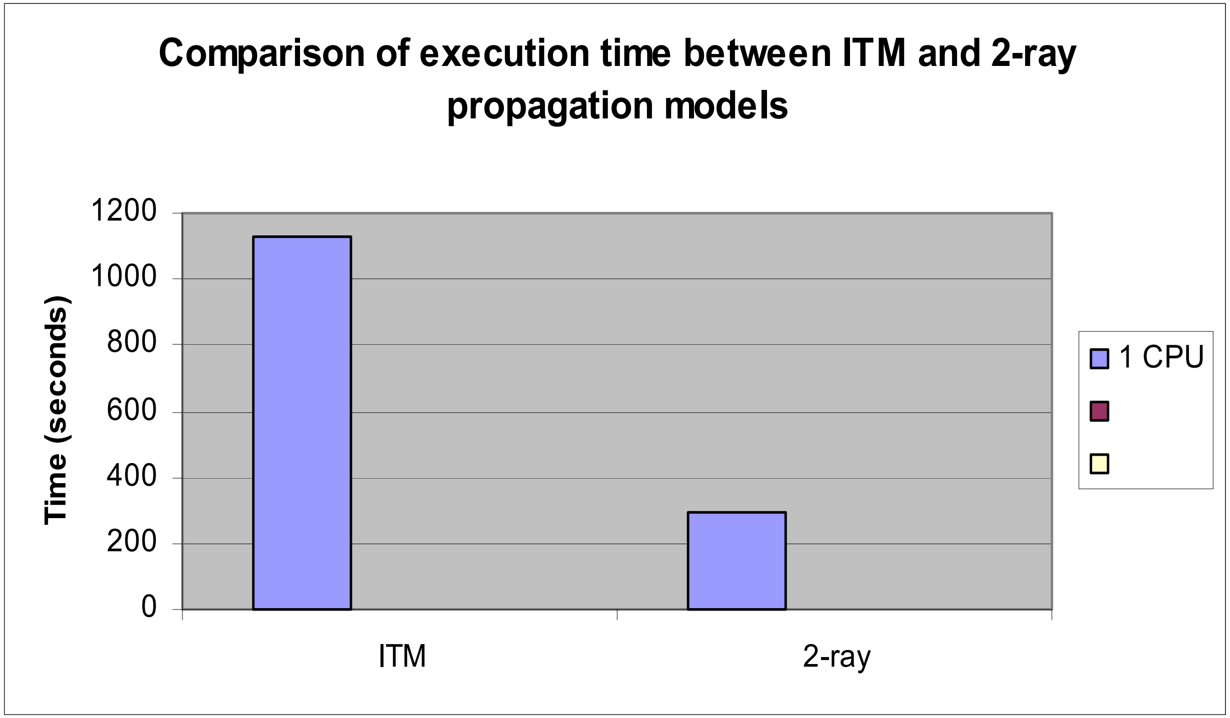
- Mean end-to-end delay differed by 3x
  - Effective transmission range much less for ITM than for 2-ray, which requires more hops between sources and destinations
  - IP forwarding statistics seem to confirm this



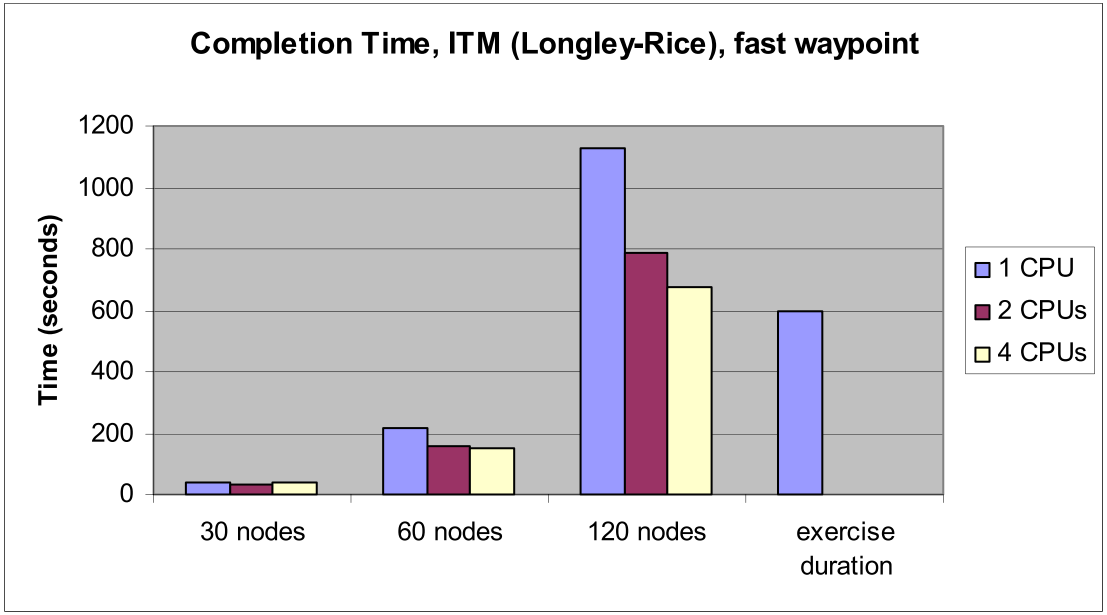


Execution Time

- Higher fidelity ITM model improves accuracy at the cost of increased execution time.
- Efficient, parallel model execution can produce substantial benefits



Simulator Performance with ITM

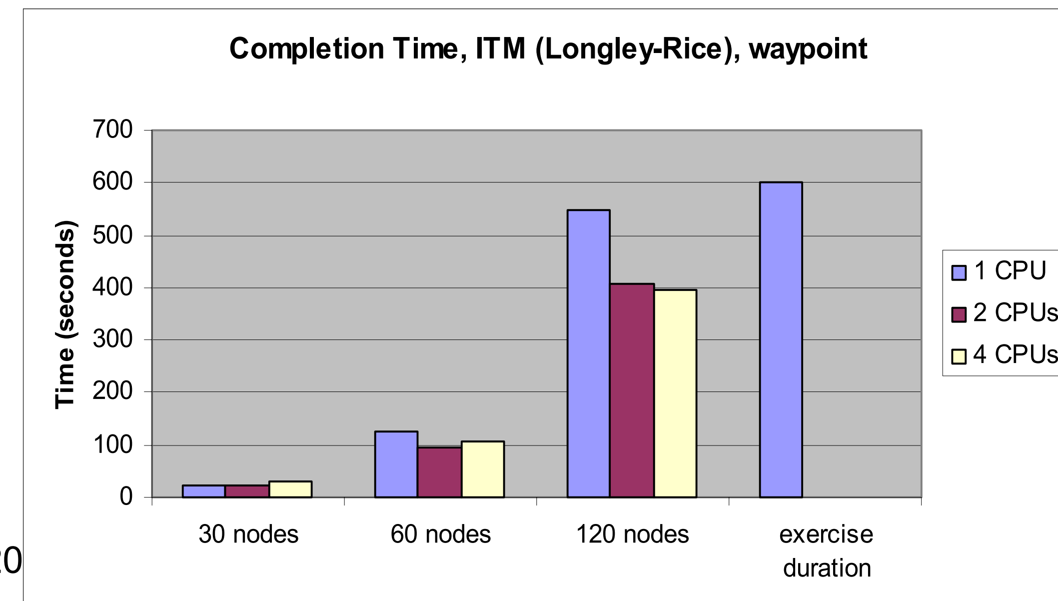


Machine Configuration:

- Dell PowerEdge 6400
- (4) P III Xeon 700 MHz w/1MB cache; 1 GB RAM
- Linux-Mandrake 7.2 (2.2.x kernel)
- $12-15K

Random waypoint :

- Fast: 0-10 m/s;
- Slow: 0-3 m/s;
- 30s pause time



QualNet Physical Layer Overview (1)

- PHY components (completed + in future release)

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)
  - Turbo
- Carrier sensing

Air interface (antenna)

QualNet Physical Layer Overview (2)

- Antenna models
  - Omni-directional uniform gain
  - Switched beam multiple patters (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

QualNet Propagation Models

- Non terrain based pathloss models
  Free space Two-ray (+ Log-normal shadowing)
- Terrain based pathloss models
  ITM (Longley-Rice) TIREM
- Fading models
  Rayleigh distribution Ricean distribution
- Results given to the physical layer (antenna models)
  Propagation delay AOA (angle of arrival)

Noise and Interference Modeling

- Parameters for noise and interference
  - temperature of the radio *T* (290 K by default)
  - noise factor of the radio *F* (10 by default)
- SINR (signal to interference and noise ratio) calculation

$$SINR = \frac{P_s}{\sum_{\text{all others}} P_{Ii} + FkTB}$$

where *k* : Boltzmann's constant (1.379×10^{-23} [W Hz^{-1} K^{-1}])
B : effective noise bandwidth of the system (data rate) [Hz]

- All the interfering signals are assumed to conform Gaussian noise

BER / PER Computation (1)

- BER (bit error rate) for a given SNR on Gaussian noise (AWGN) channel is retrieved from a precomputed look-up table
- Four BER tables are included in the QualNet release package

  Net release package

  nd without turbo coding

  without turbo coding

  ithout turbo coding

$$PER = 1 - \prod_{i}^{n} (1 - BER_i)^{L_i}$$

  thout turbo coding

  hout turbo coding

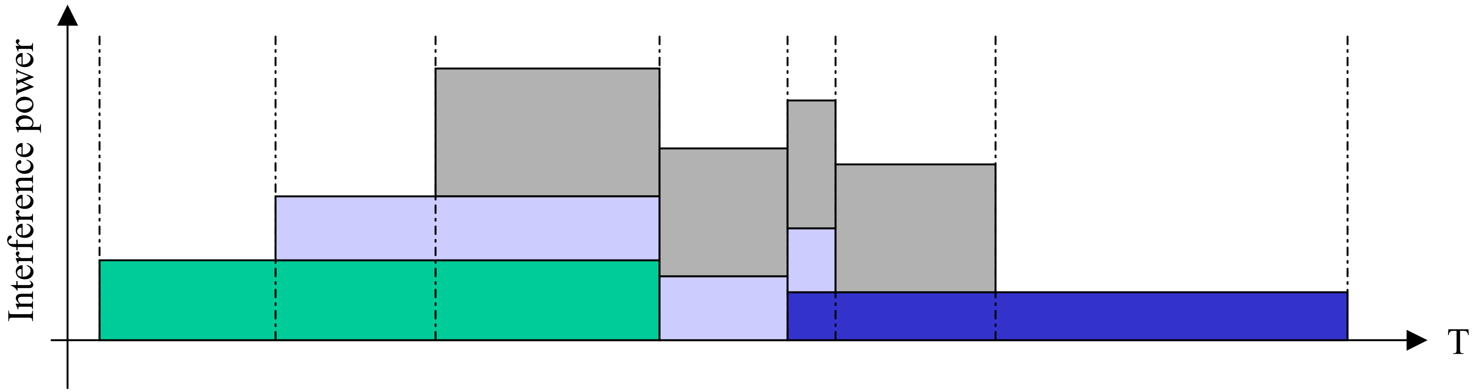
where n : number of changes in the interference power level

er level

ed i

BER / PER Computation (2)

- 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

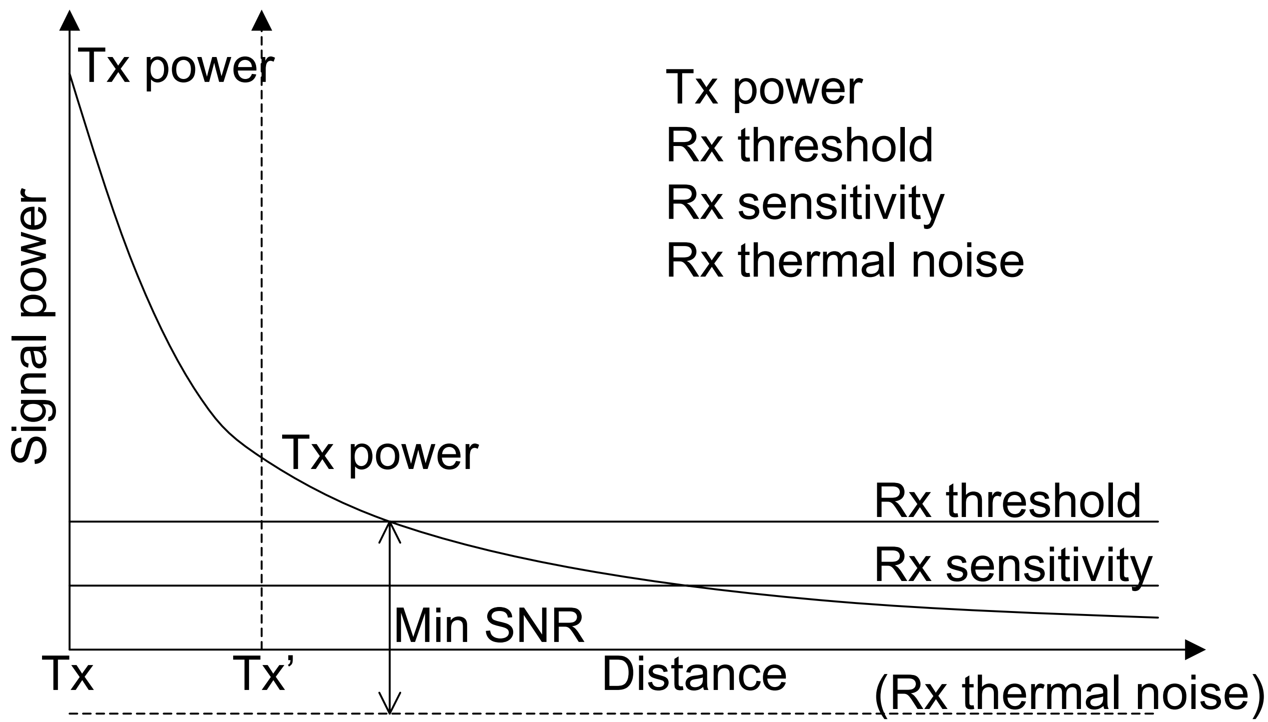


Physical Layer Parameters

- Parameters for transmiting
  - transmit power
  - data rate
  - channel
  - modulation
- Parameters for receiving
  - BER table for demodulation and decoding
  - thermal noise
  - receiver sensitivity (radio returns sensing to MAC inquiries if it detects power above the sensitivity on the channel)
  - receive threshold (radio does not try to receive signals if their power is below this threshold)
  - antenna beam (radiation pattern)

Physical Layer Parameters and Radio Communication Range

- Relationship of parameters to determine the radio range (under no interference)
- Range can be determined by Rx threshold or required SNR

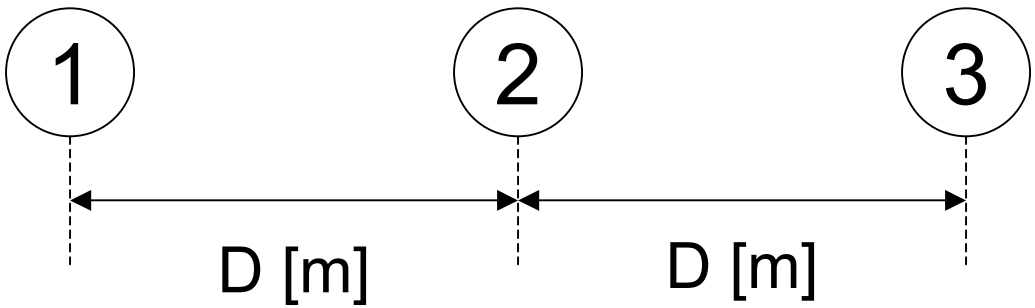


IEEE 802.11 MAC Communication Range

- Set TX power to 80 dBm (100 kW)
  - PHY RX range: 15888 m
- How long can the IEEE 802.11 MAC radio (with DSSS PHY reference parameters) reach?
  - Speed of light: $3.0e10^8$ m/s
  - aAirPropagationTime (1 us): 300 m
  - aSIFSTime (10 us): 3000 m

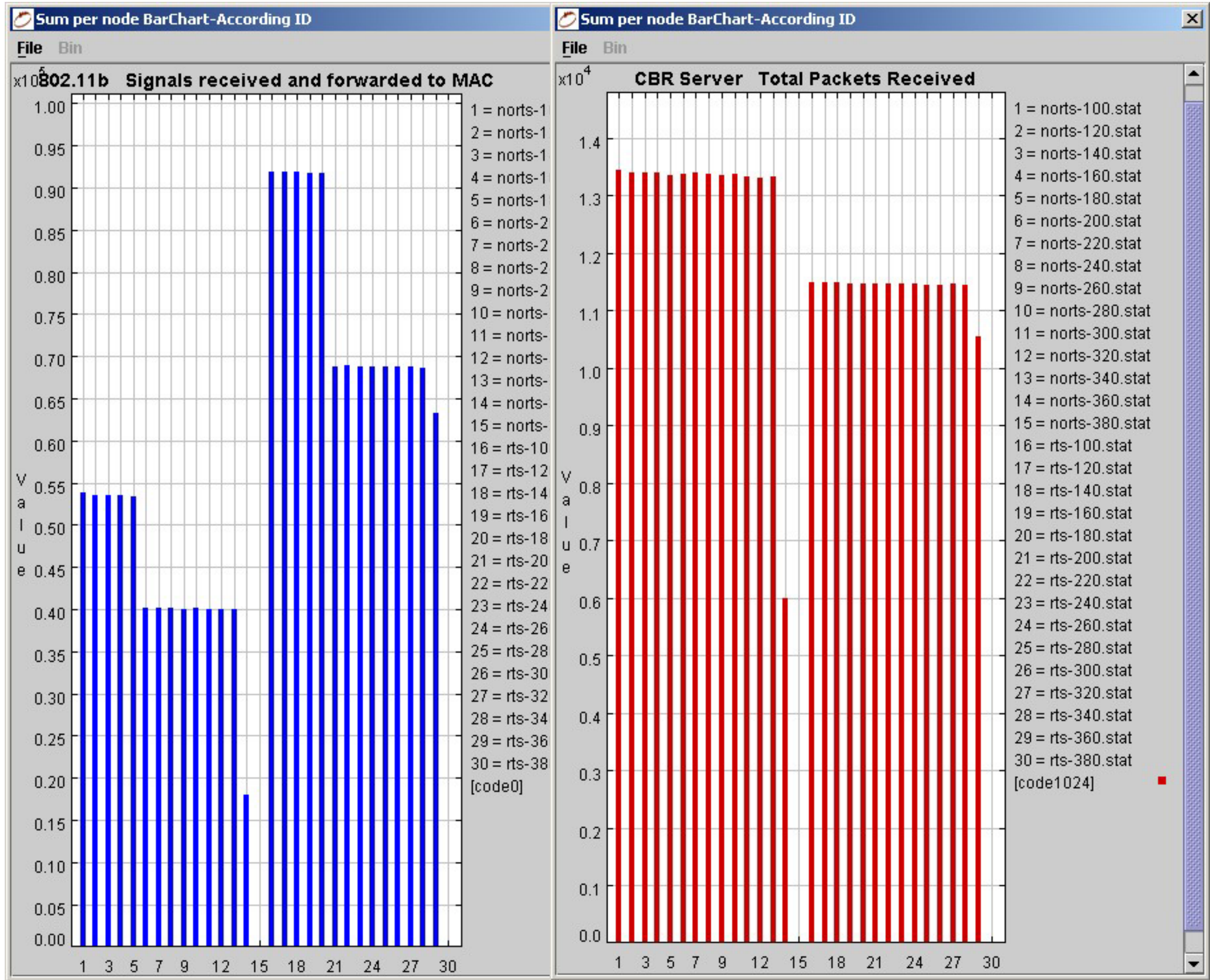
RTS/CTS Option in IEEE 802.11 (1)

- Based on the PHY parameters (two-ray):
  - RX range: 376.7m
  - CS range: 670.0m
- Vary the distance D in the configuration below
  - D = 100 - 380
  - Two heavy CBR sessions (1 -> 2, 3 -> 2)
  - With and without RTS / CTS control frames



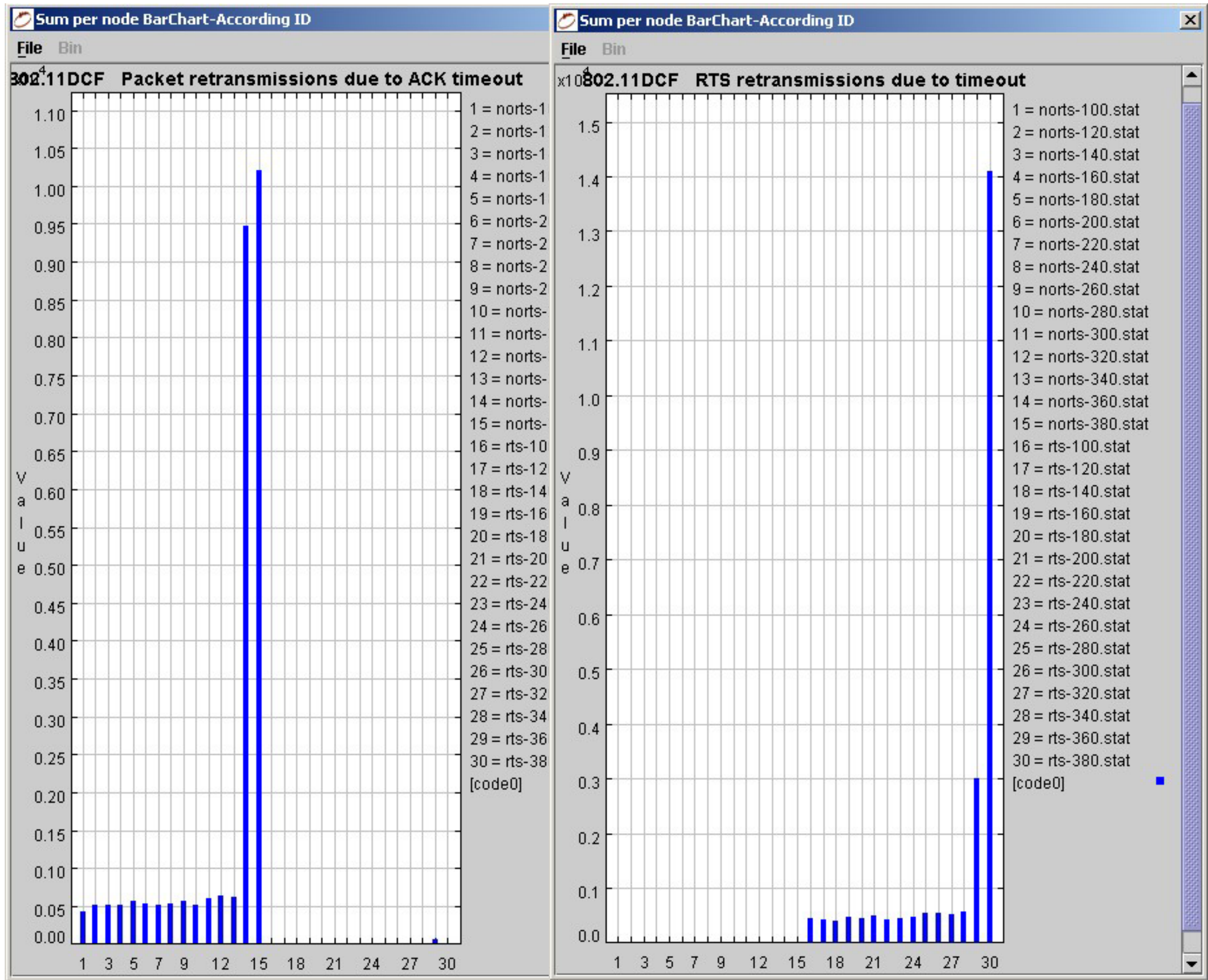
RTS/CTS Option in IEEE 802.11 (2)

- Higher throughput w/o RTS/CTS
- No difference in throughput between D = 180 and 200 (RX range/2 = 188)
- High drop in throughput for D = 360 and higher



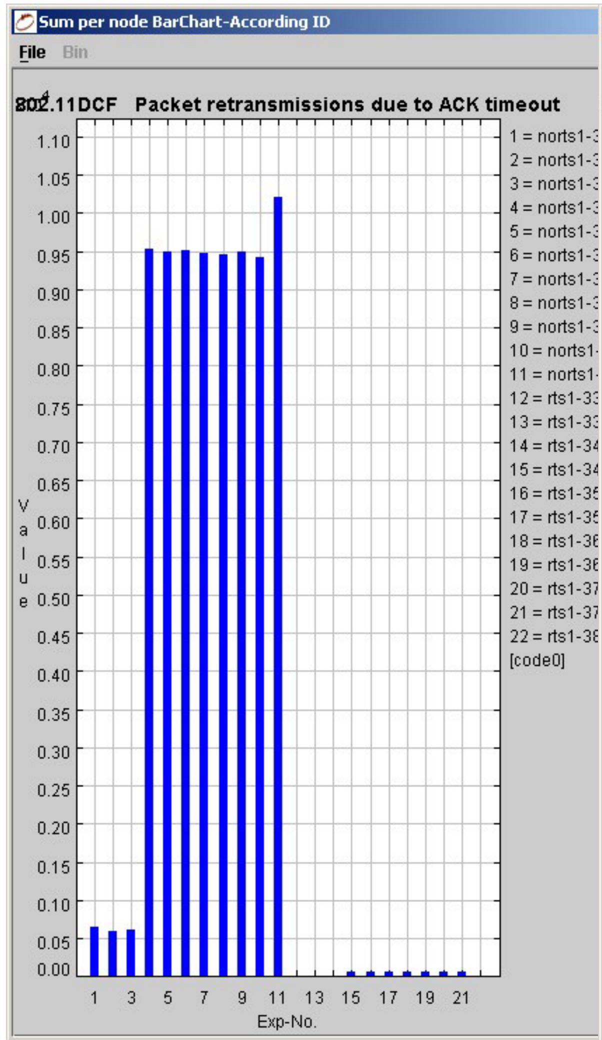
RTS/CTS Option in IEEE 802.11 (3)

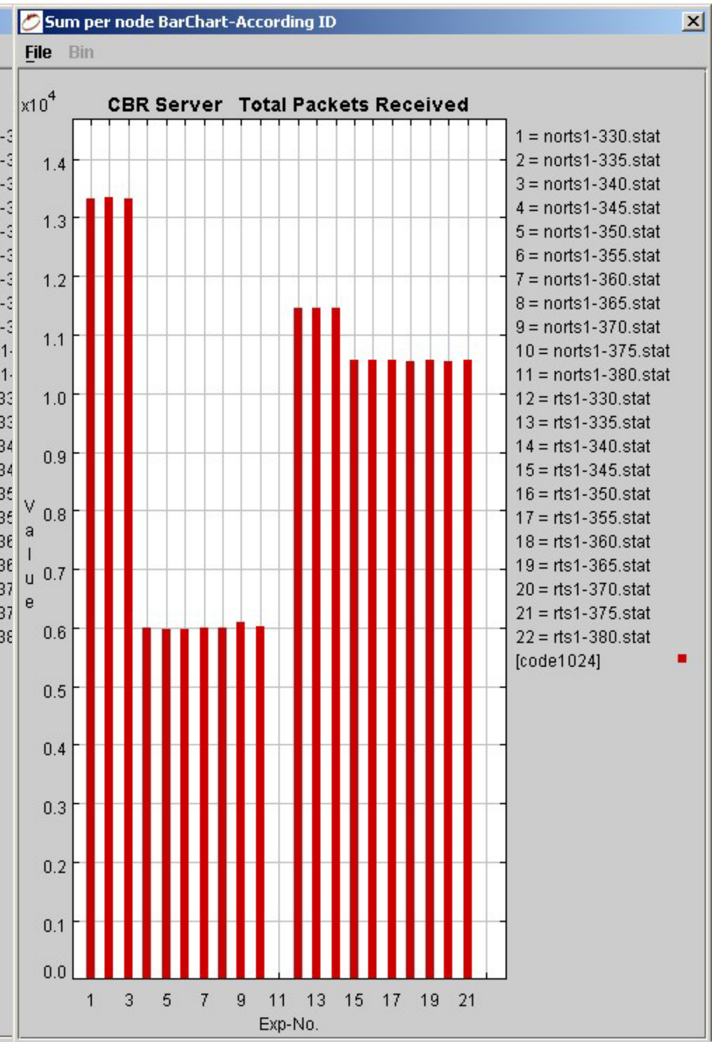
- Data frame loss w/o RTS/CTS
- RTS frame loss otherwise
- What is the benefits of RTS/CTS?
- Hidden terminal problem



RTS/CTS Option in IEEE 802.11 (4)

- CS range / 2 = 335 (+ noise)
- Hidden terminal problem shows in cases with D = 345 to 375
- What if (RX range) < (CS range / 2)?



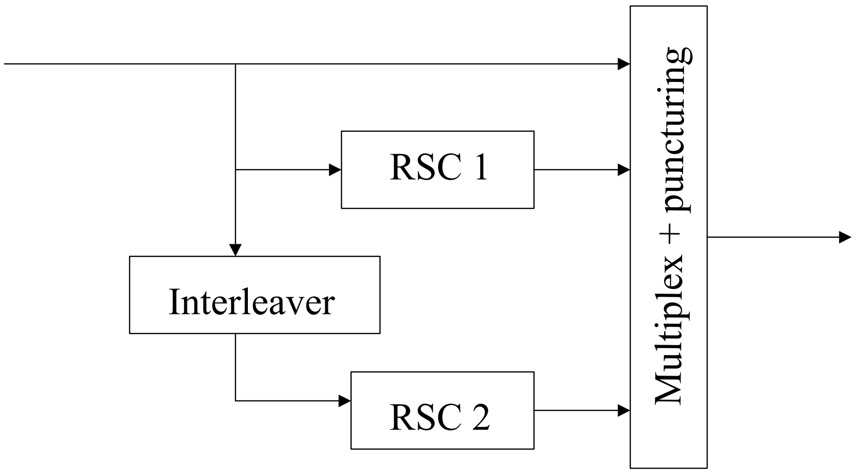


Case Study: Turbo Code Model (1)

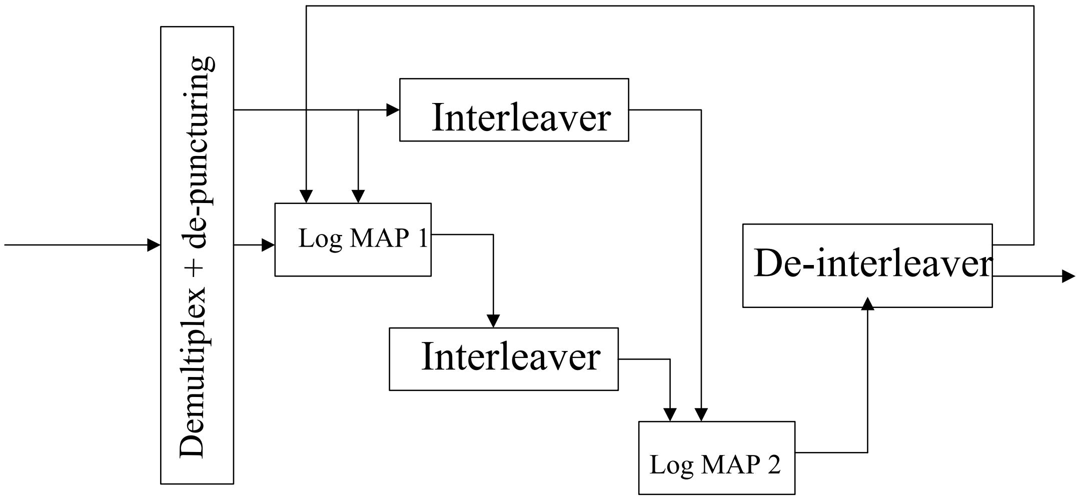
- A turbo code model has been implemented in Matlab to generate SNR - BER lookup table
  - Interleaving size: 4192 bits
  - Interleaving method: Random interleaving
  - Decoding algorithm: Log Maximum A Posteriori
  - Number of iterations: 5
  - Rate: ½
  - RSC (Recursive Systematic Convolutional) generator: 1 1 1; 1 0 1

Case Study: Turbo Code Model (2)

- Encoder

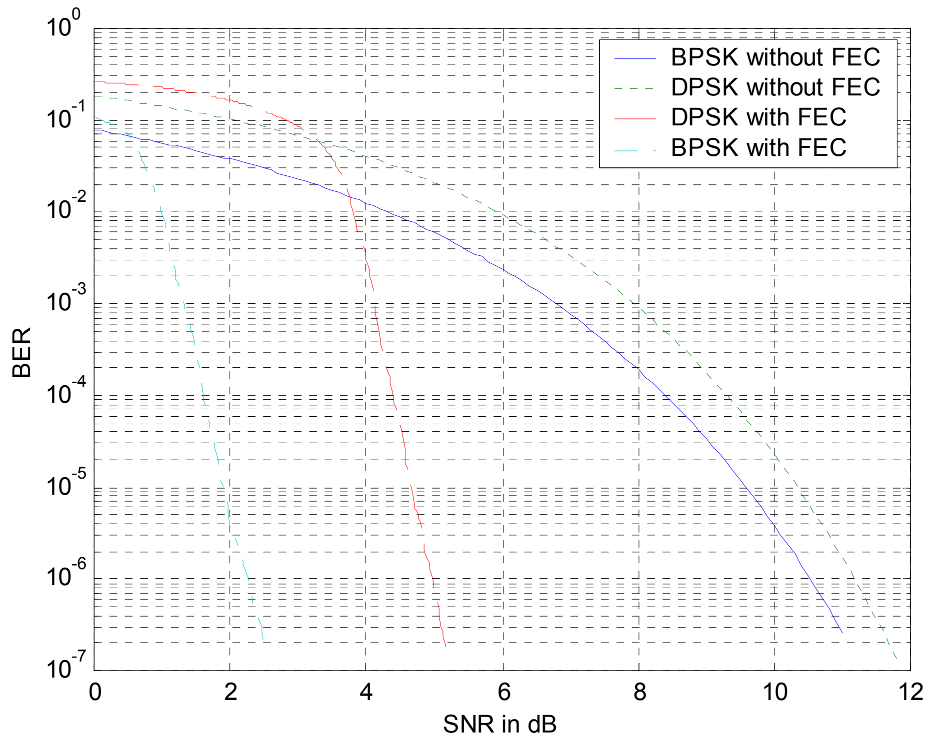


- Decoder



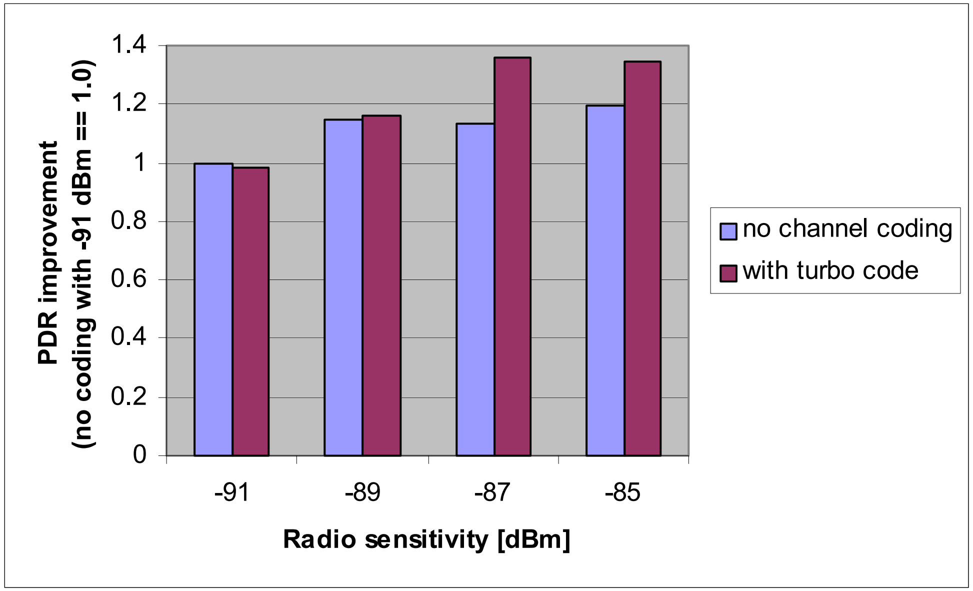
Case Study: Turbo Code Model (3)

- Encoder and decoder are modeled in Matlab
- BER performance with and without the turbo code model
- 6+ dB coding gain with DBPSK
- 8+ dB coding gain with BPSK at BER = 10^{-6}



Case Study: Turbo Code Model (4)

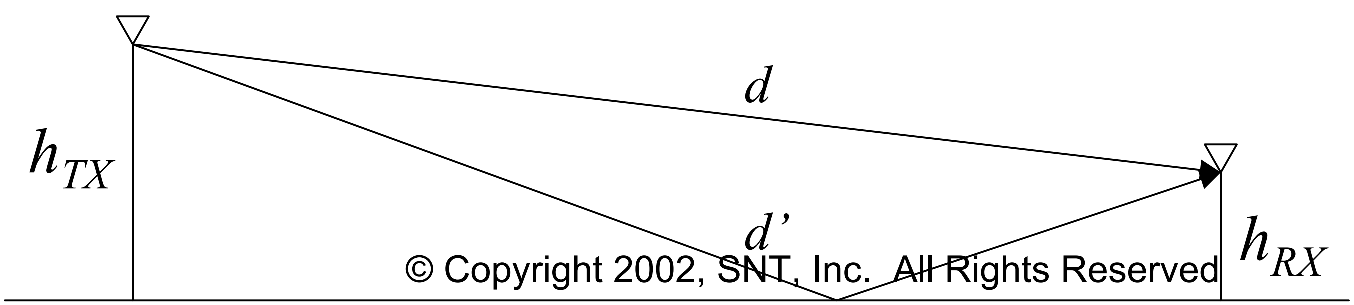
- Case study with turbo coding
  - 100 nodes spread over flat terrain (83,000 m^2/node)
  - 100 CBR sessions (160 bytes, 50 pps)
  - AODV routing protocol
  - 802.11 MAC DCF
  - 802.11 PHY DSSS
  - Rx threshold fixed at –81 dBm
  - Varying sensitivity from –91 dBm to –85 dBm



Common Propagation Models (1)

Simple Path Loss Models

- Free space
  - really means that its path loss exponent is 2.0
  - can be combined with shadowing and fading
- Two-ray
  - considers a ray bounced back from the ground
  - uses the free space path loss model for near sights
  - becomes 4.0 exponent for far sights
  - Its path loss becomes frequency independent (function of distance and antenna heights) for far sights



Common Propagation Models (2)

Consideration of Terrain Effects

- ITS (Institute for Telecommunication Sciences)
  ITM (Irregular Terrain Model)
  - a.k.a. Longley-Rice
  - has both point-to-point mode and area mode
  - Point-to-point mode works very similarly to TIREM
  - No release restrictions unlike TIREM
- TIREM
  - considers terrain intrusion to the Fresnel zones to determine the levels of diffraction

Common Propagation Models (3)

Terrain Database Types

- CTDB (Compact Terrain Database)
  - Gridded posts or TIN (Triangulated Irregular Network) polygons for elevation data
  - Terrain features in the database in the feature list for gridded database, or as terrain elements for TIN only database
- USGS DEM (DTED) interface
  - Only elevation data in mesh
  - Grid size: 3 arc-seconds
  - Terrain data are available via USGS web site

Common Propagation Models (4)

Shadowing model

- Log-normal distribution with standard deviation σ [dB]
- Updates shadowing values independently from the previous values

(Flat) Fading models

- Applies to only narrowband channels (flat fading)
  - No ISI (inter-symbol interference)
- Rayleigh distribution
  (highly mobile, no line of sight signal)
- Ricean distribution with Rice factor (K)
  - Rayleigh case when K = 0 : no line of sight component
  - No fading case when K = ∞ : strong line of sight component

Antenna Models

- Antenna models determine antenna gains for each signal on both transmitter and receiver ends
- The antenna gain is determined as:

  $G\ (DOA_a,\ DOA_e)$ [dBi], or approximately

  $G_a(DOA_a) + G_e(DOA_e)$ [dBi]

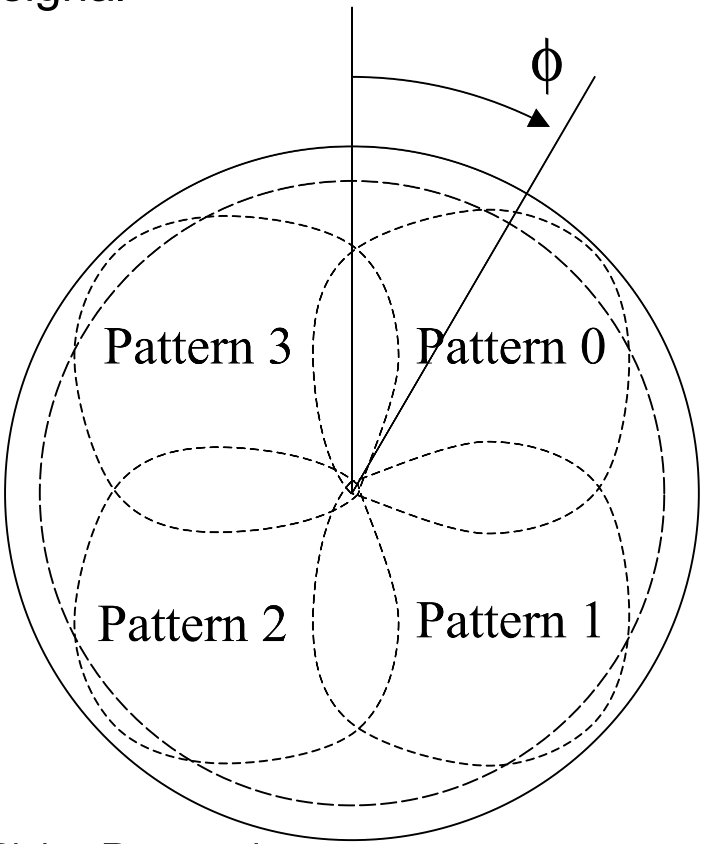
  where DOA_a and DOA_e are direction of arrival on azimuth and elevation planes respectively, and G_a and G_e are the corresponding gains for these angles
- Antenna models return the gain for an angle closest to the given angle

Antenna Models Provided in QualNet

- Omni-directional
  always returns a fixed gain for all directions
- Switched beam
  stores multiple radiation patterns and returns G_a and G_e for a given direction (AOA) with a specified pattern
- Steerable beam
  can store different radiation patterns and steer them to maximize the gain for a given direction (AOA)

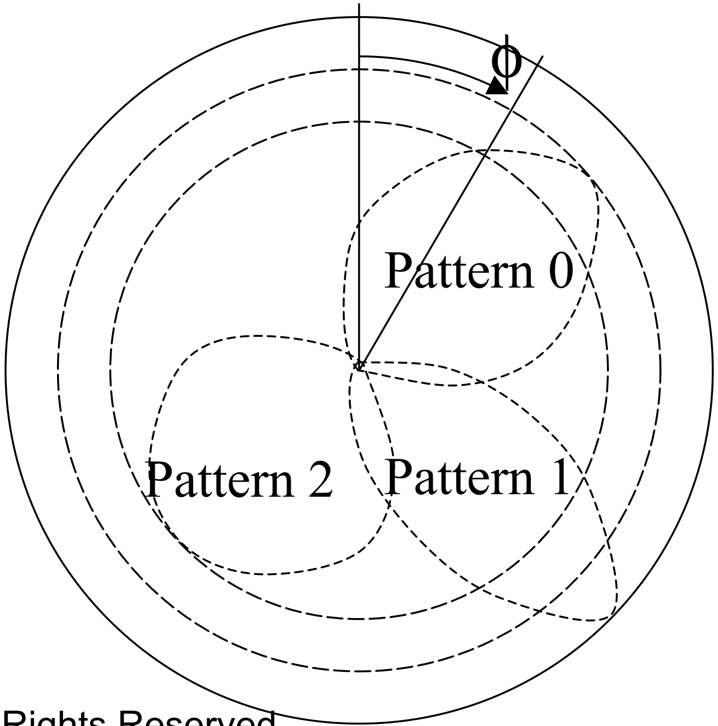
Switched Beam Antenna Model

- Switched beam antenna
  - can have multiple radiation patterns
  - can specify the pattern to use for each signal
  - can scan all the patterns and return the pattern with the highest gain for a given signal or for a given direction



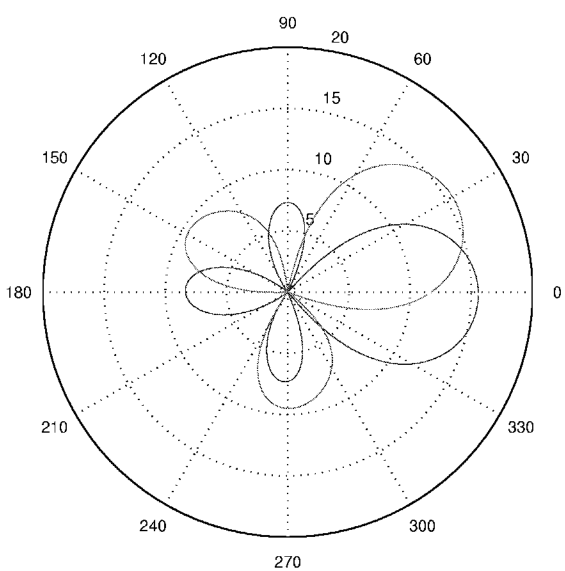
Steerable Beam Antenna Model

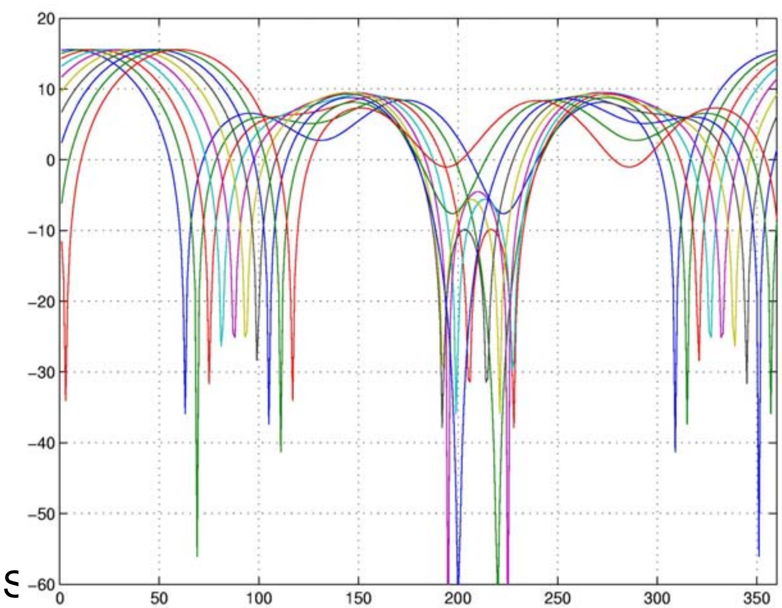
- Steerable beam antenna
  - can have multiple radiation patterns with different beam widths
  - can specify the pattern to use for each signal
  - can steer each pattern and return the angle that yields the highest gain for a given signal



Case Study: Electrically Steerable Beam Antenna (1)

- Circular antenna array with 6 isotropic antenna elements
- Only phase shifting (no amplifier with each element)
- 0.4 wavelength spacing at 2.4 GHz ISM band
- Patterns created using MATLAB and fed into QualNet





Case Study: Electrically Steerable Beam Antenna (2)

- Case study with typical MANET environment:
  - 100 nodes over 1500 x 1500 flat terrain
  - Two-ray path loss model (1.5m antenna height)
  - IEEE 802.11 DCF MAC with RTS/CTS option
  - AODV
  - 40 CBR sessions with 512 byte packets at 1 to 40 pps
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