Planning WiMAX Network Deployments
R&D Solutions for Commercial and Defense Networks
Session Abstract

Prerequisites:

- Basic understanding of wireless link performance issues
- Basic understanding of wireless propagation concepts
- Basic understanding of WiMAX
- Familiarity with OPNET modeling concepts
- Familiarity with the Wireless module

Description:

WiMAX is one of the emerging mobile broadband wireless technologies and is based on the specifications of the IEEE 802.16e standard and WiMAX Forum guidelines. The complexity of WiMAX networks is compounded by many sub-layers and protocols, leading to a large number of design choices across network components, protocol features, and parameters. OPNET Modeler® Wireless Suite provides a detailed discrete event simulation modeling framework to facilitate the evaluation of available design choices.

This session gives you an overview of the WiMAX model features necessary for R&D and planning purposes. Through the use of labs and lecture, you will learn key design choices available for planning WiMAX network deployments and how each of these options impact application performance. You will be using discrete event simulations to evaluate protocol configuration options against system level variations—such as traffic loads, mobility patterns, and physical layer impairments—to study and achieve optimal network performance.

The following topics are covered:

- Overview of OPNET’s WiMAX features and attributes
- Planning use-cases covering capacity and QoS impact analysis
- Power savings mode
- Transparent relay station support (802.16j)
- PUSC segmentation
 Agenda

- **Introduction to WiMAX**
- Supported features in OPNET’s WiMAX model
- Basic WiMAX Model Settings
- Adaptive modulation and coding
- Retransmissions: ARQ and HARQ
- Lab 1: Combining AMC and HARQ to improve application performance and frame capacity
- Special WiMAX frame configurations
  - Relays
  - Fractional frequency reuse
- Power settings
- Lab 2: Reduce power consumption on WiMAX devices
- Capacity planning
- Conclusion
WiMAX Specifications

- **IEEE 802.16-2004**
  - Air Interface for Fixed Broadband Wireless Access Systems

- **IEEE 802.16e-2005**
  - Air Interface for Fixed *and Mobile* Broadband Wireless Access Systems

- **IEEE 802.16j-06**
  - Multihop Relay Specification

- **WiMAX Forum**
  - WiMAX System Evaluation Methodology (AATG/AWG)
  - Network architecture and reference points (WiMAX Forum NWG)
    - WiMAX End-to-End Network Systems Architecture

- **Flexibility**
  - Multiple alternatives
  - Many optional features
OPNET's WiMAX Model

- OPNET named TMCnet WiMAX Distinction Award Winner in 2008 and 2010
- Implemented under the OPNET WiMAX model development Consortium (no longer active)
  - Prominent network equipment manufacturers, service providers, defense organizations
  - Members: 53
  - Founding member: Motorola
  - Guidelines from WiMAX Forum AATG/AWG
- Current model development consortium: 3GPP LTE
- Successful past consortia
  - MPLS, UMTS, DOCSIS, MANET
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WiMAX Model Newest Features

- 802.16j
  - Transparent relay station
  - Centralized scheduling
- PUSC segmentation
- Power savings (Type I, II and III)
- Uplink open-loop power control
- Multi-level ertPS allocations
- MAP and control message losses
- Frame over-booking/under-booking
WiMAX Model Features

- **MAC**
  - Bandwidth allocation and request mechanisms
    - BS scheduler for uplink and downlink
    - Scheduling service for UGS, ertPS, rtPS, nrtPS, BE
    - MSDU packing and fragmentation
    - CDMA based bandwidth requests (aggregated)
    - Piggyback bandwidth requests (incremental)

- Framing
  - Grant consolidation per Basic CID
  - Burst rectangulation
  - MAP generation
  - IP convergence sub-layer
  - Service flow configuration and mapping of traffic to service flows
  - Frame capacity reservation for implicitly modeled traffic
WiMAX Model Features (cont.)

- MAC
  - Adaptive Modulation and Coding
  - Hybrid ARQ (chase combining)
  - ARQ
    - In-order SDU delivery
    - Cumulative and selective (bitmap and block sequence) ACKs
    - Fragmentation and Packing
  - Mobility
    - Scanning-based BS selection
    - Handover
    - Access service network (ASN) assisted handover (L3)
    - Multi-target BS
  - Initial and periodic ranging
WiMAX Model Features (cont.)

- **PHY**
  - **TDD**
  - **OFDMA, SOFDMA**
    - Preset values for SOFDMA (FFT 128, 512, 1024, 2048)
  - **Co-channel Interference**
    - Subcarrier to subchannel mapping
    - Pre-computed tables for subcarrier overlap
    - Perm-base
  - **Multi-path fading**
    - ITU models (Pedestrian A, Pedestrian B, Vehicular A, Vehicular B)
    - Finite state Markov channel models
  - **Pathloss modeling**
    - ITU (Pedestrian, Vehicular)
    - Erceg (terrains A, B, C)
  - **MIMO STC 2x1** (downlink only)

- **Network features**
  - **Multi-cell**
  - **Multi-sector (3-sector BS available)**
  - **IP connectivity (IPv4 and IPv6)**
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WiMAX Model Entities

- Nodes
  - Subscriber Station Node
    - Fixed or mobile (MS)
    - Full stack
  - Base Station Node
    - Fixed (BS)
    - IP-stack (router)
WiMAX Model Entities (cont.)

- **Nodes**
  - WiMAX configuration Utility
  - Transparent relay node

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WiMAX Model Abstractions

- Four abstraction levels
  - Incremental accuracy, backward compatibility
  - Set via “Efficiency Mode” attribute of WiMAX Config node

  - **Efficiency Enabled**: MAC (fluid flow model) + no PHY
    - Most common use case: capacity planning

  - **Framing Module Enabled**: MAC (frame-by-frame) + abstracted PHY
    - Most common use case: QoS and application deployment planning
    - Delays more accurate than the highest efficiency mode

  - **Physical Layer Enabled**: MAC (frame-by-frame) + PHY
    - Most common use case: PHY transmission and channel effects
    - Co-channel interference, multipath fading and pathloss effects
    - Broadcast connections

  - **Mobility and Ranging Enabled**: Previous + Mobility and Ranging Enabled
    - Most common use case: Mobility modeling
    - Scanning and handover delays
    - Initial and periodic ranging (delays, MS power levels)
Mapping Application Traffic to WiMAX Service Flows

- Create/select a WiMAX service class
  - Symbolic name: Gold
  - Scheduling type: UGS, ertPS, rtPS, nrtPS, BE
  - Traffic contract:
    - Consider all overheads:
      - 640 bits voice + 96 bits RTP + 64 bits UDP + 160 bits IP = 960 bits packet presented to WiMAX
    - Define an acceptable delay

- Create a service flow on SS to establish traffic flow in the specified direction
  - Specify the “Service Class Name”
  - A service flow is an instance of a service class. A service class defines the traffic contract
  - Service flow also has other important attributes such as modulation and coding, retransmission schemes, buffer size, SDU size, etc.
Mapping Application Traffic to WiMAX Service Flows (cont.)

- Use classifier to “multiplex” application traffic to the service class using some property
  - Popular choice: IP ToS
  - Classifier must be on SS for UL traffic, on BS for DL traffic
  - System default: An implicit connection of type BE
  - Any unmatched traffic is mapped to this
Configuring OFDMA Technology

- New OFDMA PHY profiles can be configured on WiMAX Config node and eventually used by the base/mobile stations
  - A default 2048 sub-carrier 20MHz is available with the shipped product
  - PHY profile on a mobile node should match that of the base station to establish connectivity
Each MS can be configured with a pathloss and multipath fading profile.

To see the complete effect of physical layer models, “Efficiency Level” in WiMAX attribute configuration object should be set to “Physical Layer Enabled” or “Mobility and Ranging Enabled”.
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Adaptive Modulation and Coding

- Adaptive modulation and coding (AMC)
  - Nodes with higher SNR can use aggressive modulation and coding – saves symbols and increases system capacity. On the downside, using aggressive modulation and coding can result in packet drops.

- Challenge: Design AMC table for optimal operation
  - An AMC table specifies SNR values for corresponding modulation and coding (MCS) schemes. The system measures the current SNR and adaptively switches to the best MCS.

Conceptual idea of link adaptation: Nodes lying in various regions use different modulation and coding. Nearer nodes use very aggressive MCS and farthest nodes use a conservative MCS.
Design of AMC Table

- Choose an acceptable block error rate (BLER) for the link
- Use SNR curves for every MCS scheme and set the entry corresponding to the above BLER value as the “crossover point”

For almost 0 block errors, the required minimum SNR for QPSK ½ is about 2 dB and for QPSK ¾ is about 5.9 dB.
Understanding AMC Tables

- QPSK $\frac{1}{2} = 1$ bit per symbol
- QPSK $\frac{3}{4} = 1.5$ bits per symbol

When the SNR is dropping, the region between (5.9, 5) dB uses QPSK $\frac{3}{4}$ inducing bit errors. Link budget should take that into consideration. Minimum entry and mandatory exit thresholds can be made the same.
Effect of Retransmissions on System Performance

- AMC table can be made more aggressive to increase system capacity
  - For example, if link BLER is set to 10%, then our previous QPSK table would look like the figure shown below
  - But TCP retransmissions may offset any gains in system capacity. As a side effect, application performance will suffer as well.

- QPSK $\frac{1}{2} = 1$ bit per symbol
- QPSK $\frac{3}{4} = 1.5$ bits per symbol

![Graph showing WiMAX frame usage and application delays](image)
- WiMAX frame usage
- Application delays
- TCP retransmissions dominate
- Aggressive AMC tables
Impact of AMC on System Performance

- Nodes with adaptive MCS are able to achieve higher application throughputs while causing less frame usage
  - **Aggressive AMC**: Less frame usage but bad application throughput
  - **Conservative AMC**: Good throughput but more frame usage
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WiMAX Retransmissions: ARQ and HARQ

- TCP retransmissions can negatively impact WiMAX system performance
  - They take extra unplanned capacity from the system
  - TCP is created to avoid congestion, not to fight link errors

- **ARQ** (Automatic Retransmission Request):
  - ARQ works like TCP, with suitable timers for typical WiMAX configurations

- **HARQ** (Hybrid Automatic Retransmission Request):
  - Most suitable for WiMAX due to its hybrid nature as it takes into account both the MAC and link layer
  - Advantages of HARQ: Primarily 2 great advantages
    - Fast retransmissions, possibly in the very next frame
    - SNR gain: $SINR_k = \sum_i SINR(i)$ (where i represents each received packet copy)
      - Each retransmitted copy is combined with all prior transmitted copies. Thus each retransmission increases the probability of reception!
Impact of ARQ and HARQ on System Performance

- HARQ can be used in conjunction with ARQ
  - ARQ is treated as higher layer to HARQ
  - HARQ gives up after maximum retransmissions
  - ARQ retransmission can take over when HARQ gives up

Study Results
- Using only HARQ (light blue curve) results in some drop in throughput
- Using ARQ only (orange curve) has high delays
- Using them both (dark blue curve) gives the best performance. HARQ performs fast retransmissions and ARQ takes over in cases HARQ fails after multiple retransmissions. This gives an added layer of protection to data.
Configuration of ARQ and HARQ in OPNET

- **ARQ**: Configured per service flow
- **HARQ**: Also configured per service flow, but attributes are shared by the whole device
  - Number of channels, buffer size of the channel, ACK wait delay, etc.
  - Any HARQ enabled service flow can send its packet on any channel. Once a channel is locked this way, it is released only after successful packet reception or after reaching maximum retransmission attempts.
Case Study: Using HARQ with AMC

- Aggressive AMC tables increase bits per symbol but may result in TCP retransmissions
  - **Choice 1: Use a conservative AMC table**
    - The green line below specifies a 0% BER line. If AMC table is tuned with SNR values from that curve appropriately, it will automatically select an MCS for the given level of SNR that achieves 0% BER
  - **Choice 2: Use an aggressive AMC table with HARQ**
    - The red line below specifies a 5% BER line for example. If AMC table is tuned with SNR values from that curve, it will tune the MCS that achieves 5% BER on an average resulting in loss of packets. HARQ retransmissions will overcome packet losses
    - Frame usage reduces because on an average, more aggressive MCS is used for the same SNR. On the other hand, frame usage increases due to HARQ retransmissions. Can HARQ bridge the SNR gap with fewer retransmissions?
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Lab 1: Combining AMC and HARQ to Improve Application Performance and Frame Capacity

- **Objectives**
  - Improve network capacity
  - Improve application performance

- **Methodology**
  - Use AMC and compare its performance against static MCS
  - Examine performance of the network with aggressive AMC table
    - Examine impact of TCP retransmissions on frame utilization and application delays
  - Use two strategies to evaluate network performance with respect to frame utilization and application delays
    - Use a conservative AMC table
    - Use an aggressive AMC table with HARQ
Lab 1: Summary

- OPNET simulations can be used to tune parameters for optimal system performance in adaptive/dynamic environments
- TCP application performance and impact of TCP retransmissions on network capacity and application delays can be analyzed in OPNET
- Variations in AMC tables can lead to a different behavior. Simulations can be used to tune AMC tables for capacity optimization
  - Impact on application delays (due to HARQ retransmissions) can also be measured
- HARQ provides SNR gains with each retransmission. Hence more aggressive AMC tables could be constructed for operation in conjunction with HARQ
  - HARQ also performs fast retransmissions minimizing the adverse impact on application delays
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WiMAX Relay Stations

- **802.16j**
  - New RS (Relay Station) node model
  - Uplink relay transparent mode support
  - Centralized scheduling
    - BS performs all uplink subframe allocations for the access and the relay zones
- Achieve increased capacity
  - Note that transparent relay mode does not increase the cell range as it does not forward MAP control messages
- Configuration in relay node
  - PHY profile, antenna gain, pathloss, ranging, uplink power control, etc
- Configuration in WiMAX Config
  - Enable relay usage by setting **R-RTG** in the frame structure attribute
  - Set relay zone size in **UL/DL boundary > UL Relay Subframe Size**
  - Assign the corresponding PHY profiles to SS, BS and RS nodes
WiMAX Relay Example

- Comparing performance with (green) and without (red) relays
- SS uses more aggressive modulation/coding with relays (see bits per symbol statistic), causing
  - Higher application traffic received
  - Lower UL subframe usage: more capacity!
- Also, in the presence of relays the SS node require less Tx power
  - This is because SS transmissions need to reach the relay instead of the BS
PUSC Segmentation

- Allows fractional WiMAX channel reuse
  - WiMAX channel BW divided in groups of subchannels
  - Each group is assigned to a sector or cell
- Targets reduced interference
- Base station/sector specifies the set of subchannels to use from the configured PHY profile
  - DL segmentation has defined predefined subchannel groups
  - UL segmentation is indicated by a subchannel start and number of subchannels
- UL PHY always use PUSC
- DL PHY can be set to PUSC or FUSC
PUSC Segmentation Example

- A different PUSC segment assigned for each BS
- Compared against full use of subchannels on all BSs
  - Two cases: Same and different permutation bases
- Results: PUSC shows
  - Zero uplink packet drops (indicates no interference across cells)
  - Higher throughput
- Cons: reduced capacity (see the smaller usable subframe size)
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Effect of Power Control for Mobile Performance

- Accounts for
  - Estimated losses
  - Uplink cell noise
  - Normalized C/N target
  - Modulation and coding (or signal type)

- Enable open loop uplink power control on each MS
  - WiMAX Parameters > SS Parameters > Uplink Power Control

- Define target C/N table on WiMAX Config
  - Normalized C/N Per Modulation Definitions

- Associate C/N tables with BS
  - WiMAX Parameters > SS Parameters > Uplink Power Control > Normalized C/N Profile
  - MSs use the C/N table of their serving BS
Effect of Power Control for Mobile Performance (cont.)

- MS nodes using power control react to interference and pathloss
- MS without power control is affected by high interference and perform HARQ retx
Impact of Power Saving in the Mobile Performance

- Power Save Classes
  - Type 1: Best Effort and nrtPS
  - Type 2: rtPS, ertPS and UGS
  - Type 3: Management and broadcast

- Enable at each MS
  - WiMAX Parameters > SS Parameters > Power Saving Enabled
  - For Type 2 and 3, sleep cycles are automatically determined
  - Type 1 behavior is configured via attributes
Impact of Power Saving in the Mobile Performance (cont.)

- Power saving report indicates the time the MS spent in:
  - Normal state
  - Listening state
  - Sleep state

- Power consumption report indicates the following power consumption based on the power saving cycles:
  - Total Tx power consumption
  - Total operating power consumption

- SS operational power is set via a WiMAX Config attribute:
  - Power value settings per power saving state

- Transmission power consumption is computed as the node performs burst transmissions
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Lab 2: Reducing Power Consumption of WiMAX Devices

- **Objectives**
  - Reduce power consumption of WiMAX SS nodes
  - Maintain acceptable application performance

- **Methodology**
  - Establish a baseline deployment
  - Enable power saving mechanism
  - Deploy relay stations
Lab 2: Summary

- Power saving reduce power consumption by switching the subscriber stations through different consumption states (normal, listening, sleep) depending on the device’s activity
  - There can be a slight application delay increase due to the transitions to normal state (e.g. sleep to normal)

- When using relay mode the subscriber stations just need enough power to reach the relay stations, which will forward their traffic to the base station. This reduces the transmission power required by the subscriber stations.
  - The application delay increases by a couple of frame times because of the SS node’s CDMA based BW request mechanism being relayed. The SS nodes use BE service and then rely on CDMA based BW requests. The CDMA codes sent originally by the SS nodes to initiate the BW request mechanism need to be forwarded at a later frame by the relay, this delays the BW allocations for data.

- The total increase in delay is not as significant as the total power consumption savings achieved by both mechanisms
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WiMAX Capacity Planning Studies using OPNET

- Single BS capacity estimation case
  - Possible inputs:
    - Minimum QoS requirements of a user
      - Maximum tolerable delay, minimum guaranteed bit-rate
    - Typical average traffic pattern of a user
      - Standard/custom applications
      - ACE traces
  - Design choices:
    - Mapping the traffic to an appropriate service flow
      - BE, nrtPS, rtPS, ertPS, UGS
    - Flexible admission control
      - Overbooking, underbooking
  - Possible outputs:
    - Maximum number of admissible users
    - Amount of frame utilization for a given number of users
Using Admission Control Report in Capacity Planning Studies

- Admission control report provides raw capacity estimate
  - Collected on each BS (collected by default)
  - Provides a summary of admitted connections with overheads, MCS, etc.
  - Available from View Results/DES Run Tables menu
Using WiMAX Statistics in Capacity Planning Studies

- More granularity, dynamic information
  - Frame usage statistics, WiMAX global statistics
    - Data Dropped (bits/sec)
    - Data Dropped (packets/sec)
    - Delay (sec)
    - Load (bits/sec)
    - Load (packets/sec)
    - Throughput (bits/sec)
    - Throughput (packets/sec)
    - Traffic Received (bits/sec)
    - Traffic Received (packets/sec)
    - Traffic Sent (bits/sec)
    - Traffic Sent (packets/sec)
  - Monitor system frame utilization
  - Analyze the impact of overheads and allocation/rectangulation wastage on UL/DL subframe capacity
  - Understand the impact of MAP usage on DL subframe capacity
Case Study: Usage of Statistics to Analyze Channel Utilization

- Many users spatially distributed with typical best effort traffic profile
- MCS assigned according to distance from the BS
- System performance measured in terms of throughput, frame usage, grant allocation, rectangulation wastage etc.
Case Study: Usage of Statistics to Analyze Channel Utilization (cont.)

- Load versus throughput statistics show that at around 300 users, WiMAX network starts getting congested
- Delays start increasing at around 300 users
UL Channel utilization statistics show that UL is not overloaded; the maximum utilization is around 75% only

DL channel utilization statistics show that DL is close to full (> 90%) and is the reason for congestion
Case Study: Usage of Statistics to Analyze Channel Utilization (cont.)

- **Breakup of DL subframe statistics**
  - As number of users increase, available subframe capacity decreases since MAP takes more space
  - The rest of the DL subframe is consumed in rectangulation wastage
  - The effect of headers and allocation wastage is minimal
Case Study: Results

- Can accommodate up to 300 users with minimal impact to applications
- Plan for 17-20% overheads
- Plan for UL and DL separately
Effect of Multilevel ertPS Allocations for Cell Capacity

- Multiple allocation sizes for the granted ertPS resources
  - ertPS user may use more or less capacity at its request
  - Allows other scheduling types (e.g. BE) to use resources when those are idle
  - Still the ertPS user may obtain full resources as soon as needed

- Configurable in the “Service Class Definition” (WiMAX Config)
  - The difference between “Maximum Sustained Traffic Rate” and “Minimum Reserved Traffic Rate” is divided by four in order to find the allocation step size
  - Setting those attributes to the same value forces a “two” level ertPS allocation: zero (with CQI) and maximum
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Documentation References

- **IEEE Standards**
  - IEEE 802.16-2004
  - IEEE 802.16e-2005
  - IEEE 802.16j-06/026r3

- **WiMAX Forum** (www.wimaxforum.org/technology/documents)
  - “WiMAX Forum Mobile System Profile, Version 1.0”
  - “WiMAX Forum Network Architecture, Version 1.2”
  - WiMAX Forum whitepapers (*may require membership to access*)
    - “WiMAX System Evaluation Methodology Version 2.01”
    - “Mobile WiMAX – Part II: A Comparative Analysis”, 2006

- **Other**
  - “Guidelines for evaluation of Radio Transmission Technologies for IMT-2000”
    - Recommendation ITU-R M.1225,
  - “Channel Models for Fixed Wireless Applications”
    - V. Erceg, K.V.S. Hari, M.S. Smith, D.S. Baum et al, Contribution IEEE 802.16a-03/01, Jun. 2003,
Related OPNETWORK Sessions

- 1566 Customer Presentations: WiMAX Wireless Networks
- 1581 Understanding LTE Model Internals and Interfaces
- 1582 Planning Tactical Mobile Network Deployments
- 1500 Customer Presentations: Wireless Local Area Networks
- 1558 Customer Presentations: Wireless Ad Hoc and Wireless Personal Area Networks
- 1530 Modeling Custom Wireless Effects — Introduction
- 1580 Modeling Custom Wireless Effects — Advanced
Take-Away Points

- OPNET’s WiMAX models can be used to estimate system configuration and settings to define baselines for actual deployments

- Different types of studies can be performed
  - Capacity planning studies
  - Device and protocol design
  - Application impact analysis for different WiMAX system configurations
  - Technology/protocol integration tests
Appendix

- Appendix A
  - Acronyms

- Appendix B
  - OPNET’s Mobile WiMAX Solution

- Appendix C
  - Application Response Analysis in OPNET: Use of ACE

- Appendix D
  - Use of OPNET Modeler to Study Technology Integration

- Appendix E
  - Use of SITL to Perform Real Applications/Protocol Testing
Appendix A
Acronym List

- 3GPP: 3rd Generation Partnership Project (3GPP)
- ACE: Application Characterization Environment
- AMC: Adaptive Modulation And Coding
- ARQ: Automatic Repeat-Request
- ASN: Access Service Network
- BE: Best Effort
- BLER: Block Error Rate
- BS: Base Station
- DL: Downlink
- DOCSIS: Data Over Cable Service Interface Specification
- ertPS: Enhanced Real Time Polling Service
- HARQ: Hybrid Automatic Retransmission Request
- IEEE: Institute of Electrical and Electronics Engineers
- ITU: International Telecommunication Union
- LTE: Long term Evolution
Appendix A
Acronym List (cont.)

- MANET: Mobile Ad-hoc Networks
- MDRR: Modified Deficit Round Robin
- MS: Mobile Station
- nrtPS: Non-Real Time Polling Service
- OFDMA: Orthogonal Frequency Division Multiple Access
- PS: Polling Service (also see: nrtPS, rtPS)
- QoS: Quality of Service
- RS: Relay Station
- rtPS: Real Time Polling Service
- SNR: Signal to Noise Ratio
- SITL: System in the Loop
- SS: Subscriber Station
- UGS: Unsolicited Grant Service
- UL: Uplink
- UMTS: Universal Mobile Telecommunications System
- WiMAX: Worldwide Interoperability for Microwave Access
OPNET’s Mobile WiMAX Solution

- OPNET implements following modules for mobile WiMAX
  - Ranging
    - MS performs network entry with a BS
  - Scanning
    - MS scans for best target BS among multiple base stations
  - Neighbor advertisements
    - Each BS advertises its neighbors to all MSes within its cell
  - L2/L3 handover
    - Mobile IP (L3 only): Suffers from high delays, not preferred
    - ASN gateway configuration: Preferred method for handover
      - ASN reduces handoff delays due to anchoring
      - ASN achieves integrated L2/L3 handover
Appendix B
ASN Gateway Concept

- Specify ASN-GW IP address
- Create GRE tunnel to ASN-GW

Create GRE tunnel to each BS

IP fwd table (add these entries as indicated by BSx)
A.1, tunnel_1
A.2, tunnel_2
A.3, tunnel_3
Appendix B
Configuring ASN Gateway in OPNET

Specify ASN address on each BS
Configure GRE tunnels between each BS and ASN gateway
Appendix C
Application Response Analysis in OPNET: Use of ACE

- Medium sized enterprise network with WiMAX access network
- ACE packet capture is replayed between mobile nodes and servers in the backbone
- Application response time analysis, network migration, capacity analysis conducted
Appendix D
Use of OPNET Modeler to Study Technology Integration

- Scenario description
  - Mobiles are connected to WLAN hotspots
  - WiMAX access links provide connectivity to the core network

- Open model source code can be used to develop further examples
Appendix E
Use of SITL to Perform Real Applications/Protocol Testing

- SITL: System in the loop
  - SITL gateway node connects simulations to the real world
  - Layer-2 Ethernet packets can be translated to and fro

- Example 1: Real applications (end-to-end) testing
  - Visualize live application performance and actual end-user experience
  - Design and test new applications in a simulated WiMAX infrastructure
Example 2: Protocol testing
- Design new protocols or customize existing protocols
- Verify and validate the behavior of protocols in real network hardware

Checking WiMAX interoperability with IP infrastructure – for example, check if routing messages are exchanged over WiMAX network