

# Wireless Network Testing and Evaluation using Real-time Emulation

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## **Abstract**

Full scale physical testbeds used in network testing and evaluation of wireless network systems have certain limitations that do not allow testers and evaluators to obtain results in an easy way. Considerable time, effort and resource costs have to be invested to obtain comprehensive performance results on such testbeds.

This paper proposes an alternative approach to network testing and evaluation based on the real – time emulation capability of the QualNet simulator. It provides an overview of the approach and provides illustrations to outline how a testbed based on real-time emulation can be set up. The effectiveness of such a testbed is highlighted by a use case, where performance evaluation results are presented for a wireless ad hoc network which is to be deployed over a range of scenarios.

## **1 Introduction**

Prior to deployment of any wireless network system, comprehensive testing and evaluation must be performed with actual prototype hardware. Full-scale physical testbeds are usually employed by network testers to do such an evaluation. Applications that will run on the deployed network are run on the physical testbed and the performance of the applications is evaluated over numerous trial and testing cycles.

Various studies and research groups have worked on creating full scale physical testbeds along with tools that facilitate network testing and evaluation on the testbed. Examples of such testbeds include CMU-DSR (Maltz et al. 1999) ROOFNET (Chambers 2002), APE (Lunndgren et al. 2002), TAP (Karrer et al. 2003) and ORBIT (Raychaudhuri et al. 2005). Even though full scale physical testbeds are the next best thing to a fully deployed network in terms of their ability to unearth faults in the network, network testers and evaluators face quite a few problems with them:

1. In full scale physical testbeds it is difficult to represent the intended deployment environment of the wireless network system faithfully, hence the performance results obtained from the physical testbed may not apply to the deployed network.

2. Rapid experimentation is not usually feasible due to the large size of the testbed and the complexity of restarting experiments after making the desired changes in hardware or topology.

3. Repeatability in tests is difficult to achieve, since this requires perfect coordination and synchronization while conducting the repeated trials.

4. It is a tedious task to setup a variety of spatial layouts since this requires considerable time and effort.

5. Rarely is a full-scale testbed able to be used for a variety of network systems. Most full scale testbeds are designed for a specific set of project requirements and they cannot be reused outside of their designed scope. Only few testbeds cater to wide user communities.

6. Scalability tests on full scale physical testbeds require large number of hardware units along with considerable time and resources which translates to costs that may be 100x or even 1000x higher to conduct such tests using physical components versus simulated or emulated components.

Miniaturized physical testbeds( e.g. Sarnoff (Kaba et al. 2001), EWANT (Sanghani et al. 2003), Physical Emulation Platform (Judd et al. 2003) and MiNT(De et al. 2005) ) attempt to introduce desired features of controlled testing and rapid experimentation by artificially manipulating the RF signal emanating from the radios using attenuators and Digital Signal Processors (DSPs) to shrink the full scale physical testbed to a compact and manageable size. These testbeds however face problems in ensuring that there is no radio frequency (RF) signal leakage from the attenuators/connectors and adequate shielding is done to disallow the radios to achieve their natural radio range. Even a small amount of RF leakage may induce large errors in the testing and evaluation on such testbeds.

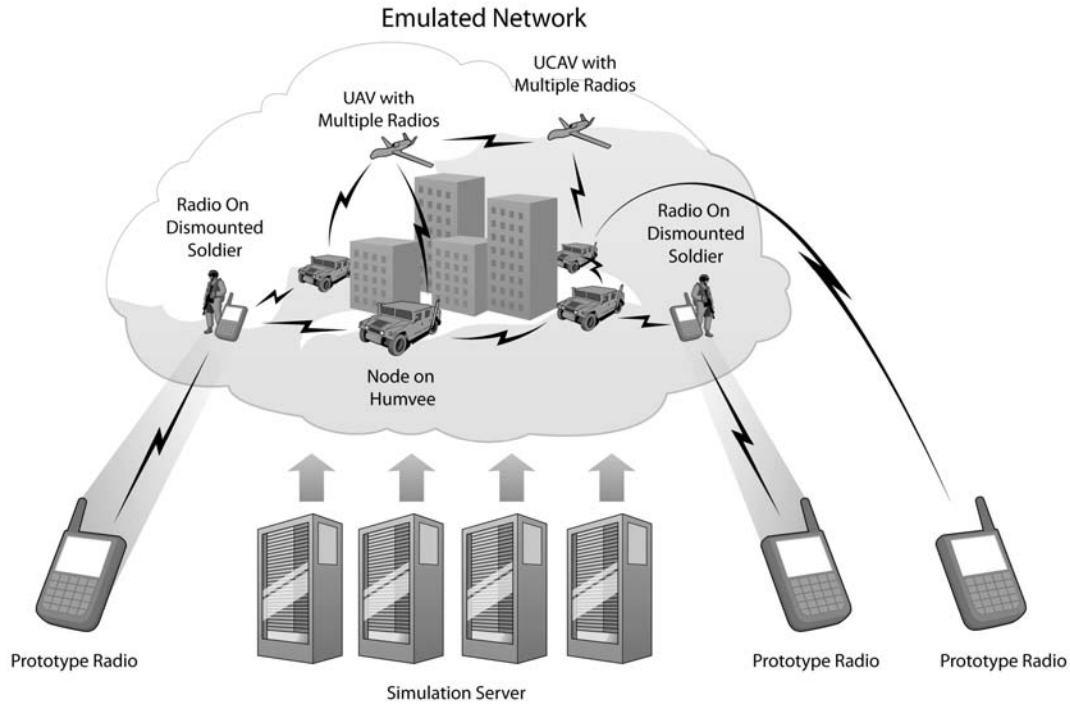
Network designers use simulation as a tool to model and analyze very complex systems with varying degrees of abstraction (or simplification vs. the real system). However simulation isn't always viewed as valuable or viable tool for comprehensive performance testing and evaluation, as there are vast differences in model fidelities and levels of abstraction between the actual system and the simulated model. In simulation, the model is often simplified or abstracted, which can mask the very phenomena (e.g., adaptive behavior) that are captured during testing on physical testbeds. Emulation, on the other hand, is achieved when a network simulation performs exactly the same as the physical system. Emulation is the highest fidelity model of the physical system and hence can serve as an acceptable replacement for the system for test and evaluation purposes.

This article describes an alternative approach for network evaluation and testing based on the concept of real-time emulation. This approach can provide the benefits of full scale physical testbeds—real data on network system performance— while at the same time enabling controlled testing, rapid experimentation and repeatability —the common benefits of simulation. Real-time emulation provides these benefits all at a lower cost as compared to full scale physical testbeds

## **2 Network Test and Evaluation with Real-time Emulation**

Real-time emulation uses a simulator to run high fidelity emulation models of protocols and applications in real-time. All aspects of the network are emulated with the highest fidelity except the physical hardware, environment effects and mobility, which are simulated. Examples of testbeds that employ real-time emulation are WHYNET (Ji et al. 2006) and TWINE (Zhou et al. 2006). These testbeds employ distributed emulations where the nodes run an emulation stack for the MAC and physical layers and coordinate propagation effects and node mobility in a distributed manner. For testing custom prototype hardware, this means modifying the prototype software to include the emulation engine. The approach proposed in this article does not involve

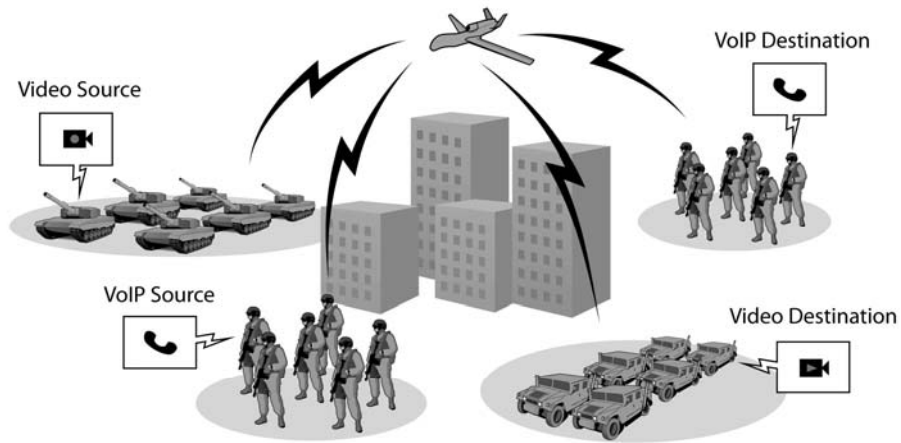
modification of the prototype hardware or software, and uses the QualNet simulator (Scalable 2006) to emulate node functionality across all layers of the protocol stack and to simulate physical environmental effects and node mobility.



**Figure 1: Overview of the Real-time Emulation Approach**

Figure 1 provides an overview of the real-time emulation based approach. . In this framework, it is possible to use a few physical devices (prototypes) while emulating the rest of the scenario using QualNet. The emulated network in QualNet interacts with the physical devices to form a hybrid network that consists of an emulated component and the real world component. As illustrated in Figure 1, the simulator can simulate mobility, add in desired terrain and apply realistic wireless environmental effects to the emulated network. Thus the network tester can create any target deployment scenario in the simulator and evaluate the performance of the applications running on the real world prototype nodes in the target scenario.

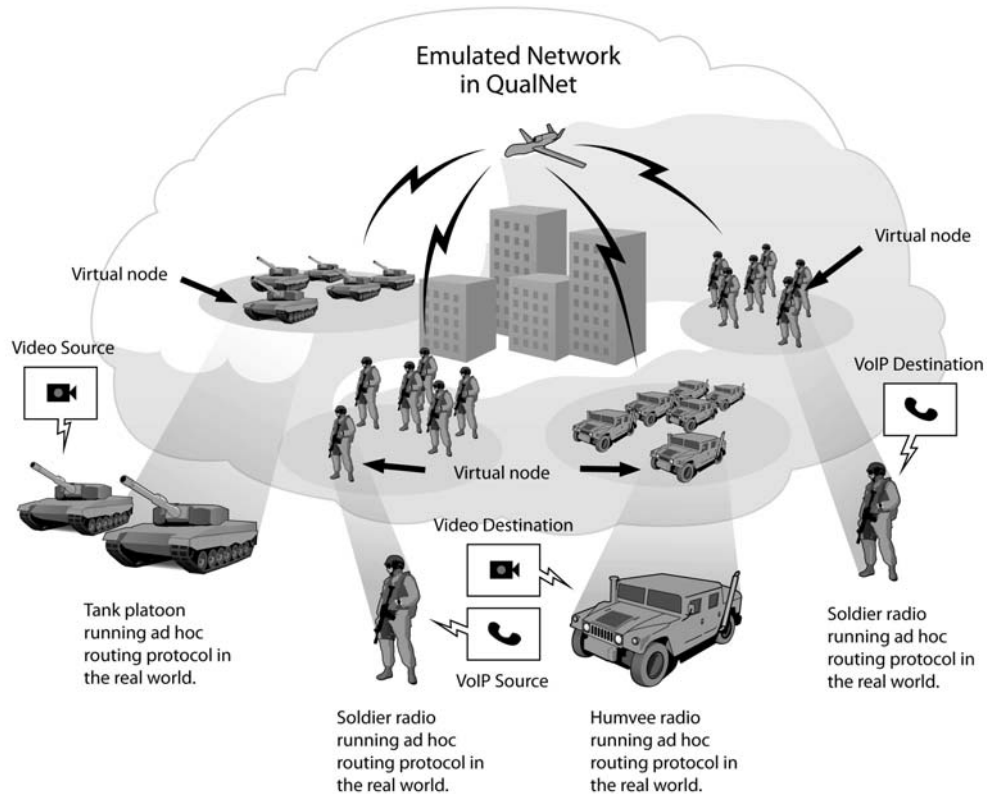
Small-scale physical testbeds facilitate validation of protocol and application design. As the physical testbeds are scaled up from a few prototypes to a few dozen, tests may reveal a problem with the application or protocols when the network is operating in a hostile environment, such as an urban wireless network with a lot of interference. Instead of manufacturing a large number of prototype hardware required for these scaling tests, real-time emulation based testing requires the designer to create only a few prototypes running the protocol on real hardware. Network designers can now create large scale networks with few prototype nodes and numerous emulation nodes and evaluate protocol and application performance in various environments. The design flaws due to issues in protocol and hardware can thus be discovered before mass prototyping and deployment.



**Figure 2: Target deployment to be tested**

To further illustrate the approach of testing and evaluation using real-time emulation, consider a situation where the performances of applications like streaming video and voice over IP (VoIP) are to be evaluated on an ad hoc wireless network formed between groups of next generation radios. These radios are to be deployed in an urban scenario consisting of dismounted soldier divisions, tank divisions and a humvee patrol interconnected through a low flying UAV as indicated in Figure 2.

One approach to comprehensively evaluate the performance is to construct a full scale testbed with the required number of radios and place them in an urban area with the soldiers, tanks and the UAV and then run the performance evaluation tests. The cost estimate for this is the sum of the costs of the actual hardware radio prototypes, the equipment cost for the tanks, humvees and UAV along with the human cost in terms of setting up mobility patterns and directing the full fledged exercise. One must also live with the limitation of not being able to perform repeatable and controlled tests and rapid experimentation among the other drawbacks faced in a full scale testbed.



**Figure 3 : Target scenario evaluation using real-time emulation**

Using the proposed real-time emulation approach, such a test can be carried out in a simple but effective manner. This involves the use of QualNet to emulate one part of the target network as indicated in Figure 3 with some part of the target network actually realized by prototype radios. The proportion of nodes realized by prototype radios can vary based on the stage of prototype design: in preliminary stages, the target network can consist of very few prototype radios and a majority of emulated nodes, whereas in advanced stages before mass deployment, prototype radios can be a major part of the target network. In this example, the assumption is that this is a preliminary stage, hence only the video source radio, a router radio in the tank platoon, video destination radio, VoIP source radio and VoIP destination radio are set up as actual prototype radios, while the rest of the network nodes exist as emulations in the QualNet simulator. The prototype node that directly interacts with nodes in the emulated network has representation in the emulated network as a virtual node. These virtual nodes act as gateways between the real and emulated worlds.

The real world prototype network and the QualNet emulated network seamlessly communicate using the real-time emulation capability of QualNet and its hardware-in-the-loop interface; the prototype node does not realize that it is communicating with an emulated node and vice-versa. The routing protocol daemons running on the prototype radios exchange routing protocol information packets with the emulated network running in the simulation. Routing updates due to topology changes caused due to mobility and physical environment effects in the simulation are

propagated to the prototype network and are reflected in the prototype routers' routing tables. The prototype video source node runs the streaming video application and the effects of the target network can be observed on the video quality at the destination prototype node. Similarly, the tester can make a phone call through the prototype node acting as the VoIP source and the voice quality of the call at the VoIP destination node can be assessed as desired changes occur in the target network in terms of mobility based on QualNet mobility scripts. The tester can very easily modify mobility patterns and even change the emulated network settings to assess the effect on the applications' performance. This allows for the rapid experimentation, controlled mobility and repeatability in testing which are much desired capabilities for comprehensive network testing and evaluation.

## 2.1 Simulator Requirements for supporting Real-time Emulation

A network simulator must satisfy a number of stringent requirements to support real-time emulation. These requirements are non-trivial, since they heavily depend on the architecture of the simulator and the fidelity of the protocol models in the simulator. The requirements can be summarized as follows:

### 1. Protocol Stack Emulation

To support real-time emulation and interaction with physical devices, it is essential that the simulator include protocol emulations. In other words, the fidelity of the protocol representation in the simulator must be identical to that of the protocol implementation on a physical device. For protocols based on standards (e.g. Request for Comments (RFCs) or Internet drafts if the standard is not yet formed) the high-fidelity models must be 100% compliant with the standards. This includes full compliance with the standard for the packet format for every protocol as well as compliance with the protocol logic as indicated in the standard. This is imperative, as any abstractions in the packet format or the protocol logic in the simulator model will lead to errors and inconsistencies when the emulated network interacts with the physical prototype network, eventually affecting the test results.

### 2. Simulator Execution Time Synchronization with Real-time

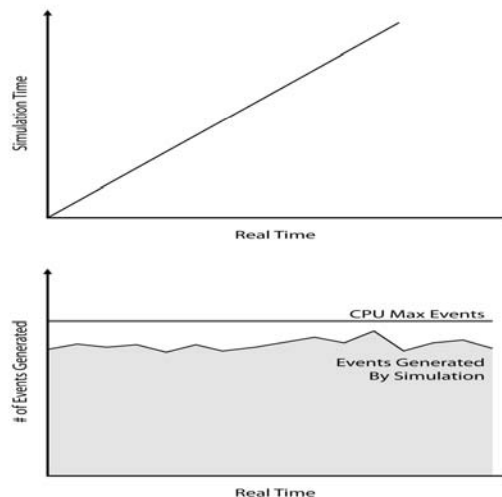
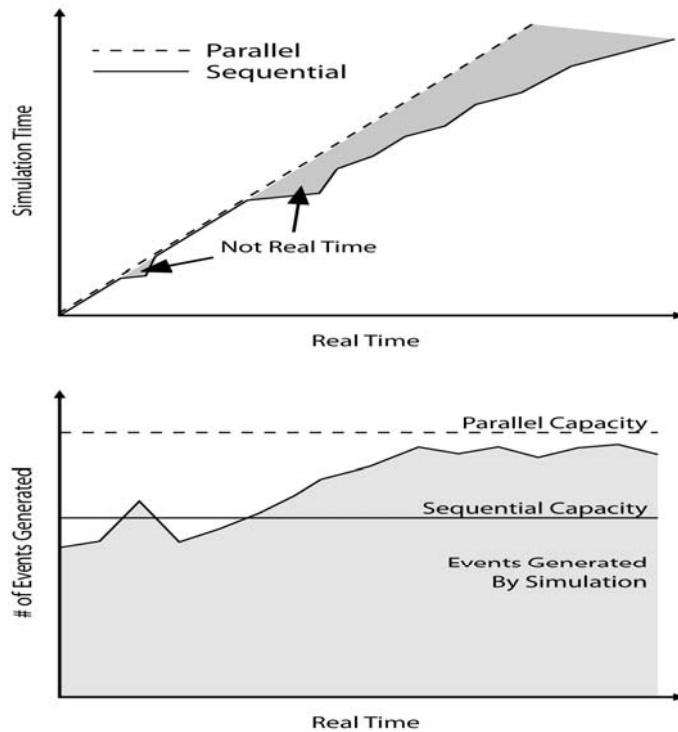


Figure 4: Ideal Simulation Time vs Clock Time Graph for Real-time Emulation

The simulation architecture must ensure that the simulation execution time is in synchronization with real-time (clock time), so that the concept of time is the same for both the emulated network nodes and the physical prototype nodes. This requires a simulation architecture that can efficiently process events generated by the high fidelity models to enable the advancement of simulation time clock on par with clock time. This boils down to the event processing capacity of the simulator. The ideal simulator should have the simulation time vs. real-time graph as shown in Figure 4, where the simulation time can continuously keep up with real (or physical) time. When real-time execution cannot be achieved, the simulator should flag all events and provide an indication during the execution. In the case of scenarios that involve a large number of emulated radios, perhaps numbering in the hundreds or thousands, the number of events generated with high fidelity protocol models is enormous. A simulator running on a single processor will typically be overwhelmed in such a case and as illustrated in Figure 5, will not be able to satisfy the constraints of real-time emulation on a continuing basis. Under these conditions, the simulation execution time will not match up to real-time speed and the network operation shall report errors. The simulator hence must support parallel execution on multiple processors or multiple computing nodes to increase its capacity to process events. With such support available, the simulator can then easily support scalability in emulated nodes with real-time operation as indicated in Figure 5.



**Figure 5: Parallel Execution Capability of QualNet Mitigates Scalability Issues**

### 3. Realistic Physical Environmental Effects

The simulated physical environmental effects have to be modeled at high fidelity in order to appropriately include effects due to fading, terrain, and weather among other environmental

effects. This is very important for a simulator since significant abstractions of these effects will introduce errors in testing and evaluation.

#### 4. Hardware-in-the-loop Interface

The simulator should have a hardware-in-the-loop capability to enable interfacing the physical network nodes with the emulated network running in the simulator construct. This hardware in the loop interface must have the capability to inject packets from the physical network nodes into the simulation and vice versa preserving the packet format and contents of the packets as the packets move from one domain to the other.

## 2.2 Real-time Emulation Support in QualNet

This section enumerates how the QualNet simulator satisfies the requirements for supporting real-time emulation.

1. **High Fidelity Models:** QualNet has an extensive set of high fidelity models ranging from the physical layer all the way to the application layer to enable modeling a variety of emulated networks. In addition, QualNet’s architecture supports integrating real world application codebases so that emulations of desired real world applications can be run in QualNet. Table 1 lists some of the high fidelity models available in Qualnet.

**Table 1: High Fidelity Protocol Models in QualNet**

Type of Model	Model Name
<b>Applications</b>	FTP, Telnet, Http, VoIP,
<b>Transport</b>	UDP, TCP, RTP
<b>Routing</b>	AODV,DSR, DYMO, Fisheye, IARP, OSPFv2, OSPFv3, IERP, RIP, RIPng, LANMAR,LAR,OLSR, OLSRv2, STAR, ZRP, BGP, MAODV,ODMRP
<b>MAC</b>	802.11, WiMAX, CSMA, TDMA
<b>Physical</b>	802.3 / Wired Bus, Satellite, IEEE 802.11a/b/g/e, WiMAX 802.16, Point-to-point Link, Switched Ethernet, Cellular Networks
<b>Antenna</b>	Omni-directional Antenna, Switched Beam Antenna, Steerable Beam Antenna, Custom Antenna
<b>Modulation</b>	BPSK, DPSK,DQPSK, GMSK, Turbo Coding / FEC, OFDM

2. **Simulator Execution Time Synchronization with Real-time:** QualNet supports parallel execution. This means a large number of events that are generated in scenarios containing hundreds of emulated nodes running high fidelity protocol models are processed in an efficient manner by running QualNet on dual core, quad-core processor machines or on parallel computing clusters. The ability of QualNet to process these events such that the clock time required to simulate every event is less than some a priori bound is termed as transactional real-time simulation (Bagrodia et al. 2006). This ability along with QualNet’s

parallel execution capability ensures that simulation time will keep up with clock time all through the simulation for such scenarios.

3. **Realistic Physical Environmental Effects:** QualNet accurately models a range of physical environmental effects as indicated in Table 2. QualNet also has the capability to include detailed terrain models in the simulation. A study done by Hsu et al. (Hsu et al. 2003) compared performance results from a real world ad hoc wireless network deployment to the results obtained from a model of the network in QualNet and concluded that QualNet modeled the deployment scenario with remarkable accuracy, thus validating the ability of QualNet to model realistic wireless environmental effects.

**Table 2: Simulation Models for Wireless Environmental Effects in QualNet**

<b>Path Loss</b>	Free Space, 2-Ray, Urban Propagation models, Weather effects
<b>Shadowing</b>	Lognormal
<b>Fading</b>	Ricean, Rayleigh
<b>Terrain</b>	ITM, DEM, DTED, TIREM, CTDB7, CTDB8

4. **Hardware-in-the-loop Interface:** QualNet has an efficient hardware in the loop interface to couple the physical network and the emulated network in the simulation. This interface manages synchronization between real-time and simulation time and handles packet insertion from the real network into the simulation and vice versa. The interface ensures that that the packet formats and byte orders in the headers match the domain in which it is being inserted.

### 3 Use Case: Performance Evaluation of a Wireless Ad Hoc Network

This section demonstrates a use case involving real-time emulation with QualNet for performance evaluation of applications running on prototype hardware over various scenarios.

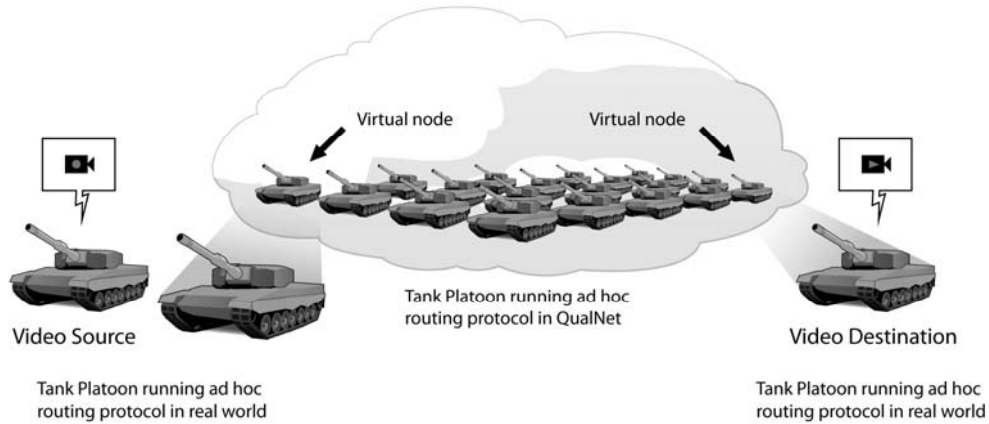


**Figure 6: Use Case Scenario**

The target network to be evaluated is a wireless ad hoc network formed within a group of 23 tanks as shown in Figure 6, each containing a radio running the Optimized Link State Routing protocol (OLSR) (Clausen et al. 2003). The performance of the network is to be evaluated by running a streaming video application between the video source and video destination nodes and also quantified by measuring metrics for throughput, end-to-end delay, OLSR routing overhead,

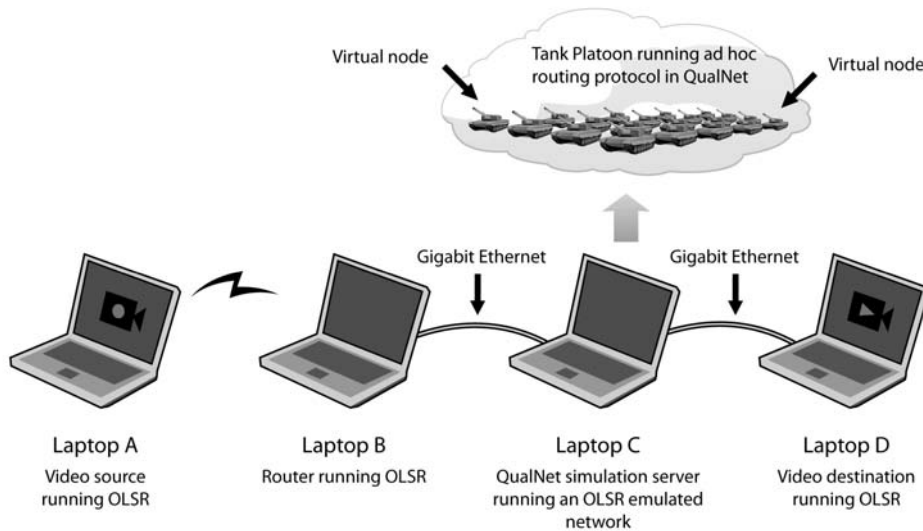
and network convergence time. This performance evaluation is to be done under the following scenarios:

1. Static scenario in rural environment
2. Mobile scenario in rural environment
3. Static scenario in rural environment with interfering network traffic
4. Static scenario in an urban environment



**Figure 7: Real and Emulated Components of Scenario**

We divide the target scenario into real and emulated components as indicated in Figure 7 using the real-time emulation approach.



**Figure 8: Target scenario setup in a laboratory environment**

The scenario is then set up in a laboratory environment indicated in Figure 8 as follows:

- The video source, one intermediate router node and destination nodes are set up as prototype nodes as Laptops A, B and D, respectively which run the OLSR routing protocol implementation (OLSR 2006) on Redhat Linux.
- The rest of the network is emulated by the QualNet simulation server running on Laptop C. Laptops B and D have representation in the emulated network as virtual nodes.

### 3.1 Configuration of Emulated Scenarios

- **Static Scenario in Rural Environment:** This is the base scenario that is modified to create the other three scenarios. To make this case study generalized, we use radios based on 802.11b. They can be readily replaced by DoD specific military radio waveform emulations like Link-16, Soldier Radio Waveform (SRW), Enhanced Position Locating Reporting System (EPLRS) and Single Channel Ground and Airborne Radio System (SINCGARS). The radio and protocol settings for the base scenario are summarized in Table 3.

**Table 3: Radio and Routing Protocol Settings for the Base Scenario**

Radio Data Rate	11 Mbps
Radio Transmit Power	15.0 dBm
Radio Receiver Sensitivity	-80.0 dBm
OLSR Hello Interval	2 seconds
OLSR Refresh Interval	2 seconds

- **Mobile Scenario:** QualNet’s random waypoint model is used to generate mobility for the mobile scenario with the tanks moving at a maximum speed of 5m/s.
- **Static scenario with interfering network traffic:** The interfering traffic in the network is set up using traffic generators in QualNet initiating Constant Bit Rate (CBR) flows within the emulated network. The data rate of the interfering traffic is 1.3Mbps.
- **Static scenario in an urban environment:** The urban scenario is set up using the available building and terrain information of the scenario in CTDB8 format and employing urban propagation models to simulate urban environmental effects in the scenario.

### 3.2 Performance Evaluation details

- The VideoLAN (VLC) media player (VideoLAN 2006) is run on Laptop A as the video streaming application and a VLC client runs on Laptop D to playback the received video. The video is streamed at 1.4 Mbps. The video quality at the destination is observed for each scenario.
- The Iperf (Tirumala et al. 2003) tool is run on Laptop A and Laptop D to measure throughput and end-to-end delay of the network. The input load into the network is 8 Mbps and the average throughput and average end-to-end delay at the destination is measured over 30 trial runs for each scenario.
- OLSR routing overhead is measured in terms of number of Topology Control Messages sent in the network using QualNet’s statistics tool.

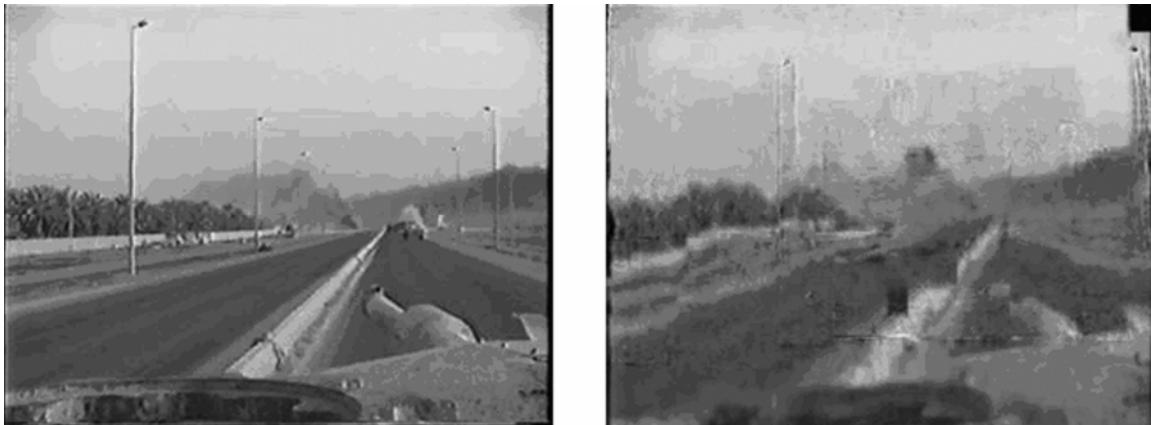
- The network convergence time is measured by noting the time required by Laptop A to obtain a route to Laptop D after the QualNet simulation has been started.

### 3.3 Results

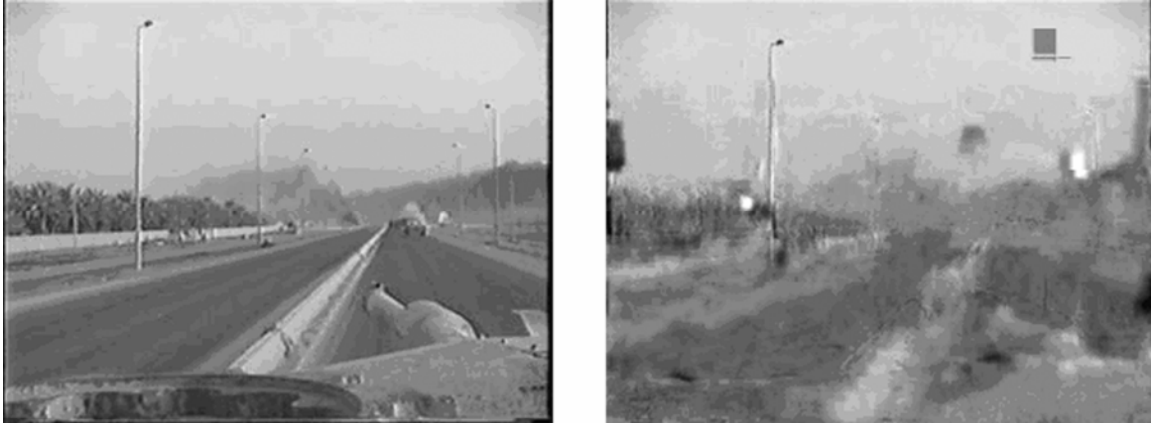
Performance evaluation results for the target scenario are presented in this section. To capture the results for the performance of the streaming video application, snapshots of the streaming video generated at the source node (Laptop A) and received at the destination node (Laptop D) are taken. These snapshots are shown in Figure 9 to Figure 12.



**Figure 9: Snapshot of video at source (left) and video received at destination (right) for the Static Network in a Rural Environment**



**Figure 10: Snapshot of video at source (left) and video received at destination (right) for the Mobile Network in a Rural Environment**



**Figure 11: Snapshot of video at source (left) and video received at destination (right) for the Static Network in a Rural Environment with Interfering Network Traffic**



**Figure 12: Snapshot of video at source (left) and video received at destination (right) for Static Network in an Urban Environment**

**Table 4: Quantitative Performance Metrics Measured**

Scenario	Average End-to-end Throughput (Mbps)	Average End-to-end Delay (seconds)	OLSR TC control packets generated in the network	Average Network Convergence Time (seconds)
Static Network in Rural Environment	1.84	0.328	1086	7
Mobile Network in Rural Environment	0.85	0.482	1486	7.8
Static Network in Rural Environment with Interfering Network traffic	1.4	0.336	1302	7.5
Static Network in Urban Environment	1.61	0.325	1203	7.3

Table 4 details the quantitative performance metrics collected for the scenarios: From the results it can be concluded that from a throughput perspective, the target network's performance slightly degrades as compared to the base scenario by 12% when the target network is deployed in an urban environment. Interference from background traffic degrades the performance by about 24% as compared to the base scenario. A mobile scenario leads to a drop in performance of 54% as compared to the base scenario. The snapshots of the video received at the destination node for each of the scenarios also reflect the trend observed in the table.

Thus, comprehensive performance evaluation and testing can be done in a laboratory environment using the real-time emulation based approach.

#### 4 Conclusions and Future work

It can be concluded from Sections 2 and 3 that the real-emulation approach using QualNet offers a viable alternative to full scale physical testbeds for network testing and evaluation. To emphasize this point, we list the desired requirements for an ideal network testing and evaluation testbed as indicated in the study done by De et al. (De et al. 2005) along with an explanation of how the real-time emulation based testbed satisfies them.

1. **Low Cost:** The testbed requires a simulation server running QualNet along with a few prototype nodes. The prototypes are connected to the simulation server using wired or wireless network switches. This is quite inexpensive as compared to the cost of a full scale testbed with large number of nodes along with the additional equipment to coordinate tests on the testbed.
2. **Ease of Management:** Given that only a simulation server and a few prototype nodes are required to set up a testbed that can evaluate scenarios with hundreds of nodes, the management overhead of the testbed is far lower than a full scale physical testbed evaluating the same scenarios.
3. **Resource Sharing:** Any network tester can construct the testbed using a computer running the QualNet simulator and the prototype network to be evaluated. Thus there are limited or no resource sharing constraints since the resource requirements for setting up the testbed are minimal.
4. **Experimental control (topology configuration, application configuration):** The topology configuration for the emulated network can be easily achieved by the use of QualNet's scenario generator tools. Mobility patterns of the emulated nodes are simple to set up via QualNet's mobility generators that include random mobility, group mobility as well as scripted mobility. The same applies to application configuration, where desired traffic patterns can be created between emulated nodes using QualNet's application generators or between prototype nodes using real applications. The QualNet architecture also enables running emulations of real applications on the emulated nodes; hence it is easy to set up application flows from prototype nodes to emulated nodes and vice versa.
5. **Analysis ability:** QualNet's analysis tools can be used to analyze overall network performance. Third party analysis tools like Iperf can also be employed to obtain performance results by running them on the prototype network.
6. **Broad Applicability:** The applicability of the testbed can be extended beyond performance evaluation and testing of the target network. Interoperability of existing networks and applications with future networks/applications can be readily investigated using the testbed by having the future networks/application models running as emulations in the QualNet scenario and having the prototype nodes interact with them.

7. **Repeatability:** The testbed enables the network evaluator to carry out controlled tests using the desired protocol implementation with full control over the mobility of the emulated nodes via QualNet's scripted mobility tool. Thus repeatability in the trials can be achieved.

Work is ongoing to develop more advanced analysis tools in QualNet to support troubleshooting along with network testing and evaluation and allow for human- in-the-loop interaction to enable evaluation of 'what if' scenarios using the real-time emulation based testbed.

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## 6 List of References

Bagrodia R., Tang K., Goldman S. and Kumar D., 2006. "An Accurate Scalable Communication Effects Server for the FCS System of Systems Simulation Environment," Proceedings of the 2006 Winter Simulation Conference.

Chambers B., June 2002. "The Grid Roofnet: A Rooftop Ad Hoc Wireless Network," MIT Master's thesis.

Clausen T., Jacquet P., 2003. Optimized Link State Routing Protocol (OLSR) RFC 3626. Available at <http://www.ietf.org/rfc/rfc3626.txt>

De P., et al, Oct. 2005. "Design Considerations for a Multihop Wireless Network Testbed," Communications Magazine, IEEE, pp. 102- 109

De P., Raniwala A., Sharma S., Chiueh T., 2005. "MiNT: a miniaturized network testbed for mobile wireless research," Proceedings of IEEE INFOCOM 2005.

Hsu J., Bhatia S., Takai M., Bagrodia R., 2003. "Performance of Mobile Ad Hoc Networking Routing Protocols in Realistic Scenarios," Proceedings of IEEE MILCOM 2003.

Ji Z., Marina M., Varshney M., Xu Z., Yang Y., Zhou J. and Bagrodia R., January 2006. "WHYNET: A Hybrid Testbed for Large-Scale, Heterogeneous and Adaptive Wireless Networks," UCLA Computer Science Department Technical Report CSD-TR060002.

Judd G. and Steenkiste P., 2003. "Repeatable and Realistic Wireless Experimentation through Physical Emulation," Proceedings of HotNets 2003.

Kaba J. and Raichle D., 2001. "Testbed on a Desktop: Strategies and Techniques to Support Multihop MANET Routing Protocol Development," Proceedings of ACM MobiHoc 2001.

Karrer R., Sabharwal A., and Knightly E., 2003. "Enabling Large-Scale Wireless Broadband: The Case for TAPs," Proceedings of Hotnets 2003.

Lunndgren H. et al. 2002., "A Large-Scale Testbed for Reproducible Ad Hoc Protocol Evaluations," Proceedings of IEEE WCNC 2002.

Maltz D., Broch J., and Johnson D., 1999. "Experiences Designing and Building a Multi-Hop Wireless Ad-Hoc Network Testbed," CMU Technical Report TR99-116.

OLSR Routing Protocol Implementation version 0.4.9. 2006. Available at <http://www.olsr.org>

Raychaudhuri D. et al. 2005., "Overview of the ORBIT Radio Grid Testbed for Evaluation of Next-Generation Wireless Network Protocols," Proceedings of IEEE WCNC 2005,

Sanghani S., Brown T., Bhandare S. and Doshi S., 2003. "EWANT: The Emulated Wireless Ad Hoc Network Testbed," Proceedings of IEEE WCNC 2003.

Scalable Network Technologies 2006. QualNet User Manual v 4.0., Culver City CA.  
<http://www.qualnet.com>

Tirumala A., Qin F., Dugan J., Ferguson J., Gibbs K., May 2005. Iperf Version 2.02, Available at <http://dast.nlanr.net/Projects/Iperf/>.

VideoLAN Project, 2006. VLC version 0.8.5. Available at <http://www.videolan.org/vlc/>

Zhou J., Ji Z. and Bagrodia R., 2006. "TWINE: A Hybrid Emulation Testbed for Wireless Networks and Applications", Proceedings of IEEE INFOCOM 2006.

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