INSC/Task6/DU/008

Interoperable Networks for Secure Communications

Task 6 Final Report

Document INSC-TASK6

This report documents the results/conclusions from Task 6 (Network Mobility) of the INSC Program, Phase 1.

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AMENDMENT HISTORY

Amendment	Description
1	Updated Appendix A re. IT Task 6 Documents
2	

INTRODUCTION

The Interoperable Networks for Secure Communications (INSC) project is an international collaborative activity between Canada, France, Germany, Italy, Norway, the Netherlands, the United Kingdom and the United States, with invited contributions from the NATO Consultation, Command and Control (C3) Agency. The objective of the project is to specify, implement, test, and demonstrate a common technical architecture for interoperable secure networks with mobility extension, using commercial technologies, products and solutions wherever possible.

The project is broken down into subtask elements. Subtask 6 is responsible for experimenting with and investigating solutions to better support network mobility. This document reports and summarizes the final results for the INSC Mobility Task, Task 6 (T6).

TECHNICAL OBJECTIVES AND APPROACH

Goals of Task 6 Testing and Demonstration

There are two fundamental technology areas targeted for testing and demonstration within Task 6: *infrastructure mobility* technology, and *edge node mobility* technology.

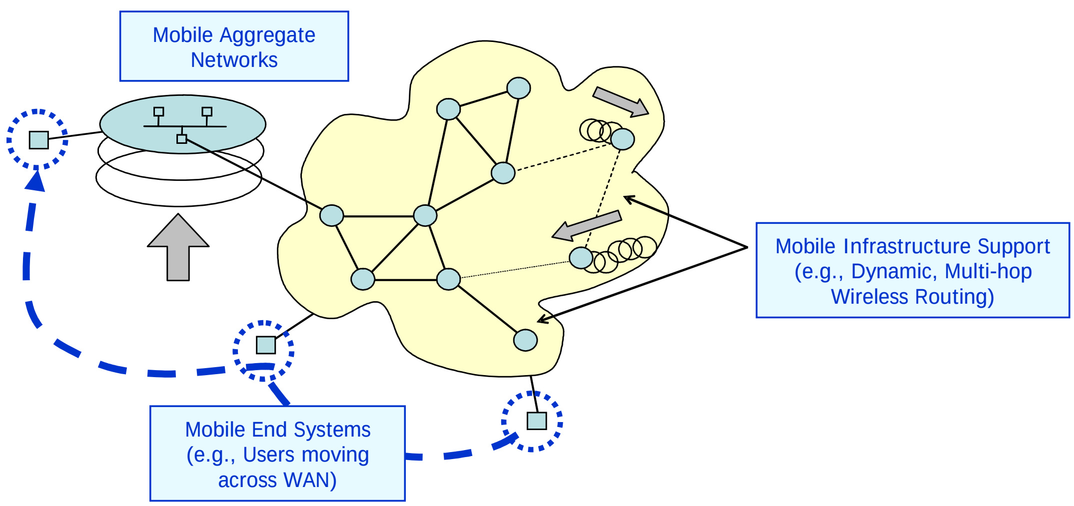

Figure 1: Architectural Mobility Variations

Figure 1 demonstrates the architectural variability involved in broad networking mobility problems and demonstrates how we roughly split these into edge system mobility and infrastructure mobility problem areas. At present mobile aggregate networks, possibly covered by networks in mobility (NEMO) technology, was not mature enough to examine but may be examined in follow-on efforts

Under this effort, T6 considered examination of the mobility of both end users and of portions of the networking infrastructure itself. In military applications, wireless network infrastructure nodes (e.g., routers) are often on the move in addition to, or in conjunction with, end users. Thus, infrastructure and local router nodes require adaptability in addition to the end users. From an INSC architectural standpoint, we envisioned different protocol mobility enhancements (e.g., end user and mobile infrastructure) both being deployed in a broader sense to solve various types of scenario-dependent and operational requirements [INSC1].

The T6 team split task investigations into infrastructure and edge system mobility problem areas. First, the present INSC mobility effort investigated and addressed mobile ad hoc network (MANET) routing technology alternatives [MC99]. The work area focused on the use of evolving IP-based MANET solutions to support mobile wireless nodes forming a dynamic localized infrastructure. This is a new evolving technology area within the Internet Standards and ultimately supports both Internet Protocol version 4 (IPv4) and version 6 (IPv6) operations. Second, the edge system mobility problem was examined through demonstration of evolving Mobile IPv6 (MIPv6) technology and potential hybrid variants [MIP03]. The edge system mobility demonstration supported coalition network nodes roaming among multiple network access facilities, while retaining their home-based IP addressability. T6 consideration was also given to autoconfiguring dynamic edge user nodes without requirements for global IP address identification and active session retention (e.g., DHCPv6 or IPv6 stateless autoconfiguration). Finally, there were additional optional T6 investigations aimed at examining the impact and performance of other issues within mobile network environments including Quality of Service (QoS) performance in mobile routing environments, MIPv6 control signaling and handoff issues, and MIPv6 operation within a MANET routing segment.

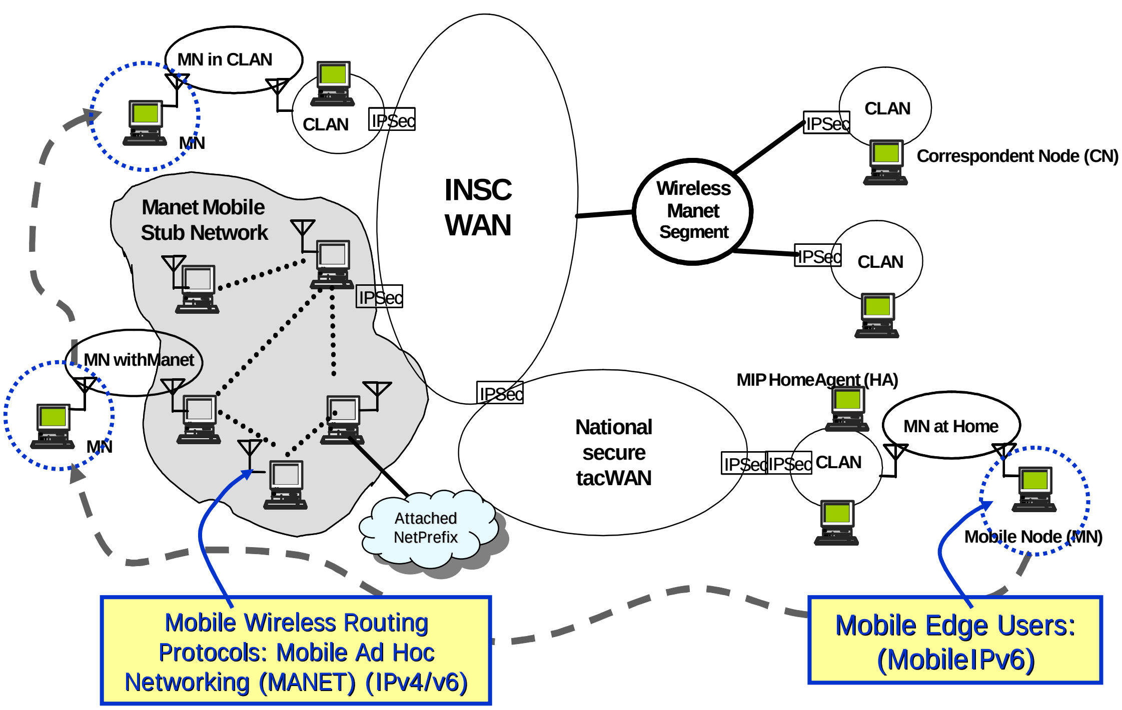

Figure 2: Examples of Task 6 Manet and MIP Test Architecture

Task 6 Demonstration Assumptions and Decisions

There are several technical and demonstration assumptions that Task 6 participants agreed to in scoping planned work in order to accomplish some basic goals. Task 6 participants expressed a consensus that this was the best use of the budgeted dollars to maximize investigation of the related emerging technology areas and opportunities.

Some of these T6 assumptions included:

- Non-proprietary IP-based solutions are of primary interest for interoperability demonstrations.
- Emerging or existing IP standard frameworks should be adopted wherever possible.
- While IPv4 mobility still constitutes an evolving technology and an area of research interest, significant effort will be spent on prototyping and investigating IPv6-based approaches.
- Advanced, mobile routing investigations will initially concentrate on stub network operation at the edges of the network (this is due to a present technology maturity issue).
- Participants will experiment using off-the-shelf wireless technology (e.g., ad hoc mode WLAN devices and APs) as a proof-of-concept capability that could later be applied to more heterogeneous tactical networks and equipment.
- In a real wireless tactical environment, it is assumed there will be lower layer security devices and methods working between wireless devices. Task 6 will not work these areas directly due to budget constraints and will focus on experimenting with interoperable network layer solutions and technology enablers. Nonetheless, the assumption that in most instances such capabilities would be in place in a real system holds, and needs to be made clear during demonstration and testing.

Task 6 assumes that an INSC network security device(s) will exist at the edge of the highly dynamic infrastructure area to enable secure joining of coalition networks. In order to support a highly dynamic networking region (e.g., forward edge of the battlespace) there is a required engineering tradeoff between network security boundaries and supportable infrastructure dynamics, especially with the state of today's key management approaches and requirements.

MOBILE AD HOC ROUTING TEST CONFIGURATIONS

As mentioned, T6 roughly split INSC investigations into edge system and infrastructure mobility problem areas. As one of the two primary areas of scoped work, we examined and applied MANET routing technology alternatives. MANET technology played a primary role in supporting multi-hop routing within highly mobile, localized segments of the INSC architecture. For the purpose of test and demonstration execution, we established wireless routing gateway points within National testbeds supporting MANET stub network operations and providing routing connectivity to the larger fixed INSC routing infrastructure. Figure 3 illustrates how this worked within the testbed and depicts a mobile router gateway supporting a mobile routing area consisting of prototype computers/routers. These MANET routing nodes were also capable of supporting additional attached fixed networks that are also dynamically advertised prefixes (e.g., this may be representative of a mobile platform with local fixed networks onboard). These mobile segments operated as stub networks in relationship to the WAN transit networks in INSC Phase 1. Again, these network areas represent operational requirements where a set of dynamic users or nodes needs highly adaptable infrastructure support.

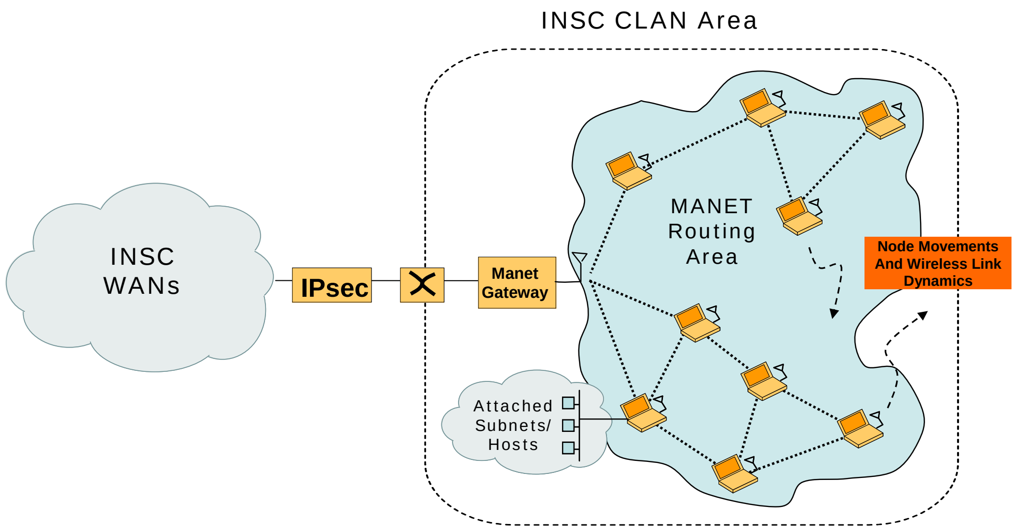

Figure 3: MANET Testbed Approach

Within INSC, the joint desire was to focus on open specification work ongoing within the Internet Engineering Task Force (IETF). For Phase 1, the Optimized Link State Routing (OLSR) [CJ03] protocol was the focus of most MANET routing investigations, although some Ad hoc On-demand Distance Vector (AODV) [PBD03] routing protocol investigations also took place. A typical local testbed configuration, as established for the MANET OLSR routing area(s) is shown in Figure 3. The stub gateway router pictured in Figure 3 has, at a minimum, one wireless interface for MANET routing support and one fixed interface (e.g., Ethernet) for external INSC connections. In most National testbeds, participants are using various 802.11b wireless local area network (WLAN) technologies to support MANET operations. These interfaces are operated in ad hoc mode, allowing the MANET routing protocol to control the forwarding of packets. This demonstration targets a “proof-of-concept” capability to test and demonstrate IPv6 and IPv4 MANET mobile routing and user roaming capabilities but does not closely examine numerous possible tactical wireless technologies. It is envisioned that the networking solutions investigated are flexible networking technologies and can be adapted to multiple application areas.

MOBILE IPv6 TEST CONFIGURATIONS

As the second primary investigative area, T6 examined Mobile IPv6 technology and potential hybrids. Related experiments involved examining MIPv6 operation as a node roamed within and among various INSC network areas demonstrating the establishment, handoff, and maintenance of appropriate MIPv6 associations and connections. T6 team members performed significant background investigations of MIPv6-oriented solutions for edge mobility and are tracking ongoing progress with related IETF standardization efforts. To support collaborative coalition testing, T6 established operating Home Agent (HA) nodes in particular participating national testbeds (i.e., Italy and Germany) and developed a strategy for other participating nations to perform surrogate host roaming demonstrations and tests at distributed locations across the INSC WAN architecture. A range of surrogate addresses spaces for roaming node tests was issued to each participating nation to support these experiments. This allowed distributed testing throughout the architecture with minimal testing coordination and planning. The general WAN-based MIPv6 testing approach is depicted in Figure 4.

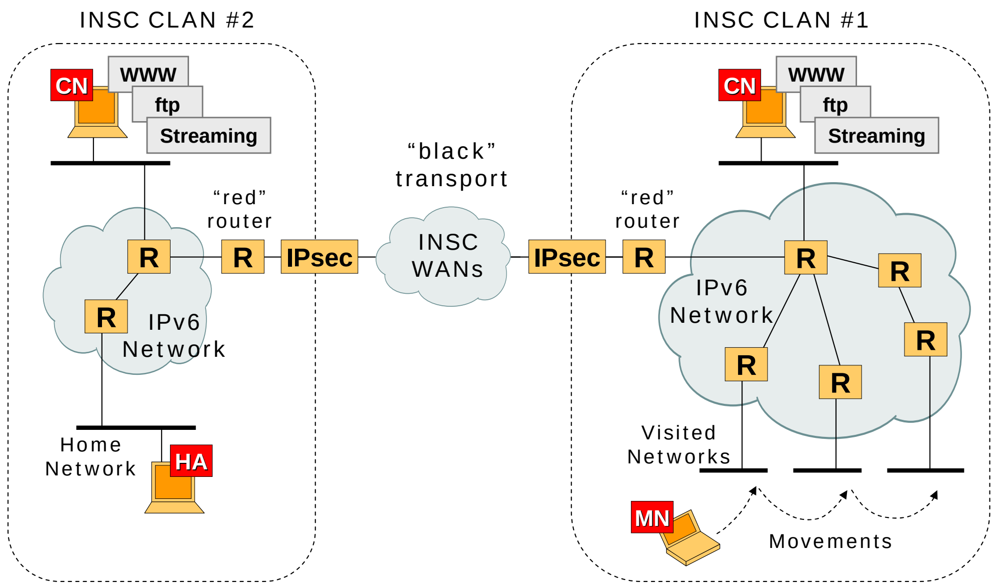

Figure 4: MIPv6 Testbed Approach

OTHER T6 WORK

Before continuing to discuss and summarize T6 core experiments and demonstrations, we quickly describe a number of other T6 work areas that were executed by various Participating Organizations (POs).

IPv4 Experiments

While a good portion of INSC work within T6 focused on IPv6 technology demonstrations, a number of participants carried out IPv4 experiments and demonstrations either leading up to or in parallel with IPv6 work. Examples of this include the work done by France, UK, and the US. The US carried out a number of early IPv4 MANET routing experiments including a live 10 node demonstration in 2002 using moving vehicles. The US also developed a testbed approach that had simultaneous support for both IPv4 and IPv6 dual-stacked mobile nodes. The UK carried out a number of experiments looking at IPv4 based OLSR and AODV MANET protocol variants, especially within low bandwidth tactical radio environments using their large network emulator (LNE) testbed. FR carried out live field experiments using 18 OLSRv7 (RFC 3626) IPv4 nodes in 2003. These 18 nodes (10 INRIA routers, 4 VAIO laptops & 4 IPAQ PDAs) were deployed indoors, in a tower, and outdoors. Experiments with pedestrian and vehicular motion were done inside and outside around the tower. The testbed and these experiments are documented in [FR05, 06, 08, 10, 11, 12, 13].

Early Related MANET Field Testing

- An early US-based 20 node mobile OLSRv4 demonstration was first performed in 2001 with 6W amplifiers and standard 802.11b wireless cards.

- A US-based 10 node OLSRv4 and AODVv4 demonstration was performed in the summer of 2002 and yielded excellent results and a set of testing tools and methods that were later applied to INSC.

Hybrid MANET/MIPv6 Experiments

Two types of hybrid MANET/MIPv6 support were demonstrated within Task 6 efforts. First, an effort demonstrated the support of a MANET routing node that also acts as a MIPv6 end system. This requires some modification and extension of existing specifications and software. A second effort demonstrated how MIPv6 nodes can be dynamically supported within attached prefix networks connected to a MANET node. This requires no specification or software changes, but assumes the MIPv6 nodes attach to a separate IP interface supported by the MANET node and advertised dynamically through the OLSR Host and Network Association (HNA) process (e.g., mobile vehicle with internal LAN interface).

- CRC (CA) developed and executed a number of experiments with IT, demonstrating an ability to operate hybrid MANET and MIPv6 nodes [T609]. They accomplished this by extending the functionality of OLSR HNA messages to support MIPv6 signaling. This functionality was of interest in a scenario where a routing node moves into an OLSR MANET and is also acting simultaneously as a MIPv6 node. Automatic mode detection and switching capability were introduced in each mobile node to facilitate handoffs between WLANs and MANETs.

- NRL (US) and IT also demonstrated that MIPv6 nodes can roam between different attached subnets supported by a MANET by using HNA messages without modifications to OLSR or MIPv6 specifications. This demonstration was designed to support MIPv6 nodes operating on a separate local interface or subnet from the interface participating directly in MANET routing. To accomplish this in a flexible way, a total aggregate address prefix was assigned to the MANET stub networking area. Operational MANET IP node interfaces were manually configured or autoconfigured to operate within a specific contiguous subprefix of this total gateway aggregate address prefix. Next, a single or multiple set of additional address prefixes, other than the MANET interface prefix, were assigned to each MANET node to support local network subnetwork and node attachments. In this way, MANET nodes discover the default WAN gateways and advertise the attached HNA prefixes to all other MANET nodes in the MANET routing area. Roaming MIPv6 nodes autoconfigure locally through normal mechanisms (e.g., RADV) operating on the second local interface attached to the MANET node. Through aggregate routing advertisement and IP “longest prefix matching” rules, the binding updates from and to MIPv6 nodes are supporting through normal IP routing mechanisms.

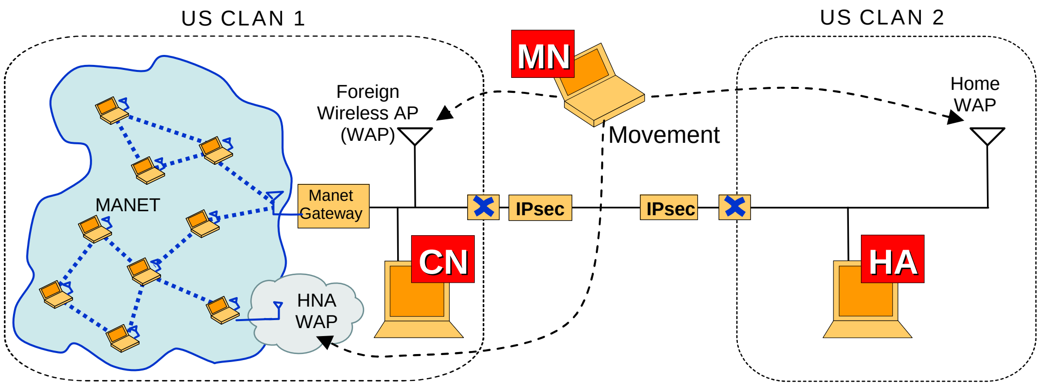

Figure 5: Example of US Hybrid MANET-MIPv6 Experiment

Mobile, Multi-hop Subnetworks

- An early examination of NRL subnet routing technology and possible applicability to INSC was investigated. The technology was not adopted for INSC demonstration purposes.

- An examination of HIPERLAN 1 MAC layer multi-hop routing technology, the basis for some of OLSR IP layer design, was included in some testing by FR. Some of these tests (WLAN / HIPERLAN1 and WPAN / Bluetooth) were describing in an INSC T6/T7 document entitled "Synthesis of flows performances tests on FR_CLAN_5 : HIPERLAN1 & BLUETOOTH / IPv6" [FR10/Tsk7].

MANET Performance and Interaction with QoS Model

- T5 and T6 often worked together throughout the early INSC schedule to define a routing QoS approach that would transition between MANET and WAN routing areas. The inclusion of protection for MANET routing control was a primary issue that was resolved.

- CRC (CA) performed a number of studies (partly under T5 efforts) to examine multiple models of QoS within a MANET environment [T502, GD03]. An approach was designed and implemented by CA and was adopted by many T6 participants for final testing. The proposed approach was thoroughly tested by CRC in a MANET environment with various traffic types.

- The US (NRL) performed a number of QoS examinations to both test the performance of the T5/CRC recommendations in protecting MANET routing control packets. Applying QoS to different user traffic flows was also tested while using T5/CRC models and effective relative improvements under a variety of traffic and mobility scenarios were noted.

MANET Mobile Routing Simulation Efforts

- T6 participants performed early ns2 simulations and produced results which examined a wide variety of MANET performance and scalability issues. The US presented a number of findings examining aspects of OLSR and AODV using up to 50 nodes under a large set of scenarios.

White Paper Studies

Throughout the INSC project, a number of technical white papers were produced within T6 to address a number of issues. Please refer to Appendix A to see a list of reports produced by T6.

TESTING AND EXPERIMENTATION SUMMARY

Methodology and Test Tools

INSC T6 participants have agreed that a proper examination of network mobility technology requires specialized investigative work to produce meaningful performance assessments and recommendations to the operational and research sponsorship community. In the early stages of this project, there were very limited software tools and methodologies addressing mobile network analysis and assessment. One of the significant outcomes of the INSC T6 work is the establishment of some testing methods and tools to improve analysis of mobile network and related protocol performance and behavior. Here we quickly review relevant methods and tools that were adapted and applied in T6 work.

First, to examine performance, a method was needed to produce dynamics or mobility within a network topology. Initially, T6 performed some examination of mobility and dynamics in a networking simulation environment (ns2). Moderate sized network simulations (~50 node networks) were used to perform initial analysis studies and T6 began targeting smaller mobile network segments (~10-20 nodes) for actual mobile routing experiments. Because of the difficulty of controlling and repeating actual field tests, mobile emulation methods were adopted within many testbeds.

Various PO's approaches here have varied, and approaches used for MIPv6 testing are different than those used in MANET testing. The usefulness of such dynamic network emulation **does not** replace the value of actual field experiments, but the capability provides repeatable and controlled testing required for more thorough investigation in the early stages of technology evaluation. An example of how the US-designed Mobile Network Emulator (MNE) [CMW03] has been adapted to support controlled, repeatable INSC MANET experimentation is shown in Figure 6.

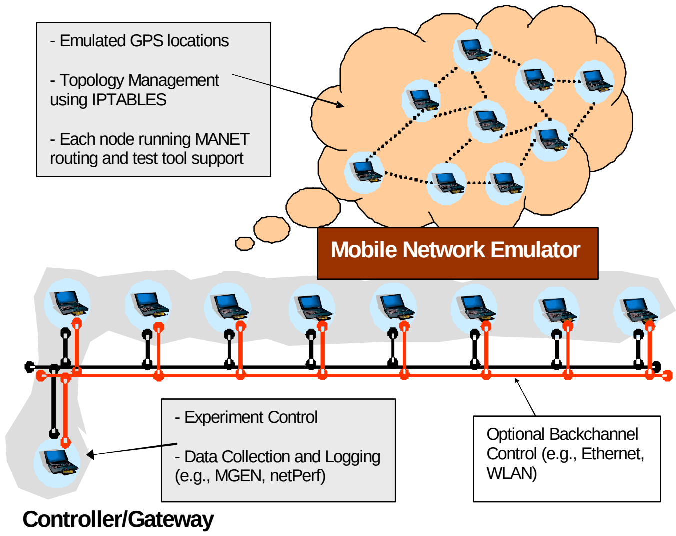

Figure 6: Emulation of Mobile Topology Dynamics

The bubble diagram shows an emulated network topology involving multiple hop routes controlled from model generation or actual recorded mobility scenarios. MANET routing or mobility protocols under examination operate within this environment while nodes undergo active topological change. The types of technical observations collected in such experiments include mobile routing convergence, supportable network data throughput, packet loss and delay statistics, and other detailed protocol behavior. T6 also developed and applied specialized test procedures, data collection, post analysis, and visualization tools to support unique requirements of mobile network testing and analysis. In the case of the MNE, represented in Figure 6, the same set of traffic tools, visualization tools, protocol implementations, and post analysis methods are applied in field testing. As an example, early OLSR-based field trials were executed within INSC and in some cases mobility traces were recorded and used later to drive the mobility patterns within emulation tests with the same traffic patterns.

The UK also used its Large Network Emulator (LNE) to carry out MANET experiments for INSC. Currently capable of fielding 50 IPv4-based routing nodes, it is designed to allow the assessment of a range of technologies and protocols over representative wireless, error-prone and narrowband links. It allows repeatable experimental conditions to be achieved, thus aiding performance analysis of mobility protocols in particular. It consists of a number of Linux PCs configured as either routers, end-systems, or both, which are interconnected using a standard Ethernet switched LAN with a Windows server configured as a controller. Bespoke software present on the PCs and the server allows the connectivity of the PCs to be changed dynamically without having to physically unplug any network connections. The addition of a MAC channel access process has made the LNE more representative of broadcast mobile networks, such as those typically found in combat radio networks and in one of the wireless LAN modes. The ability to model the hidden terminal effects by taking collisions into account further enhances the LNE's representation of these networks.

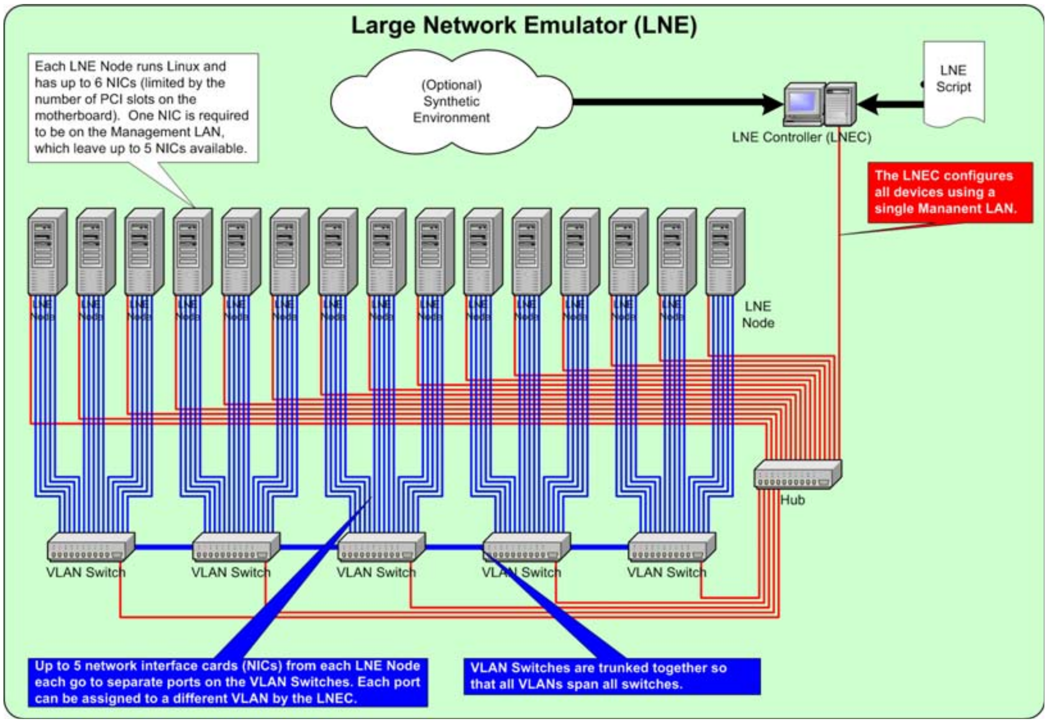

Figure 7: UK mobile network emulation tool

T6 also developed functional extensions to existing MANET routing source code to enhance existing prototype capability. These functional extensions included attached network prefix advertisement, mobile routing gateway discovery and advertisement, improved debugging and dynamic routing analysis tools, improved neighbor link management, and IPv6 porting of IPv4 routing implementations.

The breadth of possible combinations of protocol layer interactions, traffic models, and mobile network scenarios made T6 experimental formulation technically challenging. Team members agreed to limit the test scenarios to a reasonable number achievable under the tasking and covering a reasonable cross section of analytical interest [T603]. To improve the ability to analyze and understand mobile networking routing performance, we enhanced related debugging and logging facilities to track and capture MANET routing performance. In the case of OLSR routing, we can trace local neighbor and topology table information throughout the course of a demonstration experiment and we are able to visualize the routing protocol’s view of the dynamic topology as it changes during an experiment. The number of OLSR routing table recalculations can also be monitored to observe the effect of node mobility on the routing protocol.

T6 JOINT TESTING APPROACH

Within T6, a joint testing approach was developed that covered all possible testing and demonstrations, even those that were considered optional to the core goals. The following outlines the basic testing areas discussed and agreed to that would be conducted during the Summer and Fall timeframes of 2003. In many cases, subsets of tests were only performed by a subset of participants. The basic testing approaches used follow the procedures outlined in the referenced T6 Testing Framework and related Test Documents.

1. Mobile IP (Edge User) Technology Testing

    1.1. MIP WAN Testing

        1.1.1. MobileIPv6 functionality tests (WAN)
        1.1.2. MobileIPv6 performance tests (WAN)
        1.1.3. Optional MobileIPv6 and MANET tests (WAN)
        1.1.4. Optional MobileIPv4 NLAN-NLAN testing (WAN)

    1.2. Localized Testing

        1.2.1. MobileIPv6 functionality tests (local)
        1.2.2. MobileIPv6 performance tests (local)
        1.2.3. Optional MobileIPv6 and MANET functionality tests (local)
        1.2.4. Optional MobileIPv6 and MANET performance tests (local)

2. MANET (Mobile Routing) Technology Testing

    2.1. MANET PO-to-PO WAN Testing

        2.1.1. MANET IPv6 functionality testing across WAN
        2.1.2. MANET IPv6 performance testing over WAN
        2.1.3. Optional MANET IPv4 functionality testing across WAN
        2.1.4. Optional MANET IPv4 performance testing over WAN

    2.2. Localized Testing (localized performance, emulation/live)

        2.2.1. Local MANET IPv6 functionality testing
        2.2.2. Local MANET IPv6 performance testing
        2.2.3. Local MANET IPv4 functionality testing
        2.2.4. Local MANET IPv4 performance testing
        2.2.5. Optional Localized Multi-Area MANET performance testing

3. Mobile Applications and other Optional Testing Performed

    3.1. IPv6 Video
    3.2. IPv6 Voice over IP
    3.3. Web browsing

MOBILE IPv6 TESTING AND DEMONSTRATION SUMMARY

This section summarizes MIPv6 testing and demonstrations that were performed within Task 6 during the final testing phase of 2003. Figure 8 illustrates the basic configuration that was used during this testing between POs across the INSC infrastructure to support mobile node roaming, association, and handoffs experiments.

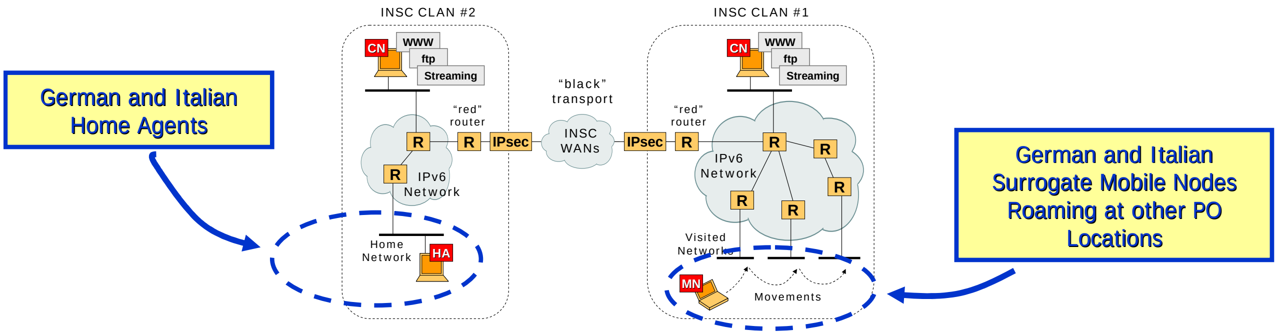

Figure 8: WAN PO-to-PO MIPv6 Testing

MIPv6 PO-to-PO WAN Testing

One of the basic goals of T6 joint MIPv6 testing efforts was to validate the ability to effectively maintain network communications to and from MIPv6 nodes as they roam within different CLANs across the INSC WAN architecture. To accomplish this, as shown in Figure 8, Home Agents (HAs) and Correspondent Nodes (CNs) were established at fixed locations for use by participants. A plan was established and executed to provide surrogate address allocations to act as foreign Mobile Nodes (MNs) distributed amongst T6 POs. This approach allowed distributed testing across the WAN and minimized travel and coordination requirements among joint testers. While many POs configured working HAs within their CLANs, two POs (Germany and Italy) provided the common surrogate HAs and address spaces to support foreign roaming tests. Other POs used this capability to execute basic roaming functionality and these tests were executed successfully. MIPL MIPv6 software distribution was used in most testbeds to carry out these experiments.

As mentioned before, WAN testing between POs was mainly focused on functional testing and not performance, because accurate performance testing requires a more controlled environment.

As part of the functional WAN testing, the following general results were achieved:

- End-to-end network demonstrations completed successfully between operational MIPv6 nodes residing and roaming within the INSC infrastructure.
- Successful demonstration of routing optimization options also performed between CN and MN.

MIPv6 Localized Performance Testing

T6 efforts were dedicated to evaluating the ability of MIPv6 to keep connections active while a Mobile Node changes its point of attachment to the network. The following example experiments were carried out to measure the performance of MIPL 0.9.5.1 for Linux, which is the reference MIPv6 implementation chosen for the INSC demonstration phase. Detailed performance tests were done locally, to exclude the non-related performance degradation caused by the INSC WAN from the analysis. MN mobility was emulated using a Layer 2 switch with programmable VLAN configuration. With the emulator, it was possible to control MN movements using pre-defined and repeatable mobility patterns.

All the example experiments presented here have been performed by cyclically moving the MN between two foreign networks (i.e. MN always away from home). Several testing sessions have been run changing the configuration of the main parameters affecting MIPv6 performance: the communication mode (i.e. bi-directional tunneling or route optimization) and the interarrival time between unsolicited Router Advertisements (RAs).

The first experimental result shows the average handoff latency experienced by the MN. It represents the delay occurring immediately after movement, during which it is not possible to send or receive packets, due to MIPv6 mobility management procedures. Figure 9 shows the MIPv6 handoff latency for communications taking place in bi-directional tunneling (BT) and route optimization (RO). The measures demonstrate that the overall handoff latency generated by MIPv6 is higher when operating in route optimization, due to the extra signaling (i.e., Return Routability function) that must be exchanged between the MN and the communicating party to secure end-to-end location updates. The graph also shows that an effective way to reduce handoff latency is to decrease the movement detection delay by increasing the frequency of unsolicited RAs, and therefore accepting a higher signaling overhead on the localized access networks.

Nevertheless, even when the movement detection delay approaches zero (with RA interval between 30 and 70 ms), the overall handoff latency remains higher than 2 seconds. This time value is not enough to enable uninterrupted real-time communications in mobility scenarios.

The reason why an increase of the RA rate is not fully reflected in a reduction of the handoff latency is the high delay caused by the Duplicate Address Detection (DAD) procedure that must be undertaken by the MN after each movement to ensure the uniqueness of the Care-of Address (CoA). DAD is triggered by the reception of the first RA from a new router and therefore can be partially or totally overlapped with movement detection. As a result, the impact of DAD on the overall handoff latency increases as the movement detection delay decreases, since it becomes less likely that the two procedures overlap. This explains why it is not possible to arbitrarily constrain the handoff latency working just on the optimization of the movement detection delay (e.g. increasing the rate of unsolicited RAs).

Another aspect that has a strong impact on performance is the policy used by the MIPv6 implementation to control the location update procedure. With MIPL 0.9.5.1, the MN sends a Binding Update (BU) to the HA and a Care of Test Init (CoTI) to the CN at the end of movement detection, without waiting for DAD to complete. This can be particularly deleterious if DAD terminates well after movement detection. In fact, in this because the access router has not yet updated its neighbor cache and therefore is not able to forward IPv6 packets addressed to the MN's Care of Address (i.e. the access router does not have the mapping between the MN's CoA and the correspondent MAC address). This loss of signaling may in turn trigger MIPv6 retransmission timers, thus generating long, and potentially avoidable, delays.

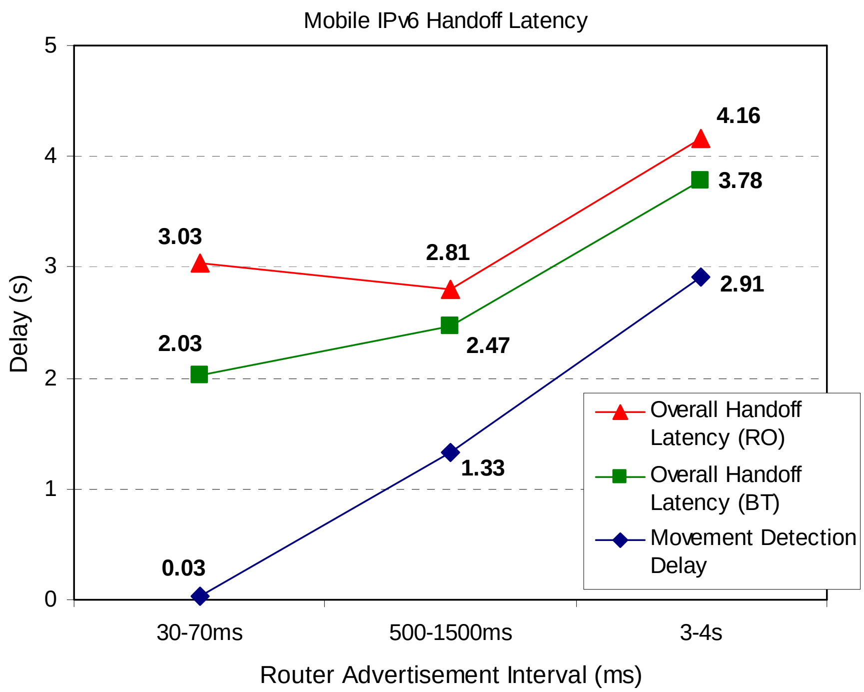

Figure 9: Mobile IPv6 Handoff Latency (Programmable Switch)

The second experimental result shows the TCP throughput achieved by a correspondent node communicating with the MN in route optimization mode. The graph in Figure 10 plots the average TCP throughput achieved during the whole testing session (100 handoffs in a row). The results demonstrate that in any network condition, the TCP throughput decreases as the MN handoff frequency increases. However, even when the MN moves at the speed of six handoffs per minute, a reasonable upper bound in many operational scenarios, the measured TCP throughput is in the range of 2.79-3.93 Mbps. This is quite high compared to the maximum of 5.99 Mbps, achieved when the MN does not move. This confirms the suitability of MIPv6 for best-effort applications like FTP and web browsing. It is also interesting to note that even if the MN remains still within the same visited network (i.e. handoff frequency equal to zero), the resulting TCP throughput is lower than the maximum throughput permitted by the test environment, which was measured by switching off MIPv6. This slight performance degradation is due to the protocol overheads introduced by MIPv6 to perform transparent packet routing towards the MN (i.e., tunneling, mobility headers, etc.).

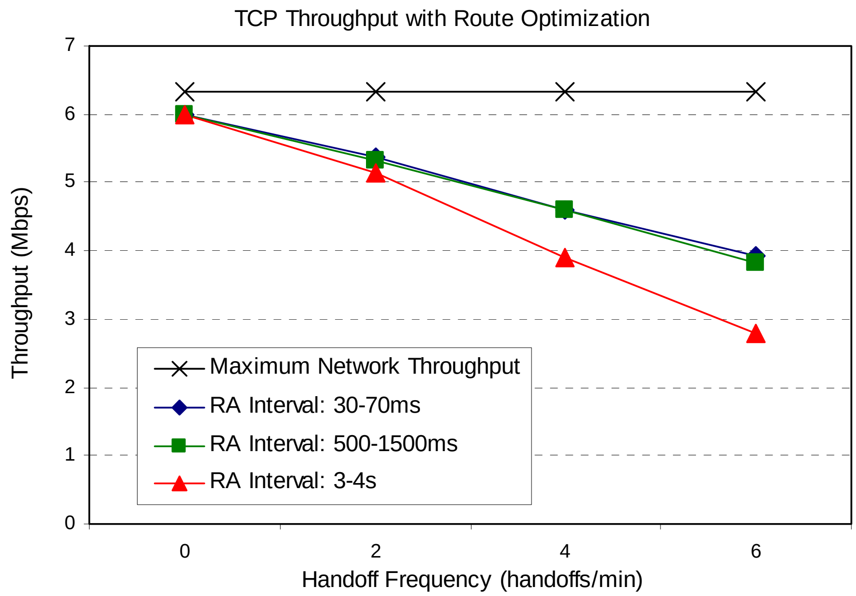

Figure 10: TCP Throughput with Route Optimization (Programmable Switch)

In a third experimental scenario, the mobility of a MN was not emulated using a programmable switch, but was actually done by moving the MN between different IEEE 802.11b WLANs. The gross bit rate on each WLAN was 11 Mbps.

The way the performance measurements were collected was exactly the same as for the programmable switch. This allows a comparison of the results obtained in an optimized programmable switch environment with the results obtained in a real WLAN environment.

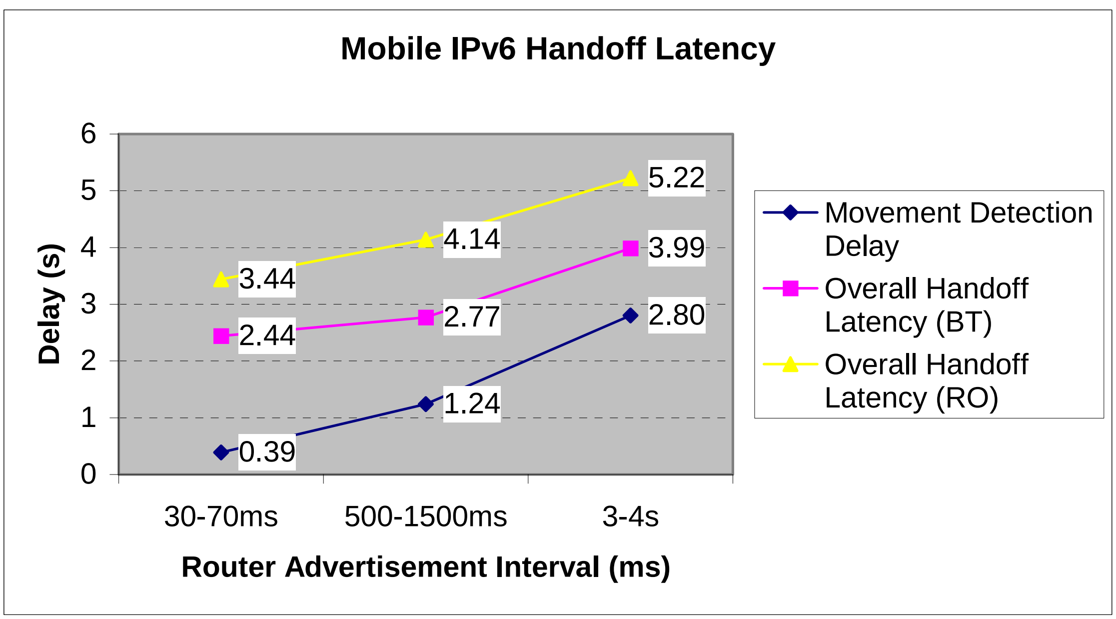

Figure 11: MIPv6 Handoff Latency (WLAN)

Figure 11 shows the MIPv6 handoff measurements obtained in a real WLAN environment. Similar to the results obtained in the programmable switch environment, the graph illustrates that the overall handoff latency generated by MIPv6 is higher when operating in route optimization mode than when operating in bi-directional tunneling mode. Also in the tested WLAN, the results demonstrate that an effective way to reduce handoff latency is to decrease the movement detection delay by increasing the frequency of unsolicited router advertisements.

As expected, the handoff latency in a real WLAN environment is higher than in a programmable switch environment. The reason for this is mainly the time required to set up a layer 2 connection from the MN to the new WLAN access point after each handoff. Contrary to the measurements done on a programmable VLAN switch, the measurement results collected in a real WLAN environment illustrate that the handoff latency is not increasing for very short movement detection delays (in the graph this is represented for RAs sent every 30 to 70 ms). The reason for this increase has been the overlapping of the movement detection and the DAD procedures. Due to the additional delay introduced by the setup of a layer 2 WLAN connection, the DAD procedure is also delayed, and an overlap is less likely.

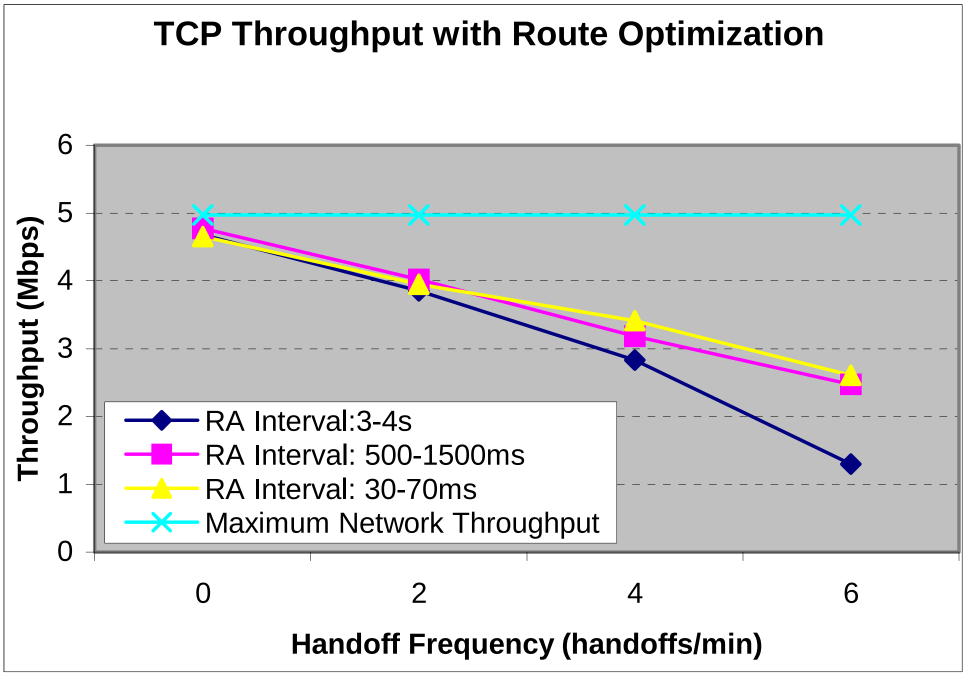

Figure 12: TCP Throughput with Route Optimization (WLAN)

Figure 12 shows the MIPv6 TCP throughput results obtained in a real WLAN environment. Similar to the results obtained in the programmable switch environment, the graph illustrates that in any network condition, the average TCP throughput decreases as the MN handoff frequency increases. It also demonstrates that the TCP throughput increases with the frequency of the RAs. Comparing the absolute values collected for the TCP throughput in a programmable switch environment with the ones collected in a real WLAN environment, the TCP throughput in a real WLAN environment is lower. This is simple a consequence of the lower maximum network throughput on the WLAN. Comparing both TCP throughput measurements relative to their respective maximum network throughput limit, the results in both environments are quite similar.

The performance evaluations carried out with MIPL 0.9.5.1 made it possible to understand the limitations of Mobile IPv6 and identify areas of possible protocol improvements. These are the main lessons learned from this effort:

- Current implementations of MIPv6 undergoing significant continuous mobility are suitable for best-effort services only. The handoff latency is too high for real-time applications like Voice over IP and video conferencing.
- Triggering location update procedures (i.e. delivery of BUs) as soon as movement detection completes does not provide any benefit on performance. In some situations, it may cause an extra delay of more than one second in handoff management. For this reason, BUs (as well as Return Routability signaling) should be delivered after the completion of DAD for the Care of Address.
- Increasing the rate of unsolicited RAs helps, but does not work on low bandwidth links. An interarrival time of 30-70ms generates a signaling overhead of more than 20 kbps on the link. Therefore, on low bandwidth links, the use of Layer 2 triggers to aid movement detection seems to be unavoidable.
- There is a need to develop solutions (e.g. QoS for MIPv6 signaling, HMIPv6) to improve the reliability of MIPv6 when used in geographical environments with low bandwidth links between the home and visited domain. In such scenarios, the occasional downgrade to bi-directional tunneling (e.g. after a movement or due to the expiration of registration timers) may cause serious congestion on the WAN and protocol failures.
- The use of adaptable protocol parameters may be an effective way to improve performance in mobile environments. The mobile node could reduce the handoff delay by adapting the retransmission timers of MIPv6 and Neighbor Discovery to its mobility pattern.

MANET TESTING AND DEMONSTRATION SUMMARY

This section summarizes MANET testing and demonstrations that were performed within T6 during the final testing phase of 2003. Figure 13 illustrates the basic configuration that was used during this testing.

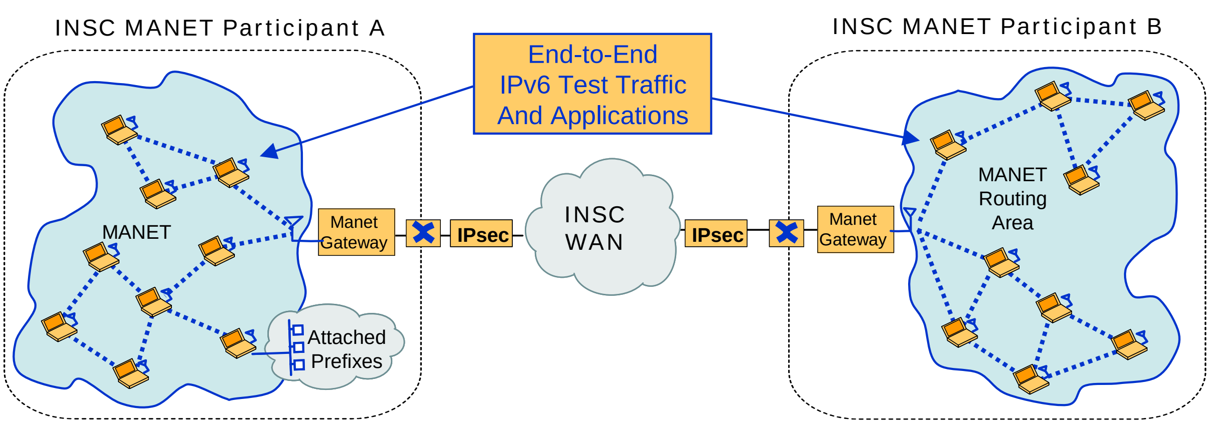

Figure 13: MANET Joint WAN Testing

MANET PO-to-PO WAN Testing

One of the basic goals of T6 joint MANET testing efforts was to validate the ability to communicate between local MANET mobile routing areas at different POs across the INSC WAN. In the case of IPv6, most POs successfully carried out such testing and verified traffic sourcing and sinking from mobile nodes within a MANET routing areas [T610]. FR did not execute these joint IPv6 MANET tests because their MANET testbed consisted of IPv4-only MANET nodes, but additional IPv4 tests [FR11] were conducted across the WAN and provided similar results to the IPv6 testing.

As mentioned before, the MANET WAN testing between POs mainly focused on functional testing and not performance, because accurate performance testing requires a more controlled environment. As part of the functional WAN testing, the following general results were achieved:

- MANET OLSR nodes communicated successfully between POs.
- Data was successfully dynamically routed during the execution of a variety of mobile node scenarios.
- Multiple MANET implementations were tested simultaneously at different PO locations.
- Prefix advertisements were successfully demonstrated allow the support of attached networks within a MANET (e.g., LAN within a mobile platform).
- Dynamic gateway advertisement and discovery was achieved using the HNA functionality within OLSR and this reduced the configuration management burden.

Localized Testing

While POs conducted functional experiments between mobile nodes and MANET routing areas across the INSC WAN, detailed performance tests were carried out under more controlled localized environments [T610]. This allowed for better scientific assessment of detailed areas of protocol performance and behavior. These findings are critically important to the overall T6 output of assessing the related technology maturity and in collecting detailed performance measures. Here we present a summary of experimental results collected within T6 using various mobility test scenarios and related tools.

Within the T6 MANET Test Framework and Test Plan, scenario guidelines were roughly outlined for conducting MANET performance testing. Numerous POs carried out these tests internally, but the scenarios are often slightly different due to the total number of testing nodes available and whether or not mobile emulation was available.

The first set of example results uses the following scenario and provides a summary look at variety of performance issues.

- 10 total operating MANET routing nodes (laptops).
- 802.11b wireless cards operating at raw link rate of 2 Mbps.
- One node acting as an INSC WAN MANET gateway.
- Traffic scenario: All mobile nodes source traffic towards the gateway.

- Mobility scenario: random waypoint motion model.
- Traffic generator: MGEN (TCP traffic generation was a streamed secure shell (ssh) connection).
- DiffServ QoS filtering/forwarding enabled on MANET nodes (Routing Control Marked).
- Traffic scenarios:
    - UDPv6 (3 phase increased loading, all 10 nodes sourcing traffic), 256 byte packets in this example.
    - TCPv6 (all nodes but gateway (9 nodes) source stream traffic to the gateway), interface MTU is 1280 bytes per INSC direction.
- Routing Protocol Parameters:
    - 0.25 sec hellos, 2 sec TC, neighbor link hysteresis function on.

The first example experimental result in Figure 14 shows the total IPv6 UDP traffic goodput[1] realized at the MANET gateway from all mobile nodes during a three-phase traffic loading test. The three phases of the test are designed to achieve low, moderate, and heavy congestion conditions using 802.11b with 2 Mbps raw link rates. Each loading phase is 10 minutes long and provides enough time for significant routing changes to occur within the topology. The maximum hop count to reach the gateway in this example scenario was observed to be 4 hops. We were able to visualize and record routing information in both partial and full link state modes of OLSRv6. Idealized goodput (no loss, no mobility effects, and no multi-hop or contention-based wireless MAC limitations) would result in 100, 500, and 1000 Kbps. The 1000 Kbps phase represents an operating region that, due to MAC contention and multi-hop relaying, the MANET network is experiencing significant traffic loading. Figure 14 demonstrates that under light and moderate loading, excellent UDP goodput is achievable under multi-hop and dynamic topology conditions. Some slight drops in goodput noted at the 800 sec mark are due to repeatable mobility scenario conditions where a node becomes physically disconnected from all network neighbors for a period of time and then reenters the network area. Under heavier congestion conditions, additional loss and delay occurs, but the routing protocol still demonstrates effective delivery of a significant amount of multi-hop user data under dynamic conditions. In other experiments executed, the protocol parameters (e.g., HELLO intervals) were adjusted to examine related effects, and in most scenarios examined only minor differences were noted.

[1] Goodput: Usable end-to-end traffic throughput at the application layer.

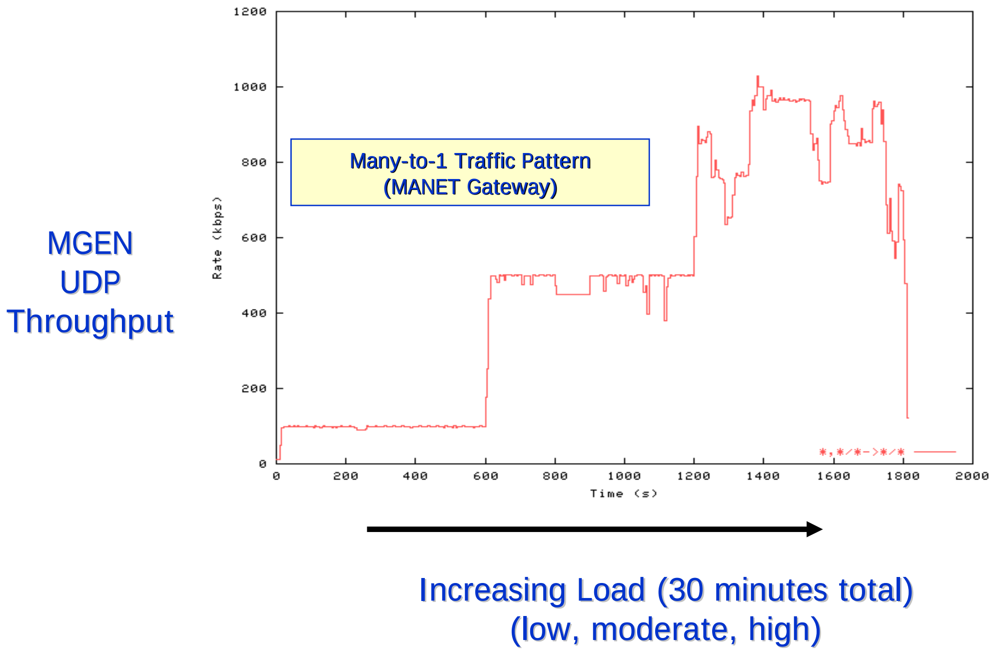

Figure 14: MANET Localized 10 Node UDP Test

The next example test result presented is from an examination of the TCP transport effects under a set of scenarios. The experimental result in Figure 15 represents the total IPv6 TCP traffic goodput achieved to the gateway from all mobile nodes during a 15 minute test. This test also demonstrates the ability for OLSRv6 to support multiple simultaneous TCP streams (9 in this case) under multi-hop and dynamic topology conditions. It should be pointed out that detailed TCP analysis can be quite complex and only a limited set of such tests were done under the present effort. Additional future mobile transport investigations are needed, but this does functionally demonstrate a basic capability to support multiple TCP streams and achieve reasonable aggregate goodput under dynamic MANET routing conditions.

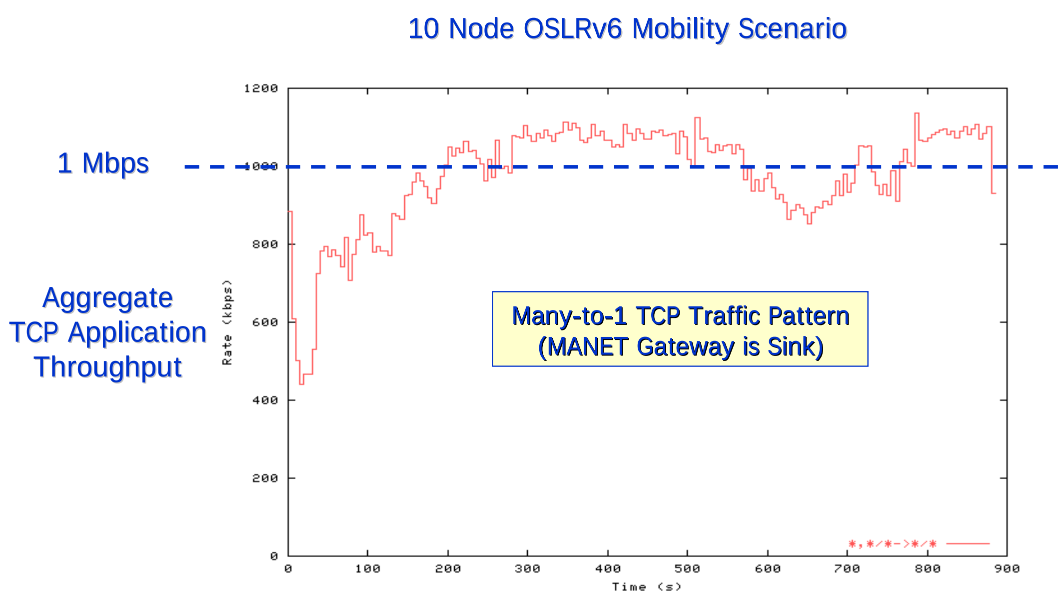

Figure 15: MANET Localized 10 Node TCP Test

As part of the MANET localized performance testing, the following general results were achieved:

- T6 validated the ability of localized proactive MANET routing to function within the INSC architecture using both IPv4 and IPv6 routing.
- T6 verified the ability of OLSR technology to reach and dynamically discover local gateways to the INSC WAN.
- MANET (specifically OLSR) demonstrated an ability to support a moderate number of mobile nodes undergoing significant topology dynamics. The UK ran a number of 20 and 36 node tests and found good scalability.
- Test scenarios examined low, moderate, and highly congested traffic scenarios. Data delivery and goodput was observed to be effective in cases studied.
- Test scenarios examined different traffic patterns.
- Multiple MANET implementations, both IPv4 and IPv6, were tested successfully.
- Multiple routing metrics and parameters were examined in order to analyze the effect on overall routing performance.
- Both UDP and TCP transport protocols showed reasonable performance measured across an aggregate number of supported network traffic flows.
- The use of a QoS mechanism demonstrated improved protection of forwarding resources for MANET routing control packets, and this improves the performance of a MANET routing under congested conditions.

Analysis of localized MANET data performance is encouraging and MANET technology demonstrates an ability to improve IP network performance under wireless dynamic conditions by providing a self-organizing and self-healing infrastructure. A number of observations were also made that require further work and development and could improve the future performance of MANET technology. We summarize some general observations as follows:

- The MANET routing layer (and IP in general) often requires higher layer detection mechanisms or indirectly infers quality information from IP layer signaling. While this maintains a strict layer separation, significant performance improvements are likely possible with improved wireless or MAC layer interface mechanisms. Future improvements in the routing-MAC layer interface could address neighbor management, link quality, and mobility detection in more efficient ways.

- While T6 concentrated mostly on proactive MANET routing protocol experiments, MANET reactive technology (e.g., AODV) may also play an important role in future system demonstrations and may be more appropriate for some situations (e.g., battery-operated sensor devices). Hybrid protocols having both reactive and proactive features are also likely to emerge in coming years.

- Techniques such as HNAs (i.e., prefix advertisement) and router willingness can enable a certain amount of management and policy to be introduced into MANET network operations. Newer MANET capabilities may also allow some transit network capabilities to be demonstrated in more heterogeneous environments. T6 has only demonstrated basic capabilities focused mainly on stub network operations during INSC Phase 1 demonstrations.

Applications in a Mobile Environment Testing Summary

In addition to the network test traffic tools that supported more controlled testing, numerous applications were also demonstrated operating end-to-end within the INSC architecture. These applications were demonstrated working between and among mobile areas and nodes. We summarize here a number of application demonstrations and additional testing that was accomplished within the final testbed architecture.

Real time video streaming was demonstrated between POs operating within localized MANET mobile areas and communicating across the WAN. The application used was an IPv6-enabled version of vic. The quality observed between mobile nodes operating video streaming within the IT and US MANET testbeds was quite acceptable even when operating end-to-end over the INSC WAN infrastructure.

Voice over IP was also demonstrated between MANET nodes using IPv6-enabled versions of the IVOX application. This application supports a number of different vocoders including lower date rate tactical variants (e.g., MELP, LPC). IVOX was used instead of rat due to its ability to run on PCs with half-duplex sound cards. The VoIP demonstration took place between a set of MANET nodes undergoing a mobility scenario and the voice conversation was quite intelligible and the signaling was robust despite the continuous rerouting and node motion that was experienced.

Other applications demonstrated included web browsing from mobile MANET and MIPv6 nodes to a number of IPv6 web servers located within the INSC infrastructure and on MANET nodes at other POs.

FURTHER WORK

MANET routing is next generation IP technology providing needed support for wireless areas of a network that contains dynamic links and potentially supports mobile routing nodes. As discussed in this paper, INSC T6 participants began significant work in experimenting and evaluating with prototype MANET technology. INSC Phase 1 has achieved significant progress in this area and T6 participants have reached consensus that there remain important evolving technical issues for exploration beyond this initial effort. Early technology specifications are rapidly evolving and are expected to become significantly more stable over the next few years. To further explore this technology and better answer more detailed questions important to coalition interoperability and operational robustness, follow-on focused work is recommended. Specific investigative areas of prefix advertisement, wireless MAC-router interlayer signaling, router willingness, and MANET transit network support are of particular interest. Mobile multicast routing technology investigations have been limited in INSC Phase 1 across the set of technologies being explored by T6. Nevertheless, it has been a rich area of academic study for many years and early potentially practical approaches are beginning to emerge from research, but these approaches require additional applied research to determine suitability and effectiveness for envisioned application scenarios.

Hierarchical Mobile for IP version 6 (HMIPv6) is an emerging technology area promising localized efficiency improvements and faster mobility support within localized regions of a network deploying significant numbers of MIPv6 type roaming nodes. This technology was not mature enough to significantly analyze during INSC Phase 1, but it has progressed significantly and future work is recommended by T6 participants to analyze and assess its military application and relevance.

Other areas of possible relevant future work related to mobile networking include: experimentation and analysis of protocol support for aggregate Networks in Motion (NEMO), enhanced MANET protocols supporting more heterogeneous networks (e.g., OSPF [M98] MANET enhancements [B03]), and improved anycast routing and distributed mobile network services.

Also, INSC Phase 1 included no special tasking to analyze transport protocols in mobile, wireless environments, but this is an important future, complex study area. Due to the relevant dynamics in delay, loss, and throughput caused by wireless mobile environments, transport protocols will face additional challenges over fixed networks in providing effective end-to-end service for multiple classes of user applications. It is anticipated that different MANET and mobile architecture solutions provide differing support behavior to IP transport and application layers, and that this should be examined. Also, the type of topology, wireless environment, traffic patterns, and mobility scenarios tested may greatly influence the performance behavior.

In addition to the above, mobile networking technology recommendations must often balance often competing operational and design requirements for adaptiveness, security, and robustness. This is a significant challenge to be met in adapting future work to specific operational scenarios and needs. The adaptation of mobile networking to sensor systems is also an area for further detailed investigation and consideration.

CONCLUSION/SUMMARY

INSC T6 investigated, demonstrated, and analyzed numerous emerging mobile network technologies within an experimental coalition networking environment. Working mobile network testbeds were constructed and integrated into the overall INSC network architecture. These mobile network test resources, along with a set of novel test tools and methodologies, were applied to support various experiments. Numerous localized performance studies and INSC WAN end-to-end interoperability experiments have been conducted for both MANET routing and MIPv6 technology areas by INSC POs. Several test examples and analysis discussions were provided in this paper.

High level lessons learned and general observations can be distilled from the present work done in T6. We summarize these as follows:

- Emerging MANET routing solutions for both IPv4 and IPv6 demonstrate improved network routing capabilities in dynamic, multi-hop wireless scenarios.

- Early simulation and emulation results demonstrate MANET-type routing approaches scaling reasonable well for supporting moderate sized network areas (e.g., 20-50 nodes).

- Early mobile network emulation and real-world testing demonstrated reasonable effectiveness of OLSR MANET routing in small, dynamic areas (e.g., 10-20 nodes).

- MIPv6 technology demonstrated basic support for roaming nodes requiring IP address retention and identification within and across the broad INSC architecture.

- MIPv6 features demonstrated a number of performance enhancements over MIPv4. However, significant performance issues have been identified through testing regarding fast handoff, address configuration, and mobility detection methods.

- Network mobility assessment requires specialized testing tools and methodologies. T6 developed numerous such capabilities under this effort and demonstrated the utility in supportive analysis.

- Mobility support is still a rapidly evolving and challenging field of networking science and future R&D work should be planned for and supported. This is especially true in order to meet the more stringent demands of the dynamic war fighting environment.

The significant T6 accomplishments under the present effort were largely the result of significant technical ingenuity, dedication, and cooperation from each of the national participants. In conclusion, the Task Leader wishes to thank all those involved for their dedication and enthusiasm and for their contributions to the documentation and success of this ongoing effort.

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APPENDIX A: LIST OF TASK 6 DOCUMENTS

Task 6 Documents

INSC/Task6/R/D/001	INSC Task6 Summary Record of First Meeting	May-01
INSC/Task6/R/D/002	INSC Task6 Summary Record of Second Meeting	Oct-01
INSC/Task6/R/D/003	INSC Task6 Summary Record of Third Meeting	Feb-02
INSC/Task6/R/D/004	INSC Task6 Summary Record of Fourth Meeting	Jun-02
INSC/Task6/R/D/005	INSC Task6 Summary Record of Fifth Meeting	Jul-02
INSC/Task6/R/D/006	INSC Task6 Summary Record of Sixth Meeting	Sep-02
INSC/Task6/R/D/007	INSC Task6 Summary Record of Seventh Meeting	Nov-02
INSC/Task6/R/D/008	INSC Task6 Summary Record of Eighth Meeting	Feb-03
INSC/Task6/R/D/009	INSC Task6 Summary Record of Ninth Meeting	Apr-03
INSC/Task6/R/D/010	INSC Task6 Summary Record of Tenth Meeting	May-03
INSC/Task6/R/D/011	INSC Task6 Summary Record of Eleventh Meeting	Oct-03
INSC/Task6/SC/DL/001	Revised Task 6 WBS and Schedule	Jul-01
INSC/Task6/SC/DL/002	Task 6 Briefing to the INSC SC	Jul-01
INSC/Task6/SC/DL/003	Task Leader Report	Jul-01
INSC/Task6/SC/DL/004	Task Leader Report	Jan-02
INSC/Task6/SC/DL/005	Task Leader Report	Jun-02
INSC/Task6/SC/DL/006	Task Leader Report	Oct-02
INSC/Task6/D/001	Initial Mobile IPv6 Testing conducted between Germany and the US	Jul-02
INSC/Task6/D/002	Mobile ad-hoc networks: Military Relevance and Operational Scenarios	May-03
INSC/Task6/D/003	Provision of HA Addressing Functionality	Apr-03
INSC/Task6/D/004	Joint Testing Framework Document	May-03
INSC/Task6/D/005	MIPv6 Test Procedures and Results	Aug-03
INSC/Task6/D/006	MANET Testing Procedures and Results	Aug-03
INSC/Task6/D/007	Mobile Networking Technology within INSC, INSC Symposium T6 Paper	Oct-03
INSC/Task6/DU/008	Task Final Report	Dec-03

US Task 6 Documents

INSC/US/Task6/D/001	Mobile and Wireless Internet Services: Putting the Piecees Together, IEEE Communications Magazine	Jun-01
INSC/US/Task6/D/002	US Program of Work	Jul-01
INSC/US/Task6/D/003	US Demonstration Architecture	Sep-01
INSC/US/Task6/D/004	OLSR Nomenclature	Oct-01
INSC/US/Task6/D/005	US Node Description and Mobility Architecture Inputs for ISNC Task 1 DA Report	Oct-01
INSC/US/Task6/D/006	US Node Description and Mobility Architecture Inputs for ISNC Task 1 DA Report	Jan-02
INSC/US/Task6/D/007	NRL (US) Task 6 Local Test Results	Dec-03
INSC/US/Task6/D/008	NRL (US) Task 6 WAN Test Results	Dec-03

CA Task 6 Documents

INSC/CA/Task6/001	New Global Positioning System (GPS)-Based Routing Protocol for Wireless Ad Hoc Networks	Apr-01
INSC/CA/Task6/002	Canadian Program of Work for Task 6	May-01
INSC/CA/Task6/003	Canadian Testbed for INSC Task 6: Mobility	Oct-01
INSC/CA/Task6/004	Software Tools Used in Canadian Testbed for INSC Task 6: Mobility	Nov-01
INSC/CA/Task6/005	Porting the OLSR version 3 source code from IPv4 to IPv6	Dec-01
INSC/CA/Task6/006	Security issues in OLSR-based MANET	Apr-02
INSC/CA/Task6/007	Interconnecting Mobile Nodes between Ad-Hoc Networks and the Internet: Gateway Discovery, Auto Configuration, and Routing	
INSC/CA/Task6/008	Status of the HNA Implementation Functionality for OLSR Version 3	Feb-03
INSC/CA/Task6/009	MANET and Mobile IP Hybrid Testing Report	Apr-03
INSC/CA/Task6/010	MANET Test Specifications and Results	Oct-03

GE Task 6 Documents

INSC/GE/Task6/D/001	German Program of Work for Task 6	May-01
INSC/GE/Task6/D/002	White Paper on IPv6/v4 Issues	Jun-01
INSC/GE/Task6/D/003	German Testbed for INSC Task 6: Mobility	Oct-01
INSC/GE/Task6/D/004	MIPv6 Security Issues	Oct-01
INSC/GE/Task6/D/005	Interoperability of transition mechanisms and IPSec	May-02

IT Task 6 Documents

INSC/IT/Task6/D/001	Italian Mobility demonstration Architecture	Jan-02
INSC/IT/Task6/D/002	Experimental evaluation of Monash University's HMIPv6 implementation	May-02

FR Task 6 Documents

INSC/FR/Task6/D/001	French contribution to INSC Task6 Mobility	Jul-01
INSC/FR/Task6/D/002	Mobility & Directory Services	Jan-02
INSC/FR/Task6/D/003	French Demonstration Architecture	Jan-02
INSC/FR/Task6/D/004	Mobility & Directory Services - 2nd document	May-02
INSC/FR/Task6/D/005	French testbed : technical specifications	Feb-03
INSC/FR/Task6/D/006	French testbed : installation, validation, & testplan	Feb-03
INSC/FR/Task6/D/007	6Wind routers & Mobile IP	May-03
INSC/FR/Task6/D/008	MANET interconnection ping tests	May-03
INSC/FR/Task6/D/009	Multicast for MANET/OLSR	Jul-03
INSC/FR/Task6/D/010	A testbed for OLSR in military ad-hoc networks	Jul-03
INSC/FR/Task6/D/011	MANET FR/UK interconnection MGEN tests	Oct-03
INSC/FR/Task6/D/012	OLSR routing for military ad-hoc networks	Jul-03
INSC/FR/Task6/D/013	OLSR performance measurement in a military mobile ad-hoc network	Jul-03
INSC/FR/Task6/D/014	Toward IPv6 OLSR	Oct-03

NL Task 6 Documents

INSC/NL-UK/Task 6/D/001	Options for joint MANET testing	Sep-02

UK Task 6 Documents

INSC/UK/Task 6/D/001	United Kingdom Program of Work	Aug-01
INSC/UK/Task 6/D/002	UK Testbed for INSC Task 6: Mobility	Feb-03
INSC/Task 6/D/002 (draft)	Mobile ad-hoc networks: Military Relevance and Operational Scenarios (IT/UK)	May-03

NC3A Task 6 Documents

INSC/NC3A/Task 6/D/001	Border Gateway Issues for Mobile Ad Hoc Networks	Jun-01
INSC/NC3A/Task 6/D/002	Mobility Categories for INSC	Oct-01