

# MANET Gateways: Radio Interoperability Via the Internet, Not the Radio

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## ABSTRACT

The objective of the DARPA Network Centric Radio System Program was to design, develop, integrate, and demonstrate the enabling communication technologies and system capabilities required to enable network-centric warfare. NCRS is a first-generation mobile ad hoc network designed to enable ground and airborne vehicle based on-the-move and on-the-halt network-centric connectivity using both IP and non-IP enabled devices. It demonstrated a gateway architecture that can offer radio interoperability among various current, future, coalition, and first responder communications radios via the network, not the radio. This capability illustrated a new dimension for communications interoperability for radio systems developers.

## INTRODUCTION

The focus of debate throughout the commercial, public safety, and military communications research communities has been on the mechanisms to enable inter- and intra-community communications interoperability. Previous attempts at providing such interoperability have focused on the physical layer by creating an “interoperability band” and a single “interoperability waveform.” The onset of wideband devices and digitally addressable analog components has recently provided a new approach in software definable radios (SDRs). The SDR approach has faced numerous technical and affordability challenges. A new approach is both possible and necessary for providing interoperable radio systems without reliance only on physical layer techniques.

The military desires highly interoperable radio systems. After Grenada, a GAO report [1] indicated that air support operations between the Army ground forces and Marines were hampered due to the incompatibility of their radios. These shortfalls continued through to the 1990 Persian Gulf War, as described in a 1992 report to Congress [2] that described the problems in establishing an interoperable network across disparate

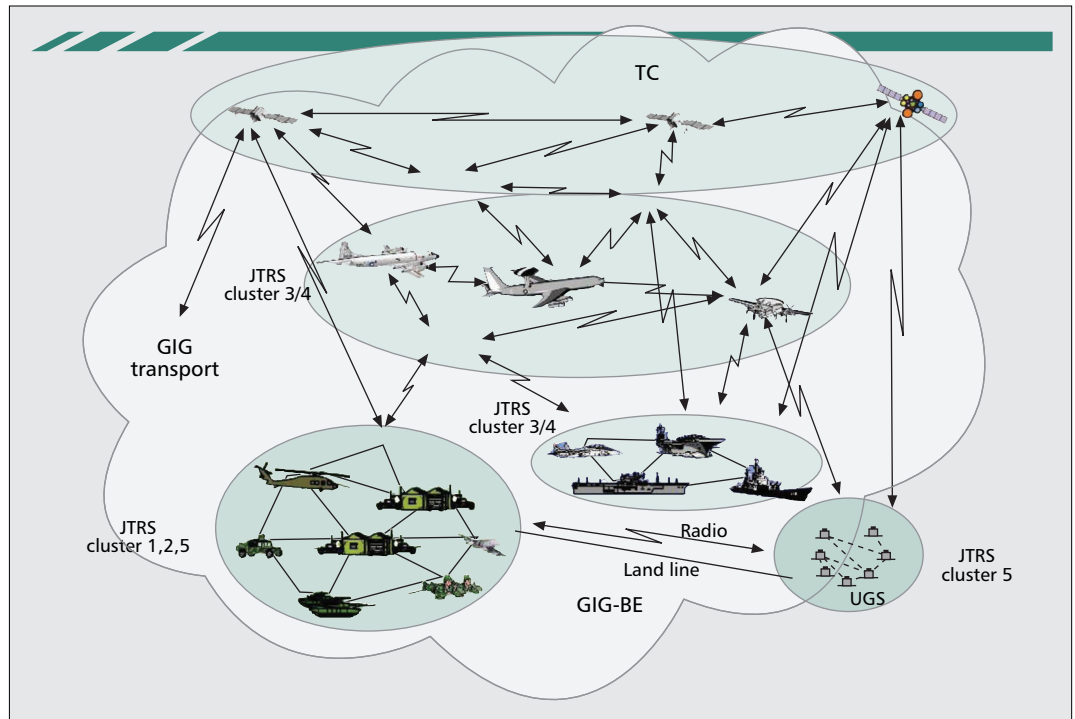
communications systems. Interoperability enables information to be directly exchanged among multiple organizations. These same issues are also prevalent in the non-military communications systems used for public safety organizations.

Early in the 21st century, the focus of many military research efforts was on how to enable network-centric warfare (NCW). In particular, NCW was to allow warfighters to take advantage of all the available information within the battlespace in a rapid and flexible manner. The key enabler to this process was development of the global information grid (GIG) communications system [3–5]. The GIG is the network fabric with which to build a “systems of systems” to fulfill the ultimate goal of network-centric warfare. Mobile networking is one piece of the GIG and is built on the use of the interoperable Joint Tactical Radio System (JTRS) [6, 7]. The primary mechanism for interoperability for the JTRS has been the use of SDR features to provide physical layer compatibility.

As noted above, the more flexible and ubiquitous solution for interoperable communications comes from the physical layer and medium access control (MAC) adaptation obtained with SDR technology. Many of the technical challenges for SDR lie in their power efficiency, size, and cost [8, 9]. These challenges motivated the Defense Advanced Research Projects Agency (DARPA) to look at alternative technologies to enable interoperability in battlefield communications through the development of a network-centric radio system.

The DARPA Network Centric Radio System (NCRS) is a first-generation mobile ad hoc network (MANET) designed to enable ground and airborne-vehicle-based on-the-move (OTM) and on-the-halt (OTH) network-centric connectivity. Its dual high (above 10 GHz) and low (below 3 GHz) band operation would provide a comparable data rate and coverage area to the anticipated JTRS wideband network waveform (WNW) vehicle-based brigade and below communications, and Warfighters Information Network-Tactical (WIN-T) for above brigade communications, respectively.

Techniques applied at both channel access and routing components ensure prioritization of critical traffic flows and reliable delivery under both nominal and congested network states in changing service conditions.



■ Figure 1. Global information grid communications system.

It became clear in late 2003 that NCRS was missing the one capability that had been plaguing developers for the past few decades: radio interoperability at the tactical level. NCRS was then modified to enable gateway architectures that offered interoperability among various current, future, coalition, and first responder communications radios, via the network, not the radio. This represented a radical departure from the traditional physical layer interoperability that is described above.

This article describes the development of a network-centric radio system including the challenges associated with providing the networking of heterogeneous nodes, network scalability, and use of efficient protocols.

## THE DEVELOPMENT OF A NETWORK CENTRIC RADIO SYSTEM

The DARPA Network Centric Radio System (NCRS) Program designed, developed, integrated, and demonstrated the basic enabling communication building blocks and system capabilities required to enable NCW. Figure 2 is the demonstrated capabilities of the initial NCRS in both low (below 3 GHz) and high band (above 10 GHz) operations during a demonstration in August 2003.

Additional network capabilities of the NCRS are evident when compared to currently deployed military communication systems:

- The incorporation of *adaptive modulation* on a per link basis continually maximizes multimegabit data rate for given link and network utilization conditions. Assured network connectivity upward of ranges up to 150 km for air-to-air and air-to-ground line-of-sight is achieved using an extended range waveform mode for wide area missions.

- The *network flexibility* of NCRS offers adaptation to a wide range of deployment scenarios, applications, and traffic types. Preliminary studies of current tactical network planning for systems such as Force XXI Battle Command, Brigade-and-Below (FBCB2)<sup>1</sup> suggests potential improvements to eliminate up to 12 of 13 database tables and upward of 150,000 entries used for network routing. Inherent to MANET protocols used in NCRS is a high level of adaptation to the dynamics of topology, network membership, and link conditions. Thus, the networking overhead is streamlined to localized links.
- Techniques applied at both channel access and routing components ensure *prioritization* of critical traffic flows and reliable delivery under both nominal and congested network states in changing service conditions. Unicast and multicast routing protocols in NCRS rapidly adapt to changing topologies for effective traffic dissemination in support of existing and emerging user applications.

In late 2003 modifications were made to NCRS to enable radio interoperability at the tactical level. The NCRS architecture now included gateways. Thus, NCRS is compatible with Transformational Communications Architecture (TCA), and offers interoperability among various current, future, coalition, and first responder communications radios via the network, not the radio.

In January 2006 a set of unscripted experiments were conducted. The nodes were deployed as military units including a mechanized infantry battalion, with battalion and company units. This heterogeneous mix of communication systems were interconnected using the Condor system

<sup>1</sup> FBCB2 will provide situational awareness and command and control to the lowest tactical echelons. It will facilitate a seamless flow of battle command information across the battlespace, and will interoperate with external command and control and sensor systems [10].

Initial NCRS metrics	Goals		Demonstrated	
<b>20-node average aggregate network throughput</b> –Low Band –High Band	<b>Anti jam performance</b> 200 kb/s 1 Mb/s	<b>High data rate performance</b> 10 Mb/s 70 Mb/s	<b>Anti jam performance</b> 203 kb/s 24 Mb/s	<b>High data rate performance</b> 10.3 Mb/s 50 Mb/s
<b>Beam pattern</b> –Low band –High band	45°AZ 4.5° EL × 12°AZ		39°AZ 4.5° EL × 12° AZ	
<b>Processing gain</b> –Low band –High band	40 dB 14 dB		41.6 dB 19.4 dB	
<b>Network latency</b> 10% of the average system load (< 200 ms) 30% of the average system load <1 s) 60% of the average system load (< 30 s)	90.0% 90.0% 90.0%		90.0% 88.8% 98.9%	
<b>Transition between high band/low band</b>	<1 s		1 s	
<b>Packet delivery</b> 10% of the average system load 30% of the average system load 60% of the average system load	90.0% 90.0% 90.0%		75.0% 73.8% 88.3%	
<b>20-node network initialization time</b>	< 6 min		2 min	
<b>Node entry time</b>	< 30 s		10 s	
<b>Detect node exit time</b>	< 10 s		5 s	

■ **Figure 2.** Demonstrated capabilities of initial NCRS low and high band operations, August 2003.

[11] in which IP routers automatically routed application data between the various elements using the most efficient routes and radio systems.

Applications that were supported by the DARPA NCRS network included Command Post of the Future, video data streams from IP cameras on selected network elements, IP chat, voice over IP (VOIP), and network maintenance data. But more important, interoperable communications was demonstrated among the following digital and analog systems during those experiments: Cisco VoIPs, the ITT Soldier Radio, the Enhanced Position Location Reporting Systems (EPLRS), HAVEQUICK I/II (PRC-117), the Single Channel Ground and Airborne Radio System (SINCGARS/PRC-119), and the High Frequency MAN-PACK Radio (HFMR/PRC-150). Here is a summary of the key demonstration achievements:

- Demonstrated rapid autonomous MANET formation and maintenance during tactical mobility scenarios (self-forming and self-healing)
- Demonstrated link ranges in excess of 60 km at full 5 Mb/s data rate (terrain/geometry-dependent)
- Demonstrated maximum link range at lower but operationally useful data ranges demonstrated to over 120 km (e.g., 800 kb/s at 150 km during one test)
- Demonstrated adaptive data rate (ADR),

also known as adaptive modulation, shifts between link data rates to maintain reliable data transfer under changing link conditions

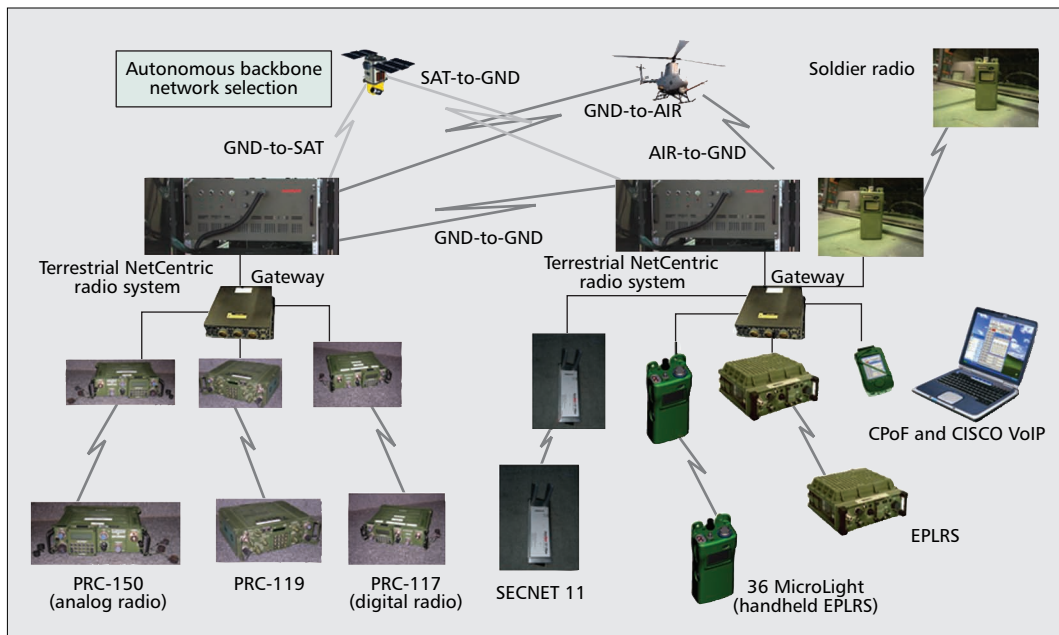
- Demonstrated low-latency multihop relay capability with adaptive throughput under changing link conditions, including arbitrary airplane, helicopter, and vehicle speeds

## HETEROGENEOUS VS. HOMOGENEOUS NETWORKING

The first challenge to address is the fundamental issue associated with using homogeneous node types or a mixture of node types. The current wired Internet is based on a common Internet protocol and a robust routing table capability. Routing tables are fairly static and change only over long timescales.<sup>2</sup> Therefore, most wireless networking technology has exploited the static homogeneous characteristics of the wired Internet. Military mobile networks exhibit a significant number of differences to the wired Internet. Mobile networks are actually a *network of networks* in both physical instantiations and network structure. Mobile networks operate and interface between unattended ground sensors, pedestrians, ground vehicles, low altitude aircraft, ships, high altitude aircraft, and satellite platforms. Each platform has different characteristics in mobility, available power, line-of-sight, latency tolerance, and so on. Each of the platforms exhibits differ-

<sup>2</sup> Mobile IP is a solution for introducing mobility for IP and routing tables. It uses an intermediate device/server to allow the routing tables to remain static, and the endpoint addressing is morphed to a temporary IP address to reflect its current attachment point in the network. In essence, it has two IP addresses: one static, one dynamic.

Coalition networks have the additional attribute that the waveforms and protocols are not common and thus negotiations are needed within the physical, MAC, and network domains. Routing, especially for secure communications, becomes problematic.



■ Figure 3. Simplified network architecture.

ing networking requirements, which places challenges on the interfaces between them.

Network of networks architectural challenges are in three operational domains: within an individual network, within network-to-network connectivity, and between coalition networks. The network scaling issues are commonly addressed in the literature. We address the additional complexities that occur with cross-networking and coalition networking.

*Network-to-network connectivity* has the additional challenge of disparate physical layers between networks that will require real-time continual adaptation and conversion between modalities (e.g., radio frequency [RF] and optical), waveforms and protocols. A gateway connects disparate nodes with differing physical attributes, waveforms, and protocols. One specific challenge is the routing and quality of service (QoS) constraints when attempting to route across networks with different capacities. The problem of transmitting a video stream across a broadband link followed by a narrowband link needs to be addressed. However, should it be addressed at the application layer (i.e., send fewer bits across the network via judicious selection) or the network layer (i.e., reduce the number of bits at the high-low bandwidth interface), or should we just let the QoS be exceedingly poor?

*Coalition networks* have the additional attribute that the waveforms and protocols are not common; thus, negotiations are needed within the physical, MAC, and network domains. Routing, especially for secure communications, becomes problematic. Coalition partners may not wish to provide detailed routing information of their network to a potentially untrusted partner; thus, new schemes are needed to provide a usable networking interface.

Heterogeneous mobile networking systems require techniques that can discover, translate, and negotiate within gateway-level architecture; these are described in later sections.

## HETEROGENEOUS NETWORKING ARCHITECTURE

The NCRS architecture addresses heterogeneous networking by providing a terrestrial backbone network for feeder stub networks integrated through heterogeneous network gateways. Airborne relays were used to provide broadband connectivity at ranges greater than 10 km. Lower data rate SATCOM terminals were used to maintain beyond line-of-sight (BLoS) connectivity during infrequent airborne relay outages. Each node autonomously selected the best available backbone network. Heterogeneous mixtures of legacy and updated stub networks (PRC-150, PRC-119, PRC-117, SECNET11, Soldier Radio, EPLRS, and MicroLite) were used for small unit tactical communications. All voice, video, and data traffic was transported between feeder networks over the backbone network. Figure 3 depicts the simplified network architecture where the vehicular node provided the autonomous backbone network selection between terrestrial and satellite paths.

### NET-CENTRIC RADIO SYSTEM

The terrestrial net-centric radio system provides the backbone for the radio gateways and incorporates a flexible design. Antennas are connected to an RF distribution module that contains the necessary RF filters, switches, attenuators, and power and low-noise amplification for high dynamic range operation. An FPGA-based receiver/exciter module performs digital up/down conversion and orthogonal frequency-division multiplexing (OFDM) waveform modulation and demodulation with reference timing from the GPS/Rubidium timing subsystem. MAC and datalink neighbor discovery, QoS, and scheduling functions are implemented on a general-pur-

pose processor (GPP). MANET routing functions run on a separate GPP.

Each node is GPS synchronized for uniform network timing. A Rubidium oscillator enables operation during GPS outages. An omnidirectional antenna for horizon and low elevation coverage, and an overhead coverage antenna (or ground coverage for airborne radio deployments are power combined for hemispherical coverage.

## WAVEFORM MODES AND ADAPTIVE DATA RATE

The waveforms implemented within the net-centric radio system are critical to provide malleable performance based on physical layer constraints (range, interference) and networking requirements. The radio modem implements a half-duplex slotted time-division multiple access (TDMA) frame structure with 5.8 ms slots. The waveform modes used a combination of different modulation, waveform coding, and bandwidth settings to achieve the desired trade-offs between data rate and receiver sensitivity. A node either transmits or receives on each time slot. When transmitting, one of seven possible OFDM-based waveform modes can be sent. The receiver modem autonomously discovers the transmitted waveform mode upon reception so that the transmitter may select the waveform mode without closed loop feedback. The waveform is capable of modulating from one to six non-overlapping 1.2 MHz wide frequency segments. Segments are placed within a 20 MHz bandwidth span and may be *discontiguous* to support fragmented spectrum allocations. The adaptive data rate (ADR) capability incrementally steps through increasing data rate modes as supported by link conditions.

The system automatically maintains the highest supportable data rates to all neighbor nodes. ADR independently adjusts the mode to every neighbor node in real time to maximize operating range and data throughput. The ADR algorithm accomplished this via closed loop mode control based on signal-to-noise ratio (SNR) at the receiving node and link packet error rates. Independent modes are maintained on each direction of every link.

## SCALABILITY OF MANETS

Although the architecture depicted addresses many of the issues of network and node heterogeneities, scalability for data routing remains as the primary challenge for MANETs. Mobility creates topology changes, causing an increase in network overhead and thus making a serious demand on network resources to maintain accurate routing tables. Military systems, especially unattended ground sensors (UGSs) and dismantled soldiers, represent the greatest challenge because of serious power limitations as well as the need to scale to thousands of nodes.

All communications systems have trade-offs in capacity, which is a function of numbers of users, SNR, and data rate/bandwidth (the Shannon limit). For example, TDMA allows a subscriber access to the peak data rate/bandwidth

only for a small interval of time (slot) allocated among many users. As the number of users goes up, the number of slots accessed goes down. The limitation comes when there are not enough slots to service the data rate needs of all users, causing the data to be buffered at each transmitting node.<sup>3</sup> The bottom line: classical communications systems do not have unlimited scaling.

How would one fix this situation? One uses directional antennas like instantiations of NCRS at frequencies above 2 GHz, as well as natural terrain masking to allow groups behind trees, obstacles, and so on to improve frequency reuse. Also, airborne relays ("cell tower") and satellite communications can also help frequency reuse via over the horizon masking of the LOS signals. Thus, one can build up tiered network architectures to provide better scaling for the network.

Thus, MANETS do not scale not because of the lack of a robust addressing scheme, but rather because the resulting data rate for a large group of users will be too low to be useful for most real applications given the normal frequency allocation in practice. Unless one is spectrum rich, all communications systems will suffer this limitation.

## NETWORKING PROTOCOLS

The networking protocols implemented in the NCRS includes MAC and networking protocols to support MANET operation in the terrestrial segment, QoS prioritization, unicast and multicast routing, and Transit Net for heterogeneous networking and autonomous backbone route selection.

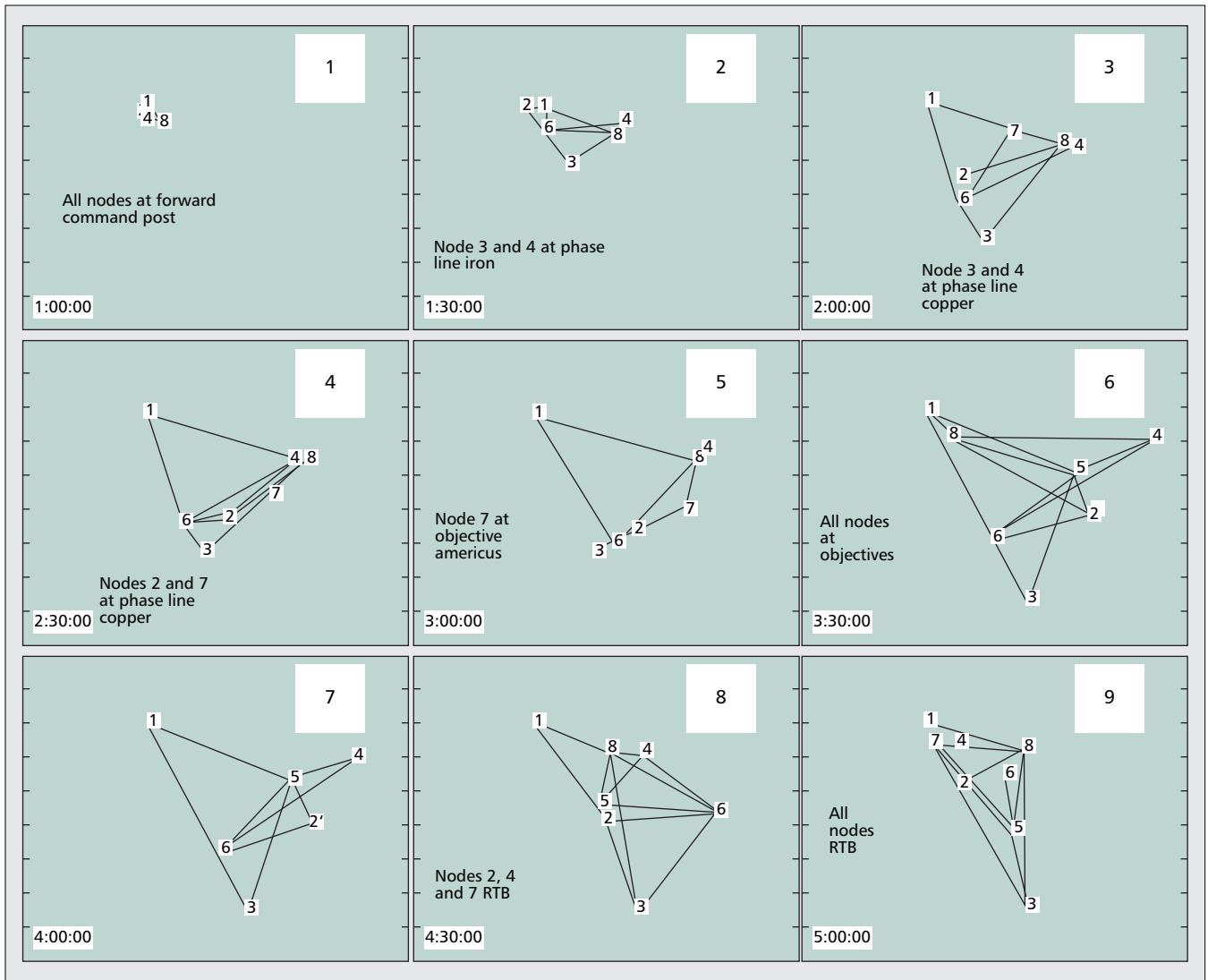
The NCRS networking protocols operate at open systems interconnection (OSI) model layers 3 and below. The network layer enables unicast and multicast routing using Scoped Link State Routing (SLSR) and Receiver Oriented Multicast (ROM), respectively [12]. The data link layer includes a neighbor protocol (including neighbor discovery) and the MAC protocol. The MAC uses a node activated multiple access (NAMA) protocol to dynamically schedule time slot transmissions. NAMA is a topology-dependent MAC protocol that uses the node identifiers, link data rate mode, and bandwidth requests of the one- and two-hop neighbors as parameters in a pseudo-random function for channel access scheduling [13]. This approach effectively enables coordinated, collision-free scheduling that is responsive to changing network demand with minimal overhead.

The protocol suite is quality of service (QoS) aware at the network and data link layers to accommodate applications developed with QoS support in the standard TCP/IP protocol suite. Priority queuing is performed at both the network and MAC layers. In the data link portion of the MAC, separate queues are maintained for each neighbor with a separate queue for each data rate and QoS level. Data is chosen for transmission in decreasing order from highest QoS/highest data rate to lowest QoS/lowest data rate.

To allow nodes to find their neighbors, and maintain knowledge of the two-hop topology of

*Military systems, especially unattended ground sensors (UGS) and dismantled soldiers, represent the greatest challenge because of serious power limitations as well as the need to scale to 1000's of nodes.*

<sup>3</sup> Cellular systems have slightly better capacity because of frequency reuse over distance, closely spaced towers, and power control, but they still suffer from the same peak capacity limitations in a limited area.



■ **Figure 4.** Topology progression during demonstration.

their neighborhood, periodic broadcast time slots are allocated to a neighbor protocol. These time slots, or control slots, are used by the neighbor protocol to send control packets to update neighbor information. No explicit acknowledgments of the transmissions are needed. Periodic transmissions of the neighbor data ensure delivery of consistent information across the two-hop neighborhood.

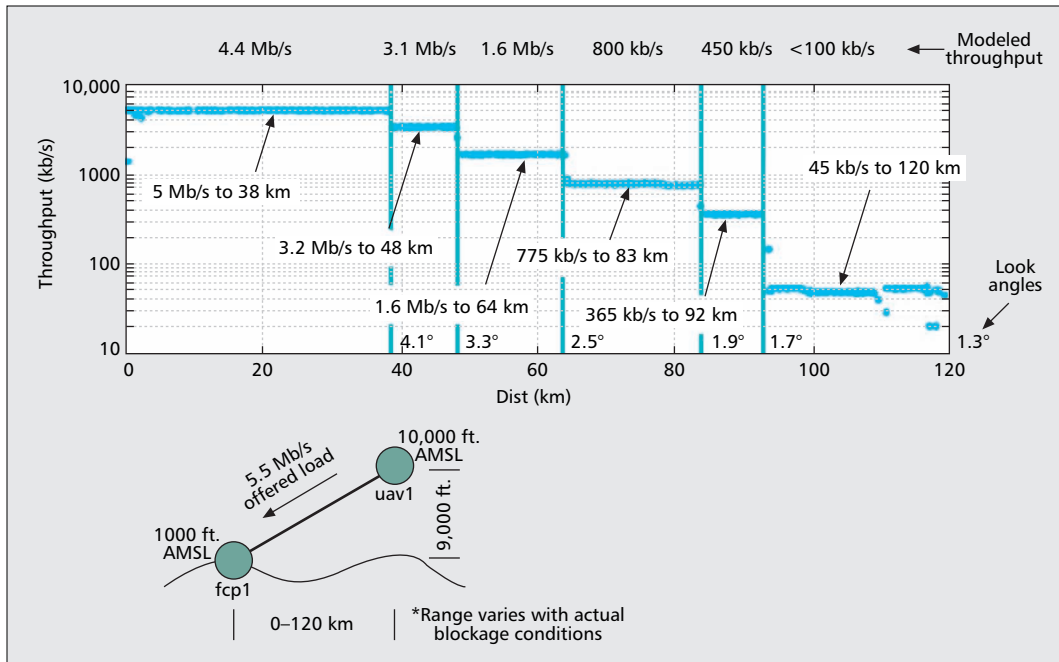
The NCRS uses a Scoped Link State Routing (SLSR) algorithm for unicast routing. SLSR introduces the concept of multi-level scoping to reduce routing update overhead in large networks. Each node stores the topology information in a topology table. Route updates are computed using the Dijkstra Shortest Path First algorithm [14]. The route on which the packet travels progressively approaches the true shortest path as the packet gets closer to its destination.

The SLSR implementation has the capability of learning of its one-hop neighbors using a hello protocol between peer routing processes or directly from the data link portion of the MAC. By reusing the neighbor information from the

data link, the SLSR control packet overhead is reduced since there is no need to re-send the inter-scope messages to the one-hop neighbors.

The NCRS uses Receiver Oriented Multicast Routing (ROM) for multicast routing. It applies on-demand routing techniques to avoid channel overhead and increase scalability. It uses the concept of a forwarding group, a set of nodes that is responsible for forwarding multicast data, to build a forwarding tree for each multicast group. The forwarding group infrastructure reduces storage overhead and can handle much looser connectivity among multicast members. The reduction of channel/storage overhead and relaxed connectivity improve ROM scalability for large networks and stability for mobile wireless networks.

ROM is an example of using a forwarding group multicast protocol (FGMP) that improves on its predecessors by exploiting a receiver advertisement scheme which is more efficient than a sender-receiver advertisement scheme. ROM can coexist with any unicast routing protocol since it finds its own routes independently. ROM is required in full when used in conjunc-



■ **Figure 5.** Adaptive data rate (ADR) performance.

*Neighbor discovery and maintenance is critical to maintaining traffic flow in a dynamically changing network. These features provide the link level connectivity that is used as the basis to determine network routing and assure that traffic is routed over the most advantageous paths/links.*

tion with on-demand unicast routing protocols.

The NCRS contains a network layer routing function capable of both routing within the terrestrial backbone net-centric radio network and sharing the route information to a commercial off-the-shelf (COTS) router for delivery of data to external destinations. This capability includes mechanisms employed to share unicast and multicast route information between the router embedded in the net-centric radio and a COTS router. The external networking routes are determined using SLNR with the Internet Engineering Task Force (IETF) standard wired Internet routing protocols (e.g. RIP, OSPF, BGP) to support routing over multiple wireless and wired networks. This function is also called Transit Net.

## NET-CENTRIC RADIO PERFORMANCE

The NCRS development culminated in experiments during January 2006. These experiments included 14 network nodes (8 NCRS-equipped nodes) at Fort Benning, Georgia. The nodes were deployed as a mechanized infantry battalion. The exercise, dubbed “DNC-E Operation Long Haul,” is summarized below and depicted in Fig. 4.

The exercise spread the radio network over a roughly 100 km × 100 km area, with air-ground link distances of up to 62 km. Throughout the exercise, including maximum range operation, all nodes maintained network connectivity for the vast majority of the operation. Based on route availability data, Node 1 (top center) maintained complete network connectivity for over 99 percent of the exercise period. Operator reports of “virtually outage free” corroborate this high level of observed network availability.

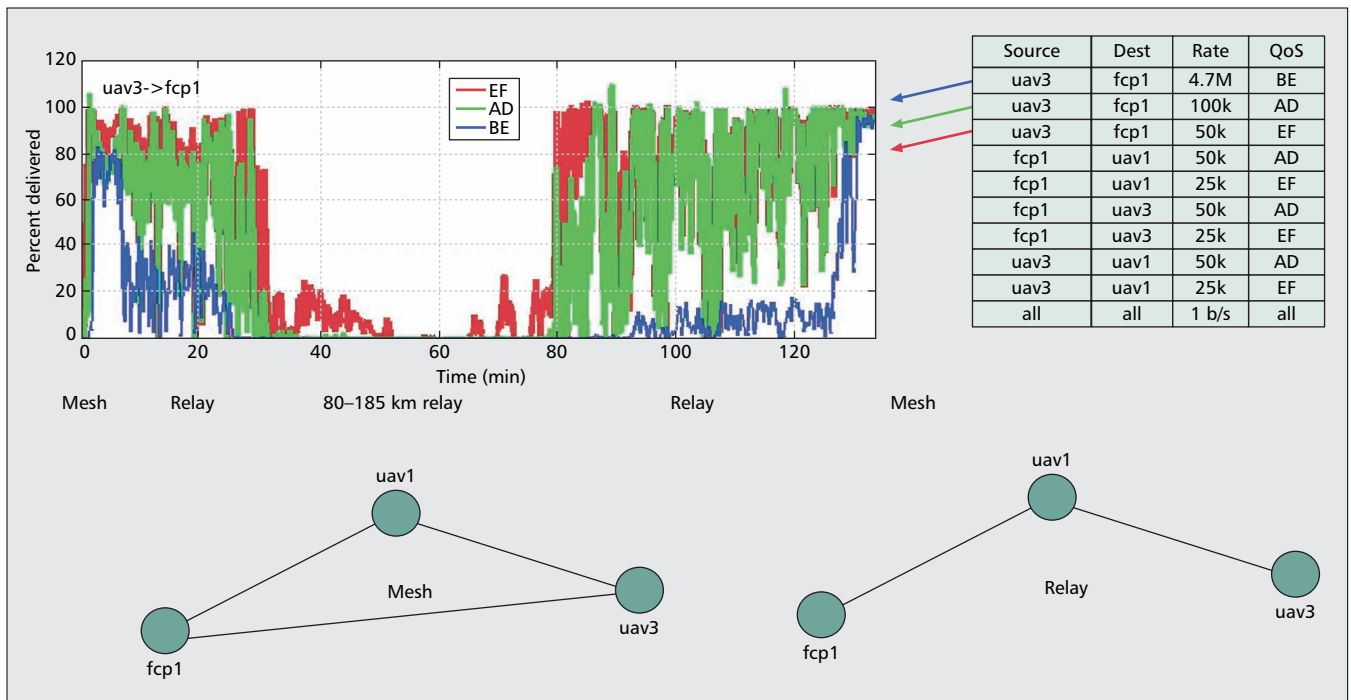
Neighbor discovery and maintenance is critical to maintaining traffic flow in a dynamically changing network. These features provide the

link level connectivity that is used as the basis to determine network routing and ensure that traffic is routed over the most advantageous paths/links. The operational exercise demonstrated neighbor discovery and maintenance during worst case highly mobile conditions. Figure 4 shows a time-sequenced frames of operation in a roughly 100 km × 100 km operational box. Links (represented by solid lines) were frequently changing with respect to both neighbors and data rate modes. The neighbor discovery and maintenance functions clearly worked as desired to maintain the network in this dynamic environment.

The exercise included two 500 kb/s video feeds: one from the UAV (Node 8) that was sent to Node 1; and one that was sent from Node 2 to Node 1. The UAV video feed was sent via a direct single-hop air-to-ground link throughout the exercise. The video stream from Node 2 was sent via a two-hop ground-air-ground relayed link when the node was deployed. When Node 2 was at or close to Node 1, the video was delivered directly via a single-hop ground-ground link.

Throughout the duration of the exercise the one-hop UAV video was received error-free approximately 91 percent of the time. The 9 percent of operation with errors resulted in occasional degraded performance such as tiling and smearing, although the video was rarely completely lost. Transmissions that included two-hop relayed video were received error-free approximately 75 percent of the exercise period. This produced more incidences of tiling and freezing due to the higher number of errors.

The NCRS adaptive data rate (ADR) capability allowed seamless switching between the seven radio data rate availability modes as dictated by range and propagation conditions. This allowed the radio system to maintain network connectivity and data exchange even as pairs of nodes exceed-



■ Figure 6. Topology progression during demonstration.

ed the usable link range for the higher data rate modes. Throughout the testing, ADR independently choose the highest reliable data rate mode for each link.

Figure 5 again shows ADR operation on a two node air-to-ground link on a typical air-to-ground reconnaissance scenario test where the air node flew out to a distance of 120 km. As the UAV node flew away, ADR automatically stepped down the data rate to maintain network connectivity and data exchange out to the maximum data range. At each step, delivered throughput compares favorably with modeled performance projections. Figure 6 shows packet delivery percentages for different QoS types as nodes maneuvered from a mesh topology to a relay topology with increasing separation and then returned to the original mesh topology. As the nodes moved away from one another, the ADR algorithm adjusted to maintain connectivity at a lower overall link and network capacity.

The system was found to provide efficient and robust forwarding of multicast datagrams. Multicast routing trees were formed and maintained throughout the test and demonstration runs, while data was forwarding along the trees such that the number of transmissions required to disseminate the data was minimized while ensuring that all nodes able to receive the data (based on bandwidth and QoS constraints) did receive the data. As expected from design considerations, some duplication of multicast packets was observed due to network topology and data rate changes.

## SUMMARY

The objective of the DARPA Network Centric Radio System Program was to design, develop, integrate, and demonstrate the enabling commu-

nication technologies and system capabilities required to enable network centric warfare. NCRS is a first-generation mobile ad hoc network designed to enable ground and airborne-vehicle-based on-the-move and on-the-halt network-centric connectivity. It demonstrated a gateway architecture that offers radio interoperability among various current, future, coalition, and first responder communications radios via the network, not the radio. This capability achieved reliable data transfer under dynamically changing link conditions and node topologies while maintaining prioritized quality of service. Link ranges in excess of 60 km were demonstrated at the full 5 Mb/s peak user data rate with connectivity maintained to distances over 120 km using airborne relays performing a “communications-primary” mission.

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## BIOGRAPHIES

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