Extreme Wirelessing: Prototyping a Future Global Network

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"The best way to predict the future is to invent it."
Alan Kay

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Note:

In compliance with the FIND solicitation, we are submitting two pages of our vision, current and future work, and its compatibility with the objectives of the FIND program. The rest of the 15 pages are included as supporting material, as requested.

1. Wireless Component of a Future Network: Vision

We envisage the transmission media of a future global network to be optical fiber at the core and radio through air – thus enabling wireless networks to extend the global connectivity to the edges. In this paper, we focus on the latter aspect of the network, the wireless component.

BBN Technologies is one of the world's centers of expertise in mobile ad hoc network and sensor technologies. We propose to bring this expertise to the FIND program, thereby contributing BBN's innovative ideas and experience in architecting and building these systems to the design of the future global network. Central to BBN's work is the strong belief that we, the research community, are a long way from achieving the potential of data networks built on highly configurable radios. Based on current and past work, BBN believes that in the next ten years the capabilities provided by emerging new wireless technologies will expand dramatically to enable:

- *Energy efficient radios and networks* composed of such devices that use 200-300 times less energy to achieve the same effective data rates as today's state of the art
- *Content-aware* as well as *location-aware networks* – the flexibility to exploit location information when possible or binding the node or subset of nodes by requested content
- *Fault tolerance during disruption of service* -- delivering content in the face of substantial node or network failure
- *Scalability* in both, geographical span and clustering density, so as to exhibit sustained performance
- *Adaptability to dynamic spectra and dynamic waveforms* – radios that can be programmed to operate at many points in the RF spectrum and use MIMO and spectrum awareness and agility to maximize the use of the available spectrum
- *Cognition* on both, the level of an individual radio, and the ad hoc network – this enables adaptability to different application domains
- *Self-organizing radio networks* composed of thousands or millions of nodes that use less than 5% of their bandwidth for coordination yet are highly stable in their connectivity
- *Flexible layering* in re-examining not only the functionality to layer mapping, but allowing this mapping to be reconfigured on the fly
- *AND affordable*, low cost radios for under $100 -- for most of these applications the current costs are prohibitive

The future evolution of mobile ad hoc and sensor technology is inextricably intertwined with that of the overall global network. Network layer solutions can no longer be thought independent of the underlying radio technology. In order to fully realize the potential of the capabilites listed above, we need a network architecture that accommodates many different kinds of wireless networks and physical layer technologies in a flexible manner. Our vision for this is an architecture built in a *composable* manner, where a variety of end-to-end requirements are met by dynamically combining the capabilities offered by wireless technologies. Central to this is the use of a software radio that hosts *cross-layer protocols* that can evolve as new, composable modules along with the requirements of the overall global network.

Software defined radios can further exploit and redefine our notions of how to build sensor networks (imagine replacing Motes with the equivalent of a mainframe attached to a low-end SONET link) and ad hoc edge data networks (imagine self organizing, cognitive and fault tolerant radios reconfiguring the functionality of their layered protocols on the fly).

2. Extreme Wirelessing: Prototype!

Our research is focused on making this vision a reality. Under contracts with DARPA, NSF and the DOD we have, or are building, most of the components. To this end, BBN has not only been exploring novel architectures and designing protocols, but most notably, developing prototypes as well as building deployable systems for real life applications. We agree that it is time for a clean slate approach to building a global network. We also think it is imperative to have hands-on experience in the novel architectures researchers are proposing. Analogous to the rapid prototyping approach of *Extreme Programming* [21] for engineering complex, large scale software systems, our research is geared toward *Extreme Wirelessing* -- rapid prototyping for the architectural innovations we propose and design. It is our strong belief that such hands-on experience with novel architectures is critical in converging on an architecture for FIND's global network effort. What worked and what didn't? And why?

Currently, under NSF's CRI grant, together with our collaborators from Harvard University, we are building CitySense, a sensor network with a plug-and-play architecture, consisting of 100+ streetlight-mounted sensor nodes, along the streets of Cambridge, MA, each equipped with a meteorological sensor package for environmental monitoring and a realtime web access. It not only serves the research community as a scalable, open real-time testbed, but is also engineered for pedagogical K-12, and meteorological applications. Our SPINDLE project, under DARPA's DTN program, has architected and built a plug-in disruption-tolerant wireless network, with content-aware access to information utilizing a declarative-language, cognitive approach.

Our JAVeLEN project, under DARPA's Connectionless program, has built radios that use 100 times less energy and yet achieve better effective data rates than ad hoc 802.11 networks using the OLSR standard. Under DARPA's WANN program, we are building MIMO software defined radios with RF spectrum agility, hundreds of megabits in link capacity, and a price target of $500 per unit. Under the DARPA ACERT program, our ADROIT project contributed to open software radio development. It also demonstrated the use of cognition to understand a radio's local environment, as well as flexible layering by designing dynamically composable wireless media access layers and data transmission stacks. Under other programs we are developing novel radio waveforms and exploring the possibility of radio networks with little or no overhead traffic.

3. FIND Meetings Participation

Leading these efforts are some of our top networking researchers: Jason Redi (JAVeLEN, MIMO), Rajesh Krishnan (SPINDLE), Greg Troxel (ADROIT), Joshua Bers (CitySense), Ram Ramanathan (JAVeLEN, MIMO, SPINDLE, ADROIT) and Craig Partridge (ADROIT, JAVeLEN).

Rather than asking FIND to invite all of these researchers to meetings, BBN proposes to have ***two attendees*** *at each FIND meeting*. One of these attendees will be Dr. Nadia Shalaby who will serve as our designated primary contact with FIND. At each meeting, one of our senior wireless research staff will accompany Nadia -- the particular individual to be chosen based on her estimate of whose expertise is most relevant to the anticipated discussions.

In what follows we summarize BBN's expertise in the wireless networking arena and list some of our senior researchers and their experience. We propose to draw our ambassadors to the FIND meetings from this list. Subsequently, we present a summary of the relevant BBN projects, outlining the programmatics and funding, central concepts, core architecture and the notable contributions for each of these projects.

4. Attendees and Expertise

BBN Technologies has a history of pioneering networking research in proposing innovative networking architectures, designing protocols, establishing standards and deploying networking systems technology. Notable examples include ARPANET, NTDR, JTRS and Quantum Cryptography. We currently focus on BBN's central role in the domain of wireless ad hoc, and sensor networks, where its research has continued to be innovative in introducing alternative, and often disruptive, technologies, thereby deviating from the more traditional, status-quo preserving path. We outline the key personnel leading these efforts.

Mr. Joshua Bers is a Senior Engineer at BBN Technologies, where he co-leads the design and deployment of CitySense, a large scale wireless sensor testbed in the Boston area, and is currently the lead software architect on Future Combat Systems Network Management System (FCS-NMS) project. Mr. Bers has also been a core contributor on Cougaar, a networking middleware layer for monitoring and controlling distributed robotics, and has been the PI for a comparative study of approaches to distributed information management for the FCS program. His research interests include multimodal human-computer interfaces and distributed systems architectures as applied to robotics, wireless ad hoc networking and network management. Mr. Bers is the author of several research publications and holds a M.S. from MIT in 1995.

Mr. Chip Elliott is Principal Engineer at BBN Technologies, where he leads the design and implementation of novel networking systems. He is an IEEE Fellow with over 85 patents issued and pending. Most recently he has led DARPA's design and build - out of the world's first quantum cryptography network - 10 optical nodes across metro Boston providing highly secure key distribution non-stop through both telecom fibers and the atmosphere. He has previously led the design and implementation of large-scale, mission-critical "ad hoc" radio networks now used in nearly a dozen nations including the United States, UK, and Canada. He received Frost & Sullivan's Award for Excellence in Technology (2005), is a Fellow of the World Technology Network, and a Finalist for the 2004 World Technology Award for his leadership in quantum cryptography. Mr. Elliott has also served on a number of national advisory panels, including the Defense Science Board, Naval Studies Board (National Academy of Sciences), Army Science Board, and the Technical Experts Panel for Quantum Cryptography (DTO), and has held visiting faculty positions at Dartmouth College, Tunghai University in Taiwan, and the Indian Institute of Technology, Kanpur.

Dr. James Freebersyser is the Director for Advanced Systems at BBN Technologies with expertise in communications systems including terrestrial and satellite communications, internetworking, and mobile, wireless (ad hoc) networks. He has held industry positions at Honeywell Aerospace Laboratories, GE AstroSpace, and GTE Government Systems, and government positions in the Advanced Technology Office (ATO) of the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research, and the Army Research Office. He received his BS, MS, and PhD degrees in electrical engineering from Duke University, the University of Virginia, and North Carolina State University, respectively. While earning his Ph.D. he was a Palace Knight with the U.S. Air Force Rome Laboratory.

Dr. Rajesh Krishnan is a Senior Scientist at BBN Technologies where he successfully led a number of networking research efforts under funding from DARPA and NASA. Dr. Krishnan is the PI for the SPINDLE project, BBN's contribution to DARPA's DTN program. Recently, he was the lead architect for BBN's policy language framework for opportunistic spectrum sharing for the DARPA XG program. His earlier work includes: investigation of mechanisms for enhancing transport layer performance over unreliable wireless and satellite networks (co-PI of NASA-funded ETEN project); study of eventual connectivity algorithms for survivable networking (task leader on DARPA-funded SUMOWIN project); and investigation of latency-aware adaptation of web applications in episodic and weakly connected environments (a key contributor to DARPA-funded WVM project). He has co-authored several networking publications, holds a U.S. patent (#6,127,799) and has several other patents pending. He is a member of the ACM, the IEEE, and the IEEE Communications Society. Dr. Krishnan obtained his M.S. (1996) and Ph.D. (2004) from Boston University.

Dr. Craig Partridge is a Chief Scientist at BBN Technologies and has led innovative networking research for twenty years. Dr. Partridge has recently focused his attention on problems of programmable spectrum use and is a key contributor to the WANN effort. Notable bits of work include designing how Internet email is routed, working with Phil Karn on TCP round-trip time estimation, and designing and building the world's fastest router in the mid-1990s. Craig has been an active member of ACM SIGCOMM and the IEEE Communications Society and chaired the National Research Council committee on how the Internet functioned on September 11, 2001. He has written over 25 journal and conference papers, and is the author of the book Gigabit Networking [18]. A Fellow of the ACM and the IEEE, Craig received his A.B., M.Sc. and Ph.D. degrees from Harvard University.

Dr. Ram Ramanathan is a Principal Scientist at BBN Technologies. He has more than 10 years of advanced research experience in MANETs and has been recognized as pioneering several areas – topology control, use of directional antennas, and scalable flat routing for MANETs. He has been the Principal Investigator for many DARPA programs including XG, FCS Communications, and Global Mobile Information Systems (GloMo). He has published over 30 refereed papers in international journals and conferences, including best paper award winning papers at IEEE Milcom, IEEE Infocom, and ACM Sigcomm. Ram received his M.S and Ph.D degrees in Computer and Information Sciences from the University of Delaware, in 1989 and 1992 respectively.

Dr. Jason Redi is a Division Scientist at BBN Technologies where he led many programs focused on the research, design, and field testing of ad hoc and sensor networks. Recent projects include the first demonstration of ad hoc network fully utilizing directional antennas, field demonstrations of large ad hoc networks for autonomous robots, and ad hoc networks which fully exploit MIMO technology. He is currently leading the DARPA Connectionless Networks program which is designing sensor network technology that uses orders of magnitude less energy than current systems. Dr. Redi is author of over 30 papers and patents in mobile communications, the Vice-Chair of ACM SIGMOBILE, General Chair of ACM SenSys 2005, and has served on many technical program committees including those for MobiCom, MobiHoc, and SECON. He was previously the Editor-in-Chief of ACM Mobile Computing and Communications Review (MC2R), and is on the editorial board of Ad Hoc Networks Journal, Wireless Communications and Networking Journal, and the International Journal of Ad Hoc and Sensor Wireless Networks. Dr. Redi is a senior member of the IEEE, ACM, Sigma Xi, Tau Beta Pi, and Order of the Engineer. Dr. Redi received a BS from Lehigh University, and an MS and Ph.D. from Boston University in 1998.

Dr. Nadia Shalaby is a Senior Scientist at BBN Technologies. She has co-led research in high performance parallel computing at Harvard University and Thinking Machines, as well as innovative network architectures at Princeton, where she led the Hierarchical Extensible Router project under the DARPA Active Networks program. Nadia has been a partner in a virtual router startup and has consulted for several institutions, such as the World Health Organization and the US AID program. This has provided her with a broad perspective of networking, from research to industry, and from networking paradigms in the operating system and hardware to networking support for high performance computing. Dr. Shalaby is the author of a dozen publications, has served on several conference program committees, and is the recipient of a Best Paper Award at the Active Nets conference, published in Lecture Notes in Computer Science. Dr. Shalaby received her Ph.D. from Harvard University in 1997.

Dr. Greg Troxel is a Division Scientist at BBN Technologies and has been the PI of ADROIT, designing adaptive and dynamic cognitive radio under DARPA's ACERT program. He also led several projects involving multicast routing over ATM and tactical IP networking, combining ad hoc networking at the subnet layer and IP mobility. Since 1995, Dr. Troxel's projects have been built on open-source operating systems, and has been accepted as a NetBSD developer. Dr. Troxel is one of 5 maintainers of Quagga, a GPL-licensed routing suite (OSPF, OSPFv3, BGP, RIP, and RIPng). Dr. Troxel's knowledge of radio propagation, RF design issues, DSP, networking, security, key management, and software engineering has enabled him to successfully lead the building of a unified platform for software radio networking. Dr. Troxel received his Ph.D. from MIT in 1994.

5. Relevant Work

BBN's long history in ad hoc networking began in the early 1980's with a key role in the Survivable Adaptive Radio Networks (SURAN) [2] program, producing the first comprehensive prototype system for battlefield networking of elements in infrastructureless, hostile environments. In the early 1990s, BBN played a crucial role in two programs: the U.S. Army's Near Term Digital Radio (NTDR), for which BBN developed scalable, adaptive networking[1]; and DARPA's Global Mobile Information Systems (GloMo). BBN completed two large GloMo projects: the Mobile Multimedia Wireless Network (MMWN) [3,4], and Density- and Asymmetry-adaptive Wireless Network (DAWN) [5,6,7,8]. These projects developed a number of technologies for real-time multimedia communication in large, dense and mobile ad hoc networks.

These early projects laid the foundation for BBN's emergence as one of the leaders in ad hoc wireless networking. As new and powerful wireless technologies emerged, BBN used its expertise to build faster and more adaptive networks by leveraging this technology. Recent projects in this regard include developing networking over beamforming antennas (DARPA FCS Comms); technology to support opportunistic spectrum communications (DARPA XG); and medium access control over MIMO links (DARPA MNM).

In addition to its work developing ad hoc networking systems, BBN has also been a "thought leader" in ad hoc networking research, often opening up new research avenues that the community is now actively pursuing. In particular, BBN has achieved recognition as the leader in the use of directional antennas for ad hoc networking [10,11,13], the development of energy

[1] NTDR was the first "real-life" ad hoc network, and was used by the Fourth Infantry Division in the recent Iraq war. It was built with ITT ACD as the prime contractor, with BBN supplying the network protocols.

conserving cross-layer protocols[12], and the concept of topology control[5,6,7], and scalable routing[8,9]. BBN's work has been deployed in a variety of systems. For example, the Hazy-Sighted Link state Protocol (HSLS) [8] developed by BBN is being used in on-going programs (e.g. JTRS WNW), and in community mesh networks [14] which were used to provide connectivity during the Katrina tragedy.

BBN is continuing its contributions to the state of art in mobile wireless ad hoc and sensor networking through a number of cutting edge research projects. These are described in detail in the remainder of this section. We hope to bring insights, protocols, experimental results and prototypes that emerge from these ongoing efforts into the FIND fold.

CitySense: An Open Urban Wireless Sensor Network Testbed

A. Programmatics

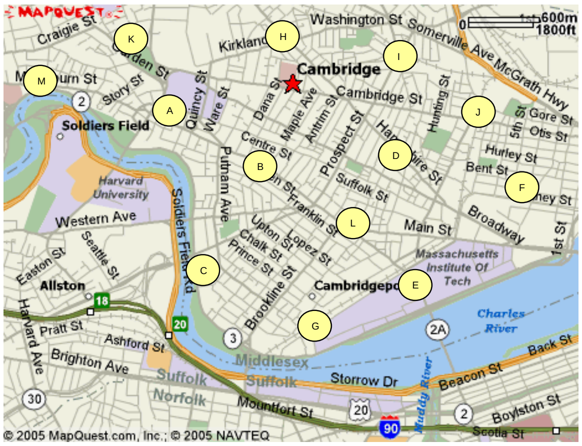
Customer: NSF CISE division, Computing Research Infrastructure grant (CRI)
Customer Program Manager: Rita V. Rodriguez
BBN Principal Investigator: Josh Bers
Co-Principal Investigators: Matt Welsh and Majid Ezzati of Harvard University
Contract length: September 2006 to August 2010
Collaborators: Harvard University

B. Concept

Wireless sensor networks have the potential to revolutionize the real-time monitoring of critical geographic areas such as cities, ports, refineries, electrical grids, and large government facilities. However, the daunting logistical challenge of experimenting with thousands of small, battery powered nodes has been one of the key limiting factors for research feedback and advancement. CitySense is a sensor network consisting of 100+ streetlight-mounted sensor nodes, mounted along the streets of Cambridge, MA, each equipped with a meteorological sensor package for environmental monitoring. The sensors will detect weather measurements, such as wind speed, direction, temperature, air pressure, relative humidity, and rainfall. Radios in the nodes will allow them to communicate across a mesh-network. All data collected will be freely available on the Internet in realtime. The network will also be an open testbed resource for the network research community worldwide, providing the opportunity to evaluate new algorithms for distributed sensor data processing and wireless networking in a real-world, large-scale, urban environment.

Unlike sensor networks addressed by our JAVeLEN technology, where battery life is a major design constraint, CitySense nodes are powered by city electricity, enabling a range of applications such as real-time environmental monitoring, correlating micro-climates with population health, or tracking the spread of bio-chemical agents. Initial plans for using the network include an urban air pollution study by the Harvard School of Public Health, as well as enabling school children to observe how urban-planning affects microclimates.

C. Architecture



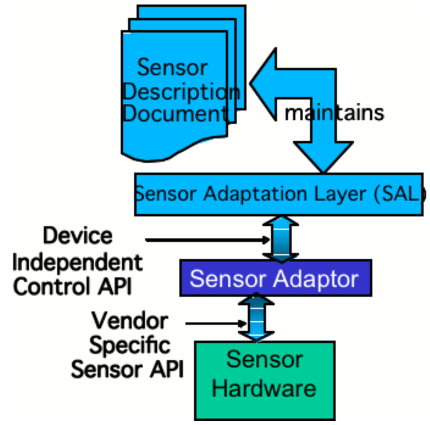


Figure 1: CitySense Plug-and-Play Sensors

We are designing an open, modular, plug and play architecture, for the network node, as shown above. This allows easy addition of new software. The Adaptation Layer defines a common meta-data (in XML) for sensors to declare themselves to shared infrastructure. Meta-data is used to allocate nodes to applications based upon their sensing requirements. Without the typical energy constraint, the sensor nodes will contain sufficient processing power and memory to handle a wide range of experimental software, plus 802.11 radios to interconnect all the nodes by multi-hop networking across Cambridge to its wireline access points. Each node comes with baseline Harvard/BBN software in flash to provide a robust sensor network architecture including reliable ad hoc networking. Other teams may use their own software, but the baseline remains in flash memory for automatic network restoration if needed.

D. Contributions

We are in the process of designing and building CitySense, which we envision to contribute to the research community and have a broader impact on society in a number of ways.

- We plan to use CitySense as an essential component of projects involving high-level programming models for sensor networks; effective techniques for resource allocation and sharing; and integration of sensor networks with Internet-based information systems.
- All nodes will be interoperable, but the plug-and-play architectures allows for easy hardware and software upgrades.
- CitySense will have significant impact on the development of large-scale wireless sensor network systems, by providing a permanent, extensible, public testbed. We will open CitySense to the broad sensor network research community, allowing external groups to remotely download their software images into all the nodes in the CitySense network, or into a sensor "swath" when multiple groups are sharing the city-wide testbed.
- We plan to test CitySense by developing a specific application: monitoring air pollution transport in a dense urban environment. This has a significant public health impact and will constitute one of the first high-resolution studies of pollution and its effects on the urban population.

- The development of a large-scale sensor network testbed will also benefit teaching and learning of engineering concepts at the graduate, undergraduate, and K-12 levels.
- CitySense is intended to be used as a tool to teach distributed systems concepts at the graduate and undergraduate levels.

<u>JAVeLEN:</u> Joint Architecture Vision for Low Energy Networking

A. Programmatics

<u>Customer:</u> DARPA-STO Connectionless Networks
<u>Customer Program Manager</u>: Preston Marshall
<u>BBN Principal Investigator:</u> Jason Redi (Phase 1); Bill Watson (Phase 2)
<u>Contract length:</u> September 2004 (start of Phase 1) to March 2008 (end of Phase 3)
<u>Collaborators:</u> Boston University, Army Research Laboratory, Oakwood, MA Com, Wescomm

B. Concept

Wireless networks are often very lightly used. Some wireless networks, most notably sensor networks, networks for robot teams, emergency personnel, or soldiers' radios, are also energy-constrained – that is, the period of time during which the network is operational depends on battery lifetime. We have designed and built a novel architecture for a mobile ad hoc network with a low offered load (of approximately 1% average loading) that uses dramatically less (often 100 times less) energy than industry standard protocols and yet achieves higher delivery reliability, handles substantially greater node densities, supports mobility, and has the ability to perform well even under high offered loads. Several innovations were required to achieve this efficiency, most notably the design of a dual-radio transceiver and careful redesign of the protocol stack (physical, media access, routing and transport protocols) to make effective use of the power of the radio transceivers [19].

C. Architecture

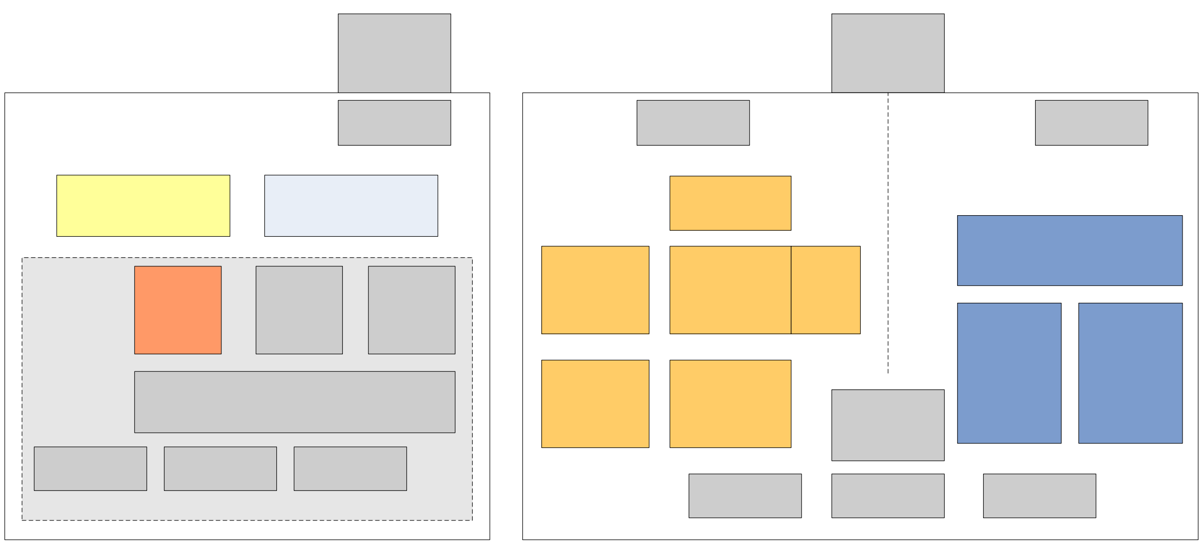


Figure 2: JAVeLEN Architecture

JAVeLEN is an ad hoc network that is extremely energy efficient, particularly when stationary or under low offered loads, and yet also supports node mobility and high data rates. This goal is a departure from many existing sensor systems such as the Berkeley Motes, which use very little energy, but only support low data rates and little or no mobility. Our broader intention was to design a system that works in a wide range of situations while yielding extraordinary energy consumption in all of them.

The JAVeLEN architecture is shown in Figure 2. The system consists of four interoperating *components* that share information and interact to minimize redundant over-the-air transmission:

- *The Physical (PHY) Component* consists of a radio that operates in two modes: a low data rate, low power "Hail" mode; and a high-speed, higher-power data mode, which provides high throughput when needed. The Hail mode consists of an ultra low power transceiver and modem that senses network activity and wakes the data radio only when necessary. The Hail mode also establishes and maintains coarse time synchronization, which enables preamble-free fine-time synchronization in support of the data mode. To keep energy consumption low, the high-speed data mode is only turned on when the Hail radio receives an incoming Hail packet. Furthermore, the entire radio itself is regularly turned off.
- *The Point-to-Point (P2P) Component* manages the one-hop exchange of information between adjacent nodes. It determines when the Hail is on, and if so, wakes up the data radio if the Hail radio determines that packets are ready to be sent or received. The P2P component also manages the detection and selection of one-hop neighbors in a way that dynamically adapts to network changes, traffic rates, and available battery power.
- *The Path Management (PM) Component* determines appropriate multicast and unicast routes over the network based on the cost and available battery energy for transmitting data over each hop. Path Management information is distributed within the network through a combination of hazy-sighted scoping and multipoint relays selected based on energy requirements so as to limit the number of nodes distributing information within an area.
- *The End-to-End (E2E) Component* provides semi-reliable, in-order delivery of packets in a way that optimizes power necessary for the total transmission of the data through cross-layer interactions with other components. The E2E component caches packets along the path to minimize end-to-end retransmissions; it sends mid-path negative acknowledgements (NAKs) when links break; and it can reroute packets dynamically in response to local congestion.

D. Contributions

From an algorithmic standpoint, an interesting discovery was the complex relationship between the E2E layer and the P2P layer. We observed that End-to-end error recovery burdens interior nodes more than the sender and receiver; that local error recover is essential; and that putting higher layer information in P2P acknowledgements is a performance win. With respect to energy efficiency, by far the largest contribution comes from intelligent and adaptive use of a two-radio transceiver, where each transceiver has particular capabilities suited for different situations. In particular, the use of the Hail radio to ensure that the high-power data radio only comes on when data will be in flight, using the Hail radio for basic timing, and skillful use of these capabilities by the P2P protocol, result in nearly two orders of magnitude in power efficiency.

We have reported simulation results where JAVeLEN consistently outperforms the standard OLSR with a 1% of lower offered load, yet uses 100 times less power, and furthermore achieves higher delivery reliability, handles substantially greater node densities, supports mobility, and has the ability to perform well even under high offered loads. We have built a prototype network of these radios whose performance corroborates our simulation results, and we are currently building a real system in the military domain to deploy our JAVeLEN technology.

MIMO: Design and Implementation of a MIMO MAC Protocol for Ad Hoc Networking

A. Programmatics

Customer: DARPA-STO Mobile Networking for MIMO (MNM)
Customer Program Manager: Steven Griggs
BBN Principal Investigator: Jason Redi
Contract: Phase 1 was subcontracted to Lucent; Phase 2/3 under negotiations with Silvus
Contract length: January 2004 (start or Phase 1) to September 2009 (end of Phase 3)

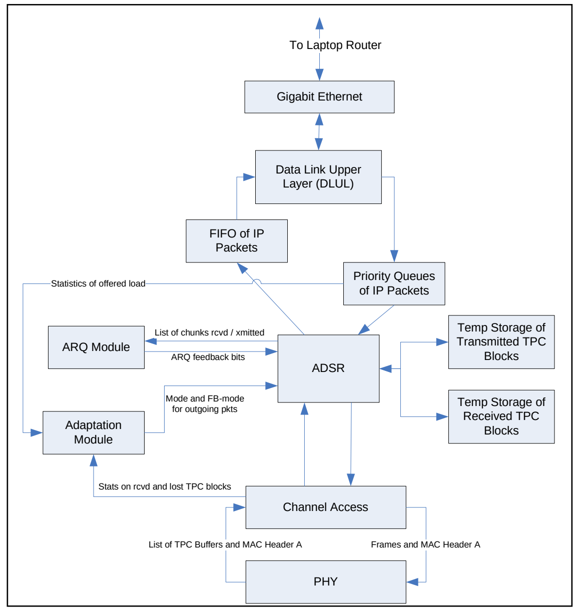
B. Concept

Multiple Input Multiple Output (MIMO) provides the potential for significant gains in channel capacity and spectral efficiency through its use of multiple element antenna systems and space-time coding. While there exist research prototypes and commercial products with a significant number of transmit and receive configurations, the use of MIMO as a modulation scheme for mobile ad hoc networking has not been built prior to this work. We have undertaken the design and implementation of a MAC protocol for a MIMO system designed to exploit the capability of 8x10 MIMO for ad hoc networks. Our work is unique in that from the start, our design considered the specific capabilities and parameters of an existing 8x10 MIMO physical layer, including non-negligible decoding delays, variable array size and coding schemes, as well as fixed frame sizes. Furthermore, given the bandwidths and antenna array sizes available, the physical layer design could achieve hundreds of megabits in link capacity, and our MAC protocol therefore needed to be designed and implemented in such a way as to maximize this capacity, particularly in a network multi-hop environment. Our MIMO-MAC protocol provides this capability while supporting multi-hop ad hoc networks through novel schemes for channel access, segmentation/reassembly, ARQ and link adaptation [20].

C. Architecture

Typically, a MIMO transmitter consists of a number of antenna elements. An independent stream of data is transmitted using each element. A MIMO receiver consists of the same or larger number of elements, each of which receives *all* of the streams. However, each stream typically has a different spatial signature due to differences in multipath. The receiver uses sophisticated space-time processing to separate these streams. Thus, MIMO actually exploits multipath instead of being limited by it. Expectedly, it works best in a rich multipath and scattering environment.

We designed a Medium Access Control (MAC) protocol for a 8x10 MIMO-based MANET, in particular based on the Lucent V-BLAST technology [woln98]. The use of MIMO in general and V-BLAST in particular places a number of constraints that render traditional (e.g. 802.11) solutions inadequate. The figure depicts MIMO-MAC modules and their relationships. Our MIMO-MAC is designed to work with Lucent Packet BLAST Transceivers mounted on mobile platforms operating in outdoor environments and collectively functioning as an ad hoc network to transport traffic demanding low delay and a high rate of successful delivery. Like MIMO-MAC is agile, adapting to current conditions, and simultaneously exploits and enhances the performance provided by BLAST, while working within the constraints of the specific BLAST implementation.



MIMO-MAC instances communicate in protocol-data units (PDUs) called *MAC Frames* or simply frames. MAC Frames are composed of a set of zero or more Turbo-Product Code (TPC) Blocks, called the *PHY Payload*, and a *MAC Message*. MAC Frames are of a fixed duration for each of the configurations. The MAC Message is coded separately from the TPC Blocks and is sent over the MAC Channel, a pre-selected set of codes or frequencies. The MAC Channel is transmitted from a single antenna to increase its likelihood of reception and preclude BLAST receive processing. BLAST receive processing is avoided so that the MAC Message can be used to configure the BLAST-decoding of the PHY Payload and not incur processing delays. The MAC Message contains information that is important to know before BLAST decoding is performed, including the source address, destination address, MIMO mode (e.g number of antennas, bits per symbol, etc), the feedback mode (described in the link adaptation section), the contention indicator (described in the channel access section), and the number of frames in this frame burst.

We have partitioned our MIMO-MAC's into four modules: (1) the framing module (ADSR) acquires packets for forwarding in priority order according to their types of service and segments and concatenates these into frames for transmission to one or more neighboring nodes; it also extracts segments from received frames and reassembles them into packets for further processing by other network control functions; (2) the channel access module (CA) promotes efficient use of the channel, through a variety of complementary techniques for collision avoidance, and also allows reservation of certain time periods specifically for multicast traffic; (3) the retransmission module (ARQ) detects when packet segments appear to require retransmission and initiates the retransmission of these segments; (4) the link adaptation (LA) module provides power control, uses information provided by the Packet BLAST Transceiver, as well as perceived demand for the link and other higher-level information about the use and performance of the link, to adapt the setting of transmission parameters and to provide to the routing algorithm a set of values for link metrics.

D. Contributions

MAC protocols that support MIMO in the commercial space, only work on space-time MIMO systems. Various MAC protocols have been proposed in the academic literature to take advantage of space-time and spatial multiplexing variants of MIMO. However, to our knowledge, no one has actually implemented any of these proposed protocols. The BBN effort described is the not only the first to design a MAC protocol from the ground up for spatial multiplexing MIMO systems, but it is also the first to be implemented and demonstrated.

Experience in real implementation is critical for such new systems because particular aspects, such as the computational delay in MIMO spatial multiplexing and the complexity impacts of building very high speed wireless systems, dramatically affect the basic design.

SPINDLE: Survivable Policy-Influenced Networking: Disruption-tolerance through Learning and Evolution

A. Programmatics

Customer: DARPA- Disruption Tolerant Networking (DTN)
Customer Program Manager: Preston Marshall
BBN Principal Investigator: Rajesh Krishnan
Contract: W15P7T-06-P638 (Funded through CECOM, US Army)
Contract length: July 2006 (start of Phase 1) to January 2008 with an option to June 2010 (end of Phase 3)

B. Concept

DARPA's Disruption Tolerant Networking (DTN) program is developing technologies that enable access to information even when stable end-to-end paths do not exist and infrastructure access cannot be assured. To this end, SPINDLE offers a vision, architecture and implementation of disruption tolerant networking focused on the end-user's purpose; namely, disruption-tolerant, content-based access to information. We address the challenge of eventual delivery under disruption by taking advantage of storage within networks, and have developed approaches for identifying destination nodes using richly attributed intentional names. SPINDLE organizes information into bundles rather than packets. Bundles [15,16] are routed through custodians that augment the capabilities of traditional routers by persistently storing the bundles and then advancing them to the next available node en route to their destinations. We address the challenge of accessing information based on content rather than the explicit location of the content, by developing distributed, opportunistic approaches to caching, indexing, and retrieval in a manner than maximizes the availability of information required even when disconnected from the global network (and access to a global caching infrastructure or search engines is unavailable).

C. Architecture

The DTN architecture is shown in Figure 3. We chose a modular or, *pluggable*, implementation architecture for the DTN reference system. SPINDLE is a robust DTN system with algorithms for opportunistic caching, indexing, and retrieval. Work is underway to plan transitioning the prototype to a domain-specific (in our case military) vehicular network setting.

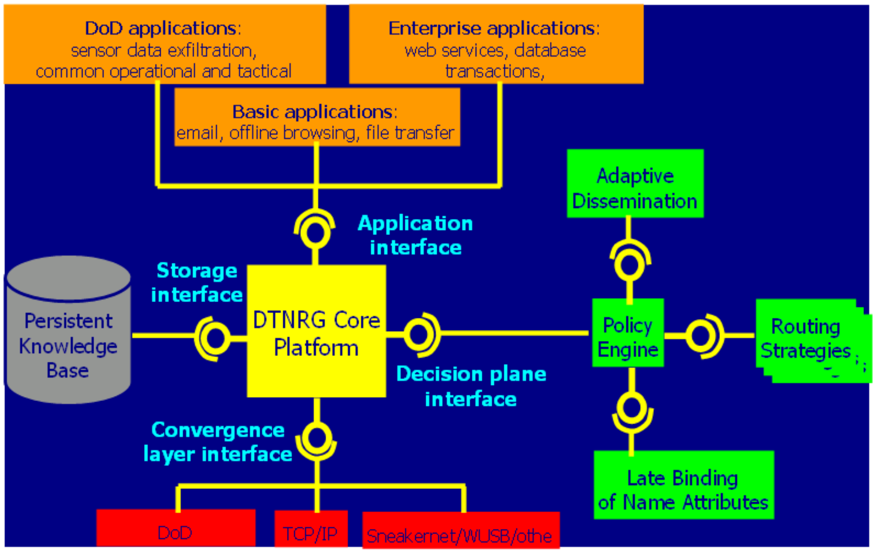


Figure 3: DTN Architecture

The SPINDLE architecture, is built around a core DTNRG platform, which is a reference implementation of the Bundle Protocol (BP) Specification and the Bundle Security Protocol (BSP) Specification. In addition to the bundle forwarding functionality specified, this module would implement four key interfaces:

1. *Convergence Layer Interface* will consist of three plug-in modules, TCP, UDP and a DTN specific plug-in with Bluetooth, 802.11g or Wireless USB technology.
2. *Persistent Knowledge Base and Storage Interface* talks to a plug-in that persistently stores bundles, bundle metadata and other network state. It allows the decision plane to access this state on demand. Metadata are declared as frames, and can be queried via a declarative query language.
3. *Control/Management Interface* provides the entry to declarative, knowledge-based decision plane plug-ins. Such a DTN architecture facilitates the declaration of facts, rules, and queries, thus capturing knowledge and enabling decision-making on network nodes. We have developed a hybrid of algorithmic and declarative logic-based approaches for adaptive routing and dissemination, late binding of intentional name attributes and policy-based resource management.
4. *Bundle Application Interface* supports opportunistic caching, indexing, and retrieval using declarative and algorithmic approaches.

D. Contributions

SPINDLE has demonstrated key performance goals: 100% reliable delivery of data with less than 20% availability of links with greater than 80% utilization of link capacities using DTN technology. The DTN approach consistently outperformed the traditional end-to-end approaches across a wide range of network disruption. Under certain worst-case network dynamics, DTN was able to reliably deliver data, whereas the traditional end-to-end approach broke down completely and delivered no data at all.

While the SPINDLE project is still ongoing and future work, we are nevertheless able to highlight the following key contributions:

- A modular architecture for a DTN system, in which the core technology is refined and engineered in a commercial setting, overlaid on available routers and links, while enabling user-specific value-added plug-ins to be developed independently and then easily integrated.
- A robust deployable system prototype based on a plug-in architecture and a demonstration in a domain-specific vehicular network setting.
- Distributed caching, indexing, and retrieval approaches for disruption-tolerant content-based access to inforrmation.
- A declarative knowledge-based approach (based on frame logic) that integrates routing, intentional naming, policy-based resource management, and content-based access to information.
- Identification of limitations in traditional approaches to route computation and network-state dissemination within DTNs, leading to the development of hybrid routing strategies that are suitable for DTNs.
- An architecture for policy-based resource management in DTNs, including a machine-understandable language to express DTN and node policy.
- A name-management architecture for DTNs that supports progressive resolution of intentional name attributes within the network (not at the source), including support for *queries-as-names* and name-scheme translation.
- Research infrastructure in the form of a flexible emulation platform, called MINAS (multi-VM infrastructure for networked applications and systems), to evaluate networked applications and systems including DTN.
- Providing feedback on the DTN-architecture bundle-protocol specification, and our first-hand interaction with the DTNRG reference implementation.

ADROIT: Adaptive Dynamic Radio Open-source Intelligent Team for Cognitive-controlled Collaboration among SDR Nodes

A. Programmatics

Customer: DARPA- Adaptive Cognition-Enhanced Radio Teams (ACERT)
Customer Program Manager: Lee Badger
BBN Principal Investigator: Greg Troxel
Contract length: October 2005 to March 2007 (Phase 1)
Collaborators: University of Kansas

B. Concept

ADROIT is an open-source software-defined data radio controlled by cognitive applications. The goal is to create a system that enables teams of radios (where each radio both has its own cognitive controls and the ability to collaborate with other radios) to create cognitive radio teams. ADROIT has taken the lead in establishing such an architecture and a reference implementation for the intended users and the networking community. A central challenge is to expand the scope of software-defined data radios to require cognition not just within the individual radio, but cognition across the teams of radios that seek to communicate with each other [17].

Our architecture seeks to achieve three broad goals:

- Enable cognitive radio teams where multiple highly-configurable radios can intelligently and dynamically assemble and configure themselves to meet the needs of a particular application or suite of applications, which are cognitive in nature and are capable of adapting the radios' behavior so as to best meet the applications' needs.

- Create an open-source real-time composable software-defined data radio. The open source approach fosters further flexibility and technical innovation. On the other hand, allowing the SDR to be composable in real-time is essential for cognition, where the ability to swiftly adapt to changing conditions is required, thus enabling the SDR to evolve its behavior while running.

- Real-time composability also would appear to be a meritorious goal in itself. A radio that can reconfigure in microseconds is, intuitively, far more powerful than one that reconfigures in seconds.

C. Architecture

Our overall architecture builds and extends on GNU Radio and a cognitive control framework to build a collaborative SDR platform. We include MAC and networking layers, an abstraction model, reconfiguration and a security architecture.

We make the ADROIT software radio composable by integrating and enhancing GNU Radio and Click, an open source modular router, whose elements represent conceptually simple computations, such as decrementing a TTL field of an IP packet. The resulting radio API is a tiered interface representing (1) the entire radio; (2) a physical layer realization and (3) a frame – single logical transmission unit. The API is asynchronous and operations may occur at any tier. Between the MAC subnet API and the Radio API lies a modular MAC layer encompassing the following modules: channel access, floor acquisiotion and control, reliability control and queueing, subnet interactions and neighbor statistics aggregation.

ADROIT's abstraction model is a collection of objects with five components: type, dependency, parameter, implementation and invocation. This structure allows parameters to be grouped into clusters of well-defined objects. It also expresses the modes in which an object may exist and gives us a way (via their type) to quickly identify related implementations or invocations. We emply *reconfiguration* to select the best components for the current task, and *adaptation* to decide how best to tune parameters in the current configuration. Because the tuning is collective, it is essential that all components have a shared view of the radio's operation, a job provided by a *broker*.

The goal of ADROIT is to optimize the team performance over moderate time intervals (where an interval is on the order of a few 100 ms). We decompose this optimization problem into local cognitively-based optimization, carried out by each radio, and classical coordination across the team.

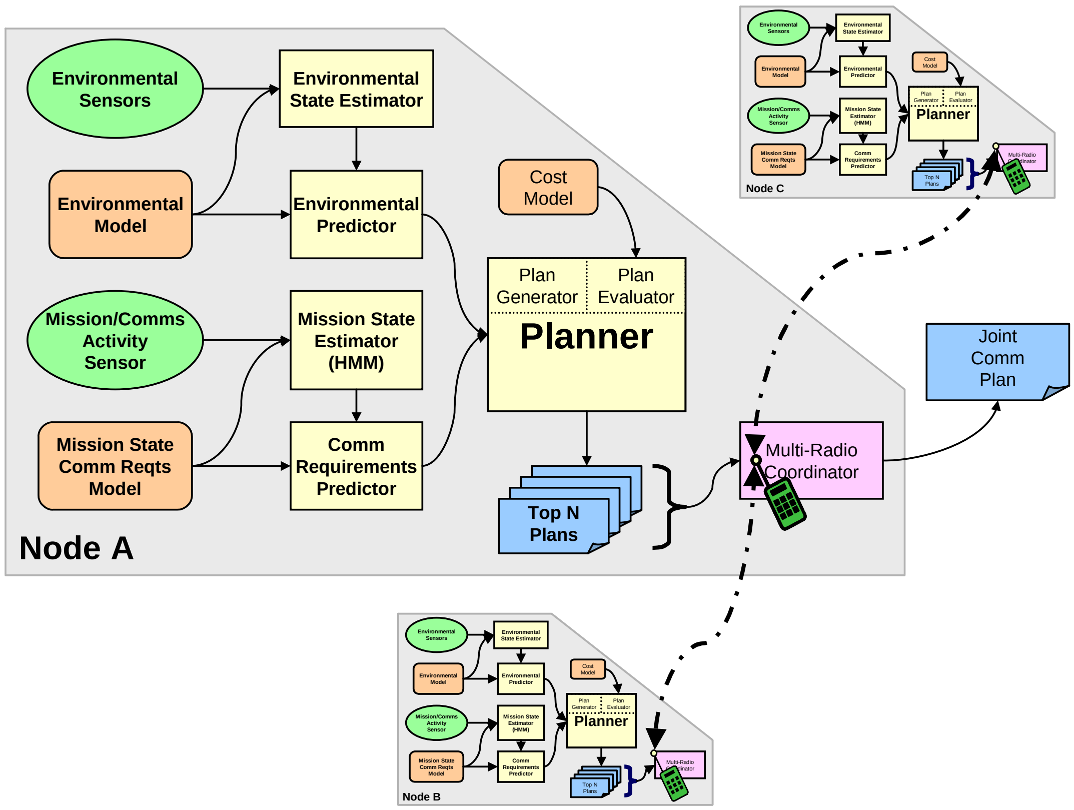


Figure 4: ADROIT Cognitive Control Architecture

The architecture of the cognitive control of ADROIT is shown in Figure 4, where we design cognitive control for both radio waveforms and network protocols. The goal of the cognitive control mechanism in each radio is to choose control parameters for both the radio and network which would optimize over the next several intervals (or, if possible, the lifetime of the current task) the performance of the group task as seen from the vantage point of the radio. In order to achieve coordinated behavior across a team of radios, the cognitive control on each radio generates a set of alternative plans and relies on a team coordination protocol to exchange information about plans and their realization.

D. Contributions

We report to have encountered two main challenges. First, it is a difficult task to identify the optimal granularity for multi-layered structured environments. Second, creating an environment for cognition is hard. Each radio, much less each radio team, contains a vast amount of data about its performance and a range of configuration options. Making sense of that information, and in a way that multiple cognitive entities can manage, proved to be a difficult task. Nevertheless, the ADROIT team has produced the following contributions:

- Designed a dynamically composable wireless media access layer.
- Produced an architecture for a dynamically composable data transmission stack.
- A cognitive control channel to allow diverse cognitive controllers to query and control diverse network modules, enabling easy integration of novel controllers and networking components.

- A cognitively-controlled mapping application that varied protocol parameters, observed the resulting performance, and chose parameters to optimize expected performance. The application was demonstrated outdoors with 4 nodes over 10,000 m^2.

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