NASA/CR—2003-212623

Proximity Networks Technology Assessment

Timothy J. Salo, Barry A. Trent, and Timothy Hartley
Architecture Technology Corporation, Eden Prairie, Minnesota

October 2003

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/CR—2003-212623

Proximity Networks Technology Assessment

Timothy J. Salo, Barry A. Trent, and Timothy Hartley
Architecture Technology Corporation, Eden Prairie, Minnesota

Prepared under Contract GS35F0038L

National Aeronautics and
Space Administration

Glenn Research Center

October 2003

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Table of Contents

1. Overview

This report summarizes an assessment performed by Architecture Technology Corporation (ATC) of technologies applicable to wireless proximity networks used in NASA applications.

NASA proximity networks are relatively small, fairly short-range, often ad hoc, wireless networks typically dedicated to tasks such as transporting in situ sensing data. The number of nodes contained within a proximity network is expected to be comparatively small, perhaps tens or hundreds of nodes at most. While "short-range" is relative, many proximity networks will have a physical diameter on the order of hundreds or thousands of meters (although some authorities have suggested that a few of these networks might be as large 100-400 km [13, 38]).

Proximity networks will operate in a variety of distinctly different environments. These different environments are likely to impose different requirements on proximity networks and demand different networking technologies. To facilitate this analysis, ATC initially divided proximity networks into four subclasses (which are described in greater detail below):

- Microsensor Proximity Networks (e.g., microsensor-lander networks)
- Intra-Spacecraft Proximity Networks (e.g., spacecraft health monitoring networks)
- Inter-Vehicular Proximity Networks (e.g., lander-rover networks)
- EVA Proximity Networks (e.g., human and robotic EVA networks)

Informal descriptions of the operations of proximity networks in typical NASA applications were developed. These descriptions provided the basis for a more thorough examination of proximity networks. They were also intended to elicit more detailed information about the behavior of and requirements for proximity networks from subject-area experts (a role analogous to that played by "use cases" in some object-oriented software analysis methodologies).

A detailed list of the characteristics of the different types of proximity networks was compiled. This compilation shows that the initial four subclasses of proximity networks can be usefully aggregated into two classes:

- Micropower Proximity Networks (microsensor and intra-spacecraft networks) and
- Intelligent Proximity Networks (inter-vehicular and EVA networks).

The technologies required to implement proximity networks were identified and categorized by proximity network subtype (microsensor, inter-vehicular, etc.) and protocol layer, scope or function (e.g., link layer, node architecture, gateway).

Finally, the maturity of each of the identified technologies was assessed.

This assessment concludes that the technologies required for micropower proximity networks are far less mature than those needed for intelligent proximity networks. As such, micropower proximity networks offer NASA the greatest potential return for its proximity network research investments. Common hardware and software platforms for micropower proximity network research, development, and deployment would enhance the opportunities for collaboration between projects, enable projects to more easily leverage the results of prior NASA-funded work and increase the overall productivity of NASA's research dollars. Live, system-level demonstrations by NASA researchers of micropower proximity networks would help focus research on identifying and solving real-world problems, as well as provide an empirical assessment of the effectiveness of proposed technologies.

2. NASA Applications of Wireless Proximity Networks

NASA identified four potential applications of wireless proximity networks for the purposes of this study, which are summarized in the table below.

Application	Number of Nodes	Max link range	Node mobility
Robotic in situ sensing for planetary exploration (fixed nodes)	5-100	1000 m	None
Robotic in situ sensing for spacecraft health monitoring	2-100	100 m	None
Robotic in situ sensing for planetary exploration (mobile nodes)	1-5	1000 m	Medium
Data delivery for EVA	2-5	100 m	High

Table 1. NASA Applications of Wireless Proximity Networks

Upon initial examination, ATC concluded that each of these applications was distinctly different than the others. As a result, ATC divided proximity networks into four categories, corresponding to each of the applications identified by NASA. These categories were assigned shorter, more descriptive names:

- Microsensor Proximity Networks - robotic in situ sensing for planetary exploration (fixed nodes)
- Intra-Spacecraft Proximity Networks - robotic in situ sensing for spacecraft health monitoring
- Inter-Vehicular Proximity Networks - robotic in situ sensing for planetary exploration (mobile nodes)
- EVA Proximity Networks - data delivery for extra-vehicular activity (EVA)

Informal overviews of the operations of these networks are presented in this section, including descriptions of the nodes that participate in the networks, and the deployment, configuration, organization, and operation of the networks. These operational scenarios represent how, in the view of the authors, these networks *ought* to behave, assuming that the requisite technologies and products have been developed and matured.

2.1. Microsensor Proximity Networks

Microsensor proximity networks support the operation of sensor systems composed of numerous (perhaps tens or even hundreds) tiny, dedicated nodes containing integrated sensing, computing, and wireless communications capabilities, referred to here as "microsensor nodes" or more simply "microsensors". NASA and other researchers have called these networked, collaborative collections of microsensor nodes "sensor webs" [18, 3]. A microsensor proximity network transports sensor data collected by the sensor web to an external network connection (or gateway), through which the data are forwarded to external users for archive and analysis.

Microsensors and microsensor networks are topics of active research. Many approaches to designing microsensor nodes and networks have been proposed and investigated, but no single approach has yet emerged as dominant. Likewise, there is not universal agreement on the precise characteristics of microsensors. Therefore, this section is a snapshot of some of the current thinking on microsensors and microsensor networks, with an emphasis on topics relevant to NASA applications.

NASA applications of microsensor webs and microsensor proximity networks include in situ monitoring of terrestrial and planetary environments. For example, a microsensor web might be deployed to collect in situ sensor data in the vicinity of a planetary lander.

2.1.1. Microsensor Nodes

Microsensor nodes are, as the name indicates, small – they generally are only just large enough to accomplish the task of acquiring, communicating and perhaps processing sensor data. Research prototypes of microsensor nodes range in size from a 15-centimeter cube [32, 1, 15] to approximately 100 cubic millimeters (with an objective of demonstrating a microsensor node only a few cubic millimeters in size) [48].

Microsensors are networked and in some applications collaborative. Numerous microsensors are deployed over an area to be monitored. After deployment, the microsensors configure themselves into an autonomous network, which communicates sensor information to the external world. In some designs, the network also supports collaborative processing of sensor data (sensor data fusion) among the microsensor nodes [7, 22, and 45].

Batteries are generally used to power microsensors, so the lifetime of a microsensor is essentially the lifetime of the battery. As a result, power conservation is perhaps the dominant consideration in microsensor designs. Numerous hardware-based power conservation strategies have been explored, including using low-power components, using lower-function components (e.g., 8-bit or 16-bit processors rather than 32-bit processors), and putting the microsensor to sleep for extended periods of time.

The compute power contained in microsensors varies widely, from 8-bit processors with only a few tens of bytes of memory to 32-bit processors with several megabytes of memory. Naturally, the functionality of microsensor nodes varies over a similar range, from relatively unintelligent nodes that merely forward sensor data to an external user for analysis, to nodes that employ complex data fusion algorithms to analyze and reduce the data within the microsensor web.

One author described microsensors as "disposable". This term is apt in the sense that microsensors are deployed for a narrow, specific, data-collection objective. The mission ends when the batteries become depleted, at which time the microsensors are abandoned in place.

As a result, many higher-level functions have limited utility, such as being able to remotely reprogram microsensors after they have been deployed.

Numerous research groups, both within and outside of NASA, are exploring designs for microsensor nodes. However, beyond basic issues such as the paramount importance of energy conservation, there is little consensus about the most appropriate architecture and design tradeoffs for microsensor nodes.

2.1.2. Microsensor Deployment and Configuration

The life of a sensor web includes deployment of the microsensor nodes, autonomous configuration of the nodes, creation of the microsensor proximity network, and operation of the sensor web until the batteries in the last remaining nodes become exhausted. The first two topics are discussed in this section, while the remaining topics are explored in following sections.

Nearly every imaginable method has been proposed for disseminating microsensors. Terrestrially, it is often practical to place these nodes by hand. Another common model is to scatter them over an area of interest from an unmanned aerial vehicle (UAV). In planetary exploration applications, a rover is a logical tool for microsensor deployment. However they are deployed, the exact placement of individual microsensors will be imprecise and difficult to predict. Because the ultimate location of the nodes cannot be accurately predicted, the possible topologies of the microsensor network cannot be accurately determined in advance. Given this environment, microsensor nodes cannot be pre-configured prior to deployment (because their precise location and network neighbors cannot be predicted), nor can they be remotely configured (because the external connectivity necessary for remote configuration doesn't exist until *it* is configured). Microsensor webs must autonomously configure themselves after deployment.

In some applications, microsensor nodes must determine or configure additional attributes. Some microsensors need to determine their location, either with respect to a global reference system (e.g., WGS-84) or relative to other microsensors [40, 51]. Likewise, microsensors may need to synchronize their clocks, again either with respect to each other or with an external time reference (e.g., UTC). The requirement for time and spatial synchronization is generally derived from the application or mission of the microsensor web, rather than from any inherent need of the microsensor nodes themselves. As a result, the detailed requirements for time and spatial synchronization (e.g., precision or relative versus absolute measurement systems) must be consistent with the scientific mission of the microsensor web.

2.1.3. Microsensor Proximity Network Organization

The microsensors' first task after deployment is to organize a microsensor proximity network among themselves. The most appropriate structure for microsensor networks is the topic of active research. Some researchers advocate a flat network structure among homogeneous nodes, while others have suggested that a hierarchical network structure can extend the life of a battery-powered sensor web [31]. Networks of heterogeneous nodes, where a few more powerful nodes (e.g., nodes with greater computational power or greater transmission range) are scattered among the microsensor nodes, have also been explored. The common characteristics of all of these solutions are:

- the microsensor nodes autonomously configure the network; the network is not pre-configured prior to deployment and is not manually or remotely configured after deployment, and
- data must be routed within the network; communications between any two nodes is likely to involve forwarding by intermediate nodes.

Alternative network organizations for microsensor webs are examined in more detail in Section 4, "Key Technologies for NASA Proximity Networks".

2.1.4. Microsensor Proximity Network Operation

Microsensor nodes do not move on their own volition, at least in likely NASA applications. As a result, the topology of a microsensor network will change only slowly, perhaps as the result of equipment failure or battery exhaustion. Nonetheless, the nodes must be able to reconfigure themselves to adapt to changes in the network topology.

Precisely how a microsensor proximity network ought to behave, however, is the subject of numerous design decisions. Perhaps most fundamentally, a decision must be made about the rate at which sensor data will be communicated. Battery-powered microsensors have a fixed amount of energy and therefore can transmit a fixed number of bits over their lifetime. These bits (or this energy) can be consumed over a short timeframe by transmitting sensor data with only short time intervals between readings or over a more extended timeframe with correspondingly greater intervals between readings. The scientists, not the microsensor designers, should decide how to allocate those bits over time, e.g., whether to use them to transmit the sensor readings over a short period of time or to transmit these readings over a longer period of time.

The rate at which sensor data will be transmitted, which undoubtedly will be different for different scientific applications, has significant implications for the design of the microsensor web. If, for example, sensor readings are transmitted much less often than the rate at which the topology of the microsensor network changes, it probably makes sense to compute routes when needed, rather than save likely outdated information about the topology of the network. Conversely, if the topology is stable relative to the traffic patterns, saving and reusing information about routes within the network can likely extend the life of the sensor web.

A corollary to these observations is that it is entirely possible that no one set of design decisions will be optimal for all NASA microsensor networks. Unfortunately, the range of solutions necessary to meet the requirements of all potential NASA applications is not entirely clear.

2.2. Intra-Spacecraft Proximity Networks

Intra-spacecraft proximity networks support wireless sensors that monitor the environmental or structural health of a spacecraft. The wireless sensor nodes are likely to be powered by either batteries or the spacecraft. Wireless sensor nodes eliminate the weight and space of cables for data and perhaps power. Their untethered operation also makes them much easier to provision, particularly after the spacecraft has been built or is operational, because the need for additional cabling is minimized or eliminated.

From a networking perspective, battery-powered wireless sensor nodes used to monitor spacecraft environmental or structural health are indistinguishable from the microsensor nodes discussed earlier. The primary design objective is to maximize the amount of data successfully transmitted from the network before the batteries expire. It is entirely likely that in practice spacecraft-powered wireless spacecraft health monitoring nodes are also (from a networking perspective) indistinguishable from microsensor nodes. Nonetheless, for the purpose of this section, the two types of proximity networks are kept separate.

2.2.1. Intra-Spacecraft Proximity Network Nodes

These wireless sensor nodes are very similar to the microsensor nodes described earlier, with the possible exception that they may receive power from the spacecraft. They are small, special-purpose devices tailored to a single task, namely monitoring the structural or environmental health of a spacecraft.

These networks may be used to monitor the cabin environment of a manned spacecraft. Shuttle mission STS-101 carried the Micro-Wireless Instrumentation System (micro WIS), a collection of wireless, battery-powered temperature sensors, which provided real-time measurements of cabin air temperature [43, 44]. The micro WIS can transmit temperature measurements to a laptop for up to five months. The wireless system reduces the cost, weight and power requirements, and significantly increases the flexibility, of data acquisition systems.

A number of researchers are exploring intelligent structures and smart materials that contain embedded sensors. These sensors are designed to provide heretofore-unavailable information about the behavior of these structures in use and advanced warning of structural problems [39, 11].

2.2.2. Intra-Spacecraft Proximity Network Deployment and Configuration

Intra-spacecraft network nodes will be deployed by hand in many applications, such as the micro WIS onboard the Shuttle. Presumably, manual placement of these devices will permit them to be repositioned to enhance propagation between nodes or reduce multipath interference.

In theory, the network could be manually configured after the nodes have been deployed. However, the adaptive, self-configuring network technologies that must be developed for microsensor proximity networks can easily and productively also be used in intra-spacecraft proximity networks. The use of these technologies would make intra-spacecraft proximity networks more robust in the face of a changing environment (e.g., nodes failing or a human or equipment situated so as to impede propagation) and minimize the risk of human error.

It is conceivable that interoperability will, in some cases, be more important for these networks than for microsensor proximity networks. For example, the Shuttle might host a semi-permanent gateway or data collection device with which different sensors are expected to interoperate over time. Note that this possible requirement does not in any way reduce the opportunity to use common technologies for microsensor and spacecraft health monitoring proximity networks.

2.2.3. Intra-Spacecraft Proximity Network Organization

Early intra-spacecraft and microsensor proximity networks have demonstrated that useful networks can be constructed with simple technologies, such as star topologies in which every sensor can communicate with a central gateway (e.g., laptop, in the case of the micro WIS). However, more advanced networking technologies, such as ad hoc routing protocols, can make these networks more robust, adaptable, and longer-lived, as they can for microsensor proximity networks.

The networking technologies developed for microsensor webs are directly applicable to intra-spacecraft proximity networks.

2.2.4. Intra-Spacecraft Proximity Network Operation

In a similar fashion, the behavior of microsensor proximity networks provides a highly accurate model for that of intra-spacecraft proximity networks.

2.3. Inter-Vehicular Proximity Networks

The term "inter-vehicular proximity network" is used in this document to denote NASA proximity networks composed of a small number (perhaps fewer than ten) of relatively capable (in comparison to microsensors), possibly mobile, nodes. Planetary landers, rovers and orbiters are typical of the devices that might participate in this class of networks.

2.3.1. Inter-Vehicular Proximity Network Nodes

A renewable power source, such as solar or nuclear cells, and a larger power storage capacity are the distinguishing characteristics of nodes that may participate in this class of proximity networks. The resulting larger system-level power budget permits these devices to possess much greater functionality than found in the minimalist designs of microsensor nodes. This has numerous implications for the design of the devices and the networking solutions.

- The lifetime of the inter-vehicular nodes is long compared to that of battery-powered microsensors; planetary orbiters have design lifetimes measured in years. Of significance to the design of the communications systems, these longer-lived devices are likely to need to interact with devices that were designed by a variety of organizations and launched over a period of years. As a result, interoperability between independent protocol implementations is important for this class of proximity networks.

- The power budget of the communications system is not traded off directly against the lifetime of the device (i.e., every extra bit transmitted does not correspondingly reduce the overall life of the device). Increased power for communications can be applied towards improved interoperability, enhanced reliability, increased flexibility and greater functionality, perhaps at the expense of additional bits transmitted.

- Individual nodes in inter-vehicular proximity networks are generally critical to the success of the mission. This contrasts with sensor webs, for example, where the web can continue to provide valuable data in spite of the demise of some of the microsensor nodes. Poor protocol design must never cause contact to be unnecessarily lost between, for example, a lander and a rover.

- Additional computational power may be available in these nodes, which may be used to provide services to lower-functioning devices. As described above, this class of devices might host gateways for microsensor proximity networks that would perform some functions on the relatively electrical power-rich inter-vehicular proximity network nodes, rather than the severely resource-constrained microsensor nodes.

2.3.2. Inter-Vehicular Proximity Network Deployment and Configuration

The mobility characteristics of these devices influence the requirements for and design of network solutions. Nodes in inter-vehicular proximity networks will exhibit one of three types of mobility:

- Immobility, such as planetary landers
- Self-mobility, such as autonomous or teleoperated rovers, and
- Planetary orbits.

As a result of these mobility characteristics, the potential for communications between two nodes may be very predictable, or may be difficult to predict. For example, communications opportunities between an orbiter and a lander are very predictable and are determined by the orbit and the lander's location. In a similar fashion, communications between a teleoperated planetary rover and a lander may predictable, inasmuch as the rover is never driven out of range of the lander. On the other hand, some have suggested that radio repeaters be deployed to extend the range of communications between a lander and rovers [2]. Depending on the networking characteristics of these repeaters (i.e., whether they behave, in networking terms, as bridges or routers) potential or optimal communications paths become more difficult to predict. In particular, it may be difficult to predict in advance for a particular location whether the rover should communicate with the lander directly or via the repeater. Inter-vehicular proximity network technologies should effectively adapt to the different styles of connectivity experienced by these devices, including continuous (e.g., a rover near a lander), predictable and episodic (e.g., an orbiter and a lander), and unpredictable (e.g., a rover potentially using a repeater). Protocols that can autonomously adapt to a changing environment (e.g., determine whether a rover should communicate with a lander directly or via a repeater) are required by more complex networking environments, such as those represented by repeaters.

2.3.3. Inter-Vehicular Proximity Network Organization

Because of the small number of nodes involved, the topologies of inter-vehicular proximity networks are fairly simple. These networks can easily be treated as a small collection of point-to-point links. In fact, in current and near-term implementations, these networks are simply a single point-to-point link. For example, the Proximity-1 Space Link protocol [14] implemented on the Odyssey Mars orbiter creates a point-to-point link between the orbiter and a lander, but does not provide a mechanism for routing traffic through intermediate nodes.

When several of these devices can potentially communicate with each other simultaneously, traditional network-layer functions (specifically, routing through intermediate nodes) can significantly enhance the functionality of communications solutions. For example, the operating range of a rover could be extended if it were able to route data through an intermediate device, such as a strategically placed repeater or another rover.

While this section uses the term "repeater", a stationary communications device intended to extend the range of a network will be much more capable and much more useful if it is a network device, specifically a router, rather than a simple analog RF repeater.

2.3.4. Inter-Vehicular Proximity Network Operation

There are two potential strategies for operating an inter-vehicular proximity network. The network could be remotely operated from Earth, with detailed configurations and operational plans uploaded into the vehicles. Alternatively, the network could operate autonomously, requiring manual configuration or intervention only rarely and under exceptional circumstances.

In an analogous fashion, devices that participate in these networks could be operated remotely (presumably from Earth) or could operate autonomously. For example, a rover could be teleoperated from Earth, with the activities of the vehicle controlled by carefully planned, detailed commands issued by earthbound engineers. Alternatively, a rover could operate autonomously, where the vehicle uses onboard intelligence to achieve higher-level goals (e.g., search for a rock different than what has been collected so far).

Network technologies designed to operate autonomously can be used with systems that are operated remotely (e.g., autonomous network technologies could be used with a teleoperated rover). However, it is unlikely that protocols designed to be operated remotely can easily or reliably be modified to either operate autonomously or to support autonomous systems. To the extent that NASA intends to increase the autonomy of planetary exploration devices, inter-vehicular proximity network technologies should be able to operate either autonomously or under remote control, depending on the requirements of the mission.

Inter-vehicular network nodes will generally need to be able to determine their location and synchronize their clocks with a standard time reference. A variety of communications- and network-based mechanisms have been proposed or developed to provide these services [40, 42, 51].

2.4. EVA Proximity Networks

Extra-vehicular activity (EVA) proximity networks support humans, manned vehicles and robots operating outside of a spacecraft.

From a networking perspective, EVA proximity networks are nearly identical to autonomous (rather than remotely configured and operated) inter-vehicular proximity networks, and common networking solutions can and should be developed for both classes of proximity networks.

2.4.1. EVA Proximity Network Nodes

EVA proximity networks can be viewed as being composed of "mobile" nodes (e.g., humans, manned vehicles, and robots) and, relative to the mobile nodes, "stationary" nodes (e.g., the ISS, the Shuttle or a planetary base station). The mobile nodes share many characteristics with inter-vehicular proximity network nodes, specifically renewable sources of power (e.g., recharging spacesuit batteries prior to an EVA) and less onerous mass constraints that those for microsensors. These nodes potentially could support significant amounts of computational power, similar to inter-vehicular proximity network nodes. The stationary nodes have access to substantial electrical power, (relative to other proximity network nodes).

2.4.2. EVA Proximity Network Deployment and Configuration

EVA proximity network nodes are "deployed" as the host nodes (humans, manned vehicles, or robots) undertake EVAs.

While theoretically EVA networks could be manually or remotely configured, in a manner analogous to some inter-vehicular networks, this approach is impractical, unreliable, hazardous and unnecessary. EVA networks should be self-configuring, and ought to require little, if any, manual network configuration after the device is initially placed into service.

2.4.3. EVA Proximity Network Organization

EVA network topologies are very similar to those of inter-vehicular networks: they contain a relatively small number of nodes, and the topologies are fairly simple, although it would be highly advantageous for these devices to be able to forward data between other devices in the network.

2.4.4. EVA Proximity Network Operation

The topology of the network may change as nodes move relative to each other. The network must adapt quickly and reliably to the new topology, in a manner similar to inter-vehicular networks composed of mobile nodes.

3. Characteristics of NASA Wireless Proximity Networks

The informal descriptions of the previous section provided the basis for a more detailed analysis of the characteristics of the different subclasses of proximity networks. This section opens with an enumeration of the attributes of proximity networks that the authors identified as the most important or distinguishing. Next, these attributes were evaluated for each of the four subclasses of proximity networks. An examination of these attributes showed that the four subclasses of proximity networks could productively be aggregated into two classes. This section concludes with a brief discussion of the most significant characteristics of these two aggregated classes of proximity networks.

3.1. Proximity Networks Characteristics

Studying the characteristics of the different subclasses of proximity networks can provide a basis for determining the technologies required by those networks. The following attributes were examined:

- **Example application** The NASA applications typical for each subclass of proximity network were briefly noted, reflecting the information contained in the preceding section.

- **Engineering objective** Two primary design objectives were identified: power conservation intended to maximize the life of battery-powered nodes and the provision of reliable communications to mobile nodes.

- **Resource constraints** The overall resource constraints (relative to other classes of proximity networks) including power, mass, and size were summarized.

- **Power replenishment opportunity** The possibility of replenishing power, perhaps using solar cells to recharge batteries or manually installing fresh batteries, significantly changes the role of power conservation in the design of proximity networking technologies and nodes. It also determines whether the lifetime of the mission is limited by the lifetime of the battery-powered network nodes.

- **Communications as percent of system power** The intent of this attribute is to suggest the likely effect on the overall system design of modest incremental increases or decreases in power consumption by the communications subsystem. When communications requires only a small portion of the total power budget, increasing communications functionality may be easier to justify.

- **Typical processor power and memory size** Highly power-constrained nodes are likely to have less processing power and less memory available than will nodes for which power is not as limited or valuable. Additional processor power and memory, of course, provide an opportunity to embed greater functionality in the network node.

- **Network size** The approximate size of a typical network provides a sense of the potential complexity of the network topology, and the resulting complexity faced by the routing protocols.

- **Node mobility** In some networks, nodes will be highly mobile and the network protocols will need to adapt quickly to potentially rapidly changing network topologies. In other cases, the network topology may change only slowly.

- **Traffic and flow diversity** Some proximity networks will need to transport only one class of traffic (e.g., sensor data) while others will potentially need to transport several different classes of traffic simultaneously, each of which may have different requirements (e.g., data, voice, video, and text messages). Greater traffic diversity may increase the need for the network to provide quality of service (QoS) assurances to the different classes of traffic. In a similar fashion, some networks may have fairly simple, predictable flow patterns (e.g., all traffic in sensor networks is directed towards external gateways), while other networks may have much less predictable traffic patterns.

- **Intra-network routing** In some cases, data will typically traverse several nodes before exiting the network, while in other cases data will traverse only a small number of intermediate nodes, if any, before exiting the network. The extent of intra-network routing affects the complexity of the traffic flows, the requirements for a routing protocol, and the potential for congestion at intermediate nodes.

- **Direct external access to network nodes** In some applications, such as a teleoperated robotic vehicle, external devices may need to interact directly with a node on a proximity network. In other networks (e.g., microsensor networks) there is little need to provide external devices direct access to individual proximity network nodes.

- **Direct access to external networks** In some instances, it will be necessary for proximity network nodes to directly access external information sources, such as an astronaut accessing an earthbound database during an EVA. Microsensor nodes, on the other hand, are unlikely to ever require direct access to devices external to the proximity network.

- **Network management access** More intelligent devices, such as robotic vehicles, may benefit from external network monitoring or management. (It most likely makes more sense for network management functions to be automated and performed from nearby platforms, such as the Shuttle or the ISS, rather than from more distant locations, specifically the Earth.) However, other types of proximity networks and their nodes, such as microsensor networks, will most likely have little need or ability to be directly monitored or managed by external network management systems.

- **Interoperability requirement** Interoperability is the ability of two independent implementations to communicate gracefully and effectively. Achieving interoperability is trivial in a network composed of homogeneous nodes. It becomes more important, and more difficult to achieve, when the network is composed of devices developed by independent groups or projects, perhaps at different times.

- **Backward compatibility requirement** Backward compatibility is the ability to interoperate with older versions or older implementations of a communications protocol. Backward compatibility is important when a new device needs to communicate with existing, long-lived devices that may use slightly different versions of some protocols.

- **Communications subsystem reliability requirement** In proximity networks where the individual nodes are very valuable and may become useless if their communications subsystem fails, the reliability of the communications subsystem is very important. In contrast, the loss of an individual sensor node may have a minimal effect on the overall mission of the sensor web. In these instances, the reliability of the communications system may reasonably be traded off against other objectives, such as increased battery life.

- **Data reliability requirement** In a similar fashion, the loss of some sensor data may not adversely affect the scientific success of a mission, and highly reliable data transfer might be reasonably traded off against other objectives. On the other hand, the loss of a message containing a command to a robotic vehicle may have adverse consequences, and the risk of this loss should be minimized.

3.2. Summary of Proximity Networks Characteristics

The table below summarizes the authors' assessment of the attributes described above for each of the four subclasses of proximity networks. It is important to note that these assessments are ideals, and assume that the requisite network technologies have been successfully developed.

Proximity Networks
Taxonomy and Characteristics

Characteristic / Subclass	Micropower Proximity Networks		Intelligent Proximity Networks	
	Microsensor	**Intra-Spacecraft**	**Inter-Vehicular**	**EVA**
Example application	microsensor/lander communications	spacecraft health monitoring	lander/rover communications	Human and robotics EVA comm
Engineering objective	maximize data transferred per battery life	maximize data transferred per battery life	reliable mobile communications	reliable mobile communications
Resource constraints	high fixed battery life	moderate/high fixed battery life?	moderate mass, power	moderate mass, power
Power replenishment opportunity	none	none or very high	moderate	high
Comm as per cent of system power	high	high	low - moderate	low
Typical processor power, memory size	8-bit processors, 100 bytes - few kilobytes of memory	8-bit, 16-bit processors, 100 bytes - kilobytes of memory	32-bit processors, megabytes of memory	32-bit processors, megabytes of memory
Network size	10s - 100s of nodes	10s - 100s of nodes	10s of nodes at most	10s of nodes at most
Node mobility	none	none	moderate	high
Traffic and flow diversity	low	low	potentially high	potentially high
Intra-network routing	yes	yes	some	some
Direct external access to networks nodes	none	none	potentially	potentially
Direct access to external networks	none	none	maybe	potentially
Network management access	not needed	not needed	potentially useful	potentially useful
Interoperability requirement	low	moderate	high	high
Backward compatibility requirement	none	moderate	moderate	high
Comm subsystem reliability requirement	low - moderate	moderate	high	high
Data reliability requirement	moderate	moderate	high	high

3.3. A Refined Proximity Network Taxonomy

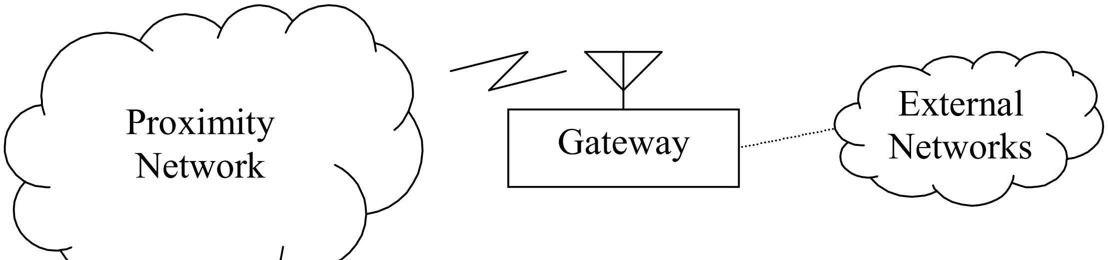
A cursory examination of the characteristics of proximity network summarized in the table above reveals that microsensor proximity networks are very similar to intra-spacecraft proximity networks and that inter-vehicular proximity networks are very similar to EVA networks. The authors concluded that the four original subclasses could reasonably be aggregated into two classes of proximity networks, which are referred to (for the purposes of this document) as:

- Micropower proximity networks, composed of microsensor proximity networks and intra-spacecraft proximity networks, and

- Intelligent proximity networks, composed of inter-vehicular proximity networks and EVA proximity networks.

3.4. Key Characteristics of Proximity Network Classes

Numerous characteristics are shared by all proximity networks, such as wireless communications. One common characteristic that warrants mention is the presence (in almost all instances) of a gateway, a network device that acts as an intermediary between the proximity network and external networks. While there is no consensus on the architectural structure of the gateway or the precise services that it ought to provide, the gateway will generally be fairly capable (compared to proximity network nodes). The gateway is likely to be hosted by a vehicle that has enough electrical power to support a reasonable amount of computational power (e.g., a 32-bit processor with megabytes of memory). Conceivably, a gateway could offload certain processing from less-powerful proximity network nodes. While the presence of a gateway will be typical, the responsibilities of a gateway may be different for different classes of proximity networks, and several architectures for gateways may eventually coexist. The most appropriate architecture for proximity network gateways is a topic of continuing research and debate.



Proximity Network Gateway Function

3.4.1. Micropower Proximity Networks

The mission of micropower networks (named to reflect the importance of power conservation) is to transport sensor data towards an external network connection. Many of these networks will be battery-powered. Because the lifetime of a battery-powered network is equivalent to the lifetime of the batteries, power conservation becomes an important, probably *the* important, engineering consideration. As a result, the designs of the nodes and network technologies are narrowly focused on transporting sensor data. Even when these nodes are powered by external sources (e.g., intra-spacecraft networks that receive power from the spacecraft) minimal, single-purpose designs similar to battery-powered designs are appropriate and likely. Distinguishing characteristics of micropower proximity networks include the following.

- **Battery power** Nonrenewable batteries will power most micropower proximity networks. That is, the networks function only until the batteries are exhausted. As a result, power conservation is a major design objective.

- **Generality and functionality may be traded off against power conservation** In keeping with the objective of maximizing the amount of sensor data that are transported over the lifetime of the network, many common network services may not be implemented. For example, in some applications, it may make more sense to transmit data on a best-effort basis, rather than to expend power on a data acknowledgement mechanism. Tradeoffs such as this ought to be made in the context of the science objectives of the mission, but generally accepted guidelines for making these tradeoffs do not yet exist.

- **Focused mission** By necessity, micropower proximity networks have a very focused mission, namely to transport as much sensor data as possible before the batteries become exhausted.

- **Potentially limited computational power** A common power-conservation strategy is to minimize the amount of computational power included in micropower nodes. Eight-bit processors are common, although some researchers have used 32-bit processors, (perhaps with the assumption that the 32-bit processors will conserve power by sleeping much of the time).

- **Autonomy** Micropower networks will undoubtedly be largely autonomous. First, inasmuch as wireless transmissions require tremendously more power than do computations, it is generally more power-efficient to design the nodes to be autonomous. Second, by their very nature, micropower networks are very difficult to configure and operate remotely.

- **Less focus on interoperability** Because these networks are likely to be composed of identical nodes and will have a limited lifetime, interoperability concerns are all but moot—it is unlikely that two uncoordinated, independent implementations will be deployed simultaneously in the same area and be expected to communicate. (This is not to suggest that the other advantages of reusing standard, proven technologies are unimportant to micropower proximity networks, merely that interoperability doesn't have the importance that it does in most other environments.)

- **Little need for direct external connectivity** Micropower proximity networks are unlikely to support direct end-to-end connections with external nodes. Rather, the gateway will act as an intermediary between the micropower network and external networks. It will translate between the different protocols and addressing schemes used by the proximity and external networks. This conclusion is based on two factors: the task of transporting sensor data simply doesn't require direct external connections, and the resources required to support external connections are better applied to the network's primary mission, namely to transport sensor data. The node that originates specific sensor data will be identified in most applications, but that doesn't imply either a need or a capability for the sensor node to communicate directly with external nodes.

- **System-level, not node-level reliability** The life of a sensor web transcends the lives of individual sensor nodes; in most cases the sensor web will continue to return scientifically valuable data even if a small proportion of the sensor nodes fail. As a result, it may be more appropriate to increase the number of sensor nodes deployed, rather than increasing the communications reliability of the individual sensor nodes at the expense of being able to deploy fewer sensors. It is highly unlikely, for example, that sensor nodes will contain redundant communications systems that will permit communications even in the event that one system fails.

One consequence of these characteristics is that tailoring network technologies to the specific needs of this environment may be an effective way to extend the life of micropower networks and maximize the science data that they return. Possibly unfortunate corollaries of this observation are that standard or existing solutions may not be optimal for micropower proximity networks and that network solutions tailored to the requirements of micropower networks may not be well-suited for other environments.

3.4.2. Intelligent Proximity Networks

Because intelligent proximity networks don't operate under the same severe power constraints as micropower networks, they generally have more computational power available, hence the name. These networks will behave more like traditional networks, in the sense that they will be expected to provide a broad range of services and support a variety of types of traffic.

- **More functional, complex devices** Nodes in intelligent proximity networks will be much more complex than those in micropower networks. They will include, for example, humans (spacesuits), robotic vehicles, and manned vehicles. These nodes will be much broader, more varied missions (compared to a micropower network's narrow mission of transporting sensor data). These broader missions will place greater expectations and stronger requirements on intelligent proximity networks.

- **More varied traffic** Many intelligent proximity networks will be expected to simultaneously transport several different types of traffic, such as voice, data, video, and text.

Quality of Service (QoS) assurances will become important in these environments, for example to ensure that video traffic doesn't displace critical data traffic.

- **Direct external connectivity** Direct connectivity between intelligent proximity network nodes and external network nodes will be important in many applications. For example, ground-based engineers may want to communicate directly with a specific robotic vehicle, perhaps to determine or diagnose its current condition. Note that a requirement for end-to-end connections does not necessarily imply a requirement for *transparent* end-to-end connections. Different protocols may be used in the intelligent proximity network and the external networks, but the gateway will probably need to support connections established by intelligent network nodes to external network nodes, as well as the converse.

- **Individual nodes important** Individual nodes on intelligent proximity networks will be extremely valuable – the loss of a single node will likely have severe adverse consequences for the overall mission. The intelligent proximity network must include reliability mechanisms to ensure that communications are maintained if at all possible.

- **Interoperability, backward compatibility more important** Because nodes in this class of proximity network are much longer-lived than battery-powered sensor nodes, interoperability and backward compatibility are much more important. While it is unlikely that a spacesuit and a robotic vehicle will be manufactured by the same organization, it is very likely that the two devices will be expected to communicate with each other. The usual techniques for ensuring interoperability between independent protocol implementations (e.g., complete, well-written, well-reviewed, well-tested protocol specifications, interoperability testing, and reusable implementations) are applicable to intelligent proximity networks. In a similar manner, the relatively long lives of these nodes increases that the likelihood that the intelligent proximity network protocols will evolve over time, and that backward compatibility with older protocol versions will be a requirement. Again, the traditional techniques of ensuring backward compatibility apply to these networks.

The requirements for intelligent proximity networks are broader than for micropower proximity networks, and have great similarity with the requirements for many traditional networks. This immediately leads to several conclusions:

- Micropower and intelligent proximity networks have vastly different requirements and most likely will require different networking solutions and protocols.

- Intelligent proximity networks have much broader requirements, and will therefore require a broader range of networking technologies than will micropower proximity networks. As a result, the cost of developing and maintaining unique network solutions for intelligent proximity networks will be much greater, in contrast to the improved cost savings, reliability and interoperability if existing, proven technologies are used.

4. Technologies Potentially Applicable to NASA Proximity Networks

Numerous networking technologies are potentially applicable to NASA proximity networks. Some of these technologies can be used directly without modifications, others may require substantial modifications or extensions to meet NASA's needs, and still others are largely research results or general techniques that often remain to be implemented. This section identifies a number of potentially applicable technologies, and discusses their match with the requirements for NASA proximity networks.

4.1. The Internet Engineering Task Force (IETF)

The Internet Engineering Task Force (IETF), the organization responsible for standardizing the Internet protocols, unquestionably represents the broadest, deepest repository of network protocol research, design, and operations expertise. Many of the technologies described below have been or are being developed within the IETF. When examining these technologies for use in NASA proximity networks, however, it is important to understand how some of the assumptions, objectives and prejudices of the IETF may differ from those necessary to develop effective proximity network protocols.

- **Focus on terrestrial environments** While Dave Clark has suggested that protocol designers shouldn't design protocols that couldn't be used between Earth and Mars (e.g., protocols shouldn't have fixed-value timers that would preclude their use in dramatically different environments) the IETF has generally focused on wired, terrestrial environments. Extensions to TCP to improve its performance over satellite links (e.g., the TCP window scale option [34] and selective acknowledgement [21, 41]) were standardized well after their desirability was identified by a number of organizations, including NASA.

  On the other hand, there are significant benefits to extending existing Internet protocols for use in space, rather than creating new protocols. Many of the protocol extensions necessary for TCP to effectively use high-bandwidth, long-delay links are now widely available, even in some Microsoft Windows operating systems. A new transport protocol designed specifically for satellite links would not be nearly as widely available.

- **Verbose on-the-wire representations** The IETF has generally been quick to trade concise or efficient on-the-wire packet formats for other objectives. Historically, bandwidth was assumed to be cheap and ubiquitously available so minimizing the number of bits transmitted simply didn't seem important. More recently, as vendors began to dominate IETF discussions, ease-of-implementation generally outweighed efficient protocol representations. (See, for example, the desire to align protocol header fields on 32-bit boundaries, or the verbose, but easy to implement, text-based protocols such as HTML.) While this attitude is changing somewhat as wireless networks and wireless Internet access become more prevalent, it is still reflected in the design of many Internet protocols. Clearly, micropower proximity networks require a much different balance between efficient on-the-air packet formats and other objectives.

The end-to-end argument The end-to-end argument [50] asserts that many networking functions are best performed in the end devices (the hosts) rather than in the network. That is, for the most part, the network should merely transparently pass data between hosts with minimal modification. Based on this principle, devices such as firewalls and network address translators (NATs) are considered architectural abominations, at best. In fact, in spite of their widespread use, the IETF has only recently (and grudgingly) begun to consider the appropriate design and role of NATs. While research on wireless networks, particularly those connected transparently to the Internet, has raised some question about whether wireless/wired gateways should be completely transparent to the end systems, the end-to-end argument still dominates the Internet architecture and protocol design. Effective solutions for micropower proximity networks are likely to conflict with the end-to-end argument, and so care must be taken in uncritically applying the conclusions of the IETF and the Internet to proximity networks.

4.2. The Internet Protocols

The Internet protocols are among the most widely deployed, the most heavily researched, and the most sophisticated. NASA has explored both using the Internet protocols directly for space communications [25] and has created modified versions tailored to the requirements of space communications [36]. The Internet protocols or variants of the Internet protocols appear to closely match the requirements of intelligent proximity networks. On the other hand, the demanding requirements of micropower proximity networks can most likely not be met by even modified versions of the Internet protocols; new protocols and solutions are undoubtedly required for this environment.

4.3. Ad Hoc Routing Protocols

The challenges of designing network architectures and protocols for mobile ad hoc networks are similar to those presented by proximity networks. Mobile ad hoc networks are autonomous systems of mobile, wireless nodes that cooperate to form a network. The participants in an ad hoc network are not known in advance. Rather, the network is composed of the nodes in the same general area (or "proximity") that wish to communicate. The nodes must identify their neighbors and determine routes within the network. In some cases, some of the nodes are able to communicate with, and act as gateways for, external networks, such as the Internet. In these configurations, information about external connectivity must be propagated throughout the ad hoc network. By definition, ad hoc networks are autonomous; they cannot assume or rely upon pre-existing infrastructure, such as wireless access points or cellular base stations.

Routing protocols tailored to the characteristics of mobile ad hoc networks (ad hoc routing protocols), have been the primary focus of research in this area. Numerous approaches have been proposed, often based on different assumptions about the behaviors of ad hoc networks, including ATC's own Source-Initiated Adaptive Routing Algorithm (SARA) [26, 27, 28, 29, 47, 35, 12, 46, 23, 24, 49]. Attributes that differentiate approaches to ad hoc routing protocols include:

- **Distance-vector versus link-state routing protocols** Mobile ad hoc routing protocols have been developed using both major approaches to computing routes, distance-vector protocols, which distribute reachability information among the nodes (such as RIP) and link-state protocols, which distribute information about the topology of the network (such as OSPF). Neither approach, and no single ad hoc routing protocol, has yet been demonstrated to be superior in all common ad hoc network reference configurations.

- **Continuous versus on-demand routing information distribution** Some solutions continuously distribute routing information among the nodes, while others only distribute information when a node wishes to communicate with another. As might be expected, the suitability of continuous versus on-demand route information distribution depends on the characteristics of the specific ad hoc network, particularly the traffic patterns and the rate at which the topology changes.

The ad hoc network model matches the needs of NASA proximity networks fairly well. One or more of the ad hoc routing protocols developed for use in the Internet may be directly applicable. On the other hand, there are some important differences between the assumptions embodied in many ad hoc routing protocols and the needs of NASA proximity networks, particularly micropower proximity networks.

- Mobile ad hoc network research assumes no pre-existing infrastructure, and so they must be entirely self-sufficient. This assumption is probably not consistent with many NASA applications. Rather, from the perspective of proximity networks, pre-existing infrastructure most likely will or can exist. A lander, rover or orbiter could provide services for planetary exploration micropower webs. Furthermore, micropower proximity networks could be designed such that resource-intensive tasks are performed on the relatively resource-rich lander, rather than on the resource-constrained micropower nodes. How responsibilities might be best distributed between a lander and a micropower proximity network to enhance the functionality or extend its life is a topic worthy of further exploration.
- Use of the Internet protocols is almost universally assumed by mobile ad hoc network research, an assumption that is questionable for NASA micropower proximity networks (because the easiest way to extend the life of a micropower web is to use a protocol with a concise on-the-air representation). Nonetheless, the algorithms and techniques employed by the Internet ad hoc routing protocols may be applicable, even if the complete protocols aren't used.
- Power conservation is rarely a major consideration of mobile ad hoc network research, rarer still to the degree necessary when designing micropower networks. As ad hoc routing protocols are evaluated for use in micropower proximity networks, particular attention should be paid to their power consumption (e.g., the rate at which data are transmitted on the air).
- Most ad hoc routing protocols are designed to deal with rapid topology changes (the classic example of rapidly changing topologies being two truck convoys passing each other while travelling in opposite directions). The topology of micropower proximity networks will change (perhaps because nodes die, or perhaps because there is a need to redistribute responsibility among the nodes to equalize power consumption) but will change slowly compared to the design objectives of many ad hoc routing protocols.

- Micropower networks will probably have very distinct traffic patterns. If little processing of the sensor data is performed within the network, then the predominant traffic flow will be towards the egress point or points (presumably a lander). On the other hand, ad hoc routing protocol research typically assumes a more arbitrary distribution of traffic flows.

4.4. Wireless Internet Research

While the lower-layer Internet protocols were designed to accommodate a wide range of link characteristics, they may perform poorly in some environments. Performance problems that result when wireless networks are connected to the Internet spurred numerous research projects. Work on wireless/wired gateways, intended to mediate between the low-bandwidth, high-error-rate wireless network and the high-bandwidth, low-error-rate wired network, is particularly applicable to the design of proximity networks. Some creative work has been done in designing transparent gateways [5]. The less-transparent proxies may be particularly useful for micropower proximity networks (even at the risk of not being consistent with the end-to-end argument) [4].

The IETF Performance Implications of Link Characteristics (PILC) working group is developing a collection of documents that summarize many of the lessons learned about using the Internet protocols with different link-layer technologies, including wireless links. Proximity network protocol designers should be familiar with the contents of many of the PILC documents, including:

- Performance Enhancing Proxies Intended to Mitigate Link-Related Degradations [10]
- End-to-end Performance Implications of Slow Links [16]
- End-to-end Performance Implications of Links with Errors [17]
- Advice for Internet Subnetwork Designers [37]
- Advice to link designers on link Automatic Repeat reQuest (ARQ) [20]

4.5. Header Compression Techniques

In spite of the promise of ubiquitous broadband Internet access, many users continue to access the Internet through low-speed dial-up lines. This drove one Internet researcher to improve the performance of his Internet link by inventing a method of significantly compressing the IP packet headers. The prospect of widespread (but low-speed) wireless Internet access has further motivated efforts to improve the bit-efficiency of the Internet protocols. The IETF Robust Header Compression (ROHC) Working Group is exploring techniques to improve the performance of Internet protocols over wireless networks by compressing the protocol headers. The results of this work are likely to be useful in intelligent proximity networks, but micropower proximity networks probably require more radical solutions.

4.6. Internet Quality-of-Service Technologies

Intelligent proximity networks will need to provide quality-of-service assurances (e.g., to ensure that critical traffic or time-sensitive traffic isn't displaced by less-important or less-time-sensitive traffic). One or both of the two approaches to providing QoS assurances in the Internet may be applicable. The initial approach to providing QoS in the Internet was the Reservation Protocol (RSVP) which enables hosts to explicitly reserve bandwidth within the network. It was quickly apparent that permitting every host to explicitly request bandwidth simply won't scale to large networks (e.g., the Internet). In response, Differentiated Services (DiffServe) was developed, which provides QoS assurances by classifying traffic into one of a small number of classes, and treating the classes differently within the network (e.g., a low-delay, low-bandwidth class for voice, etc.)

The utility of QoS assurances is less obvious in micropower proximity networks, because only one class of traffic is likely to be transported (i.e., sensor data).

4.7. Time Synchronization

While time synchronization is an important function for many network nodes, the precise requirements for time synchronization vary between environments and applications. Two aspects of time synchronization warrant additional comments.

- **Local versus global synchronization** The most common form of time synchronization is to ensure that a system's clock is "reasonably" close to a standard time reference, such as Universal Time Coordinated (UTC). In some applications, however, it may be adequate and easier to ensure that the clocks in a collection of nodes are synchronized with each other, but not necessarily with an external, standard time. For example, the nodes in a micropower proximity network could synchronize their clocks with each other, but make no effort to synchronize their clocks with anything outside of the proximity networks. Conceivably, a gateway on a nearby lander could translate the local proximity network time to a global time, when necessary.

- **Accuracy** The accuracy of different time synchronization techniques spans eight to ten orders of magnitude. The Network Time Protocol (NTP) [42] the most widely used network time synchronization protocol, easily maintains clocks synchronized within 100 milliseconds. NTP used in conjunction with Global Positioning System (GPS) receivers designed for time synchronization and modified kernel software can keep clocks synchronized within a microsecond, even on PC hardware. Some have claimed synchronization to within 1 part per 10E-12, using state-of-the-art GPS receivers, rubidium oscillators, and crystals in temperature-controlled ovens. (The US Naval Observatory usually keeps its master clock within 10 nanoseconds of UTC, but at the cost of 50 cesium-beam frequency standards and a dozen hydrogen masers.) The question for proximity network designers and users is not "How accurately can time be synchronized?" but rather "How accurately do the scientists need time synchronized, and how much are they willing to pay to do it (primarily in terms of power consumption)?" Unfortunately, ATC is not aware of an answer to the latter question.

The Global Positioning System is commonly used in terrestrial and near-Earth environments to provide time synchronization. Some GPS receivers will provide time synchronization to well within 100 nanoseconds of UTC. GPS-based solutions aren't necessarily applicable to proximity networks because GPS receivers require a lot of power (compared to micropower nodes) and the system won't be available in planetary environments.

Dave Mills' Network Time Protocol is the most widely deployed, most sophisticated, and most heavily researched collection of protocols and techniques for network-based clock synchronization. Anyone examining network time synchronization ought not to proceed without understanding NTP and its theoretical foundations.

Precise time synchronization is critical to space operations. NASA has a long history of developing techniques for time synchronization, which time and space (if the reader will forgive the expression) don't permit examining in this document. Some of these techniques and services may be of use to proximity networks.

4.8. Location Determination

Just as proximity network nodes often need to know what time it is, they often need to know where they are. In fact, in many instances the questions of time and location are closely intertwined. GPS receivers are often used by terrestrial sensor nodes, but may not be appropriate for micropower nodes and will not be useful in planetary environments.

The requirements for location determination are similar to those for time synchronization, namely whether location must be determined relative to other nodes or to a global location reference, and the accuracy with which the location must be determined.

Several research groups are exploring non-GPS-based location determination techniques specifically designed for sensor networks [40, 19].

4.9. Energy-Efficient Protocols

The energy required to transmit one bit over a radio frequency (RF) link is many orders of magnitude greater than the energy required to execute one computer instruction. This leads directly to several obvious power-conservation strategies. First, highly efficient on-the-air message formats should be used to minimize the power consumed transmitting data over an RF link (which is why the Internet protocols, with their relatively verbose representation, are rarely used in micropower networks). Second, where possible (e.g., where compute power is available in the proximity network node) compute cycles should be traded off against bits transmitted on the air. However, because developing general rules for making these tradeoffs is very difficult, this area continues to be a topic of active research. For example, the utility of saving routing information (rather than generating it on demand) varies with the rate at which the route is used, the rate at which the network topology changes, the patterns of the traffic flows, and numerous other factors. Solutions that are advantageous under one set of assumptions often perform poorly when applied against different sets of assumptions.

4.10. Power-Aware Routing Algorithms

Power-aware computing research has developed several results that are applicable to micropower networks. The most fundamental, although somewhat straightforward, conclusion is that the resource consumption of a sensor web can be reduced, and its lifetime extended, by routing traffic through intermediate nodes. That is, because the power required to transmit data increases at between the second and fourth power of the distance, power can be conserved by reducing the transmit power used and relaying the message through intermediate nodes.

Other work has demonstrated that organizing micropower nodes into clusters and electing a node to handle communications external to the cluster can further conserve power [9, 30]. Rotating this responsibility can equalize the power consumption of the nodes, thereby extending the life of the micropower web [31].

While the work on power-aware routing is similar to the work on ad hoc routing protocols, it doesn't appear that any research group has yet integrated the two sets of results.

4.11. Bluetooth

Bluetooth is a short-range radio link that uses the 2.4 GHz unlicensed Industrial, Scientific and Medical (ISM) band [8]. Its original objective was to replace cables in personal electronics devices (e.g., between a PDA and a phone or a keyboard and a computer). Bluetooth stations can form piconets composed of a master and up to seven active slaves. The range of Bluetooth communications is expected to be approximately 10 meters, although some vendors claim ranges up to 100-300 meters in specific configurations.

While Bluetooth contains technologies that may be applicable to micropower proximity networks (e.g., interesting transmit power control facilities), its range and network size limitations severely limit its applicability to NASA proximity networks.

4.12. IEEE 802.11 Wireless LAN Standards

The IEEE 802.11 family of standards provides a range of wireless LAN solutions. While the power demands of 802.11 standards and products preclude their use in micropower proximity networks, conceivably commercial, off-the-shelf 802.11 technologies could be useful in at least some intelligent proximity networks. Note that 802.11 is not a complete networking solution; it requires additional protocols that provide higher-layer functions.

4.13. Proximity-1 Space Link Protocol

Because the CCSDS Proximity-1 Space Link protocol is nominally designed for use in proximity networks, a brief examination of how it matches the requirements identified in this document is warranted.

Perhaps the most striking aspect of the Proximity-1 protocol is the extent to which it is adapted to a very specific environment and a very particular operational model.

On its surface, the Proximity-1 protocol was designed for remote operation. The protocol is a point-to-point protocol that assumes a strong primary/secondary or master/slave relationship between the end points. The presumably highly knowledgeable master node directs the behavior of the slave. Negotiation mechanisms that exist in many protocols are absent, so the secondary node isn't even able (within the Proximity-1 protocol) to indicate that it is unable to operate in the fashion directed by the primary.

Micropower proximity networks require balanced, autonomous protocols. A model of primary/secondary communications partners is all but impossible to apply to a collection of homogeneous microsensor nodes, not to mention of highly uncertain utility. As described earlier, micropower proximity networks must autonomously configure and operate themselves, a model that conflicts sharply with the operational model that appears to be inherent in the Proximity-1 protocol.

There are features of the Proximity-1 protocol that could be useful in proximity networks, such as support for time synchronization, ranging, and forward error correction. However, as is described in greater detail below, it would be beneficial if facilities such as these could share a link with other protocols, rather than be embedded within a specific link-layer protocol. Before selecting the Proximity-1 protocol because of specific, unique services it provides, it may be prudent to examine whether these services could be provided through mechanisms that share a link with other link-layer protocols.

5. Key Technologies for NASA Proximity Networks

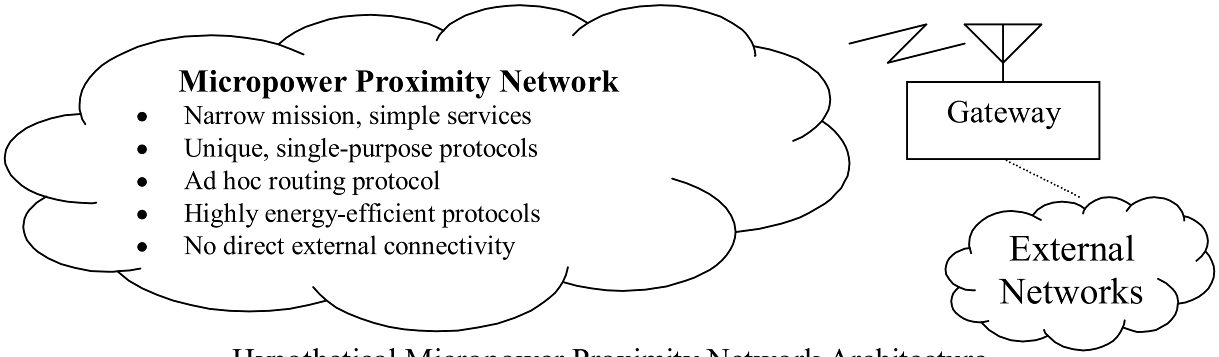
As detailed in the previous section, there are a large number of technologies that could potentially be used in proximity networks. The task of a proximity network designer is to create an integrated solution composed of complementary technologies. A good network architecture can provide useful guidance to a proximity network designer. Unfortunately, a complete, mature architecture for proximity networks does not yet exist.

5.1. Hypothetical Architectural Skeletons for NASA Proximity Networks

Proximity networks are the topic of a many current research projects. However, there is not yet consensus on the most appropriate architectures for proximity networks (papers with "architecture" in their titles notwithstanding [32]). Micropower proximity networks and intelligent proximity networks are very different: they have different objectives and requirements, require different technologies, and will have different architectures. Micropower proximity networks will undoubtedly use unique, highly efficient protocols and technologies focused on minimizing power consumption, while intelligent proximity networks will provide a broader range of services and may even use protocols similar to the Internet protocols (if not the Internet protocols themselves). Based on these observations, the broad outlines of likely proximity networks architectures are described below.

5.1.1. Hypothetical Micropower Proximity Network Architecture

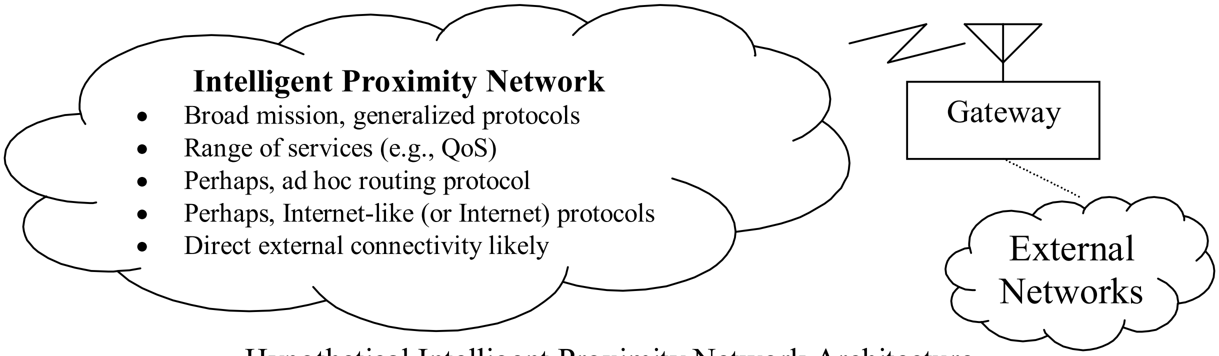
Micropower proximity networks have a simple, narrowly focused objective, namely to transport as much sensor data as possible before their batteries expire. These networks will, by necessity, offer few services beyond transporting sensor data towards an external connection. The protocols used within the micropower network will be unique and tailored to the requirements of these networks. The gateway will translate between the vastly different protocols used in the micropower network and external networks; direct connections between micropower and external networks will not be supported.



Hypothetical Micropower Proximity Network Architecture

5.1.2. Hypothetical Intelligent Proximity Network Architecture

Intelligent proximity networks will be, in contrast to micropower proximity networks, very similar to traditional wireless networks. They will support a broad range of traffic types and services; features such as QoS assurances will be important in some configurations. Conceivably, these networks could use many of the Internet protocols, presumably in conjunction with some of the extensions being developed for use with terrestrial wireless networks (e.g., header compression).



Hypothetical Intelligent Proximity Network Architecture

5.2. *Proximity Network Technology Requirements*

This section contains a compilation of requirements for proximity network technologies, many of which were identified or described earlier in this document.

5.2.1. Network Architectures and Protocols for Proximity Networks

A much better understanding of the most effective architectures for proximity networks is needed. This need is greatest for micropower proximity networks, where traditional networking solutions don't provide the proper focus on power conservation and narrowly targeted mission. A proximity network architecture ought to provide guidance on:

- services provided by the network
- distribution of function between devices (e.g., between proximity network nodes and gateways)
- functions performed by different protocol layers, and distribution of function between protocol layers
- behavior of and algorithms implemented by network devices;
- network protocols, and
- operational models.

5.2.2. Efficient Addressing Scheme

Globally unique addresses are a fundamental assumption of the Internet architecture. Unfortunately, globally unique addresses are huge. IPv6 packets may contain up to 384 bits of addresses (two 48-bit MAC addresses, two 128-bit network addresses, and two 16-bit port numbers). Micropower nodes can afford to transmit only the address bits actually necessary to identify the nodes within a proximity network (e.g., 10 bit addresses for a proximity networks of up to1024 nodes). In order to conserve address bits (and more importantly power) a single address should perform the functions performed by independent MAC-layer and network-layer addresses in most protocol suites.

The packet formats for most protocols contain both source and destination addresses. Because it is a connection-oriented, point-to-point protocol, the Proximity-1 protocol is able to include only one address in its packets. A single-address, connection-oriented, point-to-point protocol, such as the Proximity-1 is inadequate for the needs of micropower proximity networks.

5.2.3. Physical Layer Requirements

Based on the requirements of proximity networks, particularly micropower proximity networks, as well as ATC's experience with low-level protocol implementation, the following facilities will simplify the tasks of higher-level protocols.

- **Receive signal strength indication** It is valuable for a node to be able to determine the strength of received signals. This information can allow the transmitter to reduce its power, indicate the approximate range to the transmitter, and provide a basis for forming clusters, a technique for conserving power.
- **Transmit power control** A transmitter can conserve power by reducing the transmit power to only what is necessary for reliable communications, which can also reduce potential RF channel contention or interference.
- **Wake on receive** The ability for the processor to sleep until a packet is received, rather than requiring that the processor remain active while waiting for a packet, can expand the range of technologies that can be applied to micropower proximity networks (e.g., asynchronously transmitted packets become much less expensive). Note that this facility can be difficult to implement on some processors, which have wake times that are long compared to the time required to receive a packet.
- **Variable clock speed** Being able to reduce the speed of the processor clock may permit power to be conserved during periods of light processing load.
- **System sleep capability** Many power-conservation strategies assume that the processor can be put to sleep, either for a specified period of time or until some specific event occurs, typically an interrupt.
- **Subsystem sleep capability** Being able to put select subsystems, or even select portions of the processor, to sleep enables additional power-conservation strategies.
- **Synchronous communications hardware support** Synchronous communications protocols (where the receiver acquires bit-level synchronization once per message, rather than once per character) are considerably more efficient than asynchronous protocols. While many

processors include hardware support for asynchronous protocols (i.e., Universal Asynchronous Receiver/Transmitter, UART), far fewer include USARTs (Universal Synchronous/Asynchronous Receiver/Transmitter). While processors without USARTs or similar hardware can implement synchronous protocols, the code is tedious ("bit banging").

- **Hardware support for clock synchronization** Appropriate hardware features can ease the task of accurate network clock synchronization. While the Proximity-1 protocol specifies that the processor determine when a specific transition of the last bit of the synchronization sequence is transmitted, it is probably adequate for the hardware to provide an indication (interrupt) when, for example, the last bit of a packet is transmitted. The hardware is probably less complex and doesn't need to understand as much about the link-layer protocol; the processor can then compute when the event specified by the Proximity-1 protocol occurred. Note that, depending on the link-layer protocol, determining when to generate a receive interrupt may be more difficult. However, before too much effort is spent on this topic, proximity network designers ought to determine how accurately clocks need to be synchronized and whether these features are even necessary.
- **Reasonably accurate clocks** The task of keeping clocks synchronized is much easier if the clocks being synchronized are well behaved. Of course, extreme environmental conditions make this task more challenging.
- **Hardware support for range determination** Several techniques have been suggested for determining the range between two devices. Some of these techniques require that that one device echo information being transmitted by another device. This loop-back function can be performed at any of several different levels, including the analog level (a "bent pipe"), at a digital or bit level, or even at a packet level. The lower level loop-back implementations will permit more accurate range determination, but require more cooperative hardware. Again, the technique selected ought to match the requirements for range determination accuracy.
- **Hardware support for RF channel contention resolution** How RF channel contention ought to be avoided or resolved is a fundamental physical-layer design decision. Over the decades, countless techniques have been developed, and researchers are continuing to propose new solutions tailored to proximity networks [33, 6]. At this time, ATC doesn't have a strong opinion about whether, for example, the assignment of time slots (time-division multiple-access, TDMA) is more beneficial than, for example, carrier-sense, multiple-access (CSMA) schemes. Nonetheless, the design of the contention-resolution mechanism ought to be coordinated with the higher-level protocols (e.g., so that the higher-level protocols don't incorrectly assume that they can transmit asynchronously) and the hardware ought to support whatever channel contention mechanism is selected.

5.2.4. Link-Layer Protocols

Link-layer protocols are responsible for the error-free transmission of data between nodes. Proximity network link-layer protocols must provide many of the traditional link-layer services, plus some that are specific to proximity networks.

- **Highly efficient on-the-air representations** Micropower proximity networks require a link-layer protocol with a highly efficient on-the-air representation. This requirement precludes the use of an existing protocol for these networks.

- **Error detection** Link-layer protocols must detect transmission errors, typically by using a frame check sequence (FCS). Cyclical redundancy checks (CRCs) are a powerful, commonly used technique for determining the integrity of a received packet. Hardware CRC generation is useful, because software CRC generation executes slowly and is tedious to program.

- **Balanced, peer-to-peer protocol** By their very nature, micropower proximity networks require a balanced, peer-to-peer link-layer protocol (i.e., one that doesn't have a primary/secondary or master/slave relationship). Most modern link-layer protocols meet this requirement.

- **Forward error correction** Link-layer protocols for micropower proximity networks should include a forward error correction mechanism, the addition of redundant information by the transmitter that will permit the reconstruction of an error-free packet by the receiver in some cases when a packet is received with transmission errors, in order to make the best use of the available transmit power.

- **Retransmission** Because link-layer (hop-by-hop) retransmission mechanisms often interact poorly with retransmission mechanisms implemented at higher protocol layers (e.g., end-to-end retransmissions), the design of the link-layer protocol must be coordinated with the design of the higher-level protocol [20]. While the question of where retransmissions ought to be implemented can stir vigorous debate, the most important result is that the decision must be coordinated between protocol layers.

- **Connection-oriented versus datagram operation** Link-layer protocols may provide datagram services (e.g., Ethernet) or may establish a connection between communications partners before data are transferred (e.g., Proximity-1). The behavior of micropower networks (particularly in the presence of an ad hoc routing protocol) appears to match datagram-style link-layer protocols. While it may be possible to create a scheme for using a connection-oriented link-layer protocol in micropower proximity networks, ensuring that it interacts gracefully with, for example an ad hoc routing protocol, will be a challenge, plus the utility of the result is not at all clear.

- **Cooperation with range determination techniques** Link-layer protocols for micropower, and probably for intelligent, proximity networks ought to share the link with range determination techniques (rather than embed range determination within the link-layer protocol). That is, a mechanism should be provided that passes control of the link to the range-determination facility, when necessary. This approach will allow range-determination techniques to evolve independently of the link-layer protocols, and will allow the reuse of link-layer protocols across environments that may have different requirements for or different approaches to range determination.

- **Time-synchronization services** NTP provides very good network time synchronization as an application-level protocol, although it provides better results when interrupt jitter is minimized (and when interrupt latency is known). Certainly, fairly direct support for time synchronization services *can* be embedded within a link-layer protocol. On the other hand, simple techniques such as minimizing transmit and receive queuing delay for time synchronization packets may be adequate for many applications. (The Proximity-1 protocol specification appears to provide a time-synchronization service. However, all it really does is 1) specify how a timestamp relates to the transmission or reception of a packet and 2) specify a special link-layer format for transporting timestamp information, which could just be as easily be transported as link-layer data.)

- **Compression** While the most efficient method of compression is often for the application to avoid transmitting information that is not needed by the receiver, it can sometimes be useful for the network-layer protocol to provide a facility to compress application data.

- **Link-layer reliability** Link-layer protocols can provide best-effort service (transmit a packet and hope it reaches its destination) or reliable service (retransmit a packet if the intended recipient does not acknowledge receipt of the packet). Of course, reliability comes at the cost of transmitting sequence numbers and acknowledgements. The tradeoff between transmitting less sensor data more reliably versus transmitting more sensor data with less reliability should probably be examined in the design of sensor webs. In many cases, the scientific mission of the sensor web may have a strong influence on this choice.

5.2.5. Network-Layer Protocols

Network layer protocols are responsible for the end-to-end transfer of data, by potentially forwarding the data through intermediate nodes. Routing and addressing are the fundamental issues in network-layer protocol design. An ad hoc routing protocol, combined with the efficient addressing scheme identified above, matches the needs of micropower proximity networks, (although *which* ad hoc routing protocol best meets the needs of micropower networks is not immediately clear).

Quality of service (QoS) assurances are typically provided at the network layer, so mechanisms are need to identify the service class of each packet. This information is typically included in the packet header, although alternative approaches are possible (e.g., packets sent to a particular node are known to have low priority).

5.2.6. Transport-Layer Protocols

Transport protocols manage the end-to-end flow of data, ensuring that the data are received reliably and in order. They often include congestion control and flow control features.

The role of transport-layer functions in micropower proximity networks is not entirely clear, and needs to be integrated with other design decisions. One approach is to not include a transport protocol, perhaps by timestamping sensor data so that out-of-order data delivery is not an issue, and simply dropping packets in response to congestion or if the receiver is temporarily unable to accept additional packets.

5.3. Technology Readiness Assessment

ATC examined the current state of the technologies required for micropower proximity networks and intelligent proximity networks. The results of this examination are summarized in the table below, which includes the following attributes.

- **Technology** The technology being assessed is identified.
- **Applicability** An "M" indicates that a technology is applicable to micropower proximity networks, while an "I" indicates that a technology is applicable to intelligent proximity networks.
- **Reliability** The reliability of a technology is an indication of how likely a technology, in its current state of development, is to provide solutions or operate gracefully over a broad range of environments.
- **Scalability** Scalable technologies are those that can reliably support large networks with few operational anomalies or significant changes to the technologies.
- **Longevity** A technology has longevity when it appears less likely that it will be supplanted by new, alternative technologies.
- **Technology Readiness Level (TRL)** The NASA Technology Readiness Levels (TRLs) are summarized for the convenience of the reader in Appendix A of this document.

Technology	**Applicability**	**Reliability**	**Scalability**	**Longevity**	**TRL**
Micropower network architectures	M	low	medium	low	2
Intelligent network architectures	I	medium	high	high	4
Ad hoc routing protocols	M/I	medium	medium	low	2-3
Micropower physical-layer protocols	M	medium	N/A	low	2
Micropower link-layer protocols	M	medium	N/A	low	3
Micropower network-layer protocols	M	medium	high	medium	3
Internet Protocols	I	high	high	high	7
Time synchronization techniques	I	high	high	high	7
Time synchronization techniques	M	medium	medium	medium	3

6. Conclusions and Recommendations

Micropower proximity networks offer NASA the greatest potential return for its proximity network research investments. Common hardware and software platforms for micropower proximity network research, development, and deployment would enhance the opportunities for collaboration between projects, enable projects to more easily leverage the results of prior NASA-funded work and increase the overall productivity of NASA's research dollars. Live, system-level demonstrations by NASA researchers of micropower proximity networks would help focus research on identifying and solving real-world problems, as well as provide an empirical assessment of the effectiveness of proposed technologies.

Focus Proximity Network Research Investment on Micropower Networks

Micropower proximity networks and intelligent proximity networks are distinctly different, and demand different architectures and technologies. Many of the technologies required to create effective micropower proximity networks are still fairly immature, and there is little agreement on the most appropriate architectures for these networks. The requirements of intelligent proximity networks, on the other hand, can largely be met by existing technologies.

The immaturity of micropower proximity network solutions presents both a risk and an opportunity to NASA. Micropower proximity networks can enhance the success of future NASA missions, *if* mature solutions that meet NASA's unique requirements are available. NASA investments in micropower proximity network research today can ensure that solutions are available for NASA missions in a timely fashion, and that consideration of NASA-unique requirements is integral to the research and development of these networks.

Promote Common Hardware and Software Platforms

The development of a common family of micropower proximity network hardware and software platforms could effectively extend NASA's research and development dollars by:

- Enabling NASA-funded research projects to more easily collaborate, share results, and leverage prior work, because they would be using compatible hardware and software environments
- Facilitating and speeding the transfer of technologies from research to development to production, again because the use of compatible hardware and software would minimize the rework required
- Helping to focus research projects on identifying and solving real-world problems, by increasing the similarity between the research and production environments.

The functionality identified in Section 5.2.3, "Physical Layer Requirements" could be used as a straw horse to stimulate discussions about the properties of a common hardware platform for NASA micropower proximity networks. However, as noted earlier in this document, divergent opinions still exist over the desirability of using 8-, 16- or 32-bit processors in micropower networks. As such, it may be desirable to create a family of micropower research platforms that share a compatible software environment and support compatible peripherals.

Of course, the challenges of developing a common family of hardware and software platforms for NASA are complicated by the need to balance the risk of stifling innovation with the benefits of enhancing sharing and collaboration.

Promote Integrated Demonstration Projects

Live demonstrations offer valuable opportunities to communicate and empirically evaluate the effectiveness of system-level solutions. Numerous technologies have been proposed for micropower proximity networks, but there is not yet consensus on which technologies, much less which architectures composed of collections of complementary technologies, best meet NASA's requirements. The prospect of live demonstrations, perhaps at project review meetings or principal investigator meetings, would help focus researchers on integrating technologies and creating system-level architectures that will provide the micropower proximity networks required to enhance the success of future NASA missions.

Appendix A

NASA Technology Readiness Levels (TLRs)

Brief descriptions of the NASA Technology Readiness Levels (TRLs) are reproduced here for the convenience of the reader.

Basic Technology Research:

Level 1: Basic principles observed and reported

Research to Prove Feasibility:

Level 2: Technology concept and/or application formulated

Level 3: Analytical and experimental critical function and/or characteristic proof of concept

Technology Development:

Level 4: Component and/or breadboard validation in laboratory environment

Technology Demonstration:

Level 5: Component and/or breadboard validation in relevant environment

Level 6: System/subsystem model or prototype demonstration in a relevant environment (ground or space)

System/Subsystem Development:

Level 7: System prototype demonstration in a space environment

System Test, Launch and Operations:

Level 8: Actual system completed and "flight qualified" through test and demonstration (ground or space)

Level 9: Actual system "flight proven" through successful mission operations

References

1. Agre, Jonathan R., Loren P. Clare, Gregory J. Pottie, and Nikolai P. Romanov. "Development Platform for Self-Organizing Wireless Sensor Networks", Proc. SPIE, Unattended Ground Sensor Technologies and Applications, Vol. 3713, p. 257–268., Proc. SPIE, Unattended Ground Sensor Technologies and Applications, Vol. 3713, p. 257—268.

2. Alena, Richard, Bruce Gilbaugh, and Brian Glass. "Communication System Architecture for Planetary Exploration", available online at http://ic.arc.nasa.gov/publications/pdf/2001–0217.pdf.

3. Ames, Troy, Lynne Case, Chris Krahe, and Melissa Hess. "Lessons Learned from a Collaborative Sensor Web Prototype", presented at Earth Science Technology Conference 2002, June 11–13, 2002, Pasadena CA, http://esto.nasa.gov/conferences/estc-2002/Papers/A5P6(Krahe).pdf.

4. Bakre, A., and B. R. Badrinath. "I-TCP: Indirect TCP for Mobile Hosts." In *Proc. 15th International Conf. on Distributed Computing Systems (ICDCS)*, May 1995.

5. Hari Balakrishnan, Srinivasan Seshan, Elan Amir, Randy H. Katz. "Improving TCP/IP Performance over Wireless Networks " in Proc. 1st ACM Conf. on Mobile Computing and Networking, Berkeley, CA, November 1995.

6. Bharghavan, Vaduvur, Alan Demers, Scott Shenker, and Lixia Zhang. "MACAW: A Media Access Protocol for Wireless LANs", ACM SIGCOMM, 1994, p 212-225.

7. Blatt, Stephen R. "Collaborative Signal Processing for Sensor Networks", presented at DARPA SensIT PIs Meeting, April 19, 2002, http://www.darpa.mil/ipto/research/proceedings/sensit2001apr/BAE_Blatt200104.pdf.

8. Bluetooth SIG, Inc. "The Official Bluetooth Wireless Info Site" Web pages, available online at http://www.bluetooth.com/.

9. Borbash, Steve A. and Esther H. Jennings. "Distributed Topology Control Algorithm for Multihop Wireless Networks", in Proc. 2002 International Joint Conference on Neural Networks, Honolulu, HI, May 12–17, 2002.

10. Border, J., M. Kojo, J. Griner, G. Montenegro, Z. Shelby. "Performance Enhancing Proxies Intended to Mitigate Link-Related Degradations", RFC 2123, available online at http://www.ietf.org/rfc/rfc3135.txt.

11. Chang, Fu-Kuo. "A Summary Report of the 2nd Workship on Structural Health Monitoring", available online at http://structure.stanford.edu/workshop/panel.pdf.

12. Clausen, Thomas, Philippe Jacquet, Anis Laouiti, Pascale Minet, Paul Muhlethaler, Amir Qayyum, and Laurent Viennot. "Optimized Link State Routing Protocol", Internet-Draft work in progress.

13. Consultative Committee for Space Data Systems. *Proximity-1 Space Link Protocol - Rationale, Architecture, and Scenarios*. Draft Report for Space Data System Standards, CCSDS 211.0-G-0, Pre-Issue Draft, 10/4/01. CCSDS, October 1, 2001.

14. Consultative Committee for Space Data Systems. *Proximity-1 Space Link Protocol*. Draft Recommendation for Space Data System Standards, CCSDS 211.0-R3. Red Book. Issue 3. CCSDS, January 2002.

15. Crossbow Technology, Inc. "MICA Wireless Measurement System", product brochure, http://www.xbow.com/Products/Product_pdf_files/MICA%20data%20sheet.pdf

16. Dawkins, S., M. Kojo, and V. Magret. "End-to-end Performance Implications of Slow Links", RFC 3150, available online at http://www.ietf.org/rfc/rfc3150.txt.

17. Dawkins, S., M. Kojo, V. Magret, and N. Vaidya. "End-to-end Performance Implications of Links with Errors", RFC 3155, available online at http://www.ietf.org/rfc/rfc3155.txt.

18. Delin, Kevin A. and Shannon P. Jackson. "The Sensor Web: A New Instrument Concept" presented at the SPIE Symposium on Integrated Optics, San Jose, CA, January 2001, http://sensorwebs.jpl.nasa.gov/resources/sensorweb-concept.pdf.

19. Elson, Jeremy and Kay Römer. "Wireless Sensor Networks: A New Regime for Time Synchronization", available online at http://lecs.cs.ucla.edu/~estrin/papers/wsn-ts.pdf, *Under submission, July 2002.*

20. Fairhurst, Gorry, and Lloyd Wood. "Advice to link designers on link Automatic Repeat reQuest (ARQ)", Internet-Draft work in progress.

21. Floyd, S., J. Mahdavi, M. Mathis, and M. Podolsky, "An Extension to the Selective Acknowledgement (SACK) Option for TCP", RFC 2883, available online at http://www.ietf.org/rfc/rfc2883.txt.

22. Gao, Jay L. "An Adaptive Network/Routing Algorithm for Energy Efficient Cooperative Signal Processing in Sensor Networks", 2002 IEEE Aerospace Conference Proceedings, Big Sky, Montana, March 9–16, 2002.

23. Gerla, Mario, Xiaoyan Hong, Li Ma, and Guangyu Pei. "Fisheye State Routing Protocol (FSR) for Ad Hoc Networks", Internet-Draft work in progress.

24. Gerla, Mario, Xiaoyan Hong, and Guangyu Pei. "Landmark Routing Protocol (LANMAR) for Large Scale Ad Hoc Networks", Internet-Draft work in progress.

25. Goddard Space Flight Center. "Operating Missions as Nodes on the Internet (OMNI)" home page, available online at http://ipinspace.gsfc.nasa.gov/.

26. Haas, Zygmunt J., Marc R. Pearlman, and Prince Samar. "The Zone Routing Protocol (ZRP) for Ad Hoc Networks", Internet-Draft work in progress.

27. Haas, Zygmunt J., Marc R. Pearlman, and Prince Samar. "The Bordercast Resolution Protocol (BRP) for Ad Hoc Networks", Internet-Draft work in progress.

28. Haas, Zygmunt J., Marc R. Pearlman, and Prince Samar. "The Interzone Routing Protocol (IERP) for Ad Hoc Networks", Internet-Draft work in progress.

29. Haas, Zygmunt J., Marc R. Pearlman, and Prince Samar. "The Intrazone Routing Protocol (IARP) for Ad Hoc Networks", Internet-Draft work in progress.

30. Heinzelman, Wendi B., Anantha Chandrakasan, and Hari Balakrishnan. "Energy-Efficient Communication Protocol for Wireless Microsensor Networks", in *Proc. of the Hawaii International Conference on System Sciences*, January 4-7, 2000, Maui, Hawaii. Available online at http://www-mtl.mit.edu/~wendie/papers/hicss00.ps.

31. Heinzelman, Wendi B., Anantha P. Chandrakasan, and Hari Balakrishnan. "An Application-Specific Protocol Architecture for Wireless Microsensor Networks", to appear in *IEEE Transactions on Wireless Communications*. Available online at http://henry.ee.rochester.edu:8080/~wheinzel/papers/leach.pdf.

32. Hill, Jason, Robert Szewczyk, Alec Woo, Seth Hollar, David Culler, and Kristofer Pister. "System Architecture Directions for Networked Sensors", presented at ASPLOS-IX, Cambridge, MA, November 2000.

33. IEEE 802.11 Working Group. "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications", 1999.

34. Jacobson, V., R. Braden, and D. Borman. "TCP Extensions for High Performance", RFC 1323, available online at http://www.ietf.org/rfc/rfc1323.txt.

35. Johnson, David B., David A. Maltz, Yih-Chun Hu, and Jorjeta G. Jetcheva. "The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks (DSR), Internet-Draft work in progress.

36. Jet Propulsion Laboratory. "Space Communications Protocol Standards" home page, available online at http://www.scps.org/.

37. Karn, Phil, ed. "Advice for Internet Subnetwork Designers", Internet-Draft work in progress.

38. Kazz, G. J. and E. Greenberg. "Mars Communication Protocols", presented at Concepts and Approaches for Mars Exploration, July 18–20, 2000, Houston, Texas, http://www.lpi.usra.edu/meetings/robomars/pdf/6114.pdf.

39. Kessler, Seth S. and S. Mark Spearing. "Structural Health Monitoring of Composite Materials using Piezoelectric Sensors", submitted for publication to Materials Evaluation, available online at http://web.mit.edu/sskess/www/papers/materials_evaluation.pdf.

40. LeMaster, E. A., Masayoshi Matsuoka, and Stephen M. Rock. "Field Demonstration of a Mars Navigation System Utilizing GPS Pseudolite Transceivers", Position, Location, and Navigation Symposium, Palm Springs, CA, April 2002, http://sun-valley.stanford.edu/papers/LeMasterMR:2002.pdf.

41. Mathis, M., J. Mahdavi, S. Floyd, A. Romanow. "TCP Selective Acknowledgement Options", RFC 2018, available online at http://www.ietf.org/rfc/rfc2018.txt.

42. Mills, Dave. "Time Synchronization Server" Web pages, http://www.eecis.udel.edu/~ntp/.

43. National Aeronautics and Space Administration. "STS-101 Payload: HTD 1403 Micro Wireless Instrumentation System (Micro WIS) HEDS Technology Demonstration", http://www.shuttlepresskit.com/sts-101/payload62.htm.

44. National Aeronautics and Space Administration. "Say Aaahhhh', NASAexplores, March 1, 2001.

45. National Institute of Science and Technology. "Research Topic: Distributed Detection for Smart Sensor Networks", http://w3.antd.nist.gov/wctg/smartsensors/sensornetworks.html.

46. Ogier, Richard G., Fred L. Templin, Bhargav Bellur, and Mark G. Lewis. "Topology Broadcast Based on Reverse-Path Forwarding (TBRPF), Internet-Draft work in progress.

47. Perkins, Charles E., Elizabeth M. Belding-Royer, Samir R. Das. "Ad hoc On-Demand Distance Vector (AODV) Routing, Internet-Draft work in progress.

48. Pister, Kristofer S. J., Joseph M. Kahn, and Bernhard E. Boser. "Smart Dust: Wireless Networks of Millimeter-Scale Sensor Nodes", Highlight Article in 1999 UCLA Electronics Research Laboratory Research Summary, http://robotics.eecs.berkeley.edu/~pister/publications/1999/smartdust_highlight_erl99.pdf.

49. Ramanujan, R., S. Takkella, J. Bonney, and K. Thurber, "Source-Initiated Adaptive Routing Algorithm (SARA) for Autonomous Wireless Local Area Networks", in Proc. of the 23rd IEEE Conference on Local Computer Networks (LCN '98), October 1998.

50. Salzer, J.H., D.P. Reed and D.D. Clark, "End-to-end arguments in system design", *ACM Transactions on Computer Systems*, Nov 1984, p. 277–288.

51. Savvides, Andreas, Chih-Chieh Han, Mani B. Srivastava, "Dynamic Fine-Grained Localization in Ad-Hoc Networks of Sensors", MOBICON 2001, 166–179.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
October 2003

3. REPORT TYPE AND DATES COVERED
Final Contractor Report

4. TITLE AND SUBTITLE
Proximity Networks Technology Assessment

5. FUNDING NUMBERS
WBS–22–704–61–16
GS35F0038L

6. AUTHOR(S)
Timothy J. Salo, Barry A. Trent, and Timothy Hartley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Architecture Technology Corporation
9971 Valley View Road
Eden Prairie, Minnesota 55344

8. PERFORMING ORGANIZATION REPORT NUMBER
E–14181

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR—2003-212623

11. SUPPLEMENTARY NOTES

Project Manager, Obed S. Sands, Space Communications Office, NASA Glenn Research Center, organization code 6120, 216–433–2607.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 17 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report summarizes an assessment performed by Architecture Technology Corporation (ATC) of technologies applicable to wireless proximity networks used in NASA applications. NASA proximity networks are relatively small, fairly short-range, often ad hoc, wireless networks typically dedicated to tasks such as transporting in situ sensing data. The number of nodes contained within a proximity network is expected to be comparatively small, perhaps tens or hundreds of nodes at most. While “short-range” is relative, many proximity networks will have a physical diameter on the order of hundreds or thousands of meters (although some authorities have suggested that a few of these networks might be as large 100 to 400 km. This assessment concludes that the technologies required for micropower proximity networks are far less mature than those needed for intelligent proximity networks. As such, micropower proximity networks offer NASA the greatest potential return for its proximity network research investments. Common hardware and software platforms for micropower proximity network research, development, and deployment would enhance the opportunities for collaboration between projects, enable projects to more easily leverage the results of prior NASA-funded work, and increase the overall productivity of NASA’s research dollars. Live, system-level demonstrations by NASA researchers of micropower proximity networks would help focus research on identifying and solving real-world problems, as well as provide an empirical assessment of the effectiveness of proposed technologies.

14. SUBJECT TERMS
Local area networks; Signal transmission; Packet transmission; Multiple access; Packet switching; Network control; Telecommunication; Data links; Communication networks; Ethernet; Protocol

15. NUMBER OF PAGES
52

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102