N4C

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Architecture, Test Beds and Innovative Alliances
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DTN - The State of the Art

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SEVENTH FRAMEWORK PROGRAMME

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ABSTRACT

Starting in May 2008, N4C is a 36 month research project in the Seventh Framework Programme (FP7, www.cordis.lu/fp7). In cooperation between users in northern Sweden and the Kočevje region in Slovenian mountain and partners, the project will design and experiment with an architecture, infrastructure and applications in field trials and build two test beds.

This document examines the state of the art of Delay- and Disruption-Tolerant Networking (DTN) as it existed during the early part of the N4C project both from a technical point of view and in terms of the demonstrations and test beds that had been created using this technology. It also reviews other projects related to rural Internet initiatives both from a technical and business pint of view. It provides a summary of the situation, including a review of the major open questions in DTN research, some of which the N4C project is seeking to address. It will be complemented by an annotated online bibliography hosted on the N4C project wiki that provides a wealth of additional material on the more detailed aspects of the subject.

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- Krzysztof Romanowski (ITTI, Poland) – generated most of the project list in Section 8.
- Boštjan Grašič and Marija Božnar (MEIS, Slovenia) – wrote Section 7.
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Dissemination level	
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PU = Public	x
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CONTENT

1. INTRODUCTION

This document examines the context in which the Networking for Communications Challenged Communities (N4C) [N4C] has started its work. In N4C's work package 2 (WP2), Task 2.1 set out a number of pieces of work that would ensure that the project was fully cognisant of predecessor work and could take full advantage of what had gone before,

This document, Deliverable 2.1 of WP2, records the output of the three preliminary investigation strands of work in Task 2.1 that required reviews of

- the 'state of the art' in Delay- and Disruption Tolerant Networking (DTN),
- earlier user and business requirements investigations, and
- existing initiatives for access and connectivity in remote/rural areas.

N4C will build on the legacy of the previous Sámi Network Connectivity project (SNC) that has provided a core for a practice that integrates environmental, cultural and gender considerations with technical research and development. SNC was built around an outline for a network architecture, and this outline was from the start developed and presented in an integrated package that included considerations of practical and financial terms for its use in remote areas, often with a sparse population that might not be in permanently settled locations, looking at the potential for business opportunities to be exploited by the inhabitants in such areas – women and men alike, and with particular stress on environmental care.

This integrating character was continued in the formulation of the N4C application to EU FP7 and later Description of Work (DoW). It is observable in the formulation of concepts and objectives, in the Consortium's mix of Beneficiaries, in the organization of Work packages and in the profile of the Dissemination plan.

The primary objective of these reviews is to ensure that N4C integrates the information, experiences and best practices from prior work outside SNC into the N4C project work, ensuring that we advance the state of knowledge. This document provides a resource that reviews what has been achieved so far in relevant areas and summarizes the pieces that should influence the path of the work in N4C.

1.1 THE N4C CONTEXT

The Networking for Communications Challenged Communities (N4C) [N4C] project is based around two test beds that will be operated in the arctic area of northern Sweden and the Kočevje region of Slovenia. These regions are 'communications challenged' in the sense that they have little or none of the infrastructure that is needed to support today's conventional wired and wireless Internet communications, and the economics of the regions are such that it is highly unlikely that this infrastructure will be installed in the foreseeable future.

The regions have a very low population density much of which is either transitory or semi-nomadic so that there is little fixed accommodation to which cables could be laid. Mains power supplies do not exist and the topography is highly mountainous which militates against the installation of cellular telephone networks even if the expected communications traffic would be sufficient to justify these installations (and at least in parts of Swedish Lapland, environmental concerns would limit such installations). The remaining alternatives are satellite communication and wide area broadcast technologies. Satellite communications offer only a low bandwidth for very high cost both in terms of equipment purchase and ongoing per-octet traffic costs which is not compatible with the relatively low financial return on the industries indigenous to the regions. In the case of arctic regions in northern Sweden, the high latitude restricts availability to communications through polar orbit satellites giving an intermittent and uncertain service. Wider area broadcast technologies such as Digital Radio Mondiale (DRM) might offer a somewhat higher bandwidth but unidirectional service using frequencies that are not limited to line of sight. However, such services have not yet been implemented in the relevant regions and the economics are uncertain.

If conventional infrastructure cannot deliver an economic solution to the communications problem, what are the options? Increasingly we are all carrying small, wireless equipped computers often in the guise of mobile cellular telephones or Internet tablets that provide local area communications such as Wi-Fi (IEEE 802.11) and Bluetooth. Although the communications challenged regions cannot provide the base stations which these devices need for wide area communications, this does not prevent pairs of such devices engaging in communication when they come into local wireless range, even if this range is only a few tens of metres. Combined with increasingly cheap and capacious solid state storage modules in these devices, it becomes clear that these devices allow the user to become a *data mule*, carrying 'bundles' of data from place to place and transferring it to other carriers during 'communication opportunities' offered by encounters with other users who are able to take the data onward to its destination. Provided that we can solve the security, routing and resource allocation problems (not trivial problems or we wouldn't be here!), these bundles don't have to be ones 'owned' by the device user – they can become a 'common carrier' if they are willing to support the common good of the region.

This kind of opportunistic encounter driven 'store, carry and forward' network has been developed as part of research into Delay- and Disruption-Tolerant Networking (DTN). So N4C is researching whether DTN can provide a viable alternative infrastructure to make a usable Internet in communications challenged regions. This document describes the starting point, looking at the developments over the last ten years that have brought DTN to the current state of development and setting out the challenges that need to be addressed before DTN becomes an everyday reality.

Section 2 provides some background history. In Section 3 the technical architecture of the most widely investigated and commonly used DTN infrastructure is reviewed. Section 4 categorizes the usage scenarios that have been investigated by some of the numerous projects that have utilized DTN. A provides an extensive listing and outline of these projects and others that appear relevant to the N4C context for future reference. Section 4 also looks at the main challenges that need to be addressed as DTN moves forward into mainstream usage, especially the adaptation of applications to manage human expectations in a DTN environment. Sections 5 and 6 document the primary simulation and implementation resources that are available to support DTN developments. Section 7 moves temporarily away from the DTN context to look at the state of the art in Environmental Information Systems (EIS) as this is relevant to some of the work in N4C, returning to conclude with an examination of the relevance of DTN to EIS deployment. Section 8 examines the prior art in projects that have looked at the business, social and economic aspects of extending communication capabilities into rural communities, identifying case studies where DTN might applicable as a delivery medium and hence may be used to guide the business work in N4C WP9.

1.1 DTN AT THE CROSSROADS

DTN research started a little over ten years ago when Vint Cerf and colleagues started examining what would be needed to extend the burgeoning Internet beyond the confines of Planet Earth coining the phrase *Interplanetary Internet*. During this time the initiative has continued to push back the boundaries into space but has also come back down to earth first as Delay-Tolerant Networking and then as Delay- and Disruption-Tolerant Networking.

Major assumptions of the existing Internet are that messages need only be stored transiently and communications along the forwarding path are relatively rarely disrupted or interrupted. DTN seeks to provide usable Internet-style communications even where the delay between transmission and reception or request and response at the end points of the communication is far greater than either would be acceptable to the humans using today's applications or feasible using today's communication protocols. It also aims to facilitate communication where there is no guarantee that messages can be forwarded 'immediately' upon arrival at an intermediate waypoint, such as a router.

DTN stands at a crossroads because to date much, although not all, research has concentrated on a building an 'overlay' transport network that can transfer files or bundles from place to place without worrying too much about how this capability would integrate with applications that humans would find useful and without being overly concerned with integrating DTN capabilities with the existing Internet. To show that DTN is a useful technology to extend the Internet into communication challenged regions, we need both to make the infrastructure robust and design applications that provide useful, secure capabilities for business, education and leisure when running over a combined DTN and existing Internet infrastructure.

Succeeding with this aim goes beyond providing a niche solution applicable to a small portion of the population, however technically, socially and culturally laudable this aim may be. The steady growth of the conventional Internet and the growing complexity of both applications and the network infrastructure tends to come at a price: while the bits may travel end to end at near light speed, the responses seen by humans and applications at the end points may be subject to significant delay, because of additional computing, message round trips, setup delays and authorization requirements that result from added complexity in networks and applications. Applications will need to be adapted both to deal with less responsive networks and to manage user expectations so that s/he is comfortable (or at least not pestered with delay driven 'failures') with a network that has a more elastic round trip delay bound than is currently expected. This kind of adaptation needs to become mainstream and DTN-oriented research ought to provide insights that will be applicable across the whole network environment of the future.

2. HISTORY

The genesis of the concepts behind the DTN architecture as it is today came from looking at how to extend the Internet into interplanetary space. Much of the credit for the initial inspiration has to go to Vinton Grey (Vint) Cerf, who was then working at MCI, and Adrian Hooke of the NASA Jet propulsion Laboratory (JPL).

Back in 1994, Vint authored a short, futuristic fantasy tale[1] of 'Internet' communications in 2023 between locations on Earth and other parts of the Solar System (*A View From The 21st Century* [RFC1607]). He claims that this was not an influence when in late 1997 he began thinking about how to extend the Internet into an interplanetary network and use Internet style communications for links to spacecraft. At this time Adrian Hooke was already leading a small team at JPL looking into how to adapt TCP/IP to the very long delays and intermittent communication sessions that characterize communications between ground stations and spacecraft, especially those in the further reaches of the solar system.

Vint and Adrian found that they were very much on the same path and the result was that a DARPA-funded Interplanetary Internet (IPN) project was created in mid-1998 [Universe98]. The project involved JPL, Mitre, GST, Sparta and a number of US universities, and was supported by the

[1] Published as an 'April 1st' RFC (*Request for Comments* – IETF Publication Series, ISSN 2070-1721).

establishment of the IPN research group by the Internet Research Task Force (IRTF) and the IPN Special Interest Group (IPNSIG) by the Internet Society (ISOC) [IPNsig].

The first phase of the IPN project ran for about four years and its main output was a description of the problems and a proposed architecture for a communications overlay network that would support transmission of messages in the IPN environment. This was published in 2001 as *Interplanetary Internet (IPN): Architectural Definition* [IPNarch00] and set the architectural basis for much of the DTN work that has taken place since that time. The scenarios that the IPN architecture targeted were based on the sorts of extensive delays resulting from interplanetary distances and scheduled communication opportunities that are typical of spacecraft operations. The architecture also took into account additional constraints such as asymmetrical bandwidth, unidirectional communications on links and limited power, all of which make traditional IP transport protocols difficult or impossible to use.

After the IPN document had been published, researchers began to consider how the architecture could be applied to other situations where communications were subject to delays and disruptions that would make conventional Internet protocols (especially TCP) ineffective. In the IPN scenarios, delays and intermittent connectivity are due to 'the facts of physics': light speed from Earth to another planet means a delay of 20 minutes to several hours; orbiting spacecraft and rotating planets result in occultations that interrupt communications. All of these are more or less predictable, although terrestrial weather, bleeding edge equipment and the effects of chaos theory on spacecraft orbits can still intrude into a system that appears to offer predictable communications opportunities.

The architectural work in 2002-3 looked at other scenarios, especially terrestrial wireless networks such as wireless sensor networks and Wi-Fi based local area networks, where communications opportunities were much less predictable. It also provided a framework for dealing with interconnected heterogeneous networks, such as occurs at the gateway between a sensor network which does not usually use IP-based addressing/communications and a conventional IP-based network. By the middle of 2002, when an updated version of the IPN architecture was published [IPNarch01], Kevin Fall of Intel Research had coined the name Delay-Tolerant Networking (giving the initial use of the acronym DTN).

At about the same time, the IRTF IPN research group metamorphosed into the DTN research group [DTNRG] which is still ongoing as one of the premier forums for DTN collaboration. The DTNRG worked first on further generalization of the architecture publishing its first update in 2003 [DTNarch00]. The architecture was refined over the next few years and finally published as RFC 4838[RFC4838] in 2007. By this time the subject was more properly called Delay- and Disruption-Tolerant Networking but the acronym DTN is still used to cover the extended title.

A previous 'state of the art' document capturing the state of research work was published in 2003 [Akyildiz03]. This document is mostly focussed on the IPN work and covers a number of alternative approaches to space communications and analysis of existing protocols.

Since the publication of the IPN architecture in 2001, DTN research has had a number of strands:

- Various researchers have collaborated at the DTNRG to produce basic standards that implement parts of the DTN architecture, especially the Bundle Protocol [RFC5050] and a number of 'convergence layers' that allow bundles to be exchanged over diverse transport layers. The basic documents have been published as experimental standards and the DTNRG is currently (2009) pushing to get a number of the auxiliary standards currently in draft form published as experimental standards or informational documents as appropriate.

- Specialized link layer protocols suitable for use in challenged environments such as the Licklider Transmission Protocol and the Saratoga convergence layer have been developed and demonstrated.

- The interplanetary aspects have been vigorously pursued at JPL and standardized for space operations through the Consultative Committee for Space Data Systems [CCSDS]. The work at JPL has spawned the ION project at the University of Ohio which has developed a DTN protocol stack based on a bundle protocol and routing protocol implementation suitable for deployment in space craft. The recent crowning achievement of this work resulted in the software being demonstrated in communications between the Deep Impact (now EXODI) spacecraft and earth. Consequently this software is now well on the path to being 'flight qualified' and could be used on subsequent missions as part of the main communications path.

- Following on from the initial IPN project, DARPA has funded ongoing development and a number of demonstrations of DTN technology especially targeted at military applications starting in 2004. This program is in its third phase, and is now seeking to integrate DTN into 'conventional' military communication networks, just as N4C is seeking to integrate into civilian networks.

- Research continues into some of the remaining open questions, especially security, routing and schemes for naming and addressing of DTN nodes. A number of demonstrators have been created, notably DieselNet and the SNC project. There have also been a great many simulations of various aspects of the DTN system.

Finally, we should be aware that the architecture and bundling system supported by the DTN Research Group collaboration is not the only possible implementation of a DTN system. The DTN philosophy is also espoused in other contexts such as the Haggle EU 6th Framework Project but their implementation is quite different. Haggle is concerned with social networking in a purely terrestrial context (at present) with a 'lighter weight' infrastructure and has taken a different path to the IPN derived system. As N4C continues, we should be fully aware of these developments.

3. TECHNICAL ARCHITECTURE AND COMPONENTS

In this section we examine the technical state of the art concentrating on the architecture that has been developed out of the IPN requirements by the DTN Research Group collaboration The analysis will include the capabilities that are expected of the DTN architecture and the components that have been developed to support these capabilities. This architecture was used by SNC and seems most appropriate for the applications that N4C will be developing.

3.1 CONCEPTS AND CAPABILITIES

As explained in Section 2, the fundamental capabilities of the Delay- and Disruption-Tolerant Networking architecture are designed to support a communications network that can have much longer delays, and hence communication latencies, than is the expectation in the existing Internet, as well as connection disruption.

From the point of view of human users of the network, a DTN network is intended to provide service in conditions where delays and disruptions will often result in network responses arriving only after the boundaries of (unmanaged) human expectation and tolerance have been exceeded. Applications that are aware that they are running in such an environment need to be designed to manage human expectations, and continue to perform as if the network performance was expected rather than, as often happens today, treating 'excessive' delay as an 'error'. With proper user interface design and psychological cueing, it should be possible to deliver a service that the human user will consider useful, provided that they are given the proper understanding of what is happening. N4C is also looking at classes of applications that can actively make use of the ability to manage delay and disruption.

From the point of view of (existing) applications, there is often a disparity between the latency requirements of the application and the latency that the underlying networks can deliver. DTN hopes to bridge this disparity.

The existing Internet, using the IP protocol model, is able to support a degree of heterogeneity in the systems that can be attached to the network, but it makes a number of fundamental assumptions and applies certain constraints to these systems. Interoperability is achieved by every node having to use common format identifiers (IP addresses) with a packet format that has universally-obeyed semantics; packets are forwarded from source to destination with minimal delay with a routing methodology that expects a connected routing graph to exist essentially at the moment the packet is to be dispatched.

The development of DTN out of the IPN domain where scheduled communication periods are the normal situation into networks, especially Wireless Sensor Networks (WSNs), where communication periods occur in a more random, opportunistic fashion pointed up the need for DTN to support a more flexible form of heterogeneity. The IPN already envisaged that parts of the network would have different communications capabilities, and that such 'regions'[2] would be interconnected by *gateways* that could mediate translation between the capabilities of the connected regions. WSNs often use very different addressing, routing and packetization structures to the IP norms, and gateways are an essential feature when they are attached to the Internet. In space, the capabilities available between ground stations and spacecraft are also different from the IP norms, and gateways are needed if the end-to-end path traverses both ground and space segments.

Heterogeneity drives many of the capabilities of the DTN architecture. The architecture is designed to support an altogether more extensive form of 'internet' where we use the original meaning of the word that implied an interconnection of networks. The component networks are not expected to have common addressing formats or addressing semantics, and disparate routing methodologies may be employed. It is no longer expected that messages will be able to travel end-to-end with only transient storage whilst in flight; some nodes may provide non-volatile storage for messages where there are physical or temporal discontinuities in the routing path.

Removing these restrictions on the extended DTN-capable 'internet' has far reaching consequences. What is left from the IP paradigm is a common encapsulation for data to be sent through the network. The message '*bundle*' provides a flexible encapsulation for a chunk of data and a selection of meta-data that describes the data, where it should be sent and how it should be handled. Even here there is a subtle but fundamental distinction between the headers prepended to the data payload of an IP packet and the meta-data associated with a message bundle. The meta-data is much more closely associated with the user/application intent than are IP headers. The meta-data is interpreted at each DTN waypoint on the route travelled by the bundle to determine how to forward the bundle at each hop, whereas IP headers are created at the source on the assumption that the destination address, possibly in association with the source address and quality of service requirements, links the packet to a route that is predetermined at the moment the packet is despatched. The IP source doesn't need to know exactly what the path is, but the implicit assumption is that selecting addresses ties the packet to a path.

[2] The region terminology has gone out of favour in DTN work because it has become clear that the spatial association implied by the term is inappropriate in many circumstances.

In conventional IP networks, supporting other addressing formats or semantics in conjunction with IP has resulted in the widespread use of *overlay* networks, where the IP protocol is essentially used as a link layer. The DTN architecture can also be thought of as an (IP) overlay network if the underlying communication uses IP packet encapsulation and protocols, but it is rather different in that the underlying communication may use protocols that are not related to IP at all.

As we shall see in the rest of this section, DTN uses naming, layering, encapsulation and persistent storage to interconnect heterogeneous portions of a larger 'internet', irrespective of a formal layering model. The DTN architecture provides a number of key services, including *in-network data storage*, *retransmission*, *custody transfer* with *authenticated forwarding*, and *flexible node naming* to this internet.

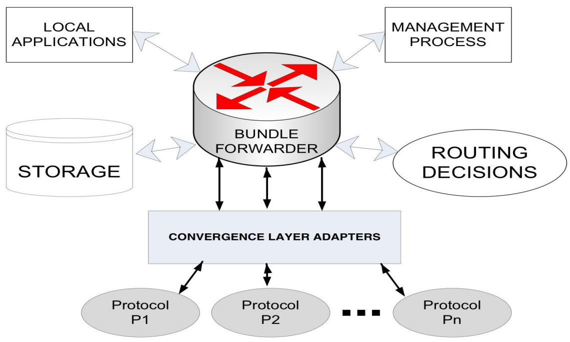

FIGURE 1 AN EXAMPLE IMPLEMENTATION ARCHITECTURE SHOWING HOW A BUNDLE FORWARDER INTERACTS WITH APPLICATIONS, STORAGE, ROUTING DECISIONS AND CONVERGENCE LAYER ADAPTORS TO DELIVER BUNDLES OVER DIFFERENT PROTOCOLS.

Figure 1 shows how the DTN architecture might be implemented within a single node. The core of the mechanism is the *bundle forwarder* that manages the bundles within the node. During communication opportunities the node can connect to other nodes using a multitude of different delivery protocols, including TCP/IP, Bluetooth, raw Ethernet, serial lines or hand-carried storage devices (sometimes called *sneakernet*). The differing semantics of the various protocols are concealed from the bundle forwarder by a collection of *convergence layer adaptors* (CLAs) that map the capabilities of the individual protocols to the functions necessary to transfer *bundles* to a peer node during a communications opportunity.

When a communications opportunity arises, either because it has been scheduled by the node *management process* or because a peer node has been *discovered*, typically by some wireless mechanism, the bundle forwarder will initiate and manage a link to the peer node using the appropriate CLA. The link will be used to transfer selected bundles stored on this node to the peer node, in accordance with *routing decisions* provided by the routing decisions process. If policy requires, the bundle may be encrypted or provided with integrity protection before being forwarded.

Depending on the kind of link, bundles may be transferred in both directions or just one way. DTN is designed to cope with both unidirectional and bidirectional links. Where the delay time across the link is significant, such as in the original IPN scenario, the link will generally be unidirectional; routing and forwarding decisions are made purely locally and the bundles will be sent in a 'fire and forget' mode, using a protocol that does not require immediate acknowledgements for reliability. Where the encounter is more local, such as an *ad hoc mode* Wi-Fi connection, the link may be bidirectional with more or less symmetric communication bandwidth in the two directions. In this case, bundles may be forwarded in both directions between the nodes and a handshaking protocol such as TCP can be used to achieve reliability on the link.

The routing decision process in the two cases could be very different, and DTN allows a different routing decision process to be used for each communications opportunity. Typically this will be dependent on the environment, such as the type of link and the semantics of the bundle addressing mechanism used by the peers. Where a low latency bidirectional link is used, the routing decision processes in the two nodes can exchange routing control information and negotiate whether to accept bundles offered for transfer, according to resource availability and knowledge of bundles already in storage, so avoiding wasting link bandwidth by transferring duplicates.

Bundles arriving at the node will be security checked and decrypted if required and then placed into the bundle storage. Depending on the destination address, the bundle will either be delivered to a local application or saved for onward forwarding. Of course, local applications will be expected to originate bundles that are placed in storage by the bundle forwarder until a suitable communications opportunity arises allowing the bundle to be forwarded towards its destination.

Embedded in the metadata of each bundle is an *expiry time*. Nodes will delete bundles from their data stores if they have not been able to either successfully deliver or transfer custody of the bundle to some other node when this expiry time is reached. This ensures that the bundle store does not become cluttered with undeliverable bundles, thereby preventing the node from accepting new bundles during subsequent encounters. Expiry times are expressed in absolute clock time which requires every DTN node to have a reasonably accurate clock tied to the UTC value: this requirement has been the subject of much debate, but given that nodes are required to operate independently there seems to be little alternative.

The DTN2 reference implementation of this architecture [DTN2] was developed under the aegis of the DTN research group and supported until recently by DARPA funding. Maintenance of the DTN2 code is currently being taken over by the N4C project. The DTN2 design has followed the general outline of Section 3.1 and several other implementations have followed this general approach.

3.2 NAMING, ADDRESSING AND BINDING

Naming and addressing are some of the most fundamental aspects of a network architecture, and one of the most tricky aspects to get right. Generally, naming has been thought of as something useful to people or organizations while addressing is more useful for network operations and routing. Names are generally expected to be variable-length strings while addresses are expected to be fixed-length identifiers. Some form of mapping or binding function is used to convert names into addresses. In the case of the Internet, this is the domain name system (DNS). In the case of various overlay network systems (e.g., Chord [Chord01]), it may be a locally-executed hash function.

In the evolution of the DTN architecture, nodes have always had identifiers. These are used in the context of the *bundle protocol* (BP) [RFC5050], which provides the basic message delivery service for DTN. Originally, identifiers in the bundle protocol were constructed as a 3-tuple of the form (region, host, application), which was able to not only identify a host, but also an application of interest on the host. A region was a portion of the network topology, and in the original IPN design was generally assumed to represent a well-connected area surrounding a planet. Routing decisions were thus relatively straightforward, based first on region, and then on host identifier, somewhat similar to the way routing is arranged in IP networks where aggressive CIDR address prefix aggregation is performed. After some consideration of the application portion of the identifier, it was merged into the host identifier, forming an aggregate demultiplexing identifier where the partitioning between host and application was determined within a region. After extended consideration of the tie between the region portion of an identifier and its required association with the network topology, the region construct was significantly modified. This decision was based primarily on the observation that nodes may have multiple network interfaces and may also be mobile, so additional flexibility was required in how they are named. It became more important to support multiple namespaces with differing naming semantics than coupling an identifier to a location in the topology to aid routing. With multiple namespaces, hosts may have multiple identifiers and these may be either assigned by users, or imposed by the networks to which nodes become connected. This began to blur the distinction of name and address. Blurring seems to be an attractive direction, as precisely distinguishing between the two has become increasingly challenging (e.g., consider vanity telephone numbers).

In recognizing that nodes may require multiple identifiers and even multiple types of identifiers, a naming structure was sought that is capable of encoding names or addresses from multiple different name spaces (and thereby also requiring a way to identify the namespaces from which the identifier had been allocated). Fortunately, work in the IETF had already been accomplished in the area of generalized naming systems, in the form of Universal Resource Identifiers (URIs) [RFC3986]. Although URIs are somewhat more complicated than required by the bundle protocol, they have a few important properties:

- **Allocated Name Spaces** – Each URI is fundamentally of the form `<scheme>:<scheme-specific-part>`, where the scheme is a string allocated from a set of well-known and administered scheme names (e.g., http, sip, file)
- **Variable Length** – Although bounded to a relatively large size, URIs are essentially free-form except for a few reserved characters that have special semantics
- **Structured Semantics** – URIs obey a general syntax and semantics, but a new scheme may define its own special additional semantics, subject to general rules that apply to all URIs

Using URIs as identifiers brings several advantages. First, they can encode names or addresses taken from many namespaces. For example, we might refer to a host by its Ethernet address as `ether://00-12-33-fe-22-31` but also refer to it using some distinguished hierarchical name like dns://myhost.foo.com. While in the Internet, the scheme specifier also tends to suggest the protocol stack used (e.g., `http` is typically http/TCP/IP) to contact remote node(s), this need not be the case for DTN; we can use the bundle protocol, or some other combination of protocols. URIs as used in DTN are referred to as endpoint identifiers or EIDs.

For a message containing DTN URIs comprising symbolic names, (i.e., URIs using namespaces apart from standard address formats), some *binding*[3] step is performed by one or more nodes along the delivery path. Such binding may be performed anywhere along the delivery path. In the Internet, this happens at multiple layers and at multiple locations.

When DNS is invoked at a sending node, this is a form of *early binding*, which is used immediately in mapping a DNS name to an IP address. Subsequent mappings are performed on the IP address in delivering its containing packet toward its destination.

DTN supports routing and direct forwarding based on symbolic names (or intentional names [Intention99]), so the early binding typical of DNS in the Internet is not generally required. Instead, messages are passed along toward their destinations based on forwarding entries present at DTN routing nodes that match against the name. This is known in the DTN literature as *late binding*. DTN supports both late and early binding, depending on the scheme used. The extent to which late binding scales to networks of many routers will be interesting to see as DTN deployments scale up.

[3] There is another use of the term *binding* to mean associating a name or address with a receiving application, a function performed by the `bind()` socket API call. We instead use the term registration to refer to the state created by that operation, which can be persistent for DTN applications.

Both the syntax and the semantics of a preferred DTN naming scheme are still the subject of research and debate, but the DTN research group has recently made some long-awaited progress in this area, and a scheme proposal seems to be within our grasp.

3.3 TRANSFERRING DATA – BUNDLES

Applications in the DTN architecture operate on messages carried in variable-length protocol PDUs called *bundles*. The name 'bundle' derives from considering protocols that attempt to minimize the number of round-trip exchanges required to complete a protocol transaction, and dates back to the original IPN work. By 'bundling' together all information required to complete a transaction (e.g., protocol options and authentication data), the number of exchanges can be reduced, which is of considerable interest if the round trip time is hours, days or weeks.

Bundles comprise a collection of typed blocks. Each block contains meta-data; some also contain application data. For much of the evolution of the DTN architecture and bundle protocol, blocks that contained only meta-data were simply called headers, but after it became apparent that the bundle security protocol (see Section 3.6) required the ability to append meta-data (e.g., a MAC) to a bundle, the term block was adopted. Blocks are chained together as extension headers are in IPv6.

The extensibility of chained blocks has been key to supporting experimentation with the bundle protocol. For example, a bit indicates whether receiving a block of unknown type causes the containing bundle to be discarded or whether the block can instead be processed unaltered (i.e., as opaque data). This is expected to be of use, for example, as new authorization (e.g., capabilities) or routing functions (e.g., source routing) are investigated.

3.3.1 Blocks

The first or *primary* block of each bundle contains the DTN equivalents of the data typically found in an IP header on the Internet: version, source and destination EIDs, length, processing flags, and (optional) fragmentation information. It also contains some additional fields, more specific to the bundle protocol: report-to EID, current custodian EID, creation timestamp and sequence number, lifetime and a dictionary. Strings are placed in the dictionary, and offsets are used as pointers to the beginnings of strings in an effort to reduce space that would otherwise be devoted to duplicate strings. Most fields are variable in length, and use a relatively compact notation called self-delimiting numerical values (SDNVs) [RFC5050].

The *origination time* in each bundle indicates the real time at which the bundle was sent from its origin. The *lifetime* is an offset of real time from the origination time giving the expiry time of the bundle. If a bundle is found to be queued at the end of its lifetime, it can be discarded. This is one of the ways in which excess bundles can be cleared from the network. It also provides a basis for implementing policy: a network operator could arrange for bundles beyond some age to be expired early (or late).

The use of real time in bundles imposes a requirement on each participating DTN node: that real time be synchronized, at least roughly. This requirement was considered repeatedly, as it represents a significant departure from common practice in the Internet today. To date, we have identified four reasons for imposing it. First, most applications for which DTN was designed are time sensitive; resources are consumed at particular points in space and time. A DTN node not knowing the time renders the DTN far less useful for most applications which themselves require time. Second, in most of the cases where DTN has been tested, and in most cases for which it is planned, access to real-time is already provided by some mechanism (including in deep space and underwater environments)[4].

[4] The common exception to this rule is when DTN has been placed in certain embedded systems that lack a real-time clock. In such cases, the system usually boots with a software clock set to the year 1970. This is expected to be a relatively minor problem, as more embedded systems become equipped with real time clocks and GPS.

Third, routing using scheduled connectivity is inherently tied to link availability at a certain time. Fourth, network management tasks, including tracing and debugging are considerably easier when a common time reference is used throughout the network.

Other than the required primary block appearing at the beginning of a bundle, additional blocks are optional but use a common basic format. The common format includes an 8-bit block type (like the extension header type in IPv6), processing flags and block length. The processing flags indicate whether the block is to be copied in any fragment created, whether a status report should be issued if the block type is unknown to the node forwarding the bundle and whether the bundle should be dropped in this case. The indication to copy the block to each fragment is really designed for blocks carrying meta-data associated with delivery of the bundle contents such as handling restrictions, retention guidelines, digital rights management, or sensitivity labels. In the environments that require them, such meta-data are typically mandatorily bound close to the data they describe.

If a bundle is carrying a data payload, the data will be contained in a single payload block.

3.3.2 Fragmentation

Allowing for bundles to be fragmented, either prior to transmission, or while in transit, has been an ongoing point of discussion since the original IPN work. Fragmentation breeds complexity, and the possibility of *custody transfer* (see Section 3.5), where responsibility for ensuring delivery of bundle is moved from the originating node to some other node on the path, interacts in very complex ways with fragmentation.

However, it became clear that because most communication opportunities in a DTN network are time limited, there was an upper limit to the number of octets that could be transferred during a given opportunity. Consequently at least *proactive fragmentation* would have to be implemented in the bundle protocol, whereby the likely octet capacity of a communication opportunity is assessed in advance, and bundles larger than this capacity would need to be fragmented in advance so as to be able to obtain any goodput in such circumstances. Proactive fragmentation is supported by the bundle protocol [RFC5050] and mechanisms allowing acknowledgement of custody for bundle fragments have been provided.

Proactive fragmentation is useful for scheduled communication opportunities, but is less satisfactory in purely opportunistic encounters. Here the duration of the encounter cannot be predicted in advance. The best that can be achieved is some statistical knowledge of the likely duration of encounters allowing the node to split a large bundle into chunks that it expects can be transferred during a typical encounter. Whether it will be necessary to implement some sort of reactive fragmentation to cope with interrupted transfers remains to be seen.

Fragmentation and encryption can also interact badly. The bundle security mechanisms (see Section 3.6) allow encryption to be carried out at intermediate points on the path of the bundle, rather than just at the source. Many forms of encryption lead to the expansion of the cleartext when enciphered. If only parts of a bundle follow a path that requires encryption, it is possible for overlapping fragments to arrive at the destination, leading to confusion when reconstructing the bundle payload. The use of *counter-mode encryptions* [Dworkin07] that do not expand the cyphertext, and encrypting only at the source, can sidestep these problems.

3.3.3 Error Detection

The bundle protocol provides no bit-level error detection or correction mechanism apart from the message integrity checks associated with the bundle security mechanisms. If bundle security is not used, it is conceivable that bundles might have bits unintentionally modified in transit. Such modifications can occur either in application data or in bundle meta-data. This was a conscious design decision made by the designers, as the bundle protocol is intended for two primary uses. First, it can operate as a network layer, essentially replacing IP. In this case, error detection and correction are left to the higher layers based on similar reasoning[5]. Alternatively, the bundle protocol can be used above existing transport (or other) layer protocols, which commonly provide data integrity checks. This arrangement leaves bundle data potentially vulnerable to corruption if errors in the DTN forwarding engine or host occur.

In addition to the two use cases mentioned above that leave the question as to whether a bundle-layer integrity check is necessary unclear, there are applications where data with errors are valuable and where retransmissions are not desirable. For example, uncompressed image data from remote sensors, even if not error-free, may be valuable to deliver as soon as possible, especially if contact opportunities may be infrequent. The current design, therefore, leaves the task of bit-level error detection and repair up to the application.

3.4 ROUTING

Section 3.1 introduced the idea that DTN networks may use multiple different routing paradigms according to the nature of the underlying network. Partly as a consequence of this DTN Routing has become almost a separate research topic. Many proposals have become the subject of simulation studies in papers and PhD theses. A limited number have actually been documented and implemented for use in demonstration networks.

DTN routing, unlike standard IP routing, is expected to cope with disconnected graphs and intermittent connectivity. The information on which routing decisions are made has to be strictly local to the node at the time the decision is made – and it may well be somewhat out of date as there is no guaranteed way to deliver routing information updates to a node that might be interested. It has become clear that DTN routing is more of a multi-parameter resource utilization optimization problem than just a matter of deciding the output interface on which to queue a packet. The routing decision needs to determine which bundles may be best transferred and/or accepted to make best use of the available storage and communication opportunity octet capacity, while choosing to route the bundles in the way that will probably lead to them being delivered to the destination as quickly and efficiently as possible.

Also, unlike IP routing that is almost entirely topologically controlled and is largely time independent, DTN routing has to take into account both physical position and time dependence. DTN implements a *'store, carry and forward'* (SCF) paradigm. The carry function may just be a matter of time – holding onto a bundle until a suitable forwarding opportunity arises, but in many cases the node is mobile and moves relative to other nodes with which it might exchange bundles. So DTN routing needs to be aware that neighbours, paths and the desirability of forwarding a bundle to a particular neighbour during a future communication opportunity are time dependent and need to be reassessed at the time of the opportunity.

DTN routing is expected to support applications in a wide variety of environments, in line with the basic principles of the DTN architecture. A given node will likely have to support a number of different routing strategies and 'protocols' – protocols is quoted because the protocol will typically be just a limited point-to-point meta-data exchange, which actually concerns not only true routing information designed to assist with optimal forwarding, but also information about the bundles available for exchange and a negotiating position on the order of such an exchange. The available

[5] IP version 4 has both an IP-layer header checksum as well as transport layer checksums covering some portions of the IP-layer header. The IP header checksum was removed when specifying the IPv6 header, leaving only the transport layer checksum for end-to-end error detection.

range of solutions will help the node to operate efficiently in the vast diversity of situations in which a node, especially a fully mobile node, may find itself.

The survey paper published by Zheng in 2006 [Zheng06] gives some idea of the range of solutions to the routing problem that has been investigated. The paper lists at least 20 separate proposals and a number of additional ones have been published since 2006. Several of these are mentioned in passing in Section 4.1.

Zheng adopts a classification system that categorizes the proposals as follows:

- Deterministic case
  - Space-time routing
  - Tree approach
  - Modified shortest path approaches
- Stochastic case
  - Epidemic/random spray of bundles on encounters
  - History or prediction-based approach exploiting movement characteristics
    - Per contact routing based on one-hop information
    - Per contact routing based on end-to-end information
  - Model-based – exploiting knowledge of node behaviour
  - Control movement of nodes to transport bundles to desired location
  - Network coding-based approaches

The DTN infrastructure is intended to support multiple different protocols that might prove to be advantageous. Several simple routing mechanisms are implemented in the DTN2 reference implementation and work is in progress to document these mechanisms, including 'epidemic' and 'static' routing. Epidemic routing [Vahdat00] is the simplest of the stochastic category, aiming to end up with each participant in an encounter carrying the union of the sets of bundles on the participants before the encounter. Static routing provides managed, pre-configured routes that may be useful to DTN capable nodes in an Internet, low latency environment or for testing.

The N4C project expects initially to make use of the PRoPHET [Lindgren03] routing protocol that was used in the predecessor project SNC. PRoPHET falls into the stochastic, history-based approach class. PRoPHET is particularly applicable to environments with many mobile nodes that are typically carried by human agents. It leverages the idea that human motions are not random, but associated with social and business patterns. Hence node encounters are likely to be repeated and provide a good basis for routing bundles. On the other hand, PRoPHET does not assume that there is a constant or even nearly constant underlying connectivity topology that can be leveraged to assist prediction. Each node maintains a delivery probability for nodes that it is aware of, and these probabilities are updated during encounters to guide both direct and indirect delivery of bundles.

At the time of writing, PRoPHET is the only DTN routing protocol that has been formally documented as a protocol in an Internet Draft or RFC [Prophet09]. We anticipate that the protocol will be developed further during the N4C project, possibly to incorporate some aspects of loosely scheduled as well as purely opportunistic encounters. PRoPHET is implemented in the DTN2 reference implementation and there are other independent implementations including one made for the SNC project which will probably form the basis of a more complete implementation of DTN for N4C.

Two other more non-trivial routing mechanisms have been documented and implemented, but are not yet in the IRTF standards process. *Contact Graph Routing* (CGR) [IONdoc08] is a dynamic routing system that computes routes through a time-varying topology of scheduled communication contacts in a DTN network. It is designed to support operations in a space network based on DTN, but it also could be used in terrestrial applications where operation according to a predefined schedule is preferable to opportunistic communication, as in a low-power sensor network. CGR is implemented in the ION DTN suite, but is not currently available in the DTN2 reference implementation.

The basic strategy of CGR is to take advantage of the fact that, since communication operations are planned in detail, the communication routes between any pair of 'bundle agents' in a population of nodes that have all been informed of one another's plans can be inferred from those plans rather than discovered via dialogue (which is impractical over long-one-way-light-time space links). This is often known as an oracle-based strategy. An Internet Draft documenting CGR is planned shortly.

Delay-Tolerant Link State Routing (DTLSR) [Demmer07] is incorporated in the DTN2 reference implementation. DTLSR addresses situations where there is underlying relatively stable topology of a constrained size but it is expected that many of the links will be unpredictably unavailable so that the probability of finding end-to-end connectivity between pairs of nodes at a particular time may be quite low. However, when communication is possible, it is assumed to be low latency bidirectional communication as seen in the Internet today. The number of nodes in the network is expected to be typical of networks where intra-domain IP routing protocols would be applicable if the connectivity was more reliable.

DTLSR uses a modified form of the link state algorithm usually seen in the IP intra-domain routing protocols OSPF (Open Shortest Path First) [RFC2328] or IS-IS [ISO8473]. Augmented topology maps in the form of link state updates are propagated between nodes using the BP so that the updates eventually propagate throughout the network area as the update bundles are given a very long lifetime and new updates are only sent if the underlying topology or other information changes rather than because a link becomes available or unavailable. The updates also include information about the resource usage in each node, the expected performance of links when active, and information about expected outages. This extra information is used in conjunction with the topology information to calculate the best route for a bundle that has to be routed, with the target of minimizing the expected delivery delay. It is specifically not required that an end-to-end connection exists at the moment the route is calculated. This protocol has been used to enhance the behaviour of networks as part of University of California at Berkeley's Tier program.

One interesting recent development is the RAPID protocol [Balasubramian07] that is from the same 'delivery predictability' stable as PRoPHET: this is the first protocol to fully treat the routing decision as a resource utilization optimization question. As mentioned previously, the 'store, carry, and forward' paradigm requires a multi-dimensional optimisation approach to make best use of the capacity of the node and its expected communications opportunities.

3.5 CUSTODY AND CONGESTION – RESOURCE MANAGEMENT

DTN custody transfer is a service that may be optionally provided to a bundle as it is delivered through a DTN. When used, custody transfer keeps track of a current 'responsible entity' or 'custodian' for each bundle, and the custodian is required to keep the bundle safe in persistent memory until another custodian has received it successfully. Bundles may be moved from one custodian to another (nominally toward the bundle's destination), and an acknowledged transfer is accomplished for each. There are circumstances where this acknowledgment procedure can fail when the connection breaks during a transfer operation, or the network does not support bi-directional data transfer [Fall03], [Duros96]. These situations are expected to be relatively rare, but insufficient deployment experience leaves the question open at this time.

The custody transfer model and use of persistent storage at intermediate nodes provides the ability to delegate the responsibility for reliable data transfers to portions of the network other than the original sender, without violating the guiding end-to-end principal in IP networks [Clark84]. This is possible, and even necessary, in the DTN context because one of the assumptions of the DTN architecture is that the original source of data may become unreachable or inoperable (e.g., due to environmental factors) before transmitted data reaches its ultimate destination(s). By migrating all the state regarding the correctness of the data transfer to an intermediate node ("custodian"), the "end point" (in the sense of [Clark84]) has merely been moved to another location; it is still ultimately responsible for the correct conclusion of a data transfer operation.

Note that the DTN approach does alter the context for interpreting Clark's "fate sharing" concept [Clark88]. His argument suggests that placing critical connection state within intermediate nodes is unwise, as the ability to withstand partial network failures decreases. In the DTN setting, however, there is no connection state. There can be critical copies of network message fragments resident in the persistent storage at custodians, but DTN allows the set of potential custodians to be configured. Therefore, the amount and location of critical state can be carefully controlled, and limited to those nodes known to be highly reliable. This is especially important in the cases where DTN intermediate nodes (e.g., potential custodians) can be more reliable and have better connectivity than end nodes, such as sensors or robots.

Not every node in a DTN needs to offer custody transfer. A node may refuse to accept custody for messages for implementation or policy reasons, because not enough free storage space is currently available, or for other reasons. The importance of having custody transfer be truly optional seems, at present, to be unclear. Many users of DTN networks wish to lose no data, so every node and every bundle operates using custody transfer or some equivalent capability. This may be adequate for a stable network with sufficient storage resources, but is not when the source rate exceeds the network delivery rate beyond the network's buffering capability. This is, in essence, the main problem of DTN congestion.

Some forms of DTN may seek to transfer bundles between nodes offering custody services through a chain of non-custodial nodes. This might be relevant if there are links between the various intermediate nodes all offering communications services at the same time so that a 'synchronous' transfer can be effected. Here the nodes offering custody form another overlay on the total DTN network as discussed in the DTNlite proposal. If the links are not all available at the same time, verifying that custody can or has taken place is difficult and needs further research. This is discussed a little more in Section 3.7.

Of course, congestion control is a major area of study in computer networking. It has been explored much less extensively in DTNs, with only a few papers having been published (see [Seligman06] and [Burleigh06]). The DTN architecture specification [RFC4838] indicates congestion is still a topic "on which considerable debate ensues." DTN congestion occurs when storage resources become scarce due to the presence of too much bundle data or too many bundle fragments. A node experiencing these situations has several options to mitigate the situation, in the following order of preference: drop expired bundles, move bundles somewhere else, cease accepting bundles with custody transfer, cease accepting regular bundles, drop unexpired bundles, and drop unexpired bundles for which the node has custody.

Given that expired bundles are subject to being discarded prior to the onset of congestion, there may be no such bundles to discard. Moving bundles somewhere else may involve interaction with routing computations; this is a reasonable approach if storage exists near the congestion point, and is the subject of [Seligman06]. It is also straightforward to cease accepting bundles with custody. This amounts to a form of flow control operating at the (DTN) hop-by-hop layer, and can result in backlogs of custody transfers as they accumulate upstream of congested nodes. To cease accepting regular bundles, the node essentially disconnects from its neighbours for some period of time. DTN tolerates such disconnections, but doing so can once again result in upstream congestion. The last two options are the least attractive, with the very last being all but prohibited. Dropping unexpired bundles results in a less predictable network from an end-user perspective, as the bundle lifetime capability is essentially disabled. While some protocol could be developed to propagate the policy-based early expiration times implemented by certain nodes, this has received no attention to date. Discarding bundles for which a node has taken custody defeats much of the delay tolerant aspects of DTN (but not the heterogeneity support). DTN attempts to provide a delivery abstraction similar to a trusted mail delivery service; discarding custody bundles is clearly antithetic to this goal.

Even after several years of design, the value of custody transfer and behaviour of DTN congestion remains to be fully understood. It is likely these will remain poorly understood until the DTN architecture is more widely deployed and carries significant traffic loads. This is not entirely surprising, as a similar story arose in the early history of the Internet. The original TCP protocol specification included no management of congestion, and the problem remained poorly understood (and largely unrecognized) until the late 1980's, more than 10 years after the first experiments with Internet technology were performed.

3.6 SECURITY

DTN security has evolved over the years. Initially, when designing for the IPN, most of the focus was on so-called 'security policy gateways', that would roughly control access to the space-segment of the network. Controlling access to that part of the network was the most important security control point, but once traffic entered, it was presumed to be authorized and so there was little or no need for cryptographic mechanisms to be defined as part of the bundle protocol [RFC5050]. At around that time, the idea of cryptographic authentication protecting only the headers was proposed. The logic was that protection of the entire payload might be expensive (in CPU terms) and that once the header was protected then the bundle as a whole could be authenticated as being "wanted traffic" as opposed to unwanted traffic. However, while this would be reasonable for the space segment of an IPN, it ignored the existence of intermediate hosts that are not part of the DTN (e.g., IP routers) that, if subverted, could then modify the bundle payload. This demonstrated the need for additional work to define a more fully-featured set of security mechanisms.

Today, the DTN bundle security protocol specification [Symington09] defines

- data integrity and confidentiality mechanisms for the data payload block in bundles, usable across multiple hops of the bundle forwarding path, including end-to-end,
- data integrity and/or confidentiality for blocks other than those directly concerned with the data payload, and
- a hop-by-hop integrity mechanism covering all blocks in the bundle across a single hop between DTN nodes.

The rationale for the separation is to provide for different types of canonicalization and key management that are likely to be used for hop-by-hop vs. end-to-end cryptographic services.

Provision for integrity and confidentiality over a subset of the complete path is useful because some DTNs (e.g., wireless sensor networks) may involve nodes that are extremely challenged in CPU terms, or more likely, in key management terms, and so cannot themselves encrypt, decrypt, sign or verify bundles. In addition, there may be some DTNs in which portions of the physical network topology are contained in physically secured facilities. Cryptographic protection at the bundle layer may not be necessary in these network segments. Accordingly DTN security allows for intermediate DTN nodes (between the source and destination) to apply or check the validity of the cryptographic credentials. The relevant nodes in these cases are referred to as the security source and security destination, respectively, which can differ from the bundle source and destination. Whether or not these features prove useful in future DTN pilots remains to be seen, but they do represent subtle differences from how cryptographic services are used in most networks today.

There are a number of open issues in DTN security [Farrell06], some of which may be more tractable than others. First, the interaction of fragmentation and the application of cryptographic mechanisms can be challenging, as mentioned in Section 3.3. Given that support for cryptographic services is optional and fragments may have followed different paths, then it is possible that a set of fragments could be reassembled where only one of the fragments contains ciphertext. Clearly such combinations are a concern, and additional deployment experience will be required before we can confidently select between the various restrictions that might ameliorate these problematic situations. As discussed earlier, the current approach uses counter-mode ciphersuites only.

While the bundle security protocol defines cryptographic services, it does not (yet) provide any way to manage the required keys. Work on this is only really now beginning and various fairly standard approaches will have to be considered before some solutions are chosen. Of course, any solutions need to be appropriate for operation in DTN environments, where regular low-latency communication may be infrequent.

The last area of security that warrants further study is a model for the authorization of traffic in DTNs that would be analogous to how the problem of authentication, authorization and accounting (AAA) is handled in the Internet today. Again, work here is just beginning, but in a sense this represents a full-circle: we now (almost) have sufficient basic mechanisms in place to finally tackle what was always going to be a major security problem in DTNs, as it is in Internet: the problem of unwanted traffic [RFC4948].

3.7 INTERACTION OF FRAGMENTATION, ROUTING, CUSTODY AND SECURITY

Operations in a DTN network that span more than a single point-to-point link between two nodes can become very complex when all four of these capabilities are used in the network. Custody transfers that require acknowledgements of transfers to be sent to the previous custodian can be lost or badly delayed if routing is unable to immediately reverse the route taken by the bundle to be transferred, as may happen where the network uses mainly opportunistic encounters. Fragments may travel by different routes and multiple copies possibly with overlapping scopes may be delivered, either at intermediate reassembly points or at the final destination. Security may be applied differently to different fragments that are routed differently and will need to be treated differently according to the security suite employed.

The ramifications of these interactions have not been fully explored and require further research.

3.8 CONVERGENCE LAYERS

The DTN architecture and the Bundle Protocol envisage using whatever underlying communications capabilities are available to transport bundles hop-by-hop between DTN capable nodes. The details of how each transport mechanism is used are hidden by the use of a *convergence layer adaptor* CLA) that provides a uniform interface to the Bundle Agent irrespective of the transport used.

The basic services required of the CLA by the BP are very simple – just being able to send and receive a bundle. Other parts of a Bundle Agent (such as the security) may require additional services.

A number of CLAs have been standardized matching the commonly available transport and link layers that implementations of DTN are likely to encounter. Additionally there are specially written transport protocols and corresponding CLAs designed to support environments too extreme for existing transport protocols.

Although the majority of DTN communications tend to use a CLA that interfaces to a transport protocol, it is possible to interface bundles directly to a link layer such as Ethernet or IEEE 802.11 Wi-Fi. There advantages and disadvantages to the 'direct to link layer' approach. On the plus side overhead is minimized and it may be possible to make use of some of the hardware knowledge (such as high efficiency in discovering new neighbours in opportunistic situations) gained from closer coordination with the physical layer, but in situations where congestion may be a problem, it would be necessary to handle this in a technology specific way as compared with, say, using TCP, and most link layers do not offer any form of reliability guarantee so that this has to supplied at a higher layer. In many cases, using UDP over the specific link layer provides a reasonable compromise combining a low overhead adaptation with the ability to provide common services that are needed in most cases.

The following sections discuss some of the commonly available CLAs.

3.8.1 TCP/IP Convergence Layer Adaptor

The TCP/IP CLA is suitable for managing links between DTN nodes in the existing Internet and may be appropriate for opportunistic connections such as between Wi-Fi capable nodes where there is an implementation of TCP/IP over the link layer. It provides a reliable bi-directional link provided that the connection latency and round trip time is not too great. The TCP CLA is in process of being standardized [Demmer08].

3.8.2 UDP/IP Convergence Layer Adaptor

Although it is possible to use the UDP/IP CLA directly from the Bundle Agent, this is not recommended practice, except possibly in isolated networks or on dedicated links. UDP used alone has no congestion management capabilities so that injudicious use could lead to congestion and denial of service to other applications. It also has minimal protection against packet corruption and, in any case, should not be used for data segments that would need to be fragmented by the network.

The UDP/IP CL is useful as a means for carrying Licklider Transmission Protocol (LTP) data segments or Saratoga data segments (see Sections 3.8 and 3.8). The UDP/IP CL is being standardized (see [Kruse08]).

3.8.3 Bluetooth Convergence Layer Adaptor

Bluetooth based CLAs have been implemented and shown to be viable. Typically they have much in common with TCP/IP. At present there is no standard in process for a Bluetooth CLA.

3.8.4 Licklider Transmission Protocol

The Licklider Transmission Protocol (LTP) [RFC5326] is designed to provide retransmission-based reliability over links characterized by extremely long message round-trip times (RTTs) and/or frequent interruptions in connectivity. Since communication across interplanetary space is the most prominent example of this sort of environment, LTP is principally aimed at supporting 'long-haul' reliable transmission in interplanetary space, but it has applications in other environments as well.

In an Interplanetary Internet deployment using the Bundle protocol, LTP is intended to serve as a reliable convergence layer over single-hop deep-space radio frequency (RF) links. LTP does *Automatic Repeat reQuest* (ARQ) of data transmissions by soliciting selective-acknowledgment reception reports. It is stateful and has no negotiation or handshakes. In a terrestrial environment it can run over the UDP/CL layer provided that the size of data segment sent is restricted to avoid the need for fragmentation of UDP datagrams.

3.8.5 Saratoga Convergence Layer Adaptor

Saratoga was designed as a file transfer protocol for intermittent, disrupted, space communications, meaning that Saratoga's expected operating environment is a DTN network. The Saratoga transfer protocol can be readily adapted as a convergence layer for the Bundle Protocol, using UDP as an encapsulation when running on terrestrial links. The CLA is documented in an Internet Draft [Wood08].

3.8.6 Ethernet Convergence Layer Adaptor

The DTN2 reference implementation provides for encapsulating bundles directly in Ethernet frames [DTN2].

4. USAGE SCENARIOS AND CHALLENGES

Groups involved in DTN research and development today are concerned with how to address the architectural and protocol design principles arising from the need to provide interoperable communications with and among extreme and performance-challenged environments where continuous end-to-end connectivity cannot be assumed. Said another way, they are concerned with interconnecting highly heterogeneous networks together even if end-to-end connectivity may never be available. Examples of such environments include spacecraft, military/tactical, some forms of disaster response, underwater, and some forms of ad-hoc sensor/actuator networks. It may also include Internet connectivity in places where there are obstacles to implementing the sort of low latency, reliable communication that the existing Internet relies on. Such communications challenged areas include both developing parts of the world and areas where the population density is very low making deployment conventional infrastructure economically unattractive or communications are inhibited by environmental factors, such as at high latitudes where satellite coverage is problematic.

4.1 SCENARIOS

In this section we briefly describe some of the scenarios that have been addressed by recent work in DTN as seen in the early stages of the N4C project. At least in the spacecraft and military tactical communications scenarios, it appears that DTN has proved itself to be a viable and, in the military case, highly effective solution. The work on these areas is moving from research into development, and we can expect to see products utilizing DTN in the medium term.

The application of DTN in the remaining scenarios is less well entrenched although there have been many experiments with sensor networks. Naming and routing issues require further research, and integrating with the existing Internet will also require further research work.

The spacecraft and military tactical scenarios are examples of two more general situations:

- Predominantly scheduled communications opportunities with potential disruption.
- Relatively high density of mobile nodes expecting reasonably frequent communication opportunities but with high probability of disruption.

The other scenarios can be categorized as:

- Networks using a relatively stable underlying topology but with frequent disruptions leading to partitioned networks.
- Networks using predetermined mobility paths but without a reliable schedule.
- Networks using directed mobility to route bundles (robot ferries) increasing the probability and frequency of encounters.
- Networks with lower expectation of communication opportunities either due to power/environmental constraints or wide area mobility in a low density network with limited communication range including sensor networks and lower density opportunistic encounter networks.

We see that there is a gradation of 'structuredness' in this and the type of routing mechanisms needed for the various scenarios changes according to how structured the scenario is.

4.1.1 Spacecraft Communications

After almost ten years of development work, the IPN can now be considered to be a reality. Two sets of tests during the second half of 2008 have demonstrated that DTN protocols provide a significant enhancement of spacecraft communications.

On 11 September 2008 Surrey Satellite Technology Ltd (SSTL) announced [SSTC08] that they had demonstrated downloading of a large image from the UK-DMC satellite using the BP and the Saratoga CLA, forwarding it to the NASA Glenn Laboratory still in bundle format where it was reassembled and 'unbundled' before being sent back to SSTL for post-processing.

Starting in October 2008, NASA JPL performed a series of experiments simulating communications with rovers on the surface of Mars relayed through a DTN bundle agent installed on the Epoxi spacecraft, previously known as Deep Impact when it visited Comet Tempel 1 in 2005, and now retargeted to rendezvous with Comet Hartley 2 in 2010. JPL announced success on 18 November 2008 [JPL08], and now plans a further series of experiments involving the International Space Station. Assuming success continues, this will lead to the JPL ION software being qualified as 'flight ready' enabling it to be deployed as part of the primary communications software for future missions

4.1.2 Military and Tactical Communications

The latest phase of DARPA's Disruption-Tolerant Networking (DTN) program is creating the first 'fieldable' equipment that uses DTN to enable access to military tactical information when stable end-to-end paths do not exist and network infrastructure access cannot be assured [BBN08]. This program is now in its third phase after extremely positive results from the technology development and prototyping in phases 1 and 2

The previous work was centred around the SPINDLE (Survivable Policy-Influenced Networking: Disruption-tolerance through Learning and Evolution) projects lead by BBN Technologies [SPINDLE07].

The primary goal of the DTN program is to develop and field (military) network services that deliver critical information reliably even when no end-to-end path exists through the network. Traditional TCP/IP networks rely on stable end-to-end connectivity, but terrain, weather, jamming, and movement or destruction of nodes can interrupt the path and halt the flow of message traffic. The DTN system can send and receive data reliably even when no stable end-to-end paths exist.

The DTN technology developed during SPINDLE II [Krishnan07a,Krishnan07b] uses the DTN2 open-source, standards based core with a plug-in architecture and well-specified interfaces, to enable independent development and insertion of innovative DoD-relevant technology while allowing the core system to be refined and engineered within a COTS (Commercial Off-The-Shelf) context. SPINDLE technology innovations include:

- routing algorithms that work efficiently across a wide range of network disruption,
- a name-management architecture for DTNs that supports progressive resolution of *intentional name* attributes within the network (not at the source), including support for 'queries as names' and name-scheme translation,
- distributed caching, indexing, and retrieval approaches for disruption tolerant content-based (rather than locator-based) access to information, and
- a declarative knowledge-based approach that integrates routing, intentional naming, policy-based resource management, and content-based access to information.

The final results from the SPINDLE demonstrators showed that the DTN approach greatly outperforms traditional end-to-end approaches across a wide range of network disruption scenarios and could significantly reduce communications bandwidth requirements, especially on critical and expensive long haul links where reduction by an order of magnitude appears likely.

The third phase of the DARPA program, which is now under way, again lead by BBN, will integrate the DTN system prototyped in the previous phase into fielded military networks that may combine several different types of nodes, including wireless, satellite, and vehicle-mounted. In addition, BBN will implement a longer term military application; investigate approaches to building large scale networks that self-organize in response to mission needs, and develop methods to maintain both the security and controlled availability of persistent data.

The characteristics of the military tactical network are significantly different from some of the other scenarios discussed below. Military networks will expect to have a rather denser set of nodes for opportunistic networking and the command and control nature of military operations assists with controlling communications opportunities. Also availability of power may be less of issue for at least some nodes, but disruptions may be very frequent also, due to attempts by the participants to hide their presence either physically or electronically, or because of enemy attack leading to damaged nodes.

4.1.3 Disaster and Emergency Response

A number of organisations have been working to use DTN in the context of disaster and emergency network support. Notably the Multimedia and Mobile Communications laboratory (MMLAB) at Seoul National University have been investigating an Architecture for Intelligent Emergency DTN [Chu08, MMLAB08] using extensive temporary wireless communications.

In this project the authors note that DTN serves four critical roles in their wireless networking concept:

1. DTN deals with the reality that mobile edge networks may not have complete source-to-destination paths
   - DTN uses opportunistic links, drop boxes, and data mules

2. DTN allows each hop in the network to be optimized uniquely and individually, vs. end to end
   - Deal with latency, congestion, and loss locally, bilaterally
   - Content cached at each hop (whether encrypted or "clear")

3. The DTN bundle is an information (vs. packet) interface
   - Any (predicate calculus) description of a node is an Address
   - Nodes supply to and request content from network using same structure – network is aware of information, not just addresses
   - Cognitive management decides on data storage, replication, …

4. DTN hides internal network details (protocols, routing, name services)
   - Allows non-IP networks, avoid OSPF flooding, DNS dependence, unstable routes,

These concepts are very close to the ideas behind the SPINDLE concepts that underlie the military tactical proposals discussed in Section 4.1

There have also been various proposals in NSF's FIND *Wireless Network after Next* initiative including *The-Day-After Networks: A First-Response Edge-Network Architecture for Disaster Relief* [Luo07] which suggests that DTN will play a role in such a network, but by no means all recent emergency response papers suggest the use of DTN (see [LeMay07] for example).

Unfortunately practical demonstrations of this scenario using DTN as opposed to theoretical and simulation work seem to have been lacking so far. However the success of the HPWREN [HPWREN08] remote forest fire camera system and its ready acceptance by fire fighters shows that there is considerable scope for using a DTN based system during actual fires to propagate pictures where there is no wireless infrastructure, or it has been destroyed by the fires.

4.1.4 Static Wireless Sensor Networks

DTN has been applied extensively to wireless sensor networks and there is a good deal of practical experience with various scenarios. These networks are typically used to collect environmental data from autonomous sensors dispersed at fixed locations over a considerable geographic area returning it by wireless hops to a gateway where it can be monitored or passed on to analysts over the Internet. On land the sensors normally communicate using radio frequencies with the frequency and power suited to the application. Underwater radio ranges are minimal and acoustic signals are typically used for communication. In addition to the usual challenges of DTN, most sensor network nodes are also

- **power challenged**, operating from batteries or low output renewable sources hence requiring that nodes use minimum power with long sleep intervals between relatively short communication opportunities in order to maximize the lifetime of the node between battery replacements. In reality nodes would be looking to achieve a lifetime of months to years between maintenance visits.

  In some areas solar panels may be a realistic option to provide renewable energy and reduce the maintenance needs, but in others (such as arctic or undersea locations) solar energy may be unavailable for all or part of the year and other solutions have to be sought,

- **memory challenged,** operating with small amounts of writeable memory and/or little persistent writeable memory, hence limiting their usability as forwarding nodes in a DTN network.

- **processing power challenged,** with nodes using low capability, low clock speed processors to minimize cost and power consumption so that complex security transforms are not feasible while also limiting the amount of transmission that can be achieved in a smaller communication interval;.

This often means that sensor networks have to operate with a multi-tier architecture in which bundles are forwarded from a large number of actual sensor nodes with minimal capabilities through one or more controller or aggregator nodes with greater capabilities. These aggregator nodes may be either other sensor nodes or specialized data collectors with greater storage capability. The DTN capability is helpful here because of the highly intermittent waking periods of nodes, which means that it is unlikely that a continuous path between a sensor node and the gateway is available when the sensor node is awake.

In this type of sensor network there is a trade-off between power usage and wireless transmitter range. Opinion varies, but it seems to be advantageous to extend the range (e.g., by using Wi-Fi) in order to keep the number of sensors and hence cost of the total network lower – given that the area covered is roughly proportional to the square of the range. If bundles are routed through several hops to reach the aggregators, there is a risk that the nodes closer to the aggregators will see significantly more use (and hence battery drain) resulting in premature exhaustion. This can lead to the network becoming partitioned; making part of the suite of sensors inaccessible until the offending nodes can be recharged or replaced leading to total loss of the data from parts of the network. The network has to be carefully designed to minimize the risk of this sort of partitioning.

A common alternative solution in many of these networks is to use mobile *data mules* that periodically visit the areas where the sensor nodes are installed, collect the accumulated data via the wireless connection and deliver it to the gateway. This system reduces the danger of partitioning but requires that the sensor nodes are accessible and within wireless range of a data mule.

If some or all of the sensor nodes are mobile, the problem becomes more complex. Sensor networks with mobile sensor nodes have not been much studied so far, apart from in animal tracking (see Section 4.1). The problem for underwater sensor nodes is even more challenging as they move in three dimensions rather than two dimensions (see Section 4.1)

A number of representative sensor network scenarios are examined in [Farrell06]. Abbreviated and updated notes on some typical examples of these scenarios are presented here:

- **The Sensor Networking with Delay Tolerance (SENDT) Project,** involving lake water pollution monitoring at a lake in the centre of the Republic of Ireland was at the heart of the book. This was an extensive project involving two of the partners in N4C which addressed many of the practical issues of long period sensor deployments in challenging environments [Farrell07]. Key challenges were:
  - Finding long lived sensors for interesting parameters that required no maintenance and would not be damaged during repeated periodic flooding/drying.
  - Providing adequate power for the sensor and its controller in a way that did not require frequent maintenance visits.
  - Ensuring that the cost of each sensor unit was low both for economic reasons and to avoid problems with sensors being stolen.
  - Dealing with a sparse deployment mandated by cost, access and environmental constraints. The resulting deployment using Wi-Fi was too sparse to support a MANET style connected network and DTN was ideal for collecting the data.
  - The data was collected by a *data mule* technique where the mule was usually carried on a boat that visited the neighbourhood of the sensors. Boats were expected to pass by sensors fairly regularly (the lake is popular with anglers using boats and the data mule units were fitted to

their boats), but there was no absolutely fixed schedule. Collected data was dumped to a sink when the boat returned to the boat house at the end of the trip.

- **Noise Monitoring** is normally carried out using a manually operated high quality microphone station. This limits the capacity for ongoing monitoring to spot transient events and periodic variation in noise. A system using unattended lower cost system using a cheaper microphone but with additional signal processing to make up for the poorer quality that records data an then passes it to a data mule might well be attractive for more comprehensive monitoring of noise in urban settings or under aircraft flight paths where noise pollution is an issue. DTN techniques can be used to collect the data without requiring infrastructure installation.

  It has also been suggested that monitoring could also be used to track noisy pests such as the cane toad in Northern Australia (a very topical subject given that an eradication effort is getting under way at present) [Shukla04].

- **Monitoring of Seismically Active Regions** is another area where DTN techniques are potentially useful. Seismic Monitoring is characterized by the large scale of the areas to be monitored. Typically only a small number of sensors are required but they need to be widely spaced. In one project, the middle America subduction experiment (MASE) [MASE05], the network consists of a linear array of nodes, each using 802.11 radios spaced roughly 5 km apart and using directional antennae to communicate. Basically, readings from a node at the 'far' end of the line are passed from node to node until they reach the sink nodes at the 'near' end of the array. In 2006 the MASE project successfully deployed a more or less linear array of 100 seismic sensor nodes in central Mexico covering a near coast-to-coast transect of over 500 km from Tampico via Mexico City to Acapulco. The photographic record in [Stubailo06] (note this is a very large file) demonstrates some of the difficulties that may arise in deploying sensor nodes in challenging weather conditions!

  This application shows that even with what is normally quite limited range radio technology, special lower-layer mechanisms (in this case large directional antennae arranged in a linear array) can be used to usefully extend a DTN technology to support applications that cover extremely wide areas. This application is also a useful example of how DTNs might be relatively easily able to operate in areas with no existing network infrastructure.

  The UCLA Centre for Embedded Network Sensing (CENS) which was a lead partner in this work has developed the tiered model for connecting groups of fixed sensors into a platform that can be applied to a range of different sensing applications. This sort of model is useful where the sensors need to placed over a wide area in relatively inaccessible places that might make visits by a data mule difficult.

- **Underwater Sensor Networks:** Pioneering example projects are SNUSE (Sensor Networks for Undersea Seismic Experimentation) for undersea seismic monitoring at USC/ISI [SNUSE] and NIMS (Networked InfoMechanical Systems) for river mapping at CENS/UCLA [NIMS]. Many of the problems that these networks encounter are due to the transmission characteristics and noise levels encountered in underwater environments. Much effort has gone into designing the link layer protocols to cope with the long latency, low bit rate and high bit error rates that are typical of such systems. DTN is a useful technology because of the characteristics of the medium which has inherently high delay and suffers from unpredictable disruption because of variable multi-path reception and temperature driven layer effects.

- **Meteorological and Other Environment Sensing Systems:** N4C will involve considerable amount of work on environmental sensing. Section 7 covers the state of the art in environmental sensing and examines how DTN can be useful.

The examples in this section demonstrate that there is a wide spectrum of applications in the general area of static wireless sensors where DTN is applicable and has been demonstrated to be useful. One thing that has become clear is that there is unlikely to be a 'one size fits all' solution. Both the tiered message passing solutions and the mobile data mule solutions have their places and the exact form of the wireless communication needs to be suited to the application and the available resources. One final example to reinforce this comes from **Glacial Movement Sensing** where wireless sensors were embedded approximately 1 metre below the ice surface. Because the normal higher frequency signals used for Wi-Fi and other sensor communications are heavily absorbed by water ice, the investigators had to use a much lower frequency to allow the sensors to communicate with a local base station on top of the ice.

4.1.5 Mobile Sensor Networks in Two Dimensions - Animal Tracking and Buoys

Adding mobility of sensors to the attributes of a DTN wireless sensor network considerably increases the technical challenges. The encounters during which bundles can be exchanged become even more opportunistic and power requirements become even more stringent. This section looks at two projects that have addressed sensor mobility in somewhat different ways.

Zebranet [Zebranet] was a project to learn more about zebra movements by developing a power-conserving, global positioning system (GPS) aware tracking collar. The collars power up every few minutes to log GPS position information and then every 2 hours attempt to turn on their radios for a short period. If two collars are within range of one another then they exchange positioning information, essentially using what we'll later call an epidemic routing approach, the net effect of which is that after some time, each collared zebra is carrying data about the movements of many others. The plan was for occasional traverses of the area to be carried out, with the scientist only having to achieve proximity to a few zebras in order to determine positioning information for many.

A test deployment in 2004 did achieve its goals of tracking zebras, reportedly producing the first night time tracking information showing that zebras are more likely to move into wooded areas at night. During summer 2005, the field work continued at Sweetwater ranch near Nanyuki in Kenya. This involved collaring four zebras spread over 100 square kilometres with a base station at a visitor centre as well as a handheld station. Over two weeks, more than 5,000 GPS data points were collected. The project continued and some of the participants have now moved on to the Sarana Project [Sarana] which seeks to produce an architecture for location and energy aware ad-hoc networks suitable for use in the sorts of situation represented by Zebranet and also in emergency response networks.

The Un-Buoy project [Curcio06] which was a cooperation between Woods Hole Oceanographic Research Institute, Intel Research and the University of California at Berkeley used small autonomous surface craft together with a fixed mother craft to investigate a smart alternative to fixed networks of buoys to be used for ocean monitoring. The craft could disperse over a region of ocean in order to monitor an event or obtain environmental readings before returning to the mother ship to dump their acquired data and refuel ready for a new trip. DTN was used both locally at the mother ship and for longer range exchanges while the 'buoys' were on station.

N4C will be investigating animal tracking primarily of reindeer.

4.1.6 Mobile Sensor Networks in Three Dimensions - Underwater and Airborne

Several experiments have been carried investigating the application of DTN to communications both between networks of surface vessels and for communications with underwater buoys and vehicles. Many of these have been carried out under the auspices of the long running US Navy/DARPA Seaweb project and not all the results have been made public. There is some limited information in this presentation by Joseph Rice of SPAWAR [Rice05].

The underwater communications environment makes DTN a highly attractive proposition: underwater communications links using acoustic modems suffer from very heavy attenuation with distance limiting the range of communications and the bandwidth for a given transmission power especially if the node does not have a large power supply as discussed in Section 4.1. Disruption is also commonplace in underwater communications due to water conditions (e.g., thermocline layers reflecting signals, communication 'voids') and noise (e.g., from the engines of passing ships or storms) overwhelming the signals.

On the other hand the three dimensional nature of the environment makes routing more complex, and the characteristics of the acoustic environment can lead to 'voids' where acoustic signals cannot pass as well as the blocking layers mentioned above. Relatively little public work is available but Peng Xie's doctoral thesis 'Underwater Acoustic Sensor Networks: Medium Access Control, Routing and Reliable Transfer' [Xie08] starts to look at this scenario. He proposes some solutions to the transmission and routing problems that may be encountered. The thesis covers a range of simulations but no practical deployments.

4.1.7 Extending the Internet

The final set of scenarios presented here concern situations where the DTN is used to 'extend' the Internet into areas where the high reliability, low latency, always on Internet is not available for one reason or another.

4.1.7.1Relatively Stable Topology with Unstable Links

Within the Technology and Infrastructure for Developing Regions (TIER) [TIER] project at the University of California at Berkeley there is ongoing work with networks that are typical of rural regions in developing countries. In many cases these networks involve a fairly stable topology of long distance wireless links, but instability in the network as a whole results from failures in individual links. These are often caused by the uncertain and unstable power supplies needed to operate these links.

DTN together with a specialized routing protocol known as DTLSR (Delay Tolerant Link State Routing) [Demmer07] can greatly improve the goodput of such a network using knowledge the underlying essentially stable topology to direct bundle traffic to points where it is expected that it can be forwarded at a future time even though no link is available at the time of the routing decision. DTLSR can support both wireless links and links provided by reasonably predictable data mule services (see Section 4.1).

DTLSR is an adaptation of the link state routing protocols such as OSPF [RFC2328] that are used in the Internet. DTLSR and DTN techniques have been trialled in some of the field networks that are partners in the TIER project.

4.1.7.2 Predetermined Mobility Paths but No Hard Schedule

A number of scenarios in which DTN has been demonstrated rely on networks where certain connections are supplied by data mules plying certain well-defined paths on a reasonably regular although not precisely scheduled timetable. The exact characteristics vary but all are able to utilize the pseudo-connections provided to forward bundles.

One of the earliest of these was DakNet (from the Hindi for 'post' or 'postal') developed by the MIT Media Lab. Deployed initially in villages in southern Cambodia and India, it is now being commercialized by First Mile Solutions Inc. [DakNet]. Bundles are passed between Wi-Fi equipped 'kiosks' in a number of villages and Mobile Access Points (MAPs) carried by whatever regular transport (buses, motorcycles, etc.) travels routes between the villages on a regular basis. They are later delivered to the destination village when the transport visits that location.

On the water, DTN was demonstrated as a means for automated data collection from environmental sensors during a project organized by Woods Hole Oceanographic Institution and Intel Research in cooperation with the Nantucket Sound ferries close to the Woods Hole base [Nantucket]. Bundles are collected from sensors in the sound and passed to the monitoring station gateway on land using Wi-Fi while the ferry travels its regular journeys across the sound. The architecture, showing where DTN is used can be seen via the 'architecture block diagram' link on the home page of the web site.

The two previous applications require only very simple routing in the DTN, but the third project has provided both a long running real world demonstrator and source of encounter 'traces' for use in simulations designed to try out new routing protocols that are considerably more complex. The DieselNet run by the University of Massachusetts at Amherst [DieselNet] involves MAPs placed an a number of buses that run routes in the city of Amherst. Data bundles are transferred between the buses and fixed and other mobile access points around the city. The buses run reasonably predictable schedules but minor variations introduce a degree of randomness that would be difficult to create mathematically. A number of experiments have been carried out including development of the RAPID routing protocol [Balasubramian07] and experiments with the SPINDLE system. The traces from DieselNet encounters provide one of the primary resources for comparing the performance of DTN routing protocols and can be retrieved from [CRAWDAD]. Several thousands of hours of operational experience has been acquired using DieselNet.

SPINDLE II also used a very simple idea to demonstrate this kind of DTN scenario in the real world deploying ElevatorNet [ElevatorNet] in one of BBN Technologies' buildings. People travelling in the elevators acted as data mules transferring data between disconnected parts of the ElevatorNet on different floors of the building. Here there was little pattern in the available transfers, although obviously at certain times of day there would be fairly predictable high traffic episodes. This provides a very different scenario and set of traces from DieselNet.

4.1.7.3 Mobility Paths Determined by Delivery Requirements

In some cases the mobile nodes that act as data mules in a DTN scenario are under the control of the network rather than being used opportunistically or because they have predetermined routes. In this case the data mules (usually semi-autonomous robots) can be directed to locate and move towards the bundle destination either because of prior knowledge or by detecting stray signals from the destination or a cluster of nodes thought to contain the destination.

A number of theoretical papers with simulations and implementations on model systems have been documented (such as [Pathiran05] and [Zhao05]). There is limited practical application of this kind of network to date although one of the CENS projects has used a robot to visit a number of sensors. (Other aspects of the CENS project have investigated placing mobile sensors using various forms of robot and planning the paths of multiple robots with sensors to cover a maximal area but this does not seem to have been integrated with the DTN work).

4.1.7.4Opportunistic Encounters with Probabilistic Delivery Expectations

Perhaps the least 'structured' of the scenarios is encountered in the predecessor project of N4C, Sámi Network Connectivity (SNC) [SNC]. Here most of the nodes are mobile being carried by people or vehicles (mostly snowmobiles or helicopters) with just a few being fixed gateways or semi-static nodes associated with temporary summer camps employed by the Sámi people when herding reindeer in the grazing ground of the Swedish arctic. The mobile nodes will act as data mules in this scenario.

Although there are a few well defined hiking trails in this area the actual paths taken by node holders, especially those involved in the reindeer herding, are not constrained either in time or space. As a result communication opportunities arise in a rather more random way than is experienced in the previous scenarios. However, the encounters are not totally random – random paths such as one might find in a simulation are not the real way that humans behave. With a scenario like this we can use the nature of human relationships to forecast that people who have met up once may well know each other and are more likely than a random selection of members to meet again. This predictive knowledge can be used to provide information to the routing system in an unstructured system such as this. The PRoPHET routing protocol [Prophet09] exploits this kind of knowledge to control which bundles are exchanged when nodes meet opportunistically.

Either in or close to both the areas in which the N4C test beds will be operating there is a thriving forestry industry. In each case there are large areas of forest that have no communications or power infrastructure. The forestry workers need to be able to receive work instructions and maps indicating their work assignments etc. Using the timber carrying vehicles as data mules would allow the forestry company to send instructions electronically and receive progress reports for the workers felling the timber.

The EU Haggle project [Haggle] is also concerned with this type of unstructured environment and relies on human social connections (as with SNC) and bundle content (as in SPINDLE) to provide forwarding decisions for bundles. Haggle does not use the DTNRG bundle protocol mechanisms at all and has a totally different architecture.

4.2 ADAPTING APPLICATIONS

Until recently the great majority of work has concentrated on the DTN infrastructure and use for transferring data files or chunks from place to place. However the emphasis is beginning to shift to examining how applications can be adapted or created to make use of the capabilities of DTN networks.

The work done in the military tactical arena for the SPINDLE II project is probably the most advanced as regards applications integration. Significant parts of the SPINDLE effort have focussed on using DTN techniques to 'move content to the edge'. The Store, Carry, Forward (SCF) technique in DTN can be exploited to produce local caches of content that can be accessed by multiple users over readily available local (low cost, relatively high bandwidth) links avoiding the need for multiple separate requests travelling over scarce long haul (expensive, often low bandwidth) links back to the original source. Also, in an operational environment, the long haul links are often unavailable at the time the information is vitally needed by newly arrived parts of the local forces, either because the link has been taken for higher priority traffic or is not operational due to terrain or hostile action. This makes DTN a highly appropriate technology for this sort of application.

SPINDLE combined the SCF capability with an innovative naming scheme known as *intentional naming* which uses the DTN EID to express not just the identity of the node that could satisfy a request but the nature of the request itself. Routing with intentional names aims to deliver the bundle to a node that can satisfy the request or make use of the data carried.

This kind of application technology would be clearly applicable in the civilian domain both to emergency response and disaster management situations and to delivering information to workers or tourists in communications challenged regions. In each case the long haul communications are likely to be intermittent and scarce: multiple users need to be able to pick up the information from one or other caches even when the long haul link is unavailable.

Other than the SPINDLE applications, the majority of DTN application work has involved leveraging DTN to deliver messages in applications that are already adapted to the SCF environment such as email and some limited demonstrations of web content caching.

It is becoming increasingly clear that the bundle store that is a key feature of all nodes using the DTN BP will be more important than was originally envisaged. Treating the bundle store in a DTN SCF node as a repository for content rather than just as a transient store backing up the time delayed forwarding capability looks as if it will be an important aspect of future applications.

The human factors aspect of adapting or creating applications to a DTN SCF environment is also becoming clearer. The SPINDLE applications show how human expectations can be managed to deal with partial and delayed delivery at least in one context. Many of today's Internet applications exacerbate human frustration with network delays and disruption by treating it as an 'error', often making the user feel at least partially responsible for the network 'problem'. The challenge to future applications is to treat possible delay in data delivery and possible discontinuities in communication as a normal and manageable situation, offering the user help to achieve his or her intentions even if data cannot be delivered 'instantaneously'.

4.3 OTHER CHALLENGES TO DTN DEPLOYMENT - SUMMARY

DTN deployments in communications challenged regions as envisaged by N4C will be challenged by all of the issues that are highlighted in Sections 4.1 and 4.1, even though not all the nodes will be associated with wireless sensors.

Key to all this will be the power needed to activate the nodes. It is unlikely that more than a few will have access to a stable external power supply whether mains or otherwise, which has parallels with the situation in developing countries addressed in Section 4.1. Thus it is vital that nodes consume as little power as possible and are able to be placed into micropower sleep modes for a large proportion of the time when not actually engaged in a communications opportunity or dealing with a human interaction. In this way the nodes will be maximally useful, minimize the amount of time and energy needed to recharge them and maximize the time that they work in the field between maintenance sessions. Focussing on the type of technology that is now used in mobile cellular telephones will offer good returns here, but it is still essential to manage the amount of power consumed by Wi-Fi and other local or personal area radio communications if realistic battery lifetimes are to be achieved.

Power sources are also a challenge. For some regions solar powered photovoltaic cells would provide a solution but for a good part of the year in the arctic, solar power is not available and alternatives need to be investigated.

Many of the nodes will be deployed in environmentally challenging situations outside shelters, with very wide temperature ranges (e.g., in the arctic, down to -50°C and up to +30°C over a yearly cycle), and with precipitation of various types (rain, snow, etc.). Ensuring that nodes can work successfully without requiring power hungry environmental conditioning equipment is another key challenge.

We have seen in Section 3 that security issues are still under-researched in the DTN environment. If regular users are to act as common carriers for bundles, we have to get the security policies and mechanisms in place to allow bundles to be carried without being compromised. Associated with this are the issues of naming/addressing and routing that will allow us to make best use of a DTN network.

Finally, we have to understand and manage the resource utilization problem that is at the heart of deploying a DTN network. As discussed in Section 3.4, routing decisions amount to a multi-dimensional resource utilization optimization problem with incomplete information, especially in the unstructured types of network that are at the heart of N4C. This is certainly a hard problem that needs some considerable further work.

4.4 IMPACT OF APPLICATION SCENARIOS ON N4C

The test beds of N4C concentrate primarily on the kind of unstructured scenario described in Section 4.1, but there will also be elements where the kind of predetermined mobility paths described in Section 4.1 will be relevant:

- in northern Sweden there are relatively regular helicopter routes which are seen as one way of delivering bundles into the heart of the N4C test bed area, and
- in Kočevje the forest outposts and environmental monitors may be visited relatively regularly by forestry operatives.

Integrating the highly unstructured basic SNC type of scenario with a more predictable type of mobility will be important for N4C.

The Hiker's PDA application to be developed by WP3 of N4C is intended to allow tourists to collect relevant information from other hikers, local people and static posts within the communication challenged test bed regions. Here the information is not necessarily specific to a particular person or destination node, and the intentional addressing mechanisms that were prototyped in the SPINDLE II project and are now being deployed in the military/tactical scenario discussed in Section 4.1 are likely to be relevant to N4C. Information can be addressed to describe its content which allows end users to determine the relevance or otherwise of such bundles.

The basic proposal for the N4C reindeer tracking application has already considered the input from the Zebranet project discussed in Section 4.1, but there is likely to be some useful synergy in looking at other projects in this general area.

The N4C partners that were previously involved in the wireless sensor project SENDT (Section 4.1) and the partners involved in environmental sensing (primarily in Slovenia) are likely to be assisted by experiences in the CENS portfolio (Section 4.1). The hierarchical sensor networks developed by CENS may prove to be of relevance here.

The work which CENS have done in the MASE project (Section 4.1, [MASE05]) is relevant to extending the range of wireless point-to-point links so that it might be possible to link gateways more closely into the communications challenged regions as is envisaged in N4C WP6.

5. SIMULATORS

Extensive simulation work has been done on a large variety of algorithms, especially routing algorithms. These simulations have been carried out on a variety of platforms, some of them purpose built for the work, and others based on the well-known *ns2* public domain network simulator.

Recently the Opportunistic Network Environment (ONE) simulator [ONEsim] has begun to be seen as the environment of choice for performing DTN simulations in opportunistic environments. It is an open source free tool which is capable of both using synthesised encounter patterns and using stored traces taken from real world demonstrators such as DieselNet [DieselNet] and Haggle [Haggle].

The ONE simulator can directly import trace datasets taken from the CRAWDAD repository [CRAWDAD].

6. IMPLEMENATIONS

There are a number of reasonably 'complete' implementations of the bundle protocol, a bundle agent, a selection of convergence layers and routing decision agents

- **DTN2**: The 'reference implementation' associated with the DTN Research Group [DTN2] provides a fairly complete suite of parts, including the Licklider Transmission Protocol (LTP), the bundle security protocol and several routing protocols – see Section 3.4. The documentation is, however, very incomplete, and the implementation is not very streamlined, especially in the routing protocol area. It is written in C++, maintained (currently by Trinity College Dublin as part of the N4C project) and should track the latest Internet drafts reasonably quickly. It is free software released under the Apache license.

- **ION:** The Interplanetary Overlay Network implementation is produced by the NASA Jet Propulsion Laboratory and partially maintained by Ohio University [ION]. It currently contains implementations of the bundling protocol, contact graph routing, LTP and AMS (Asynchronous Message Service), an application-layer service that is not part of the DTN architecture but utilizes underlying DTN protocols. Additional pieces including a TCP/IP convergence layer are planned in order to allow ION to be used in terrestrial networks as well as on spacecraft and space directed links. ION has excellent documentation [IONdoc08]. The software may be freely used, subject to some minor caveats about export regulations, but there is a slightly complicated procedure needed to obtain a copy because it is US government property.

- **IBR-DTN:** Another 'efficient' implementation for embedded systems with small memory footprints is IBR-DTN [Doering08]. This is being developed as part of the Environmental Monitoring in Metropolitan Areas (EMMA) project at the Technical University of Braunschweig [EMMA]. This currently offers a core subset of the bundle agent architecture with no security and only UDP convergence layer, but is under development. It is built on top of the Open-WRT wireless router firmware [OpenWRT].

There are a number of other partial implementations of the bundle protocol and associated software including ones for the Symbian Operating System on certain types of mobile telephones [DASM] and DTNlite intended for sensor networks with very low capability sensor motes [Patra03] targeted initially at the Berkeley Mica Mote. see the code information page on the DTN Research Group wiki site for other implementations [DTNRGwiki].

The SNC Project [SNC] developed the initial implementation of the PRoPHET routing protocol which was integrated with an earlier version of the DTN2 reference implementation. This version has been contributed to the code repositories of the DTN Research Group [DTNRGwiki], and is again under active development with the N4C project.

The Haggle DTN implementation is not related to the bundle protocol and implements a different architecture [Haggle].

7. ENVIRONMENTAL INFORMATION SYSTEMS (EIS)

One of the major components of the N4C test beds is intended to be collection of environmental information, especially in the Kočevje region of Slovenia. This section describes the current state of the art as regards Environmental Information Systems and how it relates to DTN.

7.1 INTRODUCTION

An Environmental Information System (EIS) is an automatic measuring system for monitoring the physical parameters of the environment. It typically consists of numerous automated measuring stations. Each automated measuring station (AMSt[6]) performs measurements automatically and periodically for a considerable period of time without any human manual assistance. The EIS can be focused on various different kinds of environmental parameters. The environmental parameters can be grouped as follows:

- meteorological parameters that can be additionally divided into to two subgroups: synoptic, climate, agricultural and other parameters,
- hydrological parameters,
- radiological parameters,
- seismological parameters,
- speleological parameters, and
- air pollution parameters.

An EIS may monitor several groups of parameters from the above classification. Meteorological parameters consist of parameters such as air temperature, air relative humidity, air pressure, precipitation amount, wind speed and direction, ground temperature and others. Hydrological parameters consist of parameters such as water temperature, water conductivity, water pH, nitrogen concentration in water and others. Radiological parameters consist of parameters such as gamma dose rate, alpha and beta radiation, radon concentration and spectral analysis of deposition parameters. Seismological parameters consist of parameters such as magnitude and frequency of earthquake waves. Speleological parameters consist of parameters like cave temperature, cave relative humidity, rock temperature, air flow in the cave and others. Air pollution parameters consist of parameters such as concentrations of nitrogen oxides, sulphur dioxide, ozone, carbon oxides, dust particles and others.

In general EISs can be divided into two main groups according to their primary purposes:

- The first group consists of EISs which are built to monitor the environmental data for a longer period of time where collected data is used for development, analysis and validation of environmental models (i.e., meteorological models, air pollution models, etc.) and for statistical analysis of collected data. In this case it is very important to have a high percentage of collected data while relatively long delays in communicating this data to the monitors are not detrimental. A

[6] Unfortunately the AMS acronym would be overloaded – AMS is used in the ION context (see Section 6).

typical representative of this type of EIS is the climate watch EIS which is used to study the climate changes that are becoming a serious problem for modern society.

- The second group consists of EISs for early warning systems which are used as decision making systems after unpredictable events. In this case it is important to monitor primarily the current situation in the environment which means that long delays in communications are not acceptable, while the percentage of collected data immediately available is of lower importance.

Usually most EISs are a combination of both groups, where usually one task is predominant.

7.2 STRUCTURE/TOPOLOGY OF EIS

An EIS consists of a larger number of automated measuring stations and smaller number (usually not more that one or two) of central units. The data from different EISs are very often shared. Sharing helps extending applicability of the EIS over a larger area and decreases the costs and efficiency of maintenance of such a large system (for example the. Slovenian Environmental Agency collects environmental data from their own network of automated measuring stations merging it with data from other EISs maintained by power plants, other agencies and institutions). An example of EIS structure is presented in the following figure.

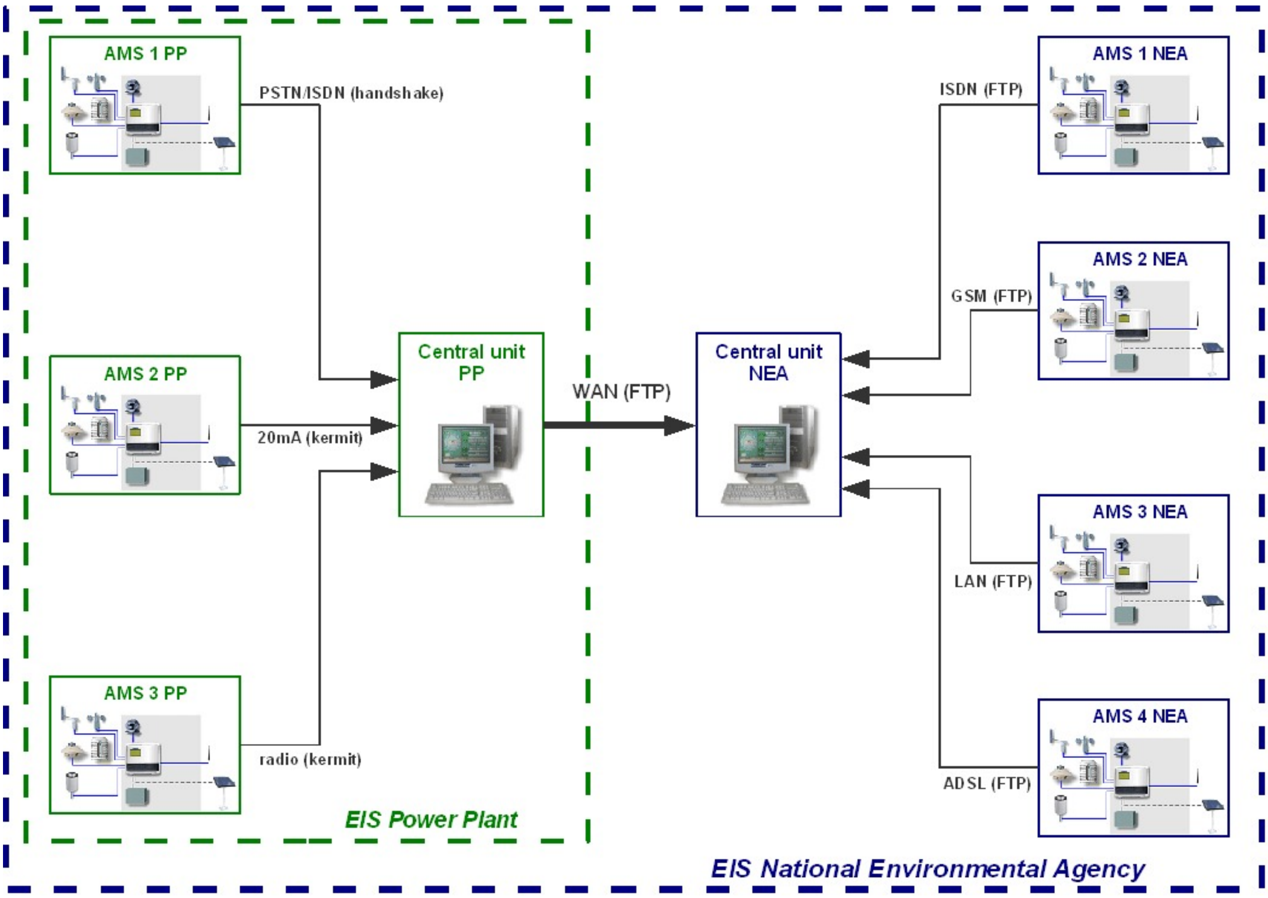

Figure 2: Typical structure of an EIS

The essential part of the EIS is an automated measuring station (AMSt). Depending on the set of measuring parameters the AMSt can vary from a relatively simple and small device (mounted in a small size sealed box) to very complex and large measuring system (mounted in an air-conditioned container). AMSt's are usually located at exposed locations which are often characterized by unstable or sometimes unavailable mains electric power. These exposed locations are chosen because they satisfy the measuring criteria to provide representative data for larger area around the AMSt. For further details of example systems in Slovenia see [Božnar04].

The main function of AMSt is data collection from sensors and monitors and transfer of collected data to the central units. There are also some other functions of an AMSt that are crucial for assuring the quality of collected data and for reliable data transfer of collected data within the EIS:

- Statistical processing of the data according to recommendations of the World Meteorological Organization (WMO) and standards of the national environmental agency.
- Data about measuring conditions (i.e., temperature of the AMSt, statuses of monitors, references and power supply) are collected to assure that the measuring devices are operating in required environment (e.g., air pollution monitors are specified by the manufacturer to operate in the temperature range from 20 deg. C to 30 deg. C). Furthermore the collection of this additional data serves as additional help for efficient maintenance of the AMSt.

Figure 3: Comparison of a simple meteorological AMSt mounted in a small size sealed box (left) and a complex air pollution AMSt in an air-conditioned container (right)

- Quality control of the measured data is the most crucial function of the AMSt. It is based on measured and statistically processed data and on collected data about measuring conditions of the AMSt. An additional status information string is appended to all measured data. This status information is usually empty if the data passes the quality control. If the measured data does not pass the quality control the status string is filled with the information about failures identified by quality control. The quality control consists of various controls which vary according to the measured parameters. Examples of complex controls include: For the wind measurements the bits of the wind direction sensor are checked and it is expected that all bits should change their status over a certain period of time. If some of the bits do not change it is expected that the measurement fails. On the other hand for the air temperature measurements it is not expected that the air temperature should change rapidly in very short period of time. If such event happens the quality control is set to warn the maintainers of the system.

- All measured and processed data are also stored in the local database of AMSt for two main purposes. The first purpose is to re-send the collected data in case of communication failures. All collected data are waiting at the side of AMSt until the communication to the central unit is re-established. The second purpose is for the maintainers of the system. The size of the AMSt database depends on the available memory resources.
- The AMSt is usually equipped with a local data presentation system. It is used to help maintainers of the system to check the data at the site. The presentation system presents data that is stored in the local database of the AMSt.
- Communication to the central unit which is described in details in following section.

The maintenance of the AMSt is also of great importance for the reliable operation of the AMSt. It generally depends on the number and type of measuring parameters and complexity of the AMSt. All sensors and monitors must also be calibrated in accredited laboratories periodically according to standards.

The central unit (CU) is usually located at the relevant agency, institution or power plant that also usually maintains the EIS. It consists of one or more computers and communication equipment. Its main functions are the following:

- Collection of data from the AMSt using different communication means that will be described in details in following section.
- The collected data is re-processed at the CU applying additional quality control and it is marked in the status string if it does not pass the control.
- Storing of collected data into central unit database. The collected data can also be additionally processed or summarized (for example from collected ½ hour averages daily averages can be calculated) and saved in this database.
- Data presentation of the database to local and remote users. This function includes generation of numerical and graphical presentations and reports.
- Collected data can also be distributed to other central units and other EISs using different communication means.

7.3 COMMUNICATIONS WITHIN THE EIS

The communications between the AMSt and CU inside the EIS represents a challenging and critical task. It is important for the reliability of the EIS. Communications are based on the different available communication media, hardware interfaces and communication protocols. The main criterion for proper selection is guided by the budget available for the establishment of the system. Another important factor in the decision is also the main purpose of the EIS. Very short or almost zero delays in communications are allowed when the EIS is intended for an early warning system, while for climate EIS longer delays are acceptable. See [Grašič03].

Within the EIS the following communication media are mainly used:

- fixed lines (V.21 FSK modems),
- commutated lines,
- analogue 4-20 mA current loop,
- RS-232, RS-485,
- ISDN - Integrated Services over Digital Network,
- ADSL - Asymmetric Digital Subscriber Line,
- mobile phone network (GSM/GPRS/UMTS),
- radio communications (dedicated frequencies such as: 150 MHz, 450 MHz or free frequencies: 870 MHz).

For data transfer various different protocols are used. The selection of protocol is based on the distance between the AMSt and CU and available communication media. When different monitors are mounted at AMSt the protocol between the monitor and data-logger must also be considered. Usually a simple string hand-shaking protocol is used. Within the EIS usually more than one of the following protocols is used:

- Kermit protocol,
- string hand-shaking,
- binary protocols (i.e. PROFIBUS),
- FTP (File Transfer Protocol),
- HTTP (Hyper Text Transfer Protocol).

Usually the data between the monitors and data-logger within the AMSt are transferred in the form of an ASCII string. Some monitors are emitting ASCII strings that contain measured data periodically (i.e. every 1 minute current measured data is emitted over RS-232 port) while other are waiting for the commands from data-logger (question/answer principle: i.e. every 1 minute data-logger sends command GETDATA and then receives a current measured data from monitor over RS-232 port).

The data between the AMSt and CU are usually transferred in a form of an ASCII file. Each ASCII file contains measured data for certain time interval. This type of files is transferred to the central unit using different protocols. An example of an ASCII file is presented in the following figure.

P 0	11:00	10/03/09	00:00	01/01/00	34.8	4.8	12
	00	43	11:00	10/03/09	00	03	30
	30	30	1f				
P10	5.9	7.1	10:58	5.0	10:34	7.0	0.7
	0						
P11	3.6	3.7	10:30	3.5	10:35	3.6	0.1
	0						
P35	64.9	74.0	10:30	55.0	10:54	56.0	6.1
	0						
P43	696.0	820.9	10:59	232.5	10:39	806.7	
	160.5	0					
P47	977.4	977.6	10:30	977.3	10:51	977.3	0.1
	0						
P100	0.7	32	2.3	336	10:46	0.0	360
	10:48	0.9	0.7	24	0.3	0.5	0.4
	0						

Figure 4: Example of ASCII file that contains measured meteorological data

When communication between the AMSt and CU is out of order the files will wait at the AMSt for the communication to be restored. When the number of ASCII files exceeds the memory resources of AMSt older files are deleted, so some measured data can be lost if the communication is not available for a longer period of time. When communication is restored the ASCII files from the AMSt buffer are transferred to the CU. This principle makes the EIS tolerant to the communication disruptions and delays.

7.4 METEOROLOGICAL EIS

In a typical meteorological EIS the following parameters are measured:

- air temperature (usually at 2 m, sometimes when a tower is available also at higher elevations)
- relative humidity of the air (usually at 2 m, sometime also higher),
- air pressure,
- solar radiation,
- precipitations,
- wind (usually at 10m, when a tower is available also at higher levels), and
- ground temperature.

The statistical processing of measured data is usually made every ½ hour. See [Lesjak02].

7.5 RADIOLOGICAL EIS

Radiological EISs are primarily built as early warning systems. They are used for warning the population in case of any accidents around nuclear facilities. In this type of systems usually a gamma dose rate measuring AMSt are used. See [Božnar97].

7.6 SUITABILITY FOR DTN

Due to unreliable communication means in the past most of EIS networks were actually working in "DTN" mode although they were not necessarily internet based. From the above enumerated types of EISs the climate ones are especially suitable for DTN type of data collection. This was the primary reason for selecting such stations for the test beds. The goal of final tests and test bed topologies is to develop DTN based network of climate stations for climate watch in remote sparsely populated areas of the planet.

8. REVIEW OF PREVIOUS, RELATED AND SIMILAR PROJECTS

Lately the European Commission has funded a series of studies (Thematic Networks, Coordinating Actions and Tenders) in order to collect more data and provide analysis of issues that affect the deployment of broadband communications in rural communities. The studies have resulted in roadmaps, technology reports and business models. The results from some of the most relevant studies are summarized in Sections 8.1, 8.2 and 8.3. Section 8.4 examines the case studies from the Rural ICT report (Section 8.3, [DGAGRI07b]) and notes those where it appears that the DTN approach to be taken in N4C could be advantageously deployed. These cases will be relevant to the business strategy analysis to be undertaken in N4C.

8.1 RURAL WINS

Project web site: http://www.ruralwins.org

The Rural Wins was a Thematic Network project in the EU 6th Framework Programme (FP6). The Strategic Roadmap [RuralWins03] encapsulates the consortium's shared vision for the roadmap of Broadband ICT Solutions in Rural and Maritime territories over the coming 5 to 10 years to provide input to FP6 in the context of eEurope 2005 and National Policies. These inputs were:

- Elaborating on the findings of user needs, technology trends and business models, and obtaining user feedback
- Building the visionary technology roadmap for the next decade

- Providing a series of iterations towards these objectives

From the Rural Wins analysis, it was concluded that for Rural Broadband access:

- The Internet is the target information distribution system
- There is a convergence towards mobility and intelligence 'anywhere/anytime'

However broadband is not being provided to rural areas for commercial reasons.

- IST services have been designed based on urban business usage models
- Providers' short-term focus operates against rural areas

Business Models for Universal Broadband Access will therefore need to be based on

- public/Private Partnerships
- new access technologies

Broadband ICTs in rural/maritime areas need to address barriers of distance, and economic and social isolation.

The Sámi community that is one of the foci of the N4C project was also of interest for the Rural Wins project [PowerLake03] In one of the cases that was studied in Rural Wins, 'The Sámi People of Eight Seasons and Three Languages', demonstrated the need of broadband in a small village school in Ammarnäs, a small village in Northern Sweden. In that community the Southern Sámi language is spoken, but no teachers were available. The Southern Sámi language is at risk of becoming a 'dead' language. So with the help of a web camera and Internet the community was able to get a teacher on-line and give children training in their mother language.

8.2 A-BARD - ANALYSING BROADBAND ACCESS FOR RURAL DEVELOPMENT

Project web site: http://ec.europa.eu/research/fp6/ssp/a_bard_en.htm

The project ran under the European Union 6th Framework Programme in 2005-2006.

Financial Project value: €630k.

Leader: National Microelectronics Applications Centre, Ireland

Partners:

- Ceske centrum pro strategicka studia, Czech Republic;
- ITTI, Poznan, Poland;
- Cybermoor Ltd, UK;
- Mainstrat, Spain;
- North West Labs Ltd, Ireland;
- Power Lake AB, Sweden.

Project Objective

To identify how ICT can be used to protect and facilitate structural change in rural areas by offering new work opportunities, and better, more cost-effective approaches to the delivery of broadband access and services. In particular,

- Focus and enhance awareness and understanding of the benefits of broadband applications and services deployment in rural areas
- Facilitate the exchange of experience and best practice to rural stakeholders and interests

- Identify the institutional and policy frameworks that are delaying broadband roll-out
- Determine areas where further research and/or development is needed to provide universal solutions

The Sámi community that is one of the foci of the N4C project was also of interest for the A-BARD project for two reasons:

- The Sámi people have special interests to protect. To be able to study on line to maintain their languages and their culture, the group is in need of broadband and broadband services.
- Lessons can be learnt from deploying broadband to the Sámi population which then can be of common interest to other outdoor workers.

Recommendations

The A-BARD recommendations addressed especially that there is a need to balance top-down and bottom-up approaches. Specifically, the following recommendations were made:

- Define an ambitious European eRural Strategy as an integral part of Sustainable Rural Development Policy
  - allocate public funding where there is 'market failure'
  - in i2010 and 7th Framework Programme, include specific infrastructure, ICT use and RTDI initiatives for rural areas
- Stimulate business and technical competition in the Rural Broadband Market
  - every user should have a choice of 2 or more broadband access options
  - stimulate Public Sector demand aggregation in rural and remote areas
- Develop sustainable Connected Rural eCommunities to stimulate demand and broadband take-up
  - enhance Regional Leadership and Local Champions
  - promote and support Awareness ('know what') and Training ('know how')
- Provide services and content that rural users want ('Killer Applications').
  - local content
  - entertainment
  - eBusiness, eLearning, eHealth and eGovernment.

8.3 RURAL ICT

The DG AGRI "Study on Availability of Access to Computer Networks in Rural Areas" provides policy makers, stakeholders and others with concrete guidance on how to maximise the benefits of Information and Communications Technology (ICT) for growth and jobs in all rural areas of Europe, using the support of rural development programmes.

The study includes a Guide and database of best practices (in Part I) and a Review of existing policies and literature (in Part II) [DGAGRI07a]. These were developed using two methodologies that formed the main research strands of the study: (a) The establishment and analysis of a database of 67 best practice cases studies and (b) a review of existing data, literature, policy and research illustrating ICT take-up. The collection of 67 case studies can be found in Annex A [DGAGRI07b].

The Review concludes that rural ICT policies need to balance top-down and bottom-up approaches. This entails the European Commission articulating recommendations coherently and centrally in strategy plans and development programmes – and individual Directorate Generals (DGs) making their own grant mechanisms more accessible to 'homespun' initiatives that have the potential to develop local access and take-up.

The Review's recommendations acknowledge the complementary roles of the EU's LEADER initiative [LeaderPlus] and the national rural development planning process in promoting 'bottom-up' approaches to development. Specifically, it recommends a coherent eRural strategy as part of a sustainable rural development policy, focusing on building capacity (i.e., developing new skills to access the Internet and make the most of ICT), even though it is often more difficult to measure the results from this. The eRural strategy should include improved control and monitoring of ICT indicators, policies and initiatives including the collection of statistical data, and measures which stimulate business and technical competition at different levels of scope and sophistication within the rural broadband market.

The strategy needs to focus on developing sustainable connected rural eCommunities to stimulate demand and ICT take-up – particularly by enhancing Regional Leadership and Local Champions to ensure that 'bottom up' projects flourish. Support is required for Awareness ("know what"), Training ("know how"), and providing services and content that rural users feel are pertinent to them, especially entertainment and local content, in addition to policy priorities such as eBusiness, eLearning, eHealth and eGovernment services. There need to be joined-up policies that ensure efficient links between LEADER and those seeking access to funding, extending investment in broadband infrastructure to all local public sector agencies and schools. There also needs to be an eProcurement process, with appropriate safeguards and online support, to fast-track ICT projects in rural areas.

Finally, the Review sets out the factors which encourage people in rural areas to use ICT and experience the benefits of the Information Society. The study believes that it is through projects providing such encouragement that the benefits of ICT will reach more rural communities. The route to wider ICT take-up and to competition in its supply lies through the growth of small initiatives providing mixed, possibly untidy and even unorthodox means of accessing broadband that can be supported simultaneously.

The Guide categorises projects according to
- **access** – focused on equipment to access the Internet;
- **content** – what people use and the services which encourage them to go on line; and
- **capacity** – developing new skills to make the most of ICT.

It assets that ICT projects which combine all three make the greatest impact.

Success Factors

The analysis of the case studies defined the actions or conditions which have allowed the achievement of each project's goals. Six major contributing success factors were identified:
- financial support from the EU,
- support from national/regional authorities (political, financial and legal),
- involvement and co-operation of local businesses and organizations,
- understanding and reacting to new business opportunities created by ICT,
- strong involvement of local communities, and
- understanding the need to promote the Information Society.

Partners in the project were:

- The National Microelectronics Applications Centre Ltd (Ireland),
- Contractor and subcontractors the Czech Centrum for Science and Society (Czech Republic),
- CyberMoor Ltd (United Kingdom)
- Institute of Communication and Information Technologies Ltd.(Poland),
- Mainstrat (Spain), and
- Power Lake AB (Sweden).

8.4 CASES FROM RURAL ICT THAT CAN BE DEPLOYED USING DTN

N4C has identified a number of the cases from the 67 in Rural ICT which we will examine further. The criteria for selection are that they might be deployable in the small communities where the N4C test beds will be trialled and that it might be technically feasible to deploy them on the DTN network infrastructure being developed in N4C. Characteristics of the cases are that they demonstrate

- How SMEs can improve their business with 'small' means (3, 4, 5, 10, 11, 13, 15, 20, 61, 62)
- eLearning tools for rural population (31)
- eWork (38)
- Development of the local community (10, 16, 22)

Based on the selection criteria, the following cases appear relevant:

Case	***Description***	***Page in Rural ICT Report Annex***
3	*Organic Denmark, Denmark* *www.organic-denmark.com*	*7*
4.	*Pro-Bio-Energy in the North Sea Region, Germany* *www.probioenergy.net*	*9*
5.	*Food and Drink, Greece* *www.foodtech-expo.com/foodanddrinks.html*	*11*
10.	*Dolina Czarnej, Poland* *www.agrowakacje.pl/dolinaczarnej*	*22*
11.	*NetBrokers, Poland* *www.netb.pl*	*24*
13.	*Introduction of ICT in the milk sheep sector, Spain* *www.mendinet.org*	*28*
15.	*Impecta Frö AB, Sweden* *www.impecta.se*	*32*
16.	*Ammarnäs, Sweden* *www.ammarnas.com*	*34*
20.	*Fjällhästen, Sweden* *www.fjallhasten.com*	*42*
22.	*Les Plus Beaux Villages de Wallonie, Belgium* *www.beauxvillages.be*	*46*
31.	*Workplace Guidance, Finland* *www.diak.fi*	*64*
38.	*eTeams International, Mid-West, Ireland* *www.eteams.ie*	*79*
61.	*Oxford Farm Shop, North East, UK* *www.oxfordfarmshop.co.uk*	*126*
62.	*Cumberland Hotel, UK, North West* *www.alstoncumberlandhotel.co.uk*	*128*

9. CONCLUSION

In the course of documenting the state of the art of Delay- and Disruption-Tolerant Networks, the N4C participants have clarified their view of the aspects of the DTN architecture where further work is needed and there can be relevant contributions from the N4C team. In one key area, naming and addressing, N4C team members have already made significant contributions to progress during the recent DTN research Group meeting in March 2009. Reviewing the ongoing work in routing has been of considerable value in identifying work that might be combined with the PRoPHET proposal to provide a protocol that would address the combined scenario (unstructured plus loosely scheduled regular trips) that characterizes the scenarios in our test beds. Providing security in such a way that data mules can readily act as 'common carriers' remains a significant issue which N4C ought to address.

The review of application scenarios has provided a useful categorization of scenarios which is novel and pointed up a number of projects that appear to contain techniques and solutions that might be useful to N4C. The intentional and content based naming used in the SPINDLE projects seems particularly applicable to the Hiker's PDA application and the forestry applications. The CENS work in long distance radio links and hierarchical data collection networks is also likely to influence the sensor based areas of N4C.

The business oriented review of existing initiatives relating to the extension of the Internet to rural areas has identified a number of scenarios that will assist when we come to suggest our own scenarios and build business models where DTN would play a major role in supporting the business.

Finally, this document will provide a useful resource both for additional project members needing to get acquainted with the range of DTN work that is in progress as well as people outside the project who are seeking to get an overview of the current state of the DTN art.

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APPENDIX ASURVEY OF RELATED PROJECTS AND STUDIES

A.1 DTN STANDARDIZATION

The organizations in this section are involved in aspects of standardization for DTN capabilities.

A.1.1 DTNRG (Delay Tolerant Networking Research Group)

Organization web site: http://www.dtnrg.org

This is an ongoing initiative that began in 2002 under the umbrella of the IRTF (Internet Research Task Force). DTNRG was formed as a result of the observation that a non-interactive, asynchronous form of messaging service, able to operate over diverse types of networks, would be useful for several networks currently in use or being contemplated. Earlier work within IRTF's Interplanetary Internet Research Group (IPNRG) appeared to be a suitable basis for a generalization to networks other than those operating in deep space. IPNRG has since been moved to historical status within IRTF, yet remains active as part of CCSDS, a standards group concerned with protocols operating in space. IPNRG itself sprang out of the earlier Internet Society Interplanetary Internet Special Interest Group (IPNSIG) [IPNsig], set up as part of the Internet Society, and now dormant.

The architecture originally conceived within IPNRG and developed further under the auspices of DTNRG proposes an alternative to the Internet TCP/IP end-to-end interactive delivery model and employs hop-by-hop storage and retransmission as a transport-layer overlay. It provides a messaging service interface conceptually similar to electronic mail, but generalized for application-independence and supported by specialized reliability and routing capabilities.

The research of DTNRG is one of the cornerstones on which the technological solutions in N4C – and, in fact, a number of other related projects mentioned here – are going to be based. This topic is discussed at much greater length in the earlier sections of this document.

A.1.2 CCSDS (Consultative Committee for Space Data Systems)

Organization web site: http://www.ccsds.org

The Consultative Committee for Space Data Systems (CCSDS) was formed in 1982 by the major space agencies of the world to provide a forum for discussion of common problems in the development and operation of space data systems. It is currently composed of ten member agencies, twenty-two observer agencies, and over 100 industrial associates.

Since its establishment, it has been actively developing Recommendations for data- and information-systems standards to a) reduce the cost to the various agencies of performing common data functions by eliminating unjustified project-unique design and development, and b) promote interoperability and cross support among cooperating space agencies to reduce operations costs by sharing facilities.

CCSDS has a DTN working group which is working with the DTN community to standardize a 'profile' of the DTNRG protocol suite that can be used for spacecraft communications. The ION software [ION] developed by the NASA Jet Propulsion Laboratory is an implementation of the proposed standards which has been space tested.

A.2 PROJECTS WORKING IN THE DTN INFRASTRUCTURE AREA

The projects in this section are principally directed at research and advanced development for DTN infrastructure (as opposed to applications running in a DTN environment – although the distinction is somewhat blurry as many of the projects design applications in order to test the infrastructure that they are developing.

A.2.1 MindStream

Project web site: http://www.cs.uwaterloo.ca/~keshav/mindstream.html

An early research project started in 2003 at the University of Waterloo, Canada using an early DTNRG implementation of the bundle protocol. The objective was to develop architecture, protocols, and a prototype system for publishing weblogs recorded on PDAs when there is an opportunity of the user coming into a connectivity region, like a hot-spot zone. The solution was to use a proxy server that was disconnection-aware. Whenever the PDA detected the presence of a hot-spot, it established a connection with the proxy and sent it *bundles* of information. The proxy reassembled bundles that came from the same PDA, even if the PDA's IP address had changed. While transferring a long file, for instance, even if the file was partially sent from one hot-spot, the PDA could continue transmission of the file from another hot-spot. The project did not address the problem of a loss-insensitive transport layer.

A.2.2 SNC (Sámi Network Connectivity)

Project web site: http://www.snc.sapmi.net/

The main goal of this project which ran from 2002-2006 was to establish Internet communication for the Sámi population of reindeer herders, who live in remote areas and relocate their base in accordance with a yearly cycle dictated by the natural behaviour of reindeer.

The SNC idea has developed network technology capable of serving remote and geographically complex areas at agreeable cost.

The background was a request from future users, a community of reindeer herders, who during part of the year operate within Laponia, an area in Northwest Sweden listed by UNESCO as World Heritage.

2.2.1. User requirements

The initial goal was the possibility to provide e-mail, cached web access, reindeer herd tracking telemetry, and basic file and data transfer services.

The requirements for the SNC project are divided into two categories:

- applications that serve the educational and community needs of the Sámi people,
- business applications pertinent to reindeer herding.

The basic IP applications that were important to the Sámi community in the initial phase of the project were: e-mail, file transfer, cached web services.

The business application requirement was for the application of telemetry to the movement of reindeer and the ability to confidentially report the movement trends of specific groups of reindeer to the herders that own them.

These application requirements need to be met in an environment where the lower-level connectivity is varied and is subject to large delays that are greater then any acceptable TCP round-trip time.

Other requirements include the prohibition against building permanent infrastructure that is incompatible with the rules that govern protected land. Much of the Sámi grazing area is located within National Parks and other natural reserves that prohibit construction of antennas, stringing of cable or power lines and any other construction of durable infrastructure. The network will have to rely on the existing infrastructure; i.e. where there already are power lines and cables, they can be used. Likewise, where GSM access is available, e.g. on the summits and east side of hills and mountains, it can be used in the construction of data links for the network. Additionally, available satellite and digital television broadcast capabilities can be used where available and cost effective.

A final requirement on the project was a social one. The installation of the network had to be in keeping with the cultural patterns of Sámi life. It also had to be a structure that was sustainable in the long run by the Sámi population itself.

One of the important considerations in this project is to allow use of the same applications in intermittently connected parts of the network that would be used by systems when fully connected to the Internet. This means that users should be able to use standard laptop and desktop systems loaded with the same applications that they would normally use when connected to the Internet.

2.2.2. Functions and solutions defined in the project

Electronic mail:

- E-mail is possibly the most popular and wide spread Internet application. It is also the typical store and forward application. With the exception of its use of TCP, it is well suited to the SNC network. Within the local network, e-mail has to work exactly as it does elsewhere. When a user sends a message, the Simple Mail Transfer Protocol (SMTP) will relay it either directly to systems in the local network or to an e-mail gateway. The gateway will then take responsibility to relay it further.

Web caching:

- Providing web access is an interesting challenge and provides several research opportunities. The assumption being made is that a large percentage of a community's web access preferences can be predicted. As a community will normally be isolated from the rest of the web, it will be necessary to redirect all requests to the community's web cache. This is assumed to be one component of the edge gateway service provided by the SNC network.

Business applications

- There are several characteristic differences between the community applications and business applications. Among these are the requirements for fault tolerance and security issues.

Reindeer telemetry

- This is a rich field, both in available technology and interesting research problems. Not only are many small and low-power devices being created, but the study of sensor networks is very active. The project studied the available devices to find the right ones for testing.

Tracking:

- A sensor network is proposed to be built which can allow herders to track their herds. It is whether it will be sufficient for this to be based on exception alarms; i.e. when the herd crosses a warning track that indicates they are headed out of the prescribed zones, or a steady tracking system which allows herders to know where their herds are at any particular time. What also needs to be evaluated is how fine the degree of knowledge about herds needs to be. While it is important to be able to delineate which herder's reindeer are being tracked, it is probably unnecessary to know which particular reindeer is being tracked. On the other hand, in order to understand the behaviour of the herd it may be necessary to show tracking paths for a specific group of reindeer within a herd.

Reporting:

- As important as it is to record the movement of the herds, applications are needed to convey that information to the appropriate herders. At a minimum, this requires alarms to indicate that the herd, or a smaller component of the herd, has moved beyond a predetermined alarm point. In the more advanced case, a graphics application that shows the movement of the herd over time with projections of future movements is required.

A.2.3 Saratoga

Project web site: http://personal.ee.surrey.ac.uk/Personal/L.Wood/saratoga/

A project started in 2007 by Lloyd Wood of Cisco, together with Surrey Satellite Technology, UK and NASA. The objective was to develop SARATOGA, a fast file transfer protocol for hop-by-hop transfers on privately-owned networks - including the intermittently-connected networks used for delay-tolerant networking. *THE PROTOCOL* was first developed to download imagery from satellites. It can also be used for delay-tolerant networking Bundle Protocol transfers.

A.2.4 DTN for Sensor Networks

Project web site: http://lecs.cs.ucla.edu/~adparker/DTN/

A project initiated in 2004 by Andrew D. Parker at the Centre for Embedded Network Sensing, UCLA, USA, aiming at investigating and testing methods of communication in sensor networks in challenged environments, including interplanetary. Delay-tolerant networking architecture is one of the major technological foundations used in the project.

A.2.5 SWIM (Shared Wireless Infostation Model)

Project web site: http://people.ece.cornell.edu/haas/wnl/wnlprojects.html

A project started in 2003 by Zygmunt J. Haas at the Cornell University, Ithaca, USA, supported by the National Science Foundation and the Department of Defense Multidisciplinary Research Initiative. The project introduced a new communications paradigm, the Shared Wireless Infostation Model (SWIM). Under this paradigm, information is shared among the network nodes by processes of replication, storing, and diffusing. The mobile nodes serve as physical carriers of information. The model uses virtual links created by mobility, as well as physical links between nearby nodes.

A.2.6 SUMOWIN (Survivable Mobile Wireless Networking)

Project web site: http://www.sterbenz.org/jpgs/sumowin/

A project started in 2000 by James P.G. Sterbenz at BBN Technologies, supported by DARPA. The primary goal of the project was to ensure that networks are resilient in the face of:

- the challenging communication environment that wireless channels impose, including interference, fades, and susceptibility to jamming and denial of service attacks
- the dynamic topology and traffic characteristics that result from mobility of network nodes

A.2.7 Message Ferrying for Sparse and Disconnected Mobile Networks

Project web site: http://www.cc.gatech.edu/~ammar/ferrying.html

A project led in 2003-2005 by Mostafa Ammar at the Georgia Institute of Technology, Atlanta, USA; supported by the National Science Foundation and the Department of Defense Multidisciplinary Research Initiative. The project was concerned with the development of a novel Message Ferrying (MF) scheme, inspired by its real life analogue, that implements this store, carry and forward routing paradigm. In the MF scheme, a set of mobile nodes called *message ferries* take responsibility for carrying messages between disconnected nodes. Message ferries move around the deployed area according to known routes and communicate with other nodes they meet. By using ferries as relays, nodes can communicate asynchronously with other nodes that are disconnected. The main idea of the MF scheme was to introduce *non-randomness* in the movement of nodes and exploit such non-randomness to help deliver data. The store, carry and forward message delivery is an important delivery paradigm that can be used to overcome partitioning in a mobile ad-hoc network. The project included three main components:

- development of fundamental architectures, algorithms and protocols leading to successful designs of message ferrying systems,
- construction of system prototypes to provide a realistic understanding of the challenges in building and deploying message ferrying systems, and
- interfacing with on-going investigations of two contexts in which message ferrying can play an important role, namely surface transportation systems and robotic teams.

A.2.8 Node localization using mobile robots in delay-tolerant sensor networks

Project web site: http://www.cse.unsw.edu.au/~sensar/research/projects/localization/

A research project started in 2004 at the Deakin University, Victoria, Australia, and the University of New South Wales, Sydney, Australia, with the support of Australian Research Council, National ICT Australia. The objective of the project was to develop a novel localization system for sensor networks in which a mobile robot could be used to perform location estimation for sensor nodes it passes by, using the radio signal strength of the messages received from them. A practical implementation has been show on a LegoRobot, and Crossbow's motes and the Stargate platform.

A.2.9 DieselNet

Project web site: http://prisms.cs.umass.edu/dome/umassdieselnet

An ongoing project initiated in 2004 at the University of Massachusetts, Amherst, USA, in the framework of the DOME (Diverse Outdoor Mobile Environment) project. The network consists of some 40 buses each with a computer called a Diesel Brick. The brick is connected to three radios: an 802.11b access point (AP) to provide DHCP access to passengers and passers-by, a second USB-based 802.11b interface that constantly scans the surrounding area for DHCP offers and other buses, and a longer-range 900MHz radio to connect to so-called ‘throwboxes’, which are inexpensive, battery-powered, stationary nodes with radios and storage. Additionally, a GPS device records times and locations. Special software makes it possible to push out application updates, take mobility, AP-to-bus connectivity, and bus-to-bus throughput traces. The network operates in Amherst and surrounding county and is a practical delay-tolerant networking test bed.

A.2.10 Drive-thru Internet

Project web site: http://www.drive-thru-internet.org/

A project run in 2004-2006 by Technologie-Zentrum Informatik und Informationstechnik, Universität Bremen, Germany, and the Helsinki University of Technology, Finland. The project investigated the usability of IEEE 802.11 technology for providing network access to mobile users in moving vehicles. The idea of Drive-thru Internet was to provide hot spots along the road -- within a city, or on a highway – placed in such a way that a vehicle driving by would obtain WLAN access for some (relatively short) periods of time; if located in rest areas, the driver may exit and pass by slowly or even stop to prolong the connectivity period. One or more locally interconnected access points formed a so-called connectivity island that might provide local services as well as Internet access. Several of these connectivity islands along a road or in the same geographic area might be interconnected and cooperate to provide network access with intermittent connectivity for a larger area.

A.2.11 Haggle

Project web site: http://www.haggleproject.org

A project run in 2006-2009 under the European Union 6th Framework Programme. The financial value of the project was €5.87M. The participants included Thomson Paris Research Lab, France (project coordinator); University of Cambridge, UK; Consiglio Nazionale Delle Ricerche, Italy; Uppsala Universitet, Sweden; Martel GMBH, Switzerland; Scuola Universitaria Professionale Della Svizzera Italiana, Switzerland; Institut EURECOM, France; Ecole Polytechnique Federale De Lausanne, Switzerland.

Haggle is a new networking architecture designed to enable communication in the presence of intermittent connectivity, in the sense of any type of network connectivity, including (but not limited to) Bluetooth, 802.11, Ethernet, whether local or through the Internet. The project proposed a departure from the TCP/IP protocol suite by exploiting application layer forwarding instead of network layer. A system was defined that used best-effort, context aware message forwarding between ubiquitous mobile devices to provide service when connectivity was local and intermittent.

A.3 DTN-LIKE DATA MULE INFRASTRUCTURE PROJECTS

This section contains a number of projects that are investigating or using store and forward technology that is similar to DTN but does not use the DTNRG architecture or protocols (primarily because the original development was taking place in parallel to the original IPN and early DTNRG work). Most of them follow the DakNet paradigm – and indeed many have been developed by First Mile Solutions, the company that took on the task of commercializing the DakNet technology.

FidoNet is included here for historical interest – it predates all (almost all? apart from simple email, all!) this work but has a striking similarity to the modern DTN.

A.3.1 FidoNet

Project web site: http://www.fidonet.org/

FidoNet is a point-to-point and store-and-forward WAN which uses modems on the direct-dial telephone network. It was developed in 1984 by Tom Jennings in the USA to exchange e-mail and news between BBS nodes and gained popularity, also outside America, mainly in the eighties and early nineties. The nodes are addressed according to a hierarchical scheme reflecting the geographical location (continent, city, host) and the messages are routed so as to minimize the required calls to remote hosts. Still, every node is self-sufficient – can operate without support from the others – and has information about all other nodes' modem telephone numbers. The calls are usually scheduled for night hours, when telephone charges are lower. There are gateways to the Internet; also, Internet connections are sometimes used instead of actual phone calls as a transport for the node-to-node communication. Although the use of FidoNet dropped significantly with the proliferation of the Internet, it is still an option for less well connected regions.

A.3.2 DakNet

Project web site:
http://www.firstmilesolutions.com/documents/DakNet_IEEE_Computer.pdf

A project initiated in 2002 by the Media Laboratory, MIT, Cambridge, USA; Media Lab Asia, India; and now being commercialized by First Mile Solutions, Cambridge, USA. The project addressed communications challenged communities in rural areas of developing countries, beginning with India. In order to provide network connectivity in areas where permanent connection would be infeasible, it developed a store-and-forward wireless ad-hoc network called DakNet. A DakNet network takes advantage of existing communications and transportation infrastructure to distribute digital connectivity to outlying villages lacking digital communications infrastructure, combining physical means of transportation with wireless data transfer in order to extend the Internet connectivity provided by a central uplink or hub (e.g. a post office or a cybercafé) to kiosks in surrounding villages. The physical transport was implemented with public bus transportation in India.

A.3.3 KioskNet

Project web site: http://blizzard.cs.uwaterloo.ca/tetherless/index.php/KioskNet

A project involving practical network deployment, initiated in 2006 at the University of Waterloo, Canada. KioskNet is a network of rural Internet kiosks. It provides a low-cost and low-power single-board-computer called a 'kiosk controller' at each kiosk. The controller provides a network file-system for recycled PCs that act as thin clients. The controller communicates wirelessly with another single-board computer mounted on a vehicle (as was pioneered by the DakNet project, also referred to in this review) that can then carry data to and from a gateway, where data is exchanged with the Internet. This approach avoids the cost of trenches, towers, and satellite dishes, allowing Internet access even in remote areas, although at the cost of increased end-to-end delay. In areas where dial-up, long-range wireless or cellular phone service is available, the kiosk controller can be configured to also use these communication links.

The system has been practically deployed on test beds in South India and Southeast Ghana. It has also been used by other projects, e.g. AMITA Telemedicine association for telemedical consultation in sub-Saharan Africa or Gram-Vaani initiative to enable media services in rural India using community radio.

A.3.4 Internet Village Motoman

Project web site: http://www.firstmilesolutions.com/Cambodia/pressrelease.htm

A project organized in 2003 in Cambodia by American Assistance for Cambodia and Japan Relief for Cambodia, with participation of First Mile Solutions, Cambridge, USA, and contributions from Shin Satellite Corp.; Asian Honda Motor Co., Ltd.; Japan Airlines;
The Sasakawa Peace Foundation; The Markle Foundation; The Future Light Orphanage;
The Ministry of Posts and Telecommunications and Telecommunications of Cambodia; and
J.P. Morgan-Chase. The idea of the project is similar to the DakNet project mentioned above, with the exception that the transportation medium is a fleet of motorcycles instead of buses.

A.3.5 Los-Santos.net

Project web site: http://www.firstmilesolutions.com/projects.php?p=costarica

A project initiated in 2004 in Costa Rica by United Villages, First Mile Solutions, and the MIT, Cambridge, USA; the Central American Business Administration Institute, CoopeSantos (Costa Rican electricity cooperative); CoopeDota (coffee cooperative); and the Costa Rica for Sustainable Development Foundation. The project is similar to the DakNet and Motoman projects.

A.3.6 Village Area Network

Project web site: http://www.firstmilesolutions.com/projects.php?p=rw-rt

Another project of the DakNet family, initiated in 2004 by First Mile Solutions, Cambridge, USA, in collaboration with e-ICT, an NGO, and Artel, a local telecommunications company. The projects implements a hybrid Village Area Network for schools and institutions in Kigali, Rwanda. The network provides real-time access to several sites within the capital city using one uplink and a few repeaters, which then serve as the hub for a truck that provide store-and-forward access out to the surrounding rural areas..

A.3.7 Wizzy

Project web site: http://www.wizzydigital.org

A project started in 2003 in South Africa to provide schools lacking Internet connection with a low-cost method to access e-mail and the Web. A school is equipped with a proxy server and the content – e-mail messages, WWW requests and requested or subscribed to pages – are transferred to and from a base station or a school that does have a direct Internet link. The transfer is performed by dialling up at night, when telephone charges are lower, or by physically transporting data on a USB flash storage device carried by a courier on a motorcycle or a bike.

A.3.8 CafNet (Carry-and-Forward Delay-Tolerant Network)

Project web site: http://cartel.csail.mit.edu/cafnet/

A project run in 2006-2007 at the MIT, Cambridge, USA. CafNet (carry and forward network) is a delay-tolerant stack that enables mobile data muling and allows data to be sent across an intermittently connected network. The CafNet protocols allow cars to serve as data mules, delivering data between nodes that are otherwise not connected to one another. For example, these protocols could be used to deliver data from sensor networks deployed in the field to Internet servers without requiring anything other than short-range radio connectivity on the sensors (or at the sensor gateway node). A related project led by the same group is CarTel – a vehicular sensor network platform that uses open Wi-Fi networks for data delivery opportunistically.

A.3.9 HikerNet

Project web site: http://publications.nr.no/hikernet.pdf

A project initiated in 2004 in the Norsk Regnesentral, Oslo, Norway. HikerNet is a messaging service network enabling electronic communication in areas without ordinary networking access. The transport of the messages is based on small devices that are carried around, and which can exchange messages at close range based on peer-to-peer connections in an ad-hoc network. The devices for the transport nodes are supposed to be inexpensive, easy to carry, and accessible by ad-hoc communication using radio, or short-distance communication technologies (like IR, Bluetooth) or possibly be operated by inserting memory devices into a docking station.

A.3.10 Postmanet

Project web site: http://www.cs.princeton.edu/research/techreps/TR-691-04

A project initiated in 2004 at the Princeton University, USA. The objective was to explore the use of digital storage media transported by the postal system as a general digital communication mechanism, called Postmanet, supporting a wide variety of applications. Compared to traditional wide-area connectivity options, the Postmanet has several important advantages, including wide global reach, great bandwidth potential and low cost.

A.4 DTN ORIENTED APPLICATIONS INCLUDING SENSOR NETWORKS

This section covers projects that concentrate on applications running over a DTN infrastructure. Again the split between infrastructure and applications projects is not totally clear.

A.4.1 DTN web server

Project web site: http://www.netlab.tkk.fi/tutkimus/dtn/web/index.html

A project run in 2008 at the Helsinki University of Technology, Finland. The DTN-enabled web server is a server which accepts bundles containing HTTP requests and returns responses of bundled resources (using MHTML); it also supports plain HTTP access. The server obtains the resources to be bundled up in a specific response either from a dependency file stored on the server (which might, e.g., be generated by a web authoring tool) or it parses the requested resource (if it is HTML) and determines the other resources to be included. A separate proxy is provided that allows arbitrary web servers to access the DTN web server using bundles. The Server software was developed by Lauri Peltola in his MSc thesis.

A.4.2 DT-Talkie

Project web site: http://www.netlab.tkk.fi/tutkimus/dtn/dttalkie/

A project run in 2008-2009 at the Helsinki University of Technology, Finland. DT-Talkie is a DTN-based voice messaging application that enables mobile users to communicate over infrastructure-less and challenged environments in the walkie-talkie fashion. DT-Talkie supports both one-to-one and group communication. DT-Talkie is primarily implemented for Maemo based Nokia Internet Tablet. A port to heterogeneous endpoints like Mac, Linux PC and Openmoko based smartphone is also being done.

A.4.3 DTWiki

Project web site: http://www.cs.berkeley.edu/~bowei/papers/dtwiki/html/index.html

A project run at the University of California, Berkeley, USA, supported by the National Science Foundation. DTWiki is a wiki system which explicitly addresses the problem of operating a wiki system in an intermittent environment. The DTWiki system is able to cope with long-lasting partitions and bad connectivity while providing the functionality of popular wiki software such as MediaWiki and TWiki.

A.4.4 TEK (Time Equals Knowledge)

Project web site: http://tek.sourceforge.net/

A software project started in 2002 at the Laboratory for Computer Science, MIT, Cambridge, USA. TEK empowers low-connectivity communities by providing an Internet experience using email as the transport mechanism. The TEK client operates as a proxy on the user's machine, enabling users to browse downloaded pages using a standard Web browser. New searches are automatically encoded as emails and sent to the TEK server, which queries the Web and returns the contents of resulting pages via email.

The software is used by a number of practical projects in communications challenged communities, including The Solomon Islands People First Network and the DakNet and related projects of First Mile Solutions, mentioned in this review.

A.4.5 WWWOFFLE (World Wide Web Offline Explorer)

Project web site: http://www.gedanken.demon.co.uk/wwwoffle/

A software project started in 1997 by Andrew M. Bishop. The `wwwoffled` program is a simple proxy server with special features for use with intermittent internet links. This means that it is possible to browse web pages and read them without having to remain connected.

A.4.6 SeNDT (Sensor Networking with Delay Tolerance)

Project web site: http://down.dsg.cs.tcd.ie/sendt/

A project run in 2002-2007 at the Trinity College Dublin, Ireland, supported by Enterprise Ireland. The project involves running real-world pilots using a sensor node for environmental monitoring designed for public authorities, NGOs and/or organisations. The pilots include lake water quality monitoring and road-side noise monitoring. SeNDT applied delay-tolerant networking technology to fill a niche for sensor nodes that cannot use more typical networks (e.g., those assuming IP or GSM/SMS connectivity). The SENDT work forms the centrepiece of the 'DTN book' [Farrell06].

A.4.7 TurtleNet

Project web site: http://prisms.cs.umass.edu/dome/turtlenet

A project run at the University of Massachusetts, Amherst, USA, in the framework of the DOME (Diverse Outdoor Mobile Environment) project. The network includes lightweight nodes deployed on so-called wood turtles (Clemmys insculpta) in the Northeast and Great Lakes regions and on gopher tortoises in southern Mississippi. The nodes tiny include wireless sensors and GPS and communicate information collected in order to study the behaviour of the turtles, including their travel patterns. Delay-tolerant networking is among the methods investigated for communication in the network.

A.4.8 EMMA (Environmental Monitoring in Metropolitan Areas)

Project web site: http://www.ibr.cs.tu-bs.de/projects/emma/

A research project at the Technische Universität Braunschweig, Germany. The goal of EMMA is to develop a decentralized and cost-efficient architecture for area-wide measurement of air pollutants. Vehicles of existing public transportation systems are used to continuously acquire environmental data. The measured values are exchanged between different vehicles with the help of WLAN. Since vehicles only meet each other sporadically, techniques from the fields of Car2X communications and delay-tolerant networks are used for data exchange. The measured values are delivered to a central gateway, which forwards the messages to the evaluation server. Here they are analyzed and any actions like bans on driving may be taken if necessary. The results of several measurements in the city of Braunschweig showed that the concept of exchanging information between vehicles works very well. Communication is possible even without direct line out sight and at higher distances between the vehicles. Besides distributing measurement values, the architecture of EMMA may also be used for e.g. the exchange of passenger information.

A.4.9 Prototype Testing and Evaluation of Wireless Instrumentation for Ecological Research at Remote Field Locations

Project web site: http://wireless.oldcolo.com

A project run 1999-2002 by Old Colorado City Communications company with the support of the National Science Foundation and in a cooperation with the US Long Term Ecological Research (LTER) Network. The financial value of the project was $1.029.000.

The project evaluated suitability of emerging forms of FCC Unlicensed Spread Spectrum, UNII, and future smart radio and ultrawide band protocol wireless technologies for the intermittent or continuous collection of biological and environmental data from sensors and data loggers emplaced in difficult and often seasonally inaccessible remote field locations and distribution of such data via the Internet.

A major finding of this project was that the widespread use of relatively few, costly data loggers can be replaced by the deployment of thousands miniature radios with singular interchangeable sensors, very small processors, and remotely-rechargeable batteries (by laser light or microwave power).

A.5 ANIMAL TRACKING PROJECTS

Only ZebraNet explicitly uses DTN, although it seems to be an ideal fit for long term animal monitoring. As with many sensor applications, the challenge is to find a power supply that does not require frequent handling of the animals, and minimizes the risk of pollution if the tracker units cannot be recovered because it has been shed prematurely by the animal or the animal is lost or becomes a victim of predation. Especially in the fragile environment of the arctic, batteries are not an ideal solution here. Power recovered through the motion of the animal is a possible solution.

A.5.1 ZebraNet

Project web site: http://www.princeton.edu/~mrm/zebranet.html

A research project run in 2002-2005 at the Princeton University, USA, with the support of the National Science Foundation through the Information Technology Research initiative. The financial value of the project was $1.3M. The main objective was to explore wireless protocols and position-aware computation from a power-efficient perspective. The project had a computer systems as well as a biology focus. The computer-related aspects were power-aware, position-aware computing and communication systems with the goals to develop, systems that integrated computing, wireless communication, and non-volatile storage along with global positioning systems (GPS) and other sensors. The biological aspects were animal migrations and inter-species interactions.

The ZebraNet, deployed in Kenya, involved store-and-forward communications between tracking nodes equipped with a CPU, flash storage, a radio communications device and a GPS receiver implemented in collars worn by zebras. The data forwarded by the tracking nodes were periodically collected by a car or an airplane. The project brought interesting experiences related to node hardware, software architecture (including Impala middleware software built in the project), and communication protocols.

A.5.2 Telespor

Project web site: http://telespor.no

A project begun in 2000 in Norway was a response to farmers' needs for tracking and supervising their animals. The project resulted in the founding of a commercial company, Tele Track AS that develops and markets a system of products and services for electronic monitoring of livestock grazing. The system consists of terminals installed in collars worn by sheep, with GPRS, VHF, or UHF transmitters and GPS receivers, wireless base stations, and a server that collects the data. The GPRS and VHF terminals communicate with the base stations; the UHF terminals forward their data via the GPRS or VHF ones. The processed data is available for the farmers via SMS alert messages and Web maps and reports, so that they can be informed of the animals' positions and alerted to unusual situations, e.g., when an animal has not moved in a specified time interval.

A.6 PROJECTS RELATING TO A DTN ORIENTED STORAGE FRAMEWORK

The Store, Carry, Forward (SCF) paradigm implemented by DTN is readily extended to encompass nodes that provide reliable storage for a network. In the DTNRG realisation bundles provide a convenient storage module for data that can be mapped from store to transmission medium easily with minimal extra encapsulation.

A.6.1 TierStore

Project web site: http://tier.cs.berkeley.edu/wiki/TierStore

A project initiated in 2007 at the University of California, Berkeley, USA in the framework of the TIER initiative (Technology and Infrastructure for Emerging Regions). TierStore is a distributed storage system and applications framework. Given the constraints related to power, intermittent connectivity, and cost of developing regions, applications can be well-served to take advantage of a multi-level system architecture. This allows a core data centre or set of data centres to provide centralized reliable storage and permanent network connectivity for applications distributed throughout the network. Then per-village or per-user proxy servers and devices can function as data caches to improve network access to shared data. A prototype has been deployed for syndicating radio station content in Guinea Bissau.

To assist and enable application development for this architecture, a storage system and API are being developed to ease application development. Applications written within the TierStore framework can leverage a common system for data synchronization that handles network outages as well as resolving data conflicts arising from network partitions.

A.7 STUDIES AND PROJECTS AIMED AT IMPROVING RURAL NETWORKS

This section contains notes on a number of projects and collaborations that focus on extending network connectivity into rural areas both from a technical and a business perspective. Some of the projects have been funded by EU (structural funds, FP6, Interreg) whereas others are funded by NGOs or commercial developments.

A.7.1 CroCoPil (Cross Border Co-operation Pilot Networks)

Project web site: http://www.cdt.ltu.se/~zcrocopil

The main goal of this project was to apply user needs as requirements for technology evaluation, development, and adaptation, in order to create core services, which may improve life and working conditions in remote rural areas, especially in the northern parts of Finland, Sweden and Norway. The major beneficiaries of the project were rural communities, innovative people in rural and/or arctic areas, and young people in these areas.

The purposes of the project were to

- create and test a so-called *CroCoPil solutions toolbox* that makes new services accessible to rural communities;
- strengthen the awareness and attitude of rural people with regard to technology and ICT (Information and Communication Technologies) technology-based services;
- establish some service pilots that shall be tested and demonstrated; and
- provide a basis for innovation and sustainable companies in all participating countries.

7.1.1. User requirements identified in this project:

Mobility:

- Being able to have mobile connectivity is the overall requirement. The users want to be able to transfer, update, and store data they gather in the field. Much of the data is confidential; hence all this has to be handled and stored in a safe manner.
- The users expect to be able to call as a result of medical emergencies.

Internet access:

- The users want the connection to Internet to be stable, fast, and secure. The respondents want to be able to perform administrative work in the evenings when they work in the field; therefore they need to have access to Internet in the cabins in the mountains. For example, the users want to be able to manage the work in the predator database, the user wants to be able to do business and communicate with customers, and they want to be able to write documents and do their accountings. Much of this is text based communication such as sending emails and sending documents and reports.

Send, Receive, and Store Data in different formats:

- The users want to be able to gather and transfer large amount of data in different formats continuously during their field work. They want to do the documentation via audio recording. They want to be able to track the herd, find lost animals, and track predators. They want to be able to do documentation related to their position when they are out in the field. For example, report on dead animals, photos or videos in relation to the impact position that can be sent to the office.

7.1.2. Functions and solutions defined in the project

Device for synchronous coordination and communication:

- To be able to coordinate and communicate in real time during work (one-to-one or one-to-many) a device with a Push-To-Talk function is asked for. To be able to use this device at all places and spaces the device should have connectivity to multiple networks and operators as different networks and different operators have connectivity in different places.

Device for GPS solutions and maps:

- The users have expressed that they want intelligent and interactive maps where both local names and Sámi names on positions are available; a device in which interactive maps are combined with GPS solutions, in which information can be stored via a touch-screen and audio recording as well as photos or videos. The user should be able to send the information, either at once from their position, or later on when docking into a computer in the cabin or in the office. Another solution or function is RFID chips in animals to be able to monitor and control their movement and position. It has also been expressed that reindeer herders want to be able to position presumptive customers to make an offer.

Field services:

- When users are out in the field they need services in which they can receive information about weather, ice, and snow conditions from their location, i.e. local information.
- They also want to have access to e-services such as news, banks, and e-commerce. They need to connect to a reindeer database in which information about specific reindeers is accessible and can be handled.

Selective network access:

- Those who value freedom and silence in the field and make a living on that, want to be able to keep the silence and wilderness as a part of their offered service. Therefore, they want to have access to a network only they can log into.

Web-based meeting places:

- Solutions for meeting and being part of the community even when working in the field are a web-based café, where people can meet and chat; web-based communities for different interest groups, where people can meet and discuss their experiences or share anecdotes with each other; web-based school for the children following their parents, who work in the field.

7.1.3. Future solutions and existing needs defined in the project

The users from rural areas need a device that transforms speech to text and even, in the next step, into well-formulated text. This is grounded in their need to communicate with authorities and their wish to be able to write well-formulated texts.

The reindeer herders have also expressed a need for a game where they can learn to be a reindeer herder so that knowledge can be transferred from one generation to the next.

Reindeer herders need virtual fences and dogs to monitor and control the reindeer herds. Moreover, they suggest a virtual helicopter, a kind of satellite monitoring to cover larger land areas. Finally, they think of a high-frequency sender which would keep insects away. The rangers in Sweden who work in solo to a large extent miss of a friend, maybe a virtual one.

The project defined various concepts of ICT solutions for rural usage, for example:

- Home Care Diary
- Online Service Ware House
- Travel Diary
- GeoBlog
- Seamless Office
- Specialized Field Device
- Ad Hoc Relay Stations (ad hoc networks)
- Extending Sensing (sensor)
- Delayed E-mail and Web access
- Information Packets
- Calculating Application
- Web Meeting Place
- Web School
- Interactive Map

7.1.4. Business requirements

A business model proposal for an online service concept was presented with the following example of service usage:

- A truck is on its way from Southern Lapland, Kemi to Northern Lapland, Levi. When approaching the Levi centre the driver activates his phone's 'business' mode and requests suitable accommodation services. The driver then gets a list (via WLAN) of available local services. Information pulling is based on the personal profile information. With the same system the driver is able to both book and pay a motel room. After this the driver wants to have something to eat and wants to find the closest restaurant. He requests these services online. The system offers a list of restaurants and he selects a suitable one and an online positioning service then guides him to the selected restaurant. After having his meal the driver leaves Levi for Oulu where he wants to find a route to Raatti.

A.7.2 PICYBU (Participation in Rural Communities by Young Broadband Users)

Project web site: http://www.picybu.org/

The project was financed by the Interreg IIIB Northern Periphery programme and ran from January 2005 till March 2007. The objective of the project was to test, pilot, and evaluate how different media and ICT applications and tools can contribute to the social participation of young people in rural communities. The idea was that participation would increase their interest in their home region and willingness to stay there. The vision was an attractive rural life style. There were four main application areas where pilots were run: media as a tool for young people participation, 24-hour society (services) for young people and business in rural areas. Participating countries are Sweden, Finland, Faroe Islands and Norway.

A.7.3 BIRRA (Broadband in Rural and Remote areas)

Project web site: http://www.birraproject.net

The project began in January 2005 and completed in June 2006.

The overall objective of the project was to develop information and communication technology and information society services for NPP areas. The purpose of the project was to analyse and compare the provision of broadband and associated services across the different regions. The result of this analysis formed the basis for developing a model similar to the EU e-adoption ladders, but focused on regions as opposed to individual SMEs. The eLadders tool showed the position of the region in comparison to others and a framework to allow a progression of each region to the next step was proposed.

A.7.4 Rural Wings

Project web site: http://www.ruralwings-project.net/

A project run in 2006-2009 under the European Union 6th Framework Programme 2006-2009[7]. The participants are: the Institute of Communications and Computer Systems, Greece (project coordinator); Telemedicine Technologies S.A., France; Hellas Sat Consortium Ltd., Greece; Progress and Business Foundation, Poland; Ellinogermaniki Agogi S.A., Greece; Fourier Systems (1989) Ltd., Israel; DBC GMBH, Switzerland; Ben-Gurion University of the Negev, Israel; European Resuscitation Council, Belgium; Hellenic Telecommunications And Telematics Applications Company, Greece; Technische Universität Dresden, Germany; University of Aegean, Greece; Alfa-Omega Communications Ltd., Estonia; Universitatea "Politehnica" Din Bucuresti, Romania; Foundation For Research And Technology – Hellad, Greece; Universitat de Barcelona, Spain; International Environment and Quality Services S.A., Greece; European Distance and E-Learning Network, UK; Stockholm University, Sweden; Institut Europeen d'Administration des Daffaires, France; Avanti Communications Ltd, UK; Gokceada Belediyesi, Turkey; EADS Astrium SAS, France; and Eutelsat S.A., France. The financial value of the project is €8.83M.

The project that proposes to develop an advanced learning platform through satellite DVB-RCS access technologies, promoting a user-centred methodological approach. The main aim is to support the creation of a new culture in rural communities promoting digital literacy and reducing resistance to the use of new technologies. It is intended to go further, encouraging users to add their significant contribution to the emerging applications by involving them in meaningful activities, tailored to address the needs of different user groups. Thus, the project aims to offer stimulating and creative learning environments to support vibrant user communities.

The main objective of the project is to offer e-learning services to a variety of users at school, at work, or at home, by installing DVB/RCS satellite terminals equipment into 126 pilot sites all over Europe. These pilot sites refer mainly to isolated and remote villages in rural areas and geographical locations such as mountainous sectors or islands where fast Internet access (e.g. ADSL) has never been possible before. The 126 pilot sites of the project are to be implemented in 13 European Countries (Greece, Spain, Sweden, France, Romania, Cyprus, Estonia, Poland, UK, Israel, Armenia, Georgia, and Switzerland), while pilot sites in South Africa and in Canada will be linked to the project. At least 25 WiFi networks are also to be implemented in order to provide access to all possible remote users in the above pilot sites.

A.7.5 Smart Communities Program

Project web site: http://198.103.246.211/program_e.asp

The Smart Communities Program was a three-year (1999-2002) program created and administered by Industry Canada to foster development and use of information and communication technologies for economic, social, and cultural development. The financial value of the program was C$60M.

The program goal was to help establish so-called 'Smart Communities' across the country so that Canadians could fully realize the benefits that information and communication technologies had to offer. A 'Smart Community' was defined as a community with a vision of the future that involves the use of information and communication technologies in new and innovative ways to empower its residents, institutions and regions as a whole.

[7] Note that this is a different project from Rural Wins (see Section 8.1).

The program had the following objectives:

- assist communities in developing and implementing sustainable Smart Communities strategies;
- create opportunities for learning through the sharing among communities of Smart activities, experiences and lessons learned;
- provide new business opportunities, domestically and internationally, for Canadian companies developing and delivering information and communication technology applications and services.

A central focus of the program were the Smart Communities demonstration projects — one in each province, one in the North and one in an Aboriginal community — centres of expertise in the integration of information and communication technologies into communities, organizations and families. Smart Communities also acted as "learning laboratories" in which the innovative use of these technologies in community life and enterprise was tested.

A related component of the Smart Communities initiative was the Broadband for Rural and Northern Development Pilot Program, created to assist those communities without broadband access, mostly in First Nations, northern and rural communities, in order to provide services in the areas of health and education, as well as to augment economic opportunities. The program conducted rounds of business plan development funding, followed by rounds of implementation funding, each with a competitive call for the submission of applications from interested communities.

A.7.6 Nunavut Broadband

Project web site: http://www.qiniq.com/project-history

The origins of the project date back to the 1990s and various conferences, documents, and small-scale network deployments in the new administrative territory, Nunavut, which was separated from the Northwest Territories in 1999. A working group called Nunavut Broadband Task Force was created in 2001 and after securing partnership from communities, municipalities, industry, a local credit corporation and local venture capital succeeded in receiving financial contributions from the Nunavut and Canada governments and in 2004-2005 built a network, called Qiniq, in a project worth over C$9M.

The Qiniq network delivers broadband connectivity to the 25 communities in Nunavut, with a population of 29,000 people dispersed over 2 million square miles. This enables residents of Nunavut to access on-line services, educational content, electronic commerce and in general, utilize modern Internet technologies. This was previously impossible, as no Broadband infrastructure existed that the average person could readily make use of, due to cost and availability factors.

The network has a number of interesting features, including:

- a full mesh network, enabling any site to talk to any other site in a single satellite hop; this is particularly important for video conferencing;
- support for dynamic bandwidth allocation, allowing satellite bandwidth to be effectively shared between all the communities, based on demand; on a second by second basis, the network re-allocates bandwidth to ensure that communities who need the bandwidth, get it;
- several technologies to enhance the performance of the overall network, including TCP/IP acceleration and transparent caching;
- a licensed wireless municipal distribution.

The network is run by a commercial company, SSI Micro, and so-called CSPs (Community Service Providers). The CSPs are local people – at least one person in every Nunavut community – trained to install wireless modems, handle basic troubleshooting and collect payment for services.

A.7.7 Information and Communications Technology (ICT) Development Project

Project web site: http://www.adb.org/Documents/Profiles/GRNT/38347022.ASP

A long-term project (2008-2014) run by the Office of the Prime Minister and Council of Ministers in Nepal, sponsored by the Asian Development Bank grant of US$25M.

The Project is designed to connect rural remote areas to the centre of the country through ICT networks and thereby reduce the geographical barriers that have disadvantaged the people of mountain and hill areas, enable them to accrue the benefits of development initiatives, access market information, access job opportunities, and access information on health, education, tourism, and government schemes and policies.

The expected results of the project are:

- Rural e-community: improving the rural connectivity using the wireless broadband networks; mobilizing community socioeconomic activities using a village network portal through which villagers can share their social capital; building telecentres to improve last mile service access in remote rural areas.
- A government ICT network, including an information and data centre, and government groupware.
- Development and implementation of e-government applications.
- Human resources development for e-governance, including building awareness, knowledge, and skills, establishing computer laboratories, and supporting development of ICT governance courses.

A.7.8 Xixuaú-Xipariná

Project web site: http://www.self.org/Brazil_Press_Release.asp

A project initiated in 2002 to bring solar power and broadband wireless Internet access to the isolated Xixuaú-Xipariná Ecological Reserve in the heart of Brazil's Amazon rainforest. The project was lead by Electric Light Fund, Washington, USA, with Associação Amazônia, Brazil; OnSat Network Communications, Salt Lake City, USA; and Institute for Sustainable Development and Renewable Energy, Fortaleza, Brazil. The funds have been donated by the Ernest Kleinwort Charitable Trust, UK.

The deployment included satellite dishes for Internet connectivity. In addition, solar panels were installed; these provide electricity not only for the network equipment, but also for refrigerators for vaccines and snakebite anti-venom, a medical diagnostic device that can upload information to the Internet for use in telemedicine, new computers and lighting at a local school for local children, and a pump to deliver fresh water from a river. Previously, power needs at the Reserve were met with an improvised and unreliable combination of kerosene, diesel, and wood. Making use of the Internet required a forty-hour boat ride to the nearest city.

A.7.9 Nepal Wireless Networking Project

Project web site: http://www.nepalwireless.net

A project initiated in 2003 (and still ongoing) in rural Nepal. Originally an initiative of Mahabir Pun, living in one of the villages, it is now run by the Himanchal Higher Secondary School in Nangi Village, Nepal with a number of partners and supporters including E-Network Research and Development, Open Learning Exchange Nepal, Gandaki College of Engineering and Sciences, Kathmandu Engineering College, Kathmandu Model Hospital, Om Hospital Pokhara, Thamel.com, and Nepal Library Foundation Canada. The target of the project are the people living in isolated villages of Himalayan region of Nepal where there is almost no chance of getting the modern means of communication in near future. The project aims at introducing information technology to villagers and show its real uses, motivating them to learn about it and use it by themselves.

There are over 40 villages connected, via WiFi links, access points and relays, sharing a common ISP connection, and using Internet, VoIP, teleeducation and telemedicine services.

A.7.10 Wireless IP based Rural Access Pilot Project

Project web site: http://www.bhutan-notes.com

A pilot project with a budget of $300K which ran in 2001-2002 using wireless and VoIP technologies to deliver communication services, including Internet access, to rural areas in Bhutan. The technical objectives of the project were:

- to deploy a wireless VoIP network at two sites;
- to evaluate the performance of a wireless point to point backbone link;
- to evaluate the performance of the point to multipoint last mile links;
- to evaluate the performance of the VoIP service over the links;
- to evaluate the overall usability of the wireless network for VoIP;
- to evaluate low cost routing hardware used for the E1 data connections.

The project involved deploying and connecting a Wi-Fi network in two locations, one in Limukha, and the other in Gelephu, serving a total of about 80 customers. The project was intended to test the technology under different conditions. Limukha is more mountainous and Gelephu is flatter but has much more rain and lightning. Existing microwave links were used to connect the remote sites to an existing network operating centre and PSTN in Thimphu. The project tested practical issues of deploying networks in challenged environments, including supplying solar power, weather proofing, and local community involvement and training.

A.7.11 First Mile First Inch

Project web site: http://www.fmfi.org.za

Initiated in 2003 in South Africa, First Mile, First Inch (FMFI) is a multi-disciplinary series of projects exploring the technological and social consequences of least-cost telecommunications implemented in remote schools, clinics, and telecentres throughout rural Africa (South Africa, Namibia, Angola, Mozambique, and Zimbabwe). The research explores how people interact with new technologies and the changes that occur in their daily lives. The projects demonstrate how the first mile in poorly served rural and marginalized communities can be bridged with Wi-Fi as well as other off-the-shelf do-it-yourself technologies. The key long-term goal is sustainability: to help local communities build their own neighbourhood networks and cultivate the skills required to manage and replicate the networks in the future. The research objectives are:

- to develop innovative information and communication technologies (ICTs) and to implement "first mile" solutions;
- to investigate how the use of ICTs has changed community life;
- to quantify what is meant by low cost connectivity;
- to evaluate the scalability and replicability of the technologies;
- to demonstrate project benefits to the regulator;
- to publish a reference book for "first mile" and "first inch" implementation in rural Africa.

The are a number of specific projects running under this initiative, mostly serving the needs of schools (e.g. Zim Wi-Fi project in Zimbabwe) and hospitals and clinics attempting to introduce telemedicine services in order to make it easier to consult remote patients (e.g. Mpumalanga Mesh project in South Africa). The technologies involved include Wi-Fi and Wi-Fi mesh for the access and distribution, and various Internet uplinks, including satellite type. The name of the initiative reflects a shift in network organisation paradigm and point of view towards the end user ("first inch") and local operator ("first mile").

A.8 PROJECTS EXTENDING THE REACH OF NON-SATELLITE RADIO

A diverse group of projects that covered some aspect of providing long, primarily point-to-point, radio links that could deliver the level of throughput needed for the sort of service to which terrestrial wired broadband network users have become accustomed.

A.8.1 WiLDNet (Network protocol design for Wi-Fi based Long Distance Networks)

Project web site: http://tier.cs.berkeley.edu/wiki/Wireless

A project initiated in 2006 at the University of California, Berkeley, USA. The objective was to design and implement Wi-Fi networks with long distance links (of the order of 50-100km), overcoming the problems stemming from the IEEE 802.11 MAC protocol when used over long distances and from high and variable loss characteristics of such links. Assuming no modification to existing 802.11 hardware the project investigated what link and MAC protocol layer modifications are necessary to achieve good transport performance.

Practical implementations were deployed in a several developing environments, including Ghana (linking remote campuses of the University of Ghana) and India (linking Aravind Eye Hospital with remote eye-care clinics).

A.8.2 CAPANINA (Communications from Aerial Platform Networks delivering Broadband Communications for All)

Project web site: http://www.capanina.org/

A project run in 2003-2006 under the European Union 6th Framework Programme. The participants were: the University of York, UK (project coordinator); Jozef Stefan Institute, Slovenia; Politecnico di Torino, Italy; EuroConcepts s.r.l., Italy; Universitat Politecnica Catalunya, Spain; Carlo Gavazzi Space S.p.A., Italy; Budapest University of Technology and Economics, Hungary; BTExact, UK; Deutsches Zentrum fur Luft- und Raumfahrt e.V., Germany; SkyLINC Ltd., UK; Centre Suisse d'Electronique et de Microtechnique SA, Switzerland; Contraves Space AG, Switzerland; National Institute of Information and Communications Technology, Japan; and Japan Stratospheric Corporation, Inc. The financial value of the project was €5.65M.

8.2.1. Objectives

The overall objective of the CAPANINA project was to develop a broadband wireless communications capability, at speeds up to 120Mbit/s, from High Altitude Platforms (HAP) to stationary users on the ground and to users on moving vehicles at speeds of up to 300km/h.

The project enabled high rate communications (of up to 120 Mbit/s) to be delivered directly to a user anywhere in the line of sight of an HAP within a coverage area up to 60 km wide, making it economically viable to deliver services typically offered to big corporations, to users who may be marginalized by geography, distance from physical infrastructure, or those travelling inside high-speed public transport vehicles.

8.2.2. Applications and services selection

CAPANINA was specifically about HAPs providing two-way broadband communications to communities where it is not possible or not feasible to offer terrestrial alternatives such as xDSL. Examples of target communities are rural, mobile (such as trains) and disaster sites. The provision of broadband (> 64 kbit/s) is not enough – it is also necessary to offer a compelling range of applications and services.

Typical services include:

- LAN Interconnect
- Web Browsing
- File Transfer
- Email
- Content Distribution (point to multipoint)
- Voice/Audio Streaming
- Video Streaming
- Content Distribution (IP Multicast)

A.8.3 HELINET (Network of Stratospheric Platforms for Traffic Monitoring, Environmental Surveillance and Broadband Services)

Project web site: http://www.elec.york.ac.uk/comms/projects/helinet/index.html

A project run in 2000-2003 under the European Union 5th Framework Programme. The participants were: Politecnico di Torino, Italy (project coordinator); Construcciones Aeronauticas S.A, Spain; Fastcom Technology S.A., Switzerland; Ecole Polytechnique Federale de Lausanne, Switzerland; Carlo Gavazzi Space S.P.A., Italy; Enigmatech Ltd., UK; Universitat Politecnica de Catalunya, Spain;

University of York, UK; Institut Jozef Stefan, Slovenia; and Budapest University of Technology and Economics, Hungary. The financial value of the project was €4.82M.

The objective of the project was to design an integrated network based on HALE (High Altitude Long Endurance) unmanned aerodynamic solar platforms. In particular, the project addressed the following tasks:

- design of a HALE platform (HELIPLAT) and manufacturing of a scaled size technological demonstrator, fully representative of the HELIPLAT, for static tests;
- study of three pilot applications (localisation/traffic monitoring, environmental surveillance data processing and transmission, broadband communications services).

A.8.4 Helios Prototype

Project web site: http://www.nasa.gov/centers/dryden/history/pastprojects/Helios/index.html

The Helios Prototype solar-electric flying wing was one of several remotely piloted aircraft, also known as uninhabited aerial vehicles or UAVs that were developed as technology demonstrators under the Environmental Research Aircraft and Sensor Technology (ERAST) framework. The participants were NASA Dryden Flight Research Center and AeroVironment, Monrovia, USA. The Helios project began in 1999. One of the applications intended for the UAV was providing a radio communications relay for extended periods of time. The prototype crashed in a test in 2003.

A.8.5 Remote Area Networking (Establishing Remote Area Networking through Wireless Radio Modems)

Project web site: http://foodindia.org.in/wireless/index.htm

A project ran in 1998-1999 in India by the Foundation of Occupational Development, Tamilnadu, India, funded by the International Development Research Centre, Ottawa, Canada under its Pan Asia Networking R&D Grants Program. Among the objectives of the project were:

- provide networking access in remote areas where there is no scope for access to information through electronic communications;
- offer e-mail, bulletin board, and conferencing services;
- establish Internet Services and act as an Internet Service Provider;
- promote original and innovative networking solutions to specific development problems in the region;
- involve experimentation, pilot studies and other practical networking activities that could create replicable results and have potential for application throughout the region.

The project included the deployment of a wireless radio modem network (AX.25-based packet radio network), as well as training local system operators – not only to maintain the network, but also to develop and serve local services, such as local Web content – and training the end users. One of the local subnetworks expanded into a full-fledged Internet Service Provider.

A.8.6 Gyan Sanchar

Project web site: http://www.gyansanchar.net/

An India – Canada Telecommunications Operations Project, initiated around 2004 to bring affordable and cost effective services to rural India, as a pilot project in 32 villages of Babai and Khirkiya tehsils of Hoshangabad and Harda districts of Madhya Pradesh. Funded by the Canadian International Development Agency, the project was a partnership between Bharat Sanchar Nigam Limited, Government of Madhya Pradesh (GoMP) India and a Canadian business team comprising IBM Business Consulting Services and Sasktel International in collaboration with the Madhya Pradesh

Government. The project goal was to develop a model for sustainable expansion of telecommunication services and ICT applications in rural India.

The network employed a number of technologies, with focus on corDECT – a fixed wireless local loop standard developed in India, based on the DECT standard, with both voice and Internet connectivity provided over links of up to 25km.

A.9 PROJECTS EXTENDING THE INTERNET VIA SATELLITE RADIO

A group of projects that are primarily investigating the use of satellites to provide the sort of service to which terrestrial wired broadband network users have become accustomed. There is some overlap with the rural initiatives projects.

A.9.1 TSIS (Transportable Satellite Internet System)

Project web site: http://www.osc.edu/oarnet/initiatives/tsis.shtml

A project started in 2002 by OARnet (a division of the Ohio Supercomputing Center in Columbus), ITEC-Ohio (Internet2 Technology Evaluation Center), and the Ohio State University, Columbus, USA with a $65,000 grant from the American Distance Education Consortium (ADEC). The objective of the project was to build and operate a Transportable Satellite Internet System (TSIS).

The system comprised a small trailer that carried a 1.2 meter diameter dish receiver plus all related electronics, and could be pulled by any vehicle with a trailer hitch. The TSIS provided 24 10/100 Ethernet network ports for connection to nearby computers or LANs. The total speed of the satellite connection was 1.5 Mbps/s downlink, and 512kbps/s uplink. The system included a local IEEE 802.11b wireless capability, which could penetrate the wall of a nearby building and provide connectivity inside it. It also included a generator and batteries so as to be self-contained and able to run for more than 24 hours unattended. The system was designed so that it could be set up and operated by a single person.

This applications for the system included distance learning and special events in rural areas and at conferences where good regular Internet connectivity is not available. It was also a laboratory vehicle to evaluate and evolve the system design, as well as to measure its effectiveness in delivering distance education.

A.9.2 AISEP (Advanced Internet Satellite Extension Project)

Project web site: http://www.adec.edu/nsf

A project run in 2000-2002 to develop and deploy advanced Internet services and technologies over satellite infrastructure for purposes of enhancing research, instruction, and learning in institutions of higher education. The participants were the American Distance Education Consortium (ADEC), Tachyon, Inc., and the following US universities: University of California at Davis, University of Illinois at Urbana-Champaign, University of Maryland, North Carolina Agricultural and Technical State University, North Carolina State University, Washington State University, and University of Nebraska-Lincoln. The project was sponsored by the National Science Foundation; the financial value of the project was $5.5M.

The main objectives of the project were to:

- explore the use of satellite technology to deliver Internet services so as to determine the compatibility of this new technology with services and applications being developed within the Internet2 project;
- explore the deployment and integration of distance education applications, including collaborative applications at rural, remote institutions and extension learning centres that have previously been unable to access such technologies.

Among the research objectives of the project were the following:

- establish what constitutes "pretty good Internet" for remote locations;
- investigate how to establish, build, and support a satellite based IP network;
- study network performance;
- investigate how to use QoS to deliver through the Internet including satellite wireless last mile solution;
- investigate QoS utilizing Tachyon/Internet2 Quality of Service capabilities to enable distance education applications;
- determine what is required to support this type of network;
- determine the parameters for a sustainable business model.

The objectives included also actual connection deployments:

- connecting the Tachyon satellite gateway to the San Diego Network Access Point;
- providing Tachyon Access Points to selected ADEC members not accessible via the traditional Internet infrastructure.

A.9.3 NICSN (The Northern Indigenous Community Satellite Network)

Project web site: http://smart.knet.ca/satellite/index.html

The NICSN is the first inter-provincial community owned and operated broadband satellite initiative in Canada. The project was initiated in 1998 by Keewaytinook Okimakanak (a non-political Chiefs Council serving Deer Lake, Fort Severn, Keewaywin, McDowell Lake, North Spirit Lake and Poplar Hill First Nations in Canada) together with Telesat Canada and Industry Canada, initially to find a solution for delivering broadband services to Fort Severn. The initiative was being developed by common satellite broadband usage and deployment of earth stations, with over $5 million in strategic capital investment by Industry Canada, and partnerships from industry, not-for-profit organizations, and the government.

The network is organizationally a cooperative venture connecting over 30 remote communities from the northern regions of Manitoba, Quebec and Ontario. It is being administered through an innovative partnership of Keewaytinook Okimakanak, Keewatin Tribal Council and the Kativik Regional Government.

A.9.4 BRASIL (Broadband to Rural America via Satellite Integrated Links)

Project web site: http://www.dvb-brasil.org/

A project run in 2007-2009 under the European Union 6th Framework Programme. The participants are: Ansur Technologies AS, Slependen, Norway (project coordinator); DLR, Germany; TriaGnoSys, Germany; University of Bologna, Italy; Unisat, Brazil; Provisuale, Brazil; Norintec, Norway. The financial value of the project is €990,253.

The project aims at supporting increased relationships between Latin America and Europe in the field of DVB-RCS broadband satellite communication. The main task in the project are:

- investigate needs for, and impact of satellite technologies in bridging the digital divide;
- support networking, exchange of information through workshops and symposia;
- identify relevant topics for future joint research and potentialities for deeper strategic cooperation;
- establish privileged partnerships for the joint development of DVB / satellite technologies, applications and services.

Specific trials are planned in the project, including:

- Satellite integrated links, combining radio and satellite into multi-user networks;
- applications of DVB-RCS:
  - as a unique satellite communications solution,
  - with GSM, Wi-Fi, or WiMAX access;
- applications for development of rural communities: eEducation, eMedicine, eGoverment etc.

The region of interest in the project is the Amazon, with the population of ca. 11 million people over the area of over 3 million square kilometres.

A.9.5 Pacific RICS (Rural Interconnectivity System)

Project web site: http://pacrics.net/index.php

A deployment project being implemented in 2007-2009 in the framework of the Pacific Plan digital strategy by the Secretariat of the Pacific Community, Noumea, New Caledonia, and the Pacific Islands Forum Secretariat, Suva, Fiji, supported by the Australian government with a A$2M grant. The goal of the project is to provide cheap, fast, and reliable Internet connectivity to rural and remote communities in the Pacific islands region.

The network makes use of VSAT satellite terminals and Wi-Fi local connections. There are going to be 16 "pilot sites", fully equipped by the project (a VSAT, a server, a Wi-Fi access point, a network switch, a printer, together with satellite broadband rental cost). Further 100 sites are to have a "public good" status, which means the project will cover the satellite broadband operator costs. The average speed of a satellite link in the project is in the range of 128 to 512kb/s.

A.9.6 Linking Everest

Project web site: http://www.linkingeverest.com

A project implemented in 2003 in the Khumbu Region, Nepal, by Tsering Gyaltsen with the participation of the Sagarmatha Pollution Control Committee and WorldLink Communications of Nepal. The objective of the project was to provide Internet connectivity in a Mount Everest's base camp in Nepal. The system consists of a satellite dish and a server in the Kalapathar base (at an altitude of 5450m), and a Wi-Fi link to the Everest base camp (lower, at 5300m, but without suitable ground to mount the dish on). The installation operates commercially.

A.10PROJECTS EXTENDING THE INTERNET VIA HF RADIO

This final group of projects use HF (High Frequency) radio communications in 3 – 30MHz band (the terminology is perhaps misleading these days when frequencies in the gigahertz range are used routinely, but the historical term is maintained because it is so common). HF radio is not limited to line of sight unlike higher frequency bands, and can cover long distances (hundreds of kilometres) due to reflections from the ionosphere in the upper atmosphere. The downside is that the low carrier frequency limits the available bandwidth – speeds of less than 10Kbits per second are typical, depending on conditions, with half duplex operation limiting effective speed to as low as 300 bps – but the equipment is cheap and easy to install and it does go a long way!

A.10.1PFnet (The Solomon Islands People First Network)

Project web site: http://www.peoplefirst.net.sb/general/PFnet.htm

People First Network is a rural networking project initiated in 2001 that promotes rural development by enabling affordable and sustainable rural connectivity and facilitating information exchange between stakeholders and communities across the Solomon Islands. It has established a growing rural communications system based on wireless email networking, in the HF band, and deployed with full community ownership. The project has had a number of partners, the main being the Department of Provincial Government and Constituency Development of the Solomon Islands Government, and a number of sponsors, including the United Nations Development Programme, the governments of Japan, UK, and Republic of China, the New Zealand Aid, Pan Asia Networking, the EU Micro Projects Programme, the EU Rural Fisheries Enterprise Project, the EU Solomon Islands Association of Rural Training Centres, and AusAid Community Peace and Restoration Fund.

PFnet has two key components. One is an Internet Café in Honiara (People First Internet Cafe), which allows residents of the capital city to access the Internet for writing e-mails to any location across the Solomon Islands or the Internet. They can also browse the World Wide Web or publish their own information. The Café has been operational since February 2001 and has become financially self-sufficient. The Café also serves as a training facility for a number of rural development stakeholders and the broader public.

The second and most important component of PFnet is the network of rural community e-mail stations located in remote islands across the country. The stations are usually hosted in provincial clinics, schools, or other accessible and secure public facilities. E-mail operators assist users to send and receive e-mails at a nominal cost. The stations use a simple and robust technology, consisting of a short-wave radio (already ubiquitous and well-known in the South Pacific), a low-end computer, and solar energy.

The technology is deployed with full community ownership and communal access appropriate to the culture.

On schedule, several times a day, each remote e-mail station connects to the hub station in Honiara. At such time, incoming and outgoing e-mail is transferred between the remote station and the hub, and between the hub and the Internet.

A.10.2Bushmail

Project web site: http://www.bushmail.co.za/

A commercially operating e-mail network that works via HF radio in Africa (including South Africa, Zimbabwe, Botswana, Zambia, Tanzania, and Mozambique). The nodes are powered by a 12-Volt battery, and use an HF radio, an HF modem and an antenna, which can all be installed on a do-it-yourself basis. It is extremely robust and even works during cyclones. Bushmail does not allow browsing the Internet, as it is purely just a highly economical e-mail system. The HF radio does allow voice communication as well. The Bushmail stations, fixed or mobile, connect via HF radio waves to a fixed HF radio network and through it to a gateway server and the Internet. The network is commercially operated on a flat fee basis.

A.10.3HF Radio Email

Project web site: http://www.crmf.com/content/7.html

An e-mail network operating on top of a HF radio network in Papua New Guinea, run by the Christian Radio Missionary Fellowship. The technology used is very similar to that of the Bushmail network.

A.10.4Radio E-mail

Project web site: http://www.linuxjournal.com/article/6299

Another e-mail network project started in 2002 in Guinea by Wayne Marshall for a local office of the International Rescue Committee also based on HF radio modems. The remote nodes use TCP/IP protocol over PPP on radio links to a central hub site in Conakry, which hosts a gateway to the Internet.