HELSINKI UNIVERSITY OF TECHNOLOGY

Department of Electrical and Communications Engineering

Omar Mukhtar

Design and Implementation of Bundle Protocol Stack for Delay-Tolerant Networking

Master's thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology

Supervisor: Professor Jörg Ott (Networking Laboratory)

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HELSINKI UNIVERSITY OF TECHNOLOGY Abstract of the Master’s thesis

Author:	Omar Mukhtar
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The Internet family of protocols (TCP/IP) has dominated the computer network communications; offering services such as worldwide web (WWW), file transfer (FTP), e-mail and voice-over-IP (VoIP) to the scientific, research and business communalities and to the common users. The TCP/IP protocols are also merging with other telecommunication paradigms such as 3G and 4G cellular networks. Despite of wide deployment, TCP/IP protocols are ill suited for some extreme networks because of some strict fundamental assumptions regarding end-to-end communication, built-into their architecture. These assumptions do not always hold in the emerging challenged networks such as mobile ad hoc networks, deep space communication, sensor networks, low earth orbiting (LEO) satellites etc., because of variable requirements of bandwidth, longer end-to-end delays, intermittent connectivity and higher error rates.

Delay-Tolerant Networking tries to solve some of the issues by relaxing many of the assumptions used in the TCP/IP regarding end-to-end communication. It defines an overlay network for end-to-end message delivery, which uses the Bundle protocol. In the thesis work, we have implemented the Bundle protocol stack for Symbian based smart phones to extend DTN for mobile phone based interpersonal communication and the networks formed by socializing of people. We have also designed and implemented a convergence layer for Bluetooth. The software architecture is generic, extensible and provides API for the development of customized DTN applications for mobile phones.

Keywords: Delay-Tolerant Networking, Bundle protocol, Symbian application design.

Foreword

This Masters of Science thesis was written in Networking Laboratory in Helsinki University of Technology. The thesis works was carried out the under the supervision of Professor Jörg Ott.

I would like to thank Professor Ott for giving me the opportunity to work under his supervision. He has provided invaluable inspirations, guidance and encouragement during the entire course of the thesis work. He has been very friendly and supportive; especially when the deadlines used to be close and during the reviews of this literature.

I also appreciate the support from the laboratory staff, especially to the department secretary Raija Halkilahti and her coordinator Arja Hänninen. I especially thank to the study program coordinator Mrs Anita Bisi for her support in finalizing the timely submission of the thesis.

Finally, I express my deepest gratitude to my family for their prayers and encouragement.

Omar Mukhtar

Espoo, August 8, 2006.

Table of Contents

Abbreviations and Acronyms

AA	Application Agent
API	Application Programming Interface
BGP	Border Gateway Protocol
BP	Bundle Protocol
BPA	Bundle Protocol Agent
CL	Convergence Layer
CLA	Convergence Layer Adapter
DLL	Dynamically Linked Library
DTN	Delay Tolerant Network(ing)
EGP	Exterior Gateway Protocol
Gbps	Giga bits per second
GPRS	General Packet Radio Systems
GUI	Graphical User Interface
HIP	Host Identity Protocol
ID	Identifier
IP	Internet Protocol
IPC	Inter-Process Communication
IPN	InterPlaNetary
IPv4	IP version 4
IPv6	IP version 6
kbps	kilo bits per second
LAN	Local Area Network
MANET	Mobile Ad hoc Network
Mbps	Mega bits per second
MFC	Microsoft Foundation Classes
MMS	Multimedia Messaging Service
MVC	Model View Controller
OOP	Object Oriented Programming

OS	Operating System
PAN	Personal Area Network
PDA	Personal Digital Assistant
PPP	Point-to-Point Protocol
QoS	Quality of Service
RF	Radio Frequency
RIP	Routing Information Protocol
SDK	Software Development Kit
SDNV	Self-Delimiting Numeric Value
SDP	Service Discovery Protocol
SMS	Short Message Service
SPP	Serial Port Profile
STL	Standard Template Library
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UI	User Interface
UML	Unified Modeling Language
URI	Uniform Resource Identifier
URL	Uniform Resource Locator
UUID	Universally Unique ID
VoIP	Voice over IP
WLAN	Wireless LAN
WTCP	Wireless TCP

INTRODUCTION 1

The first chapter provides an introduction, background and motivation of the thesis work. It starts with a short analysis of success and failures of conventional and most commonly deployed communication network, the Internet and its family of protocols. The next section presents a brief account of history, background and introduction of Delay-Tolerant Networking. Subsequent section discusses motivation and outline of this thesis work. In the last section, an outline of material, presented in this document, is provided.

1.1. Internet Protocols – Pros and Cons

During past two decades, the Internet has become widely deployed with extreme popularity of its services such as e-mail, web and now VoIP. It has greatly influenced other communication networks, to an extent that conventional circuit-switched networks are converging towards packet-based services, e.g. 3G and 4G. The Internet family of protocols, also known as TCP/IP protocol suite, is becoming the basis of numerous kinds of applications and inter-networks. In fact, most of today's PANs, MANs and WANs follow an hour-glass paradigm, with IP protocol at the heart and a large number of different and diverse application level protocols and physical layers at the edges [COMER], as shown in Figure 1.

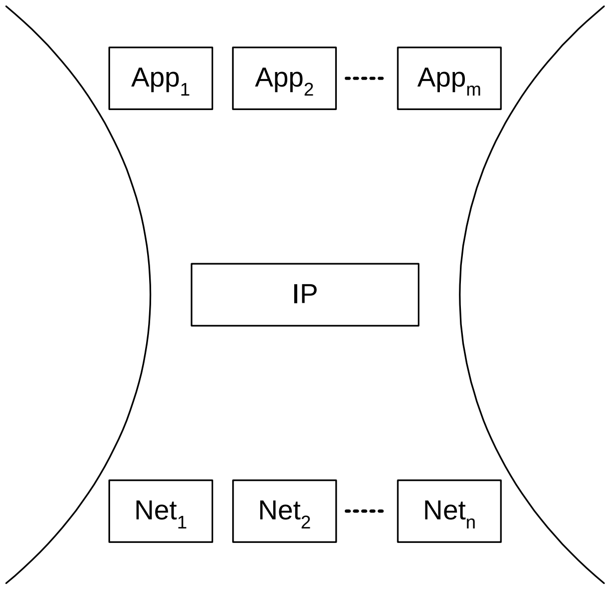


Figure 1. Hour-Glass Paradigm

This paradigm has also enabled internetworking of several heterogeneous networks, at IP layer. IP can be used directly at network layer or can run on top of other network layer protocols. One such example is Bluetooth LAN Access profile [BRAY], as shown in Figure 2.

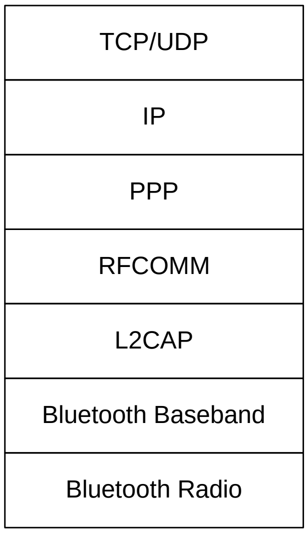


Figure 2. Bluetooth stack for LAN Access Profile

Despite of success and wide deployment of Internet family of protocols, the shortcomings of TCP/IP are being observed by researchers as new heterogeneous networks and communication paradigms are emerging, such as wireless networks, PANs, MANETs, 3G and 4G cellular technologies, and seamless ubiquitous and pervasive connectivity [BALA97].. The Internet and TCP/IP protocols were built using some fundamental assumptions for underlying network architecture, which do not hold when TCP/IP protocols are adapted in emerging networks and communication paradigms. Researchers have proposed different solutions to fix some of the problem, but mainly it turns out to be 'one solution for one problem' model. Some issues and proposed solutions as described below.

TCP/IP protocols assume end-to-end connectivity, low error rates, small end-to-end delays, and many algorithms are built over these assumptions. With the advent of mobile wireless networks in particular, the flaws posed by these assumption becomes evident. For example, TCP slows down the transmission assuming congestion in the network rather than loss of packets. In wireless networks, on the contrary, error rates are quite high and TCP throughput is degraded significantly, because TCP should transmit more vigorously. Researchers proposed some solutions to improve the performance of TCP, but the problem cannot be eliminated entirely because of end-to-end connectivity model

[TANENBAUM] [BPSK97]. With the growth in usage of Internet, wireless networks and cellular networks, mobility and multi-homing issues have become evident as well. Mobile devices such as laptops, smart-phones, PDAs have become sophisticated computing and communication machines, often equipped with multiple communication interfaces. A single TCP connection maps to one IP address for an entire session, and hence multiple communication links each identified by a different IP address cannot be used for a single session, taking advantages of multi-homing or vertical handovers. Mobile IP [RFC2002] and Host Identity Protocol (HIP) [RFC4423] propose independent solutions for such problems. Routing between IP and non-IP networks has also been investigated especially for VoIP and circuit-switched telephony, and solutions such as ENUM [RFC2916] have been proposed.

With the advent of wireless and mobile networks and devices, the demand for ubiquitous and pervasive connectivity is also increasing. Despite efforts to increase coverage area of network and communication services, studies and research efforts indicate that intermittent connectivity is becoming a rule rather than an exception [OTT04] [SESB05] [BAIG06]. Intermittent connectivity is also evident in sparse ad hoc networks. TCP/IP protocols fail as end-to-end model breaks again.

Besides all the research efforts mentioned above to *mend* the Internet, research is going on to design new communication paradigms that do not follow some of the basic assumptions strictly, upon which Internet TCP/IP protocols were built. One such effort is *delay tolerant networking,* which aims at a variety of challenged, extreme and stressed networks.

1.2. Delay Tolerant Networking

As described in last section, existing Internet protocols do not work well in some environments, due to some strict fundamental assumptions built-into the architecture. Delay-tolerant networking is an emerging communication paradigm that tries to solve some of the issues described earlier. The DTN architecture has conceived to relax most of those assumptions. Briefly, it relaxes end-to-end error control, continuous connectivity, and very low propagation delays. It defines a layer-agnostic interconnection of heterogeneous (IP and non-IP) networks by introducing a new internetworking layer with relaxed requirements. DTN targets a broad range of challenged, stressed and extreme networks, which cannot maintain end-to-end connectivity, have longer delays, or infrequent interrupted connections. Such networks include deep space communication, sensors-based network, satellite connections with periodic connectivity, sparse mobile ad hoc networks etc. The major differences between these emerging networks and conventional Internet are discussed in [BURL03] and [FALL03], and are summarized in Table 1.

Table 1. Comparison of conventional Internet and emerging heterogeneous inter-networks

Conventional TCP/IP Internet	**Emerging Heterogeneous Inter-networks**
Smaller signal propagation delays, order of milliseconds, because of high-speed LANs and Optic fibers.	Varied signal propagation delays, order of up to several minutes, because of wireless links, satellite channels.
High data rates, from a few Mbps to several Gbps, in access networks and in backbones.	Varied data rates from a few kbps, as in PANs, to several Mbps, as in WLANs.
Often bidirectional communication on each connection, because of same protocol suite and similar policies across the connection over Internet.	Possibly time-disjoint periods for transmission and reception, due to multi-path links and different policies among differently managed dissimilar networks.
Continuous end-to-end connectivity.	Might be intermittent, scheduled or opportunistic connectivity in dissimilar heterogeneous environment.
Low end-to-end error rates, due to reliable physical links, and error correction at several layers of protocol stack.	High error rates, due to wireless links, dissimilar protocol stacks etc.
Homogeneous protocols used at network	A new paradigm of heterogeneous

and transport layers across the end-to-end path; all nodes including end stations support TCP/IP stack.	networks, protocol families and management policies.
Single route selection between end nodes for acceptable communication performance.	Heterogeneous environment may not offer a single bi-directional route.
Identical naming convention for routing and delivery.	Not possible among dissimilar networks.
Poor recovery mechanism in case of temporary connection loss or hardware failures/reboots. End-to-end communication session needs to be re-established.	End-to-end connection setup among dissimilar and disjoint networks and intermittent connections may not be viable from practical point of view, due to less time & cost efficiency.
Uniform routing schemes across end-to-end path (RIP. BGP, EGP).	Complex disparate routing schemes (epidemic routing, flooding, statistical, multi-path routing etc.) used in different regions of dissimilar networks across end-to-end path.

1.3. Background and Related Work

This section describes the history and background of research efforts that have led to the evolution of DTN and associated family of protocols. It also discusses other research efforts with similar goals, which now can be combined with DTN. Initially, the research efforts for Interplanetary Internet became the most fundamental basis for DTN architecture and protocol suite. Later on, other research areas with similar problem set were also included as requirement specifications. This resulted in a common protocol suite for DTN, now known as bundle protocol. The research is going on under IRTF umbrella.

1.3.1. InterPlaNetary (IPN) Internet

The history of DTN architecture dates back to late 1990’s when NASA started an effort to investigate an IP-like protocol suite for communication across the solar system. This research effort was termed as Interplanetary Internet, which aimed at an open, layered and globally interoperable architecture supporting fairly long round trip delays between the planets and astronomical equipments. During 1990’s, Internet has already dominated being the biggest terrestrial communications network. Internet has been mostly wired to high-speed fiber backbone, very low delays and negligible error rates. The backbone offers symmetric data channels and is always-connected. IPN internet has to support both wired (fiber, cable, copper) and wireless (satellites, WLAN, MANETs etc.) networks with a number of challenging constraints, to become future’s communication network,. These include significant delays, higher error rates, power and bandwidth limitations, irregular connectivity and asymmetric channels [BURL03] [JACK05].

1.3.2. Disconnected MANETs

As practical applications of ad hoc networks are being investigated, new kinds of mobile ad hoc networks are emerging and being deployed, termed as MANETs. These have different sets of practical constraints, physical limitations, performance requirements and data-delivery goals. They also use divergent set of protocols. Such MANETs also cannot fulfill the stringent protocol requirements of TCP/IP family. Some details of such MANETs are given below.

Sensornets

Sensor networks, also known as sensornets, is an ongoing research area in ad hoc networks. Sensornets may have a sparse distribution of network nodes and data-retrieving occasions are rare. Examples of such networks are: ZebraNet for wildlife monitoring

[JUANG02], whales and seals for water monitoring, data mules and message ferries [ZHAO05] etc.

Disjoint Information Resource Access Networks

Some experimental networks have been deployed in remote areas to access information resources, such as web and e-mail, where deployment of a permanent infrastructure is not feasible. Data-nodes arrive from time to time to form an ad hoc network and provide intermittent connectivity. Examples are Daknet [PENT04] in Cambodia and India, SNC in Lapland [SNC], Wizzy in South Africa. Conventional TCP/IP protocols are not feasible in such ad hoc infrastructure also.

1.3.3. Nomadic Networks

In order to access Internet via WLAN, while in a vehicle speeding on a long highway, conventional infrastructure cannot work; other access networks (UMTS, satellite) being too expensive or unavailable. There may be established some hot-spots along the way but the intermittent connectivity is too short to work with conventional IP protocols based communication for e-mail exchange, web-browsing etc. Hence conventional Internet protocols fails here again. Drive-Thru Internet is an effort in similar directions in order to define a non-conventional disruption tolerant architecture [OTT04]. Other efforts in similar directions are DieselNet [BURG06], FleetNet [LOC03], Network-On-Wheels [LEIG06] and in [SCH05].

1.4. Motivation of the Thesis Work

With increasing penetration of smart mobile phones and PDAs, a new kind of multi-hop mobile ad hoc networking architecture is under investigation, termed as Social-Networks. These personal devices are capable of wireless communications, often supporting more than one link-layer technology, and people tend to always carry these devices with them. This results in mobile ad hoc network as people meet at some place. The topology of such mobile ad hoc networks is based on socialization behavior of the people, hence termed as Social Networks [NEW04]. This is an on-going research area and new architectures for communication, mobility modeling and routing are being investigated by researchers [MUS06] [HUI05].

The motivation behind this thesis work is to implement and extend the DTN architecture to smart mobile phones based MANETs. In particular, this work intends to provide a DTN software framework, which could be used to investigate and explore DTN applications in mobile ad hoc networks formed by smart phones. This could also help investigating social networks formed by such mobile ad hoc networking.

Another interesting aspect of this research work is to provide a framework for smart phone applications, which could effectively be configured to use multiple communication links and networks in a ubiquitous fashion. Thus some of human-input responsibilities, such as selection and configuration of multiple links and communication channels; user-interaction in order to complete a communication operation, can be taken up by communication applications themselves. This will hide such complex operations from common users, enabling them performing data communication operations, such as file transfer; web browsing; exchanging e-mails etc., seamlessly and more effectively in disruptive, intermittent environments, like Drive-Thru Internet, social networks etc., which is not possible with conventional TCP/IP based architectures.

Symbian OS based smart mobile phones have been selected for this purpose. Symbian OS has significant advantages over other peer technologies available such as:

- Symbian-based smart mobile phones have more than one on-board link-layer technologies available; like GPRS, MMS, WLAN, Infrared, and Bluetooth.
- Symbian OS provides a generic abstraction for underlying communication infrastructure, including telephony services, with a rich set of APIs.

- Symbian OS offers a broad range of APIs to perform many primitive tasks for handling communications, media and data, efficiently.
- Symbian-based phones dominate the smart mobile phones market [SYMB06].
- Good tools and SDKs are available to write sophisticated and larger software of release quality.
- Using native programming language for Symbian provides the advantage of integrating protocol stack into the OS, in later stages.

1.4.1. Similar Work

DTN is an on-going research area. The specifications are still maturing. Many topics have gathered intention of researchers including routing, naming-conventions, user-level applications, link-layer convergence protocols etc. There is a reference implementation available on the research group's web page, for Linux. Although that has been ported on some PDAs like Nokia 770 tablet[1], yet there's no known implementation for smart mobile phones explicitly. There is a Java based simulator and Java implementation of DTN [DTNRG]. There is also an implementation for TinyOS [PATRA04].

1.5. Outline of Thesis Work

An implementation of the Bundle protocol for Symbian based mobile phones has been carried out during this thesis work. Interoperability testing has been performed against reference implementation.

A brief background and motivation of this thesis work has been given in this introductory chapter. Next chapters describe DTN architecture and associated family of protocols in detail. A brief overview of Symbian OS and application design is also given, in order to

[1] This porting work has also been carried out in Networking Lab Helsinki University of Technology by the same research group.

facilitate extension of this work in future. Also a detailed design description is provided in subsequent chapters. Finally, an example scenario is explained and demonstrated. Appendices contain more details about design, and provide guidelines in order to build, configure and use this implementation for further research, development and testing.

1.6. Summary

In this chapter, introduction and motivation to the thesis work was presented. A brief review of related work was also given. DTN is an emerging communication paradigm for challenged networks such as mobile ad hoc networks and other intermittent networking scenarios. The thesis work aims at design an implementation of DTN applications for mobile phones in order to provide a software framework for smart phones based inter-personal communication over social networks. Next chapter discusses DTN architecture and protocols in detail.

DTN – ARCHITECTURE AND PROTOCOL SPECIFICATIONS 2

This chapter starts with the description of architectural principles of Delay-Tolerant Networking. Subsequent sections discuss the semantics of different DTN-family protocols.

2.1. DTN Architecture

As described in Chapter 1, the motivation behind DTN is to embrace unusual, extreme and challenged emerging networks. Such networks may have occasional or scheduled intermittent connectivity, long delays, and may comprise a divergent set of protocol families. End-to-end communication across such networks using the IP family of protocols cannot be achieved due to various reasons described in previous chapter.

DTN is an overlay network of DTN nodes (nodes that participate in DTN) on top of existing internets. DTN defines an abstraction layer on top of transport layers and below application layers, called *bundle* layer. Although, some of the responsibilities, such as session management and synchronization on connection break ups [TANENBAUM], makes it , analogous to Session layer in OSI model. Nevertheless, it is a full-fledged internetworking layer, responsible for routing the data from source to destination. DTN neither defines any fixed-length data units nor does put any upper or lower bounds on application data unit size. It talks about messages, which a user wants to deliver to other end. Bundle layer is responsible for end-to-end delivery mechanism of messages, called virtual message forwarding [DTNARCH05].

As mentioned earlier, IPN formed the basis for DTN. The research efforts under IPNSig led to DTN architecture, termed initially as Bundle Space, which defined core requirements for IPN design. These include heterogeneous networks, long delays, short contacts (possibly one-way), data being too expensive for end-to-end retransmissions and smaller transaction size matching available bandwidth-delay product [IPN99]. This led to key design decisions for IPN:

- Deployment of an overlay network on top of existing internets, including Internet, forming networks of internets with gateways and relay nodes to bridge low latency environments with those with higher one.
- Late binding of names to addresses; routing between internets is based on names. Actual address translation may be performed very late in the overlay-network.
- Relaying of data between heterogeneous environments depends upon intermediate nodes. To cope with longer delays, a store-and-forward model (similar to e-mail) is suitable.
- Along with conventional proactive control of transaction size, reactive control can lead to performance in disruptive environment.

2.1.1. Key Architectural Principles

The DTN Research Group refined the architectural principles further to incorporate all kinds of extreme challenged and disruptive networks. They also elaborate on the differences between delay-tolerant networking and convention inter-networking models, especially the Internet [DTNARC05]. Some of the key points are summarized below:

Virtual Message Switching

Application data units are structured as variable-length messages, instead of limited size packets. This abstraction is closer to user's perspective of communication of data. A message can be a huge file or a short e-mail message.

The communication abstraction of messages can also help enhance the ability of network to make better decisions of routing, scheduling and path selection.

Naming and Addressing Mechanism: End-Point IDs

A generic naming syntax augmented with late binding to enhance interoperability between heterogeneous internets. Late binding means that actual name-to-address translation is carried out late in the delivery process. This concept does not require an end-to-end connectivity prior to start of communication. The other advantage is that routing between heterogeneous networks can be performed based on names, and hence no address-to-address mapping mechanism is required prior to start of communication, as opposed to DNS resolution in Internet.

Store and Forward Model

DTN uses a store-and-forward model like e-mail system. This breaks down the requirement of having an end-to-end always connected path. Messages can be stored in the network for longer periods. To increase reliability and to cope with hardware failures, persistent storage is recommended. Whenever a scheduled or opportunistic link becomes available, the network can deliver the message over that. Hence end-to-end path connectivity is not required from the source node's perspective.

Non-conversational Asynchronous Communication

DTN uses asynchronous, minimal conversational model that differs from conventional query/response model of communication. Conventional services using the TCP/IP family of protocols use end-to-end query/response model messages. For example FTP can use up to 10 end-to-end transactions exchanged for a simple file transfer (requests and responses for connection, log-on, transfer mode, directory services, file exchange, log-off etc.). In an extreme environment of networking, including possibilities of unidirectional links, such conversational models cannot work. DTN suggests a non-conversational asynchronous model. So applications should be designed or adopted in a way to minimize the end-to-end transactions, using larger self-contained messages.

Bundling

DTN suggests combining all application level data and metadata to form a single *bundled* message, in order to minimize end-to-end transactions. For example, all FTP metadata (login-name, password, file name(s) etc.) and actual data (file(s) if applicable) can be sent to FTP server, bundled in one message. This is why DTN layer in protocol stack is called Bundle Layer.

Routing

Routing in DTN networks is an area under research and has not been fully defined as yet. Being in a heterogeneous environment with a divergent set of protocol families, the possibilities of routing algorithm that can be used efficiently are numerous. DTN nodes can deal with different types of communication links available, which may have different requirements of delays, bandwidth, availability etc. Links, or as termed as *contacts* in [DTNARCH05] can be:

- Persistent (always-connected links like DSL)
- On-demand (like persistent but require initial setup, like dial-up connections)

- Scheduled (an intermittent link available periodically for some time, like deep-space satellite connection)
- Opportunistic (an intermittent link formed unexpectedly when the nodes become available in the vicinity of each other, like a visitor in a shop etc.)
- Predicted (an intermittent link which is likely to be in a certain locality due to previous known history or by other measures such as scheduled transport vehicles or planetary dynamics)

With such a divergent set of links, the routing graph does not remain a simpler fully connected one (like in IP networks), rather routing information spans over multiple graphs possibly not fully connected. All this requires more sophisticated routing algorithms with a bunch of matrices to decide from (including but not limited to capacity, time and duration of link availability, probability of getting in contact with other network or nodes). In contrast with the Internet routers, a Bundle node can defer the routing of a bundle if a better link is known to be available in the near future. Further details can be seen from [LEG05] and [LIND06].

2.2. Network Hierarchy and Protocol Stack

As described earlier in introductory sections, DTN defines an overlay network, which works on top of transport layers (or equivalent) and below application layer. The protocol used by DTN nodes is called *Bundle protocol*, and hence the layer it works at is termed as bundle layer. The Bundle protocol is layer-agnostic and hence can inter-connect heterogeneous internets. The nodes that participate in DTN, running bundle protocol, can be configured in a number of ways including hosts, gateways, routers, proxies etc. An example topology is described in Figure 3.

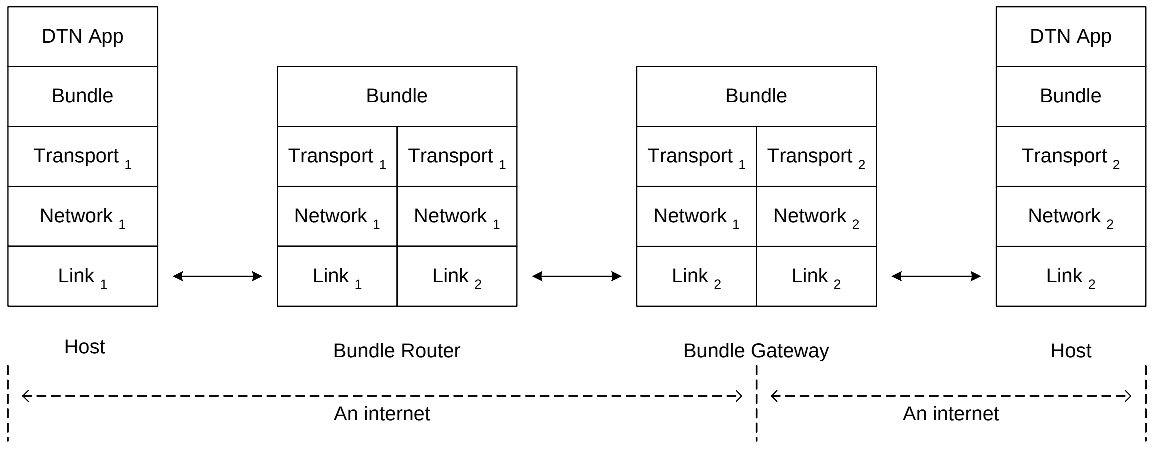


Figure 3. DTN network hierarchy

The Bundle layer itself can be divided into 3 logical sub-layers, defined by Bundle protocol specifications, as illustrated in Figure 4. The core functionality of Bundle protocol (BP) is implemented as *Bundle Protocol Agent*. Depending upon application layer services offered, an *Application Agent* entity could provide interfaces to upper layers. It can also be used for configuration, user interactions and any policy-based settings for the bundle layer. It can be simple enough to configure the bundle layer only, or complex enough to implement logic for registrations and other services for applications using BP.

One or more *Convergence Layers* provide an abstraction from under-lying transport and network technologies, thus making Bundle protocol agent independent of lower layer services. DTN defines the possibilities of a number of convergence layers used; including but not limited to TCP, UDP, Bluetooth, ATM and File-based.

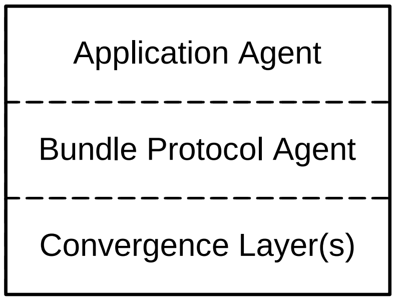


Figure 4. Bundle Layer Anatomy

2.3. DTN Family of Protocols

The DTN research group has defined a basic bundling protocol. There are other drafts produced by researchers for convergence layers, routing and security protocols. In the following sub-section, a general notation and terminology used throughout in those documents is described. Later on, the semantics of basic protocols are discussed.

2.3.1. Protocol Design Principles

DTN has defined some new general terminologies and concepts used in the design of DTN family of protocols, which are presented below.

End-point Identifiers

As described earlier, DTN uses a general naming scheme to identify nodes. These names are called End-point Identifiers or EIDs. EID's are based on URI schemes with the syntax:

<*scheme name*> **:** <*scheme specific part or SSP*>

Any of the standard URI schemes can be used and DTN also defines its own scheme, denoted as "*dtn*". A special case is *dtn:none*. Since DTN employs the concept of *late binding*, EIDs are not translated to addresses in the very beginning, in contrast to the Internet protocols. Instead routing is performed based on EIDs directly.

EIDs are also a unique concept in a way that a node can be member or multiple EIDs and one EID can be associated with multiple nodes. Thus routing becomes more complex, and this is an on-going research area. A *singleton* EID is the one, which is associated with a single node only. Some of the protocol semantics, such as custody transfer, are only defined for singleton EIDs only. The Bundle protocol specifications state that a Bundle node must be member of at least one singleton EID.

Bundles

DTN payloads are in the form of messages, formally called *Bundles*. As explained earlier, DTN suggests combining all application layer data and associated meta-data into one message called bundle. Bundles can be of variable sizes.

Custody Transfer

As described above, DTN uses store-and-forward operations, which are different from conventional store-and-forward mechanism of the Internet. The Internet routers store packets for a very short interval of time directly proportional to queuing and transmission delays, and discard them if no route to the destination is available. By definition, DTN has to keep messages or bundles in queues for longer time. DTN also strongly suggests keeping queued bundles in some form of persistent storage. This helps coping hardware failures or device startups.

Since there may not be an end-to-end path in DTN networks, conventional end-to-end reliability mechanisms like retransmissions cannot work. DTN moves the responsibility of reliable delivery from source node to other DTN nodes deeper in the network. This is achieved by moving a copy of message ‘closer’ to destination (in terms of some routing metric), and termed as *custody transfer*. Hence, retransmission related responsibilities move away from source node gradually, breaking the requirement of end-to-end retransmissions, as done in the Internet.

The node, which currently has the custody of bundle, is called *custodian* of the bundle. When a node gains responsibility of retransmissions of bundles, it *accepts custody*; when it discharges, it *releases custody*. Not all the DTN nodes in the network are required to accept custody, so it is not a strictly hop-by-hop mechanism. The bundle includes a request for its custody transfer, so it is an optional mechanism. A node is free to choose accepting the custody for a bundle, depending upon some policy metrics.

Administrative Records

The basic Bundle protocol defines unacknowledged, prioritized but not guaranteed, message delivery mechanism. For reliability and diagnostic purposes, it defines two kinds of special messages.

Bundle Status Reports, or BSRs, are informational and diagnostic bundle messages, that provide information how a bundle is progressing through the network. It is analogous to ICMP messages of Internet, with a difference that ICMP messages are sent back to source node. Where as BSRs are sent to a special node identified by *Report-to* EID, which may or may not be same as *Source* EID. Another difference is that ICMP messages report only diagnostic or error reporting, whereas BSRs are used for positive acknowledgements as well.

Custody Signals are bundle messages, which carry information about custody-acceptance (success or failure) status by generating nodes. These are sent to current custodian of the bundle. If custody was accepted successfully, the generating node becomes the current custodian and upon reception of the custody signal, the previous custodian releases the custody.

Fragmentation

DTN allows fragmentation and reassembly of bundles in order to utilize link capacity effectively. BPA can fragmentation bundles *proactively* into multiple smaller bundles if link capacity related information is known a priori or predictable.

In some cases, if a bundle is partially transmitted to next hop and the two peer nodes detect this, the transmitting node may *reactively* fragment the remaining portion into a new bundle. Similarly, the receiving node may modify the incoming portion of bundle to make it a fragment. Reactive fragmentation is an optional capability because it depends upon services offered by underlying convergence layers, whether they provide mechanism for partial transfers.

Like in IP, fragmentation is done on only one 'level', i.e. a bundle is fragmented into two to make new bundles. If needed, those new bundles can be fragmented further. This process is loosely analogous to *mitosis* process of biological cell division, in which a cell is divided into two. Also like IP, reassembly is performed at destination node only.

Class of Service

DTN defines a coarse-grained postal-style prioritized delivery services. The quality of service metrics are different from conventional Internet style traffic, as DTN traffic is generally not interactive, may be one way, and obviously with least timely delivery requirements. There are 3 priority classes defined in DTN architecture (priority low to high): *Bulk*, *Normal* and *Expedited*. DTN nodes should transfer bundles with high priority first. At the moment, there is no well-defined quality of service mechanism in DTN.

Self Delimiting Numeric Values

DTN specifications define protocol formats in such a way that it can be easily modified in future. One fundamental concept is how to represent fields that contain numbers denoting lengths and sizes. DTN defines a new scheme for number representation that is similar to ASN.1 encoding. This is termed as *Self Delimiting Numeric Values* or SDNVs, and as name implies, they can be of variable length. Each byte representing the number field contains a special marker bit, so that last byte can be detected. Hence with a small overhead of total marker bits, greater flexibility is achieved. Hence the any arbitrary length of a field can be described without changing the header in future. DTN architecture recommends using SDNVs in all relevant protocols, which have been or could be defined. For details see [BPSPEC04].

DTN Time Stamps

DTN also defines a new notation for representing time stamps. Time stamps are 64-bit fields, with first 32-bits (in network byte order) contain number of seconds elapsed since start of year 2000. The remaining 32-bits contain number of nanoseconds since start of current second at the time of creating time stamp. All relevant protocols must use this notation to describe any time-related information.

2.3.2. Bundle Protocol

The primary DTN protocol running at Bundle layer is called Bundle protocol. Bundle protocol defines semantics, formats and sequences of protocol messages in order to carry out basic bundle layer services, including:

- Asynchronous message transfer
- Generation of Bundle Status Reports messages
- Custody transfer related signaling

The Bundle protocol design is based upon the architectural and protocol design principles described in the earlier sections. It defines a primary bundle message header, along with a payload header and administrative records' header formats [BPSPEC04]. The Bundle protocol permits use of additional extension headers specified by supplementary protocol specification documents. Some important fields of these headers are described here; for details see [BPSPEC05].

Primary Bundle Header

This header[2] contains the basic information required to route the bundle to destination. It is included in each and every type of bundle including administrative records. The format of the primary header is illustrated in Figure 5 and important fields are explained below. For details, refer [BPSPEC04]. Note that the length fields use SDNVs and can be of variable sizes. The format shown in figure is just for the convenience of representation.

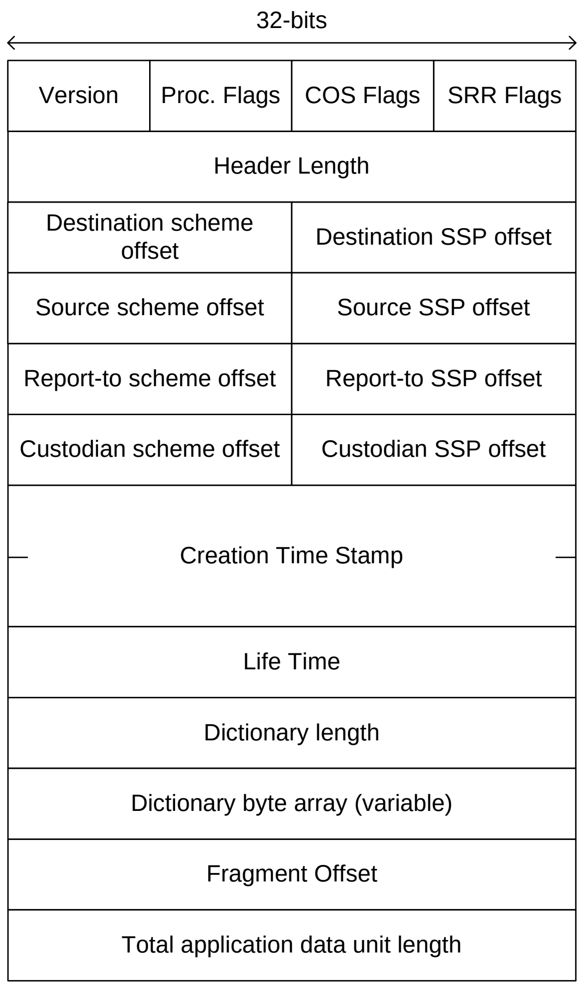


Figure 5. Primary bundle header

[2] A discussion is going on within DTN research group about referring 'header' as 'block'. But the current documents use the old notation, so we also adhere to that.

The VERSION field describes protocol version used. Currently only 0x04 is defined.

FLAGS indicate directions to process and interpret the fields of the headers. They also describe class of service and status report generation options.

HEADER LENGTH indicates length of remaining header, using SDNV notation.

OFFSET values indicate EID offsets within a special buffer containing all EIDs used by the headers. A bundle message must refer to source and destination EIDs and may refer to report-to node and custodian node EIDs.

CREATION TIMESTAMP indicates creation of bundle in terms of DTN time.

LIFE TIME indicates interval in seconds a bundle can exist in the network at the most, with respect to creation time. After that is must be deleted from network.

DICTIONARY LENGTH & BYTE ARRAY fields define a special buffer in the header containing all EIDs used in the primary header. The advantage of this approach is that if an EID is used more than once, it would occur only once in the dictionary. Different header fields can refer to an EID using offset values within the dictionary. The length of this dictionary is also described in SDNV notation and hence can vary without changing the fields of header in future. Another advantage on this approach is that variable size EIDs can be used, as opposed to fixed 32-bit IPv4 or 128-bit IPv6 addresses.

FRAGMENT OFFSET & TOTOAL ADU LENGTH are optional fields that denote the offset of fragment in aggregated application data payload, and the length of aggregated application data payload, if the bundle is a fragment.

Bundle Payload Header

This simple header describes the type of payload (which is currently always 0x01), flags indication directions to process the header and a length field in SDNV notation to describe the length of payload. The format is illustrated in Figure 6. The length fields use SDNVs and can be of variable sizes. The format shown in figure is just for the convenience of representation. Additional protocol documents can define more payload header types such as routing information, security headers. At the moment, payload can either be application level data or an administrative record header.

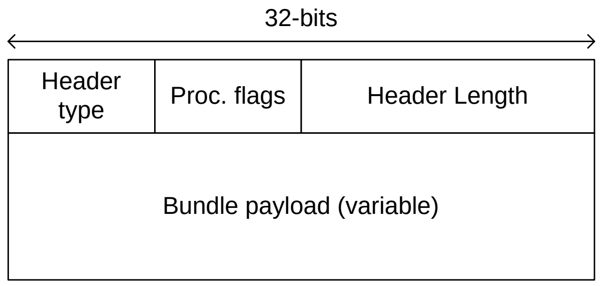


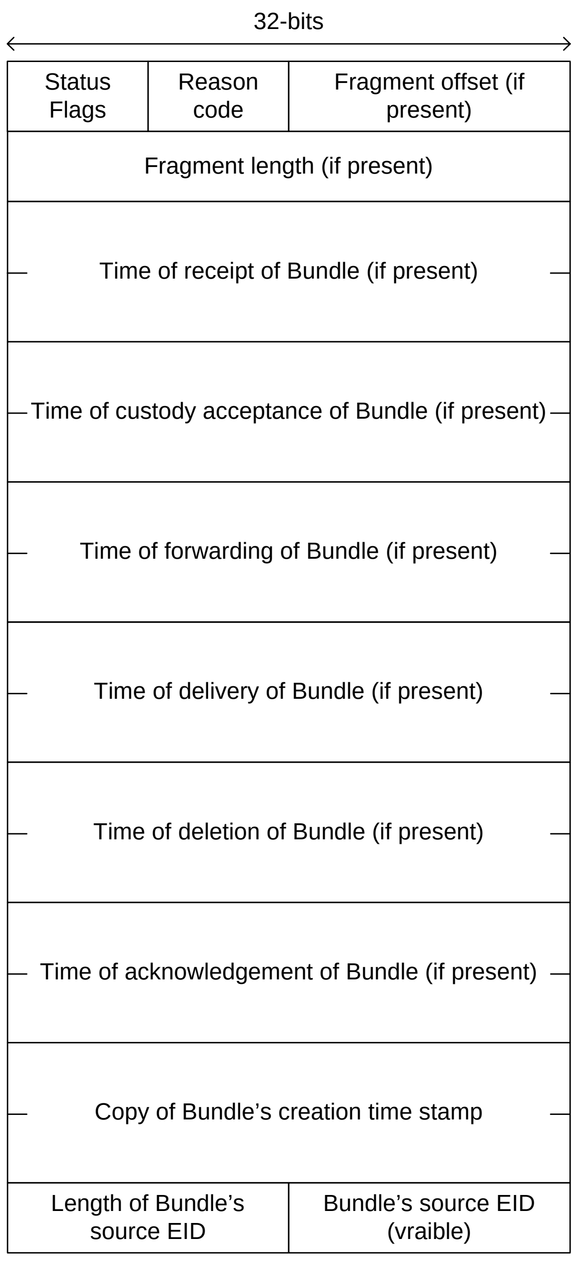
Figure 6. Bundle payload header

Bundle Status Report and Custody Signal Formats

If the primary header's processing flag indicate that the bundle payload is an administrative record then the payload is processed according to a specific format. The first byte describes the type of administrative record (status report or custody signal) and some optional flags for additional information describing directions to interpret remaining fields.

If the administrative record is a status report then the remaining fields describe type(s) of status report and the time when the event took place, for which the report was generated, in DTN timestamp format. One administrative record message can aggregate multiple reports for the same bundle, thus reducing network traffic. The format is shown in Figure

7. The length fields use SDNVs and can be of variable sizes. The format shown in figure is just for the convenience of representation.



32-bits
Status Flags
Reason code
Fragment offset (if present)
Fragment length (if present)
Time of receipt of Bundle (if present)
Time of custody acceptance of Bundle (if present)
Time of forwarding of Bundle (if present)
Time of delivery of Bundle (if present)
Time of deletion of Bundle (if present)
Time of acknowledgement of Bundle (if present)
Copy of Bundle's creation time stamp
Length of Bundle's source EID
Bundle's source EID (vraible)

Figure 7. Bundle status report format

If the administrative record is a custody-signal message then it just contains the information regarding success or failure of the custody transfer operation, along with an optional reason. It also describes the time when the signal was generated using DTN time notation. The format is shown in Figure 8. The length fields use SDNVs and can be of variable sizes. The format shown in figure is just for the convenience of representation.

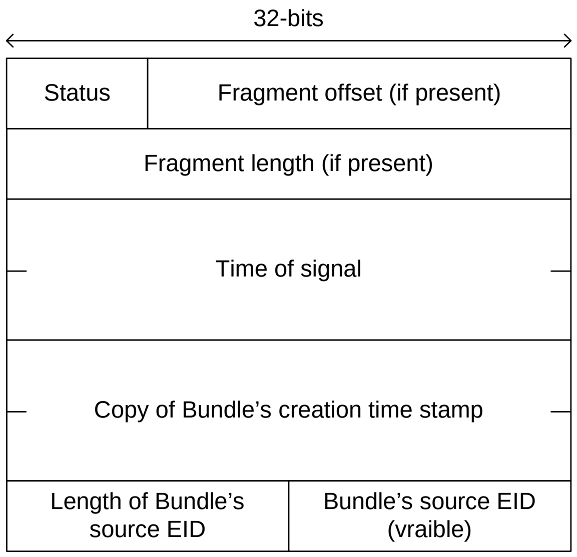

32-bits
Status
Fragment offset (if present)
Fragment length (if present)
Time of signal
Copy of Bundle's creation time stamp
Length of Bundle's source EID
Bundle's source EID (vraible)

Figure 8. Bundle custody signal format

A bundle can be identified uniquely by its source EID, creation timestamp and fragmentation offset and length fields if bundle was a fragment. Administrative record messages also contain a copy of the fields taken from the corresponding bundle, the very record relates to.

2.3.3. Convergence Layer Protocols

Although the Bundle architecture or protocol specifications do not describe any specific protocols for convergence layers, they do summarize some basic principles and services that should be provided by convergence layers protocols [BPSPEC04]. Most fundamentally, Bundle Protocol Agent entity expects from underlying convergence layers to perform the following tasks reliably on behalf of it:

- Transmission of bundles, entirely or partially; notification of delivery status.

- Reception of bundles, entirely or partially; notification of reception status.
- Connection management (establishment, teardown, error detection etc.) specific to underlying transport technology.

Convergence layer protocol operations can be as simple as connection management and message boundary marking in case of a reliable underlying transport like TCP. On the other hand for a connection-less unreliable transport protocol, like UDP, a convergence layer protocol should implement its own reliable delivery mechanism.

There is an unofficial release of a draft document for TCP (available in the release package of reference implementation code), which in principle can be use for any connection-oriented stream protocol. The same protocol has been adapted for Bluetooth convergence layer.

TCP Convergence Layer Protocol

Since TCP is a connection-oriented reliable transport protocol, this convergence layer has to perform only two basic tasks:

- Marking message boundaries with delimiters, as TCP is stream-oriented protocol, it does not define and boundaries for application layer data units. So convergence layer must define its own mechanism to extract segmented or aggregated messages obtained from the contiguous stream.
- Detection of connection and transmission status. Although TCP provides a reliable delivery mechanism, it does not offer any services for upper layer to acknowledge delivery of data to the application running on peer node. Applications using TCP must devise their own mechanism to provide precise information regarding data delivery, connection teardown etc. Applications are not precisely notified about TCP connection failures in some scenarios. To cope such issues, the TCP CLA exchanges application level acknowledgements and regular keep-alive messages between the peers of a connection.

A draft has been proposed describing TCP convergence layer [TCPCL]. It defines TCP CL level messages with short headers and delimiters to mark message boundaries. In addition to that, it defines mechanisms for graceful connection establishment and teardown by sending messages and using timers.

The TCP CL protocol defines a connection to be a unidirectional[3] link in terms of data transfer direction. Since a TCP connection itself is a bi-directional link, TCP CL protocol level messages can be sent in either direction over same connection. The peer, which initiates a connection, is termed as ‘connection-initiator’ and is responsible for deciding direction of connection. A connection-initiator can be a receiver. This helps in situation when the node is behind a NAT (firewall), so it can establish a connection to some node outside NAT (firewall). Hence no NAT (firewall) traversal mechanism is required.

Following is description of basic message formats defined by protocol.

CONTACT HEADER message is sent upon connection establishment, by both the peers. It contains connection parameters, which define the flow of information over the connection. After preamble, a 4-byte constant representing ASCII codes of letters in string “dtn!”, a version field indicates current version of protocol as 2. Flags identify connection direction and request for application level acknowledgements. An interval, in seconds, is offered for keep-alive message exchange.

There is a 32-bit number denoting partial acknowledgement length, which enables the receiver to send regular acknowledgements during the coarse of bundle transmission. This feature is useful to detect connection drop earlier, and is particularly useful if bundle is quite large. In case of partial transfer of a bundle, if the connection drops, the BP layer can fragment the bundle reactively to send remaining portion.

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[3] This is going to be changed in the near future.

BUNDLE DATA message starts with a message type code and a 32-bit bundle ID. It also contains the length of the bundle in SDNV notation. After that, the actual bundle is sent as payload of this message. In this way, the receiver can identify the start and the end of bundle.

BUNDLE ACKNOWLEDGEMENT message also starts with a message type code. It is a short message that just contains bundle ID, for which this ACK is being sent, and the acknowledged length, denoted as SDNV, indicating number of bytes successfully received.

KEEP-ALIVE messages comprise just one-byte to indicate the message type code. Upon its reception, the peer node updates the timers, knowing that connection is up. Keep-alive message is sent when no other data is sent or received by the node for the keep-alive interval negotiated in contact header.

If no data including keep-alive message is received for twice the keep-alive interval, then connection is assumed to be in idle state and is closed immediately.

SHUT DOWN message is a one-byte message type code, sent in order to gracefully shut down the connection. Upon reception of this message, the CL should close the connection.

Bluetooth Convergence Layer Protocol

As mentioned earlier, the TCP convergence layer protocol has been adapted for Bluetooth serial communication links. All protocol messages and their sequencing is exactly same. Bluetooth serial communication is stream-oriented like TCP and while operating within short ranges (10 meters), Bluetooth devices are pretty much reliable in delivery of data. So no special operations are required other than those described for TCP convergence layer.

Bluetooth RF serial communication (or serial port profile, SPP, in Bluetooth terminology) is the basic communication mechanism supported by every Bluetooth device. A Bluetooth device is assigned a 48-bit unique MAC address, which is used to identify the device in serial communication, as IP is used in the Internet. Each application using SPP is identified by a unique channel number (similar to port numbers in TCP/IP). Bluetooth protocol specifications define an 8-bit channel number ranging from 0 to 255. Serial communication is also stream oriented. All these similarities with TCP makes it possible to adapt the TCP CL protocol easily.

2.3.4. Routing Protocols

At the moment, DTN does not define any particular routing protocol to use with the Bundle protocol. A variety of routing algorithms and protocols can be used, depending upon DTN application area, from simple epidemic routing to complex statistical and heuristic algorithms. Nevertheless, researchers have proposed some routing algorithms and protocols for DTN. A couple of epidemic routing algorithms have been implemented in the reference implementation and in this thesis work as well. In the following, a brief description of some routing algorithms and protocols is provided; while there are many further research efforts, the routing approaches listed below have been implemented for the DTN reference implementation.

Static Routing

Static routing is the simplest form of routing, in which the routes from source to all possible destinations are provided statically at system startup. Usually, the routing information does not change, or new routes may be added manually. Hence no protocol is required for routing information propagation.

Flooding

Flooding is another simple routing algorithm, in which the incoming data is transmitted to all the links except from which the data arrived. Flooding also does not require any protocol for routing information propagation. Nevertheless, some mechanism is required to prevent loops, so that source node should not keep on forwarding same data over and again. One simplest mechanism is to keep hop count, and discarding data using some threshold value. Another mechanism is to keep track of transmitted data using some unique identifier. If the same data arrives again, it can be discarded.

PRoPHET

A probabilistic algorithm PRoPHET (Probabilistic Routing Protocol using History of Encounters and Transitivity) has been recently proposed for DTN. It exploits the mobility patterns followed by users carrying mobile devices, which may form an ad hoc network. Normally, a random movement of nodes is assumed in an ad hoc network. But users in daily life follow a fixed pattern repetitively. PRoPHET discusses mechanism to keep track of this pattern and use these metrics for deciding the routes. The details are provided in [LIND06].

2.3.5. Neighbor Discovery

One of the largest application areas of DTN is the MANETs with intermittent connectivity, having no end-to-end path available most of the time. The nodes participating in the mobile ad hoc network may not have time or means to configure network parameters, particularly if the connectivity interval is quite short. Examples are ad hoc networks formed in a market or at a disastrous place or on board in a public transport vehicle. In order to achieve effective communication, the nodes should be able discover each other and establish a network automatically on the fly. Some routing protocols for ad hoc networks, such as PRoPHET, also depend upon such mechanism provided by underlying layers. We propose a mechanism for neighbor discovery in Bluetooth based Ad Hoc networks.

Bluetooth family of protocols specifies a mechanism to advertise the device information, application services and parameters for the services. Bluetooth devices can query each other for such information in order to establish a connection. This mechanism is called Service Discovery Protocol (SDP) and is built into the Bluetooth protocol stack. SDP works at L2CAP layer and uses a predefined reserved channel. The advertising device maintains a service database and each service is identified by a universally unique identifier (UUID). Upon request from another Bluetooth device, the service information is sent to it. In this way, a device can determine what applications are supported by the others and how those devices can be connected to [BRAY].

We have used SDP to advertise the device MAC address and channel identifier for SPP using RFComm service UUID. This information has been termed *DTN-service*. The Bluetooth convergence layer in our implementation advertises its DTN-service information and discovers other devices in neighborhood advertising their DTN-service information. The implementation details are provided in Chapter 5.

2.4. Summary

In this chapter, DTN architecture has been explained. It also included an overview of DTN family of protocols, mainly he Bundle protocol and convergence layer protocols. A few experimental routing protocols have been discussed briefly. Finally a neighbor discovery mechanism for Bluetooth convergence layer has been proposed. Next chapter describes implementation architecture for DTN, tailored for Symbain based smart phones.

IMPLEMENTATION ARCHITECTURE 3

This chapter describes the top-level architecture of Bundle protocol implementation for Symbian mobile phones. Although the overall design is tailored for Symbian OS, top-level architecture is generic enough to be used on other platforms. This chapter does not give any detailed design or algorithms, rather describes architectural design decisions used in the implementation.

3.1. Conceptual Model of Bundle Node

A *Bundle node* is a logical entity on a DTN node, which implements the Bundle protocol to send and receive bundles. It can be a thread, or process running on general-purpose computer, or dedicated hardware device. As described in Chapter 2, the Bundle protocol works above the transport layer and below the application layer. Hence it uses services offered by transport layer and offers Bundle layer services to applications, which could communicate over DTN. Bundle protocol specifications subdivide Bundle layer into 3 logical sub-layers, as illustrated in Figure 4.

3.1.1. Bundle Protocol Agent

The core protocol logic is handled by the Bundle Protocol Agent. BPA is responsible for generating and receiving bundles and administrative records. It may also maintain persistent storage. Besides, BPA is responsible for all routing decisions.

3.1.2. Convergence Layers

To use transport layer services from an abstract level, BPA utilizes one or more convergence layers. Each convergence layer is optimized for a different transport layer – but should offer BPA a uniform Service Access Point at an abstract level.

3.1.3. Application Agent

To offer its services to application layer programs, BPA utilizes Application Agent sub-layer. Depending upon targeted DTN applications, AA should be customized in order to hand over application layer data and meta-data to BPA. AA may also maintain DTN applications' *registration* information. Registration is a mechanism used by an application-layer program to identify itself as DTN user-application. It is analogous to 'handle' abstraction used in many OS services like file, networking, graphics etc. Each application using such services is assigned a unique handle, which is used as a reference to invoke system calls for those services. DTN expands this concept to a more abstract level and in slightly loosely-coupled fashion. An application may remain 'registered' for a DTN service even if the program is not running. DTN defines *active* and *passive* registration states for this purpose.

DTN Applications

DTN applications are application layer programs using Bundle node in order to communicate in delay-tolerant networks. Since DTN uses a different concept of network communication, applications may need to be tailored accordingly. For example, conventional FTP cannot be used as it is in DTN networks. So either FTP client applications can be altered to provide all data and/or meta-data at once to Bundle protocol, or some gatewayapplication can be designed to bridge between conventional applications and Bundle node.

3.2. Architecture for Symbian OS

Although the top-level architecture is quite generic, it mainly targets Symbian OS. Symbian OS programming issues are discussed in detail in next chapter. Nevertheless some general features are described here, before discussing the top-level design.

3.2.1. Symbian OS

Symbian OS is the dominant OS for smart phones and other handheld devices like PDAs [SYMB]. Such devices have constrained resources; battery-power, memory, processing capabilities etc. Yet they are becoming widely used devices, carried by users most of the time, to most of the places they visit. This makes smart-phones based inter-personal communication an interesting and potential application platform for DTN.

Owing to be running on devices with constrained resources, Symbian OS introduces may architectural and system design concepts, which are different form other operating systems running on general purpose computers. It offers OS-level services asynchronously, and provides a rich library of utility functions, algorithms and data-structures especially optimized for constrained-devices. To execute asynchronous tasks, Symbian OS defines its own mechanism of multitasking (explained in next chapter). Symbian OS also defines a unique IPC mechanism, which is used by OS services as well.

3.2.2. Top-level Architecture

The top-level architecture of bundle-node application follows the conceptual model described in earlier sections of this chapter. The software comprises 3 main components: BPA, AA and CLA(s). For modularity, these components are subdivided into logical blocks. This is illustrated in Figure 9. *BPA* component implements the core logic of Bundle protocol. It utilizes a *Router* component to make routing decisions. At the moment, Router component obtains routing information from a file, because at the moment, Bundle protocol does not define any semantics for route information propagation. Router component can be expanded to determine routes on its own, as it executes asynchronously. Alternatively, BPA can also update its routing information.

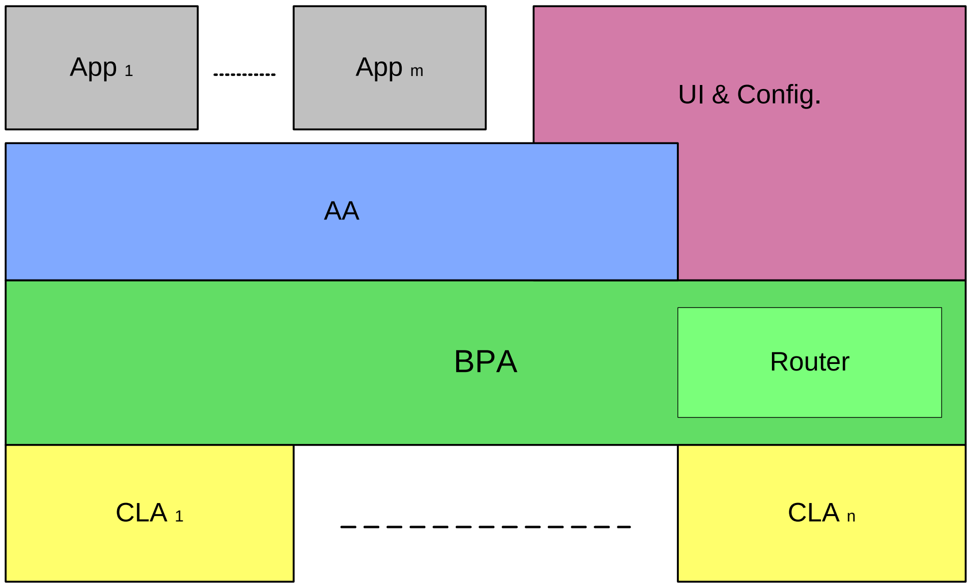


Figure 9. Top-level Architecture

BPA can utilize one or more Convergence Layer Adapters in order to use underlying transport layer services. CLA components provide a generic API as Service Access Points. Currently, two convergence layers are supported in the design: TCP CL for TCP/IP and Bluetooth CL for serial communications. BPA can launch either or both of these upon user request.

Application Agent provides a SAP to DTN applications (referred as *App* in above figure) wishing to utilize BPA services that can be access through Symbian OS IPC mechanism. DTN applications can register with the AA, which presents bundle transmission requests to BPA on behalf of DTN applications. IPC mechanism enables multiple DTN applications to utilize BP services, asynchronously. This enhances modularity and new DTN applications can be developed without modifying BP application.

User-Interface component is mainly used to configure the application while it is executing. The user can configure different options for BPA, start CLA services and enable/disable logging information etc. It provides a graphical user interface for this purpose, in the form of menus and dialog boxes etc. Another use of UI component is to invoke BPA services locally, without needing any external DTN application. This functionality is useful for demonstration and diagnostic purposes. User can send any media file to other mobile-phone using Bundle protocol, which is received and saved by BP application on that device.

In the following we discuss some fundamental architectural concepts used in the implementation.

Asynchronous Interaction via Message Queues

The layered architecture of application requires that components should not use synchronous or blocking operations, which could take significant processing time. This would degrade the performance; for example if application is listening for a connection synchronously, it will not be able to perform any other tasks. Hence the different components of application interact asynchronously. Symbian OS applications utilize a concept similar to threads for multitasking and asynchronous operations, explained in next chapter.

Components require some mechanism in order to exchange data and use services offered by other components, asynchronously. A notion of 'message queues' is used for this purpose. Every component owns two queues to store data, operational instructions and status. One queue holds requests for the services offered by the component, termed as *TxQ*. The other queue holds replies (results and status) for those requests, termed as *RxQ*. In order to relate requests and replies in two queues, an identifier is used. The queues operate as a FIFO; first-in, first-out queues.

IPC based API

Application Agent offers Bundle protocol services to DTN application via a generic API, which is based upon Symbian OS native Inter-Process Communication. Bundle node executes as server applications. DTN applications connect to Bundle node as client application. This process may include registration, implicitly or explicitly. DTN applications then can use Bundle protocol services to send or receive data.

User Interface Design Issues

Different Symbian devices may vary in user interface styles. This is the reason why Symbian OS variants offer a common base for basic OS services, but can use slightly varying API for user interface designs. The application is designed in such a way that decouples UI component from other components. Hence a customized version of UI components can be implemented for each variant of Symbian OS, while the core components of Bundle protocol are reused without modification.

3.3. Summary

This chapter described a generic software architecture for the Bundle node implementation, tailored for Symbian OS. The architecture is decomposed into several components, while preserving the protocol hierarchy as described in the specification documents. Next chapter provides a crash course for Symbain OS application design, before each component is described in detail.

PROGRAMMING FOR SYMBIAN OS AND DESIGN PATTERNS 4

This chapter describes some of unique aspects of Symbian OS programming in detail. This chapter also discusses some design patterns used by Symbian applications in general or specifically by this implementation of the Bundle protocol.

4.1. Programming for Symbian OS

As mentioned in the previous chapter, Symbian OS was specifically designed for hand-held devices (such as mobile phones, PDAs) with constrained resources (screen size, memory, battery power, processing capabilities). Symbian OS has been developed in C++ programming language, hence C++ being native programming language for it. It also supports other programming languages such as Java, Python with the support of virtual machines, interpreters etc. Since this application developed in the thesis work functions as a server program, it has been implemented using C++ for better performance in terms of code optimization and speed of execution.

Although Symbian OS uses C++, which is a standardized, widely used and well matured programming language, the roots of Symbian OS dates back to mid 90s when C++ was still going through standardization process. Hence some of the advanced features of OOP languages were not supported by compilers at that time. Symbian OS introduced its own mechanism similar to concepts found in modern OOP languages today. For example, exception handling is not supported by Symbian OS; nevertheless Symbian OS uses its own mechanism to achieve similar behavior.

Symbian OS also does not use standard library functions and data-structures used by C++ programmers, such as Standard Template Library (STL), IOStream, file-handling. These library functions and data-structures require significant memory space for code and data, making them infeasible for hand-held devices with limited memory. Symbian OS provides its own library functions and data-structures to serve these purposes.

Symbian OS provides an API for a wide range of library and utility functions such as file handling, graphics, communication and networking, inter-process communication, string handling and processing. Some of unique features of Symbian OS, which govern the application design considerations, are discussed below.

4.1.1. Code Optimization

As mentioned earlier, Symbian OS provides a wide range of library functions. Since hand-held devices have limited permanent storage and physical memory for code execution, these library functions are specifically optimized for hand-held devices in terms of code size and execution speed. The OS code itself, along with library functions, is placed in ROM in the form of DLLs. Applications programs are also stored as DLLs in the Flash memory. These DLLs contain only executable code and read-only data.

When an application executes, only one copy is loaded in the RAM, which is shared by all the instances of the programs using it. The OS code and library functions do not need to be fetched into RAM for execution; rather they are directly accessed and executed from ROM. RAM only holds application program DLLs, stack and the heap. This is termed as *in-place execution*.

4.1.2. Clean-up Stack & Leave Mechanism

Since memory is an expensive resource in Symbian OS devices, loosing memory chunks, due to *memory-leaks* in programs is not affordable. Memory is leaked when it is allocated dynamically and then not destroyed properly, after use. When a dynamically allocated memory is freed, it goes back to heap; in case of a memory-leak, it does not. Hence the application would run short of heap memory and program execution would cease or crash. Unfortunately, C++ does not offer any neat and clean mechanism for handling memory-leaks gracefully, like *garbage collector* used in Java. Symbian OS defines a similar mechanism via *clean-up stack* and *function leave* mechanism. Function leaving is similar to *exceptions* found in OOP languages.

A function leaves (i.e. returns) abnormally if any exception occurs due to some erroneous condition like resource unavailability. Many of the API functions offered by Symbian OS can leave. If a function leaves, dynamically allocated memory by that function would be leaked, as all the references available for that would be lost. Since exception can occur at any stage in function execution, it is necessary to keep track of all the memory dynamically allocated, so that it could be deleted when function leaves. Symbian OS provides a neat mechanism for this purpose. A reference of each object, dynamically created, is pushed to a clean-up stack provided by the framework. Hence if a function leaves, framework pops all the references previously pushed onto it and destroys the memory. Hence clean-up stack, together with the leave mechanism, co-serves as garbage collector and exception handling mechanism. Nevertheless, unlike garbage collector used in Java, this mechanism does not work always automatically. The programmer has to explicitly call the API functions to destroy objects from the cleanup stack in normal cases. Nevertheless, the objects are deleted automatically if an exception occurs and the function leaves abnormally.

4.1.3. Thin Templates

Templates are often used in C++ to provide blueprints of algorithms for data structures. Hence the algorithms can be reused for any data type without recoding. Compilers automatically generate code for template classes. In some cases, it results in a separate copy generated for each version, hence increasing code size significantly. Symbian OS uses a concept called thin-templates to keep its code size smaller. The basic idea is to separate the code, which uses template references from other code, by breaking it into small functions. Hence a very small portion of code is replicated for each template class. This reduces OS code size. All the collection classes (queues, arrays etc.) of Symbian OS use thin-templates.

4.1.4. Active Objects

Symbian OS discourages the use of threads for performance reasons. Threads require context-switching mechanism, which is an overhead for system resources: memory and CPU time. Moreover, multi-threaded applications require some kind of intra-process synchronization mechanism via *mutexes* or *semaphores*. This also requires extra coding. Nevertheless multitasking is necessary for sophisticated applications to perform background tasks and asynchronous operations. Symbian OS introduces *co-operative* multitasking in contrast with *preemptive* multitasking used in conventional operating systems using threads as basic execution unit. In co-operative multitasking, each execution unit performs a small operation and then gives chance to others for completing their operations; hence termed co-operative. OS does not preempt the execution before completion. Hence no mechanism for intra-process synchronization is required.

Symbian programs achieve this by using *active objects*. Classes, which perform asynchronous or background tasks, are derived from active-object class. The framework creates an *active scheduler* for each process. When a function is called which requires asynchronous execution, active scheduler is signaled. The Active Object class provides a *callback* function, which is called by framework when associated asynchronous task is completed. Each active object is allowed to have only one request pending for asynchronous operation. While the requested asynchronous operation is being executed in the background, the active object stops further execution, giving chance to the other active objects to perform their operations.

4.1.5. Naming Conventions

In order to better utilize resources, Symbian divides classes into four types. T-classes objects are of small size and can be created on stack; hence can be used as automatic variables. M-classes encapsulate abstract classes, which define interfaces. Objects of such classes cannot be instantiated, and these classes are only used to derive from them. C-classes contain member objects, which are too large to be created on stack. Hence such objects are created on heap, and their reference is placed on clean-up stack. R-classes contain handles, which are references to other services offered by operating system servers or application servers. These letters are prefixed in the names of classes.

Leaving function names are appended by letter ‘L’ to denote that this function can leave. A function calling other leaving functions is also a leaving function. In order to break the nesting, a function, which calls other leaving functions, can place a *trap harness* by using a macro. The leaving process stops at the first occurrence of the trap harness.

4.1.6. Strings and Binary Data

Symbian OS does not supports conventional C-style *char*-pointer based strings and STL-strings are not available either, in library functions. Symbian OS provides thin-template based wrappers for single-byte data types. Strings are special case of binary data. This mechanism also provides an abstract interface for Unicode character set which requires two bytes per character. These data types in Symbian are called *descriptors*.

4.1.7. Client-Server Framework

Symbian OS offers its services via special programs executed by the kernel. These programs are called *system servers*. Symbian OS provides a generic IPC API to use these services. Some examples are file server, serial communication server, socket server, and window server. User-level programs can also offer their services utilizing the same IPC mechanism; hence termed as *application servers*.

4.2. Design Patterns

Design patterns are algorithmic solutions to commonly occurring problems in software engineering. They speed up the design process by providing an efficient, documented and tested algorithm for the problem. Like other OOP languages and systems, Symbian OS also utilizes many design patterns, both in framework and in application design. A couple of design patterns, which are used in the implementation of Bundle node, are briefly described in the following.

4.2.1. Model-View-Controller Pattern

MVC pattern describes a software architecture that splits an application’s data, view and control logic into three components i.e. model, view and controller respectively. As a result of this decoupling, modifications of any of the components have minimal effect on other components. This pattern is used by many toolkits for GUI based applications like Symbian, MFC, and QT etc. In Symbian, the basic GUI application framework follows this pattern. Model holds the data and algorithms to process the data. View component is responsible for drawing the data on screen. The controller logic handles user interactions and decides how to manipulate the model. This is illustrated in Figure 10.

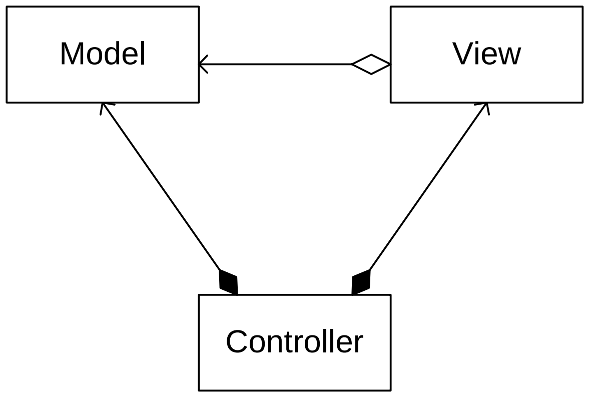


Figure 10. MVC pattern

In Bundle node, BPA, AA, CLAs, all components form *model*. View and controller are placed in UI component.

4.2.2. Observer Pattern

Observer pattern is used often in *event driven* programming. This pattern defines two components: *subject* and *observer* or *listener*. A subject component generates an event and then observer is notified via a *callback* function. This is illustrated in Figure 11.

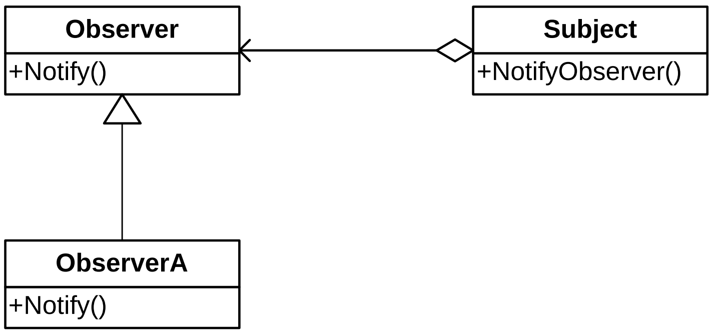


Figure 11. Observer pattern

In Bundle node, all components forming a ‘model’ mimic multitasking via use of periodic timer events. Each component is associated with a timer active object, which generates periodic tick events as a *subject*. The component itself is derived from an abstract *observer* class, which provides a virtual function as a callback. On each tick of timer, the component performs operations on the data in the message queues.

4.3. Summary

This chapter presented an overview of Symbian OS programming and application design considerations. Symbian OS applications use many design patterns, not so common in other platforms such as Windows and Unix. Next chapter describes the details of software components and the use of design patterns described in this chapter.

Design and Implementation Details 5

This chapter describes detailed design of the Bundle node's implementation. Design details include breakdown of components into classes, interaction and relation between the classes, and brief description of functionality of each class. Each component of the software is discussed in separate sections, using a bottom-up approach. System APIs and built-in classes are beyond the scope of the document.

5.1. Utility Classes

Utility classes implement some general algorithms or data-structures used by other classes belonging to different components of the Bundle node.

5.1.1. FNV Hash

FNV-hash is a simple yet efficient public-domain algorithm for computing smaller (32 or 64 bit) hash values with low collision rate. They are used in several software systems to compute table indexes, unique identifiers and for similar purposes [FNV].

FNV hash is used to compute unique bundle IDs. A bundle is uniquely identified by its creation timestamp, source EID and, if applicable, fragmentation length and offset values. Nevertheless this information cannot be used as such for indexing purposes. Moreover, TCP CL uses a 32-bit bundle ID while transmitting bundle over the network. To maintain uniqueness of these values within the network, a 32-bit hash is computed from the creation timestamp, the source EID and the fragment offset and length fields of a bundle. This hash value is termed as *Bundle ID* and can be used for indexing purposes as well.

FNV Hash Algorithm

FNV hash algorithm, described below, is encapsulated in a class, and can be accessed via a static function.

- Initialize 32-bit hash value with a number proposed in algorithm.
- For each byte in data buffer, do the following:
    - Take XOr of current data-byte and least-significant byte of hash value.
    - Multiply hash value with 32-bit prime number proposed in the algorithm, using modulo-32 operations.
- Final value is the hash value.

5.1.2. EID

This class manipulates end-point IDs and offers following services via member functions:

- Parsing of URIs into scheme and scheme-specific parts. The EID is stored in the member variables in this decomposed form and can be accessed individually.
- Composing the scheme and SSP back to complete URI.
- Comparing the EIDs.
- Cloning of an EID into a new copy.

The EID class also stores an *application tag* field. This field is used by the AA to demultiplex incoming data units to the DTN applications. Such mechanism is not specified by the protocol specification documents, and at the moment, is implementation dependent. Since EID can be based on any URI scheme, the manner, in which application tag filed is extracted, is URI and implementation specific. For “dtn” URI scheme, we propose that application tag should be identified by the last ‘/’ occurring in the SSP. Hence the format of SSP becomes:

<Bundle node identifier>/<application tag>

Any string after the ‘/’ denotes the application tag, which is stored in the EID class and is used by the AA for demultiplexing to the corresponding DTN application.

5.1.3. SDNV

This class encapsulates the SDNVs and can perform the following operations:

- Parsing of an SDNV string to extract the numeric value. The current implementation of the algorithm supports extraction of numbers up to 32 bits in size.
- Generating SDNV string from 32-bit numeric value.
- Computing the length of SDNV string from numeric value.

SDNV String Parsing

SDNV class maintains an array of bytes. It extracts bytes from an SDNV string until last byte (with the most-significant bit set to 0) is found, and stores into array. Then it computes the numeric value using the following algorithm.

- Initialize 32-bit numeric value with 0.
- Set shifting-index to 0;
- Starting from last byte in array till first byte in array, do the following in each iteration:
  - Set most-significant bit of current byte to 0, as it is just marker bit.
  - Shift left, the bits of the value obtained in previous step, shifting-index times.
  - Add the value obtained in previous step to numeric value.
  - Increment shifting-index by 7.
- Numeric value placeholder contains SDNV encoded value.

Calculating Length of SDNV String

This algorithm computes the number of bytes a numeric value possesses when encoded into SDNV string.

- Determine minimum number $x > 0$, such that 2^x is greater than the numeric value.
- Multiply the value obtained in previous step with 9; divide by 8; ceil the result to nearest integer.
- Divide the result obtained in previous step by 8; ceil the result to nearest integer.
- The resultant value is the length of SDNV string in bytes.

Composing SDNV String

The following algorithm describes how to encode a number into SDNV string:

- Calculate the length of SDNV string from numeric value using the algorithm above. Generate a byte array of that much length.
- Starting from last index of array till first index, repeat the following:
    - Store least significant byte into array at corresponding index.
    - Set most significant bit of stored byte to 1, except for last iteration. For last iteration, set this bit to 0.
    - Shift number to right 7 bits.
- The byte array holds SDNV string.

5.1.4. Schedular-Timer

This class is derived from CTimer, which is provided by Symbian OS. CTimer is an active-object and encapsulates a timer object, which can be set to generate an event after certain amount of time. Schedular-Timer class uses Observer pattern. This class implements virtual callback function *RunL*, called every time the event is generated. This function sets timer to fire again, and calls the notify function of the listener object. Hence the listener object will be notified periodically in order to execute its services. After experimenting with different variations of the timer value, a value of 100 microseconds has been chosen in order to ensure good responsiveness of the software.

5.1.5. Event-Notifier

This is an interface or abstract base class for observer or listener classes using observer pattern. It declares a virtual function *EventHandler* only, used as callback function by subject class.

5.2. Convergence-Layer Adapter Classes

The classes used by convergence layers are described in this section. There are two main sub-groups of these classes.

5.2.1. Connection Classes

Connection classes encapsulate the basic socket operations for connection opening, closing, reading and writing data. Symbian sockets perform these services asynchronously; hence a connection class has to be an Active Object. Connection classes are derived from an abstract base class. Two derived classes are used in this implementation: one for TCP connection and the other for Bluetooth RF Comm. Connections. This hierarchy is shown in Figure 12.

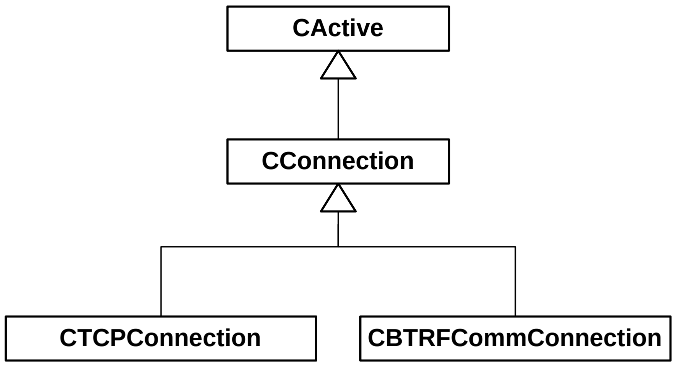


Figure 12. Connection classes

Since a connection class performs its services asynchronously, there is a message queuing mechanism as described in Chapter 3, implemented in the base class CConnection. A connection object retrieves command messages for data transmission, connection opening or closing etc., from its *TxQ*. It places the status of these requests or data received in its *RxQ*. The entity, which owns a connection object, can use *Push()* and *Pop()* functions in order to handover and retrieve data, respectively.

Since an Active Object can have only one asynchronous operation pending, Connection classes implement a state machine to save the state of current operation. Once the current operation is completed, the framework calls the callback function. In the callback function, a request for next operation is placed and the state is changed accordingly.

A connection is a bi-directional link, so it is used for both sending and receiving. Since a connection object can perform only one operation at a time, it switches the roles of sending and receiving alternatively in order to maintain a fair behavior.

Since a Connection class offers its services to a CLA class asynchronously, the latter does not know about connection or transmission failures until it reads the status message from Connection's *RxQ*. This can lead to synchronization problems; e.g. a Connection object is in closed state but the CLA, still being unaware of that, hands over more data to transmit. To avoid such issues, the CLA always checks the state of Connection object, and does not handover any data to it if the later is in closed state.

Even though a connection is closed, the CLA does not delete the Connection object until it retrieves all the status messages from Connection's *RxQ*. A connection's *TxQ* is always emptied by itself when it goes to closed state, and a failure status is placed in its *RxQ* message for each transmit request.

5.2.2. CLA Classes

These classes implement the convergence layer protocols. A CLA class maintains an array of Connection-Info objects, which encapsulate a Connection object, and some other information related to that connection such as connection state, direction, a temporary buffer for segmentation and reassembly. The relationship between these classes is shown in Figure 13.

The CLA class creates new connection if an existing one cannot be located in the array. A CLA object must be able to accept incoming connection requests as well. For this purpose, CLA class encapsulates a listening socket, which is always waiting on a particular interface for new incoming connections. Since socket operations in Symbian OS are performed asynchronously, the CLA class is an Active Object.

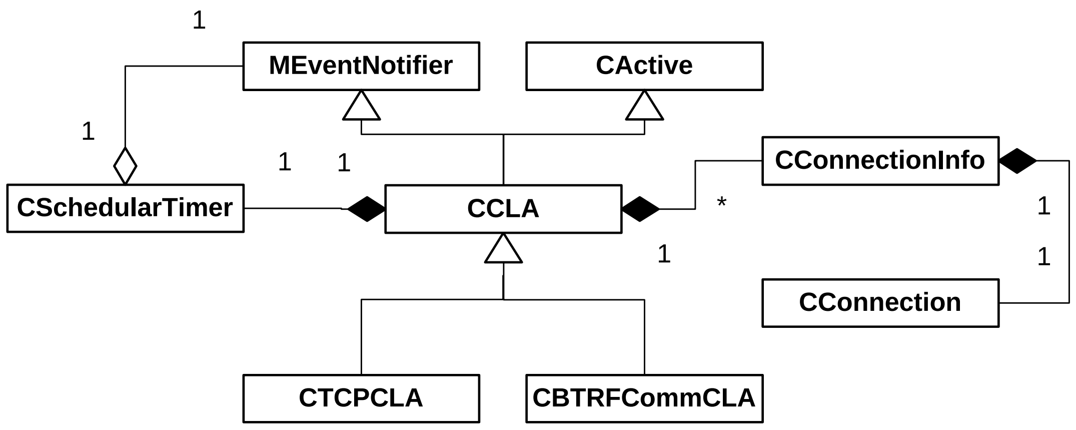


Figure 13. CLA classes

Since CLA and Connection classes interact asynchronously, they exchange operation and status codes via message queues. The CLA pushes requests message into the connection's *TxQ* and pops status or reply messages from the connection's *RxQ*.

The CLA class has to perform its protocol-level operations continuously. It simulates a thread-like behavior by using the *observer* design pattern. It owns a Schedular-Timer object, which serves like a *subject* in the observer pattern. The CLA class itself behaves like a *listener* and provides a callback function to the *subject* via the Event-Notifier interface class. When the Schedular-Timer generates a timed event, it notifies CLA by calling that function. Hence CLA class performs its operations periodically, mimicking thread-like parallel execution. These operations are divided into 3 categories:

- Transmit operations include locating a connection object, creating a new connection object if an already existing is not found, and handing over out-going bundles to connection object.

- Receive operations include retrieving status messages from existing connection objects, extracting incoming bundles, reassembly and segmentation of bundles if needed. A bundle is reassembled if it is received in segments. A received bundle is segmented if it is merged with next data unit in the stream.
- Auxiliary operations include connection activity detection based on timers, performing CLA protocol auxiliary operations (e.g. sending Keep-Alive message), and deleting terminated connection objects.

BTRFComm-CLA class is conceptually same as TCP-CLA class because they use identical protocol. Minor differences are due to different API and data-structures used for communication over Bluetooth. The only significant difference is that the BTRFCOMM-CLA class owns an object of the BTNeighborhoodDiscovery class.

BTNeighborhoodDiscovery Class

As described in Chapter 2, some routing protocols such as flooding and PRoPHET utilize the presence of other Bluetooth capable Bundle nodes in the neighborhood as the routing metrics. The BTRFComm-CLA class implements a mechanism, via BTNeighborhoodDiscovery class, to discover neighboring devices, which advertise their capability of exchanging the Bundles over a particular RFComm channel. The anatomy of this class is illustrated in Figure 14.

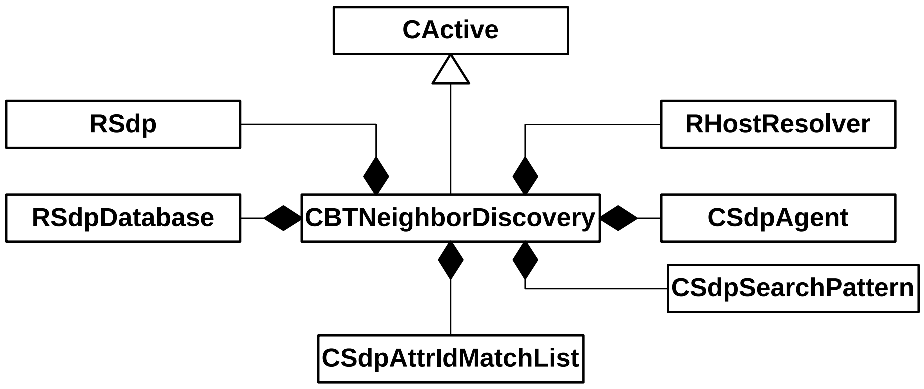


Figure 14. Bluetooth Neighborhood Discovery class

This class performs two main tasks: service advertisement and discovery. It starts advertising the RFComm channel for the Bundle node when the BTRFComm-CLA is enabled and stops the advertisement when the BTRFComm-CLA is disabled. The SDP record, which comprises the UUID of the service, channel ID and a textual description of the service, is added into the SDP database of the device when the service advertisement is started, and is removed when the advertisement is stopped. This mechanism is achieved via RSDP and RSDPDatabase classes provided by the framework.

Secondly, this class is responsible for discovering the neighbors and their DTN-service information continuously on regular basis. This task involves two operations: device discovery (for the device address) and service discovery (for the channel ID). It discovers the Bluetooth device addresses of the neighboring Bundle nodes via RHostResolver class. Then it enquires to all the devices, discovered in this way, about their SDP records using the CsdpAgent class. The CsdpSearchPattern class is used to narrow down the search criteria to DTN-service information records only, which uses the corresponding service UUID to filter out irrelevant service records thus saving computing resources. The service discovery tasks are performed in the background using the Active Object design pattern.

When a DTN-capable device is discovered in the neighborhood, the information retrieved is sent to the BP-Router component by the BTRFComm-CLA class. The BP-Router component may utilize this information for computing routes by using algorithms such as flooding or PRoPHET. The BTNeighborhoodDiscovery class maintains a local cache for the devices discovered so far. The service discovery operation is performed only for new entries in the cache. Old entries, which cannot be detected in the neighborhood anymore, are removed from the cache and the BP-Router is also notified so that it can also remove the corresponding entry from its routing records.

5.3. Bundle Protocol Agent Classes

The BPA component implements the core logic of the Bundle protocol; so it uses all the classes described earlier, directly or indirectly, as shown in Figure 15. In order to perform protocol level operations, it uses the observer pattern via the Schedular-Timer and the Event-Notifier classes, similar to the CLA component. The other classes are described below in detail.

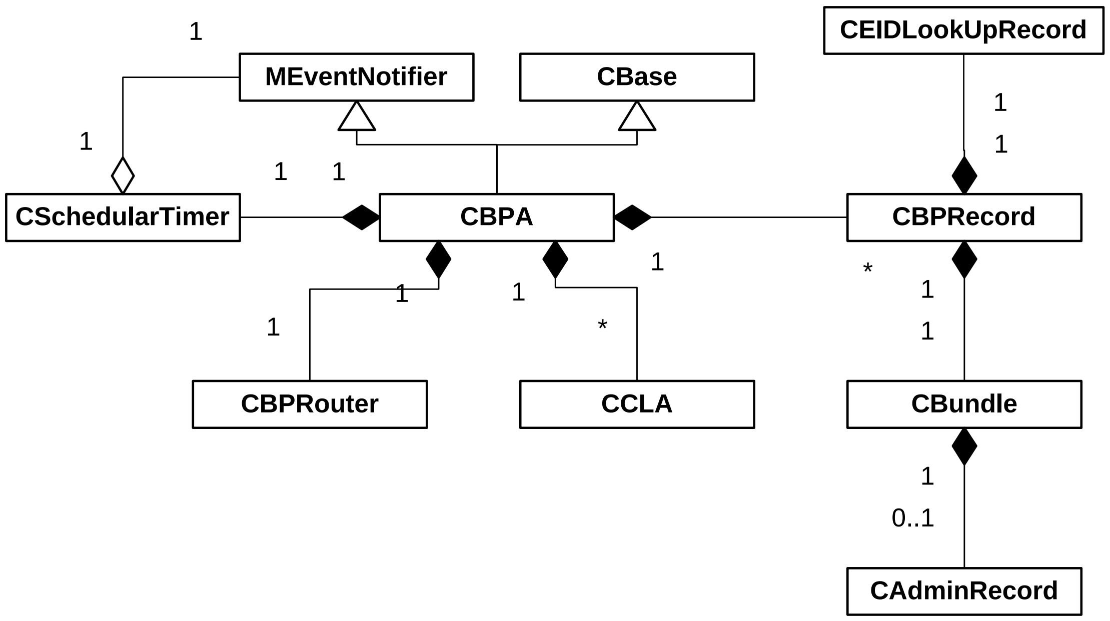


Figure 15. BPA classes

5.3.1. BPA Class

This is the main class of the BPA component and contains the protocol state-machine logic. It also creates and owns CLA objects, a BP-Router object and maintains a list of bundles for transmission and reception. This class also provides an interface for the AA component via message queues, *TxQ*, *RxQ*. Since it does not perform any asynchronous operation locally, rather calls asynchronous services of other components, this class itself is not derived from *CActive*. Owing to being created on heap, it is therefore derived from *CBase*.

Like the CLA class, BPA class performs protocol level operations when its callback function is called in response to timer event generation. These operations are categorized into 3 groups:

- Transmit operations include finding routes for out-bound bundles and handing them over to the state-machine, which results in handing over the bundles to the CLA objects.
- Receive operation mainly includes the processing of the incoming bundles by the protocol state-machine. This either results in forwarding of a bundle to the other Bundle nodes or the bundle is local delivered to the AA component.
- Auxiliary operations include the creation of out-bound bundles retrieved from Application-Agent, handing over locally-delivered bundles' payloads to Application-Agent, clearing the queue of bundles by deleting to-be-discarded bundles, and retrieving bundles from CLA objects.

This class also maintains a *processing queue*, which holds the out-bound or incoming bundles.

Bundle Protocol State-Machine

The bundle protocol state-machine is described in detail in [BPSPEC04]. A compact version is illustrated in Figure 16. This illustration describes the steps executed during the processing of out-bound or in-coming bundles while stored in the processing queue. It does not discuss how bundles are stored in or removed from the processing queue. Such steps are performed in auxiliary operations.

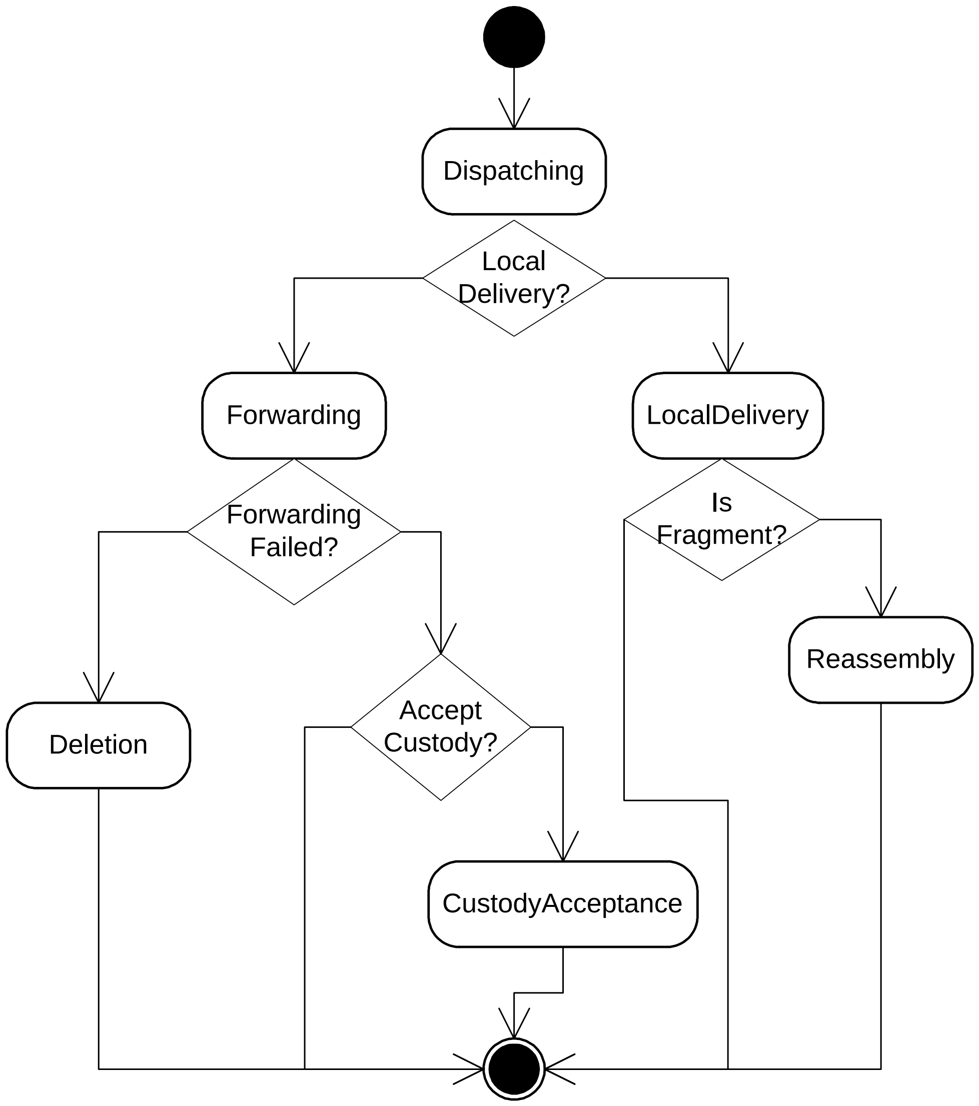


Figure 16. Bundle Protocol State-Machine

These states are directly mapped to what is termed *retention constraints* by the protocol specifications. When a new bundle is created, it does not have any retention constraints. As bundle undergoes processing by the state-machine, it may be associated with one or more retention constraints, which may be removed as processing proceeds further. The BPA must not delete a bundle as long as it has any retention constraints associated. For example, if the BPA accepts custody of a bundle, it adds a retention constraint indicating this decision. BPA must hold a copy of the bundle until some other Bundle node accepts the custody or the bundle is expired.

An out-bound or an incoming bundle is placed in the *dispatching* state, after its destination route has been determined by consulting to the BP-Router component. If the bundle is to be destined for local delivery and is a complete bundle then it is delivered to the AA. If such bundle is a fragment, its state is changed to *reassembly* and it is kept in the processing queue until all the fragments are reassembled and ADU is delivered to the AA, or the fragments expire. If the bundle in dispatching state has to be forwarded to another Bundle node and forwarding is failed then the bundle is deleted. On the other hand if bundle is forwarded successfully and its custody acceptance is requested, the BPA can accept the custody depending upon the local policy. If it does so, then the bundle is kept in *custody-acceptance* state. The bundle is removed from the processing queue if it does not have any retention constraints.

Configuration File

The BPA component uses a configuration file in order to load configuration parameters at the startup. BPA class is also responsible for loading and parsing the contents of the configuration file. The file consists of name-value tuples. The tuples are separated by a ‘;’ sign and white spaces are ignored. Within each tuple, the filed name and value are separated by a ‘=’ sign and white spaces are ignored. The current implementation uses four tuples: local EID, report-to EID, TCP listening port and Bluetooth listening channel ID. The syntax of the file is generic enough to add more entries.

5.3.2. Bundle and Admin-Record Classes

This class represents a data-structure for a bundle message. It provides the API for the following operations:

- It parses a bundle message in binary format, and extracts different header fields to store in the respective member variables.

- In the BPA, a bundle message is stored in parsed form. This class provides the API for setting and getting values of different fields of header. Hence a bundle message can be processed and modified efficiently.
- It composes a binary bundle message using the information stored in different fields.

This class stores the payload in binary format, which is delivered to the AA as it is. Nevertheless, if the bundle is an administrative record then it further decomposes it and creates an object of Admin-Record class, which provides the API for further analysis of the payload.

5.3.3. BP-Router Class

This class maintains the routing records for BPA. It reads the entries from a routing file, on program startup. Entries in the file are stored in the following format, one per line:

<EID> <Transport Type> <Priority> <Node Address> <Service Identifier>

Each field in the entry is separated by one or more white space characters. The first field contains EID in standard URI format, as explained in Chapter 3. *Transport Type* field denotes underlying link-layer technology, used to select corresponding convergence layer adapter. Currently, two values are defined: ‘TCP’ for the Internet connections and ‘RF_Comm’ for Bluetooth connections. These values are case insensitive. *Priority* field is an unsigned numeric value, which is used for routing decisions by the static routing algorithm for selecting the high priority route in case multiple routing entries exist for a particular destination. *Node Address* is a transport-type-dependent field denoting IPv4 addresses for TCP or Bluetooth device address for RF_Comm. *Service Identifier* is again a transport dependent numeric value, usually used by protocol stacks for selecting the application that uses the particular service identified by this value. For TCP, it corresponds to the ‘port number’ a listening socket is accepting connections on, and the ‘channel ID’ for Bluetooth connections.

BP-Router class is derived from *CBase* and *MEventNotifier* classes, and uses the timer-based observer design pattern, as used by some other components. Hence, its callback function is called in regular intervals, simulating a thread like parallel execution of the component. Each time, the records from the routing file are updated; hence entries can be modified without restarting the program.

DTN specification documents, at the moment, do not define any mechanism for routing information propagation. In fact no routing algorithm has been selected at all, as this is an on going research area. At the moment, BP-Router class also does not implement any sophisticated algorithm for routing decisions. Routes are statically defined in the routing file and simpler algorithms, such as static routing and flooding, are used for routing decisions. When BPA component enquires the router object for some routing information, it provides information to use for a particular routing algorithm. In case of static routing algorithm, the router object simply selects the first route with highest priority. In case of flooding algorithm, all routing entries stored are used to forward bundles. BPA maintains a *flooding queue*, holding signatures (which comprises source EID, creation timestamp and fragmentation information, if applicable) of the bundles forwarded, to prevent routing loops.

Nevertheless, since BP-Router component performs route updating asynchronously, it can be extended to determine routes by other means such as neighbor discovery in which it determines surrounding devices forming an ad hoc network using Bluetooth or WLAN. Such information can be used by routing algorithms such as flooding. In future, DTN protocol specification documents may define additional protocols for routing information propagation (e.g. PRoPHET), which can be incorporated into modular architecture of BPA or BP-Router components. In the current implementation, the Bluetooth CLA detects other devices in the neighborhood and this information is stored in the BP-Router component. BPA can enquire the routes by specifying a particular algorithm. In case of the flooding algorithm, the BP-Router component returns routes to all the devices in the neighborhood, from its *NeighborhoodQ*.

5.3.4. EID Lookup Record Class

This simpler class is used in order to exchange routing information between BP-Router and BPA components. It implements a linked-list, each node of which contains a single routing entry stored in BP-Router component. The Number of nodes in the list depends upon the routing algorithm used. The same class can be utilized to add new entries into BP-Router by BPA component, as well.

5.4. Application Agent Classes

Application Agent component provides a seamless interface to application programs, via Symbian IPC mechanism, for utilizing DTN communication. As described in previous chapter, Symbian provides a client-server framework for IPC. The AA component executes as application server. An application program can connect to the server. When this IPC session is created, the application *registers* for a particular service such as ‘DTN file transfer’, by providing an *application tag*. The application tag is used by application agent to demultiplex incoming bundle payloads, and is used in EIDs based on DTN URIs. While the IPC session is maintained, DTN applications can send and receive their data identified by the tag. Application Agent maintains two queues for incoming and outgoing application data units. The incoming data is not discarded if the session with corresponding application program does not exist. In such case, the application program can receive the data whenever it establishes a session with the AA, using a particular application tag for registration.

A mechanism is provided in Bundle node UI to send and receive test bundles. In this case, no registration is required and the UI directly accesses queues for sending or receiving ADUs.

The classes used in the design of the AA component are illustrated in Figure 17 and are discussed in detail below.

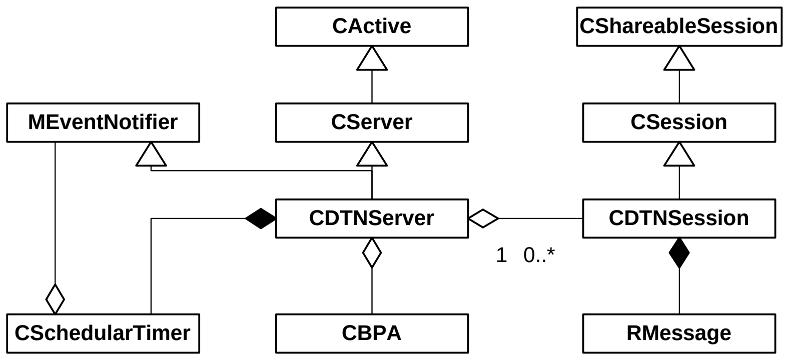


Figure 17. AA classes

5.4.1. Symbian Client-Server Framework Classes

The classes shown in above figure follow a fixed design pattern of Symbian client-server framework. The server application creates a server object, which waits for new IPC session requests. When a client program requests the kernel to establish a connection with the server program, the kernel dispatches a session request to the server program. This logic is built into the framework provided by *CServer* class. Upon receiving this request, a session object for that IPC connection is created by the server object. While the session is established, the client program can issue synchronous or asynchronous service requests. The actual logic of service execution is handled in *CSession* class. A session object receives service request parameters in the object of the *RMessage* class. When the client program terminates the session, the framework deletes the corresponding session object.

5.4.2. DTNServer Class

The server class is an Active Object, waiting for new IPC session requests. It maintains two queues for holding incoming and outgoing ADUs. Additionally, it uses the timer-based observer design pattern for multiplexing and demultiplexing the outgoing and incoming ADUs, respectively. It performs the following operations in its callback function periodically:

- Iterates through all the session objects to extract outgoing ADUs and places them in the queue along with application tag for corresponding registration.
- Iterates through all the incoming ADUs in the corresponding queue and hands over them to the corresponding session object if found any.
- Hands over new outgoing ADUs to BPA
- Extracts new incoming ADUs from BPA. The notification of success or failure while sending outgoing ADUs is also received in the same channel.

The server object registers only one session per application tag. That is, it refuses to register an application for a service if another application is already registered for that service. This simply results in the graceful termination of the new IPC session by the framework.

5.4.3. DTNSession Class

The session class receives the request messages from the client via the IPC framework. Each message comprises a message type and zero or more arguments. The session class decodes the message type in order to determine type of service requested and performs the corresponding operations, synchronously or asynchronously. Four types of requests are handled by current implementation:

- A *registration* request is serviced synchronously. This must be the very first request issued by client programs. The session is closed if any other request is issued in prior to the registration request. The session is also terminated if another session is already established for that registration. The client application must terminate the session in order to cancel the registration.

- A *transmission* request is serviced asynchronously. An outgoing ADU is created, using the arguments passed along, and buffered temporarily. The session object then waits for the completion of request asynchronously. The server object extracts this ADU and hands over to BPA. When BPA notifies about the transmission status, whether success or failure, the client is informed.
- A *reception* request is also serviced asynchronously. The client program requests for any ADU received for the particular registration. The request completes when either any ADU for that registration is sent to client, or the request is canceled by the client.
- A *cancel* request cancels any pending asynchronous request. Naturally, it applies to transmit or receive requests only.

5.5. User Interface Classes

UI classes follow a fixed design pattern of Symbian GUI applications. They create and start other components, directly or indirectly. They provide graphical interface, in the form of menus and dialog boxes, to users for configuring and using Bundle node services. The relationship between the classes is illustrated in Figure 18. The user interface framework varies for different variants of Symbian OS. The classes shown in the figure correspond to Series80 implementation, and may vary for other builds. A brief description is provided below. For details, consult Symbian SDK documentation and other literature such as [HAR03].

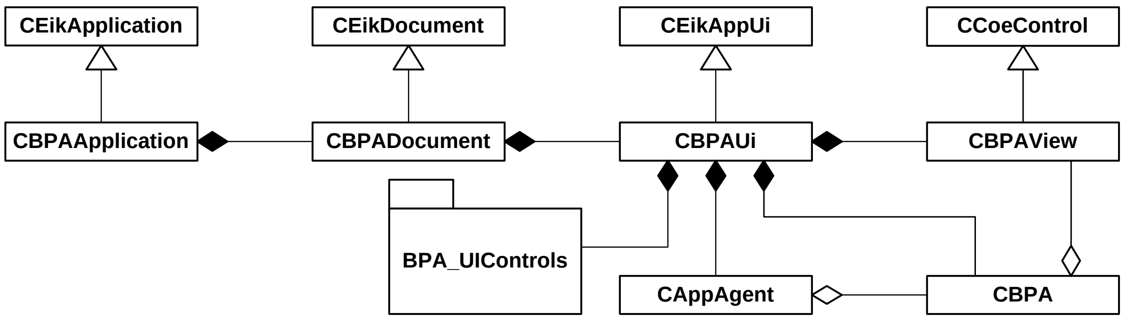


Figure 18. UI classes

In Symbian OS, every GUI application is a DLL and *CBPAApplication* class simply provides a startup entry point for the DLL. *CBPADocument* class does nothing but creating the UI object. *CBPAUi* class handles all the user inputs. It also creates BPA and AA components on startup. *CBPAView* class provides a mechanism for drawing and printing on screen. BPA class uses its services to print information and debugging messages.

Some simple classes in *BPA_UIControls* package create dialog boxes for getting more information from the user about the requested operations. For example, one dialog box enquires about bundle sending options. Another provides interface for file selection.

5.6. DTN Applications

As described in Chapters 2 and 3, DTN defines a new paradigm for communication, and a variety of applications can use the Bundle protocol. This is an ongoing research area and no particular structure for such applications has been defined so far. A simple application has been developed during this thesis work for demonstration purposes. It sends and receives files using Bundle protocol. More applications can be developed using Symbian client-server framework for IPC. This section briefly describes the framework and design patterns of client applications, which can connect to and utilize Bundle node server application. For more details, consult Symbian SDK documentation and other literature, such as [HAR03].

5.6.1. DTN-Socket Class

This class provides the API for establishing a session with the server (i.e. Bundle node), sending and receiving data, and closing the session. It is illustrated in Figure 19 and provides the following functions for using Bundle protocol services.

- Connect() function establishes a session with server.
- Register() function registers for a particular service. The name of service is provided in argument as a descriptor. This operation completes synchronously.
- Send() function sends request for transfer of data. The data and meta-data (i.e. options for sending data e.g. destination address etc.) are packed in a data-structure and passed as the argument of the function. This operation completes asynchronously.
- Receive() function checks for any data received. This operation completes asynchronously when data is available for this registration.
- Cancel() function cancels any pending receive or send operation.
- Close() function closes the session.

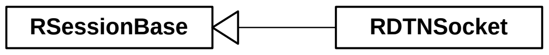


Figure 19. DTN-Socket class

5.6.2. Application Design Principles

A DTN application can be as sophisticated as a web browser or as simpler as basic console-based FTP client, as far as data processing presentation is concerned. DTN communication is as simple as using a socket. The IPC based interface, as described above, is asynchronous. Application should create an object of DTN-Socket class and register for a particular service. It may then issue request for sending or receiving data. For sending request, it should pack all the data and metadata in a data-structure defined in the implementation. Meta-data includes destination EID, lifetime, custody transfer requests etc.

Applications can use Active Objects or can just wait synchronously for the completion of operation, by blocking the execution. The latter is achieved by calling

WaitForRequest() function. It can cancel any pending request to issue a new one. It may terminate the session by calling Cancel() followed by Close() function.

5.6.3. Application Design Example

A sample application, *DTN File Transfer* or *DFT* has been designed for the sake of demonstration and reference. This simple application transfers a media file (image, audio, video) or a plain text file using DTN. The DFT application uses the Active Object design pattern for asynchronous operations. At the startup, the application connects to the Bundle node application using the DTN-Socket API, and registers to it by specifying an application tag. While executing, the application may issue a send or receive request, which complete asynchronously. The DFT application prepends a MIME header before the contents of the file. On the receiver end, this helps determining the type of incoming data. The same information can be used later on by other applications such as DTN e-mail gateways.

The DFT application has a structure and user interface similar to that of UI component of the Bundle node application, except that the former uses an IPC interface in order to connect the AA component of the Bundle node application. The UI component of the Bundle node performs the same functionality (i.e. sending and receiving media files) by directly invoking the AA services. Hence the UI components of both the applications are similar, with minor differences in menu commands. The *engine* component (or *model* in terms of MVC design pattern) of the DFT application is illustrated in Figure 20.

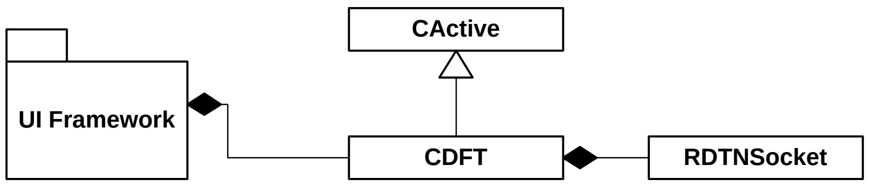


Figure 20. DFT application structure

The DFT class implements a callback function, which is called by the framework when the asynchronous request completes. If a file is sent then the Bundle node notifies the DFT application, when it successfully forwards the Bundle to next node. In the current application, no end-to-end acknowledgement mechanism is provided. If the application requests for reception of a file, it completes when the file is received. The incoming data is stored in a file. A new request placed always cancels the previous one. New DTN applications should use a similar pattern.

5.7. Summary

In this chapter, a detailed description of implementation of the Bundle node for Symbian platform was presented. Using a bottom-up approach, some utility classes were described first, followed by the classes used in each component. Finally the UI components was described, which instantiates all the components and provides the entry point for the application startup. The last section discussed some guidelines for designing DTN applications, which can use the Bundle node’s services using native IPC mechanism of Symbian platform. The design of a sample DTN application was also presented as a reference. Having discussed the detailed design, the next chapter focuses on testing and demonstration of the software.

6 VERIFICATION AND DEMONSTRATION

This chapter focuses on some verification techniques employed for the Bundle node application testing. First, different types of testing performed for the software are described. Later sections describe a demonstration setup, presented in a conference.

6.1. Verification

Verification or testing is the integral part of research and development life cycle. A significant effort has been placed for verification of software before it has been released publicly. A complete description of testing plan and test cases is beyond the scope of this document. In the following, a brief description of different test strategies is given.

6.1.1. Functional Testing

Functional testing verifies the correctness of algorithms and protocols, validating that software functions as well as described in requirement and design specifications, from user’s perspective. Individual components (classes or modules) are not tested separately, as done in *unit testing*. Rather overall behavior of integrated components is evaluated. The following aspects of software behavior are considered as metrics, while performing functional testing:

- The *functionality* of application. Each component and class works exactly as described in protocol specification documents and software design description.
- The software *stability* during execution. The application must not crash at any stage. It should be able to handle unwanted scenarios gracefully, such as invalid inputs, resource unavailability. It should start and exit gracefully.
- The *fair utilization of resources*. Software uses different resources available in the execution environment, such as memory, processing power. It should acquire and free those resources gracefully. There must not be memory leaks. No component should create a deadlock, consuming all the processing power forever.

Functional testing has been performed mostly by using emulator and debugger. For every use case, the code has been stepped-into and iterated-through. Inputs are either provided via UI component (e.g. when user initiates a bundle transmission) or they come from network (e.g. when the application receives a bundle from another instance of the application). For every input, the complete path of execution is traced to eliminate logical bugs. A logging mechanism is provided to print informational and debugging messages on screen. This helps tracing problems, while the software runs on real device. Using same techniques and tools, memory leaks have been detected and eliminated to maximum, in order to ensure the stability of software.

6.1.2. Interoperability Testing

The purpose of interoperability testing is to verify the protocol using a reference design. This provides a next level of confidence, after functional testing, regarding the correctness of algorithms and protocols. A reference implementation, DTN2 [DTNRG], has been used throughout the design and verification life cycle for interoperability testing. In the testing, the version of the reference design used was 2.2.0, latest package taken from the CVS repository available at that time.

6.1.3. Performance Testing

Performance testing for measurements and analysis has been conducted on the stable working application. Usually, the measurements are compared with some reference data to show performance boost. Since DTN architecture is in early stages of research and development, performance comparisons are out of the scope of this thesis work and hence the measurements are not compared with any reference data. Nevertheless, some statistics have been collected in terms of end-to-end delay, to show performance of application, while using different communication links. End-to-end delay is the sum of transmission delay, propagation delay, queuing delay and the nodal processing delay [ROSS03]. The test setup is shown in Figure 21.

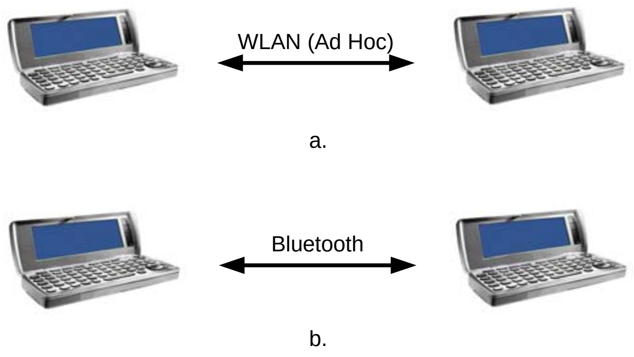


Figure 21. Performance Testing Setup

In scenario (a), two mobile phones exchange bundles in ad hoc mode over WLAN channel. In scenario (b), two mobile phones exchange bundles over Bluetooth RF channel. The same files are transferred over Bluetooth, using a built-in utility in mobile phones in order to show a comparative performance of the software.

During the verification, when Bundle node application running at a mobile phone receives a bundle, it records the end-to-end delay by calculating the difference between current time and the creation time. The measurements have been recorded for different sizes of bundles. Each step is repeated thrice in order to take an average value for the results. The plots of recorded data are shown in Figure 22 and Figure 23 respectively. For the correctness of results, the clocks of the devices must be synchronized. The accuracy of the results is +/- 1 second.

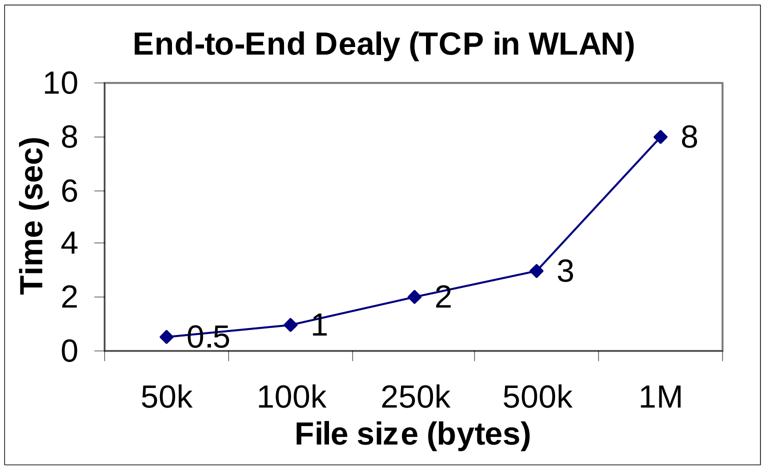


Figure 22. Performance Testing (scenario a)

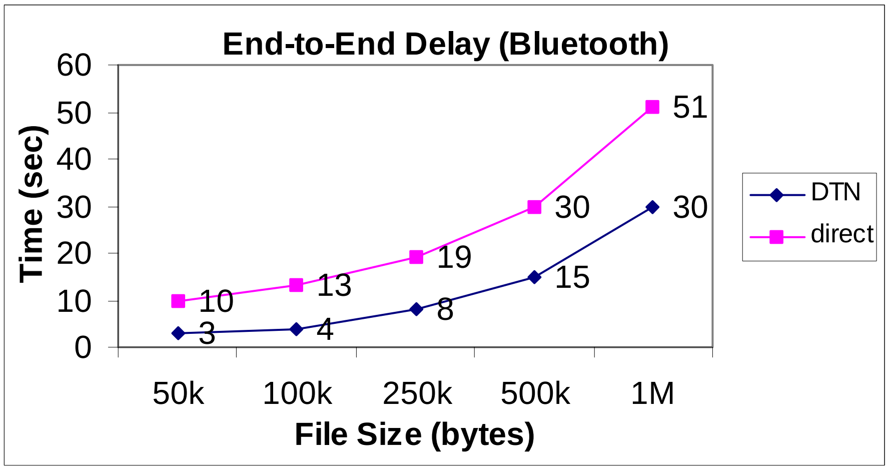


Figure 23. Performance testing (scenario b)

6.2. Demonstration Setup

The application developed during this thesis work was demonstrated in a poster session at the RealMAN 2006 workshop [JO06]. In the demonstration, two Nokia mobile phones (Communicators 9500 and 9300i) running the very application, one Nokia Internet Tablet 770 running DTN2, and one laptop also running DTN2 were used. A small application was also running on laptop, which received media files (e.g. images) via DTN2 and displayed them in the browser. This setup is illustrated in Figure 24.

We captured images in real time using built-in camera of one mobile phone, sent it to laptop using Bundle protocol, routed through other mobile phone and the Internet tablet. This also demonstrated a seamless vertical handover between Bluetooth and WLAN networks, using the Bundle protocol.

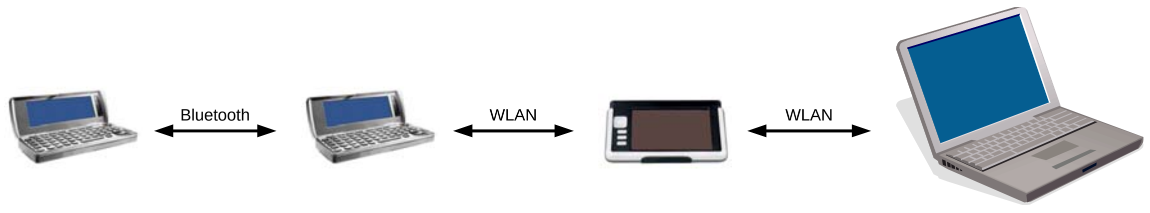
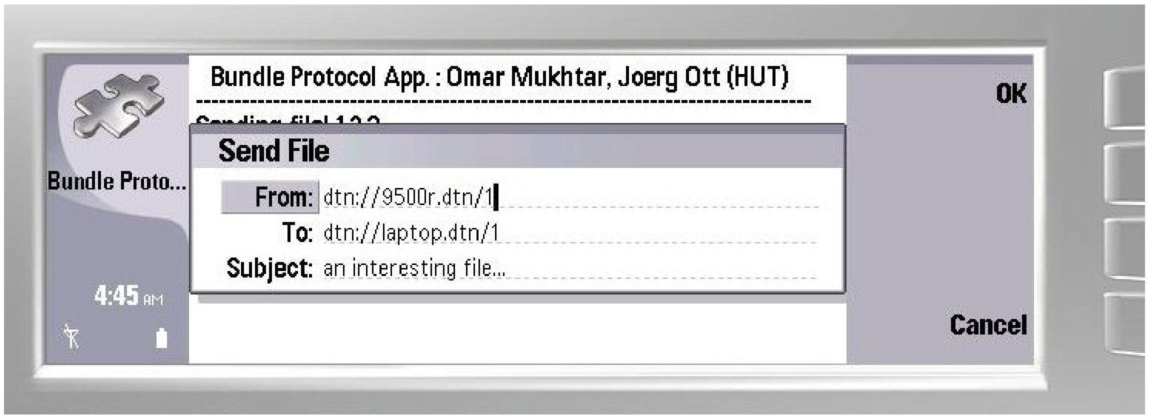


Figure 24. Demo Setup

The screen-shots of the application running on mobile phone for sending the images using DTN, and the application running on the laptop for receiving and displaying the images using DTN, are shown in Figure 25 and Figure 26 respectively.



Bundle Protocol App. : Omar Mukhtar, Joerg Ott (HUT)

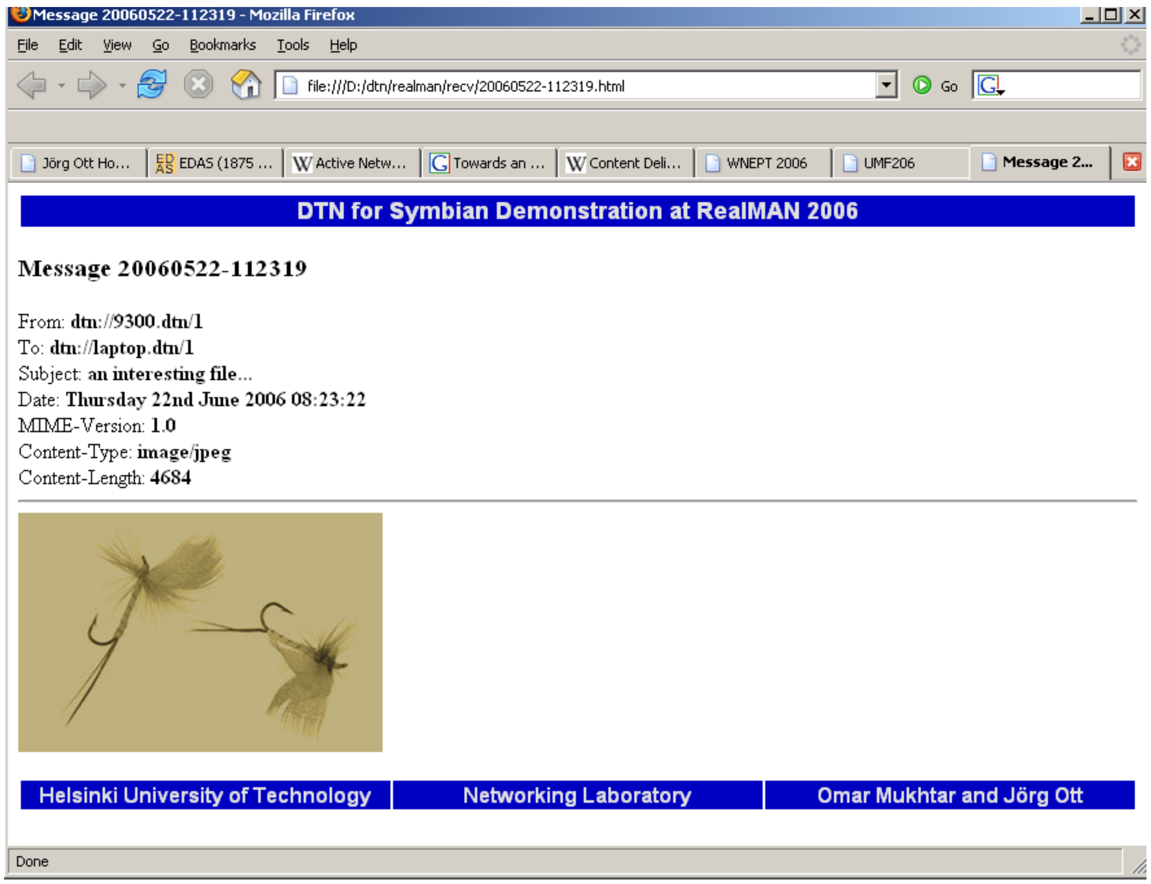
Send File

From: dtn://9500r.dtn/1

To: dtn://laptop.dtn/1

Subject: an interesting file...

Figure 25. DTN application for Symbian Mobile-phone screen-shot


Message 20060522-112319 - Mozilla Firefox
File Edit View Go Bookmarks Tools Help
file:///D:/dtn/realman/recv/20060522-112319.html
Go
Jörg Ott Ho...
EDAS (1875 ...
Active Netw...
Towards an ...
Content Deli...
WNEPT 2006
UMF206
Message 2...
Done

DTN for Symbian Demonstration at RealMAN 2006

Message 20060522-112319

From: **dtn://9300.dtn/1**
To: **dtn://laptop.dtn/1**
Subject: **an interesting file...**
Date: **Thursday 22nd June 2006 08:23:22**
MIME-Version: **1.0**
Content-Type: **image/jpeg**
Content-Length: **4684**

Helsinki University of Technology | Networking Laboratory | Omar Mukhtar and Jörg Ott

Figure 26. Screenshot of received image at laptop

6.3. Software Release

The code of the software developed during the thesis work has been released in public domain under GNU GPL license. This would provide the researchers with the further research and development opportunities, which would help extending and enhancing the work carried out so far. For more information, visit the following website:

http://www.netlab.tkk.fi/u/jo/dtn/index.html

6.4. Summary

A brief description of different verification techniques was provided in this chapter. A demonstration setup was also explained to show various application scenarios of DTN. In the next chapter, conclusions and recommendations drawn during the thesis work are discussed.

7 Conclusions and Recommendations

In this final chapter, a brief summary of the document is provided. Conclusions drawn during the research and development work are also discussed shortly. The chapter itself concludes with some recommendations and guidelines for further research.

In the very beginning, an introduction and motivation to the thesis work was presented. A comparison between the Internet and DTN architectures was discussed. In addition to that, an overview of related work was also given, along with the scope and outline of the thesis work. Next was discussed the DTN architectural design including an overview of DTN family of protocols, mainly the Bundle protocol and convergence layer protocols. This was followed by the description of the mapping of architectural design to a generic software top-level design, yet considering general guidelines for Symbian OS application design. Next, the unique features of Symbian OS and design patterns for the application design was covered. It was followed by the description of the implementation in details such as UML diagrams, algorithms.. In the last, a discussion of some testing strategies, employed for the verification of the software developed during the thesis work, was presented.

In earlier chapters (the first and the second), a brief analysis of the Internet family of protocols was given with a focus on functional and performance issues arising with the emergence of mobile ad hoc networks. Different solutions proposed for these issues were mentioned briefly, and the approach used by DTN was discussed in detail. DTN defines an overlay network on top of existing heterogeneous networks. It uses EID-based generic naming-scheme along with concepts such as late binding, multi-graph routing tables, in order to deal routing problems in heterogeneous networks where no single routing solution can work. It uses notion of virtual messaging; a message bundles all the application level data and meta-data into one data-unit, called bundle, in order to minimize transactions between sender and receiver. This as opposed to conversational style protocols such as HTTP, which are ill-suited for intermittent connections. DTN also does not follow end-to-end connectivity paradigm strictly. The communication may commence even if no connected path to destination is available at the moment. It introduces a concept of custody transfer, in which the bundles are moved away from source into the network closer to the destination. Hence for final delivery, source node is not necessarily involved, breaking end-to-end model. DTN supports multiple transport and network topologies via one or more convergence layer adapter. The main role of CLAs to provide a generic interface to Bundle layer for point-to-point reliable delivery services between the bundle nodes. We have proposed a neighborhood discovery mechanism for Bluetooth convergence layer, using SDP. The information gathered by this mechanism can be utilized by routing protocols such as flooding and PRoPHET.

DTN is an emerging paradigm for communication across a set of heterogeneous networks and protocols, each with divergent and distinct requirements such as quality of service, delays, routing, queuing, power, storage and applications. For example, a delay-tolerant network may comprise a set of sensors nodes on some planet using a satellite connection for deep space communication for sending data to earth. Being a relatively new area, research is going on in many areas to define and refine protocols to support a larger set of networks and protocol families. Routing protocols for route information propagation, policy based statistical and heuristic routing algorithms, custody transfer to non-singleton nodes, multicasting in DTN, uses of URI schemes to multiplex application data, security issues in DTN, convergence layer designs for non-conventional transport technologies such as SMS, MMS or flash disks, DTN aware application design or gateway application design enabling legacy applications to use DTN etc. are to name a few.

This thesis work can be extended in several ways mentioned above. At the moment it supports only trivial routing algorithms such as static routing and flooding. The BP-Router component can be extended to incorporate more complex routing algorithms, such as PROPHET, Swarm routing [KASS01]. Integration of Bundle Security Protocol is also one of the primary future goals. New applications design such as FTP over DTN, Web over DTN is also an area of interest. Automatic time-synchronization among the devices in an ad hoc network requires some research and development activity.

Finally, real word testing of applicability and measurements is also very important, as exploring DTN for real world inter-personal communication using mobile phones was the primary motivation factor of this work.

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