

Bachelor thesis

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Reliable UDP and Circular DHT implementation for the MediaSense Open-Source Platform

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Abstract

MediaSense is an EU funded platform that is an implementation of an Internet-of-Things framework. This project adds two fundamental functions to it, namely a new lookup service based on a peer-to-peer Distributed Hash Table (DHT) called Chord and a reliable communication protocol based on UDP (RUDP). The lookup service makes the use of a central server, that can be a single point of failure or get compromised, unnecessary. Reliable UDP transmits data from the very first packet on and avoids connection management as it is packet based. The methodology for both functions was to develop a simulation environment, compatible to MediaSense, at the beginning where functionality can be tested and measurements can be taken. The resulting DHT simulation environment enables deep insight into and control of the state and action of the DHT. The resulting graphs reveal performance properties of both, DHT and RUDP. In conclusion the MediaSense platform has been extended by two usable functionalities that leave space for further development like security enhancements.

Keywords: Internet-of-Things, MediaSense, Peer-to-peer, Chord, Distributed Hash Table, Networking, Reliable UDP, Simulation

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Terminology

Acronyms

API	Application Programming Interface
ARQ	Automatic ReQuest
BSD	Berkely Software Distribution
DHT	Distributed Hash Table
FSM	Finite-state machine
IoT	Internet-of-Things
P2P	Peer-to-peer
QoE	Quality of Experience
QoS	Quality of Service
RTT	Round Trip Time
RUDP	Reliable UDP
TCP	Transmission Control Protocol
UDP	User Datagram Protocol

1 Introduction

This work is the final thesis for the programme European Computer Science Studies at Hochschule Osnabrück created during exchange studies at the Mid Sweden University in Sundsvall.

1.1 Background

Applications that can change their behavior based on the context of the users are called context-aware applications. By the introduction of smart mobile phones that carry a multitude of sensors and actors, these applications have had a very large market penetration. The Mid Sweden University has so far produced initial components for the accumulation of context information from sensors and wireless sensor networks from numerous sources, e.g. sensors attached to home networks or mobile phones. This project comes along with the development of a next generation Internet-of-Things (IoT) architecture and their supporting protocols. The IoT is defined as applications that use information from sensors and actors to provide personalized, automatized or intelligent behaviors to the users.

1.2 Overall aim and problem motivation

To initiate a connection between two MediaSense instances (contexts) a lookup-service is needed. To handle the communication between two contexts a transport protocol is necessary. The present lookup-service, that has been implemented by the Mid Sweden University so far, is based on a client-server architecture. The well-known network protocols Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) can be used for data transmission. Since its beginning it is a requirement to the MediaSense platform to not have a single point of failure. The client-server architecture does not fulfil that need. For this reason a distributed lookup-service will be developed during this thesis work. The data transmission of the MediaSense platform has to be reliable and packet oriented. Neither TCP nor UDP fulfil both requirements at the same time. So the need for a self-made communication protocol arises.

1.3 Detailed problem statement

To have verifiable goals eight milestones are defined that are used throughout the development process and this report.

1. Develop a simulation environment, using the same Application Programming Interface (API) as MediaSense, that allows the parallel running of multiple DHT clients
2. Implement a circular Distributed Hash Table (DHT) based on Chord running inside the simulation environment that enables register and resolve operations executed in $O(\log(n))$ time
3. Evaluate the performance of the DHT in terms of self healing capability and network usage
4. Transfer the DHT solution into the MediaSense platform
5. Develop a simulation environment, using the same API as MediaSense, able to host two clients communicating over an exchangeable protocol
6. Develop a reliable packet-based communication protocol (RUDP) based on Berkely sockets (BSD sockets)
7. Compare RUDP to TCP in terms of speed and reliability
8. Transfer the RUDP solution into MediaSense platform

1.4 Scope

The DHT implementation is focused on handling client joins, leaves and fails while remaining the DHT health. For the RUDP implementation the thesis focuses on transmitting data with the very first packet and avoiding a 3-way handshake to synchronize sender and receiver.

This thesis does not focus on counteractive measurement regarding security issues like network attacks and data encryption for both, DHT and RUDP.

A further requirement to this thesis work is that the code is free of external licensing. For that reason both parts will be created from scratch.

1.5 Ethics etc

State the problems issues TODO

1.6 Outline

Chapter 2 describes the necessary background to understand this work. Nevertheless a good knowledge of networking and computing is needed. Chapter 3 describes the approach on how to solve the milestones defined in the detailed problem statement. Chapter 4 presents details of the implementation and continues with the results and measurements in chapter 5. The following chapter 6 is a conclusion covering the reflection of the thesis work including ideas for further work that arose during project time. This document also includes 3 appendices, consisting of program output, that will make some descriptions in the text more clear.

1.7 Contributions

In about 50% of the time we did pair programming where one person was programming and the other was checking and contributing orally. The other 50% we split work into small parts where the effort was in the range of some hours to a day. Because the working units were so small a detailed listing is not useful. From time to time we had meetings where we discussed the current state and the further line of action.

2 Theory

To understand the following chapters in this report, the reader needs to have some background knowledge. This required knowledge will be given during this chapter.

2.1 Internet-of-Things

The “Internet-of-Things” aims specially for two main aspects. The first one is, to interconnect all possible sensor and actors over the Internet. These sensors might be of all imaginable kindnesses, for example a GPS sensor integrated in a mobile phone, a temperature sensor in houses or a camera looking at the traffic at certain points on the streets. Also the actors can be from all imaginable kindnesses, to follow the earlier examples, an application that can tell you where your friends are, and automatic heating regulation or electronic traffic signs that change their speed limit related to the traffic situations. That all produces a larger input than humans are doing by their keyboards or mice. And exactly this is, why the IoT not only aims the interconnection of everything but also to get its components intelligent. What means that the sensors and actors should show intelligent behaviors on the output from other sensors/actors without any human help (machine to machine communication) [1].

The Mid Sweden University so far developed an approach to build a framework that is able to connect sensors and actors over the Internet and to share information between them. This approach defines nine main requirements to provide an adequate Quality of Service (QoS) and Quality of Experience (QoE). They also built a first distribution of their framework, which allows to implement new features in the future without a complete redistribution. The interested reader who would like to have more information about MediaSense should read [2].

2.2 Peer-to-peer computing

The term peer-to-peer (P2P) refers to a computer network in which each participant (peer) acts as client and server for the other participants.

This architecture allows, to share data over a network without the need of a central server [3].

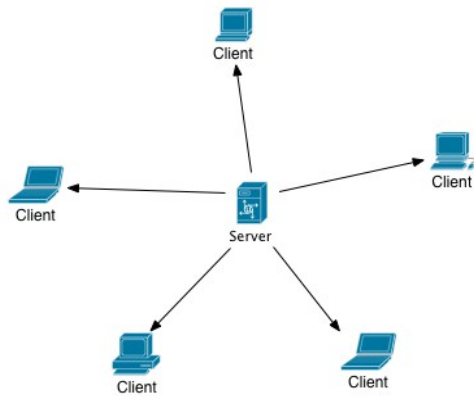


Figure 1: Client-Server model

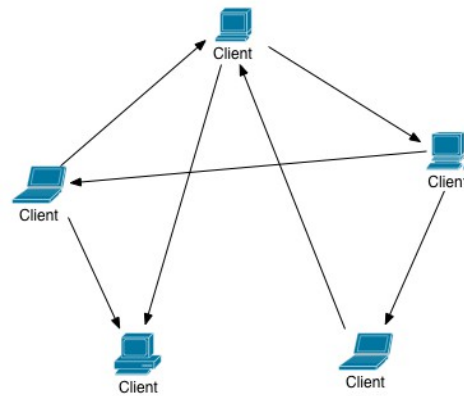


Figure 2: Peer-to-peer

P2P is a distributed application architecture that partitions duties and responsibilities among all participating peers. Each peer, often also referred to as node, has to set aside a portion of its resources to make it directly available for the other P2P participants. That means, in a P2P architecture each client has the same rights and responsibilities. In contrary to a P2P network, where each node acts as supplier and consumer, stands the client-server-model, where only servers supply and clients consume the information [3]. Figure 1 and Figure 2 present this in an illustrated way.

2.2.1 Architecture of peer-to-peer systems

Generally P2P systems are implemented as an abstract overlay network in the application layer, not influencing the physical network layer underneath. This overlay performs the indexing and peer discovery and makes the peer-to-peer system independent from the network topology [4].

P2P networks can further be divided in structured and unstructured systems. Structured systems organize their peers and resources with specific algorithms typically using distributed-hash-tables (DHT) what is explained in chapter 2.3.2. Whereas unstructured systems do not use any structure in their overlay networks [4].

2.2.2 Advantages and weaknesses

In comparison to client-server networks, P2P networks come along with the big advantage, that there is no single point of failure (i.e. the server in client-server networks). In fact P2P networks are getting more stable, the more clients are participating. Another advantage of P2P networks is, that all available resources are getting more when more clients join the network, while in client-server networks the available resources per client are getting less, because all clients have to share the resources from the server. On the other side, P2P networks also bring some disadvantages. Since each client in the system is responsible to share (publish) some of its resources, the whole system is more vulnerable for untrusted or unsigned content. This would not happen in client-server networks because there is a system administrator, who is responsible for publishing the resources [3].

2.3 Hash function

A hash function maps data of variable size to a fixed size hash-value using an algorithm that transforms the data. To be usable for a hash table the hash function has to be deterministic, which means that it always produces the same output with a given input data. The function should also produce values that are uniformly spread over the possible range of hash values to reduce hash collisions. A collision occurs when two different input keys produce the same output [5].

An important property of a hash function is the output length, specified in bits. A function with n bits output length produces hash values in the range of $0-2^n-1$ and the amount of possible values is 2^n [5].

2.3.1 Hash table

A hash table is a data structure that stores key-value pairs. The value can be any user-specified value that should be associated with the key. A hash function is used to transform the key into a hash-value that is then used as an index which indicates where the associated user-value is stored. The use of a hash function introduces the possibility of hash collisions. There are several ways to deal with a collision situation, where the easiest way is to deny the colliding key [5].

The hash-table used in this project does not use advanced collision handling techniques, so they are not described in this document.

2.3.2 Distributed Hash Table

A distributed hash table (DHT) is the same as a hash table, except that the table is distributed among several parties, where each party is responsible for a certain amount of the hash space. In the sense of P2P, party means one connected client in a distributed system. [5]

To partition the DHT, each node must have a unique identification key from the hash space that is either random or derived from unique data. [5]

Every node of a DHT can store and retrieve values in the DHT and must be able to handle requests when the requested key is in the own space of responsibility. The DHT nodes have to be connected to each other in some way to be able to interchange requests [5]. There are many different possibilities to split up the hash space in smaller parts, as CAN, Tapestry, Pastry, Chord and others [6]. This project deals with Chord, which is described in more detail in chapter 2.3.3 .

2.3.3 Chord

The Chord lookup protocol arranges its participating nodes in a circle with a maximum number of nodes limited by the amount of possible values of the used hash-function [7].

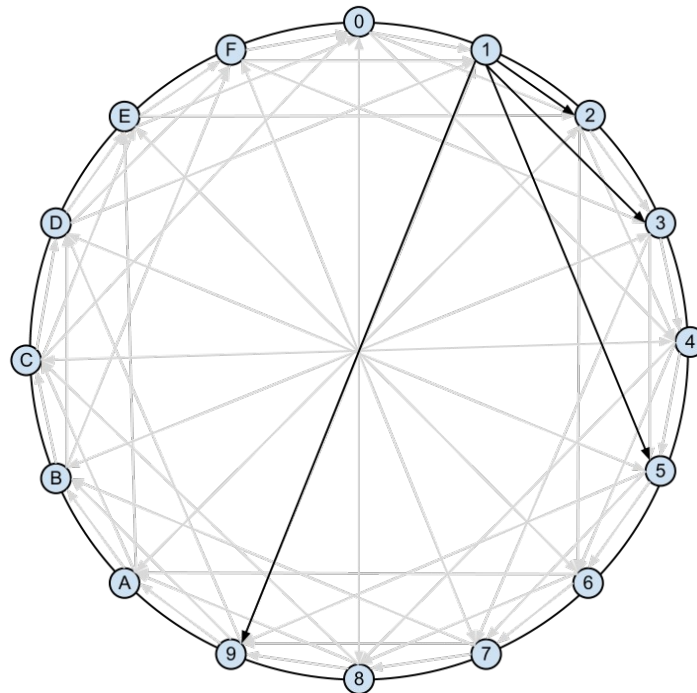


Figure 3: Chord example with 16 nodes showing the finger table of node "1"

Each node is responsible for all hash values between its own key and the key of its successor minus one: $[id, id_successor)$. As nodes enter, leave or fail, the range of responsibility changes continuously and key-value pairs have to be shifted to keep the DHT valid [7].

To be able to forward requests, and to know the responsible range of hashes each node must at least know its successor node. In this case a message between two random nodes will take $n/2$ steps on average, because every node can only forward it to its successor and the average traversal distance is half the circle. This means that the effort to find a position increases linearly with the size of the DHT. The effort can be expressed as $O(n)$. To reduce the effort a finger table is used. Figure 3 gives you a graphical overview over such a finger table [7].

Each node in a chord DHT contains a list of known other nodes of the DHT. This list is also referred to as finger table. The finger table speeds up the query process. The definition of Chord requires the finger table to point to the succeeding nodes of the hash value calculated with the following formula 1:

$$(n+2)^{i+1} \bmod m \quad \text{Formula 1: Finger entry [7]}$$

where n is the key of the node, i is the finger table entry and m is the size of the hash-value.

This means that a node can have up to n finger entries (where m is the maximum value of the hash function). Using this method the effort to find a position is at maximum $O(\log_2(m))$ because after every step the distance is decreased to the half [7].

The successor, that is also the very first finger in the finger table, is the direct succeeding node in the DHT. If the finger table contains wrong links the efficiency decreases. Despite that, the direct successor has a special role as it is important to have the DHT circular and not containing side-loops, intersections or orphaned nodes, what could cause the queries to fail. Because of that check and repair mechanisms are used to keep the correct successor, which we will be explained at a later point in this chapter.

A joining node has to do the following steps to safely enter the DHT [7]:

- query the position it is supposed to be
- ask the predecessor of that position to update its successor to that of the new node and
- ask the predecessor for its last successor which becomes the new successor of the new node
- the preceding node has to register the key-value pairs, it is no longer responsible for, to the new node
- start a finger table update process at the new node

A node that wants to leave the DHT regularly has to do the following steps [7]:

- register all of its key-value pairs to the predecessor

- send the succeeding node to the predecessor so that this node can form a circle again

Every node should do checking and repairing to keep the DHT functional and stable. This can be but is not limited to the following list [7]:

- ask for the predecessor of the succeeding node and check if it is the asking node
- regularly update the finger table entries to keep the query time at $O(\log_2(n))$

Every node in the DHT can query the predecessor of a position in the DHT. This query is either forwarded to the closest preceding node in the finger table or, if a node finds itself being the predecessor of that position, answering it directly [7].

Chord itself does not specify a method for broadcasting. But in [8] an efficient approach is demonstrated.

If a node wants to initiate a broadcast it is seen as the root of a spanning tree that covers all nodes in the DHT. The broadcast process uses unicast messages that originate at the root node and are propagated from other nodes until every node has received the broadcast. Broadcast in this case must not be confused with network layer broadcast as used in TCP / IP for example [8].

To avoid redundancy the broadcast message contains a limit value that defines the upper key in the DHT to which the broadcast shall be forwarded to. The lower limit is the node itself [8].

Assumed that Node 0 in Figure 3 wants to initiate a broadcast, the range is the whole circle from his key to his key minus one. The first step is, that Node 0 then sends messages with the following limits to its fingers:

- Node 1: [1,2) - covering one 16th of the DHT
- Node 2: [2,4) - covering one 8th of the DHT

- Node 4: $[4,8)$ - covering one 4th of the DHT
- Node 8: $[8,0)$ - covering one half of the DHT

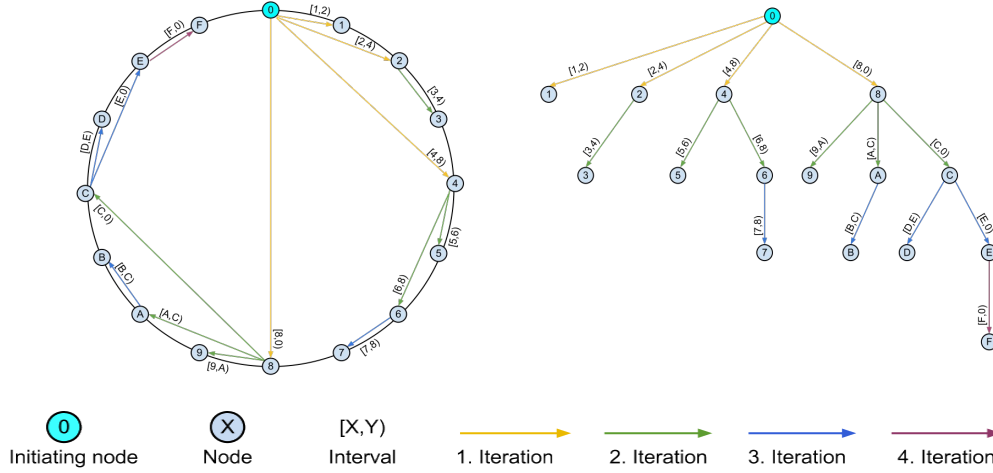


Figure 4: Broadcast algorithm

The receiving nodes forward the message to all fingers that are in the range of their own key and the received limit, without changing the limit. See Figure 4 for visualization of the message propagation in several steps. The figure shows the propagation of the message in the circle (left) and shows also an easier to understand visualization of the propagation in a tree structure (right).

All ranges combined cover the whole DHT excluding the originating node 0. If multiple fingers point to the same node, because the DHT is not complete, the message is just send once to avoid duplicates. If a finger is missing the broadcast is propagated correctly anyhow (assumed that the DHT is a correct continuous circle), but the efficiency will decrease [8].

2.4 Network data transmission

Typically network connections protocols are put in 2 categories which are packet oriented and connection oriented [5].

The packet oriented protocols sends packets from a source to a destination. The path the packets take is not predetermined and can change from packet to packet. If more packets are sent the order can change on the way to the destination. Packets can also get lost without

any notice. It is up to the application programmer to include meta information into the packet data if correct order and reliable transmission is required [5].

The User Datagram Protocol (UDP) is one famous packet oriented data transmission protocol [5].

A connection oriented protocol does not handle data as separate packets but as a continuous stream of bytes. To enable this, some arrangements have to be taken to overcome data reordering, corruption, and loss of data [5].

Usually a connection oriented connection can be split into 3 stages [5]:

1. Connection establishment - The sender contacts the receiver and tries to setup connection parameters and synchronization. If the receiver agrees a virtual link is established between both sides.
2. Data transmission - Both sides can send and receive data during this phase.
3. Connection shutdown - One side decides to shut down the connection link, informs the other side about that decision, and both start a shutdown process, like emptying buffers and stop sending data. After that the virtual link is considered to be closed. No data can be transmitted beyond that point.

Reliable data transmission uses several techniques to detect and correct errors. Those who are important for this project are explained in the following sections.

2.4.1 Cyclic Redundancy Check

A CRC algorithm calculates a value of fixed length from data of variable length (similar to a hash function). The CRC value is unique for given data and small changes to the data should lead to totally different CRC values [5].

Before transmission the CRC value is calculated and attached to the data. After reception at the destination the CRC value is calculated

again and compared to the sent data. If both values differ the data or the sent CRC have been altered during transmission and the data can be considered as erroneous [5].

The precision to detect one or more errors depends on the length of the calculated CRC value. Assuming the CRC value consists of n bits the probability to detect an error is $(2^n - 1)$ and the probability to miss an error is $1/(2^n)$ [5].

2.4.2 Window flow control

The task of flow control is to not overload the receiving side of a communication link with data. This means that the sender stops to send information after a certain amount of sent data or packets and waits for information from the receiver when to continue [5].

Window in this sense means that the receiver has a window in form of a buffer the sender can send data to. For this to work every data unit needs a sequence number that identifies its position in the data stream. The receiver has to make sure that it can at least receive as many data as would fit into the window buffer [5].

A typical implementation is a \gg moving window \ll that has a starting point and a length. The sender starts to fill the window from on side with increasing sequence numbers but only until the window length is reached. The receiver consumes received data in ascending order and then shifts the window to the point of the last unconsumed data unit. This way the opposite site of the window gets free for additional data to be received. The sender has to be informed about the window shift so it knows when it is allowed to continue data transmission [5].

2.4.3 Reliable UDP

The term Reliable UDP (RUDP) originally refers to a simple packet based transport protocol that was defined to transport telephony signaling across IP networks. The IETF defined in their draft the following criteria [9]:

- *“transport should provide reliable delivery up to a maximum number of retransmissions (i.e. avoid stale signaling messages).”*

- *“transport should provide in-order delivery.”*
- *“transport should be a message based.”*
- *“transport should provide flow control mechanism.”*
- *“transport should have low overhead, high performance.”*
- *“characteristics of each virtual connection should be configurable (i.e. timers).”*
- *“transport should provide a keep-alive mechanism.”*
- *“transport should provide error detection.”*
- *“transport should provide for secure transmission.”*

Further it was defined that RUDP should be defined in a way that it is easy possible to allow different characteristics for each connection so that the header length could be kept as short as possible [9].

3 Methodology

The project consists of two separate parts. Part one is the development of a Distributed Hash Table (DHT) and part two the development of a Reliable User Datagram Protocol (RUDP). The approach to solve each milestone as defined in chapter 1.3 will be described in this chapter.

All the development is done using the Eclipse [10] Integrated Development Environment (IDE) and all project related content will be shared over a Git repository [11].

3.1 Develop a simulation environment for DHT clients

The simulation environment should have the identical API as the MediaSense platform to ease the later transfer of the implemented DHT. Furthermore the simulation environment should enable the following operations:

Host an theoretical unlimited amount of DHT clients (limited by resources only)

- Allow clients to join the network
- Allow clients to leave the network
- Simulate network connection delays and failures
- Regularly record client and DHT properties for statistical evaluation
- Monitor messages exchanged between clients
- Allow listing of detailed client information like finger-table, successor, predecessor, internal state etc.
- Visualize the DHT in a Graphical User Interface (GUI)

3.2 Implementation of a circular DHT

As described in the background chapter, a DHT is a virtual space of addresses containing at least one client. Each client is responsible for the address range between his own address and its successor, further each client has exactly the same responsibilities and rights in the DHT. The following list shows the functionality that each DHT client should have:

- Insert a joining node as the new successor if the clients address is between the current clients and successors address
- Forward queries to the client in the finger-table whose address is closest to the destination address
- Maintain a list of fingers (finger-table) to other clients in the DHT.
- Detect and handle unreachable clients
- Execute self-checks regularly and correct wrong links if necessary
- Initiate and forward broadcast messages

Generally each query to a client that is participant of a DHT should return an answer.

3.3 Evaluate the performance of the DHT

To produce comparable characteristics the DHT solution should be evaluated as specified in the following list. The comparison to other implementations is not part of this project. Note that N represents a different amount of nodes.

- Measure the health of the DHT in the following situations
 - N nodes joining
 - N nodes leaving
 - N nodes failing

- Measure average transmitted data per node in the following situations
 - N nodes joining
 - N nodes leaving
 - N nodes failing
 - Idle DHT with N nodes

3.4 Transfer the DHT solution to the MediaSense platform

After successful simulation and evaluation, the DHT should be transferred to the MediaSense platform. Although the API is the same it must be verified that the DHT still fulfills the desired functionality. The DHT will be tested by installing the MediaSense platform on several computer systems inside the University network.

3.5 Develop a simulation environment for communication protocols

The simulation environment should have the identical API as the MediaSense platform to ease the later transfer of the implemented RUDP. Furthermore the simulation environment should enable the following operations:

- Host two MediaSense communication instances
- The first instance should be used to send data and the second to receive data
- Check the transmitted data for errors
- Record statistical data during data transmission
- Simulate network delay, packet corruption, packet loss, packet reordering and packet duplication

3.6 Develop a reliable packet-based communication protocol

The RUDP protocol should be a reliable and packet-oriented communication protocol using UDP as the underlying transmission protocol. The protocol should have the following properties:

- Connectionless (no connection establishment and disestablishment needed)
- Detect and request the re-sending of corrupted and lost packets
- Detect and drop duplicate packets
- Reorder disordered packets if possible - request re-sending otherwise

3.7 Compare RUDP with TCP

As TCP is a sophisticated protocol that has been tuned over the years of use, comparison to this protocol seems reasonable to figure out where the strengths and weaknesses of RUDP are. Within the simulation environment both protocols will be compared in the following disciplines:

- transmission speed in error free environment
- transmission speed in erroneous environments
- transmission overhead
- required additional traffic in error situations

3.8 Transfer RUDP to MediaSense

After successful simulation, the RUDP protocol should be transferred to the MediaSense platform. Although the API is the same it must be verified that the protocol still fulfills the desired functionality. RUDP will be tested by installing the MediaSense platform on several computer systems inside the University network.

4 Implementation

This chapter describes the implementation process of the goals defined in chapter 1.3. Figure 5 illustrates this process. A sub-chapter to each defined goal describes detailed the important points.

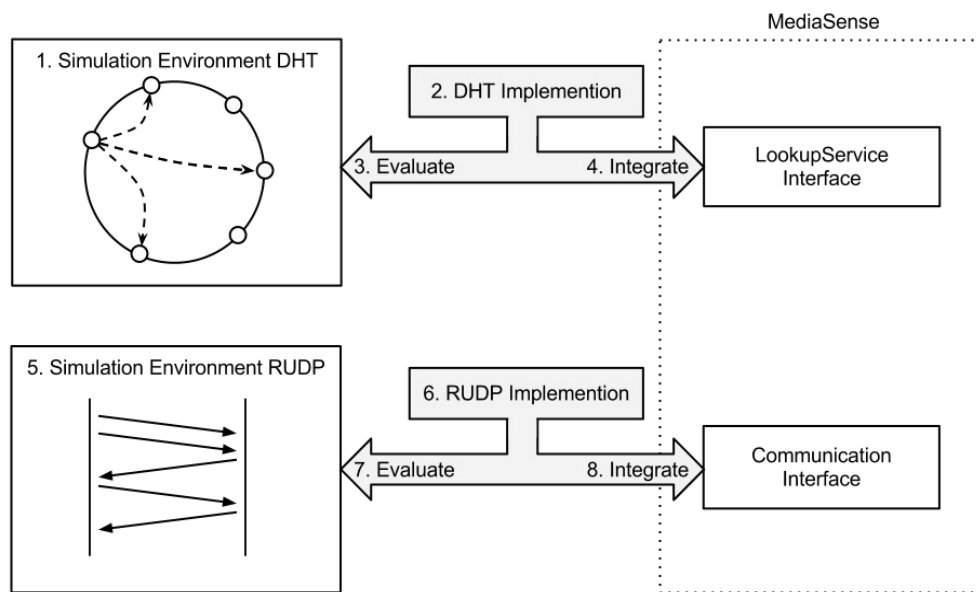


Figure 5: Workflow

4.1 Develop a simulation environment for DHT clients

Since one of the defined goals is to integrate the developed DHT solution to the MediaSense framework, the simulation environment is build upon the same interfaces as the framework uses. Figure 6 shows a rough class diagram about how the simulation environment is structured.

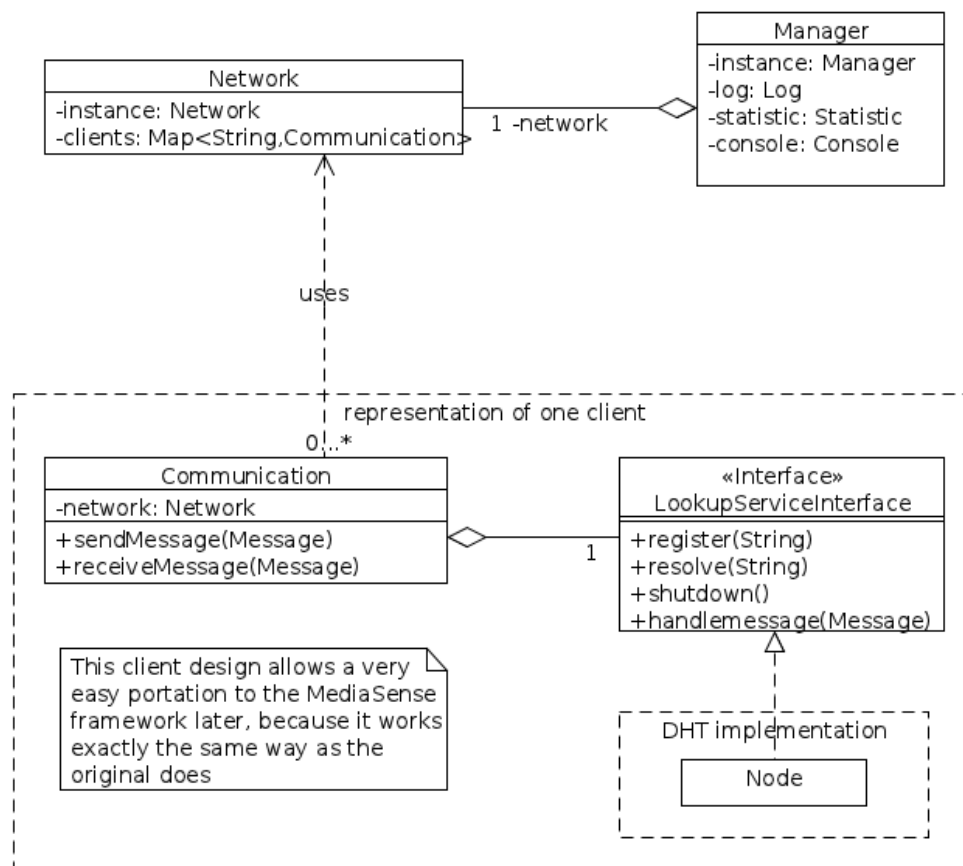


Figure 6: Class Diagram

4.1.1 Manager

The Manager class is the main entry point to the simulation environment. Here everything is tied up, what in fact means, the debug log is started, the statistic for performance measuring is controlled and the commands from the console are forwarded.

4.1.2 Client Simulation

To simulate exactly the same per-requirements that follow from the MediaSense framework, each client consists of an Communication object and an LookupService object running separately in independent threads. The Communication object is responsible to send (send means, receive from the LookupService and forward to the network layer) and receive (receive means, receive from the network layer and forward to the LookupService) messages, and can be seen as the glue between the network and the DHT implementation.

4.1.3 Network

Because the development of the lookup-service is independent from the physical network layer, the simulated network is a fully reliable message forwarding service between the nodes. It allows to define different communication delays for each node or the whole network. To be able to forward messages to all clients, the network holds a map with Communication objects related to their address. Because it is only possible to have one big network, this class is implemented as singleton.

4.1.4 Console

The Console class is the main interface to the user, to control the simulation environment. The most important functionality is that clients can be added or removed from the network and that sensor can be registered and resolve attempts can be started. A complete overview of all commands and a short description is placed in appendix A.

4.1.5 Graphical User Interface

From the console it is possible with the command “g” to start a graphical user interface. The GUI is built with basic Java Swing components, and kept as simple as possible. Further the GUI draws a visualization of the hash space and how the clients act in this space, therefore Java AWT Graphics classes are used.

4.1.6 Log

The Log class writes a text file with all possible debug outputs from the simulation environment. The debug outputs do include the following points:

- Joining, leaving and disappearing nodes
- All messages forwarded by the network.
- Keep-alive initiations
- Finger changes

4.2 Implementation of a circular DHT based on Chord

Figure 7 shows a finite-state machine (FSM) which illustrates the life cycle of a node. It has to be mentioned that this FSM is only a brief mapping of the real implementation, but nevertheless shows the most important functionalities.

The state q0 is the entry point when a node starts and q5 is the final state, which will be reached when a node shuts down.

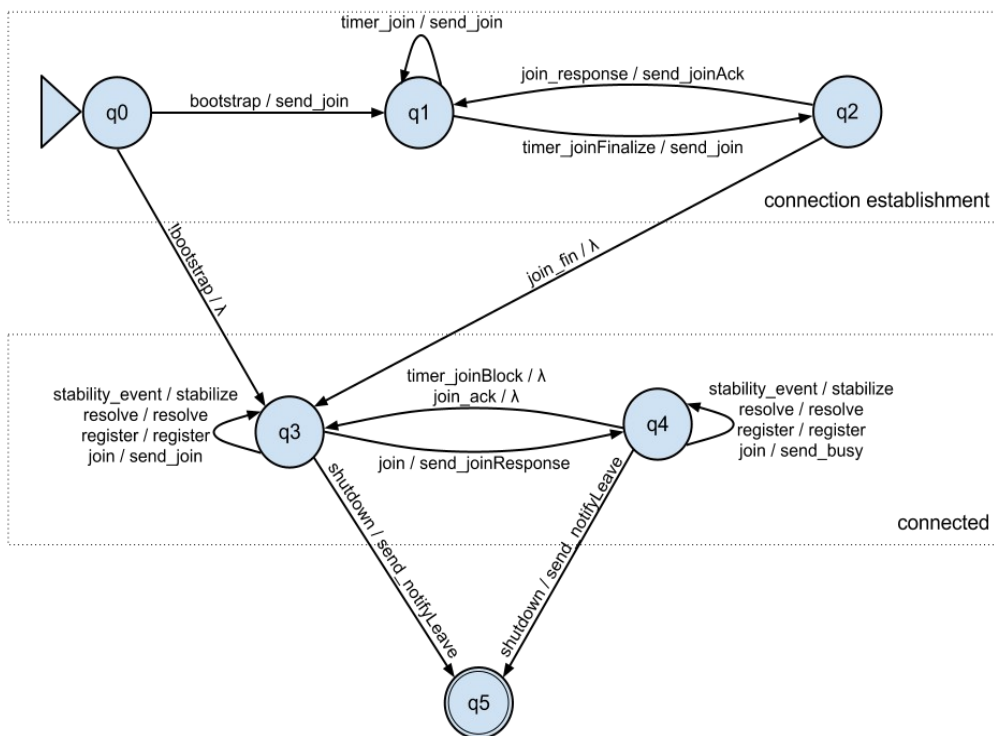


Figure 7: Finite State Machine for a node

4.2.1 Join process

The join process is illustrated in the box “connection establishment” in Figure 7. Starting in q0 there are two different possibilities. The first one is, that the node has no bootstrap address and therefore acts itself as a bootstrap node (create a new DHT instance). Is that the case, the node immediately changes to the connected status and the connection establishment box is left. The second possibility is, that the node gets a regular bootstrap address. In that case, the node will try to establish a connection to a already running DHT instance. If the connecting node

does not get an answer in a specified time, it will start a new attempt to join the DHT.

If a node is responsible for another node to join the circle, it is “blocked” for this process and can not insert other nodes until the insertion process has finished.

4.2.2 Leave process

There are two possible ways in a DHT how the nodes might finish their availability. The regular way should be that the node sends a NOTIFY_LEAVE message to the DHT to inform all other nodes about its disappearance, but there are of course also problems like failing links when the node is not able to inform the DHT about its disappearance. In that case, the first node that recognizes the a failing node, has to send a NODE_SUSPICIOUS message to all participants in the DHT.

4.2.3 Message types

The DHT implementation uses 3 different categories of propagating messages. Each category contains several message types, where each type can contain additional data that is associated with that type

Some messages are directly send to another node without being further forwarded. The following messages are direct node to node messages:

- REGISTER_RESPONSE - Response from a node that register a key-value pair that it is responsible for to the initiating node
- RESOLVE_RESPONSE – Response from a node that knows the location of a registered sensor to the queried key
- JOIN_RESPONSE - Response from the predecessor of a new joining node that the new node can enter the DHT directly after the predecessor
- JOIN_ACK - Acknowledge that a new joining node has accepted the response and accepted the predecessors former successor is its new successor

- JOIN_FINALIZE - Last message in the 3-way handshake to join the DHT that informs the joining node to consider itself to be regularly connected
- DUPLICATE_NODE_ID - Response to a JOIN-message if the joining node tries to join with an already existing hash value
- FIND_PREDECESSOR_RESPONSE - Response from a responsible node to a FIND_PREDECESSOR-message to find the predecessor of a certain hash-value
- CHECK_PREDECESSOR - Request the predecessor of the destined node
- CHECK_PREDECESSOR_RESPONSE - Response to a CHECK_PREDECESSOR-message, containing the predecessor of the answering node
- CHECK_SUCCESSOR - Request the successor of the destined node
- CHECK_SUCCESSOR_RESPONSE - Response to a CHECK_SUCCESSOR-message, containing the successor of the answering node

Another possible message type are query messages. Query messages can be send to any node in the DHT regardless a node is responsible or not. The message is either forwarded to a node of the finger that is closest to the queried destination or answered if the receiving node is one responsible for the destination. For this reason every message must at least contain a hash value (key) that represents the destination position. The following messages are query messages:

- REGISTER - Query to register a key-value (usually a sensor / actor) pair in the DHT
- RESOLVE - Query to resolve a value associated to a key stored in the DHT
- JOIN - Query of a new node to enter the DHT

- `FIND_PREDECESSOR` - Find the predecessor of a key specified inside the message

The last possible message type are broadcast messages. A broadcast message is a container that can encapsulate any other message. As described in chapter 2.3.3 a broadcast message needs a limit which is the maximum hash value to which a certain node should forward a message. The initiating node sets these limits according the position in the finger table. For this to work a broadcast message must at least contain a start-key and an end-key to specify this range. For a normal broadcast the start-key is always the initiating / forwarding node. But to be able to send multicast messages in the future a start-key field is also present that contains the redundant information of the current node at the moment. The following messages are used for broadcast propagation:

- `BROADCAST` - Container itself; Only contains the start-key, end-key and the encapsulated message
- `KEEPALIVE` - Message that is regularly send to check the network connection and to advertise nodes for finger table upgrading.
- `NOTIFY_JOIN` - Send by a node after the join process to inform all other nodes of its arrival
- `NOTIFY_LEAVE` - Send by a node before the shutdown process to inform all other nodes of its planned leaving
- `NODE_SUSPICIOUS` - Send by a node that has encountered a network problem with another node to inform all other nodes in the DHT of that

4.3 Evaluation of the DHT solution

This sub-chapter explains the functionality that has been built to evaluate the DHT solution. Additional to those parts that are defined in a sub chapter, testing the DHT implementation in the simulation environment also is a part of the evaluation.

4.3.1 Health

The health of the DHT can be measured using the health function. These function returns a value between 0 and 1 where 0 represents the worst case and 1 represents a perfect DHT. The manager class is able to calculate which node must have which fingers in its finger table and checks how many fingers are missing or not at the correct position. Out of that calculation the health is built.

4.3.2 Statistic

With the command “`statistic file-path`”, it is possible to write a statistic to the specified file. The statistic is triggered once per second and writes the following data points to a matrix in the specified file. For an example statistic see Appendix C.

- **Timestamp:** A timestamp when the data in this line has been collected
- **Sec:** Absolute seconds since the statistic has started to collect data
- **Hth:** The health of the DHT
- **Con:** Currently connected nodes in the network
- **Fin:** Fingerchanges that happened
- **Data:** Data that has been submitted over the network
- **Pkt:** Number of messages that have been submitted over the network
- **ConD, FinD, DataD, PktD:** See upper definition, but as delta since the last second

4.4 Transfer the DHT solution to the MediaSense platform

As the API of the simulation environment was adopted from the MediaSense platform moving the source files was enough despite the removal of the debug functions. These were designed in a way where

they could be removed easily without influencing other program parts. The existing MediaSense framework has already a layer for Lookup-services since it has already a client server solution. Regarding this a new package has been constructed where the source files has been inserted.

4.5 Develop a simulation environment for communication protocols

Since another goal defined in chapter 1.3 is to integrate the developed RUDP solution to the MediaSense framework, the simulation environment is build upon the same interfaces as the framework uses.

The hardware setup consists of 2 pc's connect through a router. The network bandwidth was 100 MBit/s. One PC was sender, and the other receiver of random data packets of 1024 Bytes length. The first 4 bytes were replaced with a continues check sequence starting from 0. The receiver checked the sequence for continuity to detect transmission failures. Each measured data point is made of a new transmission of 200000 packets what leads to a total data amount of 200 MB. Figure 8 shows a visualisation of the setup.

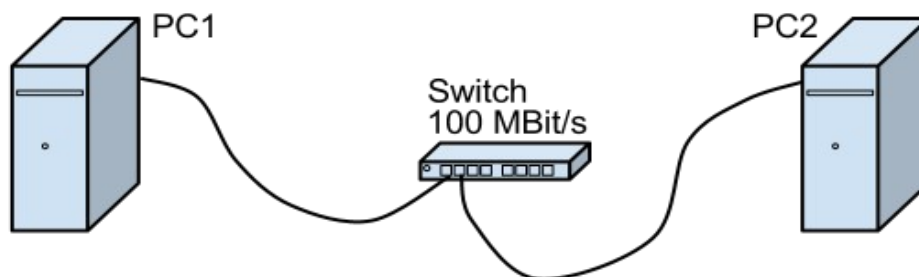


Figure 8: Hardware setup reliable udp simulation

4.6 Develop a reliable packet-based communication protocol

Figure 9 and Figure 10 show to two finite state machines describing the behaviour of the receiver and sender. Both need to receive /send a FIRST flagged packet first to know each others state and to proceed to synced state. The FIRST packet can already contain user data. After synchronisation packets can be sent and received as described in the following sections. A RESET packet can be used to reset the SENDER if

the synchronisation state was unequal. If the link is not used after a certain amount of time it is shut down.

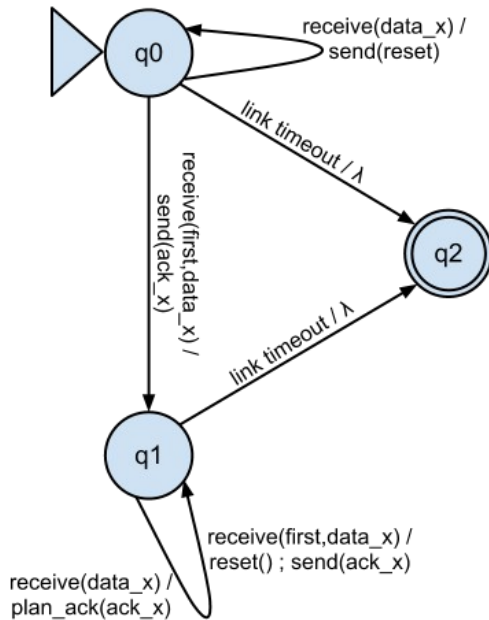


Figure 9: RUDP receiver

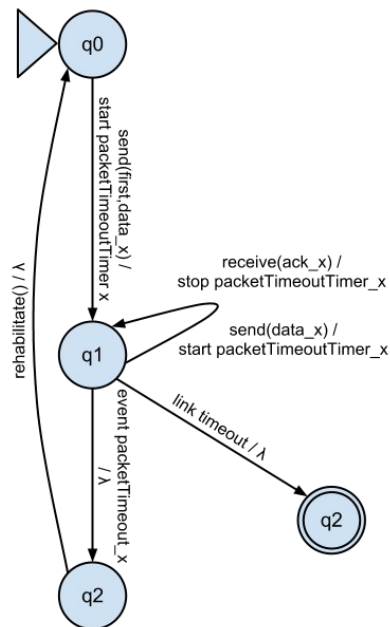


Figure 10: RUDP sender

4.6.1 Packet structure

Each RUDP packet consists of several fields as shown in table 1. The function of each field is described below the table. Not every packet has the same structure because some parts (i.e. the acknowledgement fields and the data fields) are optional,

Name	Offset (Bytes)	Length (Bytes)	Type
Flags	0	1	Bit field
Packet sequence	1	4	Integer
Window Size	5	4	Integer
Fragment number	9	2	Short
Fragment count	11	2	Short
<i>Acknowledge sequence</i>	13	4	Integer
<i>Acknowledge field size</i>	17	2	Short
<i>Acknowledge field</i>	19	$n * 2$	Short-array $0 < n < 32$
<i>Data</i>	13 - 83	0 - 65362	Byte array

Table 1: RUDP packet fields (*Italic* fields are optional)

- Flags (8 bits) - bit field containing flags
- First (bit 0) - first packet containing application layer data
 - Reset (bit 1) - request to reset receiver state
 - ACK - (bit 2) - packet contains acknowledge information
 - Data (bit 3) - packet contains application layer data
 - Resend (bit 4) - packet was resend
 - Fragment (bit 5) - packet is fragmented
 - Persist (bit 6) - request an acknowledge packet
- Packet sequence - continuous number that identifies each packet
- Window size - specifies the window size of the sender's receiving window
- Fragment number - specifies the fragment number of a fragmented packet from 0 to fragment count - 1

The following fields are only present if the ACK flag is set:

- Acknowledge sequence - specifies the start sequence of the acknowledged window
- Acknowledge field count - specifies the amount of acknowledge regions
- Acknowledge field - contains the acknowledged regions

The following field is only present if the Data flag is set:

- Data - contains application layer data

4.6.2 Data integrity

RUDP is based on UDP which uses a CRC value to ensure data integrity. The CRC value is 16 bit long and is placed in the UDP header. In case of a corrupted packet the underlying layer will automatically drop this packet, so no additional checksum field has been implemented in RUDP.

4.6.3 Link synchronization

Each packet that is used to transport user data, marked with the DATA flag, is associated with a sequence number that identifies this data. The packet number is valid between two communicating hosts, also called a link. Each direction, sending and receiving, have an own sequence number. The very first packet that is sent on a link is marked with the FIRST flag and contains the first sequence number the sender can choose. Every packet, that follows the first packet, must have a sequence number increased by 1. Using this mechanism the receiver is able to recover the packet stream, if packet loss or reordering occurs. The range of the sequence number is $-2,147,483,648$ to $+2,147,483,647$. So care has to be taken on the overflow that occurs at the maximum value. RUDP does this by never using absolute comparisons.

Both, sender and receiver, have to be in a well-known state when the data transmission starts. Virtually that means that a receiver must know the current sequence number of the sender, and the sender must know the state of the receiver window start and size. The first data packet on a link is marked with the FIRST flag. A new receiver must always get a FIRST flagged packet at the beginning and takes the used sequence number as a reference for all proceeding packets. A new sender assumes the receiver's window size to be 1 and is thus only allowed to send one packet at the beginning, that is also marked with a FIRST flag. The receiver then places its receiving window start to that sequence number and sends an ACK packet immediately which contains the own window size. Take a look at Figure 9 and Figure 10 for easier understanding.

Unsynchronized situations can appear where the knowledge about each others state is not consistent. If the receiving side of the link gets a FIRST flagged packet when it does not assume one or it gets an unflagged packet when it assumes a FIRST packet it resets itself and

sends a packet with the RESET flag set. After reception of a RESET the link must reset its state and behave like a newly created link.

Every sent packet has to be acknowledged implicitly or selectively, as described in the following paragraphs. Packets can be acknowledged in groups. An acknowledgement is sent in the following situations:

- If the receiver buffer is less full than 2/3rd: 100 ms after a packet has been received. The 100 ms wait time is used to collect more packets and reduce the number of ACK packets
- If the receiver buffer is filled equal or more than 2/3rd: immediately after a packet has been received
- If the receiver buffer was completely full and gained new space
- If a packet with a PERSIST flag has been received

Take a look on Figure 11 after reading each of the following paragraphs. This will give you the opportunity to understand the different acknowledgement possibilities and the shifting of the windows easily.

If a receiving side of a link received and consumed data packets, it shifts its own receiving window to the next unconsumed or unreceived packet. The next outgoing ACK packet contains this new window start sequence. Every packet that lies between the old and the new window start is implicitly acknowledged as successfully received.

Received packets can explicitly acknowledged by the receiver. This is done when the receiver window contains gaps with unreceived packets or the packets have not been consumed yet and still block the receiver window. Acknowledge field count and acknowledge field are used to carry the selective acknowledge data. Acknowledge field count specifies the number of the following acknowledge fields (possible amount is 0 to 32). All acknowledge field data is relative to the acknowledge window start value. The format of the acknowledge field is as follows:

The acknowledge field contains acknowledge field count + 1 values of type short. Number n to number n+1 specifies a range of n to (n+1) - 1.

Every even range with an even number specifies acknowledged packets and every odd range specifies unacknowledged packets. Have a final look to Figure 11 now to understand the whole thing.

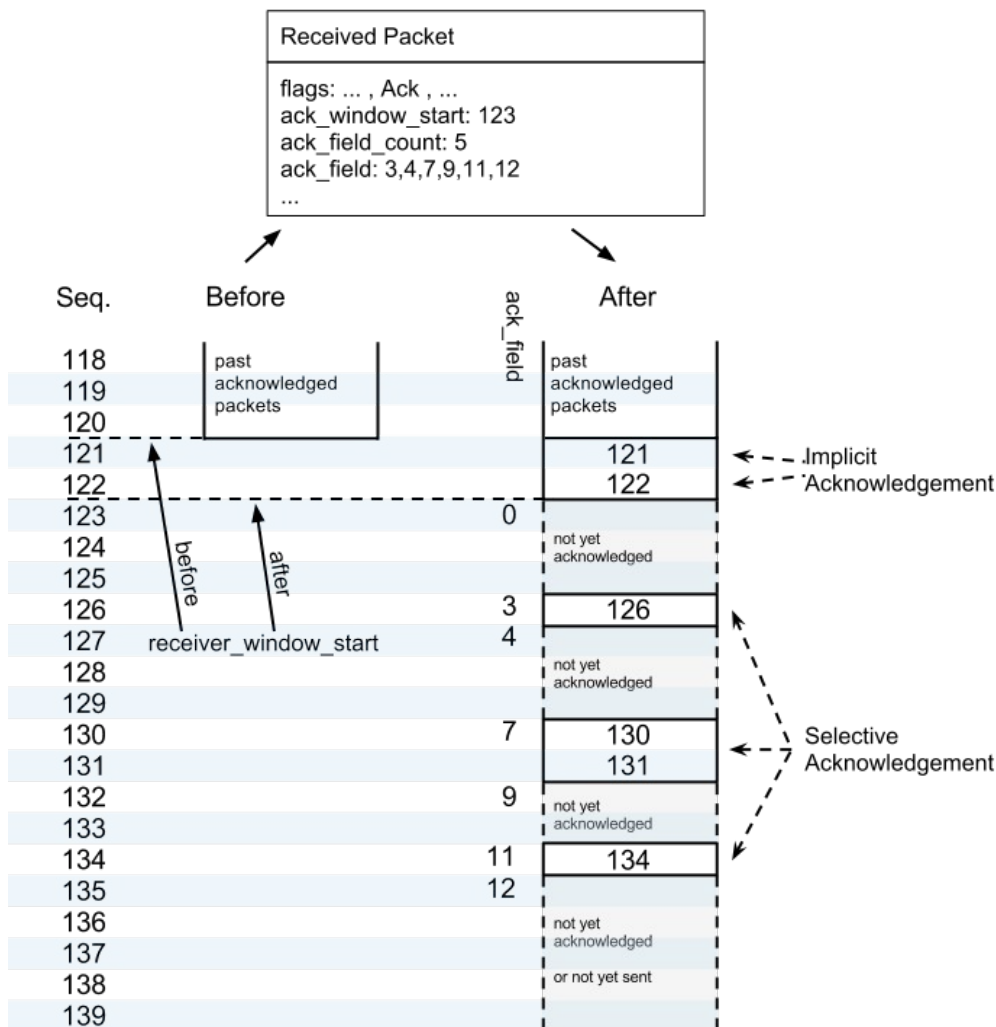


Figure 11: Example of receiving an acknowledgement packet

If a packet is not acknowledged implicitly or selectively after a fixed amount of time the packet is resent and the wait timer for this packet is started again with the wait time doubled. After 5 unacknowledged tries the link is assumed to be failed and put into shutdown state.

A link is considered as failed if a packet is not acknowledged after 5 send tries. The whole link, including sender and receiver, is then put into link-failed state. Every send and receive attempt on that link will then lead

to an exception of type *DestinationNotReachableException*. The link can be reset using the `rehabilitate()` function. The link is then put into an initial state and all buffers are cleared. Failed packets have to be resent by the user application.

When the receiver window is full the receiver informs the sender when the buffer contains free space again to receive more packets. If this ACK packet gets lost a deadlock situation can occur. To prevent this a persist timer is started at the sender when the last, buffer filling, packet was sent. After expiration of the timer a packet with the PERSIST flag is sent and the receiver answers with an ACK packet informing about the buffer state. The persist packet has the same resend behavior as a normal data packet, but does not contain data itself. If the persist packet is not acknowledged or the receiver buffer is not free within the persist packet transmission attempt, the link is considered failed and put in link-fail state.

4.6.4 Flow control

Every link consists of a sender and a receiver part. The receiver has a receiving buffer, or receiver window, whose size the client can decide as appropriate. The sender sends data “into” this window specifying the current position with the sequence number and is only allowed to stay within window bounds. The receiver can shift the window towards positive direction if it received and consumed packets. The sender is informed about the new window position through the Acknowledge sequence field in ACK packets. See Figure 12 for an example of receiver window action.

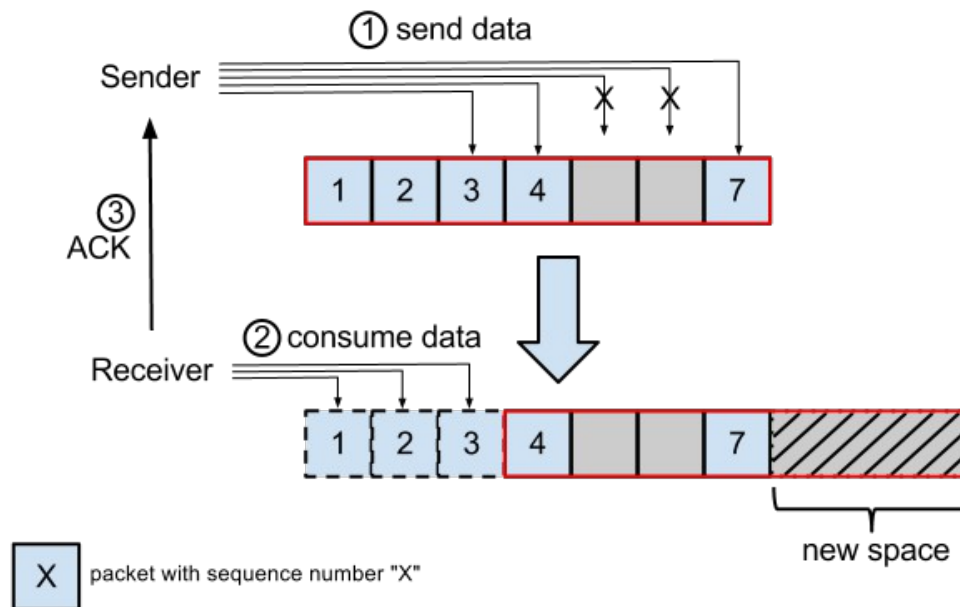


Figure 12: Visualization of the window shifting process

The client has to make the consideration about the window size. A smaller window consumes less memory and a larger window allows more unacknowledged packets and less reaction time.

4.7 Compare RUDP to TCP in terms of speed and reliability

We used the simulation environment for the evaluation. Two RUDP sockets are connected to each other over an isolated network. The reliability has been checked by transmitting random data in one direction between the 2 sockets and comparing the correctness and order of the data after reception.

To test bad conditions in a reproducible way the Linux tool `>>tc<<` (traffic control) was used to simulate packet loss, packet reordering, and packet delay. This tool changes kernel network parameters for outgoing packets.

4.8 Transfer RUDP to MediaSense

As the API of the simulation environment was adopted from the MediaSense platform only the class files had to be moved. For performance purposes the debug functions have been disabled before

integration. For verification the MediaSense software has been tested with RUDP as the underlying protocol for the dissemination layer.

4.9 Additional changes

Some improvements have been made apart from the mentioned milestones. The improvements have been implemented during the DHT implementation phase. The need arised because we discovered some design issues we did not want to adopt or software to.

4.9.1 Message serializer interface

The source and destination addresses are now passed as arguments to each message serializer as this information is available from the context of the underlying network layer. Also it is not necessary to include the source and destination addresses in the application layer protocol as they are always available from the network layer.

4.9.2 Binary message serializer

Additionally to the “EnterSeparatedMessageSerializer” a binary message serializer was implemented to have an efficient protocol without any redundancies. See Figure 13 and Figure 14 for details of the message fields for unicast and broadcast messages respectively.

Bit offset	0-7	8-31
0	MAGIC_WORD	
32	Type	Begin of user defined data

Figure 13: Unicast packet structure

Bit offset	0-7	8-31
0	MAGIC_WORD	
32	Type	start-key
256	...start-key	end-key
480	...end-key	Begin of user defined data

Figure 14: Broadcast packet structure

5 Results

This chapter describes the results of the project. These include the output of both implementations we applicable. Mainly this chapter focuses on the results of the measurements and evaluations.

5.1 Chord simulation environment

The simulation environment contains 2 input / output methods. The first is a command line that allows every possible action on the DHT and to monitor events of the DHT. The second is a GUI whose main purpose is to visualize the structure of the DHT in a graphical way. The GUI contains only a basic set of DHT actions.

The command line takes commands, where each command has a different amount of parameters or no parameters. A command is always one contiguous word. If parameters follow, they are separated by a coma from each other and with a space from the command. Output is printed to the same command line. For a complete reference of all commands and their parameters see Appendix A. The functions of the command line are as follows:

- Add, remove and kill nodes
- Watch events like transmitted messages, node changes and finger changes
- Print node information like fingers, id and network address
- Print the health of the DHT
- Control other simulation functions like the GUI and the statistics function

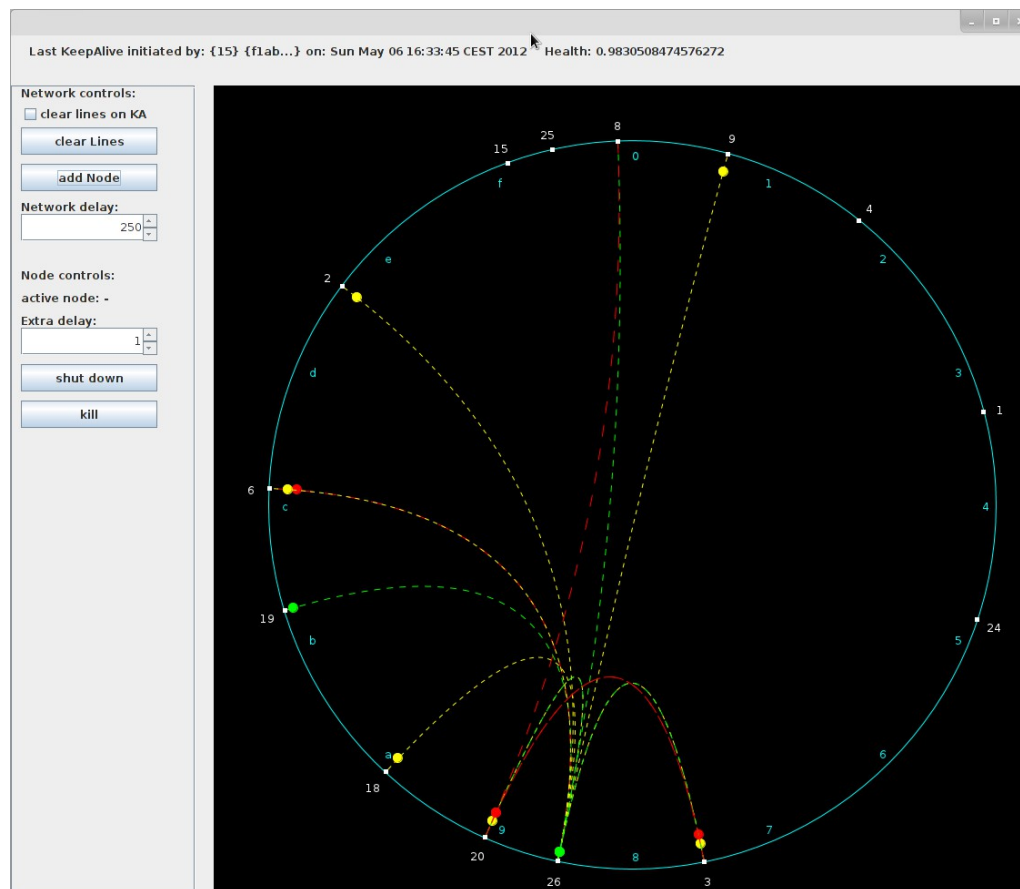


Figure 15: Screen-shot of the GUI

In the GUI the DHT is visualized in a circle that represents the hash space of the DHT. Every node is marked as a small rectangle on the position of its hash value on the circle and the network address attached to it. By hovering a node with the mouse the current finger table of that node is displayed in a purple. Every finger change of a node is indicated by a line going from the node that contains the finger to the finger itself. Different colors indicate which finger action was monitored as described in the following list:

- New finger added
- Finger removed
- Better finger added (that replaces a worse finger)
- Worse finger removed (that was replaced by a better finger)

Every finger change is added up. The lines can be removed by either clicking “Deletes lines” manually or on every keep-alive broadcast message by checking the box “Clear on ka”. The later allows for good visualization on which effects the last keep-alive event had on the health of the DHT. The GUI further allows some basic control of the DHT. That is adding nodes, removing nodes and changing the network and node delay. For a screen shot of the GUI look at Figure 15.

When the amount of events is too high inspection of events on the command line could become too complicated. For that purpose a log-file is created that contains exactly the same information. The log file can be used for further evaluation like using in a text editor. The log file is automatically created every time the simulation environment is started and is saved to a file in the users directory called “media_sense.log”. Every event produces a new line in the file always starting with a timestamp. The following events are logged:

- Transmitted messages
- Node add, remove and kill events
- Finger change events
- Keep-alive events

See appendix B for an example log file.

5.2 Chord statistics

The following graphs were constructed by gnuplot [12] using the data files that have been written from the statistic class. Each graph will be described by a following text for better understanding. The graphs will show the described scenarios from chapter 3.3.

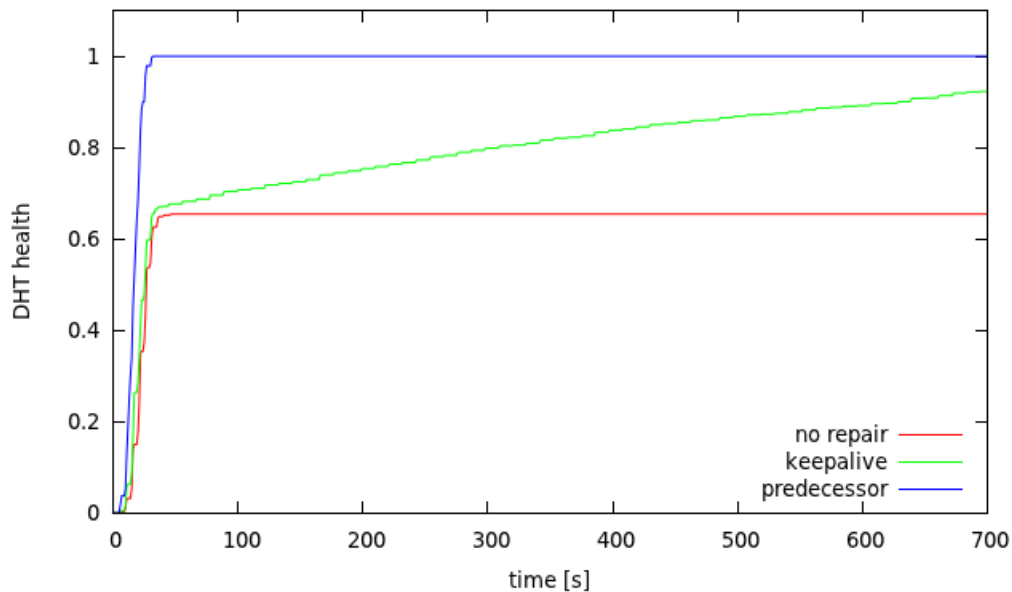


Figure 16: Health in different development statuses

Figure 16 shows the DHT health in relation to the passed time. The data lines have been recorded at different development phases, but all in the same scenario. This scenario was to insert 1000 nodes directly after starting the system. The red one (no repair) was at a very early level, when the DHT solution did not have any repair algorithms. It shows that the DHT health was never better than approximately 0.6 what means that 60% of all fingers in the DHT are correct. When `KEEPALIVE` messages had been included (green line), the health did not stay at a certain level, but increased logarithmically over time towards 100%. At a certain point in the development process we had the idea to store the predecessor of every node additionally to the finger table. With this extra information it is possible to have 100% health immediate after the insertion of all nodes.

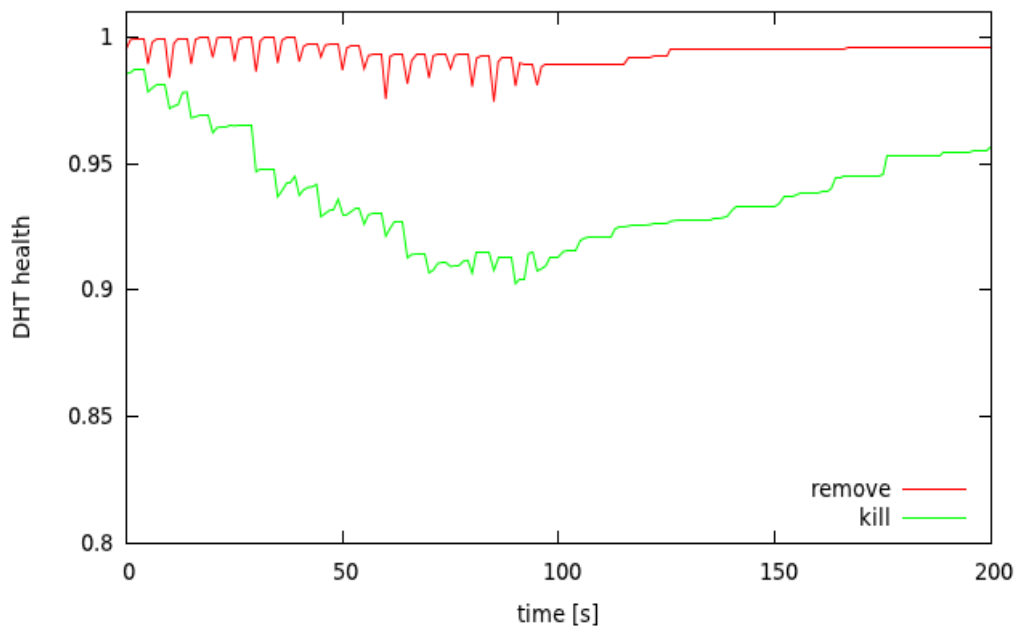


Figure 17: Comparison between leaving and failing nodes

Figure 17 shows two scenarios. In both cases 500 nodes were added to the DHT after that the statistic was started. After the DHT was set up 100 nodes were removed in groups of 5 and in periodic intervals of 5 seconds. The lines show the different behavior of nodes leaving the DHT regularly (red line) and nodes that fail (green line). Because the regularly leaving nodes send leave notifications with helpful information to other nodes, the health is immediately at a value of nearly 100% again. That is not the case if the nodes fail (for example imagine the nodes just loose network connection), here you can see that the health drops to approximately 90% and after that slowly returns towards 100%. This is because failing nodes can not send recovery information to other nodes in the first moment, but the needed information propagates with help of keep-alive and repair messages over time.

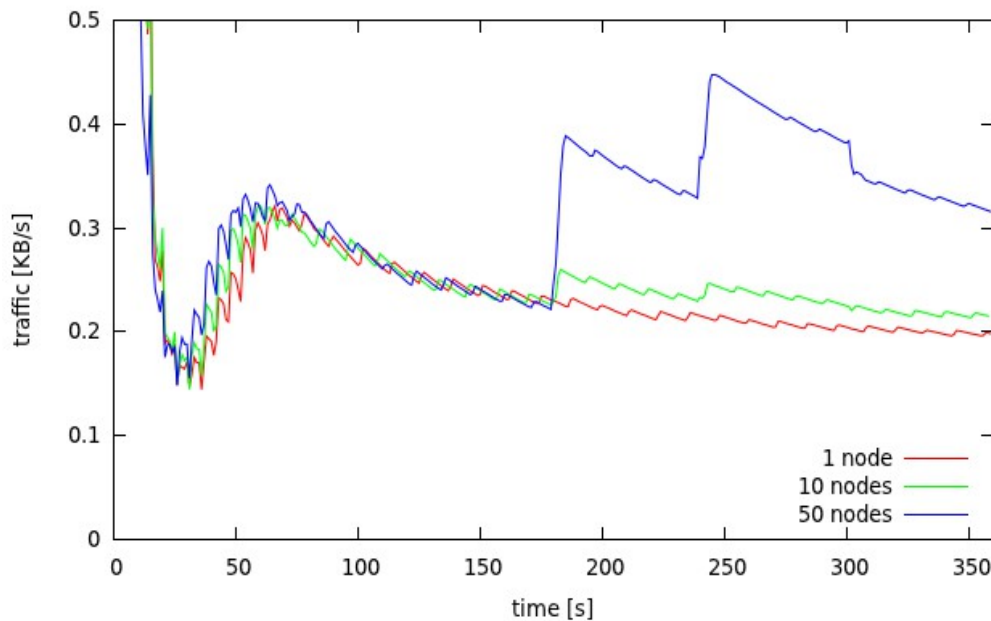


Figure 18: Average traffic per node per second

Figure 18 consists of three data lines. All of them show the traffic that is produced by the DHT in Kilobyte per second for each node in average. The test scenario was that 500 nodes were inserted immediately after program start. After that a pause of 180 seconds has been made to see the normalization of an idle DHT. When the pause was over, a certain amount of nodes were leaving the dht (blue = 50 nodes, green = 10 nodes, red = 1 node). After another break of 60 seconds the same amount of nodes were failing (simulated) in the DHT. After the last break (60 seconds again) the same amounts of nodes were added to the DHT. This measurement proves, that the average data amount that is produced for each node is at an average level of 200 Bytes per second. If there are very many nodes leaving the DHT at the same time, traffic peaks will be produced what is caused by the broadcast messages. Adding nodes to the DHT does not infect the traffic generation in a negative way.

5.3 RUDP simulation Environment

The simulation environment does not have any user input methods. After startup it starts immediately with transmitting data at maximum speed between two sockets using the hostname specified. The transmission speed is displayed in MB/s and is updated every 500 ms. The measurement can be started with two parameters specified the

transmission side (sender / receiver) and the used protocol (RUDP / TCP).

The number of transmitted packets and bytes is hardcoded. If the connection is so bad that the RUDP implementation considers the link as failed, the application stops with an error message.

5.4 Comparison of RUDP and TCP performance

The following 2 graphs show the performance evaluation of RUDP in contrast to TCP which can be seen as a reference implementation because it can be considered sophisticated enough to deal with every kind of network failures.

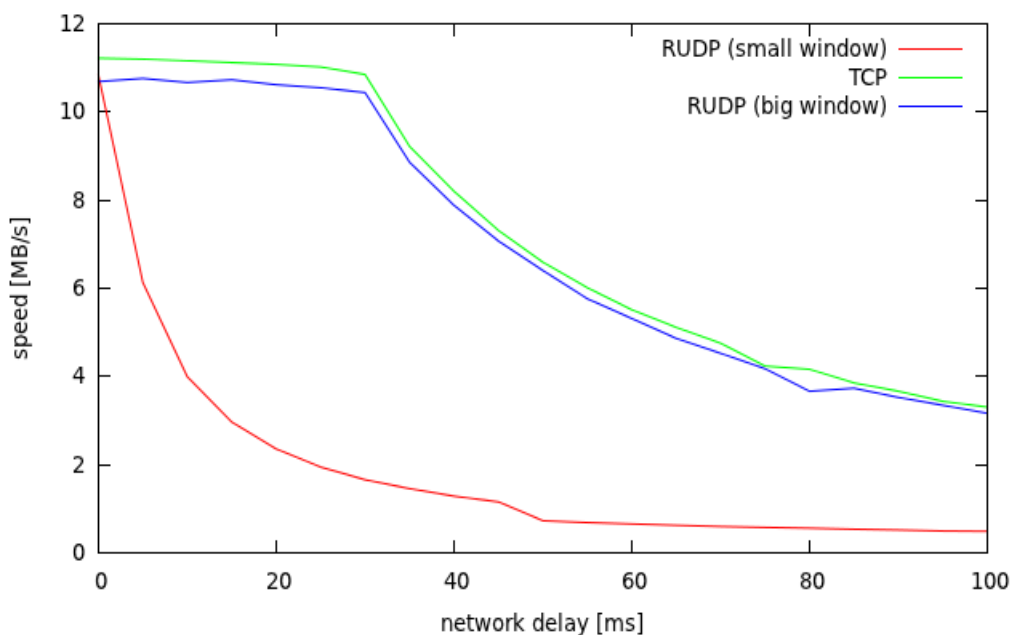


Figure 19: Comparison of RUDP and TCP in packet delay

Figure 19 shows the performance of TCP and RUDP with increasing network delay. The small RUDP window has bad performance because the sender has to wait for the acknowledge answers. After tuning the window size manually RUDP performs quite is good as TCP. The breakdown at milisecond 30 is due to a full network output buffer.

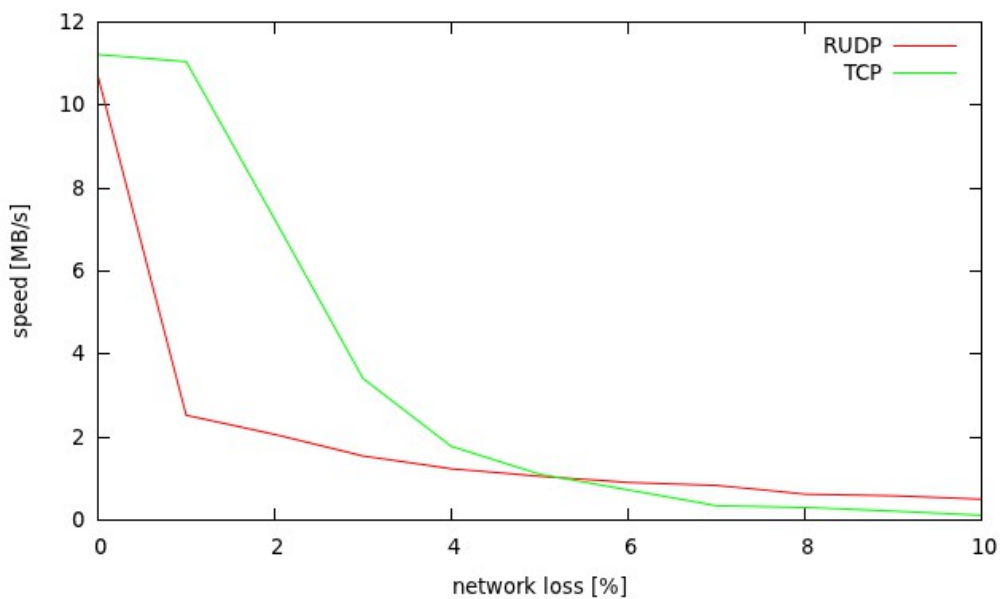


Figure 20: Comparison of RUDP and TCP in packet loss

Figure 20 compares both protocols under certain packet loss situations. TCP performs much better than RUDP at low loss rates. At higher loss above 5% RUDP is slightly better than TCP. A window size of 1000 had been used for the RUDP evaluation.

6 Conclusion

Every goal listed in the detailed problem statement has been achieved successfully. The simulation environment for Chord got a quite powerful tool that assisted us very well during development.

We did not have any expectations for the measured results but they are all reasonable and gave us a good feedback that lead to ideas for future development. One example for that is the evaluation of the RUDP protocol. The evaluation made clear that fixed parameters like window size will never work in all situations. But we were surprised that we are better than TCP in the situation of high packet loss. A question that arised here is the amount of data overhead, which means how much data is actually needed to successfully transfer one bit from the source to the destination. This was not measured during this project and we expect TCP to be better in this discipline. Some improvements were implemented immediately because they exposed design issues.

6.1 Future Work

During the project we figured out some possible improvements that would not fit into the given effort of the project. Also some implementations were out of scope of this project but would be nice to have. These could be subject to future work.

One both have in common is that they have only been tested in laboratory environments and need more practical testing on “real” networks. The deployment of a beta product could fit that need.

6.1.1 Chord

At the moment the measured results for the Chord implementation are not relative because they have not been compared to other DHT solutions like Pastry, Tapestry or CAN. This should be done to get more reflection on this implementation.

The redundancy of data could be improved even more. At the moment they are stored at 2 positions, the originating node and the node the is

responsible for the hash value. Saving the data a more nodes would give more safety and faster lookup possibilities.

The DHT solution has been tested by simulate different situations in the test environment. A automatic test scenario which can be produce tests over longer terms (for example a night) would be nice to have.

Actually the hash value (the node id) for the nodes is generated from the nodes network adress. Maybe there is a more useful algorithm to generate the node id. For example to build groups of nodes.

6.1.2 Reliable UDP

All parameters of the RUDP implementation like acknowledge time, window size, and more are fixed. The performance might be increased by finding appropriate values, or better, by implementing algorithms that vary the parameters depending on the available context like average round trip time (RTT) and others. RUDP needs a different link fail detection. At the moment if a packet fails after a certain amount of retries the link is considered as failed even if others packets have been transmitted successfully. A better approach would be set the link failed only if NO packet at all could be transmitted for a certain amount of time.

To speed up the acknowledge process the sender could not only resend packets after the resend timer expires but also when an acknowledge packet arrived that contains gaps in the ACK field because these packets are most probably lost.

Security vulnerabilities have not been taken into consideration during development. They have to be figured out and countermeasures have to be implemented.

It would be nice to have a C/C++ implementation so RUDP is not only bound to Java. We tried to keep the packet structure simple so it is easy to parse RUDP packets on embedded devices.

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Appendix A: Console commands

The command is separated with a space from arguments. Arguments are separated by a comma from each other. The command usage syntax is as follows:

Bold - type exactly like that

Italic - replace with an appropriate argument

Underlined - argument can be repeated

[Brackets] - argument is optional

node__add__n *count*

Add count nodes to the DHT. The network addresses are the next free addresses in continuous order.

node__add address

Add multiple nodes with the specified network address(es). Address could be any string.

node__remove *address*

Remove multiple nodes specified by their network *address(es)*. The node(s) is / are shutdown normally.

node__remove__n *count*

Remove count nodes. The node(s) is / are selected randomly. The node(s) is / are shutdown normally.

node__kill *address*

Kill multiple nodes specified by their network *address(es)*. The node(s) is / are killed without any notice. This is the simulation of a network failure.

node__kill__n *count*

Kill *count* nodes. The node(s) is / are selected randomly. The node(s) is / are killed without any warning. This is the simulation of a network failure.

```
msg_watch ([! | all | broadcast | !broadcast] | [[!]join | [!]join_response |  
[!]join_ack | [!]join_finalize | [!]join_busy | [!]duplicate | [!]register |  
[!]register_response | [!]resolve | [!]resolve_response | [!]keepalive |  
[!]find_predecessor | [!]find_predecessor_response | [!]check_successor |  
[!]check_successor_response | [!]check_predecessor |  
[!]check_predecessor_response | [!]join_notify | [!]leave_notify))
```

Activate and / or deactivate monitoring of the specified message categories or specified messages. The categories are **!** for none, **all** for all, **broadcast** for activating keepalive, notify_join, notify_leave and node_suspicious, and **!broadcast** for deactivating them. **[!]broadcast** does not interfere with other message types. Either a category or a list of specified messages can be entered.

register *address, sensor*

Register the sensor *sensor* at the node specified by *address*.

resolve *address, sensor*

Try to resolve the *sensor* starting at the node specified by *address*.

g *radius*

Start the GUI. Optionally specify the *radius* of the DHT circle in pixel.

node_info [*address*]

Print information about all nodes or the node specified by *address*. The information contains state of connectivity, state of blocking and if blocked, for which node the block is held, and the hash value of the node(s).

sensor *address*

Show sensor information for the node specified by the network address *address*. The information contains a list of own sensors and where these are registered, and a list of foreign sensors this node is responsible for and the network address of the originating node.

node_watch *address*

Opens a small window for every node specified by its network address *address*. The list contains the finger finger-table of that node and is automatically updated on changes.

msg_delay *[[delay], address]*

Shows the current global network delay when no parameter is specified. Sets the global network delay when *delay* is specified, and sets the node specific network *delay* if an *address* is specified.

circle *address*

Iterate through the DHT circle starting by the node specified by the network address *address*. Every traversed node is shown in order including network address and hash value. The traversal stops if the starting specified by *address* node is reached again, a side-loop or a hole has been detected. After the traversal orphaned nodes, if any, are listed.

finger *address*

List the finger table of the node specified by the network address *address*. The information includes the logarithmic position to the base of 2 of the finger, the hash value of the finger and the network address. The predecessor, that is not a part of the finger table, is also included in the listing. Successor and predecessor are marked with **SUC** and **PRE** respectively.

ka_watch

Switches the monitoring of keepalive events **on** or **off** depending on the former state.

health [*m*]

This command shows the current health of the DHT. The health is the percentage of correct fingers of all nodes. Fingers that are present but not perfect are treated as not present. The *m* option includes a list of missing fingers that were needed to reach 100% health.

wait *delay, [random_delay]*

Waits the specified *delay* in milliseconds. If *random_delay* is also specified this command waits between *delay* and (*delay* + *random_delay*) milliseconds selected by a random number generator. This command is only useful inside script files. See the **exec** command for further details

exec *file*

Execute the script file specified by *file*. A script must contain valid

command line commands or comments. A comment line starts with a `#` and is valid for the current line only. There is one command that is only valid inside script files, which is the **goto** command. See description of the goto command in the section for more details.

statistic *file*

Start a statistic and write it to the file *file*. Only one statistic can be run at a time. If a statistic was already running before, it is closed before the new statistic is started. See chapter 4.3.2 inside the project report for more details on statistics.

break *address*

This command is for debugging purposes only and works only when the simulation environment is started within a Java debugger. It stops the execution of the node specified the network address *address*. Outside the debugging mode this command does nothing.

goto *mark*

This command is only valid within script files. It jumps the current execution pointer to the line that is marked with *mark*. A mark can be specified by a **colon** followed by a *mark*-name. A mark cannot be combined with other commands on the same line.

This example waits 1000 ms, adds 2 nodes and then jumps to the beginning.

```
:make_nodes  
wait 1000  
node_add_n 2  
goto make_nodes
```


Appendix B: Example log file

Logging started Sat May 05 18:02:56 CEST 2012

```
-----
18:03:04.783 | MSG: type: MSG-JOIN - from: (1) - to: (0) key: {356a...} -
origAdr: (1)
18:03:05.036 | MSG: type: MSG-JOIN-RESPONSE - from: (0) - to: (1) | joinKey:
{356a...} suc: {b658...} pre : {b658...}
18:03:05.288 | MSG: type: MSG-JOIN_ACK - from: (1) - to: (0) key: {356a...}
ADD-NEW finger: (1)-{356a...} @NODE: (0)-{b658...}
ADD-NEW finger: (1)-{356a...} @NODE: (0)-{b658...}
ADD-NEW finger: (0)-{b658...} @NODE: (1)-{356a...}
18:03:05.541 | MSG: type: MSG-JOIN_FINALIZE - from: (0) - to: (1) key: {356a...}
ADD-NEW finger: (0)-{b658...} @NODE: (1)-{356a...}
18:03:08.640 | MSG: type: MSG-JOIN - from: (2) - to: (1) key: {da4b...} -
origAdr: (2)
18:03:08.892 | MSG: type: MSG-JOIN - from: (1) - to: (0) key: {da4b...} -
origAdr: (2)
18:03:09.144 | MSG: type: MSG-JOIN-RESPONSE - from: (0) - to: (2) | joinKey:
{da4b...} suc: {356a...} pre : {b658...}
18:03:09.396 | MSG: type: MSG-JOIN_ACK - from: (2) - to: (0) key: {da4b...}
ADD-NEW finger: (2)-{da4b...} @NODE: (0)-{b658...}
ADD-BETTER finger: (2)-{da4b...} @NODE: (1)-{356a...}
18:03:09.649 | BROADCAST:{356a...} -> {b658...} | MSG: type: MSG-JOIN-NOTIFY -
from: (0) - to: (1) hash: {da4b...} - Adr: (2)
ADD-NEW finger: (1)-{356a...} @NODE: (2)-{da4b...}
18:03:09.649 | MSG: type: MSG-JOIN_FINALIZE - from: (0) - to: (2) key: {da4b...}
ADD-NEW finger: (0)-{b658...} @NODE: (2)-{da4b...}
18:03:09.901 | MSG: type: KEEP-ALIVE - from: (1) - to: (2)
18:03:13.106 | MSG: type: MSG-CHECK_SUCCESSOR - from: (0) - to: (1) | hash:
{b658...}
18:03:13.107 | MSG: type: MSG-CHECK_PREDECESSOR - from: (0) - to: (1) | hash:
{b658...}
18:03:13.359 | MSG: type: MSG-CHECK_SUCCESSOR_RESPONSE - from: (1) - to: (0) |
preHash: {b658...} preAddr: (0)
18:03:13.359 | MSG: type: MSG-CHECK_PREDECESSOR_RESPONSE - from: (1) - to: (0) |
preHash: {da4b...} preAddr: (2)
18:03:15.793 | MSG: type: MSG-CHECK_SUCCESSOR - from: (1) - to: (2) | hash:
{356a...}
18:03:15.794 | MSG: type: MSG-CHECK_PREDECESSOR - from: (1) - to: (2) | hash:
{356a...}
18:03:16.046 | MSG: type: MSG-CHECK_SUCCESSOR_RESPONSE - from: (2) - to: (1) |
preHash: {356a...} preAddr: (1)
18:03:16.046 | MSG: type: MSG-CHECK_PREDECESSOR_RESPONSE - from: (2) - to: (1) |
preHash: {b658...} preAddr: (0)
18:03:18.298 | Node: {b658...} Addr: 0 initiated KEEP-ALIVE
ADD-NEW finger: (0)-{b658...} @NODE: (2)-{da4b...}
18:03:18.551 | BROADCAST:{da4b...} -> {356a...} | MSG: type: KEEP-ALIVE - from:
(0) - to: (2)
18:03:18.551 | BROADCAST:{356a...} -> {b658...} | MSG: type: KEEP-ALIVE - from:
(0) - to: (1)
18:03:19.903 | MSG: type: MSG-CHECK_SUCCESSOR - from: (2) - to: (0) | hash:
{da4b...}
18:03:19.903 | MSG: type: MSG-CHECK_PREDECESSOR - from: (2) - to: (0) | hash:
{da4b...}
18:03:20.155 | MSG: type: MSG-CHECK_SUCCESSOR_RESPONSE - from: (0) - to: (2) |
preHash: {da4b...} preAddr: (2)
18:03:20.155 | MSG: type: MSG-CHECK_PREDECESSOR_RESPONSE - from: (0) - to: (2) |
preHash: {356a...} preAddr: (1)
18:03:23.107 | MSG: type: MSG-CHECK_SUCCESSOR - from: (0) - to: (1) | hash:
{b658...}
18:03:23.107 | MSG: type: MSG-CHECK_PREDECESSOR - from: (0) - to: (1) | hash:
{b658...}
18:03:23.359 | MSG: type: MSG-CHECK_SUCCESSOR_RESPONSE - from: (1) - to: (0) |
preHash: {b658...} preAddr: (0)
18:03:23.359 | MSG: type: MSG-CHECK_PREDECESSOR_RESPONSE - from: (1) - to: (0) |
preHash: {da4b...} preAddr: (2)
18:03:25.794 | MSG: type: MSG-CHECK_SUCCESSOR - from: (1) - to: (2) | hash:
{356a...}
18:03:25.794 | MSG: type: MSG-CHECK_PREDECESSOR - from: (1) - to: (2) | hash:
{356a...}
18:03:26.046 | MSG: type: MSG-CHECK_SUCCESSOR_RESPONSE - from: (2) - to: (1) |
preHash: {356a...} preAddr: (1)
18:03:26.046 | MSG: type: MSG-CHECK_PREDECESSOR_RESPONSE - from: (2) - to: (1) |
preHash: {b658...} preAddr: (0)
18:03:28.759 | Node: {b658...} Addr: 0 initiated KEEP-ALIVE
```

Appendix C: Example Statistic file

```
# TriggerType: TRIGGER_SECOND
#-----
#TimeStamp      Sec      Hth      Con      ConD      Fin      FinD      Data      DataD      Pkt
PktD
15:00:19.505    0        0.0      1         1         2         2         22731     22731     1079
1079
15:00:20.505    1        1.9708316909735908E-4  1         0         4         2         22760
29      1080      1
15:00:21.505    2        1.9708316909735908E-4  1         0         4         0         22760
0        1080      0
15:00:22.505    3        1.9708316909735908E-4  1         0         4         0         22760
0        1080      0
15:00:23.505    4        1.9708316909735908E-4  1         0         4         0         22760
0        1080      0
15:00:24.505    5        1.9708316909735908E-4  2         1         6         2         52071
29311   2171     1091
15:00:25.505    6        1.9708316909735908E-4  3         1         25        19         54762
2691    2434    263
15:00:26.505    7        1.9708316909735908E-4  3         0         25        0         54762
0        2434      0
15:00:27.505    8        1.9708316909735908E-4  3         0         25        0         54762
0        2434      0
15:00:28.505    9        1.9708316909735908E-4  3         0         25        0         54762
0        2434      0
15:00:29.505   10        1.9708316909735908E-4  4         1         28        3         88737
33975   3533     1099
15:00:30.505   11        1.9708316909735908E-4  7         3         90        62         94885
6148    4005     472
15:00:31.506   12        1.9708316909735908E-4  7         0         90        0         95050
165     4010      5
15:00:32.506   13        1.9708316909735908E-4  7         0         90        0         95050
0        4010      0
15:00:33.505   14        1.9708316909735908E-4  7         0         90        0         95050
0        4010      0
15:00:34.505   15        1.9708316909735908E-4  8         1         93        3         130200
35150   5100     1090
15:00:35.505   16        7.883326763894363E-4  15        7         209       116         145538
15338   5826     726
15:00:36.505   17        9.854158454867955E-4  15        0         236       27         148435
2897    5875     49
15:00:37.505   18        9.854158454867955E-4  15        0         236       0         148435
0        5875      0
15:00:38.506   19        9.854158454867955E-4  15        0         236       0         148435
0        5875      0
15:00:39.505   20        9.854158454867955E-4  16        1         238       2         183251
34816   6943     1068
15:00:40.505   21        0.002364998029168309  29       13         418       180         212895
29644   7987     1044
15:00:41.505   22        0.002562081198265668  30        1         565       147         232091
19196   8299     312
15:00:42.505   23        0.0027591643673630273 30        0         588       23         233676
1585    8324     25
15:00:43.505   24        0.0027591643673630273 30        0         588       0         233676
0        8324      0
15:00:44.505   25        0.0029562475364603865 31        1         591       3         267367
33691   9355     1031
15:00:45.505   26        0.005912495072920773  56       25         799       208         309561
42194   10677    1322
15:00:46.505   27        0.012810405991328341  59        3         1329      530         401714
92153   12074    1397
15:00:47.505   28        0.014584154513204573  59        0         1379      50         418839
17125   12319    245
```