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Acknowledgments

I would like to thank Stig Frode Mjølsnes for guidance and valuable suggestions throughout the process.

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`Data`	is the packet sent in response to an `Interest`.
$\mathbb{G}$	group of prime order.
global passive adversary	is an adversary which can monitor the entire network flow.
host	is a node that holds the relevant `Data`.
`Interest`	is the packet sent from a node to another, requesting some content with a `Name`.
`Name`	is the name of content related to a `Data` packet in NDN.
node	is referred to as a machine participating in a Named Data Networking (NDN) network.
p	prime order.
publisher	is the owner/producer of the `Data`, and is required to signed its `Data`.
receiver	is a node that has expressed an `Interest` to some `Data`.
simple assumption	is defined through a security game in which an adversary first gets a a challenge whose size only depends on the security parameter, and must then output a unique solution without further interaction [HKS15].

synchronization group	is group of nodes that synchronizes with a given `Name`.

List of Acronyms

ACL Access Control List.

AES Advanced Encryption Standard.

ARP Address Resolution Protocol.

ASP Application Service Provider.

BAS Building Automation System.

BDH Bilinear Diffie-Hellman Problem.

BMS Building Management System.

CCN Content Centric Networking.

CDN Content Distribution Network.

CEK Content-Encryption Key.

CGM Continuous Glucose Monitor.

CIA Confidentiality, Integrity and Availability.

CS Content Store.

DBDH Decisional Bilinear Diffie-Hellman Problem.

DDoS Distributed Denial of Service.

DNS Domain Name System.

DOI Digital Object Identifier.

DoS Denial of Service.

FIA Future Internet Architecture.

FIB Forwarding Information Base.

FSM File Synchronization Module.

HIBC Hierarchical Identity-Based Cryptography.

HLR Home Location Register.

HSS Health Sensor System.

IBC Identity-Based Cryptography.

IBE Identity-Based Encryption.

IBS Identity-Based Signature.

ICN Information-Centric Networking.

ID Identity.

IoT Internet of Things.

IP Internet Protocol.

IPsec Internet Protocol Security.

IPv4 IP version 4.

IPv6 IP version 6.

IRTF Internet Research Task Force.

KB Kilobyte.

LAN Local Area Network.

MACAW Media Access Protocol for Wireless LAN's.

MITM Man In The Middle.

MPK Master Public Key.

MSK Master Secret Key.

NDN Named Data Networking.

ndn-cxx Named Data Networking C++ library with eXperimental eXtension.

NFC Near Field Communication.

NFD Named Data Networking Forwarding Daemon.

NSF National Science Foundation.

NTNU Norwegian University of Science and Technology.

PARC Palo Alto Research Center.

PBC Pairing-Based Cryptosystems.

PIT Pending Interest Table.

PK Public Key.

PKG Private Key Generator.

PKI Public Key Infrastructure.

PyNDN2 Named Data Networking Client Library in Python.

RIB Routing Information Base.

RSVP Resource ReSerVation Protocol.

SDSI Simple Distributed Security Infrastructure.

SHA1 Secure Hash Algorithm 1.

SK Secret Key.

SSN Social Security Number.

TCP Transmission Control Protocol.

TLS Transport Layer Security.

TMPK Temporary Master Public Key.

TMSK Temporary Master Secret Key.

TTP Trusted Third Party.

UCLA University of California, Los Angeles.

UDP User Datagram Protocol.

URI Uniform Resource Identifier.

URL Uniform Resource Locator.

Chapter 1
Introduction

1.1 Motivation

The translation from name to address and location is a fundamental problem to all networks. NDN is a proposal for content-centric discovery and routing approach to networking going on at the University of California, Los Angeles (UCLA), which is part of the inspiration and a contact point for this work.

In general, the name to address resolution can either be maintained by a catalogue lookup service, such as Domain Name System (DNS) (Internet) and Home Location Register (HLR) (mobile networks), or resolved on-the-fly by a protocol on request, such as Address Resolution Protocol (ARP) (Local Area Network (LAN)). There has been done a tremendous amount of work on the naming problem in distributed systems, some became big failures (e.g. X.500) others such as the web Uniform Resource Locator (URL)s are very successful. Bringing things even further, the Digital Object Identifier (DOI) system is a Uniform Resource Identifier (URI) directed at the content/object itself rather than a location. Very much related to the name/address problem is the information security problem of efficient and practical public key distribution, which remain unsolved in practice, even though a significant number of digital certificate and verification protocols and schemes have been proposed, and systems tested over the last two decades. One notable and early theoretical proposal is Adi Shamir's Identity-Based Cryptography (IBC) proposal [Sha84], and subsequent work, that may be revisited and applicable to NDN.

1.2 Problem and Scope

When designing a new network protocol for the future Internet, one of the most significant changes should be security. Trust management plays a big part in security, and thus we cannot design trust management on known Internet Protocol (IP) failures such as X.500. Public Key Infrastructure (PKI) is a tough challenge to solve and it

is probably not rigid solution, but rather case specific. NDN is being designed with security in mind, but the issue of trust management is yet to be solved.

I address the trust management issue in a thought sensor device network, i.e. a health sensor network. By using the Named Data Networking Forwarding Daemon (NFD) I will implement my proposal for such a sensor network over NDN, and contribute with ideas and concepts around such a network.

1.3 Methodology

First I design the application flow in sequence diagrams. Based on how NDN is designed, I try to implement the proposed design and see where changes can be made to minimize communication overhead, maximize security (i.e. Confidentiality, Integrity and Availability (CIA)) and usability. The implementation will be tested and discussed.

1.4 Outline

This paper will first introduce NDN, one of the proposed protocols for the future Internet. I will explain the architecture of NDN as well as some related work regarding my application proposal and IBC. The application modules will be explain in detail and implementation choices will be discussed. At last I will present the results of the implementation and my conclusion of the trust model the application uses.

1.5 Notations

Notations used throughout in this thesis is listed in Table 1.1.

Symbol	Description
MPK_i	Master Public Key belonging to i
MSK_i	Master Secret Key belonging to i
SK_i	Secret Key belonging to i
PK_i	Public Key belonging to i
ID_i	Identity belonging to i

Table 1.1: Notations used throughout the thesis.

Chapter 2
Background

"We model the future on the past. Sometimes that's a mistake."

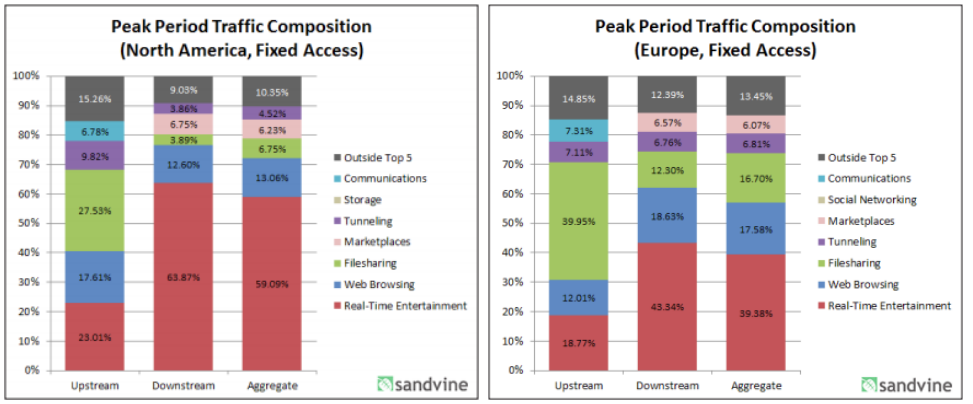
— Van Jacobsen, *SIGCOMM 2001*

This chapter will give a brief overlook of the motivation for Information-Centric Networking (ICN), as well as explaining more details of the ICN protocol NDN. The NDN architecture will be reviewed. Finally there will be a quick summary of related work.

2.1 Motivation for Information-Centric Networking

When Internet was created in the 1960's, the researchers where inspired by the existing communication network; the telecommunication network. Because it was natural and logical to think that people would send and receive short messages and instructions, the point-to-point communication model was a logical architecture. As Internet have developed, the traffic has increased enormously over the past few years. In the Global Internet Phenomena Report 1H2014 done by Sandvine [San14], close to 64% of all IP traffic in North America was Real-Time Entertainment streaming. In Figure 2.1 it can easily be seen that most of the traffic is content download, and not communication as Internet was designed for. With this in mind, the IP architecture does not provide an efficient transport model for what we are actually using the network for.

Designing the IP network, security was not the first priority. A logical thought considering that they did not know what the Internet is being used for and how big it has become. Many protocols related to Internet have been designed and deployed mainly with the goal of functionality, not thinking about security. In the years after the birth of Internet, it was discovered that Internet needed security at several layers, due to that the application requirements and transmission importance increased. Internet Protocol Security (IPsec) is a very good example of work trying to patch up security flaws in the design of Internet.



(a) North America (b) Europe

Figure 2.1: (a) Peak Period Aggregate Traffic Composition - North America, Fixed Access [San14]. (b) Peak Period Aggregate Traffic Composition - Europe, Fixed Access.

Today, WiFi is disseminated across homes and buildings in many countries. Wireless technology has grown rapidly and it is predicted continuous growth in the years to come [Ros14]. The Internet of Things (IoT) trend is coming and the IP network is not designed for broadcast. Therefore wireless connection is not as easy as it should and could be. Devices should easily be able to communicate directly with each other without having to interconnect through a router.

Another problem is the network redundancy. Looking at Figure 2.1 and reading [San14] where it comes to light that Netflix stands for 34.21% of all content download in America, one can conclude that there are a lot of movies downloaded from x users geographically located close. And thus the network path from the source (e.g. Netflix) to this geographical place is allocated x too many times. This is because a node in an IP network does not know *what* it processes, but rather the packet's endpoints, i.e. *where* it goes and *where* it comes from. This makes every node dumb, hence the network is designed for redundancy when it comes to content download.

These design failures are some the reasons why the research for the future Internet began. ICN [ADI+12] is a concept developed under this research. It is built upon delivery of content, rather than the point-to-point model we previously have seen in IP. ICNs goal is to build an infrastructure of a new Internet that can achieve efficient, secure and reliable distribution of content. In 2012 Internet Research Task Force (IRTF) established ICN working group.

2.2 Content Centric Network & Named Data Network

The first network protocol purposed for ICN, Content Centric Networking (CCN), was presented by Van Jacobsen at a Google Talk in 2006. He, amongst other contributors of CCN, has been working on developing the Internet as we know it since the early start. Jacobsen has contributed to Transmission Control Protocol (TCP)/IP with his flow control algorithms [Jac88] and TCP header compression [Jac90]. CCN focuses on naming content, instead of naming IP-addresses. The research project is lead by Palo Alto Research Center (PARC). A branch of CCN is the NDN [ZAB+14] research project started in 2010, which Jacobsen also have contributed to. One of the biggest contributers is UCLA, with Lixia Zhang in the lead. Zhang is known for her contribution to, amongst many other, Resource ReSerVation Protocol (RSVP) [BZBH97] and Media Access Protocol for Wireless LAN's (MACAW) [BDSZ94]. The NDN project is also one of few projects funded by National Science Foundation (NSF) in their Future Internet Architecture (FIA) program [Fou].

2.3 NDN Architecture

Since the knowledge of how NDN works is not disseminated amongst computer scientists, it is essential for this thesis to describe how it works. This section will describe the basic architecture of NDN [ASZ+15] and compare some solutions with the equivalent solutions in IP.

2.3.1 Brief Introduction

In NDN there are two types of packets, `Interest` and `Data` packet. All `Data` has be given a content `Name` by its publisher. To publish some content to the network, a user have to register the prefix, i.e. announcing the contents `Name`, which tells the network that the content can be retrieved on the announced `Name`. The retrieval can only be achieved if someone expresses an `Interest` to the content `Name`. If a user expresses `Interest` in the `Name`, the network will route the `Interest` to the closest node that holds the `Data`. The `Data` packet can be retrieved from any node, trusted or not, over any type of communication channel, secure or not. Finally the requester will receive the `Data` packet containing the content. The `Data` can be verified by the requester ensuring that the publisher who "owns" the content actually is the owner, because its cryptographically signed. It is because of the signature we can retrieve the `Data` from any node. If confidentiality is needed, the `Data` can be encrypted itself.

2.3.2 NDN - Based on Existing Concepts

The goal for the network design is essentially making it more secure and applicable for content without removing the communication service that IP was designed for. Designing a new network protocol we have to look at what measurements have been done in the existing IP network to tailor it towards content sharing. As the reader might notice after reading the background material, NDN is built upon concepts that we can map to well working solutions deployed over TCP/IP. Some examples are:

- BitTorrent - The concept of sharing bits of files between peers in a network is a well-working distributed method for sharing content. Requester does not care where the content comes from, but only that the content is what is requested.

- Content Distribution Network (CDN) - Many Application Service Provider (ASP)s, such as Netflix and YouTube, have found out that their service performs a lot better for their costumers if they cache up their `Data` close to where the users is located.

2.3.3 Packets

There are two types of packets in NDN; *`Interest` packet* and the corresponding answer, i.e. the *`Data` packet*, illustrated in Figure 2.2.

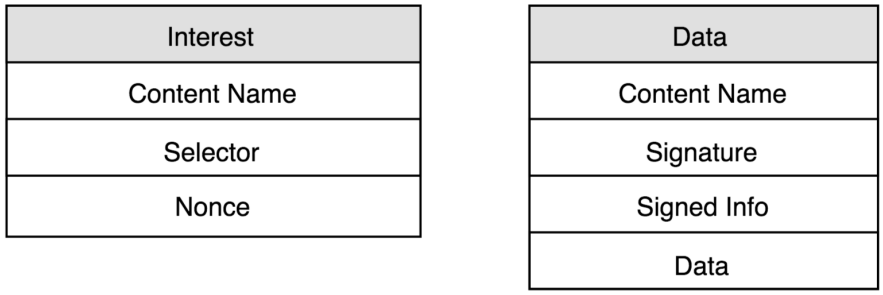


Figure 2.2: `Interest` packet and `Data` packet

The `Interest` packet specifies a content `Name`. The `Name` can have a hierarchical structure and signatures can be added after the URI, e.g. "/ndn/no/ntnu/haakon/-file/1/<signature>". An `Interest` can also contain a set of different Selectors to specify original requirements for the `Data` response. Some of the Selector fields are:

- KeyLocator - can be used to specify where the Public Key for the signature can be found.
- Exclude - can be used to specify a list or a range of names that should be excluded from the `Name`. I.e. if the `Name` is "/ndn/no/ntnu" and the Exclude contains "/item", the returned `Data` cannot contain "/ndn/no/ntnu/item".
- MustBeFresh - if True, a node cannot answer with a `Data` packet where the FreshnessPeriod has expired. FreshnessPeriod is a time value of how long some `Data` is fresh.
- ChildSelector - can be used to select either the leftmost (least) or the rightmost (greatest) child, e.g. content version.
- Min/MaxSuffixComponents - refers to `Name` components that occur in the matching `Data` beyond the prefix.

The Nonce field sets automatically. This is used to uniquely identify an `Interest` and prevent looping in the network.

The `Data` packet is a response to the `Interest` packet, and contains the content `Name` and the Content itself. It also has a MetaInfo field that is used to specify the FreshnessPeriod (milliseconds), ContentType and FinalBlockId. When somebody requests a file "/ndn/no/ntnu/haakon/file/1" with an `Interest`, the response will have the same `Name`, but also containing the file.

Because a `Data` packet can only exists if there is a corresponding `Interest`, NDN is pull-based. Hence unsolicited `Data` packets will be thrown away, i.e. there is no content in the network, that is not requested from someone. This reduces unwanted traffic compared to User Datagram Protocol (UDP) in IP, and minimizes the Denial of Service (DoS) vulnerability drastically.

2.3.4 Names

In todays Internet we are well familiar with the mapping of URL and IP addresses. This mapping, done by the DNS, eases the pain of remembering an IP version 4 (IPv4) (32-bit) address and lately also IP version 6 (IPv6) (128-bit) addresses.

In the NDN network a node does not have an address nor a `Name`. The routing of packets is done by content lookup, rather than address lookup. This means that all content in the network do have a `Name`. When an `Interest` is sent, each node asks the network: "Where can I find a node that can provide me with this content?".

There is no strict rules for a `Name` in NDN. This means that a network node only routes an `Interest` based on longest prefix match. Naming is left to the application

design, thus it can be customized for the applications best purpose. However the network assumes hierarchical structured names, hence routing will perform better with a hierarchical `Name` design.

For the network to perform even better, the `Interest` can append some Selectors that can help the network to decide which `Data` to retrieve and where to route. With Selectors a partially known `Name` can successfully retrieve the right `Data`. E.g. when a user want to download the newest version of some content, lets say "/ndn/no/ntnu/haakon/file/<version?>", but do not know which version is the newest, the user can append a ChildSelector to choose the newest version.

The fact that `Data` has a `Name` makes Simple Distributed Security Infrastructure (SDSI) and IBC highly applicable to NDN. Namespace-based trust was introduced in SDSI [RL96], binding names to public keys. IBC will be explained in detail in chapter 4.

2.3.5 Network Node

It may sound like a impossible task to force todays network from IP to NDN. But as IP first ran over the telecommunication network and later established its own, NDN can run over the IP network and later create its own network. Also, if we look at an existing model of an IP node Figure 2.3 and compare it to a NDN node Figure 2.4, we see that they look much the same. The only significant difference in hardware is the storing capacity, which becomes cheaper and cheaper each month. However, the logic behind a NDN node is a bit more complex, and thus lead to more knowledge about *what* content the node has to offer. To understand this, the following entities in a NDN node should be understood:

1. Face - A term used for generalization of different interfaces, e.g. physical like Ethernet, or overlay like TCP and UDP. A Face can also be a UNIX-domain socket for communication with a local application.
2. Pending Interest Table (PIT) - All pending or recently satisfied `Interest`s are stored here, together with the incoming and outgoing Face. If a new incoming `Interest` matches an entry in the PIT, the incoming Face will be added to the entry.
3. Content Store (CS) - When a node receives a `Data` packet that has the corresponding entry in the PIT, it stores the `Data` packet in CS as long as possible. The CS works like a cache for the node.
4. Forwarding Information Base (FIB) - Forwarding strategy is stored for each `Name` prefix. When a node forwards an `Interest`, it will do a longest prefix lookup in the FIB and send the `Interest` further to the best matching Face.

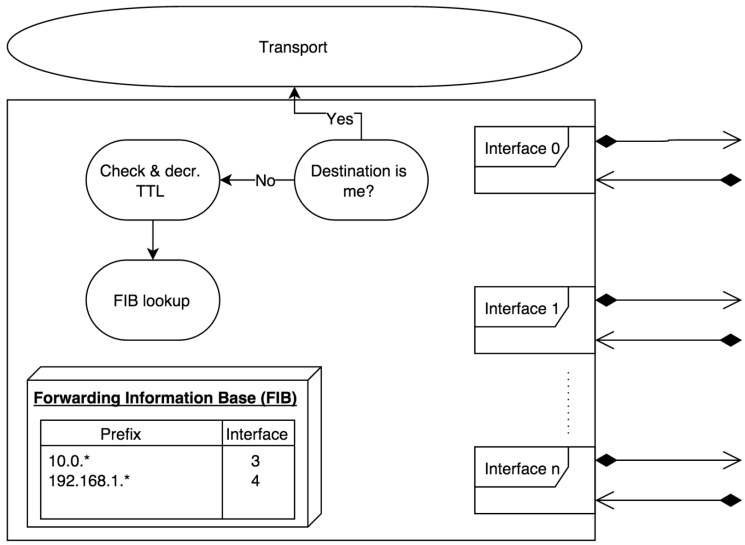


Figure 2.3: Model of IP node. A packets enters the node through an interface. The node decides whether the packet is for the node itself, or passes it further to next node, found in the FIB.

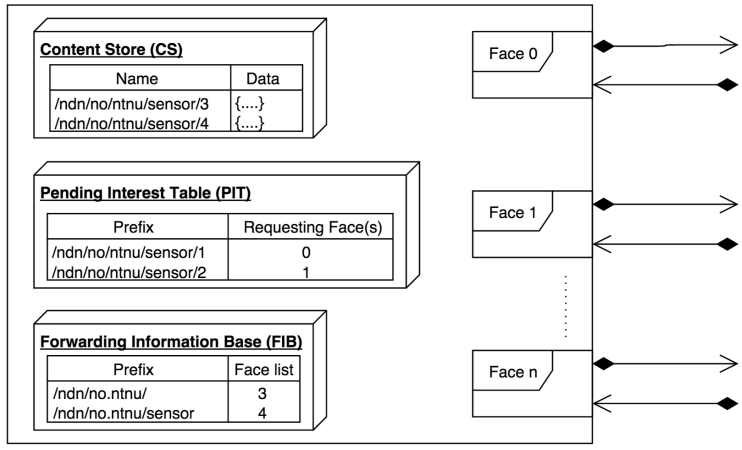


Figure 2.4: Model of NDN node. A packet enters through an Face. The node checks whether the `Interest` is already queried in the PIT, or stored in the CS, or passes it further to next node, found in the FIB.

In contrary to an IP node, a NDN node knows *what* content comes through itself. Since all content is associated with a `Name`, a NDN node can know 1) *what* is requested, but not satisfied (i.e. PIT), and 2) *what* has been satisfied earlier and still available, i.e. still cached in CS. With this knowledge the network can now satisfy `Interests` with content already stored in cache, hence the network can naturally offer multicast on network layer. Figure 2.5 illustrates a NDN network where we can see that the network does not nearly have to send equal amount of traffic than in an IP network. The mobile expresses an `Interest` (1) in a file named `/ntnu/file1`. The `Interest` finds its way to the publisher of the file, and thus the publisher responds with a `Data` packet (2) named `/ntnu/file1` containing the file. When the second computer expresses the same `Interest` (3), the consecutive node has already cached the `Data` response matching to the `Interest` in its CS, hence the `Interest` is satisfied already at this point (4), and not forwarded any further. Same happens when the third computer expresses again the same `Interest` (5) to the network. Given that the file (`/ntnu/file1`) these computers are interested in is 4 gigabyte, the network saves a lot of traffic with multicast. Best case scenario in NDN is illustrated in Table 2.1. Worst case scenario, the NDN nodes will perform equal to the IP nodes.

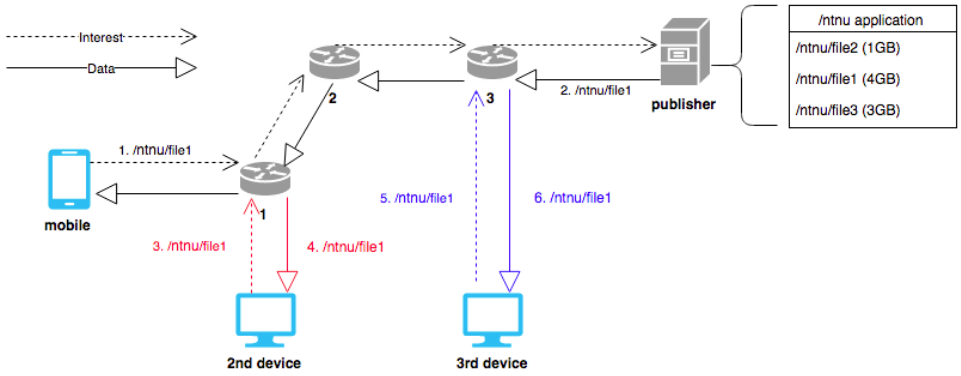


Figure 2.5: Multicast in NDN.

Node	Data in/out IP	Data in/out NDN	% bandwidth needed in NDN
1	8GB/8GB	4GB/8GB	50%/100%
2	8GB/8GB	4GB/4GB	50%/50%
3	12GB/12GB	4GB/8GB	33%/66%
Publisher	-/12GB	-/4GB	-/33%

Table 2.1: Node bandwidth allocation comparison in IP and NDN (best case). Mobile, 2nddevice and 3rddevice requests `/ntnu/file1` (4GB). The NDN nodes allocates bandwidth 44.3% (in) and 66.3% (out) compared to IP nodes.

2.3.6 Incoming Interest

In Figure 2.6 we see an incoming `Interest` through a Face. The node checks the PIT for pending or recently satisfied `Interests`. If there is no match, the node will do a lookup in CS to see if a corresponding `Data` packet is cached. If there is a match in the PIT it will only add the Face to the PIT entry. If there is a match in the CS the node will return the `Data`. If there is no match in either the PIT or the CS the node will make a new PIT entry and do a longest prefix match lookup in the FIB to decide which Face(s) to forward the `Interest`. The node waits for incoming `Data` and satisfies the PIT entry when the `Data` arrives, explained in subsection 2.3.7. Each PIT entry has its own routing strategy. I.e. whether, when, and where to forward the `Interest`.

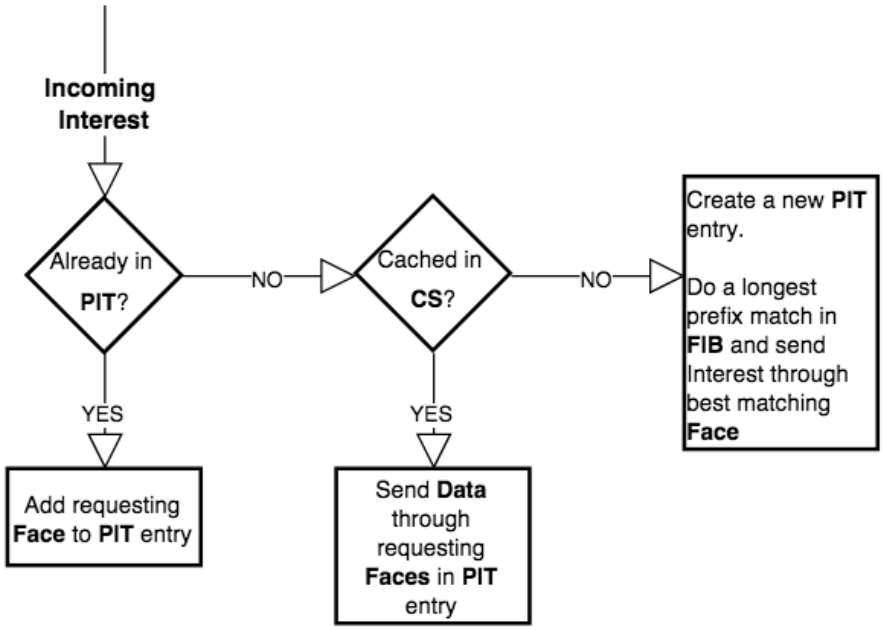


Figure 2.6: Decision tree for a NDN node when receiving an `Interest`.

2.3.7 Incoming Data

In Figure 2.7 we see incoming `Data`. The node will check the PIT for an entry, if a match is found the node will forward the `Data` to all the Faces registered in the PIT entry. If no match, the node will disregard the `Data` because it is unsolicited content. The node checks the `Data` from local applications cached in CS first, if there is no match, it stores the content in CS and sends the `Data` to all requesters (i.e. through all Faces stored in the PIT entry).

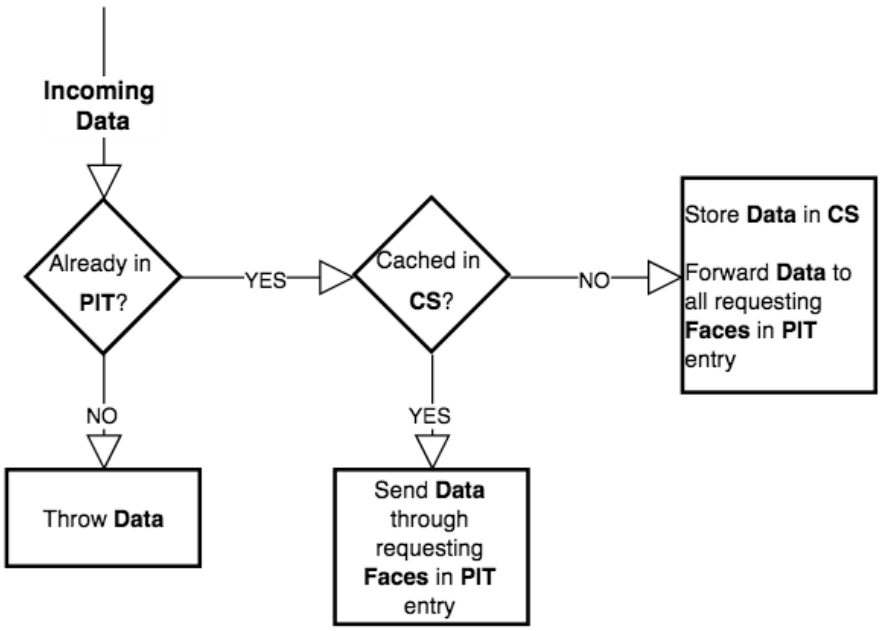


Figure 2.7: Decision tree for a NDN node when receiving `Data` packet.

2.3.8 Security

Below I will present why NDN facilitates good security properties, explaining some of the security aspects around NDN discussed in [SJ09], and the difference in securing data and securing channel.

Trusting Host versus Trusting Content

Doing a whole lot of mapping at different layers is not a good security model since each mapping introduces a potentially vulnerable target for forgery. The IP network is designed in a way that makes us want to trust the host. What we are actually trusting is the mapping of the URL to the IP address. DNS points to a host address that speaks for the URL you are interested in, and thus if someone manages to forge this address, you cannot tell if you talk to the right host.

The content is rarely encrypted and the confidentiality is not preserved, unless there is established a secure channel using e.g. Transport Layer Security (TLS). This is a problem due to the issues concerning tampering and eavesdropping. The content the host we trust provides can contain malicious software and important information can be swapped even though the channel is secured. This is the concept of securing

the channel, and the trust is based on certificates. This trust is an issue itself. Due to the global PKI and essentially because the certificate is signed by a Trusted Third Party (TTP) all trust comes outside the namespace. This makes it problematic to retrieve content over IP from other sources than the trusted host because you do not trust any other than the host you are connected to via the secure channel. The host does not provide any assurance that the content is verified by the host itself, it only assures a secure channel.

A goal is to get the desired content from the intended source, unmodified in transit. Therefore a better solution would be to trust the content rather than the host of the content. This concept requires us to change the network trust. Skipping 1) all the trust based in mapping of hosts, 2) where the data comes from, and 3) securing the channel. The content should be linked to the publisher and this linkage should be signed by the publisher. The concept is to mathematically prove that the content originates from the believed publisher, and that its not modified nor been exposed to unauthorized parties (if necessary). This introduces a possibility that anyone can retrieve any piece of data from anyone, trusted or not, regardless of secure channel or not. The question is how can this idea be achieved? As Diana Smetters and Van Jacobsen says [SJ09], we must ensure the content's validity, provenance and relevance.

- Validity - Complete and unmodified content from the publisher.
- Provenance - Should the publisher be trusted with the content requested?
- Relevance - Is the content what the requester intended?

There exist concepts to achieve these goals. One can do hash verification on the content to be sure that the content is unmodified. But there should also be a binding between the `Name` to the content. However, this does not provide provenance nor relevance because the publisher is not linked to the data, and thus we cannot be sure the publisher knows what the content contains. Hence there should be a linkage between the publisher, the `Name` and the content. A solution is to do a triple mapping of the `Name` (N) and content (C), cryptographically signed by the publisher (P) seen in Equation 2.1. This mapping is unique, relying on the hash computation done in the signing, providing validity, provenance and relevance. A requester can easily verify the `Name` and content binding, as well as authenticating that the data originates from the publisher who knows what the content is. Now anybody can retrieve $\texttt{M}_{\texttt{(N,P,C)}}$, hence an untrusted host and an insecure channel is not so bad anymore.

$$M_{(N,P,C)} = (N, C, Sign_P(N, C)) \tag{2.1}$$

A clear benefit of this approach is that it scales. The `Name` can be of any form because of the nature of hashing. Different naming rules should apply for different applications as there are no global naming rules that are optimal for each application.

This concept is integrated in the NDN protocol and it is required that every packet delivered from application layer is signed by the application. The protocol also provides an easy way for the application to encrypt data providing confidentiality. Encrypting the content with symmetric keys that are distributed to parties obtaining access right to the content together with the validity, provenance and relevance provides a way of securing data rather than securing communication channels.

Anonymity

Based on the nature of this architecture, NDN facilitates the practice of anonymity in the network. In a Tor network [DMS04], each node participating in a circuit only knows the two neighboring nodes. Only a global passive adversary that can monitor the entire network is able to decide the whole packet path, hence an adversary can know *who* is requesting and *who* is responding. Since the packet format (subsection 2.3.3) in NDN has no source or destination specific field as in a IP packet, the privacy of the network is more similar to a Tor network. If a packet is captured at any arbitrary point of its path, the only information an adversary will get, is the two nodes between the packet capture and the content `Name`. Unless monitoring a complete network, it should be close to impossible to track packets. However, because of the semantic naming there are some issues related to privacy as it easily can be seen in the `Name` *what* the content contains in many cases. Also since signing of each `Interest` is required by the sender, some privacy information might leak. DiBenedetto et al. try to address these problems in [DGTU12] with an approach that use existing solutions from the Tor network. In 2010 the NDN-team planned to implement TORNADO [ZEB+10, Section 3.7], the NDN version of Tor, to demonstrate the privacy preservation capabilities of the network.

more in this section

2.4 Attacks

Paolo Gasti et al. identifies several DoS attacks on NDN in their paper about DoS and Distributed Denial of Service (DDoS) in NDN [GTUZ13]. Other works have been done related to DoS in NDN [WCZ+14, SNO13, CCGT13]

In [LZZ+15] Zhang et al. propose an extension of the NDN protocol for addressing the access problem of cached `Data` in nodes. The NDN network is also potentially susceptible to content poisoning attacks which Ghali et al. addresses in [GTU14].

2.5 Related work

The work in this thesis builds upon three main concepts: synchronization, theoretical sensor networking and IBC. Some related work done will shortly be presented in this section.

2.5.1 Synchronization

There have been done work to show that NDN is well suited for synchronization. A synchronization application built by the NDN-team is ChronoSync [ZA13]. As explained in chapter 3, I use ChronoSync to achieve synchronization of files over NDN. There is also an application called iSync [FAC14], which is a scalable and high performance synchronization protocol.

2.5.2 Secure Data Retrieval from Sensors

Amadeo et al. [ACM14] propose a solution for reliable retrieval of `Data` from different wireless producers which can answer to the same `Interest` packet. This is highly applicable to a sensor network where you want to communicate with the closest sensor, e.g. the light in *this* room. In [ASLF14] Abid et al. simulate `Data` aggregation in wireless sensor networks. Jeff Burke et al. addresses efficient and secure sensing over NDN [BGNT14]. Burke has also contributed in developing and installing a system that secures building management systems at UCLA using NDN [SDM+14].

2.5.3 Identity-Based Cryptography in Named Data Networking

There is little research done on IBC in NDN. In [ZCX+11] Xinwen Zhang et al. propose a hybrid scheme with traditional PKI and IBC.

explain whats differs to this thesis

Chapter 3
File Synchronization over Named Data Network

This chapter will present ChronoSync, and explaining what the File Synchronization Module (FSM) is built upon, its purpose over the NDN network and its purpose in this thesis.

3.1 ChronoSync

Since NDN provides multicast in the network layer as explained in Figure 2.5, we do not have to think of network load in the same way as in IP. To achieve distributed synchronization of a `Dataset`, the NDN-team has developed ChronoSync, a decentralized synchronization framework over NDN. ChronoSync assumes that a group of nodes knows the `Name` of a synchronization group, e.g `/ndn/broadcast/FileSync-0.1/<group_room>/`. The synchronication application is built upon state digests, which is that each participating node stores a hash of its current `Dataset`. Each node in a ChronoSync application broadcasts its sync state in a Sync `Interest` (e.g. `/ndn/broadcast/FileSync-0.1/<group_room>/<state>`). When a node receives a Sync `Interest`, it will inspect the state of the `Interest`, and compare with its own state. Each node holds a state tree that is used to detect new and outdated states. If the incoming `Interest` state is equal to the receiving node's state, the node has no reason to do anything, as the system is in a *stable state* from the node's point of view. If not, the receiving node has to find out whether the incoming `Interest` is 1) a state the node itself has been in, or if its 2) a new state. In case of 1), the receiving node has new `Data` and should provide the new content as a response to the incoming `Interest`. In case of 2), the receiving node should send out a Recovery `Interest` for the new state.

1. *Sync* ***`Interest`*** is an `Interest` that a participating node sends out to discover new `Data`.

2. *Sync* ***`Data`*** is a response to 1), if a participating node has new `Data`.

3. *Recovery* `Interest` is an `Interest` sent out if a node discovers that another node has a newer state.

4. *Recovery* `Data` is a response to 3).

When the group is in a stable state, each Sync `Interest` is equivalent, hence only one entry at each router's PIT is created, forming a temporary multicast three. This `Interest` is periodically sent out from each subscriber maintaining the multicast three, resulting in that the producer has the possibility to answer the Sync `Interest` with Sync `Data` whenever the producer has a new `Data`set.

ChronoSync is only taking care of `Data` discovery, and leaves other logic to the application that is using ChronoSync. Such logic can be e.g. what should happen when a new participant enters the room. Should all history be downloaded? Or who is allowed to publish content in each synchronization group?

ChronoSync is explained in detail here [ZA13].

3.2 File Synchronization Module

The goal for the FSM is to distribute `Data` to a large group of nodes. Each node wants to verify that the distributed `Data` originate from the publisher. Each node always wants to have the newest version of the `Data`. One example where FSM is applicable is when we want to distribute a list of public keys within a domain. Let us say there is a list owner, e.g. a TTP that could be a university like the Norwegian University of Science and Technology (NTNU). NTNU wants to distribute to a large set of nodes, i.e. each student and employee at NTNU. Every node wants to have every public key in NTNUs domain up-to-date. When the list of public keys gets updated, caused by for instance a key revocation or a key initialization, every node should immediately synchronize with the updated list.

There can be two types of roles in the FSM.

1. Distributor

2. Subscriber

Distributors are list-owners and have read-write access. Subscribers only have read access. A node can be both a distributor and a subscriber, and there can be several distributors that are equal, i.e. several owners of the list. However, there is one root distributor (i.e. the true owner) that should be able to delegate write access to other nodes that should act as a distributor. The capabilities is distributed to all nodes

and signed by the root distributor. These capabilities is needed so that every node can verify the integrity and authenticity of the distributed list. If confidentiality is required, it can be achieved by symmetric encryption, and key exchange in the subscription protocol, i.e. using asymmetric encryption. However this becomes quite complicated concerning possible key leakage and redistribution of a new symmetric key when the number of subscribers is high. In the case of public keys list, the `Data` would not have to be confidential, but rather rely on integrity and authenticity.

In Figure 3.1 the subscribers (`a`, `b` and `c`) wants to subscribe to the distributor's (`d`) list of public keys. In order to achieve this goal, the following actions should occur.

1. `d` announces that it wants to distribute a list to the network by registering the synchronization group prefix.
2. `a`, `b` and `c` ask for subscription to this list, and somehow authenticates them selves to `d` if confidentiality is required.
3. `d` approves those who should be approved, and returns a symmetric synchronization key. This step is only done if confidentiality is required.
4. `a`, `b` and `c` now knows that they are a part of the synchronization and have read access. They expresses a Sync `Interest` with their state, receiving Sync `Data` whenever `d` has announced a newer state.

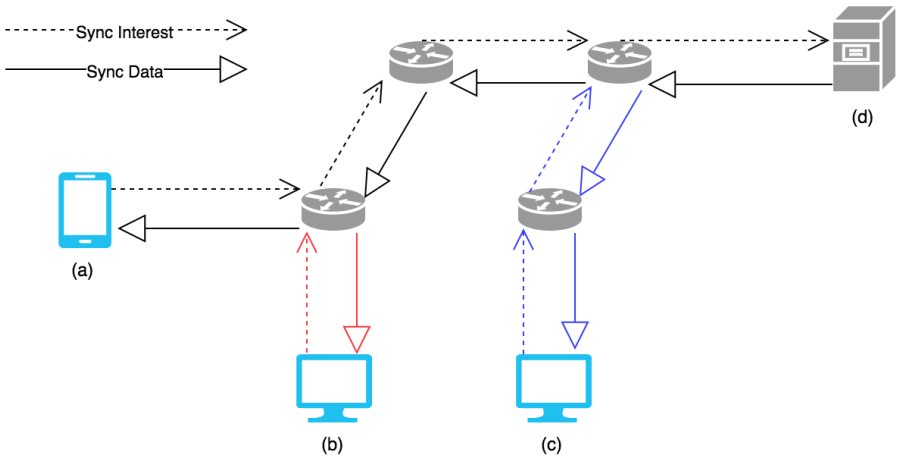


Figure 3.1: File Synchronization in NDN.

There are some issues that could occur in such a system. DoS on Sync `Interest` and Sync `Data`. If the FSM is used to revoke public keys as suggested, an attacker

who has found the compromised Secret Key (SK), can try to deny the distribution of the new list, i.e. the Sync `Data`, from the distributor. This is however a complicated attack and an updated list would spread fast. Performing DoS on every node is not easy, and would block the network access for the adversary anyway.

Chapter 4
Identity-Based Cryptography

This chapter will present the concept of Identity-Based Encryption (IBE) and Identity-Based Signature (IBS), and why it is highly applicable to use this type of cryptography in NDN. The possibilities to use the file synchronization module to do key distribution and revocation will be introduced.

4.1 Concept

IBE was first proposed by Shamir [Sha84] in 1984. Shamir proposed a scheme for IBS, but not a scheme for IBE. The concept of IBE builds upon every user having an Identity (ID) that is used as the Public Key (PK). This ID can be anything, i.e. email, phone number, Social Security Number (SSN), or a `Name` (subsection 2.3.4). The SK that is extracted from the ID is issued by a TTP. Notice that if every user could have created their own SK, then so could anybody else with the same computational power, since the user does not obtain any "privileged" information about its ID [Bid06]. This eliminates the need of certificates because the SK allocation itself is a verfication by the TTP. The IBE implementation remained unsolved until 2001, when Dan Boneh and Matthew K. Franklin proposed [BF01]. However the scheme has only been shown to be secure within the random oracles model [Wat04], hence less practical.

IBE is based on performing asymmetric encryption with a publicly know ID working as the PK. As seen in Equation 4.1, the ID can be a `Name` (e.g. "/ndn/no/ntnu/haakon"). Hence the `Name` becomes the PK (from now referred to as ID). Therefore IBE is highly applicable to NDN.

$$ID_{device} = PK_{device} = Name_{device} \tag{4.1}$$

In IBE there is a TTP that is called Private Key Generator (PKG). The PKGs task is to extract a secret key given an ID and provide public parameters (Master Public Key (MPK)) needed for performing encryption, decryption, signing and verifying.

In Figure 4.1 the IBC methods is illustrated in practice. First the PKG runs Setup(). device1 can then request a SK by sending $\texttt{ID}_{\texttt{d1}}$ to the PKG. In return the device1 receives the $\texttt{SK}_{\texttt{d1}}$ as well as the $\texttt{MPK}_{\texttt{PKG}}$. device2, which is already a part of the trust domain, sends a signed request for Data to device1. device1 verifies the signature and responds to the request with a signed, encrypted content. device0, which do not have a SK generated from the PKG and thus is not a part of the trust domain, sends a request to device1 that is declined.

1. Setup() generates a key pair, MPK and Master Secret Key (MSK). These keys are used by only the PKG to extracting secret keys, encryption and decryption.
2. Extract($\texttt{MPK}_{\texttt{PKG}}$, $\texttt{MSK}_{\texttt{PKG}}$, $\texttt{ID}_{\texttt{device}}$) generates a secret key from a given ID.
3. Encrypt($\texttt{MPK}_{\texttt{PKG}}$, $\texttt{ID}_{\texttt{device}}$, message) encrypts the message.
4. Decrypt($\texttt{MPK}_{\texttt{PKG}}$, $\texttt{SK}_{\texttt{device}}$, cipher) decrypts the cipher generated from the encryption.
5. Signing($\texttt{MPK}_{\texttt{PKG}}$, $\texttt{SK}_{\texttt{device}}$, message) signs a hash digest of the message (e.g. Secure Hash Algorithm 1 (SHA1)).
6. Verify($\texttt{MPK}_{\texttt{PKG}}$, $\texttt{ID}_{\texttt{device}}$, message, signature) verifies the signature.

To encrypt a message with IBE, the user encrypts a Content-Encryption Key (CEK) with the recipients ID. The user encrypts the message using the CEK together with symmetric encryption [AMS09, section 2.2.2], and sends both the encrypted CEK and the encrypted content to the requester.

There are some drawbacks related to IBE such as issues around trusting the PKG considering that the PKG generates all SKs. If the PKG is compromised by an adversary, the adversary will retrieve all SKs belonging to the corresponding ID. Suspicion of Man In The Middle (MITM), where the PKG is the adversary, can be a problem for users. The same issue does however occur in Kerberos, which is a well recognized security system. Initializing might also be a problem because to allocate SKs, a secure channel has to be established. However, this is not a bugger problem than in existing networks. Pre-shared secrets or Diffie-Hellman key exchange might be a good solution.

4.2 Secureness

When designing protocols in cryptography one first usually designs an ideal system where all parties have random oracle access, then proves the security. A random oracle is like a “black box” that outputs truly random numbers. Second, one replaces

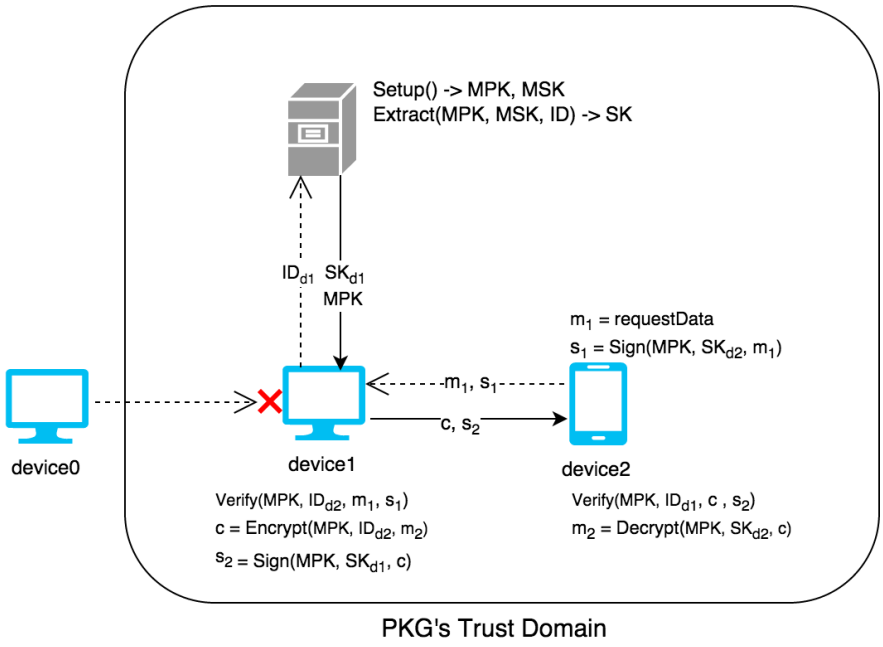


Figure 4.1: Methods of an IBC systems illustrated in practice.

the oracle access with a hash function. This gives an implementation of an ideal system in the real world, but without random oracles [BR93]. It is perfectly fine to make statements based on the ideal system, but debatable whether the same statements yields for the implementation in the real world. Canetti et al. concluded that there exist secure schemes in the *Random Oracle Model*, but for which any implementation of the random oracle results in insecure schemes [CGH04]. Boneh and Franklins IBE scheme is only secure when using random oracles, and relies on elliptic curves [BF01].

Following the *Standard Model* one does not resort to the random oracle heuristic and does not rely on non-standard complexity assumptions. Hence proving security in the standard model is preferably. In 2004 Boneh and Boyen proposed a fully secure scheme in the standard model [BB04]. However the scheme is not efficient.

First practical scheme was introduces by Brent Waters [Wat04]. But as David Naccache states in his paper [Nac05], Waters' scheme without random oracles introduces too large public parameters (164Kilobyte (KB)!). Naccache proves that he was able to construct a practical and fully secure scheme in the standard model based on the Decisional Bilinear Diffie-Hellman Problem (DBDH) assumption. The scheme is a

modification of Waters' scheme, but with public parameters of just a few KB size.

Waters created a fully secure IBE system with short parameters under simple assumption in 2009 [Wat09].

The complexity assumptions is based on bilinear maps. Let $\mathbb{G}_1$ and $\mathbb{G}_2$ be groups of prime order p, and g be a generator of $\mathbb{G}$. We say that $\mathbb{G}$ has a bilinear map $e : \mathbb{G}_1 \times \mathbb{G}_2 \to \mathbb{G}_T$ if e is efficiently computable, e is bilinear, i.e. $e(g^a, g^b) = e(g, g)^{ab}$ (for all a and b), and e is non-degenerate, i.e. $e(g, g) \neq 1$. For more details about bilinear maps and Bilinear Diffie-Hellman Problem (BDH) used in IBE, the reader is encouraged to take a look at [BF01, Nac05].

4.3 Key Distribution

In traditional PKI, each public key is signed by a certificate authority and the generated certificate is sent as a response over a secure channel then validated by the the client. I want to make the certificate authority obsolete by distributing every ID. This can be done through the FSM presented in section 3.2. In Figure 4.2 we see that the PKG multicasts the ID list to all devices that have joined the trust domain. Each device can verify the integrity and authenticity of the sync state `Data` and validate that the ID list surely originates from its own PKG, i.e. the distributor.

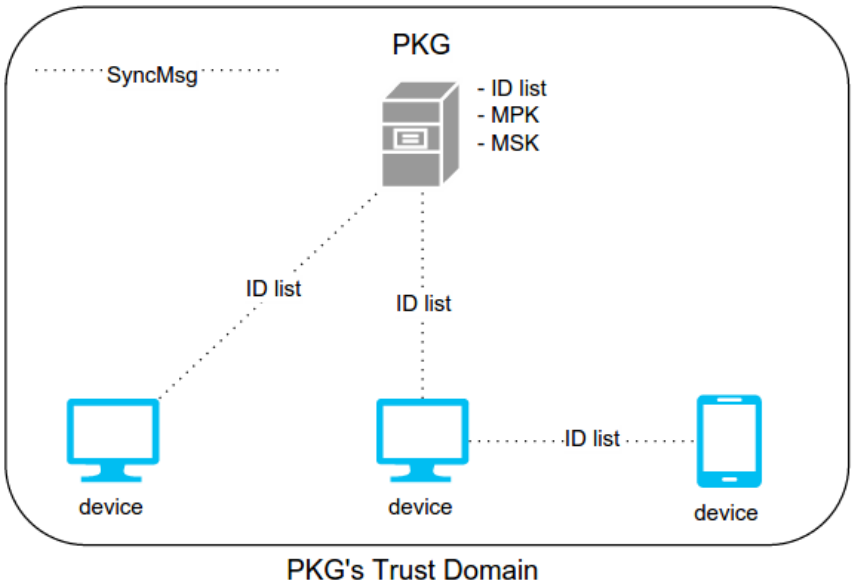


Figure 4.2: FSM with tree devices (subscribers) and a PKG (distributor).

more existing solutions

4.4 Key Revocation

Key revocation in systems are studied well in traditional PKI. However, few alternatives to revocation schemes in IBE PKI have been proposed. One suggestion is to allocate secret keys with the ID combined with some sort of date, e.g. month-year or just year [BF01, section 1.1.1]. In this alternative a user has to renew its secret key each time the date changes, i.e. either the month or the year depending on the date format. The problem with this revocation solution is that it can be cumbersome for the PKG. Boldyreva et al. proposes a revocation scheme [BGK12] based on efficient key-update, which makes the workload for the PKG a lot easier. This scheme was only proven secure in the selective-ID setting where adversaries can attack an ID given they choose which one at the beginning of the game. The work done by Benoît Libert and Damien Vergnaud in [LV09] solves this problem. However, efficiently delegating both the key generation and revocation functionalities was a problem left open. Jae Hong Seo and Keita Emura solves this in [SE13].

If a key is compromised, we want to revoke the key immediately letting everybody know that this specific ID has been revoked. One problem with key revocation is that there is no way of revoking this key, and thus the ID has to be changed and distributed. However, a partially revocation can be sufficient in some networks. By partially, I do not mean revoking the private key, but rather only distributing the new public key (i.e. ID) to every node in the trust domain. In short, the compromised key should be removed from a distributed ID-list and the list containing only valid IDs should be disseminated. With the FSM, the list is distributed automatically when updated, and only a DoS attack together with a compromised key would make the system vulnerable. On the other side, some periodic renewal might be necessary because it is not always known that a key has been compromised.

Chapter 5
Security in Sensor Network

In this chapter the sensor application will be presented. Several sequence diagrams will be explained, as well as concepts needed to understand the flow of the application.

5.1 Health Sensors

There is an ongoing discussion of when the health technology revolution will come to human bodies now that IoT have become so popular. By revolution, I mean sensors placed in the human body. Sensors that can read your blood pressure, heart rate and measure insulin levels. Sensors that can detect whether your body is missing a substance, or if it is poisoned. There is no limit for what can be done. Everything that should be measured, will be measured by sensors integrated in the human body. But who will be able to read the `Data`? Or perform instructions to the sensors/devices? There is some major privacy issues related to this discussion, and problems that needs to be solved.

In 2011, Jerome Radcliffe discovered that his insulin pump easily could be hacked [Rad]. Basically the pump would take instructions from anyone and do anything, with no questions asked. This is a worst case scenario when it comes to hacking medical devices attached to a human.

For this matter I propose a Health Sensor System (HSS) that is built upon NDN with IBC ensuring a secure and locked environment. First, let me introduce you to The Stig. He has developed diabetes and he does not want to manually monitor his glucose levels and adjust the insulin pump every meal. He has injected a Continuous Glucose Monitor (CGM) to monitor his glucose levels and report to the insulin pump, automatically. In addition to his diabetes, he has a heart disease which forces him to monitor his heart rate at any given time. In Figure 5.1 we can see The Stig with all his sensors and devices. The CGM reports periodically to the insulin pump, and all sensors reports to The Stig's mobile so that The Stig can watch what is going on.

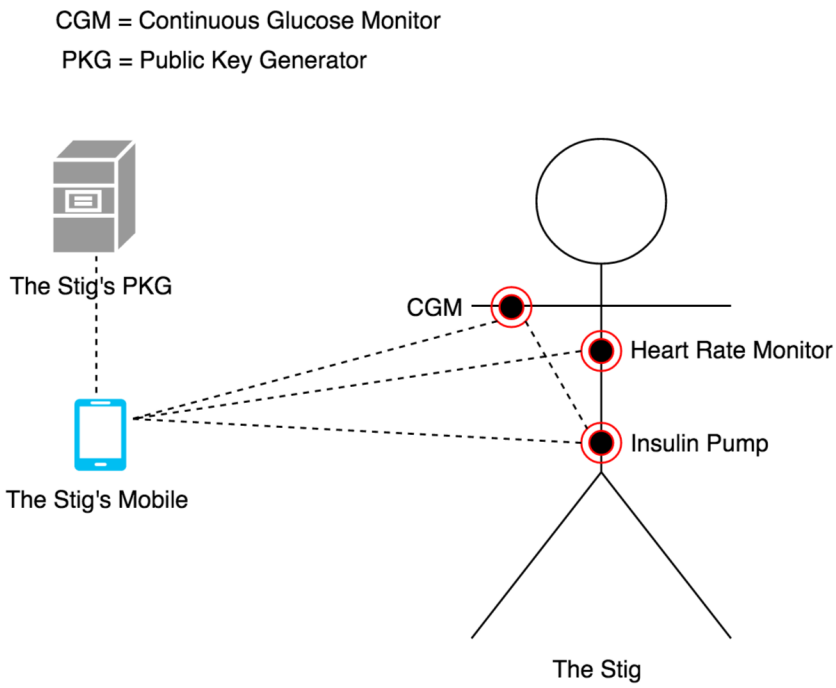


Figure 5.1: Health Sensor System

5.2 Health Sensor System

To have a secure system, it needs to be established trust between the sensors and the devices. There need to be integrity controls, confidentiality protection and access control. In the following sections, I will describe the protocols suggested for achieving the mentioned goals.

5.2.1 Rendezvous Authentication

One of the best solutions for authentication of an identity in cryptography is rendezvous authentication, the concept of meeting face-to-face for authenticating who you are talking to. Most cases in IoT we have the advantage of identifying devices in a physical manner. This means that it is possible to authenticate devices, such as sensors. Typically, this kind of authentication will rely on 1) manually inspection and 2) digital connection, e.g. through Near Field Communication (NFC). In the proposed system, I assume that this type of authentication is achieved in a secure manner and do not discuss how this should be done.

Also there is the concept of human-computer authentication [GRS05, JW05, Wei05]. This authentication method uses a shared secret before authentication.

5.2.2 Initialization

The goal for the initialization protocol is to achieve a secure one-round secret key exchange. For the protocol to be secure, there are several issues that need to be addressed. The response message containing the secret key has to be 1) encrypted. This can be achieved by using asymmetric encryption on a CEK which is used to do symmetric encryption on the secret key. The response message has to be 2) signed by the PKG for integrity and authenticity reasons. For it to make sense applying 3) a nonce for replay protection, the communication between the device and the PKG has to be unique of some kind. This implies that the device has to authenticate itself in a way that an adversary cannot do, e.g. a shared secret. This secret can for instance be a hardware implemented secret in the device that the user reads (from the package) and authenticates manually at the PKG before the initialization.

When The Stig is setting up his HSS, first he wants to configure the PKG. Any type of computer can play the role of the PKG and The Stig has chosen his home server, from now "the PKG". The PKG creates two key pairs that is used to do IBE and IBS. Second, he wants his mobile device, from now "the mobile", to be a part of the PKGs trust domain, and further add all of the other devices and sensors, from now "device(s)".

In Figure 5.2 the device plays the role as the mobile. The ID of every device is a part of the `Name`. A device register the prefix `/ndn/no/ntnu/<device>/<resource>` and hence its ID is `/ndn/no/ntnu/<device>`. To be able to communicate securely under initialization, the device have to create a key pair, Temporary Master Public Key (TMPK) and Temporary Master Secret Key (TMSK), and then extract a temporary secret key for its ID. At first, the device has to act as a key generator for itself to ensure that the receiver (i.e. the PKG) can encrypt the extracted SK. The trust between the device and the real PKG is based on the concept explained in subsection 5.2.1. The device sends an `Interest` appending the TMPK and the ID to the PKG asking to join the PKGs trust domain. The PKG encrypts a CEK with the TMPK and the ID received from the device. The PKG extracts the secret key for the device (this will be the key belonging to the PKGs trust domain) and uses the CEK to do symmetric Advanced Encryption Standard (AES) encryption on the secret key. The `Data` packet response to the initialization `Interest` will contain the identity-based encrypted CEK, the symmetric encrypted secret key and the PKGs MPK. To finish the initialization protocol, the device decrypts the CEK, throws away the temporary keys, and finally decrypts the secret key. The device has established a trust with its PKG and can verify other devices in this domain.

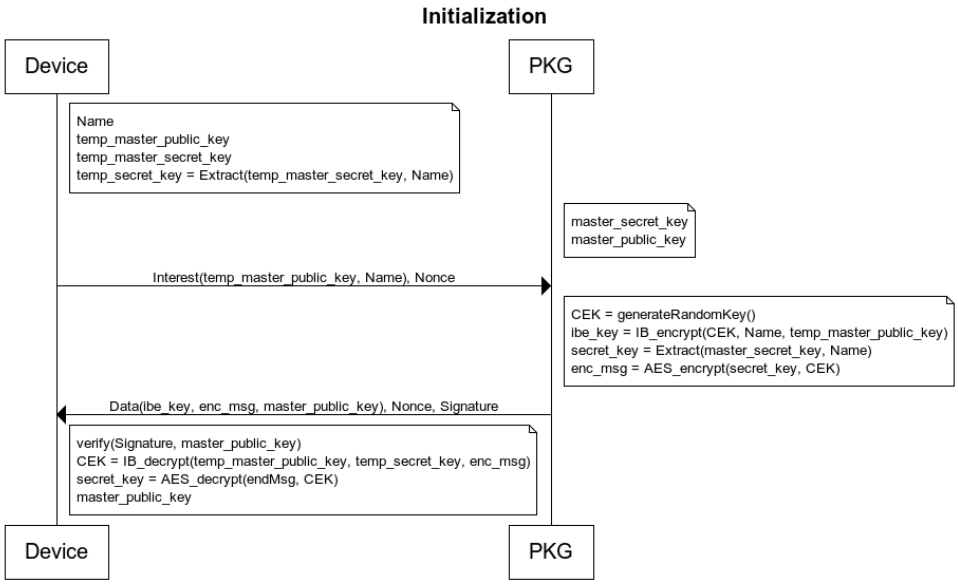


Figure 5.2: Initialization IBE

Now that the mobile is authenticated, devices can connect to the mobile through e.g. NFC for initialization. This results in a rendezvous authentication between the device and the mobile, and if the mobile is given the authorities to perform initialization (subsection 5.3.2), the new device can join the PKGs trust domain.

prove secureness of initialization protocol

5.2.3 Data Pull

The goal for this protocol is to achieve a secure one-round `Data` pull with authorization and integrity. For the protocol to work and the `Data` pull to be successful, 1) both devices has to belong to the same trust domain (i.e. has initialized with the same PKG) and 2) the requester has to have granted access rights for the resource requested.

As illustrated in Figure 5.1, the device has joined the PKGs trust domain and is ready to communicate with other devices. This flow is illustrated in Figure 5.3. First the requester has to express an `Interest` to the target device asking for a specific resource. The requester signs the `Interest` and appends it to the content `Name`. The receiver checks whether the requester has access rights to the requested resource and verifies that the requester is a part of the same trust domain. If the receiver is authorized, the receiver responds with the `Data` containing the resource. The receiver will also do a symmetric encryption on the sensor `Data` and do a asymmetric

encryption on the CEK with the requester's ID. This step is only performed if `Data` confidentiality is needed. Then the `Data` packet is signed and sent. Finally the requester receives the `Data`, verifies the signature and decrypts the sensor `Data`.

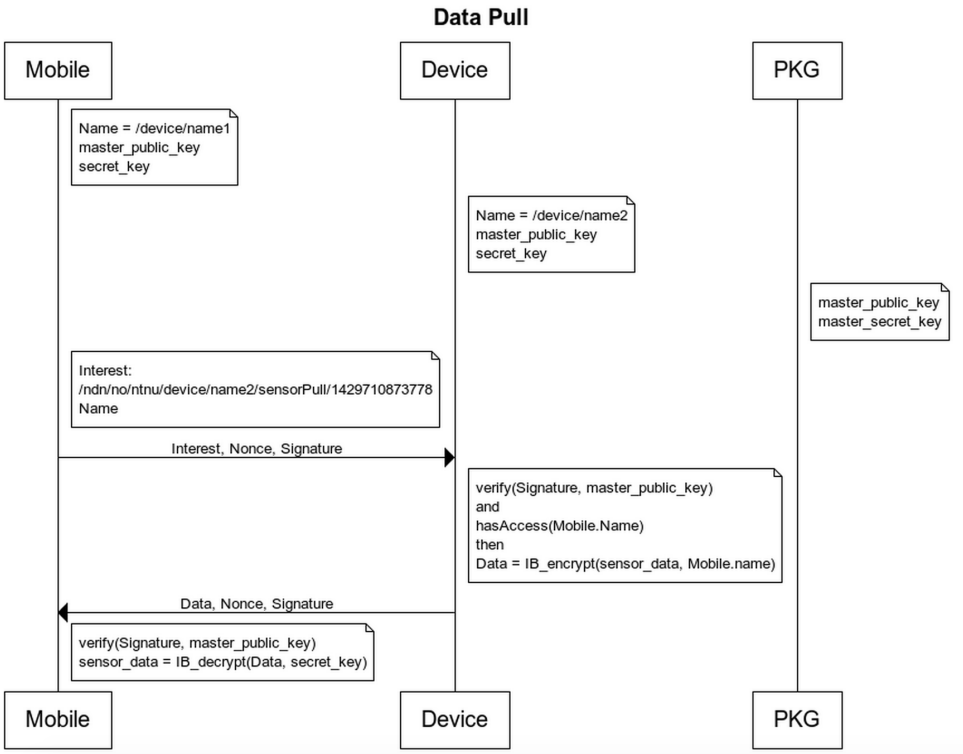


Figure 5.3: Mobile performing a data pull from a device in the network.

prove secureness of data pull protocol

5.2.4 Distribution using File Synchronization Module

The Stig wants to have full control over the devices that are a part of the trust domain, and be able to remove a device if necessary. Each device should have an updated list of all public keys, i.e. every devices' ID. The distribution of this list can easily be achieved by using the FSM (section 3.2 & section 4.3). The PKG will be the distributor in this synchronization and each device will be a subscriber.

5.3 Security Analysis

In this section the security of the protocols presented in subsection 5.2.2 and subsection 5.2.3 will be proven. Security analysis code in section A.1

!!

5.3.1 Threat Model

I assume the following threat model:

1. An adversary might try to eavesdrop information.
2. An adversary might try to send bogus commands (new, replay).
3. Devices might be physically hijacked, e.g. theft of mobile.

write more..

I assume that the PKG cannot be compromised by any adversary, and thus the MSK will always be hidden from any adversaries. An idea introduced by Aaditeshwar Seth and Srinivasan Keshav in [SK05, Section 5.4] is to avoid storing the SKs in devices that is more likely to be lost or stolen, e.g. a mobile. Using Hierarchical Identity-Based Cryptography (HIBC), one can extend the key hierarchy by another level that is time-based. These time-based keys can then be downloaded to the mobile on a daily basis, hence the time the mobile will be compromised is reduced.

5.3.2 Access Control

Since the $\text{ID}_{\text{device}}$ is appended to the `Interest` and the `Interest` is signed by the corresponding $\text{SK}_{\text{device}}$, the ID of the device can easily be authenticated. When a device retrieves an `Interest` for its sensor `Data`, there should be an authorization mechanism. One can argue that once a device has been authenticated in the PKGs trust domain, everyone in the domain can be sure that the device will not abuse the information or functionalities available. However, due to scalability this is not a secure way to handle access control. If a device does not need a privilege, it does not need it. Hence it should not have it. That is the least privilege access principle, which is default in Capability Based Approach to IoT Access Control [GPR12]. This approach has some additional benefits for the HSS, such as

- delegation support - A device can grant access rights to other devices, as well as granting the right to further delegate these rights to a third device.
- capability revocation - If the PKG have granted delegation rights to a mobile, and the mobile is not found trustworthy after a while, the capabilities issued by the mobile can easily be revoked.
- information granularity - Specific resources from a device can be granted access to in different granularity.

Another solution can be an Access Control List (ACL) based approach equivalent to what Wentao Shang et al. did in [SDM+14].

5.3.3 Confidentiality

The confidentiality is achieved by doing asymmetric encryption on a CEK that is used for symmetric encryption on the content. As explained in the sequence diagram (Figure 5.3) presented in the above sections, each `Interest` appends the requester's ID (Equation 4.1). Since the $ID_{requester}$ always is appended it can always be used to do asymmetric encryption, hence all CEKs can be encrypted only for the requesting device, and thus the confidentiality in the system can always be achieved.

5.3.4 Integrity and Authenticity

Each device will obtain a secret key allocated by its superior PKG, as explained in section 4.1. With the concept from subsection 5.2.1 together with the PKGs MPK, you can trust that the device is authorized for the PKGs trust domain. Hence all signed packets can be verified by anyone with the MPK. In this setting, a verified signature acts as an assurance of authentication and integrity.

Every `Interest` has a timestamp attached to the `Name` (e.g. `/ndn/no/ntnu/device/name2/sensorPull/1429710873778`), i.e. milliseconds from `UTC 1970-01-01 00:00:00`, that can be used for protection against replay attack.

5.3.5 Availability

This is a harder problem to solve. The network is purely wireless, hence vulnerable to jamming. An adversary could try to send infinite `Interest`s to a device with an invalid signature, hence the device may be overloaded with work and might run out of battery fast. Therefore one should check the MPK before doing any crypto. This is also why I have chosen to append the MPK in the packet Figure 6.3.

5.3.6 Trust Model

For a system to be secure, cryptography together with trust is essential. The HSS trust model is built upon trusting a centralized authority, typically the user's home server, rendezvous authentication and IBC. The fact that it runs over NDN makes it easier to achieve security goals and usability for third party developers.

The PK is the `Name` of the device, and all content published by the device will begin with this `Name`, hence it is easy to verify that the publisher is the owner of the content. To be able to verify and encrypt messages, the device need the MPK_{PKG} and the ID of the user it wants to communicate with. If allowed by the PKG, the public parameters MPK_{PKG} is public for everybody that is not a part of the trust domain. To be able to sign and decrypt messages the device have to be a member of the trust domain and be issued a secret key mapping to the ID_{device}. Each device builds its

trust on other devices based on that it has been verified by an administrator that controls the PKG.

Chapter 6
Implementation and Testing

This chapter will first introduce the most significant frameworks that must be installed to be able to run NDN applications. Then the various designs and implementation choices will be explained. Finally the test result will be presented.

6.1 Installing Named Data Networking Protocol

There are several libraries that is required for experimenting in a NDN environment. Installation guides can be found at the Github project [NT15a]. First we need to install the Named Data Networking C++ library with eXperimental eXtension (ndn-cxx). ndn-cxx is a implementation of NDN primitives. It is a fundamental framework that NDN application requires. Second we need to install the NFD [AMY+] which is a network forwarder and also in the core implementation of NDN. The major modules implemented in NFD is:

- Core - Common services shared between the different NFD modules (such as hash, DNS resolver, face monitoring etc.).
- Faces - Generalization of different interfaces, explained in subsection 2.3.5.
- Tables - PIT, CS, FIB, explained in subsection 2.3.5.
- Forwarding - Packet processing.
- Management - Enables users/programs to interact with the NFD forwarder state.
- Routing Information Base (RIB) Management - Managing routing protocols and application prefix registration.

The NDN project is under development, and thus the implementation of NFD has its deficiencies. Ideally we want the devices to communicate directly with each other

using WiFi, without running over IP. This face functionality is not yet implemented, and thus NDN is running over IP in my experiments.

6.1.1 Installing PyNDN2

The work done in this thesis is written in Python, hence the Named Data Networking Client Library in Python (PyNDN2) [NT15b] is used. This is an easy to use implementation of NDN and comes with great code examples.

Because the NDN protocol require signing of `Data` packets (subsection 2.3.8) some new implementation in the PyNDN2 source code was necessary to be able to sign and verify with IBS. I added the `python/pyndn/sha256_with_ibswaters_signature.py` file that follows the pattern of the existing RSA Signature (`python/pyndn/sha256_with_rsa_signature.py`) and is of type `Signature`. Some small additions in the `python/pyndn/encoding/tlv_0_1_1_wire_format.py` and the `python/pyndn/encoding/tlv/tlv.py` is added so PyNDN2 recognizes the IBS when the `Data` packet is encoded and decoded.

6.2 Installing Identity-Based Cryptography

To be able to run IBC the Pairing-Based Cryptosystems (PBC) [Ben07] needs to be installed. I use the Charm framework [AAG+13] implements several IBE and IBS schemes in Python. Charm is a framework for rapidly prototyping cryptosystems.

Some small modifications had to be done in the Waters-IBS [Wat04] implementation in Charm. In `charm/schemes/pksig/pksig_waters.py` there is a global variable, i.e. `waters`, that is used throughout all the methods in `pksig_waters.py`. The problem is that this variable is declared in the `setup()`, which is only called at PKG, and not by another devices that do not play the role of a PKG. And thus, the declaration of `waters` must be moved to the `__init__()` in `pksig_waters.py`.

6.3 File Synchronization Module - Implementation

FSM is a python application that runs over NDN and synchronizes all files in a specified path, with all participants within the synchronization room. Application goals are explained in section 3.2. The module is highly based on the Python implementation of ChronoSync [NT15b, test-chrono-chat.py]. The code can be retrieved from the thesis work repository [Mø15, fileSync.py]

The implementation of the FSM does not use IBS. This is because all packets that are sent is managed by ChronoSync. ChronoSync uses the PyNDN2 KeyChain to sign

and verify all `Interest` and `Data` packets. I do however demonstrate that it works perfectly fine to perform both IBE and IBS over NDN in the HSS implementation.

The module triggers synchronization when files that are watched is changed, or when a file is added or removed. A library that makes it possible to watch files in OS X, Linux or Windows, is Watchdog [Pyt]. The implementation is illustrated in the class FileWatch in Figure 6.1.

6.4 Health Sensor System - Implementation

The HSS is a python application that runs over NDN. Application flow explained in chapter 5. The implementation does not deal with sensor `Data` retrieval from actual sensor, nor deal with sending instructions from devices to each other, but rather focuses on the trust and security protocols between devices in a local network. The code is divided into several pieces shown in Figure 6.1.

The Device class [Mø15, device.py] implements the role of a device that can both express `Interest` and offer `Data`.

The PKG class [Mø15, publicKeyGenerator.py] implements the role of a PKG.

IdentityBasedCrypto [Mø15, identityBasedCrypto.py] implements two IBE schemes and one IBS scheme.

Waters05 [Nac05] that is a variant of Brent Waters IBE scheme [Wat04], but with smaller key size, hence more practical.

Waters09 [Wat09] that is also a fully secure implementation of IBE scheme.

Waters [Wat04] that is a implementation of IBS scheme.

6.4.1 Access Control

In subsection 5.3.2 I present a possible solution for access control. This is however not implemented in the application, because it is considered too high workload for this thesis.

6.4.2 Packet Design

The packet format is designed with Google Protocol Buffers, which is a language-neutral, platform-neutral, extensible mechanism for serializing structured `Data`.[1]

[1] Google Protocol Buffers - https://developers.google.com/protocol-buffers/

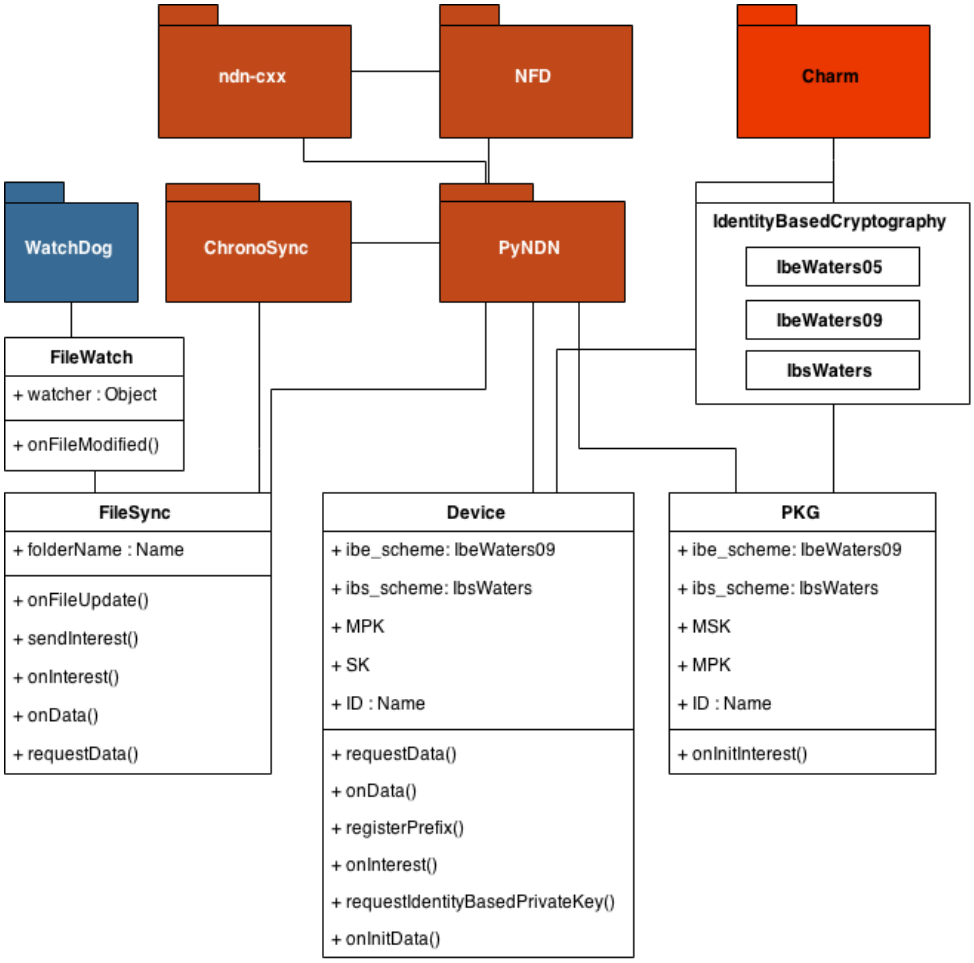


Figure 6.1: Packages and Classes.

Initialization packets have the structure presented in Figure 6.2. Initially the idea was to have the TMPK appended to the content `Name`. However, I experienced a problem where the Init `Data` never arrived at destination node. After some research in `ndn-cxx` documentation I found that the packets have a `MAX_NDN_PACKET_SIZE` of 8800 bytes and the Init `Data` exceeded this limit and reached 8904 bytes. Because the TMPK is approximately 2KB and was appended to the content `Name` in the `Interest`, the `Data` response off course had to have the same content `Name`, hence 2KB overhead in the `Name`. The TMPK can as easily be appended to the KeyLocator `Name`, hence the `Data` response can be 2KB less, resulting to a 6866 bytes Init `Data` packet.

Sensor packets have the structure presented in Figure 6.3. The code can be reviewed in [Mø15, messageBuf.proto].

`Init Interest` - The `Init Interest` can be seen in Figure 6.2 and consist of three fields: Content Name, KeyLocator and MustBeFresh. KeyLocator can be of type `Name`. As described in the NDN Packet Format [NT], generally this field can be used to specify where to download the certificate used to sign the `Interest`. However, in the trust model I use this field to publish the requesters `Name`, i.e. the requesters public key. This is very useful when using IBE and IBS.

`Init Data` - The `Data` response to the `Init Interest` is illustrated in Figure 6.2.

`Sensor Interest` - As in the `Init Interest` the KeyLocator field is used to define the $\mathrm{ID}_{\mathrm{requester}}$. The packet is illustrated in Figure 6.3.

`Sensor Data` - The `Data` response to the `Sensor Interest` uses the same structure as the `Init Data`. It is illustrated in Figure 6.3

The `Init` and `Sensor Data` responses in the HSS have a structure that is defined in [Mø15, messageBuf.proto]. The fields are:

- `MessageType` is an `enum` and can be either Init or Sensor.
- `EncAlgorithm` is an `enum` and represents which type of encryption scheme is used on the content.
- `IbeAlgorithm` is an `enum` and represents which type of IBE scheme is used on the CEK.
- `IbsAlgorithm` is an `enum` and represents which type of IBS scheme is used to sign the `Data`.
- `MasterPublicKey` is the PKGs public parameters used to do IBE.
- `SignatureMasterPublicKey` is the PKGs public parameters used to do IBS.
- `SymmetricKey` is the symmetric key used to encrypt the content. The key is encrypted.
- `Cipher` is the encrypted content.
- `Session` is a nonce.

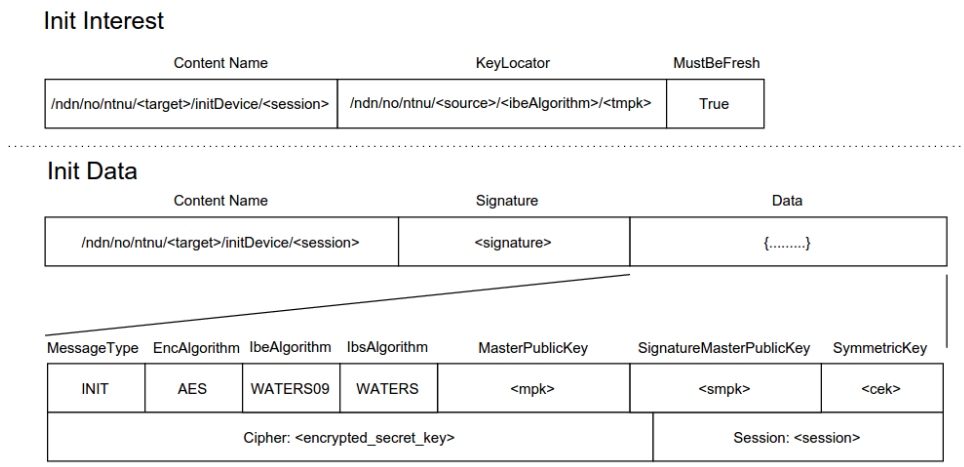


Figure 6.2: Initialization `Interest` and `Data`

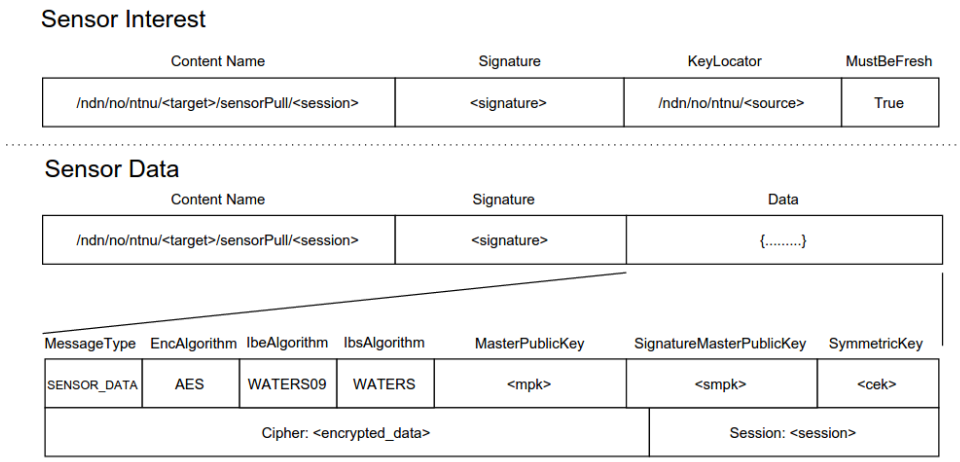


Figure 6.3: Sensor `Interest` and `Data`

6.4.3 Running the Code

First the NFD must be started on each device shown in Listing 6.1, if not already running. Then we have to make sure that each device participating in the network know the `Name` and IP address binding, since the testing will run NDN over IP. This is accomplished by registering the mapping in the FIB at each device showed in the second line in Listing 6.1.

On the device playing the role of the PKG, run the code presented in Listing 6.2.

This will create the key pair MPK_{pkg} and MSK_{pkg} and register the prefix where the other nodes can find the PKG.

On the device playing the role of e.g. a sensor, run the code presented in Listing 6.3. This will automatically register the prefix of the sensor, and start the initialize protocol with the PKG.

On the device playing the role of the user device (e.g. a mobile), run the code presented in Listing 6.4. This will automatically start the initialize protocol with the PKG. Running `r` will make the device expressing an `Interest` for sensor `Data` from the sensor.

```
1  $ nfd-start
2  $ nfdc register /ndn/no/ntnu/<\gls{data}-device> udp://<device-ip-
       address>
3  $ nfdc register /ndn/no/ntnu/<pull-device> udp://<device-ip-address>
4  $ nfdc register /ndn/no/ntnu/<pkg> udp://<pkg-ip-address>
```

Listing 6.1: NFD Start

```
1  $ python application.py
2  $ pkg
```

Listing 6.2: Start PKG

```
1  $ python application.py
2  $ \gls{data}
```

Listing 6.3: Start a device registering a prefix.

```
1  $ python application.py
2  $ pull
3  $ r
```

Listing 6.4: Start a device that will express `Interest` in `Data`.

6.5 Testing

In this section it will be presented which computers will be used during testing. The measurement results will be presented together with the key/content sizes related to the HSS.

6.5.1 Computers

The plan was to test the application with several Raspberry Pi's to simulate a sensor network, with limited computation power. However this is not possible with the Charm framework as it is not compatible with ARM processors. The HSS is tested over several computers presented in Table 6.1. Each computer is assigned an ID which will be used for reference in the performance measurements.

ID	Computer	Operating System	Processor
C1	Macbook Pro	64-bit OS X 10.10	Intel Core i7 @ 2.0GHz
C2	Garsbook	64-bit Ubuntu 14.04 LTS	Intel Core i5 @ 3.0GHz
C3	HP	64-bit Ubuntu 14.04 LTS	Intel Core i7 @ 2.8GHz

Table 6.1: Computers used during tests.

6.5.2 Key Sizes

It is listed in Table 6.2 the different sizes for keys related to the IBE and IBS that is used in the HSS implementation. The CEK is generated as a group element and is extracted to 40 bytes when performing encryption and decryption with AES. I would prefer to encrypt and send the extracted version of the CEK, i.e. the hash value of 40 bytes, but the IBE encryption scheme demands a certain type of format on the `Data`, and thus the whole CEK must be sent. The CEK is a random $\mathbb{G}_T$ element (section 4.2), and is generated with `group.random(GT)`.

Data	Scheme	Size
Content Encryption Key (CEK)	Hash($\mathbb{G}_T$)	244 bytes
IBE Master Public Key	Waters09	2014 bytes
IBE Secret Key (SK)	Waters09	1164 bytes
IBE Encrypted CEK	Waters09	1472 bytes
Encrypted SK	AES	1633 bytes
IBS Master Public Key	Waters	2360 bytes
IBS Secret Key (SSK)	Waters	260 bytes
IBS Signature	Waters	412 bytes
Encrypted SSK	AES	437 bytes

Table 6.2: Sizes of different keys used in the health sensor system implementation.

6.5.3 Performance

To be able to evaluate if IBC is applicable to devices with small computation power and limited battery, it has to at least perform somewhat in the range of regular asymmetric encryption (read RSA), and signing. Naccache suggested that if the prime p is 1024-bit, the scheme would provide equivalent security as a RSA 1024-bit key. For comparison reasons, the RSA key pair is therefore generated with the size of 1024-bit. In Table 6.3 the results from running different cryptographic methods on the computers listed in Table 6.1 are presented.

Method	Scheme	C1	C2	C3
IBE PKG key pair generation	Waters09	99.65 ms	27.09 ms	36.08 ms
IBE Encrypting CEK	Waters09	52.65 ms	189.15 ms	24.86 ms
IBE Secret Key (SK) generation	Waters09	56.14 ms	17.86 ms	23.27 ms
Encrypting SK	AES	0.13 ms	0.10 ms	0.15 ms
IBS PKG key pair generation	Waters	97.55 ms	27.15 ms	35.02 ms
IBS Secret Key (SSK) generation	Waters	9.76 ms	2.87 ms	3.72 ms
IBS Sign	Waters	9.90 ms	2.88 ms	3.69 ms
IBS Verify	Waters	7.58 ms	2.66 ms	4.32 ms
Encrypting SSK	AES	0.06 ms	0.02 ms	0.04 ms
RSA (1024-bit) key pair generation	RSA	254.27 ms	119.34 ms	165.99 ms
RSA Encryption	RSA	14.80 ms	4.40 ms	6.52 ms
RSA Decryption	RSA	14.72 ms	4.45 ms	6.49 ms
RSA Sign	RSA	16.15 ms	4.59 ms	6.69 ms
RSA Verify	RSA	15.72 ms	4.53 ms	6.74 ms
ECDSA key pair generation	ECDSA	0.57 ms	0.20 ms	0.32 ms
ECDSA Sign	ECDSA	0.50 ms	0.21 ms	0.33 ms
ECDSA Verify	ECDSA	0.90 ms	0.37 ms	0.58 ms

Table 6.3: Cryptographic methods time chart. Each measurement is the mean time of 100 rounds and measured in milliseconds.

The initialization protocol described in subsection 5.2.2 and the `Data` pull protocol described in subsection 5.2.3 is tested on the computers listed in Table 6.1. The results of the round trip time are presented in Table 6.4.

Protocol	C1	C1	C3
Initialization	202.9 ms	70.8 ms	116.3 ms
`Data` Pull	61.4 ms	31.0 ms	46.2 ms

Table 6.4: Round trip time chart. Time is measured in milliseconds.

The HSS is tested on two of the computers in Table 6.1. The topology is shown in Figure 6.4.

6.6 NDN Testbed

The NDN testbed is a network of NDN nodes created for research purpose. NTNU joined the testbed contributing with the 24^{th} node in the NDN testbed. The map of

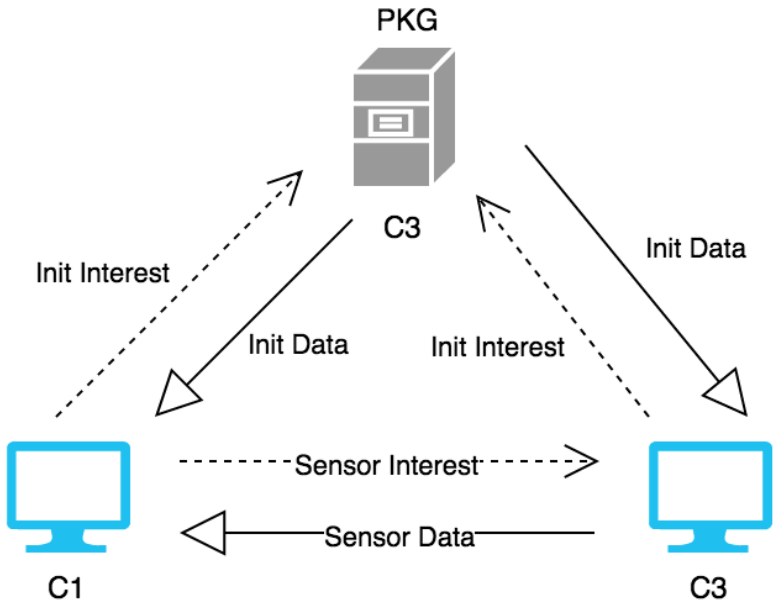


Figure 6.4: Health Sensor System implementation tested over two computer. C3 runs two nodes, i.e. the PKG and one device. C1 runs a second device.

the NDN testbed is shown in Figure 6.5.

Figure 6.5: NDN Testbed Map

Chapter 7
Discussion

In this chapter the work done in conjunction to this thesis will be discussed. First I will talk about the pros and cons using IBC in NDN. Then I will discuss the HSS and possible drawbacks in the system. Scalability issues and other applicable networks for the application will be mentioned.

7.1 Identity-Based Cryptography in Named Data Networking

Concerning key revocation, one suggestion has been to add a monthly timestamp to the `Name`, but the the PKG has to renew private keys for everybody each month. This solution do not scale very well due to a lot of computation at the PKG. With the FSM, every user will be notified when a identity is revoked. There is no use for periodically checking names. But the renewal of keys might not be an issue in the HSS.

more..

Can authenticate `Data` even using insecure DNS or HTTP. There is only one linkage between the `Name` and the content, and if the user obtains the right MPK, there is no doubt where the `Data` originates from and that it is not altered. In RSA public key cryptography we have to find the key related to the signature. In worst case this will be equivalent of retrieving the MPK each time, which is not likely. Or the MPK can be appended to the message.

refactor this section

7.2 Development Usability in Named Data Networking

Once a basic perception of the NDN architecture is understood, it is easy to begin developing. The PyNDN2 framework comes with good examples of how to develop simple applications with packets that are signed and encrypted.

The concept of naming `Data` introduces more simplicity, but also a new way of application design thinking. Addressing is dealt with one place in the architecture compared to an equivalent system over IP. Security is easily applied in NDN.

7.3 Health Sensor System

The application is not tested on with real sensors, hence I cannot conclude with anything regarding the computational power of such devices, nor the life time of the battery when performing IBE.

In subsection 6.5.3 we can see that IBC is performing better than regular asymmetric cryptography, RSA.

Encrypting with same symmetric key for each set of `Data`, limits the encryption computation for the device if several devices requests the same `Data`. Using a unique key for each time `Data` is requested is more secure and can be used for more sensitive content.

Who can play the role of a device? As mentioned in subsection 5.2.1 and subsection 5.2.2 there should be a limitation of which devices that can be initialized to the trust domain.

hm... something here?

Storing the SK in a secure fashion.

7.4 Scalability

Distributing the ID-list can be an issue, as the list can grow linearly with the number of participants in the trust domain. However, this might not be a huge problem in the use cases that is addressed in this thesis, considering that the number of devices in the HSS will not grow larger than e.g. 100 devices.

7.5 Sync

The sync application makes it possible for users to know who has a valid public key within the PKGs domain. One drawback with the key distribution using FSM is that for the sender to be 100% sure that the message is encrypted with the latest ID, the sender has to rely on that it has received the latest sync state available from the PKG. Likewise when a receiver verifies a signature, it has to rely on the same principle to be able to know if the belonging ID is still valid. Since the scalability is not that big of an issue in this scenario, the monthly (or even more often) timestamp appended to the ID might be a good solution to reduce the time of exposure when compromised.

In [SA99] Frank Stajano and Ross Anderson mentions possible DoS attacks, such as radio jamming and battery exhaustion. All applications that relies on some sort of crucial information derived using FSM (section 3.2) are vulnerable to this kind of DoS.

7.6 Other Use Cases

The trust model used in the HSS can be used in any network where the use of a TTP is accepted. Such a system can for instance be:

1. Home Automation Systems
2. Building Automation System (BAS)
3. Building Management System (BMS)
4. Open mHealth

Chapter 8
Conclusion and Future Work

In this chapter the conclusion of thesis will be presented and the future work will be listed.

8.1 Conclusion

NDN is easy to use for developers once the architecture is understood.

In this thesis I have developed a Health Sensor System in Python with Identity-Based Cryptography used for signing and verification, encryption and decryption. The system is built over the new network protocol called Named Data Networking.

I have suggested how a secure system easily can be implemented, achieving confidentiality, integrity and authenticity, as well as trust.

The system is tested to see how the suggested protocols for initialization and data pull performs with IBC. This work is an attempt to show how applicable NDN together with IBC are for IoT, and to design secure protocols for local device networks.

8.2 Future Work

The implementation of the HSS does not include integration of the FSM, which is a part of the future work. The system is not tested on relevant sensors and devices.

An implementation of a full worthy IBC solution in PyNDN2. This include making IBC as a part of the PyNDN2 framework, so that developers easily can make use of IBE and IBS.

The IBC schemes used in the Charm framework does not provide a scheme that implements IBE and IBS together. This should not be a huge task to implement, but it will decrease the initialization round-trip time as well as minimizing the use of

several keys, i.e. easier key management, as it is explained how to derive a signature scheme from any IBE scheme [Wat09, Section 4].

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Appendix A
Code

A.1 Scyther Security Analysis

```
1 hashfunction SHA256;
2 usertype ContentEncryptionKey, Content;
3
4 const pk: Function;
5 secret sk: Function;
6 inversekeys (pk,sk);
7
8
9 protocol HSSDataPull (PKG, D1, D2)
10 {
11
12   role PKG
13   {
14     #receive Interest D1
15     #send Data D1
16
17     #receive Interest D2
18     #send Data D2
19   }
20
21   role D1
22   {
23     # send Interest PKG
24     # reveive Data PKG
25
26     var Ra: Nonce;
27     fresh Rb: Nonce;
28
29     # send Interest D2
30     send_1(D1, D2,  Rb, D1,  {SHA256(Rb, D1)}sk(D1) );
```

```
31
32      # reveive Data D2
33      var CEK: ContentEncryptionKey;
34      var Data: Content;
35      recv_2(D2, D1,        Rb,    {D2, CEK}pk(D1),      { Data }k(D2
            ,D1)   ,   {SHA256( Rb,      { {CEK}pk(D1) }sk(D2),      {
            Data }k(D2,D1) )}sk(D2));
36
37      claim_D11(D1, Alive);
38      claim_D12(D1, Secret, CEK);
39      claim_D13(D1, Secret, Data);
40      claim_D14(D1, Weakagree);
41      claim_D15(D1, Niagree);
42      claim_D16(D1, Nisynch);
43    }
44
45    role D2
46    {
47      # send Interest PKG
48      # reveive Data PKG
49
50      fresh Ra: Nonce;
51      var Rb: Nonce;
52
53      # receive Interest D1
54      recv_1(D1, D2,    Rb, D1,   {SHA256(Rb, D1)}sk(D1) );
55
56      # send Data D1
57      fresh CEK: ContentEncryptionKey;
58      fresh Data: Content;
59      send_2(D2, D1,        Rb,      {D2, CEK}pk(D1) ,      { Data }k
            (D2,D1) ,   {SHA256( Rb,      { {CEK}pk(D1) }sk(D2),      {
             Data }k(D2,D1) )}sk(D2));
60
61      claim_D27(D2, Alive);
62      claim_D28(D2, Secret, CEK);
63      claim_D29(D2, Secret, Data);
64      claim_D210(D2, Weakagree);
65      claim_D211(D2, Niagree);
66      #claim_D212(D2, Nisynch);
67    }
68  }
```