

Network	Application	User	Mobile
network load	Throughput	acceptable cost	energy
coverage area	Delay	service quality	mobility
connection time	Jitter	Design	
available bandwidth	Packet loss rate		

Table 1: An example table.

Parameters			
Network conditions	network load	Dynamic	Minimized
	network coverage	Static	Fixed
	network connection time	Dynamic	Minimized
	available bandwidth	Dynamic	Minimized
Application requirements	throughput	Dynamic	Minimized
	delay	Dynamic	Minimized
	jitter	Dynamic	Minimized
	PLR	Dynamic	Minimized
	energy consumption	Dynamic	Minimized
User preferences	budget	Static	Fixed
	cost	Static	Fixed
Mobile equipment	battery level	Dynamic	Fixed
	mobility	Dynamic	Fixed

Table 2: An example table.

Protocol	Frequency	Range	IEEE	Data Rate	TX Active Power @ 3V
WLAN	2.4GHz	35m	802.11	54 Mbit/s	800mW
BLE	2.4GHz	100m	802.15.1	1 Mbit/s	25mW
6LoWPAN	2.4GHz	20m	802.15.4	250 kbit/s	<75mW
ZigBee	2.4GHz	20m	802.15.4	250 kbit/s	<75mW

Table 3: Protocol specification overview [1]

Protocol	Frequency	Range	IEEE	Data Rate	TX Active Power @ 3V
Lora	2.4GHz	35m	802.11	54 Mbit/s	800mW
SigFox	2.4GHz	100m	802.15.1	1 Mbit/s	25mW
6LoWPAN	2.4GHz	20m	802.15.4	250 kbit/s	<75mW
ZigBee	2.4GHz	20m	802.15.4	250 kbit/s	<75mW

Table 4: Protocol specification overview [1]

- [2] Many studies have identified **SDN** as a potential solution to the WSN challenges, as well as a model for **heterogeneous** integration.
- [2] This **shortfall** can be resolved by using the **SDN approach**.
- [3] **SDN** also enhances better control of **heterogeneous** network infrastructures.
- [3] Anadiotis et al. define a **SDN operating system for IoT** that integrates SDN based WSN (**SDN-WISE**). This experiment shows how **heterogeneity** between different kinds of SDN networks can be achieved.

- [3] In cellular networks, OpenRoads presents an approach of introducing SDN based heterogeneity in wireless networks for operators.
 - [4] There has been a plethora of (industrial) studies synergising SDN in IoT. The major characteristics of IoT are low latency, wireless access, mobility and heterogeneity.
 - [4] Thus a bottom-up approach application of SDN to the realisation of heterogeneous IoT is suggested.
 - [4] Perhaps a more complete IoT architecture is proposed, where the authors apply SDN principles in IoT heterogeneous networks.
 - [5] it provides the SDWSN with a proper model of network management, especially considering the potential of heterogeneity in SDWSN.
 - [5] We conjecture that the SDN paradigm is a good candidate to solve the heterogeneity in IoT.
 - The IETF Constrained Application Protocol
 - The IETF Constrained RESTful Environments
 - CoAP is bound to UDP
 - CoAP can be divided into two sub-layers
 - messaging sub-layer
 - request/response sub-layer
 - a) Confirmable.
 - b) Non-confirmable.
 - c) Piggybacked responses.
 - d) Separate response
 - CoAP, as in HTTP, uses methods such as:
 - GET, PUT, POST and DELETE to
 - Achieve, Create, Retrieve, Update and Delete
 - Ex: the GET method can be used by a server to inquire the clients temperature
- Ver: is the version of CoAP
 T: is the type of Transaction
 OC: is Option count
 Code: represents the request method (1-10) or response code (40-255).
 – Ex: the code for GET, POST, PUT, and DELETE is 1, 2, 3, and 4, respectively.

Message ID: is a unique identifier for matching the response.

- Message Queue Telemetry Transport
 - Andy Stanford-Clark of IBM and Arlen Nipper of Arcom
 - Standardized in 2013 at OASIS
 - MQTT uses the publish/subscribe pattern to provide transition flexibility and simplicity of implementation
 - MQTT is built on top of the TCP protocol
 - MQTT delivers messages through three levels of QoS
 - Specifications
 - MQTT v3.1 and MQTT-SN (MQTT-S or V1.2)
 - MQTT v3.1 adds broker support for indexing topic names
 - The publisher acts as a generator of interesting data.
- Message type: CONNECT (1), CONNACK (2), PUBLISH (3), SUBSCRIBE (8) and so on
- DUP flag: indicates that the message is duplicated
- QoS Level: identify the three levels of QoS for delivery assurance of Publish messages
- Retain field: retain the last received Publish message and submit it to new subscribers as a first message
- Extensible Messaging and Presence Protocol
 - Developed by the Jabber open source community
 - An IETF instant messaging standard used for:

Management architecture	Management feature	Controller configuration	Traffic Control	Configuration and monitoring	Scapability and localization	Communication management
[6] Sensor Open Flow	SDN support protocol	Distributed	in/out-band	✓	✓	✓
costanzo_sofia_2014 SDWN	Flow recycling, aggregation, routing	Centralized	in-band	✓		
[7] SDN-WISE	Programming simplicity and aggregation	Distributed	in-band		✓	
degante_smart_2014 Smart	Efficient in resource allocation	Distributed	in-band		✓	
SDCSN	Network reliability and QoS	Distributed	in-band		✓	
TinySDN	In-band-traffic control	Distributed	in-band		✓	
Virtual Overlay	Network flexibility	Distributed	in-band		✓	
Context based	Network scalability and performance	Distributed	in-band		✓	
CRLB	Node localization	Centralized	in-band			
Multi-hope	Traffic and energy control	Centralized	in-band			✓
Tiny-SDN	Network task measurement	-	in-band			

Table 5: SDN-based network and topology management architectures. [4]

- multi-party chatting, voice and telepresence
- Connects a client to a server using a XML stanzas
- An XML stanza is divided into 3 components:
 - message: fills the subject and body fields
 - presence: notifies customers of status updates
 - iq (info/query): pairs message senders and receivers
- Message stanzas identify:
 - the source (from) and destination (to) addresses
 - types, and IDs of XMPP entities
- Advanced Message Queuing Protocol

Application protocol	DDS	CoAP	AMQP	MQTT	MQTT-SN	XMPP	HTTP
Service discovery	mDNS			DNS-SD			
Network layer				RPL			
Link layer				IEEE 802.15.4			
Physical layer	EPCglobal			IEEE 802.15.4		Z-Wave	

Table 6: Standardization efforts that support the IoT

0 1	2 3	4-7	8-15	16-31
Ver	T	OC	CODE	Message ID
Token				
Options				
Payload				

Table 7: CoAP message format.

0-3	4	5 6	7
Message type	DUP	QoS level	Retain
Remaining length			
Variable length header			
Variable length message payload			

Table 8: MQTT message format.

- Communications are handled by two main components
 - exchanges: route the messages to appropriate queues.
 - message queues: Messages can be stored in message queues and then be sent to receivers
- It also supports the publish/subscribe communications.
- It defines a layer of messaging on top of its transport layer.
- AMQP defines two types of messages
 - bare messages: supplied by the sender
 - annotated messages: seen at the receiver
- The header in this format conveys the delivery parameters:
 - durability, priority, time to live, first acquirer & delivery count.
- AMQP frame format
 - Size the frame size.
 - DOFF the position of the body inside the frame.
 - Type the format and purpose of the frame.
 - * Ex: 0x00 show that the frame is an AMQP frame
 - * Ex: 0x01 represents a SASL frame.
- Data Distribution Service
- Developed by Object Management Group (OMG)
- Supports 23 QoS policies:
 - like security, urgency, priority, durability, reliability, etc
- Relies on a broker-less architecture
 - uses multicasting to bring excellent Quality of Service
 - real-time constraints

- DDS architecture defines two layers:
DLRL Data-Local Reconstruction Layer
 - * serves as the interface to the DCPS functionalities
- DCPS Data-Centric Publish/Subscribe
 - * delivering the information to the subscribers
- 5 entities are involved with the data flow in the DCPS layer:
 - Publisher: disseminates data
 - DataWriter: used by app to interact with the publisher
 - Subscriber: receives published data and delivers them to app
 - DataReader: employed by Subscriber to access received data
 - Topic: relate DataWriters to DataReaders
- No need for manual reconfiguration or extra administration
- It is able to run without infrastructure
- It is able to continue working if failure happens.
- It inquires names by sending an IP multicast message to all the nodes in the local domain
 - Clients asks devices that have the given name to reply back
 - the target machine receives its name and multicasts its IP @
 - Devices update their cache with the given name and IP @
- Requires zero configuration aids to connect machine
- It uses mDNS to send DNS packets to specific multicast addresses through UDP
- There are two main steps to process Service Discovery:
 - finding host names of required services such as printers
 - pairing IP addresses with their host names using mDNS
- Advantages
 - IoT needs an architecture without dependency on a configuration mechanism
 - smart devices can join the platform or leave it without affecting the behavior of the whole system
- Drawbacks
 - Need for caching DNS entries

OS	Architecture	Multi threading	Scheduling	Dynamic Memory	Memory protection	Network Stack
Contiki/Contiki-ng	Modular	✓	Interrupts execute w.r.t.	✓	✗	uIP Rime
MANTIS	Modular	✗	Priority classes	✓	✗	At Kernel COMM layer
Nano-RK	Layered	✓	Monotonic harmonized	✗	✗	Socket abstraction
LiteOS	Monolithic	✓	Round Robin	✓	✓	File

Table 9: Common operating systems used in IoT environment [8]

- Routing over low-power and lossy links (ROLL)
- Support minimal routing requirements.
 - like multipoint-to-point, point-to-multipoint and point-to-point.
- A Destination Oriented Directed Acyclic Graph (DODAG)
 - Directed acyclic graph with a single root.
 - Each node is aware of its parents
 - but not about related children

- RPL uses four types of control messages
 - DODAG Information Object (DIO)
 - Destination Advertisement Object (DAO)
 - DODAG Information Solicitation (DIS)
 - DAO Acknowledgment (DAO-ACK)

Paper	Archi- tec- ture	Avail- abil- ity	Reli- abil- ity	Mo- bil- ity	Per- for- mance	Man- age- ment	Scal- abil- ity	Interop- erability	Se- cu- rity
IoT-A									
IoT@Work									
EBBITS									
BETaaS									
CALIPSO									
VITAL									
SENSAI									
RERUM									
RELEY- onIT									
IoT6									
OpenIoT									
Apec IoV									
Smart San- tander									
OMA Device									
OMA- DM									
LWM2M									
NET- CONF Light									
Kura									
MASH									
IoT- iCore									
PROBE- IT									
OpenIoT									
LinkS- mart									
IETF SOLACE									
BUTLER									
Codo									
SVELETE									

Table 10: An example table.

Platform	COAP	XMPP	MQTT
Arkessa			✓
Axeda			
Etherios			
LittleBits			
NanoService	✓		
Nimbits		✓	
Ninja blocks			
OnePlatformv	✓	✓	
RealTime.io			
SensorCloud			
SmartThings			
TempoDB			
ThingWorx			✓
Xively			✓
Ubidots			✓

Table 11: IoT cloud platforms and their characteristics

- Standard topologies to form IEEE 802.15.4e networks are
 - Star contains at least one FFD and some RFDs
 - Mesh contains a PAN coordinator and other nodes communicate with each other
 - Cluster consists of a PAN coordinator, a cluster head and normal nodes.
- The IEEE 802.15.4e standard supports 2 types of network nodes
 - FFD Full function device: serve as a coordinator
 - * It is responsible for creation, control and maintenance of the net
 - * It store a routing table in their memory and implement a full MAC
 - RFD Reduced function devices: simple nodes with restricted resources
 - * They can only communicate with a coordinator
 - * They are limited to a star topology

Preamble	PHDR	PHDRCRC	MHDR	FHDR	FPort	Payload	MIC	CRC
----------	------	---------	------	------	-------	---------	-----	-----

Characteristics	6LoWPAN	LoRaWAN	SigFox
Frequency band (MHz)	902-929 868-868.6	902-928 863-870 and 434	902 868
Number of channels (channels for MHz)	0016 for 2400 0010 for 915 0001 for 868.3	80 for 915 10 for 868 and 780	25
Channel bandwidth (MHz)	0005 for 2400 0002 for 915 0600 for 868.3	0.125 and 0.50 for 915 0.125 and 0.25 for 868 and 780	0.0001-0.0012
Maximum data rate (kbps for MHz)	0250 for 2400 0040 for 915 0020 for 868.3	0.00098-0.0219 for 915 0.250-0.05 for 868 and 780	0.1-0.6
Channel coding (dBm for MHz)	-085 for 2400 -092 for 915 -092 for 868.3	-137	-137
Protocol data unit (bytes)	6+127	x + (19 to 250)	12+ (0 to 12)
Channel coding	Direct	CSS	Ultra
Transmission range	10-100 m	5-15 km	10-50 km
Battery lifetime	1-2 years	<10 years	<10 years

Table 12: LPWan Characteristics [9]

Feature	Wi-Fi	802.11p	UMTS	LTE	LTE-A
Channel width MHz	20	10	5	1.4, 3, 5, 10, 15, 20	Up to 100
Frequency band(s) GHz	2.4 , 5.2	5.86-5.92	0.7-2.6	0.7-2.69	0.45-4.99
Bit rate Mb/s	6-54	327	2	Up to 300	Up to 1000
Range km	Up to 0.1	Up to 1	Up to 10	Up to 30	Up to 30
Capacity	Medium	Medium	✗	✓	✓
Coverage	Intermittent	Intermittent	Ubiquitous	Ubiquitous	Ubiquitous
Mobility support km/h	✗	Medium	✓	up to 350	up to 350
QoS support	EDCA Enhanced Distributed Channel Access	EDCA Enhanced Distributed Channel Access	QoS classes and bearer selection	QCI and bearer selection	QCI and bearer selection
Broadcast/multicast support	Native broadcast	Native broadcast	Through MBMS	Through eMBMS	Through eMBMS
V2I support	✓	✓	✓	✓	✓
V2V support	Native (ad hoc)	Native (ad hoc)	✗	✗	Through D2D
Market penetration	✓	✗	✓	✓	✓

Table 13: An example table.

Feature	RFID	ZigBee	NFC	LTE	LTE-A
Channel width MHz	20	10	5	1.4, 3, 5, 10, 15, 20	Up to 100
Frequency band(s) GHz	2.4 , 5.2	5.86-5.92	0.7-2.6	0.7-2.69	0.45-4.99
Bit rate Mb/s	6-54	327	2	Up to 300	Up to 1000
Range m	3-10	10-100	Up to 6.1	Up to 30	Up to 30
Capacity	Medium	Medium	✗	✓	✓
Coverage	Intermittent	Intermittent	Ubiquitous	Ubiquitous	Ubiquitous
Mobility support km/h	✗	Medium	✓	up to 350	up to 350
QoS support	EDCA Enhanced Distributed Channel Access	EDCA Enhanced Distributed Channel Access	QoS classes and bearer selection	QCI and bearer selection	QCI and bearer selection
Broadcast/multicast support	Native broadcast	Native broadcast	Through MBMS	Through eMBMS	Through eMBMS
V2I support	✓	✓	✓	✓	✓
V2V support	Native (ad hoc)	Native (ad hoc)	✗	✗	Through D2D
Market penetration	✓	✗	✓	✓	✓
Data rate	Up to 640 kbps	250 kbps	106424 kbps	✓	✓

Table 14: An example table.

Use cases			
Health Monitoring			
Water Distribution			
Electricity Distribution			
Smart Buildings			
Intelligent Transportation			
Surveillance			
Environmental Monitoring			

Table 15: Use cases [10]

Phy protocol	Radio band (MHz)	MAC address	Data rate (bps)	Scalability
IEEE 802.15.4	868/915/2400	TDMA, CSMA/CA	20/40/250 K	65K nodes
BLE	2400	TDMA	1024K	5917 slaves
EPCglobal	860-960	ALOHA	varies 5-640K	-
Z-Wave	868/908/2400	CSMA/CA	40K	232 nodes

Table 16: IoT cloud platforms and their characteristics [8]

Routing protocol	Control Cost	Link Cost	Node Cost
OSPF/IS-IS	✗	✓	✗
OLSRv2	?	✓	✓
RIP	✓	?	✗
DSR	✓	✗	✗
RPL	✓	✓	✓

Table 17: Routing protocols comparison _rpl2_

Application protocol	Rest-Full	Transport	Publish/Subscribe	Request/Response	Security	QoS	Header size (Byte)
COAP	✓	UDP	✓	✓	DTLS	✓	4
MQTT	✗	TCP	✓	✗	SSL	✓	2
MQTT-SN	✗	TCP	✓	✗	SSL	✓	2
XMPP	✗	TCP	✓	✓	SSL	✗	-
AMQP	✗	TCP	✓	✗	SSL	✓	8
DDS	✗	UDP TCP	✓	✗	SSL DTLS	✓	-
HTTP	✓	TCP	✗	✓	SSL	✗	-

Table 18: Application protocols comparison

1 | Introduction

1.1 hgh

1.2 Introduction

1.2.1 Context & motivation

The exponential growth of 5G networks and the development of IoT that will greatly come with it, would considerably raise the number of Smart Cities applications. The aim of such technology is mainly to improve the comfort and the safety of users through wireless IoT networks. Wireless Sensor Networks (WSNs) are the source of sensed data of cities things, i.e. roads, cars, pedestrians, houses, parking, etc. The cloud is the entity that collects the sensed data and allows users and machines to do data analysis and improve services. For Smart Cities, one objective is improving the welfare of citizens as well as its safety getting real-time information about the city infrastructure. One application would be the transportation systems, and traffic lights control having as an objective avoids congestion and dangerous situations. A static cycle of traffic lights has a direct impact on traffic jams. The long period at red or green light could impact the fluidity of the city traffic. The Internet of Things (IoT) would give an answer to the required interoperability between heterogeneous wireless networks. Our objective is to model, prototype and evaluate a traffic control system. Indeed, different infrastructures have different purposes and technologies, this means that it is not possible to state communication between two infrastructures following a Device-to-Device approach. However, thinking of an indirect or Device-to-Cloud communication between infrastructures seems useful when every connected system has its own technologies, e.g. Zigbee, LoRa, SigFox, ITS-G5. Consequently, IP stack would be the suitable mediator for interconnecting these networks. It removes the barriers of rigid standard specifications of the hardware despite the overhead of the extra network configuration. Furthermore, we want to have a scalable solution not limited only on the traffic light management system. We can deploy sensors and actuators to measure noise or air pollution via panels or roads and offer new services, e.g. where and when jogging is better. To implement our Urban Traffic Light Control based on an IoT network architecture (IoT-UTLC), we setting a real IEEE 802.15.4 WSN devices that would act as actuators and sensors. All these small traffic light devices are driven by a Border Router (BR) which is a gateway to the Internet. This BR

1.2.2 Methodology and contributions

1.2.3 Organization of the thesis

2 | State of the art

2.1 Introduction

NY ny

Plan de controle Controle d’admission Réservation de ressources Routage Signalisation	Plan de gestion Controle et supervision de QoS Gestion de contrats QoS mapping Politique de QoS
Plan de doonnées Controle du trafic Façonnage du trafic Controle de congestion Classification de paquets Marquage de paquets Ordonnancements des paquets Gestion de files d’attente	

Table 2.1: An example table.

2.2 Hardware and software platform for Internet of Things

2.2.1 Software platform: Operating systems

The operating system is the foundation of the IoT technology as it provides the functions for the connectivity between the nodes. However, different types of nodes need different levels of OS complexity; a passive node generally only needs the communication stack and is not in need of any threading capabilities, as the program can handle all logic in one function. Active nodes and border routers need to have a much more complex OS, as they need to be able to handle several running threads or processes, e.g. routing, data collection and interrupts. To qualify as an OS suitable for the IoT, it needs to meet the basic requirements: Low Random-access memory (RAM) footprint Low Read-only memory

(ROM) footprint Multi-tasking Power management (PM) Soft real-time These requirements are directly bound to the type of hardware designed for the IoT. As this type of hardware in general needs to have a small form factor and a long battery life, the on-board memory is usually limited to keep down size and energy consumption. Also, because of the limited amount of memory, the implementation of threads is usually a challenging task, as context switching needs to store thread or process variables to memory. The size of the memory also directly affects the energy consumption, as memory in general is very power hungry during accesses. To be able reduce the energy consumption, the OS needs some kind of power management. The power management does not only let the OS turn on and off peripherals such as flash memory, I/O, and sensors, but also puts the MCU itself in different power modes. As the nodes can be used to control and monitor consumer devices, either a hard or soft real-time OS is required. Otherwise, actions requiring a close to instantaneous reaction might be indefinitely delayed. Hard real-time means that the OS scheduler can guarantee latency and execution time, whereas Soft real-time means that latency and execution time is seen as real-time but can not be guaranteed by the scheduler. Operating systems that meet the above requirements are compared in table 2.1 and 2.2.

OS	Architecture	Multi threading	Scheduling	Dynamic Memory	Memory protection	Network Stack
Contiki/Contiki-ng	Modular	✓	Interrupts execute w.r.t.	✓	✗	uIP Rime
MANTIS	Modular	✗	Priority classes	✓	✗	At Kernel COMM layer
Nano-RK	Layered	✓	Monotonic harmonized	✗	✗	Socket abstraction
LiteOS	Monolithic	✓	Round Robin	✓	✓	File

Table 2.2: Common operating systems used in IoT environment [8]

2.2.1.1 Contiki

Contiki is a embedded operating system developed for IoT written in C [12]. It supports a broad range of MCUs and has drivers for various transceivers. The OS does not only support TCP/IPv4 and IPv6 with the uIP stack [9], but also has support for the 6LoWPAN stack and its own stack called RIME. It supports threading with a thread system called Photothreads [13]. The threads are stack-less and thus use only two bytes of memory per thread; however, each thread is bound to one function and it only has permission to control its own execution. Included in Contiki, there is a range of applications such as a HTTP, Constrained Application Protocol (CoAP), FTP, and DHCP servers, as well as other useful programs and tools. These applications can be included in a project and can run simultaneously with the help of Photothreads. The limitations to what applications can be run is the amount of RAM and ROM the target MCU provides. A standard system with IPv6 networking needs about 10 kB RAM and 30 kB ROM but as applications are added the requirements tend to grow.

2.2.1.2 RIOT

RIOT is a open source embedded operating system supported by Freie Universität Berlin, INIRA, and Hamburg University of Applied Sciences [14]. The kernel is written in C but the upper layers support C++ as well. As the project originates from a project with real-time and reliability requirements, the kernel supports hard real-time multi-tasking scheduling. One of the goals of the project is to make the OS completely POSIX compliant. Overhead for multi-threading is minimal with less than 25 bytes per thread. Both IPv6 and 6LoWPAN is supported together with UDP, TCP, and IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL); and CoAP and Concise Binary Object Representation (CBOR) are available as application level communication protocols.

2.2.1.3 TinyOS

TinyOS is written in Network Embedded Systems C (nesC) which is a variant of C [15]. nesC does not have any dynamic memory allocation and all program paths are available at compile-time. This is manageable thanks to the structure of the language; it uses modules and interfaces instead of functions [16]. The modules use and provide interfaces and are interconnected with configurations; this procedure makes up the structure of the program. Multitasking is implemented in two ways: trough tasks and events. Tasks, which focus on computation, are non-preemptive, and run until completion. In contrast, events which focus on external events i.e. interrupts, are preemptive, and have separate start and stop functions. The OS has full support for both 6LoWPAN and RPL, and also have libraries for CoAP.

2.2.1.4 freeRTOS

One of the more popular and widely known operating systems is freeRTOS [17]. Written in C with only a few source files, it is a simple but powerful OS, easy to overview and extend. It features two modes of scheduling, pre-emptive and co-operative, which may be selected according to the requirements of the application. Two types of multitasking are featured: one is a lightweight Co-routine type, which has a shared stack for lower RAM usage and is thus aimed to be used on very small devices; the other is simply called Task, has its own stack and can therefore be fully pre-empted. Tasks also support priorities which are used together with the pre-emptive scheduler. The communication methods supported out-of-the-box are TCP and UDP.

2.2.2 Hardware platform

Even though the hardware is in one sense the tool that the OS uses to make IoT possible, it is still very important to select a platform that is future-proof and extensible. To be regarded as an extensible platform, the hardware needs to have I/O connections that can be used by external peripherals. Amongst the candidate interfaces are Serial Peripheral

Interface (SPI), Inter-Integrated Circuit (I²C), and Controller Area Network (CAN). These interfaces allow developers to attach custom-made PCBs with sensors for monitoring or actuators for controlling the environment. The best practice is to implement an extension socket with a well-known form factor. A future-proof device is specified as a device that will be as attractive in the future as it is today. For hardware, this is very hard to achieve as there is constant development that follows Moores Law [4]; however, the most important aspects are: the age of the chip, its expected remaining lifetime, and number of current implementations i.e. its popularity. If a device is widely used by consumers, the lifetime of the product is likely to be extended. One last thing to take into consideration is the product family; if the chip belongs to a family with several members the transition to a newer chip is usually easier.

2.2.2.1 OpenMote

OpenMote is based on the Ti CC2538 System on Chip (SoC), which combines an ARM Cortex-M3 with a IEEE 802.15.4 transceiver in one chip [18, 19]. The board follows the XBee form factor for easier extensibility, which is used to connect the core board to either the OpenBattery or OpenBase extension boards [20, 21]. It originates from the CC2538DK which was used by Thingsquare to demo their Mist IoT solution [22]. Hence, the board has full support for Contiki, which is the foundation of Thingsquare. It can run both as a battery-powered sensor board and as a border router, depending on what extension board it is attached to, e.g OpenBattery or OpenBase. Furthermore, the board has limited support but ongoing development for RIOT and also full support for freeRTOS.

2.2.2.2 MSB430-H

The Modular Sensor Board 430-H from Freie Universität Berlin was designed for their ScatterWeb project [23]. As the university also hosts the RIOT project, the decision to support RIOT was natural. The main board has a Ti MSP430F1612 MCU [24], a Ti CC1100 transceiver, and a battery slot for dual AA batteries; it also includes a SHT11 temperature and humidity sensor and a MMA7260Q accelerometer to speed up early development. All GPIO pins and buses are connected to external pins for extensibility. Other modules with new peripherals can then be added by making a PCB that matches the external pin layout.

2.2.2.3 Zolertia

As many other Wireless Sensor Network (WSN) products, the Zolertia Z1 builds upon the MSP430 MCU [25, 26]. The communication is managed by the Ti CC2420 which operates in the 2.4 GHz band. The platform includes two sensors: the SHT11 temperature and humidity sensor and the MMA7600Q accelerometer. Extensibility is ensured with: two connections designed especially for external sensors, an external connector with USB, Universal asynchronous receiver/transmitter (UART), SPI, and I²C.

2.2.3 Communication protocol

Several different wireless communication protocols, such as Wireless LAN (WLAN), BLE, 6LoWPAN, and ZigBee may be suitable for IoT applications. They all operate in the 2.4GHz frequency band and this, together with the limited output power in this band, means that they all have a similar range. The main differences are located in the MAC, PHY, and network layer. WLAN is much too power hungry as seen in table 2.6 and is only listed as a reference for the comparisons.

2.2.3.1 IEEE 802.15.4

The IEEE 802.15.4 standard defines the PHY and MAC layers for wireless communication [6]. It is designed to use as little transmission time as possible but still have a decent payload, while consuming as little power as possible. Each frame starts with a preamble and a start frame delimiter; it then continues with the MAC frame length and the MAC frame itself as seen in figure 2.2. The overhead for each PHY packet is only 4+1+1 133 tild 4.5%; when using the maximum transmission speed of 250kbit/s, each frame can be sent 133byte in 250kbit/s = 4.265ms. Furthermore, it can also operate in the 868MHz and 915MHz bands, maintaining the 250kbit/s transmission rate by using Offset quadrature phase-shift keying (O-QPSK).

Several network layer protocols are implemented on top of IEEE 802.15.4. The two that will be examined are 6LoWPAN and ZigBEE.

1) **6LoWPAN** is a relatively new protocol that is maintained by the Internet Engineering Task Force (IETF) [7, 6]. The purpose of the protocol is to enable IPv6 traffic over a IEEE 802.15.4 network with as low overhead as possible; this is achieved by compressing the IPv6 and UDP header. A full size IPv6 + UDP header is 40+8 bytes which is tild 38% of a IEEE 802.15.4 frame, but with the header compression this overhead can be reduced to 7 bytes, thus reducing the overhead to tild 5%, as seen in figures 2.3 and 2.4.

2) **ZigBee** is a communication standard initially developed for home automation networks; it has several different protocols designed for specific areas such as lighting, remote control, or health care [27, 6]. Each of these protocols uses their own addressing with different overhead; however, there is also the possibility of direct IPv6 addressing. Then, the overhead is the same as for uncompressed 6LoWPAN, as seen in figure 2.5.

A new standard called ZigBee 3.0 aims to bring all these standards together under one roof to simplify the integration into IoT. The release date of this standard is set to Q4 2015.

2.2.3.2 Bluetooth LE

BLE is developed to be backwards compatible with Bluetooth, but with lower data rate and power consumption [28]. Featuring a data rate of 1Mbit/s with a peak current consumption less than 15mA, it is a very efficient protocol for small amounts of data. Each frame can be transmitted 47bytes in 1Mbit/s = 376Mus; thanks to the short transmission time, the transceivers consumes less power as the transceiver can be in receive mode or completely off most of the time. BLE uses its own addressing methods and as the MAC frame size (figure 2.6) is only 39bytes, thus IPv6 addressing is not possible.

Starting from Bluetooth version 4.2, there is support for IPv6 addressing with the Internet Protocol Support Profile; the new version allows the BLE frame to be variable between 2 257 bytes. The network set-up is controlled by the standard Bluetooth methods, whereas IPv6 addressing is handled by 6LoWPAN as specified in IPv6 over Bluetooth Low Energy [29].

2.2.4 Summary and discussion

2.3 IoT applications

2.3.1 Transportation and logistics

2.3.2 Healthcare

2.3.3 Smart environnement

2.3.4 personal and social

2.3.5 Futuristic

2.3.6 Summary and discussion

2.3.7 Summary and discussion

2.4 IoT security

2.4.1 Summary and discussion

2.5 Conclusion

3 | Chapter 2

3.1 Introduction & problem statement

3.1.1 Background

Internet of Things (IoT) is a concept aiming at connecting all things to the Internet [1]. The different kinds of devices range from simple sensor devices to complex machines such as industry robots. Home automation has been available for a few years in the forms of timers and remotely controlled devices, such as lights, garage door, and climate control equipment. Also in the industry and workplace, there are current systems that have some of the functionality of IoT, e.g. sensors in robots and machines which keep track of the system status so that maintenance can be scheduled at the right time. However, these systems or sensors rarely communicate with each other or make decisions based on other sensor values; instead they depend on input from a user. In the same way cellphones connected people and made them constantly connected to the Internet, IoT will connect devices and make them constantly connected to the Internet [2]. In theory, this could lead to a future with autonomous technology all around us. The benefits could be huge as it would save time and energy for both the individual at home and for the industry [3]. IoT could be used in industry to automate power-heavy tasks to run when the electricity price is low. This principle can also be applied for the home user with laundry machines and charging of e.g. electric cars. This practice would lead to reduced energy consumption and thus a reduced environmental footprint. i3tex AB wants to investigate potential fields of applicability of this upcoming technology. i3tex AB has customers in the automotive, communication, and pulp industries; those customers have made inquiries on how to integrate IoT and sensor networks into production. As technology evolves, size and energy consumption of the IoT devices will decrease and computation power will increase [4]. This reduction in size and energy consumption, together with the increased computing power, will open up new fields for IoT. Thus, i3tex AB want to have an IoT platform to present to their current and potential customers. The interest in IoT is rapidly increasing, and thus, in the near future, the number of devices connected to the Internet is expected to increase rapidly. To support this huge increase in both number of connected devices and the sheer amount of data that will be sent over both wired and wireless networks, the communication technology must be ready [5].

3.1.2 Purpose (Goal)

The purpose of this project is to find and examine a communication method for devices that are made to be a part of IoT. This will be done by examining the available technologies and then developing a prototype based on the findings, which will be used for examining the communication method. This project will examine the physical, link, and network layers [6, 7] of the Open Systems Interconnection model (OSI model) [8], in order to find suitable technologies on the market. As IoT is still only defined as a concept, there are several technologies to take into consideration and examine in further detail. The prototype will be delivered to i3tex AB together with appropriate documentation, e.g. technical specification, hardware manual, software manual, and API specification.

3.1.3 Limitations

To be able to achieve the project goal within the available time, limitations need to be defined in the three main areas of: Operating System (OS), hardware, and communication method. The OS will not be custom-made, but rather selected amongst those already on the market. Thus, to simplify the hardware selection, only those OSs which already have hardware support that meets the requirements will be taken into consideration. Furthermore, support for either 6LoWPAN, ZigBee, or Bluetooth Low Energy (BLE) as communication method is required, since development to make those standards available is outside the scope of the project. On the hardware side, the limitations will be to only use existing devices and parts as there will be no time for developing hardware or Printed Circuit Boards (PCBs). However, the hardware does not need to have an integrated radio transceiver, but needs to support at least one transceiver supporting IEEE802.15.4 [6]. Thus, communication methods will be primarily selected from specifications building on the IEEE 802.15.4.

3.1.4 Method

To ensure that the right technologies were selected and investigated, the first phase of the project was a literature study. The study served as a foundation when developing and performing the evaluation of the communication methods. At the end of the phase, a requirements specification was formulated to serve as a platform for the next phase. After the literature study, a selection process was performed, where the most promising technologies that met the requirements were examined in further detail and brought into the development phase. This process included the selection of development tools and other decisions bound to the product development. In the development phase, the chosen set-up was configured and assembled to prepare for testing; it was then tested according to throughput, range, latency, and energy consumption. Throughput was measured in kilobyte per second (KB/s) and tested by transferring data of different sizes in both congested and uncongested network set-ups to simulate real world and lab environments. The same set-up was used to measure the latency of a transmission, which was measured in microseconds (μs). Range was calculated instead of measured, with meters (m) as the unit.

The power consumption was measured in watts (W). Each week a meeting with the company supervisors was performed, to keep the work on the right track. Here, feedback was be given and other issues and questions handled.

3.2 Background

The goal of the implementation phase is to have a working prototype for future assessment. To make the process of implementing the prototype possible, the first part of the implementation process will be to create a set of requirements. When these are set, the process will continue by comparing the data from chapter 2 to find the candidates that fulfil the requirements. After the technologies are selected, the process will continue with setting up the workspace, which includes the platform for development and the required tools to build, debug and test the prototype. Finally, when these three steps have been performed, the next step will be to start with the actual prototype development.

3.2.1 Selection of technology

3.2.1.1 Requirements

As the time dedicated for development is limited, the requirements have to make sure that the development process does not run into any major obstacles. All parts of the total prototype need to fit together seamlessly. However, the hardware platform and the operating system are tied most closely together. Therefore, they need requirements that complement each other, so that they can act as a platform for software development. Naturally, both the hardware and the operating system requirements might have to be altered slightly to enable the best match.

1) Hardware Transceiver with IEEE 802.15.4 or IEEE 802.15.1 Integrated sensor/sensors MCU with low power mode under 5MicroA Wakeup from low power mode with timer Border router ability Joint Test Action Group (JTAG) support

2) Operating system Support for the SoC/MCU and transceiver 6LoWPAN, ZigBee or BLE stack Soft real-time RAM and ROM footprint matching the hardware

3) Communication protocol IPv6 addressing support Existing OS support Network type is mesh UDP

3.2.1.2 Hardware

Each platform examined in chapter 2 has different strengths and weaknesses. When looking at the MCU, OpenMote has a ARM Cortex-M3 which is more powerful compared to the other two alternatives: it features a 32bit 32MHz core with 32KB RAM and 512KB flash memory compared to the MSP430 16bit 25MHz core with 10KB/100KB memory configuration. In terms of peripherals all three platforms are comparable, with similar amount of DAC, GPIO pins, and external busses. All of the platforms have a temperature sensor and an accelerometer, but OpenMote also features an light/uv-light sensor and a voltage sensor built into the MCUs ADC. The MSP430 platform has a somewhat lower power consumption in active RF mode thanks to the less power-hungry sub-GHz transceiver. On the other hand, the less powerful MSP430 MCU has a better deep sleep power consumption, but as the radio is not integrated in the chip as it is in the CC2538 SoC, that advantage is offset by the external transceiver. Comparing the transceivers, there are two 2.4GHz models and one subGHz model; the sub-GHz CC1100 has a higher transmit power of 10dBm compared to 0dBm for CC2420 and 7dBm for CC2538. Also the sensitivity is similar for all the alternatives but gives a slight advantage to CC2538 with -97dBm compared to -95dBm and -93dBm for CC2420 and CC1100. Using these numbers and Friis range equation (equation 4.1) the range of each transceiver with a Fade margin (FM) of 20dB can be seen in figure 3.1. The benefits of working with lower frequencies can clearly be seen as the theoretical range of CC1100 is almost 3 times longer than the 2.4GHz transceivers.

Adding all this information together, the choice of platform will land on OpenMote with the CC2538SoC. It both has a MCU with more memory and better performance, and a transceiver with really good characteristics both in terms of energy consumption and range. Also OpenMote is the only option that can act as a border router using OpenBase; it lets the SoC interface with USB, UART, JTAG, and Ethernet, which enables the standalone border router mode without the need to be connected to a computer or other hardware. The OpenBattery extension lets the SoC operate as a node in a mesh network and provides a dual AAA battery slot connected to the PCB.

3.2.1.3 Operating system

As a modern operating system can be compiled to match almost any hardware, the most important thing to have in mind is the out-of-the-box hardware support. Only RIOT and Contiki have full support for the ARM Cortex-M3 of the considered operating systems and thus both TinyOS and freeRTOS are directly eliminated as developing the support would take too much time. Compared to RIOT, Contiki also has full driver support for the sensors and transceiver, which should decrease the implementation time significantly. When compiled into binary form, RIOT uses less RAM and ROM and thus probably is a bit faster compared to Contiki, which could be important if the application consumes much resources. The lower memory usage might also give RIOT an advantage in being future-proof. Contiki also has support for soft real-time scheduling compared to the hard real-time scheduling of RIOT; this is however not crucial, as the software that will be running on the OS does not have any hard real-time constraints. Both RIOT and Contiki have support for 6LoWPAN but no support for either ZigBee or BLE; this is due to the fact that these are proprietary stacks. Support could be added but would take some time to customize

for the given OS. What gives Contiki the largest advantage is that it also have border router software ready for deployment, which in the RIOT case would have to be developed. All in all, as the project has such a limited time frame, Contiki will be selected as the OS; this, mainly because Contiki comes with most advantages time-wise; this choice means that the focus of the software development will be the creation of a test and evaluation system.

3.2.1.4 Communication protocol

The OpenMote platform has a IEEE 802.15.4 transceiver and thus supports both ZigBee and 6LoWPAN; this means that BLE is not an option. As ZigBee does not have full IPv6 support yet and is not integrated into Contiki, the natural choice is 6LoWPAN. This choice will not only save some development time but also enables evaluation of the header compression. As seen in figure 3.2, the 6LoWPAN stack in Contiki will replace the IP stack while maintaining the same functionality. As the functionality is the same, TCP and HTTP will work with 6LoWPAN, but including them in the source increases the OS build size considerably. On top of the UDP layer, Contiki also has a working implementation of CoAP that can be used for retrieving data from the nodes in a power efficient manner. CoAP is a stateless protocol that uses the HTTP response headers to achieve a very low overhead in transmissions while using application level reliability methods to ensure packet delivery.

3.2.1.5 Workspace and tools

The ARM Cortex-M3 chip that OpenMote and CC2538 is built upon requires the GCC ARM Embedded compiler. This tool-chain is free and runs on both Linux, OSX, and Windows; however, there is no bundled development application so a secondary application for programming is needed. In Windows, there are several Integrated Development Environments (IDEs) such as IAR Workbench ARM [30], Code Composer Studio [31] and the Eclipse plug-in ARM DS-5 [32, 33]; these IDEs use various proprietary toolchains and have a price tag ranging from free to several thousand SEK. Most of the IDEs also have a code size restriction for the free versions. To minimize the costs, the development machine development machine used in this project will run Ubuntu 14.04 LTS, the used tool-chain is GCC ARM Embedded, and Geany is used as the code development application. To analyse the network traffic in real-time, the open source tool Wireshark is used together with a IEEE 802.15.4 packet sniffer. Together with a laptop, the packet sniffer will grant the ability to traverse the mesh network and analyse the network in real-time as it is seen by the nodes.

3.3 Prototype Development

The goal of the development process is to have a functional border router and at least two nodes to be able to test how response time and throughput differs with each hop in a mesh network. To be able to measure response time and throughput, each node needs to have a CoAP server which can respond to ping and also receive an arbitrary amount

of data for throughput measurement. It is desirable for each node to be able to send information about each sensor so the project can be used as a tech-demo. The first part of the development was to set-up of the workspace and tools mentioned in section 3.1.5. Ubuntu OS was installed in a VirtualBox Virtual Machine to make it easier to duplicate and backup; this procedure gave a noticeable decrease in performance and it is recommended to have a dedicated native Ubuntu machine for this type of development. Even though Ubuntu uses an easy-to-use package system, there were some problems in finding a version of GCC ARM Embedded tool-chain that was compatible with Contiki's built-in simulator Cooja [34, 35]; eventually, version 4.82 was used to successfully build Contiki. Cooja is a useful tool for testing and debugging network configurations but does not have support for the CC2538 MCU; instead, nodes called Cooja Motes are simulated with generic hardware. As Cooja is written in Java and runs in a JVM, Oracle Java 1.8 was also installed.

3.3.1 Drivers and firmware

Figure 3.3 shows an overview of the full system. The foundation is the SoC with the MCU, transceiver, and sensors. The Contiki operating system implements the soft real-time kernel together with the firmware for the SoC/MCU and the drivers for the peripherals and sensors. The last part is the communication stack, which provides TCP and UDP connectivity over 6LoWPAN. On top of the TCP and UDP protocols, HTTP and/or CoAP can be implemented. The firmware required for the OS to work properly on the hardware platform was already implemented. However, the drivers for the I²C bus and the sensors were not implemented. The I²C driver is required for the sensor drivers which in turn enables the MCU to communicate with the sensors on the OpenBattery platform.

3.3.2 CoAP server

In order to make each node's sensor data accessible, a CoAP server was implemented as an application running on top of Contiki. A CoAP server in general can handle any number of resources; in this implementation, one resource was made for each sensor value i.e. temperature, light, humidity, and core voltage. The temperature, light, and humidity sensors all work in a similar fashion. When their value is requested, the I²C bus is initialized and then a request is sent over the bus. When the response with the value arrives, that data is put into either a plain-text or JavaScript Object Notation (JSON) formatted message depending on the request and then sent back to the requester. As the core voltage sensor is part of the MCUs ADC, that value is retrieved by simply getting data from a register (a somewhat faster operation). As a buffer for testing throughput speed was also needed, a resource with a circular buffer was implemented. This resource is configured with CoAP's block-wise transfer functionality for arbitrary data size; however, the buffer in itself is only 1024Kb to allow the program variables to fit into the ultra low leakage SRAM. For testing purposes, the data could have been discarded instead of actually saved into the buffer, but then the transfer can not be verified. Resources are defined by paths as CoAP works in a very similar way as HTTP.

Each resource is registered in the server with its path, media type, and content type. When a package arrives on the CoAP port, the server starts to break down the package to be able to direct it to the right resource. It starts with verifying that the package is actually a CoAP package, and then it checks the path and sends it to the correct resource. The resource then inspects the method field in the package header to direct the incoming data to the right function. CoAP package method can be either GET, PUT, POST or DELETE. This function then inspects the request media type and answer content type so that the function can parse the request and send a correctly formatted answer. If the resource does not implement the received method, the server responds with 405 Method not allowed and if the content/media type is not supported the answer is 415 Unsupported Media Type. The content/media types are text/plain, application/json, application/exi, and application/xml.

3.3.2.1 Testing

Contiki is shipped with a simulation tool called Cooja which is written in Java; it can simulate an arbitrary number of nodes with different roles and configurations. All simulation data, such as radio packages and node serial output may be viewed through different windows and exported to various formats. Unfortunately Cooja did not have support for ARM Cortex-M3, but the general set-up was still tested by using Cooja Motes, which are nodes without specified hardware, and MSP430 nodes such as Wismote or Skymotes. With this simulator the basic understanding of the communication between nodes was gained; also, before the hardware arrived, early testing was performed to test the OS and application software.

3.3.2.2 Final prototype

The final prototype consists of four OpenBattery nodes and one OpenBase border router. Both the nodes and the border router are deployed with Contiki. Each node runs a CoAP server, described in section 3.2.2, on top of the OS in its own thread. The border router runs a router software called 6lbr that acts as a translator between Ethernet and IEEE 802.15.4 [36]. Both types of hardware are configured with a 8Hz Radio Duty Cycle (RDC) driver to keep the power consumption to a minimum. RDC is a OS driver that cycles the listening mode of the transceiver to reduce power consumption. As Contiki puts the MCU into Low Power Mode (LPM) when no function is running and the transceiver is off, the RDC driver indirectly controls when the MCU is in LPM. When using the RDC protocol, the nodes repeatedly send messages until the target node wakes up and sends an Acknowledge packet (ACK); this makes communication seamless, even though most of the time the nodes transceivers are not active. Also, an always-on RDC driver, where the transceiver is constantly listening, will be used to be able to look at the performance impact of the 8Hz RDC.

3.4 Performance evaluation

In this chapter the results from each type of assessment are presented. The first assessment is range, followed by response time, after that connection speed, and finally the power consumption. The only assessment that is not performed on the prototype is the range assessment.

3.4.1 Range

Range is very hard to measure without advanced equipment and isolated rooms but can be roughly estimated with equation 4.1 called Friis range equation [37]. P_t is the sender transmit power, P_r the receiver sensitivity, d is the distance between the antennas in meters, f is the signal frequency in hertz, and λ is the wavelength. G_t and G_r is the antenna gain for the transmitter and the receiver. The last term in equation 4.1, when inverted, is the Free-space path loss (FSPL) and can be expanded as shown in equation 4.3. $P_r(\text{dB}) = P_t + G_t + G_r + 20 \log_{10}(\lambda) - 40 \log_{10}(d) - 20 \log_{10}(f) - 147.56$ (4.1) (4.2) (4.3) Unlike Friis range equation, the Link budget equation 4.4 also takes external loss like FM into account [38]. This is needed to make a correct estimation of the actual range as there are several things in the environment that obstructs and distorts the signal. $P_r = P_t + G_t + G_r - FM - FSPL$ (4.4) Combining equation 4.1, 4.3 and 4.4 gives us the equation for the estimated distance as seen in equation 4.5. $d = 10^{\frac{P_t + G_t + G_r - P_r - FM + 147.56}{20}} \log_{10}(f)$

With this equation an estimation of the transceiver range can be made for different FMs and transmit powers. When deployed, the transceiver is configured to only accept packages with a signal strength of -70dBm and above to minimize packet loss and corruption. The antenna gain for OpenMote is 0dBi and can thus be omitted. Figure 4.1 shows a comparison between three different levels of FM: 0dB, 10dB, and 20dB. A FM of 0dB means that there is no signal loss except the FSPL and this is very hard to achieve outside of a lab environment. When increasing the FM to 10dB, which corresponds to a normal home environment, the maximum range drops to 22m. However, in these kind of environments the desired range is usually around 10m which would let the device reduce the transmit power to around 0dBm. Finally, the FM is increased to 20dB which is roughly what it would be in a office or industrial environment. The maximum range in this environment is now reduced to only 7m when transmitting at maximum power.

Response time Before measuring the response time, some theoretical estimations are needed to be able to evaluate the real values. The theoretical values are based upon the radio duty cycle (RDC) and the average response time to reach a node can thus be derived from equation 4.6, 4.8, 4.9 and 4.10. As each node only

3.4.2 Response time

Before measuring the response time, some theoretical estimations are needed to be able to evaluate the real values. The theoretical values are based upon the radio duty cycle (RDC) and the average response time to reach a node can thus be derived from equation 4.6, 4.8, 4.9 and 4.10. As each node only checks the radio every 125ms, this duration combined with the data packet send time of 4ms (equation 4.7.) and ACK send time corresponds to the worst case delivery, as the node needs to wait a whole cycle before being able to send the package the desired node. When the target node is already listening, the best case delivery time is 5ms. Thus, the average theoretical delivery time to reach any adjacent node is 67.5ms. Radio duty cycle: $1s = 0.125s = 125ms$ (4.6) $133B + 4B = 4ms$ (4.7) Worst case delivery: $125ms + 4ms + 1ms$ (4.8) Best case delivery: $4ms + 1ms$ (4.9) $130ms + 5ms = 67.5ms$ (4.10) 2 The delivery time is only calculating the time to send a packet over a link, but when calculating the response time, the acknowledge (ACK) response has to be included in the calculation. Each ACK also needs to wait for the target node to be awake, adding one more instance of average delivery time, resulting in 125ms in average response time. This time will multiply with each hop, resulting in equation 4.11, 4.12 and 4.13. Avg. delivery: Avg. response time: $(2 \times 67.5ms) \times \text{hops}$ (4.11) Best case response time: $(2 \times 5ms) \times \text{hops}$ (4.12) Worst case response time: $(2 \times 130ms) \times \text{hops}$ (4.13) After doing a test with real nodes set-up with a 8Hz RDC with three hops, as seen in figure 4.2, the values in table 4.1 were obtained. Each node was pinged 200 times at a one minute interval to simulate some traffic on the network. What can clearly be seen in the average field of the table is that the average of 765ms is much higher than the expected average of 135ms; the difference is mainly due to the worst-case pings that in some cases had response times up to 30 seconds. However, when looking at the geometrical mean which is better at smoothing out big spikes seen in figure 4.3, the observed response time is still 265ms which is a bit longer than the expected worst case response time for one hop. Also, for two and three hops the observed average is high, but the geometrical mean shows that this is due to the spikes. The estimated response time for two hops is 270ms which as seen in the geometrical mean table 4.1 is way off by 500ms. The same observation goes for three hops where the observed geometrical mean response time is 1181ms which compared to the estimated response time of 405ms is significantly higher.

With these observations in mind, the estimation could be described much better with equation 4.14. which would result in an average response time of 266, 532 and 1064 ms for one, two and tree hops. However, this would mean that the response time is doubled for one hop and then doubled for each consequent hop making the response time exponential which should not be the case.

With the RDC disabled, i.e. the transceiver is always listening and the MCU does not go into sleep mode, the response time is completely different. As seen in table 4.2 the average response time is around 12ms per hop and the spikes seen in the response time for 8Hz RDC is gone. Furthermore, the estimated best case response time of 10ms is very close to the observed average response time. The response time also scales to the number of hops as expected and is roughly 12ms per hop. It appears there might be a problem in

3.4.3 Connection speed

Connection speeds can be measured in several ways each with their own different pros and cons. One of the most popular ways is throughput, i.e. the amount of data over the link is divided by the time it took to reach the target. However, this gives a false picture of how fast the connection actually is from the developers point of view, as the measured data does not only contain application data but also headers and checksums. IEEE 802.15.4 has a theoretical data rate of 250kb/s as seen in equation 4.15. but this is only a measure of how many bits per second the transceiver is able to output. The application data part, when using no header compression, is only 41% of the total transfer. Thus, resulting in a theoretical application data rate, also called goodput, of only 12.81KB/s. Data rate: $250\text{kb/s} = 31.25\text{KB/s}$ $133\text{B} - 54\text{B} = 79\text{B}$ Theoretical goodput: $31.25\text{KB/s} \times (1 - 0.59) = 12.81\text{KB/s}$ Overhead: (4.15) (4.16) (4.17) When using CoAP as the application level protocol, each package can carry either 32 or 64 bytes of application data. In practice, the 64B mode is only applicable when sending packages between nodes on the same mesh network, as the addressing fields then can be fully compressed. When using applications outside the mesh network, each package can only carry 32B of data, resulting in a packet size of 111B as shown in equation 4.18; this does not affect the theoretical data rate but has a noticeable impact on the goodput due to the large overhead of 71B as shown in equation 4.19. To be able to use the full data rate, the application needs to use a protocol without handshakes, i.e. UDP, as the transceiver then can send the packets as fast as physically possible. CoAP is implemented on top of UDP and thus has a low transport layer overhead, but uses its own mechanism for handshaking, delivery and ordering. The theoretical CoAP application throughput can be estimated by looking at the average response time of the node and then add that time to the data delivery time. Each package needs to be acknowledged before the next package is sent, and thus the node response time needs to be taken into consideration. When doing so, the throughput as calculated in equation 4.20. is only 1.64KB/s and thus the theoretical goodput is reduced from 12.81KB/s down to 0.48KB/s as shown in equation 4.21. Packet size: $133\text{B} - 54\text{B} + 32\text{B} = 111\text{B}$ Actual overhead: $79\text{B} = 0.71 \times 111\text{B}$ (4.18) (4.19)

Using the packet size of 111B together with the theoretical response time from equation 4.11 would give the results shown in figure 4.4. To verify these calculations, the same test set-up as shown in figure 4.2, which also was used in section 4.2, was used to test throughput and goodput at different number of hops. Each node was sent 1KB data each minute for 200 minutes; the time from the first package sent to the final acknowledge packet received was measured for each 1KB transmission. The first test was performed with an RDC of 8Hz and resulted in the values shown in figure 4.5. As the chart shows, the theoretical throughput and goodput is much higher than the observed values, but this is due to the fact that the actual average response time is higher than the theoretical one. With some calculations made the observed throughput and goodput are within range of what is expected, given the observed response times in table 4.1. Equation 4.22 uses the observed values to calculate the average response time, given the values in figure 4.5.

3.4.4 Power consumption

To measure power on devices that use very low power and also changes the power consumption very rapidly and frequently is not an easy task. According to the currency specification from the CC2538, the different power modes have the consumption seen in table 4.3 using the built in voltage regulator TSP6750 that switches the input voltage down from the 3V to 2.2V. The components on the OpenBattery supplied directly by the 3V batteries have the current and power consumption specifications as seen in table 4.4.

Given these power profiles, combined with the time it takes to receive and transmit packages, and retrieve a measurement, the theoretical power for one RDC cycle results in the chart seen in figure 4.7. The node starts in sleep mode using 112.81W and after 109ms wakes up and goes into RX mode where a request for a sensor value is received. The node then switches off the radio and fetches the sensor value. After the value is retrieved from the sensor, the radio is once again put in to RX mode for a Channel Clear Assessment (CCA) before entering TX mode and sending the payload. The transmission is successful and the node goes into RX mode to listen for the ACK, when it is received the node enters sleep mode again. For this cycle the average power consumption is 4.8mW which would drain the 2250mWh batteries in 19 days.

However, as the nodes have a RDC running at 8Mz, most of the time there will be no package for the node to receive and thus no measuring and transmitting, as seen in figure 4.8. This cycling reduces the average power consumption to 0.47mW, which would make the batteries last for ca 200 days. The goal is to have a node that can run for one year without having to change the batteries and to be able to do this on 2xAAA batteries with 750mAh the average consumption has to be under 257W as calculated in

To verify these assumptions, we used a Keithley 2280S power supply [39] to measure the total current draw of the prototype. The node was connected to the power supply, which was set up to make 277 measures each second with a supply voltage of 3V. Several measurements were performed. One of the most interesting ones can be seen in figure 4.9. In this picture, we can clearly see the different operating modes, as the node performs 3 transmissions during the interval. In the first transmission at the 1.6s mark, the strobing feature of the RDC protocol is seen as the package is sent 5 times before the receiving node is awake and can receive the package. In the two following transmissions, the package is delivered on the first try. As our measurement is limited to 277Hz, the current peaks when only waking up to listen for traffic are sometimes missed, and the peak value is hard to extract; but the 8Hz RDC cycle is still visible. The average power consumption for these cycles is 8mW, which would make the batteries only last for 11 days. However, when taking the average of a measuring series without any transmissions, the average goes down to 4mW, which increases the battery time to 23 days. The theoretical sleep power of 0.11mW compared to the measured of 3mW is what makes the average power consumption that high.

Reducing this power consumption by a tenfold would result in an average consumption of 0.39mW, which is closer to the theoretical average power consumption. A discovery made when measuring the power was that the nodes consumed less power when supplied with a lower input voltage. Simply by reducing the voltage from 3V to 2.6V re-

duced the power consumption in LPM by 15%. However, this reduction could affect the range of the nodes.

3.5 Discussion

Internet of Things can be realised in several ways as there are still many viable options on the market, mainly in terms of hardware, operating systems, and communication standards. Given the recent development in the field, Thingsquare recently released a technology demo using the same practices as used in this thesis; the choices taken are on track with the latest development [40]. Also, both Google and Microsoft have announced that they are developing IoT OSs. When these products are released, it would be very interesting to compare them with Contiki. It would be exciting to see if an open-source project can surpass the commercial offerings in terms of speed, RAM and ROM footprint, and device support. Furthermore, an in-depth comparison between RIOT and Contiki would give much insight into the kind of OS practices that benefit IoT development the most. Google have also started to develop a substitute for 6LoWPAN and UDP that they have named Thread [41]. As 6LoWPAN and ZigBee, it runs on top of IEEE 802.15.4 and thus might be able to out-compete the existing implementations. Google promises lower latencies and power consumption compared to the existing technologies.

3.5.1 The prototype

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3.5.1.1 Results

Collecting the data went well and were reasonably straight forward; it was easy to transition between the two different test set-ups and thus making several test scenarios. Assessments were made in the areas of range, response time, connection speed, and power consumption. In each area, the theoretical values were first calculated and then compared to the retrieved measurements; except in the range case, as the required equipment for measuring was not economically justifiable to purchase.

1) Range The theoretical range for OpenMote when transmitting at full power in an office environment is only 7m. As measuring the range was not a viable option due to the cost of measuring equipment, only distance estimations from the placement of the nodes when maintaining a stable connection can be used as a reference. Using a map of the office and the position of the nodes the range seems to be around 10m, which would mean that the effective FM of the office is around 16dB using the always-on RDC. The FM changed a bit when using the 8Hz RDC as more packages congested the air and the range dropped to somewhere around 5m; resulting in an effective FM of 23dB. To increase the range of the transceiver, a switch to the 860MHz frequency band would be the most effective solution; with a FM of 23dB, the theoretical range would increase to 14m with the same transceiver properties, and with a FM of 16dB the range would be 31m. Usually, transceivers with a lower frequency output also have a lower power consumption while transmitting. Working in sub-GHz also gives the benefit of less interference as fewer other devices use those frequencies. Changing to a sub-GHz band would thus decrease the power consumption and increase the range, without changing the functionality of the nodes.

2) Response time Initially when measuring the response time the always-on RDC was used and the measured response time was very close to the theoretical value. However, when using the 8Hz RDC protocol the values started to drastically differ from the theory. This behaviour is likely to originate from the way the RDC driver predicts the next time when the target node should be awake. The procedure is called phase optimization; when enabled, the node saves the time when the node was last seen, it then uses this value to predict the next time the node should be awake based on the RDC cycle. However, this prediction is based on the nodes internal clock. As the clock can differ from those of the other nodes, misalignments seem to occur, resulting in misses when trying to reach the target node. Each misalignment increases the time it takes to reach the target node as the node then needs to strobe the package until the target node wakes up again. In theory, when sending strobos the target node should wake up and receive the package within one cycle (125ms); however, this is not guaranteed as other transmissions might occupy the air, further increasing the response time. If the phase optimization could be improved to guarantee the alignment between the nodes, the response time should get much closer to the theoretical value; as the time to reach the node would be maximum one cycle and the air would not be as congested by nodes sending strobos.

3) Connection speed The connection speed, when using CoAP or any other protocol with perpacket ACK, is directly bound to the response time. IEEE 802.15.4 has a relatively low data-rate, only 250kbps, compared to other solutions, e.g. BLE (1Mbps) and WLAN (>54Mbps). As throughput is based on datarate over a longer period of time, both the overhead and the response time is needed to make a good estimation. CoAP has a very low header size compared to many other communication protocols, but due to the very small frame size, the overhead is still relatively high. As of now, the results clearly show that when a reliable transfer is desired the connection speed of IEEE 802.15.4 and CoAP is only sufficient for data exchanges around 32 bytes. When the nodes use the always-on RDC, the goodput is less than 3KB/s for one hop and is halved for every hop; however, when the 8Hz RDC is enabled, the goodput is reduced to under 0.1KB/s. Using messages without per-packet ACK, thus removing the response time from the equation, would let the nodes transfer real-time audio and maybe even highly compressed video. However, using messages without the per-packet ACK disables the reliable transmission guarantee, and thus it can only be used with data streams where packet loss is acceptable.

4) Power consumption Making a rough estimation of the power consumption of the platform was straight forward task and so was measuring the actual consumption. When comparing, the two the values differed by a factor of 30, which was not expected. The reason probably originates from the clock interrupt which is triggered every 8ms. Initially, this interrupt was assumed to be disabled when the system entered the lower power modes, but this was not the case. As the interrupt fires at 125Hz and the time to wake up and go back to LPM is only 272s, the power spikes from these interrupts were not seen on the measuring instruments. As seen in figure 4.9, even the peaks from the listening cycles were hard to record and those lasted for at least 4ms; instead, the power consumption from the clock timer looks like an increased LPM power consumption. At the time this was discovered there was no time to fix it, but doing so should decrease the average power consumption to within the limits, granting the nodes the ability to run on battery power for a year. As no delays from calculation could be observed, the clock speed on MCU could, in all probability, have been reduced to save power on the nodes. However, this reduction would only have affected the consumption when the node was in active mode, which is only a few percent of the total cycle time. The OpenMote chip has a step-down DC-DC converter for this purpose which is switched off in LPM mode to reduce quiescent currents; however, as most of the time is spent in LPM, reducing the input voltage to 2.1V by changing battery type and removing the step-down converter would be preferable as it would reduce the power consumption. These changes could affect the range of the device, but this has to be assessed.

3.5.2 Project execution

Looking at the time plan and the milestones, as seen in Appendix A and B, each milestone matches a task or transition in the time plan. The planning report was not submitted to the examiner until the 6/2-15, which is two weeks behind schedule, exceeding the time planned for milestone M1. The first draft was submitted before deadline, but several revisions were necessary. In retrospect, the literature study should probably have been planned in parallel with the planning report, as the information from the study helped

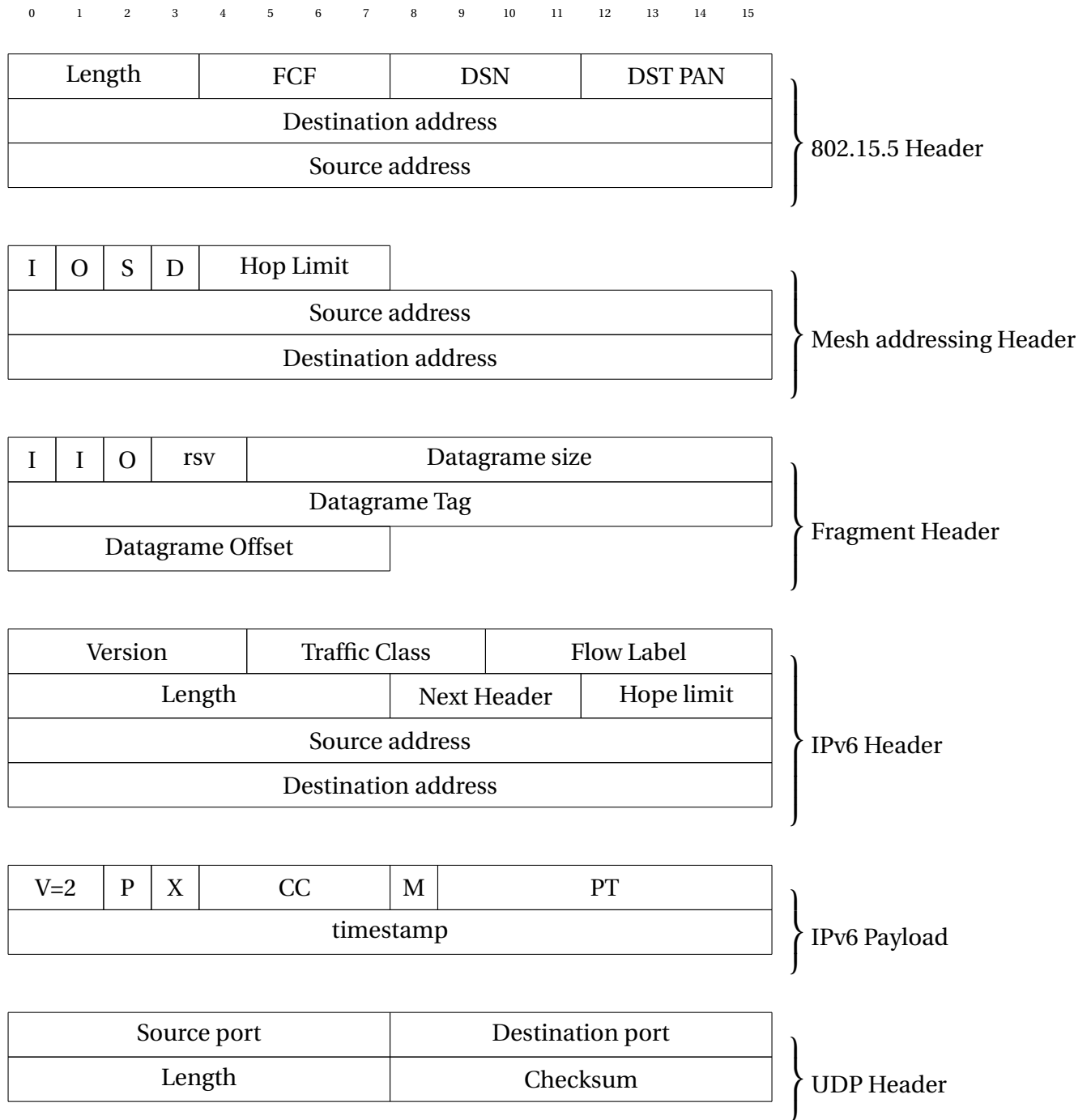
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3.6 Conclusion

The purpose of the project was to find and examine a communication protocol that could be suitable for IoT applications, by investigating the current hardware, OS, and communication protocols and building a prototype from the selected choices. What can be said about the investigation is that it is difficult to examine all candidates in detail; this means that a rough selection has to be made based on initial knowledge potentially discarding good options. The general feeling is, however, that all of the examined candidates in this project were relevant and added valuable insights to the current technology status. The assessment gave relevant and interesting results that improved the understanding in what IoT can be used for, and what further areas of investigation could be. One of the most interesting areas of further investigation would be the RDC driver, as it directly affects the response time and thus also the connection speed. Even though the power consumption was not in line with the expectations, the reason has been found and can be resolved. Another conclusion is that IoT is not ready for real-time applications as the latency is much higher than expected, for the technologies assessed in this thesis, and also has a high spread. As the latency increases for each subsequent network hop and the minimum observed latency per hop is 11ms, when using the always-on RDC, this type of communication will probably only be used for applications where response time can vary greatly, without affecting the functionality. CoAP as a communication protocol shows a lot of promise when combined with 6LoWPAN and IEEE 802.15.4. It performs well given its simplicity but has one disadvantage: the large overhead which comes from the MAC

addressing fields in the IEEE 802.15.4 frame. If this overhead could be reduced from the current 71% to only 30% the goodput would double. A solution would be to use a similar mechanism as BLE where the packet size varies depending on application. Each node also has computing time left as the MCU is more powerful than needed for the given application; an improvement would be to use a less powerful MCU, like the ARM Cortex-M0+, to reduce the clock speed as suggested in the discussion. When looking at the future-proof aspect the later suggestion is probably the better, as the clock then could be increased if more computing power is needed. In the future, batteries will hopefully be able to store more energy, thus increasing the time between battery changes or reducing the battery size.

4.1 Introduction & problem statement



Application	CoAP, MQTT			
Transport	UDP/TCP			
Network	IPv6 RPL	IPv4/IPv6		
	6LowPan	RFC 2464		RFC 5072
MAC	IEEE 802.15.4	IEEE 802.11 (Wi-Fi)	IEEE 802.3 (Ethernet)	2G, 3G, LTE
	2.4GHz, 915, 868MHz	2.4, 5GHz		
	DSS, FSK, OFDM	CSMA/CA	UTP, FO	

Table 4.1: An example table.

4.2 Background

4.3 Approach

4.4 Performance evaluation

4.4.1 Environment description

4.4.2 Results exploitation

4.5 Discussion

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4.6 Conclusion

5 | Chapter 4

5.1 Introduction & problem statement

5.2 Background

5.3 Approach

5.4 Performance evaluation

5.4.1 Environment description

5.4.2 Results exploitation

5.5 Conclusion

6 | Conclusion & perspectives

7 | Publications

7.1 List of publications

A | Appendix A

A.1 Introduction & problem statement

A.2 Background

A.3 Approach

A.4 Performance evaluation

A.4.1 Environment description

A.4.2 Results exploitation

A.5 Conclusion

B | Appendix B

Year		Factors	Computation Model	Results interpretation
2018	alemany_estimation_2018	-Closeness Centrality -Degree Centrality	Estimation	Closeness have a high d correlation with privacy
2017	zhang_privacypreserving_2017	-Users Credibility	Privacy-preserving	Correlation between ide and user's credibility is
2016	li_algorithm_2016	-Influence probability -Degree Centrality -Number of seeds neighbors -Number of experts neighbors	Utility degree and Utility privacy cost ratio discount algorithms	Methods evaluations: -Number of seeds activa -Number of expert activ
2015	pandey_computing_2015	-Attitude Information -Popularity (Page rank) -Privacy Settings: visibility	Users trustworthiness	Relationship between u and privacy risk
2015	yongbozeng_study_2015	-Node information diffusion -Link information diffusion -Undesirable Destination	Birnbaum's measure (BM)	Users trustworthiness
2015	b.s._privacy_2015	-Tie-strength -Communication information -Number of mutual friends	Bezier curve	Sorting user's Friends P
2015	vidyalakshmi_privacy_2015	-Communication frequency -Privacy setup	Cubic bezier curve	Estimating friends priva users dispositions to pr
2014	caliskanislam_privacy_2014		3-class supervised learning	Correlation between Us Friends Privacy Score
2014	zeng_trustaware_2014	-Undesirable Destination -Closeness centrality -Diffusion centrality -User's behavior	Probability trust model	-The information diffus depends on the users be -The information diffus depends on the close
2013	nepali_sonet_2013	-Sensitivity, Visibility	Linear model	Users privacy exposure
2013	biczok_interdependent_2013	-User valuation on app -Network valuation on app	Collaborative Interdependent Privacy Game, Nash equilibrium Sub-optimal Equilibrium	Show how network and the behavior of social ne to app usage
2012	akcora_risks_2012	-Attitude similarity	Baseline estimation Learning Friend Impacts	Risks of friendships can users attitude towards fr
2012	ahmad_coat_2012	-Sender address -Sender password -Message body	Collaborative outgoing anti-spam technique	Once a message is tagge the signature of that me other SMTP server
2011	gundecha_exploiting_2011	-Individual index -Community index	Unfriending vulnerable friends	Correlation between un security improvement is
2011	liu_framework_2010	-User behavior	Item response theory	Behavioral, Quantitative
	maximilien_privacyasaservice_2009	-Sensitivity and visibility		privacy evaluation
2011	hu_detecting_2011	-Number of privacy conflicts -Trust of an accessor -Sensitivity and Visibility	Collaborative privacy	Quantify multiparty pri Evaluate multiparty priv a resolving score
2010	xiang_modeling_2010	-Interaction level -User similarity	Unsupervised linear model Link-based latent variable model	The estimated link weig and lead to improved cl
2010	tran_social_2010	-Trust path	Trust path probability	Message paths trustwor
2010	talukder_privometer_2010			
2010	fang_privacy_2010	-Community membership -Online activity	Privacy-Preference Model as a classifier	Community structure o resource when modelin
2010	qian_networklevel_2010		Cluster-based reputation	
2009	yang_socialfilter_2009	-Nodes IP -Reporter Trust -Identity uniqueness	Distributed SocialFilter- repository	Node reputation
2009	hao_detecting_2009	-Geodesic distance -Number of recipients	Classifier: Supervised Learning	Sender reputation syste email senders based on
2009	baden_persona_2009		Attribute-based encryption	
2009	paradesi_integrating_2009		Multi-agent reputation	
2008	mislove_ostra_2008			
2004	lixiong_peertrust_2004	-Community settings	Trust computation	

-Number of malicious peers

Table B.1: Social metrics

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