

# **SUSIE Report**

**version 1**

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# Introduction

A vocabulary of technical terms used in this report is found in the appendices.

This report describes a part of the process of digitalizing the heating infrastructure at Christiania, Copenhagen. The heating infrastructure goes under the name "Nabovarme" and is organized as a collection of wooden pellet stoves heating groups of households or apartments through heated water and radiators. Nabovarme currently uses pen and paper to document each customers heating usage by checking the heating meters in each household once a year. It was decided that digitalizing the collection of usage data would give better data and data with a much higher frequency. This higher frequency would first of all make the billing much easier since all data was already existing in the database when billing time came around. The higher frequency however would also open up a list of opportunities like giving customers the ability to follow, and react upon, their usage and maybe lead to a lower pellet usage for whole Christiania. I started this project as a prototype that includes a device that transmits household heating usage to a central server that will visualize it in html.

## Collaboration

The project has been a collaboration between Johannes Jørgensen and Kristoffer Ek from Christiania Nabovarme. All source code, pcb layout, debugging and development in general has happened onsite at Christiania Nabovarme. All sources are released through the github accounts belonging to Nabovarme. See <https://github.com/nabovarme/kamstrup-wifi> for details

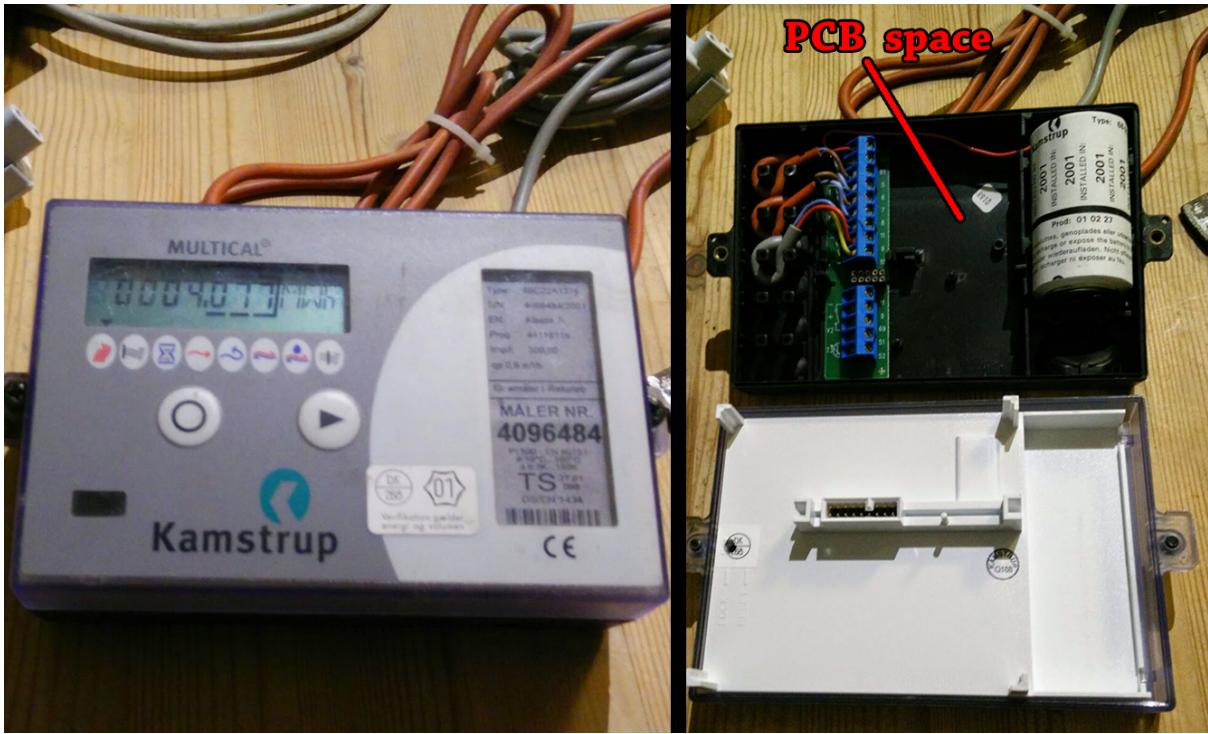
## Problem formulation

Nabovarme wants a device that is able to communicate with the class of heating meters found in all households in Christiania. The device has to be embedded inside the heating meters and use the same built-in power supply if possible. The device has to sample at a predefined frequency and sleep between samples if possible, all samples must have been sent to a central server or at least attempted to be sent once. The device has to use wifi to transmit samples and an NTP (network time protocol) client must exist on the device to timestamp all samples. The device has to be easily configured, with regards to what wifi hot-spot it will use for transmission, and it has to strive for end-to-end encrypted packages so interception is not an issue. The device has to be cheap and relatively low powered and available in large quantities. A PCB will have to be made for connecting the device to the heating meter.

## Requirements

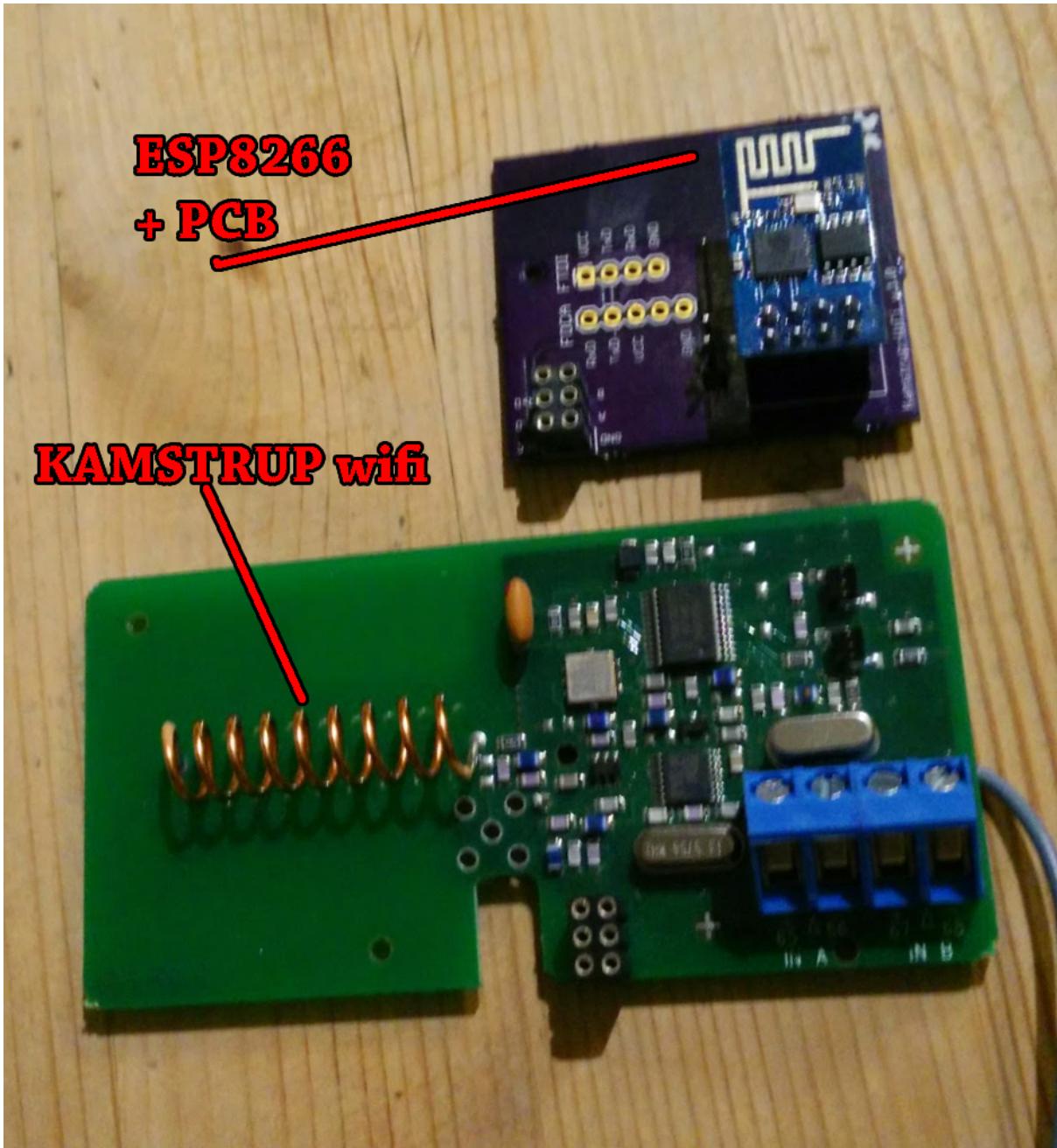
Name	Description
R1	The protocol for serial communication with "kamstrup multical 601" has to be reverse engineered and implemented in C.
R2	The device must use the protocol MQTT to transmit samples to a central server
R3	The device must use wifi for data transmission and feature a grace period for configuring which accesspoint to join
R4	The device must use dns for looking up the ip of the central server and use ntp for getting the unix timestamp it uses in its RTC.
R5	A central server has to receive and save the samples in a sql database and the same server has to serve a demo web page where the data of a single device can be seen visualized as a graph
R6	The device has to sleep between samples
R7	The device has to transmit all samples at least once if possible (QoS)
R8	A PCB should be designed and manufactured for the device to be placed inside the kamstrup meter

## Design



The kamstrup multical heating meter and its internals, including space for expansion boards.

The heart of the system is the Kamstrup Multical 601 meter. This meter is found in households in Denmark and other countries as well. The Meter is normally the property of the company providing the heating infrastructure. Therefore they are mostly locked to keep endusers from mangling and manipulating the device. This however is not the case at Christiania where we have bought the meters and installed them ourself. This gives us a rare opportunity to open the meter and install new electronics inside it where Kamsturp left room for expansion boards like shown underneath:



*Our ESP8266 pcb, its uart daughterboard and in comparison the proprietary kamstrup wifi module.*

Connected to the kamstrup meter is a microcontroller using a UART connection to talk to the Kamstrup meter. The microcontroller has onboard wifi and an external antenna is connected to the device with an extension cable. Both the microcontroller and the Kamstrup meter gets power from a builtin power supply.

The "meter unit" (Kamstrup meter and wifi microcontroller) has an established connection to a nearby wifi hot-spot. The meter unit transmits samples through the wifi hot-spot, over the internet to a central server.

The central server collects samples and serves a web page where the samples can be seen in a graph.

## Implementation

### Hardware

The hardware in this project is pretty generic except of the embedded device in the meter. The server can be any linux server with the ability to run an ntp server, web server, a mysql database and a MQTT broker. The wifi hot-spots can be of any kind and is not configured by Nabovarme.

## Implementation

The embedded device was chosen based on these features:

- Price
- Onboard wifi
- Power consumption
- Onboard flash
- Clock speed
- Ease of development

The following embedded solutions were explored:

- Arduino with cc3000 wifi modem
- Raspberry pi with usb wifi modem
- Esp8266 microcontroller (RISC)

Based on the research i created the following table:

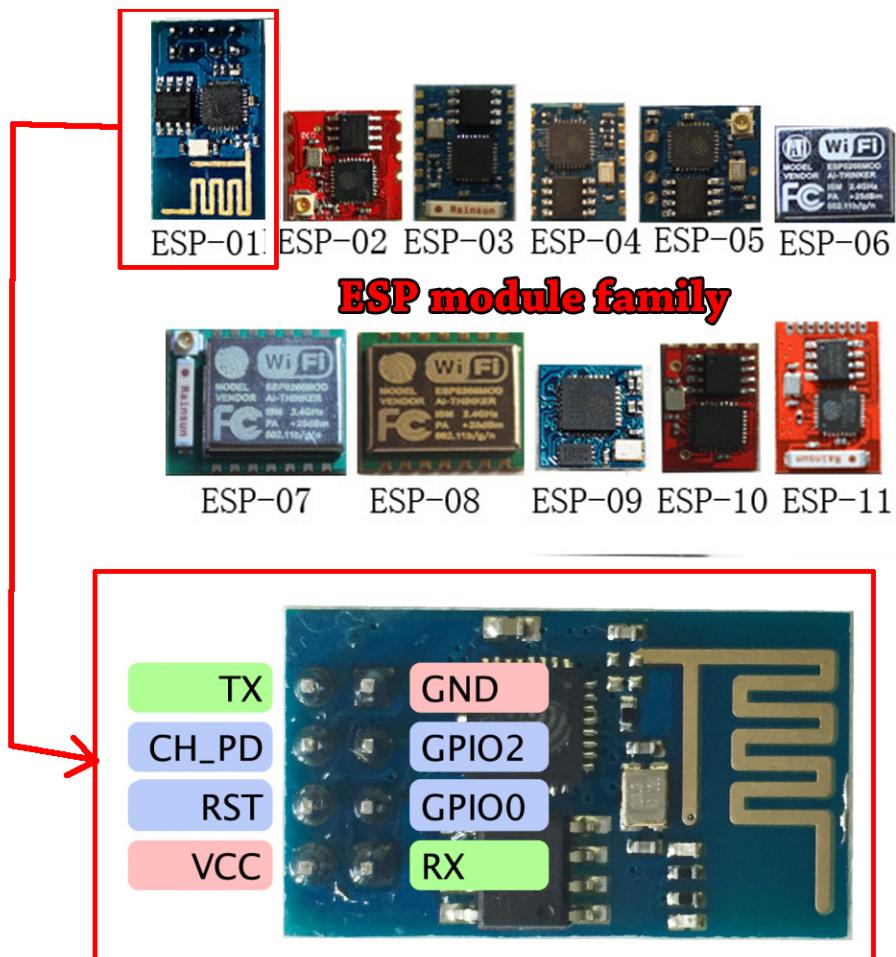
Solution	Price	Onboard wifi	Transmit Power consumption	Onboard Flash	Clock speed	Development
Arduino with cc 3000	ca. 75\$ (40 + 35)	No	ca. 270mA, (20 + 250)	16kb	16Mhz	C like, easy
RaspberryPi, edimax usb wifi	77 (52 + 25)	No	250mA (210 + 40)	None	700Mhz	Linux, easy
Esp8266	2,5 \$	Yes	215mA	512kb	80Mhz	C sdk, moderate

*sources*

[1](#) [2](#) [3](#) [4](#)

I concluded from the data above that the ESP8266 with a price of 2.5\$, onboard flash and 80 mhz clock speed was ideal as a platform for the project.

## ESP8266



The esp8266 module family and the esp8266-01 i am using in this project.  
Note also the esp8266-07 with fcc stamps.

The ESP8266 is a new microcontroller with onboard wifi sold in modules including a 512 kb spi flash. It was introduced to the global market by Espressif in 2014 and has since gained a large following in hacker and maker circles around the world.

Espressif has released an sdk for the ESP8266 and have kept updating the sdk for the bimonthly. The sdk has some binary blobs but a project called Esp-open-sdk tries to replace these with open source alternatives. The binary blobs make it a little difficult to develop software for the esp since you cant research the inner workings of specific core api calls.

The sdk is based on freertos and give you a task handler as well other abstract os features. Most of its core api calls are callback based which means you have to think asynchronously when developing.

### Esp8266 family

I chose to use the esp8266-01 in this project because it was ready made and included header pins for easy prototyping. The esp-01 however is the most sparsely broken out module of the family. The esp8266 chip itself features a lengthy list of gpios including uarts, i2c, spi etc. While all these features exist aboard the esp-01 only a few are broken out, namely two gpio's and a single uart. This however is enough to implement my prototype.

#### Esp8266-07

This module will probably be the one that the next prototype will use. Reasons are:

- Faraday cage
- ceramic antenna
- connector for external antenna
- more gpios broken out

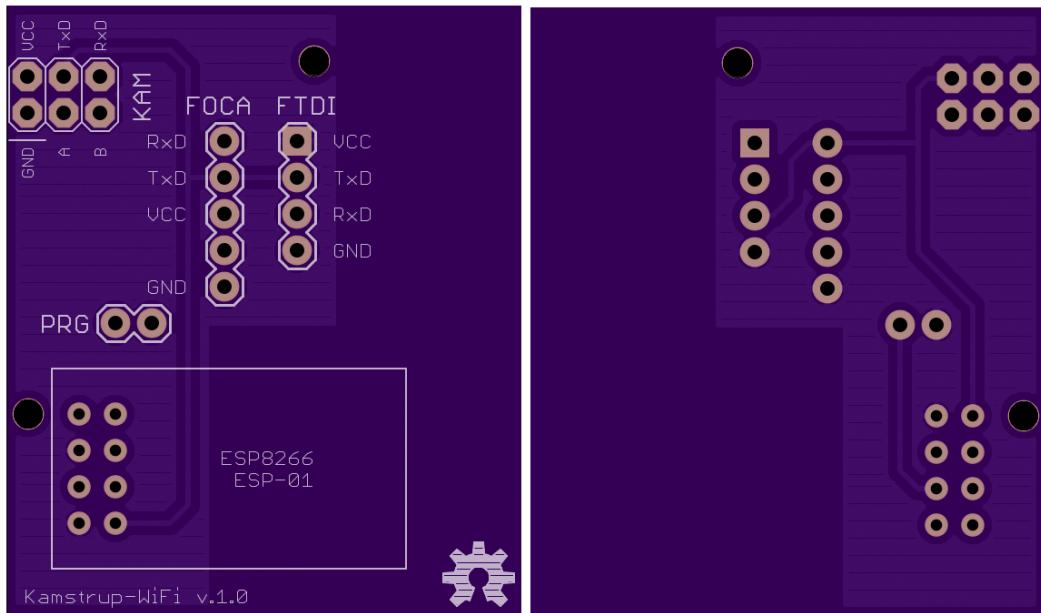
## Software

The external antenna ability would provide much needed better wifi reception in the indoor environments where the meters are installed.

### PCB

The kamstrup meters are designed with a space for extension boards. (see the image in start of design section) A pcb layout was created in order to host the ESP8266-01 and facilitate uart connectivity with the kamstrup bus as well as providing power from the builtin psu.

The pcb was uploaded to the pcb manufacturer "oshpark.com" where it is released as open hardware. Oshpark creates cheap pcb's with their purple signature tint. Eagle cad free edition was used for the pcb layout and the design files are in the github repository.



*The pcb layout for the esp8266-01 as hosted on oshpark*

## Software

Software had to be developed to extract the samples from the Kamstrup meter and send them to a central server In order to do this a few core protocols must be known.

### Protocols

I have chosen to document the kamstrup multical 601 protocol since its not available in the public domain and protected by an NDA so i regard the work done on freeing the protocol as a public service. The MQTT protocol is also documented more loosely since its freely available. DNS and ntp are not documented since they not represent major parts of the system and are documented many places.

### Kamstrup multical 601

The kamstrup multical 601 protocol is a serial protocol with 1200 bits per second. The protocol is a request-response protocol where the data is encoded in many frames where each is 8 bits.

- 
- 1 <https://nurdspace.nl/ESP8266>
  - 2 <http://raspi.tv/2014/pi hut-wifi-dongle-vs-edimax-power-usage>
  - 3 <https://github.com/esp8266/esp8266-wiki/wiki/W25Q40BVNIG>
  - 4 <http://www.arduino.cc/en/Main/ArduinoBoardDuemilanove>

The data frame is based on the OSI model. In this protocol, only three layers of the OSI model are used. These are the physical layer, data link and the application layer. The figure below show how each of the layers (shown as shaded) is related to the data frame.

Field name Number of bytes in each field OSI – layer	Start byte 1	Destination address 1	CID 1	Data 0-?	CRC 2	Stop byte 1
				Application layer		
				Data link layer		

Physical layer

### Physical layer

Data is transmitted byte wise in a binary data format. 8 data bit represent one byte of data. The physical layer uses 'Byte stuffing' to compensate for byte values reserved as start, stop and acknowledge. The method is to substitute the reserved bytes values with a pair of byte values.

### Data link layer

The destination address is included in order to prepare a future enhanced version of the protocol. For heat meters the destination address is 3Fh. The logger top module use 7Fh and the logger base module use BFh. Included in the data link layer is a CRC with reference to the CCITT-standard using the polynomial 1021h. Only deviation from the standard is the initial value, which is 0000h instead of FFFFh. The CRC result is calculated for destination address, CID and data. CRC is transmitted with MSByte first and LSByte last.

I decided to include a table of all possible crc checksums for the given length in my code so i did not have to compute it on each frame. In the `*user/kmp.c` file you can see the checksum table.

### Application layer

Most data in the application layer is handled in a KMP register format. You use command id's (CID's) to tell the kamstrup which registers you are interested in.

The kamstrup specifies a variable lenght register format. This format includes three bytes show below:

Unit	NoB	SiEx
0	1	2
XX	XX	XX

- The first byte defines which unit the value is in
- the second byte defines the byte length of the value
- the third byte tells about the sign and exponent of the value.

Kamstrup implements floating numbers by the use of the following equation:

Sign + exponent								
Bit 7	6	5	4	3	2	1	0	
SI	SE	E5	E4	E3	E2	E1	E0	

$$\text{Floating point value} = -1^{SI} \cdot (\text{integer}) \cdot 10^{-1^{SE} \cdot \text{exponent}}$$

SI tells if the value is negative, if SI is 1 then the value is negative. The SE tells if the value is a decimal fraction, if SE is 1 then the value is less than zero. The integer represents the value before translated into the floating point value.

Because the Kamstrup protocol only uses base 10 floating points, later computations are easily done by modifying the point index by dividing with 10.

In order to compute power of values i needed a power function. This exist in libmath. But i didnt want to link all libmath into this project just to gain a power function, and when i did it also gave compile errors for lack of flash. So i wrote my own power function, this can be seen in `user/kmp.c - kmp_pow`.

Libc printf does not have its own string formatter for floating point numbers. So a function had to be written in order to translate the received numbers into strings ready for transmission.

## MQTT

MQTT is a Client Server publish/subscribe messaging transport protocol. It is light weight, open, simple, and designed so as to be easy to implement. These characteristics make it ideal for use in many situations, including constrained environments such as for communication in Machine to Machine (M2M) and Internet of Things (IoT) contexts where a small code footprint is required and/or network bandwidth is at a premium.<sup>5</sup>

### MQTT vs HTTP

Why bother with MQTT when you have HTTP? The answer is compression and asynchronous messaging. HTTP v 1.1 is synchronous which means it works in a request-response model. You can ask a question and wait for the answer. An added inconvenience is that only the client is able to ask questions.

The MQTT protocol implements a channel based messaging platform where you publish and subscribe to channels and best of all you can implement certain degrees of quality control where you retransmit or buffer messages until they are delivered to clients that have been offline.

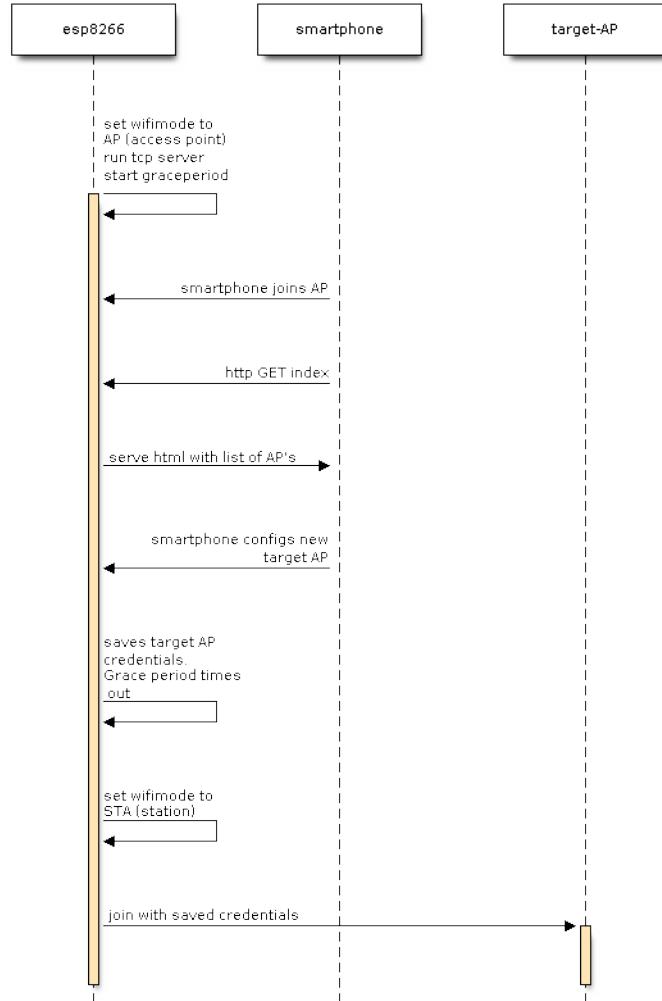
MQTT is also binary vs HTTPS heavy ascii headers. This is really good since we want as compressed a packet as possible in order to minimize power usage.

## Esp8266 firmware

The firmware has the following main objectives:

- When booted it should enter a grace period and let the user config which access point to join
- After a grace period it should lookup the current time from an ntp server and save it to its rtc and then enter sample mode
- Everything in the firmware is timer based.

## Config mode



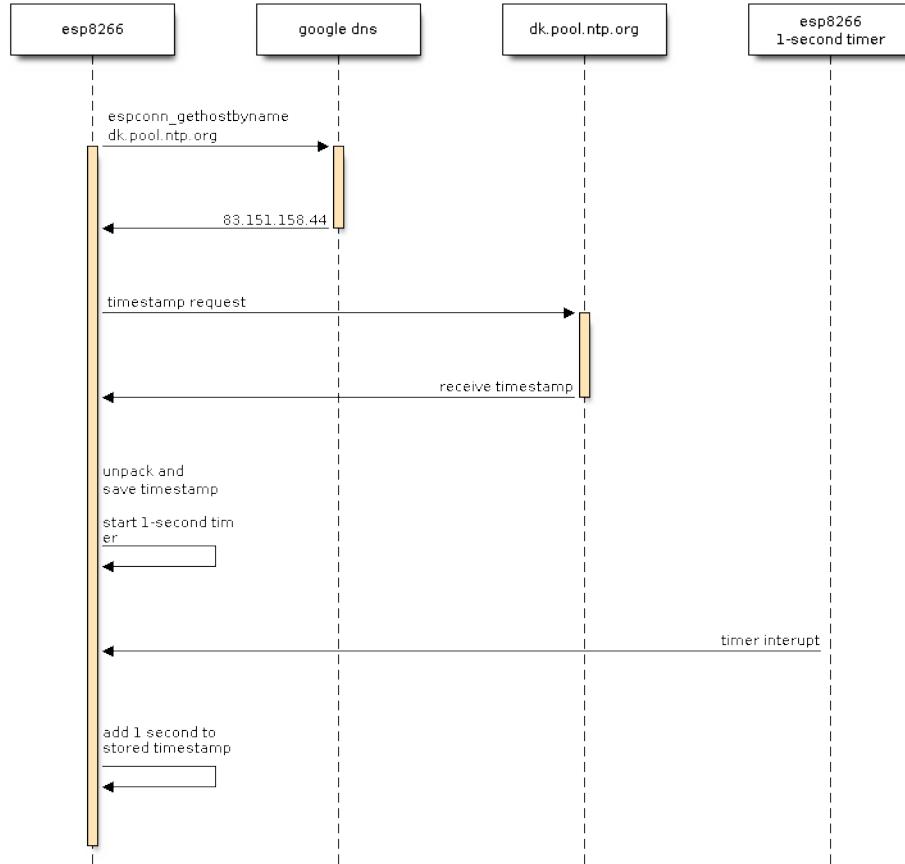
*Diagram shows the successfull configuration of an esp8266 using a smartphone within the graceperiod*

This mode features a grace period where the esp will act as an access point and serve a html site where the user can edit which access point the esp will join later on. The config mode access point is protected by wpa encryption and credentials are generated when flashing a new esp.

If the user changes the preferred access point of the esp it will be saved using sdk functions for saving and loading configs. These api calls go to the binary blobs and are not documented further. The configs are permanently saved.

After the graceperiod ends the esp will set its wifi mode to station and try to connect to saved ssid with saved credentials.

### Ntp transition



*Diagram shows how we use the builtin dns to lookup ntp servers, request a timestamp and store it*

When grace period ends, the esp will transition into sample mode. This transition features a continuous try at getting a timestamp from a predefined ntp server. The esp will stay in this transition until it successfully receives the timestamp which it then will save in ram.

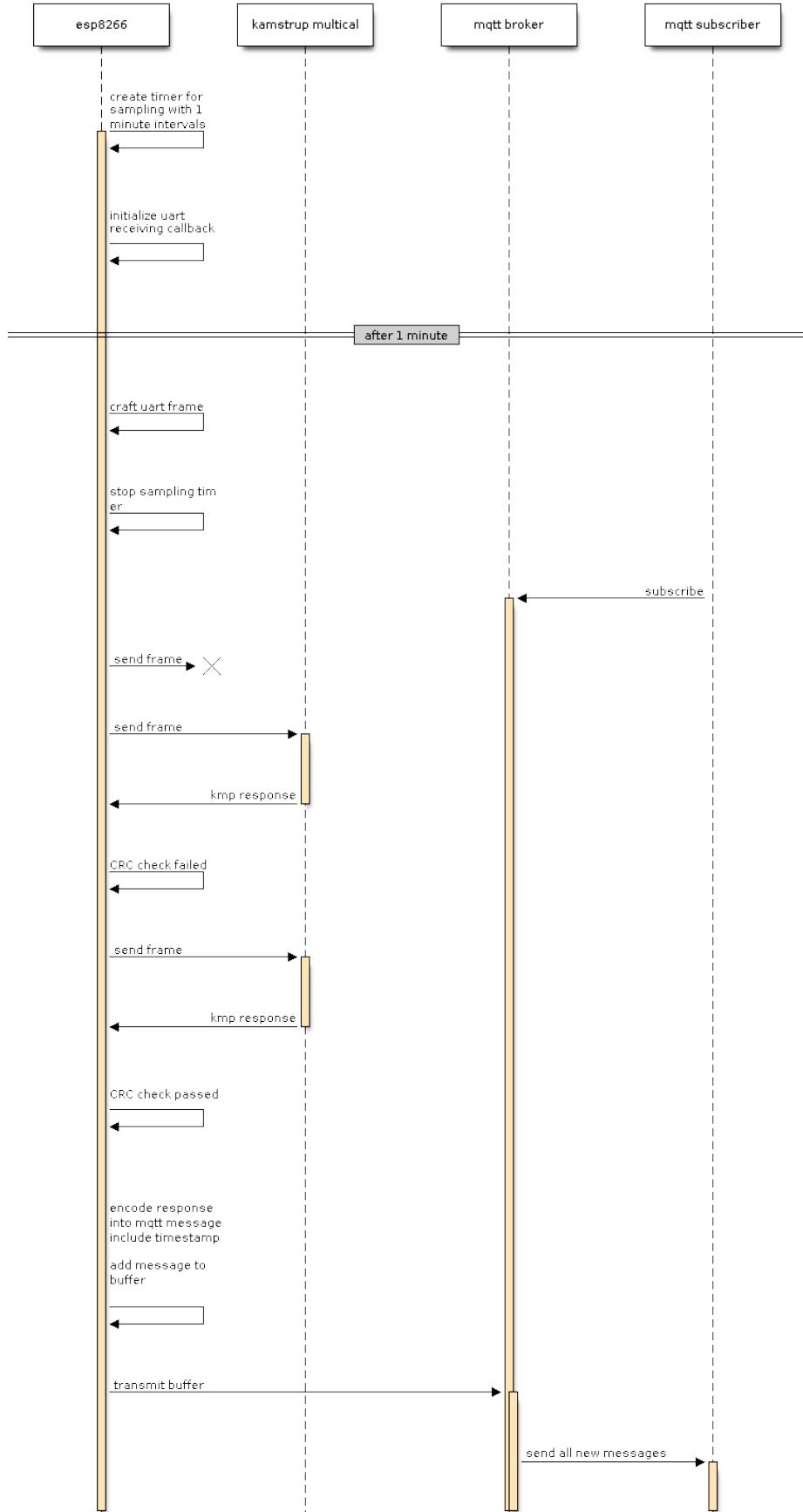
The timestamp is saved in a resolution of seconds and a timer based on the rtc increments the stored timestamp every second. In this way we have a guaranteed unix timestamp that holds its time down to the rated precision of the RTC.

Of course we never reach the precision threshold where seconds are dropped since we update the stored timestamp on a frequency of an hour plus random minutes between 0 and 60. The random minutes guarantee that all meters not ask for NTP time at the same time.

Both the RTC and the integer we store the unix timestamp in are 32 bit. This means that the RTC can only hold about 1 hour and eleven minutes which affects max sleep time. And the timestamp we increment every second will overflow in 2038, this is not a problem since something better probably has replaced the system by then.

### Sample mode

## Software



Sample mode is about sampling from the kamstrup meter and reporting the samples using MQTT. A timer runs every minute and sends a kmp request to the kamstrup meter. This breaks the idea of a request-response protocol but we have not experienced any kamstrup meters sending the same sample twice, so the idea of a malformed

response is experienced, therefore it was chosen to sample at a fixed frequency and asynchronously listen for the responses.

When ever a response is received, it is formatted into a string for transmission by MQTT. It is then stored in the MQTT queue (circular buffer) and MQTT will try to transmit the sample until it either is successfully transmitted or is pushed out the queue by new samples filling the queue. It could be tempting to store the raw samples in the queue and decode them when transmitting because they all ready are compressed but we need to compute crc on them, and maybe retransmit kmp request, before storing them in the queue.

It is a part of the plan to downscale the sample frequency and introduce a deep sleep break between samples. This deep sleep period would heavily reduce the power usage of the esp. The esp sdk comes with a standard way of doing this that implies the use of free user memory in the rtc. This memory can be used to store a timestamp. If you know beforehand how long you sleep then when you wake you can just append that to the stored timestamp and you have the current time again without ntp. The esp rtc overflows at 32 bit microseconds which means that you can max sleep ca. 71.58 seconds before having to wake again. If you want to sleep longer you would have to wake up append sleep period to stored timestamp and then sleep again. The esp has the ability to define which mode to wake up in so you actually tell it to wake up without wifi which makes power usage even lower with extended sleep.

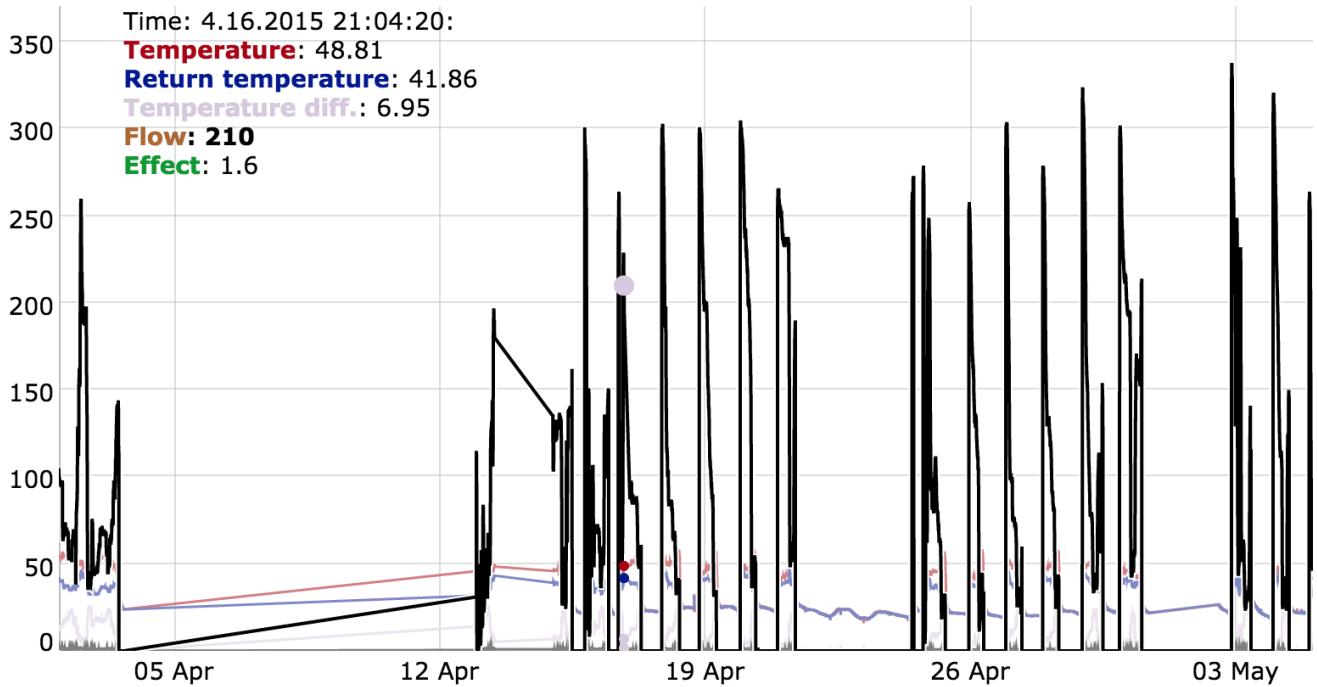
## Vizualisation

A prototype was created for visualizing the data created by the meter unit.

The visualization is provided by the same server running the MQTT broker and sql database.

A Perl script serves a html site where a javascript generated graph is populated with latest entries from the sql database.

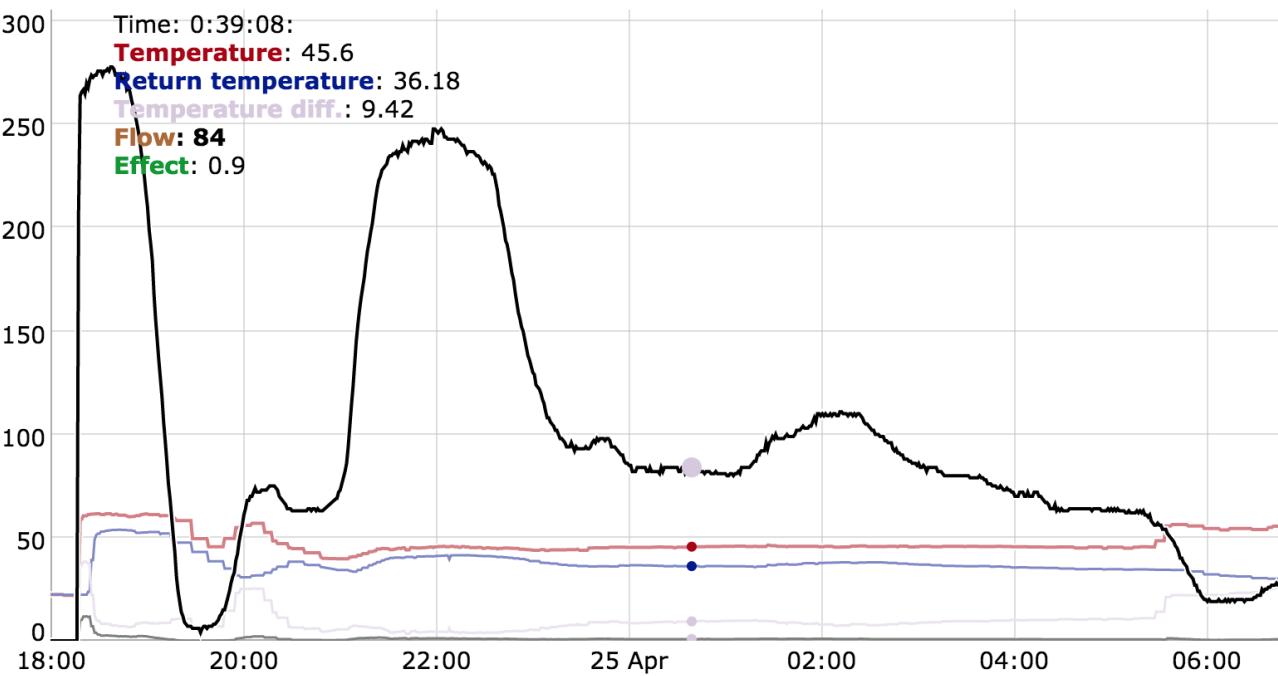
The graph is zoomable in both x and y and a screenshot is shown below:



*When you hold the mouse above a point in the graph you can observe the different data fields.*

Here is a zoomed in version

## Analysis



As you can see the sample resolution is 1 minute intervals. And the flow is has a climax around 22:00 in the evening.

## Analysis

The objective of this project is not to create a power efficient meter logger but to reduce overall heating usage for ca 1000 people. So to talk about power usage in this project can not be isolated from the greater scale of the Nabovarme project.

The ESP8266's power usage statistics can be seen in the table below:

Mode	Typical	Units
802.11b, CCK 1Mbps, POUT=+19.5dBm	215	mA
Deep sleep	10	mA
Standby	0.9	uA

source: <sup>6</sup>

In this table a few sample situations and their current drain can be seen.

The implications of meter logger on the Nabovarme project can be:

If the ESP8266 knows the temperature the water in each household then we dont have to produce and distribute max heated water to all households unless they need it. We imagine that an meter logger notifies the heating production when its local warm water container drops below a certain threshold. This will have a major influence when for example at night when nobody is using warm water etc.

Another dimension is to give people a live view of their usage. We imagine that if a user can see and follow a live correlation between heating usage and money spent they will react by changing their behaviour. The reasons can be economically but also ecologically since we can also corellate usage with ressource usage and notify people on how many trees are flowing through their radiators.

## Power considerations

The esp8266 firmware is designed with minimum power consumption in mind and the ambition is to implement the following power usage decreasing measures:

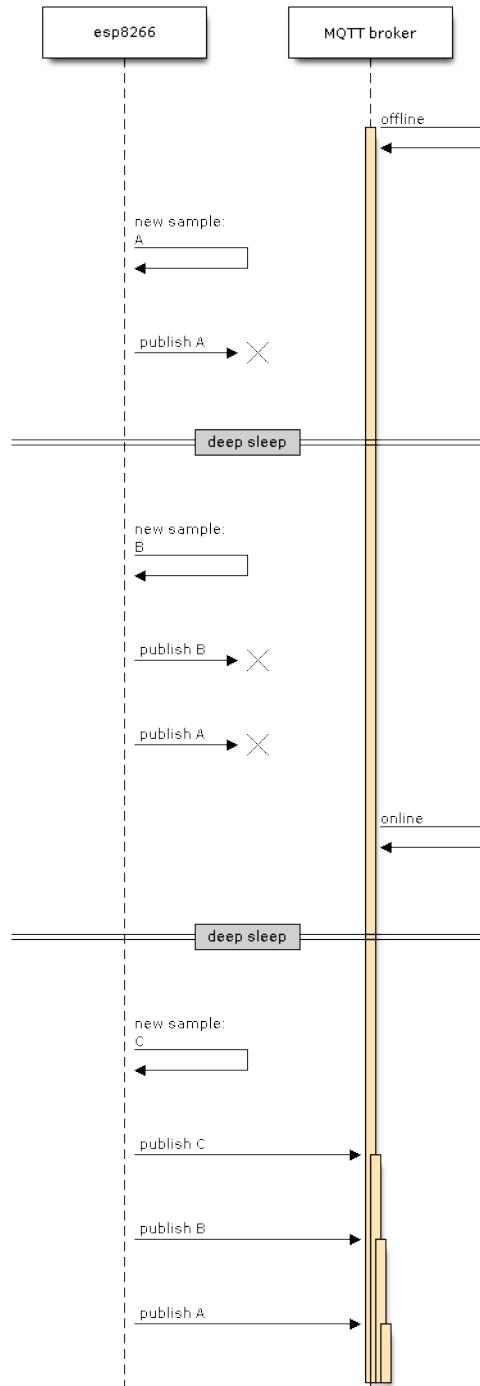
**deep sleep**

Implement deep sleep and reduce sample frequency to once an hour. The esp8266 only uses about 10mA when in deep sleep and the rtc continues to hold precision.

## MQTT

When using MQTT we are using a very compressed binary payload with minimal protocol header. This mean a very power efficient frame.

MQTT together with sleep will create a unique low power scenario where we can do the following:



The diagram shows how the buffering together with deep sleep creates the foundation for infrequent bursts of transmission when the connection is established again later. The size of the buffer, and thereby connected spi flash, describes the max size of the buffer queue and thereby how many sleep cycles you can go through before losing data.

## Conclusion

This of course can't happen without the existance of a DRAM flash added to the pcb for data persistence during deep sleep.

## Conclusion

The project has been a great success and i am happy to see that it is being rolled out to more than 200 households in Christiania.

I am certain that my project will provide a data foundation for further reducing of resource spending in the Nabovarme project and that it will be robust enough to support future improvements and usecases.

|

## Appendices

## Footnotes