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Simulating the Arctic Tundra

Battery performance at sub-zero temperatures

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To my son, Andreas.

“Science cannot solve the ultimate mystery of nature. And that is because, in the last analysis, we ourselves are a part of the mystery that we are trying to solve.”

–Max Planck

Abstract

The Arctic Tundra is an extremely cold desert-like environment. It is the home to many different species of animals and plants. With the oncoming threat of climate change, this biome is at risk of losing its biodiversity. This disruption of the Arctic Tundra caused by climate change, is what researchers at COAT with the assistance of UiT's DAO project is trying to monitor. To be able to achieve this task, the DAO project is researching and creating Observation Units(Ous). These OUs need to tackle the challenges of withstanding the extreme conditions of the Arctic Tundra. These challenges are composed of the remoteness, where network availability and strength is poor or non-existing. Energy consumption where energy production or energy harvesting is challenging, and OUs will have to rely on a limited energy source like batteries. These OUs will observe in hard to reach places where trips for maintenance or data-collection will be time-consuming and challenging.

To be able to design and build OUs that can be used in these conditions, the use of simulation is very valuable. With a good simulator, newly theorized solutions can be tested in conditions similar to the ones found in the Arctic Tundra. Using simulation will save time and resources. Long periods of time can be simulated in a fraction by simulation and the risk of losing hardware to failed deployments can be mitigated completely. This is where ESDS comes in, a simulator with the purpose of simulating node networks found in cyber-physical systems, distributed systems. This simulator is still a work in progress and is not yet able to cover all the challenging aspects of the Arctic Tundra.

This thesis focuses on what aspects are needed to be able to simulate this environment. It focuses on the inclusion of the effects of extremely cold weather. To include this aspect in the simulator, a battery plugin is created. Batteries are directly affected by the ambient temperatures, causing the battery's performance to aggravate at low temperatures. The battery plugin is used to create a prototype of the effect that low temperature has on the batteries. To summarize and evaluate the effect, simulations using real weather data from the Arctic Tundra is used. The results show that having a feature like this is very insightful for simulation and brings up the importance of battery conservation and creating OUs that are energy efficient.

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1 Introduction

The Arctic Tundra is one of the most extreme and harsh environments found on earth. It is the coldest of the biomes on earth. With the advent of climate change, this biome is at great risk of being harmed and ruined.

1.1 DAO

The Decentralized Arctic Observatory (DAO) project is trying to tackle the challenges of observing and monitoring the remote and harsh environments found in the Arctic Tundra. The climate and remoteness of the arctic offers challenges of communication, with poor or no access to networks. Energy challenges, where the observation units need to have the energy to operate for long periods of time without the possibility to replenish the energy. This begs the need for well planned power usage of the observation units and solutions for recharging or replacing batteries. [20]

1.2 COAT

The Climate-ecological Observatory for Arctic Tundra is a research project aiming to observe and document the effects of climate-change on ecosystems, bio-diversity and natural resources found in the Norwegian arctic. COAT is the use-case for the observation units being researched and developed by the DAO project. [1]

1.3 ESDS

To be able to theorize and experiment with solutions, creating simulations is very valuable. The usefulness of having a powerful and capable simulator is being able to plan, test and see results of ideas while saving the time and possibility of real failure when trying out new ideas in the real world. When knowing all the details about a scenario and how frequent they are, one can simulate years in just a fraction of the time with a simulator. One can identify worst-case scenarios and look for optimal ones. This is why the Extensible Simulator for Distributed Systems and Cyber-Physical Systems(ESDS) was created. [10] With the goal of simulating scenarios like the ones found in the DAO project. ESDS was developed with distributed systems, cyber-physical systems and wireless sensor networks in mind. It offers coarse-grained network simulation, giving users the ability to define and create networks of nodes with various network properties.

Creating simulations with ESDS is very straight-forward. The API is easy to use and most of its functionality is well documented. The simulator has a sandbox environment, where the simulation's complexity is decided by the user. In a typical implementation, nodes will be divided into senders and receivers, making ESDS an agent-based simulator. Network quality between nodes or the system as a whole is defined by choosing a network interface(wired, wifi) for each node. Network speed and the option to add interference is available. It also features a plugin called power states which tracks power and energy consumption by nodes. A substantial part of the work and purpose for this thesis was being one of the first users of ESDS, learning how to use it and figure out what works and what does not. It is still a work in progress and has not yet been officially published at the point of writing this thesis. ESDS is and will be very useful for future work on the DAO project.

1.4 Problem statement

What features are missing from ESDS to portray and simulate the environment and conditions found in the Arctic Tundra?

The missing features that were identified:

- Simulating weather/environmental factors - temperature, precipitation(snow, rain), flooding, humidity.
- Physical dimensions - Distance between nodes in the system, height difference, obstacles(mountains, woods) could play a part in signal strength.
- Simulating specific hardware - sensors, cameras, micro-controllers etc.
- Simulating events like maintenance, UAV-missions etc.

1.5 Scope

The scope of this thesis involves bringing weather and environmental conditions to the simulator, this is done by looking at what happens to batteries when they are exposed to extremely cold temperatures and trying to recreate the effect it has in a simulator. The aim is to produce life-like simulations of cyber-physical systems placed in real locations in the Arctic Tundra. This thesis will not focus on the intricate details of chemical reactions or thermophysics involved in batteries, but will try to identify and recreate the behavior as close as possible. It will also not reveal or go into more detail than necessary concerning ESDS, as this is an unpublished work in progress by other authors. The scope and focus is on extending the basic functionality of the simulator and providing new ideas for further development.

1.6 Approach

Everything created and stated is based on definitions, formulas and relations found in physics. The data used is either directly calculated using these relations or gathered from reputable sources or related research. All results and features can be recreated and evaluated from the information stated in the thesis. All features and results are evaluated and discussed for reliability and usefulness.

1.7 Contributions

The contributions of this thesis is to include the ability to simulate the effects cold weather can apply to a cyber-physical system located in the Arctic Tundra. This is done by introducing a prototype of battery monitor plugin, with behavior as close as possible to real batteries. The effects of cold temperature can be applied to this battery plugin and is the main contribution.

1.8 Outline

The outline of the thesis:

Chapter 2 - Background: Presents research and technical details concerning electricity and batteries and other relevant research to the topic.

Chapter 3 - Design: The planning and design of the battery plugin is described.

Chapter 4 - Implementation: Show how the design is implemented and integrated into ESDS.

Chapter 5 - Experiments and Evaluation: features experiments to both validate and showcase the different aspects of the battery plugin.

Chapter 6 - Discussion: Discusses the results and findings of the thesis, weaknesses of the thesis and suggestions for future work.

Chapter 7 - Conclusion: Concludes and summarizes the thesis.

2

Background

2.1 Technical background

This section describes the technical concepts of batteries and electricity. This is to to be able to understand the implementation and design of the battery plugin and to give perspective on the results it produces.

2.1.1 Electricity

Definition 1. Ampere - Current

Ampere is the SI-unit for electrical current, it is defined as the charge of 1 Coulomb per second. 1 Ampere is also the current in a circuit with a resistance of 1 Ohm and a voltage of 1 Volt.

Definition 2. Watt - Power

Watt is the SI-unit for power, defined as 1 Joule per second. 1 Watt is the power of a circuit with 1 Ampere and 1 Volt.

Definition 3. Volt - Voltage

Voltage is the difference in potential between two points. 1 Volt is 1 Joule per Coulomb.

Device	Ampere	Watt
Desktop computer	1.3A+	300W+
Laptop	<0.5A	<100 W
Dishwasher	10A	2200W
Raspberry Pi 4	0.5A idle / 1A on	2.7W idle / 5W on
PyCom FiPy v2	20 μ A deep-sleep / 60 mA idle / 150 mA on	0.2 W idle / 0.5 W on

Table 2.1: Energy and power consumption of different devices [9] [4] [16]

Definition 4. Coulomb - Charge

Coulomb is the SI-unit for electric charge, 1 Coulomb is defined as 1 Ampere per second.

Definition 5. Joule - Energy

Joule is the SI-unit for energy, it takes 1 Joule to move 1 Newton 1 meter.

Definition 6. mAh - Capacity

Unit for electric charge. Often used for capacity. Ah or mAh means how much capacity is available if there is a constant current (A) for one hour (h). Often expressed in milli-ampere hours (mAh) and is used to express the the capacity of batteries. 1 Ah = 1 Wh x 1 V

Definition 7. Wh - Capacity

A Watt-hour is the unit for change in power and can like mAh be used as a unit of capacity. It tells how much capacity is available if the power (W) is consumed for h(hour). Watt-hour = Ampere x Volt 1 Wh = 3600 Joules

Batteries can be connected in parallel to increase the total capacity of the system or they can be connected in serial to increase voltage.

To give an idea of how much an ampere-hour or milliampere-hour really is, it is useful to know what some common appliances and devices relevant to cyber-physical systems use:

2.1.2 Battery

A battery is a container of energy built up by chemical cells that convert chemical energy to electricity. The chemicals used and the manufacturing details of the

battery will decide its capabilities. Some batteries have the ability to reverse the chemical process and thus make the battery rechargeable. [18]
This thesis includes 3 different battery types with different chemical structures. Lithium-ion is one of the most suitable batteries for the purpose of powering a cyber-physical system in the Arctic Tundra. It performs well in environments facing both cold and hot temperatures and it offers great capacity and voltage. The implementation of Li-ion in this thesis is based on the Energizer L91 AA battery with the specifications [7]:

Lithium-Ion	AA
Capacity	3500 mAh
Operating temperature	-40 °C to 60 °C
Nominal Voltage	1.5 V

Table 2.2: Specifications of Energizer L91 AA [7]:

This is the battery used in an earlier deployment by researchers of the DAO project [14]
This battery has a chemistry made up of Lithium and Iron Disulfide (Li/FeS_2)
To compare with Li-ion, NiMH(Nickel-Metal Hydride) is included and it based on the Energizer NH15. [8]

NiMH	AA
Capacity	2300 mAh
Operating temperature	-20 °C to 45 °C
Nominal Voltage	1.2 V

Table 2.3: Specifications of Energizer N15 AA [8]:

Alkaline (Zinc-Manganese Dioxide (Zn/MnO_2), based on the Energizer E91 [6]

Alkaline	AA
Capacity	3000 mAh
Operating temperature	-18 °C to 55 °C
Nominal Voltage	1.5 V

Table 2.4: Specifications of Energizer E91 AA [6]:

2.2 Related work

This section provides research closely related to the DAO project and research related to the challenges and problem statement of the thesis. The papers presented have acted as strong sources of inspiration and/or provided valuable information to the subject of the thesis.

2.2.1 Experiences Building and Deploying Wireless Sensor Nodes for the Arctic Tundra [14]

In this paper, the authors describe the process of designing, implementing, building and deploying wireless sensor nodes in the Arctic Tundra. These wireless sensor nodes are named observation units (OUs). A total of 18 OUs were deployed in the Varanger peninsula(a part of Norway's Arctic Tundra) consisting of 2 deployments, over a period of 2 years. The goal of the OUs was to measure temperature and carbon-dioxide levels over the winter. The paper provides valuable insight into the challenges of deploying such a system to an environment like the Arctic Tundra. At the end of the deployment, all OUs had ceased to communicate and after investigation provided different reasons for failure. The cause of failure included environmental factors like spring-time flooding causing hardware to fail, battery issues(completely drained), corrupted data and software issues(stuck in crash loops). This paper has served as a great inspiration to identify what is needed for a simulator and also why simulation is an important consideration before deploying a cyber-physical system into the real world.

2.2.2 Impact of loosely coupled data dissemination policies for resource challenged environments [17]

The problems of energy-scarcity and poor network conditions for cyber-physical systems in resource-constrained environments is examined in this paper. The paper proposes and evaluates policies for loosely coupled data dissemination. It identifies the issue of coupled data dissemination where nodes will waste time and energy waiting or scheduling tasks. The goal of the research is to reduce the overall energy consumption and uptime of nodes, while successfully disseminating updates or observational data. The use of loosely coupled data dissemination policies are looked at and evaluated as a potential solution. In a loosely coupled scenario, the nodes wake up at random intervals having random lengths of uptime. Two policies were proposed, hints: a receiving node will share a timestamp for the sender's next uptime with other receivers that are up at the same time. Extended: when an overlap happens in a receiver and sender's uptime, the uptime will be extended to successfully finish the data transmission between them. Both policies and a combination are experimented with and evaluated using flow-level network simulation, comparing the results with a baseline consisting of no policy applied. The simulations were made using SimGrid and results showed improvements regarding energy consumption using the policies or combination of them depending on the scenario it was applied on. This research provides important findings to tackle the challenge of energy-consumption in cyber-physical systems and was used for practice and inspiration when creating this thesis.

2.2.3 Simulation of the Internet of Things [2]

This paper describes the challenges of simulating large-scale IoT systems. Scalability and the high level of detail(fine granularity) being the main ones. It gives an overview of the state of the art of existing techniques and simulators available to do this. The paper proposes a solution of multi-level simulation; a simulation composed of multiple models, providing different levels of detail and being assigned to specific tasks. IoT and cyber-physical systems both being composed of wireless sensor nodes and other devices share a lot of the same challenges when it comes to simulating. The fine-grained level of detail and the complexity of larger-scaled systems.

2.2.4 Simulators, Emulators, and Test-beds for Internet of Things: A Comparison [15]

The authors of this paper present and compare a wide range of simulators, emulators and test-beds for IoT. It further states the importance and usefulness of going through the stages of simulation, emulation and using test-beds before implementing and deploying the real IoT system.

2.2.5 Temperature effect and thermal impact in lithium-ion batteries: A review [13]

This paper goes into detail about the thermal impact and effect of temperature on batteries with lithium-ion chemistry. Both higher and lower temperature, outside the battery's operational range has a negative impact on the battery's performance. At low temperatures, which this thesis is concerned with, the lithium-ion batteries suffer a reduction in ionic conductivity and an increase in charge-transfer resistance. This leads to lower capacity of the battery. Batteries with lithium-ion chemistry are one of the best choices for the purpose of powering a cyber-physical system in a cold environment and is the primary battery technology of focus in this thesis.

3 Design

This section describes the architecture and design of the battery plugin and temperature effect. It goes into detail of how the features were planned out and what design decisions were made.

3.1 Battery

The first thing the battery plugin needed was a component representing the battery itself and keeping track of the energy consumption. The base battery functionality needs to represent batteries of various characteristics and allow a user to define and experiment with different variables related to energy consumption and chemistry.
A battery's capacity is usually defined in the units mAh or Ah (milliampere-hours or ampere-hours). It gives a measure for how long a battery will last given the electric current in amperes.(For example, given an electrical appliance consuming 1 A a battery with 1000 mAh or 1 Ah would last 1 hour.)
To create this functionality, the battery's capacity needs to be converted to a suitable unit that can be updated during simulation run-time to accurately display the battery's remaining capacity and usage.

ESDS has a plugin called power states that will measure energy and power consumption in joules(J) or watts(W). To be able to integrate the battery plugin with ESDS and leverage the functionality of power states, the capacity will be converted to joules when calculating and updating the total remaining capacity.

From section 2 - Electricity it is stated that: A Joule is a measure of energy and it is composed of a charge carried by a voltage.

$$Joule(energy) = Volt(voltage) \times Coulomb(charge)$$

A Coulomb is the unit representing electric charge. 1 Coulomb is equal to the charge of 1 Ampere constant current for 1 second.

$$Coulomb(charge) = 1Ampere(Current) \times 1second$$

An ampere-hour(Ah) provides the amount of energy charge per hour and joules provide the rate of energy per second. By finding the charge contained in a milliampere-hour(mAh), the capacity can be converted to joules. By using these relations, one can find that an Ampere-hour which is 1 A for 1 hour (60 minutes x 60 seconds = 3600 seconds) would equal to 3600 Coulomb, whereas a milliampere-hour would equal to:

$$\frac{1}{1000}Ampere \times 3600seconds = 3.6Coulomb$$

Knowing this, one can find and convert the amount of energy (Joules) found in the capacity(mAh) in a battery.
A typical AA-sized battery contains between 1000-3500 mAh of capacity at a nominal voltage of 1.5 V. This means that the amount of energy this battery contains is:

$$1.5V \times 3.6C \times 2000mAh = 10800J$$

Using this conversion allows the battery plugin to leverage the power states plugin to keep track of energy consumption and update the battery's capacity. When displaying remaining capacity, the value is converted back to mAh.

Capacity and energy consumption relies on voltage, and voltage fluctuates or declines as a battery is being used. This is something that is hard to predict and simulate accurately. This made the decision to always use the nominal voltage specified for each battery. The nominal voltage is what is considered typical or normal for the usage of the battery, but will in reality fluctuate above or below this level. The nominal voltage value is specified for each battery in Section 2. The nominal voltage is used to specify capacity in every experiment or validation test.

3.2 Temperature effects on battery

Temperature has a very substantial effect on batteries. Temperatures found at the extremes of the battery's operating temperature will affect the battery's max capacity, lifetime, ability to charge and more. This is due to the internal resistance in the battery changing. At higher temperatures a battery's capacity will increase, but lifetime will decrease. At low temperatures the capacity will greatly reduce and reach zero when approaching the lower end of a battery's operating temperature.

It is important to note that the capacity is not completely lost, it just becomes harder to utilize the battery's full potential as chemical reactions are slowed down.[5] So in other words, if temperature fluctuates greatly from lower temperatures to higher, the capacity will be regained.

For the sake of this paper, the focus will be on max capacity at the lower-end of the temperature scale. The battery's internal temperature will be the same as ambient for simplicity. To represent the diversity of batteries and the impact of temperature, specific AA-sized batteries with different chemical compositions will be used as basis for the effect of temperature on batteries.

The effect of temperature varies widely depending on a battery's chemistry. It will also vary between manufacturers and units. This makes it challenging to create a generalized model that can accurately predict any battery's performance. This resulted in a decision to use specific data for specific type of batteries to portray different battery chemistry. The assumption is that it will give a close enough estimate of how the battery will perform and due to the effect being caused by the battery's chemistry reacting to temperature, the difference between manufacturers and individual units will be small enough to be negligible.

The focus of simulation is at sub-zero temperatures, as the difference in capacity at above 0 °C is often negligible and the focus is on simulating sub-zero temperatures found in the arctic.

The effect of cold temperature on batteries is widely known and documented, but finding hard data describing this behavior proved to be difficult. The best information and data describing specifically how batteries perform in cold temperatures was found in the handbooks of batteries. The data used for this implementation is provided by the battery manufacturer Energizer.

Energizer's battery handbooks provide detailed information about how well their different battery technologies perform. This information is provided by curves, which made the design decision of reverse-engineering these curves and reading the values from them.
The numbers were approximated from the curves and then calculated to a value between 0 and 1 to represent the percentage of total capacity. This is done by reading the reduced capacity's value from the curve and dividing it by the total capacity, this is then rounded to a number with max 2 decimal points. This gives a rough estimate of the percentage of battery capacity lost at different sub-zero temperatures.
As the effect of temperature is not only dependent on chemistry, this process was repeated for the different rates of constant current discharge.

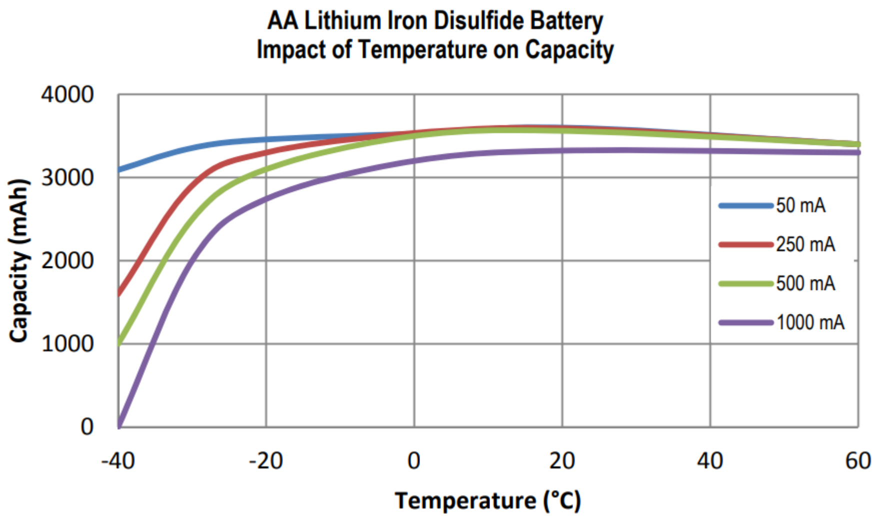


Figure 3.1: Capacity vs. Temperature for Energizer L91 Ultimate Lithium [7]

Temp °C	50 mA	250 mA	500mA	1000 mA
-40	0.9	0.45	0.3	0
-35	-	0.65	0.6	0.25
-30	0.95	0.8	0.75	0.45
-25	-	0.9	0.85	0.6
-20	1	0.95	0.9	0.75
-15	-	0.97	0.95	0.8
-10	1	1	0.97	0.85
-5	-	1	0.99	0.9
0	1	1	1	0.95

Table 3.1: Capacity percentage levels approximated for the Li-ion battery at different constant current discharge levels.

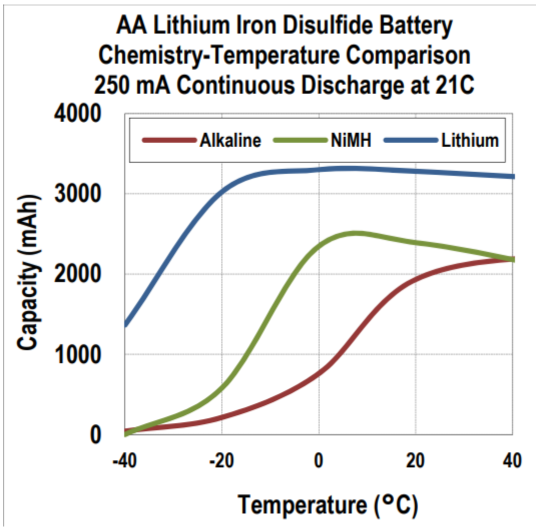


Figure 3.2: Li-ion vs Alkaline and NiMH [7]

Temp °C	Alkaline: 250 mA	NiMH: 250 mA
-40	0	0
-35	0.05	0.05
-30	0.05	0.1
-25	0.1	0.15
-20	0.1	0.20
-15	0.15	0.45
-10	0.2	0.65
-5	0.25	0.9
0	0.35	1
10	0.7	-
20	0.9	-
25	1	-

Table 3.2: Capacity percentage levels approximated for the Alkaline and NiMH battery at 250 mA constant current discharge levels.

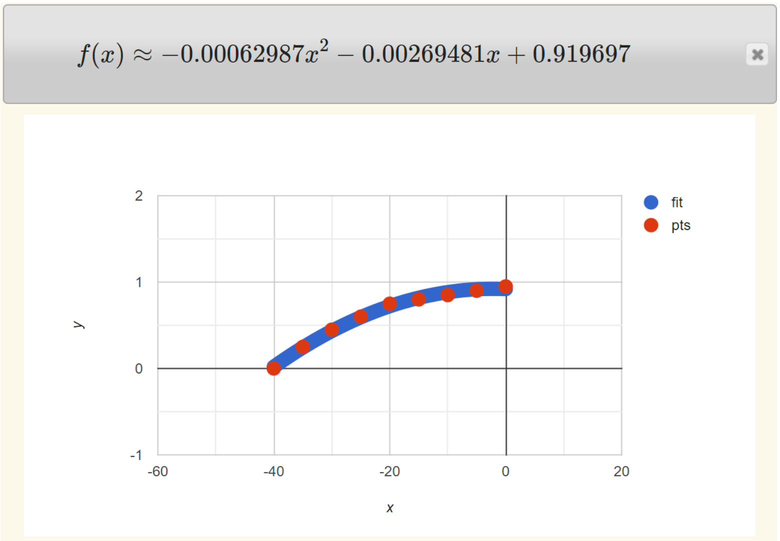


Figure 3.3: Approximated function for capacity - Li-ion - 1 A constant current discharge [3]

The points consist of a temperature value and a percentage value. By the use of an online function equation finder from dCode, [3] these points were approximated and fitted to a parabolic curve where each temperature value between 0 and -40 would return a value between 0 and 1 to represent the capacity remaining when the battery was exposed to a certain temperature.

A parabolic function is on the form:

$$f(x) = ax^2 + bx + c$$

3.3 Weather

To have realistic weather and climate conditions, Frost API from Meteorologisk institutt is used. The API gives access to a wide range of data collected by many weather stations located around Norway. It can give historical data about precipitation, wind, temperature, humidity and more. By finding the source-name of a location you want and setting a timeline you can retrieve the data. To really simulate harsh conditions, the town of Karasjok located in Finnmark was chosen as test grounds for most of the experiments. It is one of the coldest towns in Norway, with a record-low temperature of -51.4°C. It is also a place that often reaches temperatures below -30°C, pushing the limits of the batteries operating temperatures. [12]

4

Implementation

This section describes the process of implementing and integrating the design and architecture into ESDS. Detailing how the features are integrated and leveraging the functionality of the original ESDS. This section also provides information about how simulations are made and presented.

4.1 Setting up ESDS

ESDS architecture is composed of a simulation orchestrator, consisting of a network event loop keeping track of the simulation's network environment and network node events. The nodes are thread-based running of one or more node implementations, where the simulation's user specifies the events.
ESDS is built in Python and uses YAML for creating configuration files. Building simulations is done by using the simulator's API calls in separate node implementation files. Details regarding interface, interference and node-specific options are located in the configuration file.

The node details of the configuration file states how many nodes the system consists of, what implementation files they should use and also feature a dictionary of arguments. The arguments can be used to determine whether a node is a sender or a receiver, or in the case of this work used as a way to determine the type of battery and current used. The interface decides if the network simulation is wireless/Ethernet, which nodes have a connection link and the performance of communication transmissions.

Listing 4.1: ESDS YAML config file

```
general:
    interferences: on
nodes:
    count: 2
    implementations:
        - all node.py
    arguments: {
    "0": "li-ion-50",
    "1": "li-ion-250"
    }
interfaces:
    wlan0:
        type: "wireless"
        links:
            - all 50 kbps 0s all
        txperfs:
            - all 50kpbs 60s
```

4.2 Extending ESDS

The extensible part of ESDS comes from the ease of extending the simulator's use cases by creating and incorporating your own plugins. The battery plugin is created as its own module in the plugins directory. This means that any user of ESDS can import the module to use in their own simulations.

4.3 Battery monitor

The battery monitor plugin works by having each node define and create their own battery. The battery monitor has 5 arguments:

1. Capacity - The battery's max capacity in mAh
2. Node - A reference to the node itself to be able to interact with ESDS API
3. Volt - The operating voltage of the battery

4. Power - Power consumption in Watts
5. Multiplier - To multiply the amount of batteries

To initialize the battery component, the capacity is first converted to joules. The node reference and power argument is used to create an instance of the power states plugin to be able to measure the energy and power consumption. Power is in watts and has to be calculated by multiplying the current in Amperes with the voltage. The energy consumption method keeps track of the difference in energy and subtracts it from the capacity converted to joules. There are also methods to update power and voltage, to allow for dynamic voltage and power.

Listing 4.2: API of the Battery Plugin

```
class BatteryMonitor():
    def __init__(self, capacity, temp, api, volt, power, multiplier=1):
        - Initializes the battery and its attributes
        - Sums up multiples of battery
        - Calculating capacity in joules
        - Setting up instance of power states to record power consumption
    def energy_consumption(self):
        - Calculates and updates the energy consumption,
        keeping track of total energy consumption
        and difference in energy consumption since last updated.
    def update_capacity(self, temp, type, current=1):
        - Updates the battery's current capacity using
        the new temperature value and computes the
        new capacity sorted by battery chemistry type and current.
    def update_voltage(self, volt):
        - Updates voltage
    def update_power(self, power):
        - Updates power consumption
    def get_capacity(self):
        - Returns current capacity in mAh
    def print_battery(self):
        - Log function to show different attributes and status of battery
```

4.4 Temperature effect

There are many variables involved to find the capacity and calculate the loss of capacity for a battery. To make the simulation work closer to the real life counterpart, the options had to be narrowed down. Instead of a general option for each type of battery chemistry, they are reduced to different chemistries with different current discharge rates. All options are divided into static constant current discharge rates, based on the AA-sized batteries by Energizer, mentioned in Section 2 - Technical Background - Battery.

4.5 Realistic Temperatures

To bring real life data regarding weather and temperatures, FROST API by MET is used. The Frost API gives a wide range of measurements from different weather stations located in Norway. To simulate the extreme conditions found in the Arctic Tundra, a winter season from Karasjok is used. Temperature is updated hourly for a period of 6 months. The temperatures from Karasjok give a great variety of temperatures in the sub-zero range, pushing the batteries capacity close to their non-recommended operative temperatures. [12]

Listing 4.3: Endpoint and Parameters used for Frost API

```
endpoint = 'https://frost.met.no/observations/v0.jsonld'
parameters = {
    'sources': 'SN97251',
    'elements': 'air_temperature',
    'referencetime': '2022-10-01/2023-04-01',
}
```

The data retrieved is in JSON format and gathered using RESTful API. As the battery plugin only supports temperature, air temperature is the only element retrieved from the weather data.

4.6 Creating and showing simulations

To create a simulation, a node implementation or more is needed. The node implementation file is where all the events and the duration of the simulation are decided.

Listing 4.4: Example of Simulation Implementation

```
import battery_monitor as battery
import power_states as ps
import weather as w

def execute(api):
    type=api.args
```

```
temperatures = w.generate_weather() #temperatures from FROST API

bm = battery.BatteryMonitor(3500, node, volt, power, multiplier)

clock = api.read("clock")
winter = clock + (182*24*60*60)
uptime = 600
days = 182*24

for hour in range(days):

    clock = api.read("clock")

    //If capacity is 0, turn off node and wait till end of simulation
    if bm.get_capacity() <= 0:
        curr_clock = api.read("clock")
        duration = (winter - curr_clock)
        api.turn_off()
        api.wait(duration)

    //Logging the hourly status of the node and its battery
    print(hour, capacity, type, temperatures[hour])

    //Updating power consumption and capacity with the new temperature.
    bm.update_power(power)
    bm.update_capacity(temperatures[hour], type, current)

    //Uptime loop doing work
    while (api.read("clock") < clock + uptime):
        api.send()

        // Updating energy consumption every 60 seconds
        if api.read("clock")%60 == 0:
            bm.energy_consumption()

    //Updating power to represent sleeping for the remainder of the hour
    bm.update_power(watt)
    while (api.read("clock") < clock + (3600-uptime)):
        api.send()

        if api.read("clock")%60 == 0:
            bm.energy_consumption()
```

This node example is simplified for readability, but represents a node doing work for 10 minutes, then sleeping the next 50 minutes every hour. This simulation lasts for 182 days.

ESDS is terminal-based, writing the output of simulation results and progress to the terminal. The simulator has many built in logging features, logging to terminal when a node is sending/receiving, turning off or on. To use the results of the simulations, custom prints writing battery-type, hour, temperature, capacity and so on were written to text-files and then parsed afterwards to present the results/data of the simulation in plots. All plots are made in Python's Matplotlib.[11]

5

Experiments and Evaluation

This section provides evaluations of the battery plugin and its reliability and accuracy. It also showcases the utility and use case of the plugin with experiments based on real scenarios using real weather data.

5.1 Evaluating the accuracy and reliability of the temperature effect

Before doing proper simulations, it's important to evaluate the accuracy of the battery plugin and its temperature effect. To evaluate the implementation of the temperature effect, each battery's loss of capacity is calculated versus a range of temperatures from 0°C to -40 °C without energy consumption. As these are results from approximated parabolic functions, the results vary in correctness. When comparing to 3.1 and 3.2 one can see that the resulting curves from the approximated functions are very similar. The worst approximations seem to be Li-ion at 250 mA and 500 mA, having wrong capacity at the higher range of the temperature. (0°C to -15 °C). The capacity is too low at 0°C and too high at around -15°C. This is also the range where the temperature effect is the least significant for li-ion and will not affect the simulation's accuracy to a great degree.

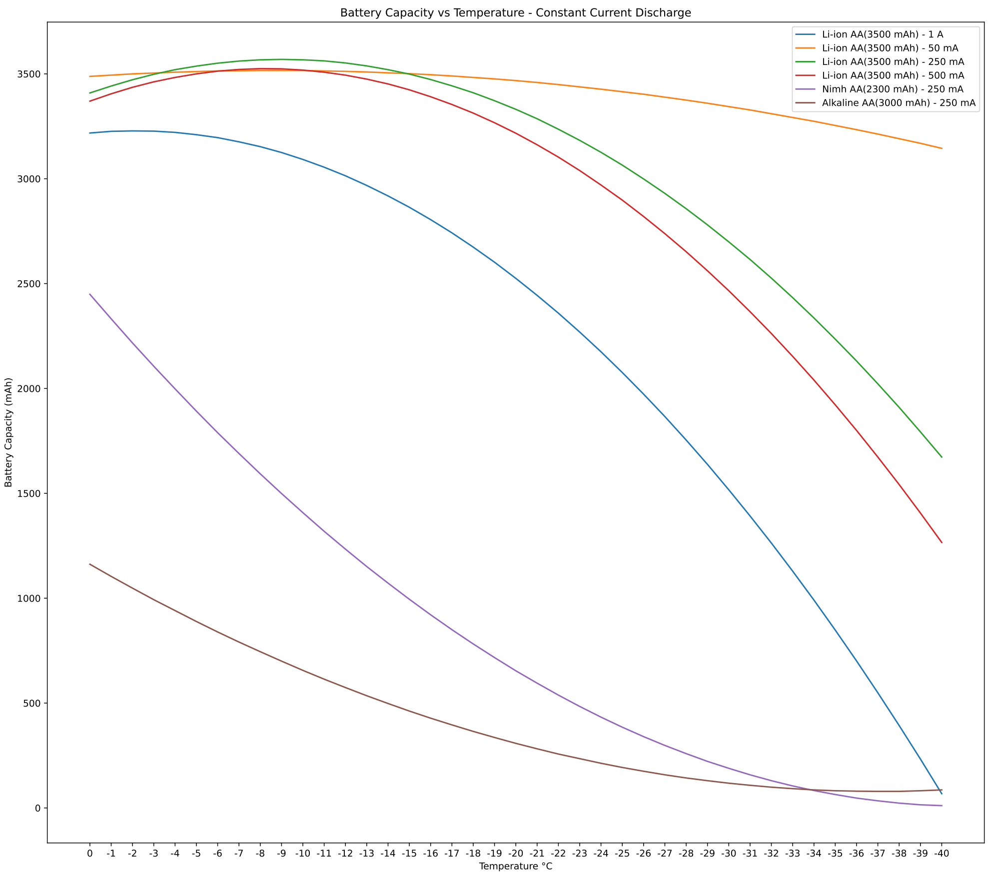


Figure 5.1: Capacity vs. Temperature for the different batteries supported

5.2 Evaluating the reliability of regained capacity

The regain of capacity was also evaluated for correctness. If the temperature rises quickly from low temperatures to higher, the lost capacity is regained. However, it should never surpass the capacity of a battery at optimal conditions with the same constant current. To test this, the battery plugin is run with an increase of 5°C per hour while comparing to batteries running at constant optimal temperature.(Optimal conditions, constant current).

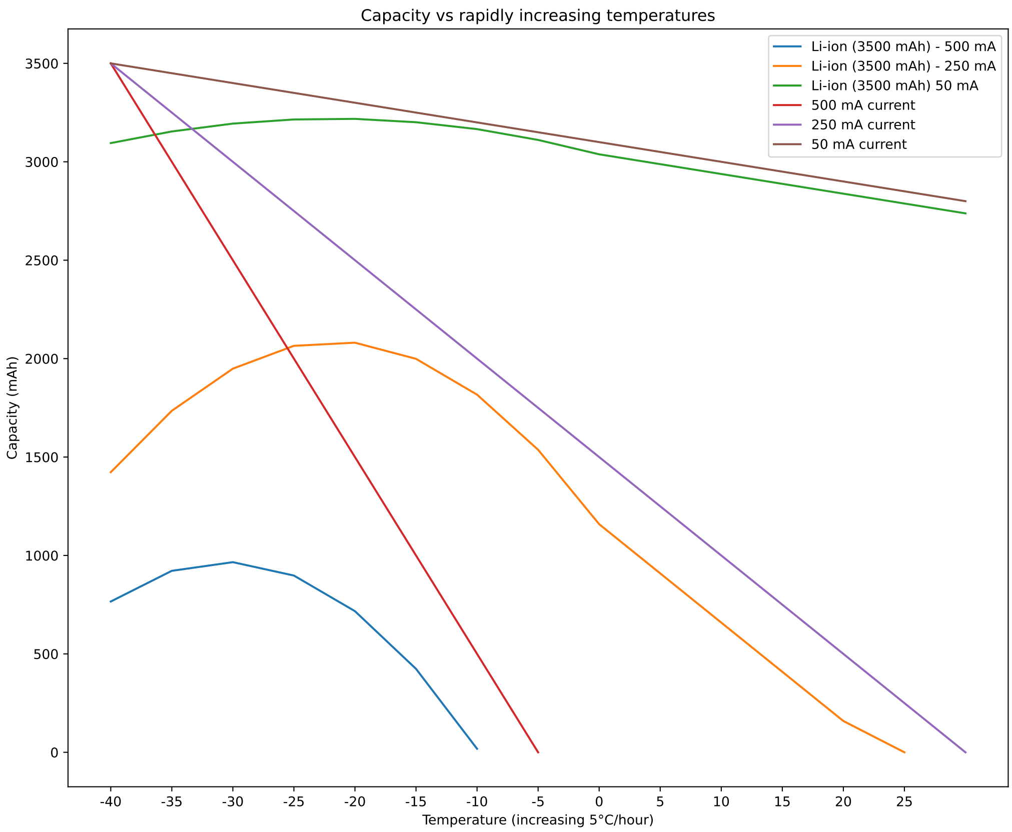


Figure 5.2: Capacity vs. increasing temperature

The results show that the batteries do regain capacity and keep below the threshold made by the same battery chemistry and constant energy consumption with optimal temperature.

5.3 Batteries vs real temperatures

To bring these new features to light, some simulations were done to experiment and showcase the usefulness and evaluate the correctness of the plugin. In the first experiment the 3 different battery types were tested with real world temperature gathered from Karasjok in the period from 01.01.2023 to 01.04.2023 (90 days - 3 Months).
The temperatures are updated hourly. 12 batteries of each type are put in parallel to increase the total capacity, resulting in 3500x12 = 42 000 mAh for Li-ion, 12x2800 = 33 600 mAh for Alkaline and 12x2300 = 27 600 mAh for NiMH. Two different current discharge rates are tested for Li-ion and one for Alkaline and Nimh. Temperatures provided in the simulation are in the range between 0 to -25 °C.

The expected outcome of this experiment is for the batteries to perform significantly worse than they would in ideal room temperature conditions, significantly for the less suitable Alkaline and NiMH batteries.
In ideal conditions with constant current discharge, the results would be the following:

Li-ion 250 mA =

$$\frac{42000mAh}{250mA} = 168hours$$

Li-ion 500 mA =

$$\frac{42000mAh}{500mA} = 84hours$$

Alkaline 250 mA =

$$\frac{33600mAh}{250mA} = 134hours$$

NiMH 250 mA =

$$\frac{27600mAh}{250mA} = 110hours$$

From the results of the experiment one can see that the lithium-based batteries fall just short of their expected optimal performance, with the 250 mA losing 10 hours of operating time and the 500 mA losing 4 hours. This is somewhat expected as Lithium-ion is very suitable for the temperatures in this experiment(A minimum of -25 °C is well within operating range of -40°C to 60°C, and the fall-off in capacity is not very drastic until reaching below -30°C.
The less suitable batteries Alkaline and NiMH endure a massive loss of capacity. Where NiMH (Operating temperature -20°C to 50°C) suffers a loss of about 70 hours and Alkaline(Operating temperature -18°C to 55°C) 100 hours.

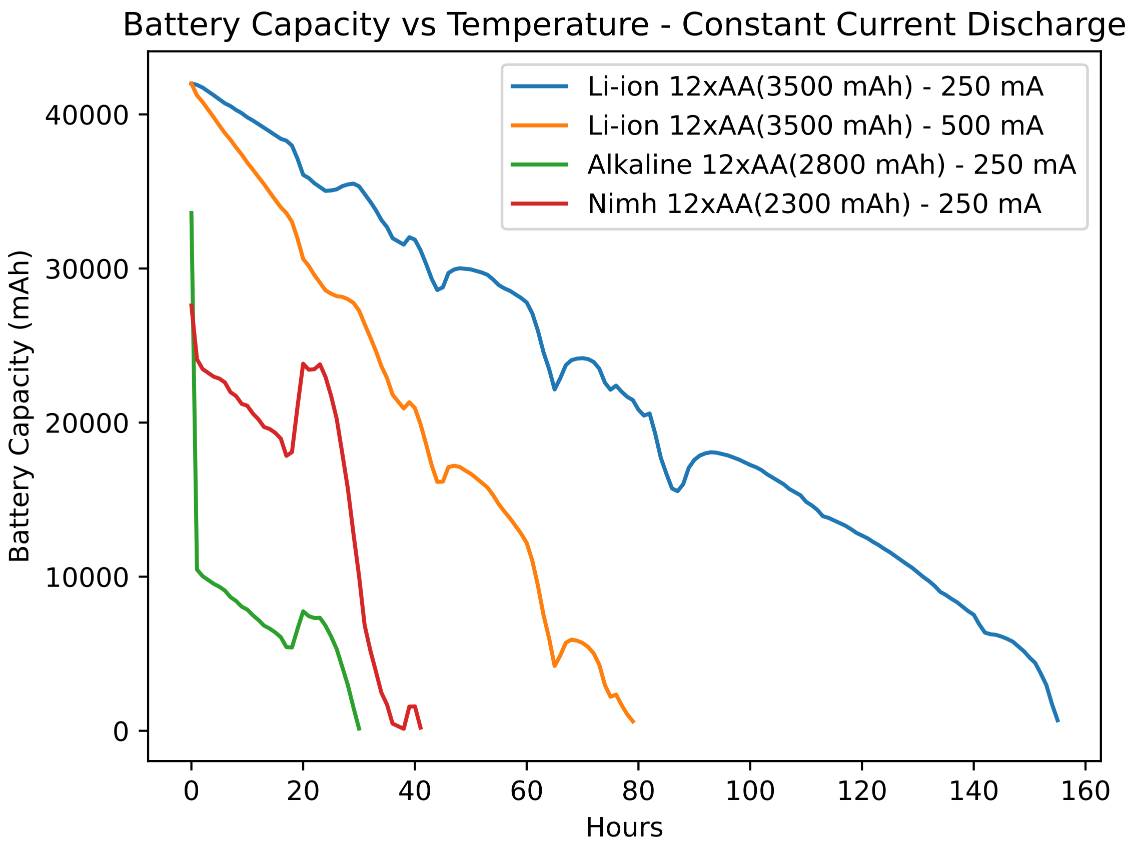


Figure 5.3: Capacity - 3 winter months in Karasjok

The results fall in line with the temperature graph showing at 40 hours in the simulation the temperatures were below the respective operating temperatures of these batteries.

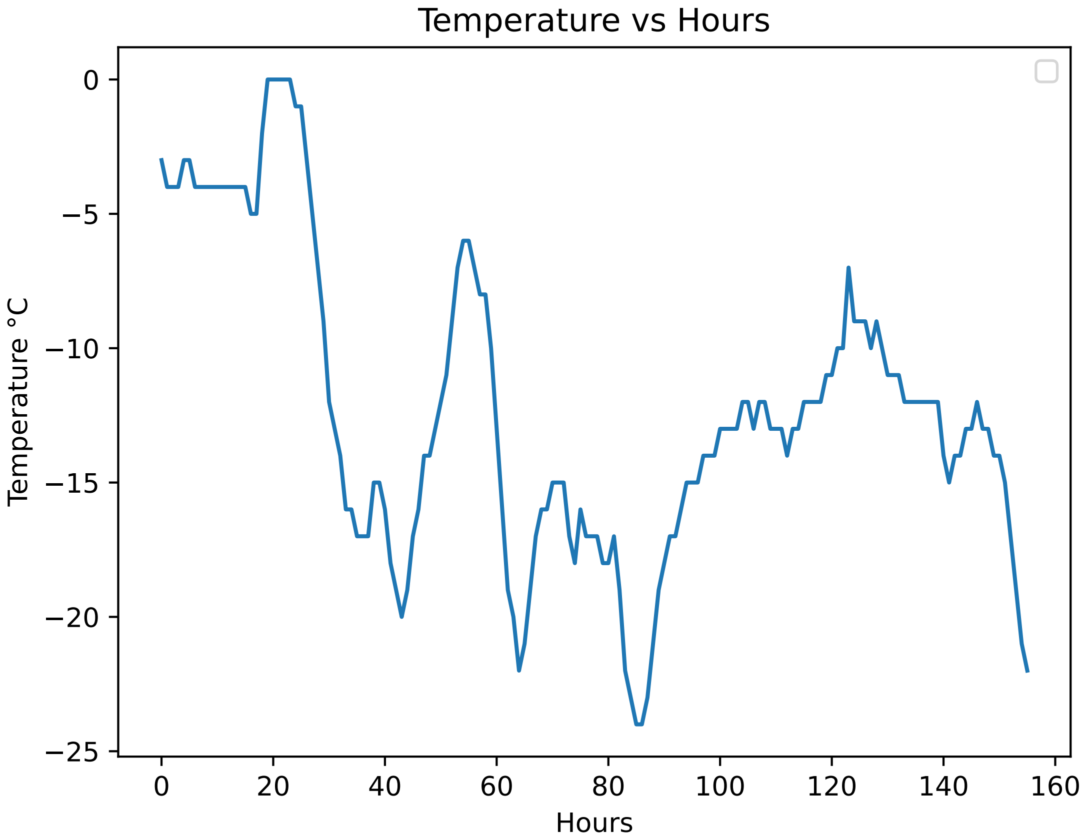


Figure 5.4: Temperature - 3 winter months in Karasjok

5.4 Observation unit in the Arctic Tundra

In this experiment, the goal is to simulate a node representing an observation unit (OU) in an arctic environment during the winter months. The OUs are designed to be power-efficient and spend a majority of their time in a deep-sleep state with an energy consumption of μ A. A previously deployed OU is stated as having 12 li-ion AA-batteries. This was expected to support the OU for year, with measurements performed every half hour and up to 8 minutes of LTE communication per day [14] At a nominal voltage of 1.5 V, this will provide 42 000 mAh of capacity.
The power consumption of the CO2 observation unit with a FiPy micro-controller is stated as consuming 120 mA when communicating on LTE, 70 mA when doing measurements and between 24-443 *mu*A in deep-sleep. In a previous deployment attempt, it spent 3 minutes/day communicating, 14-15 sec/day measuring and the rest of the time in deep-sleep mode.
The batteries that were used were the Energizer Ultimate Lithium [7], consisting of battery-packs of 3 connected in serial to provide 4.5 V of voltage and 4 of these packs connected in parallel to provide a total capacity of 3500 mAh × 4 = 14 000 mAh. [19]

To simulate a similar, but more extreme scenario, the node will be up for 2 minutes per hour, operating with an energy consumption of 250 mA (375 mW @ 1.5 V) and spend the rest of the time sleeping with 1 mA (1.5 mW @ 1.5 V) energy consumption. The node will be equipped with 12 AA-batteries in parallel for 12 times the capacity. (3500 × 12 = 42 000 mAh). As the battery plugin only supports currents of 50, 250, 500 and 1000 mA and the effect of temperature is based on a nominal voltage of 1.5 V, simulations are created with this in mind.

This is tested using real temperatures from Karasjok in the period 1st of October 2022 - 1st of April 2023 - 182 days of winter. Values are provided by FROST Api using data from MET's weather station. [12] and are in the range between 10°C to -40°C.

In ideal conditions the system would perform: 250 mA for 2 minutes:

$$\frac{250mA}{60mins} \times 2 = 8.33mA \approx 8mA$$

1 mA for 58 minutes:

$$\frac{1mA}{60mins} \times 58 = 0.967mA \approx 1mA$$

The max capacity in ideal conditions would in theory last:

$$\frac{42000mAh}{9.3mA} = 4516hours \approx 188days$$

This would in theory give the node a small overhead of capacity to endure a winter of 183 days in Karasjok.

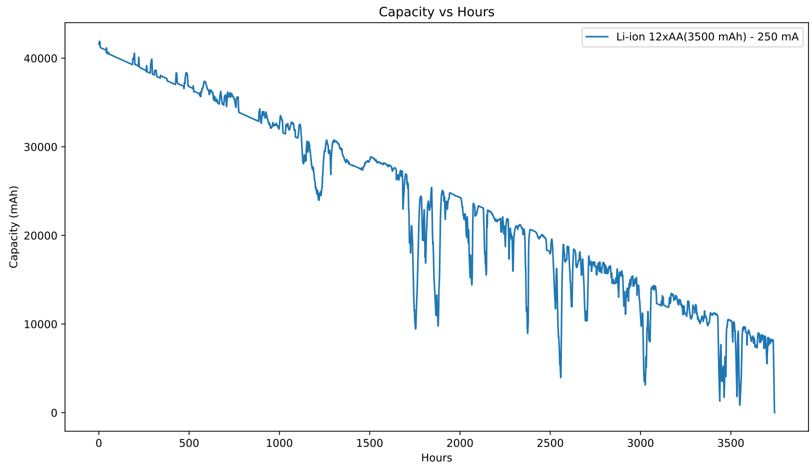


Figure 5.5: Node in winter-time Karasjok - 250mA on, 1mA sleep

From the figure [5.5] one can see that the node ended up lasting for 3744 hours ≈ 156 days.

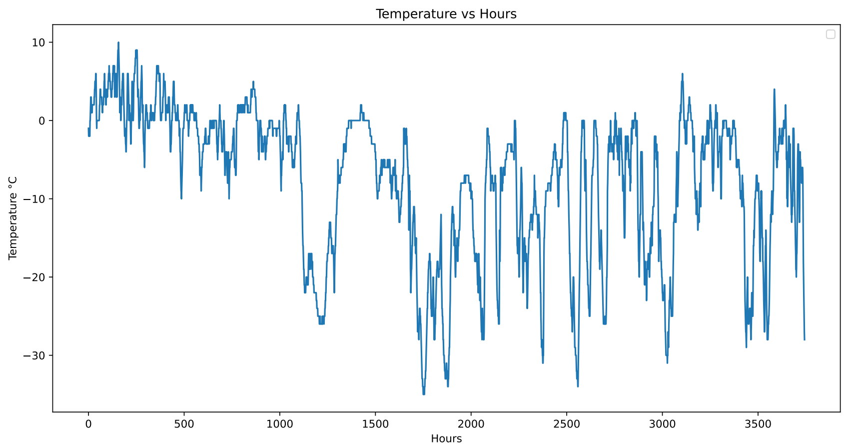


Figure 5.6: Temperature in winter-time Karasjok

The temperatures ranged from -35.9°C at the coldest at 1755 hours into the simulation and 9.3°C at 252 hours. The simulation ends at a temperature -28.8°C [fig: 5.6] At hour 3743, the remaining capacity is 53 mAh and temperature -27.5°C

To interpret and evaluate this result, we can look at the total capacity (mAh) consumed and compare it to the reduced capacity at day 156 (-28.8°C).

$$3744hours \times 9.3mA \approx 34819mAh$$

The reduced capacity for the Li-ion batteries operating at 250 mA with a temperature of -28.8°C (Calculated with the approximated function for Li-ion at 250 mA):

$$42000mAh\times \approx 0.799 = 33558mAh$$

This means that the remaining capacity at day 156 was 33 558 mAh, while the node had consumed 34 819 mAh. This gives an inaccuracy of:

$$33558mAh - 34819mAh = -1261mAh$$

Meaning an average error of:

$$\frac{-1261mAh}{3744hours} \approx 0.33mA$$

0.33 mA too much was consumed hourly.
After investigation it seems likely that this inaccuracy is caused by the node implementation of the simulation, and not the battery plugin itself. As small inconsistencies can result in larger discrepancies in long simulations. It is also important to note that while the node shut down and had zero remaining capacity at 3744 hours, the battery pack still has unused capacity available if the temperature rose to more optimal levels. This can also be interpreted as the node being stuck in deep-sleep, not being able to perform the work consuming 250 mA. In a real scenario this could mean a node ceasing communication or observational routines.

5.5 A successful winter in Karasjok

This experiment is very similar to the previous experiment, but with the energy consumption of 250 mA (375 mW @ 1.5 V) swapped to 50 mA (75 mW @ 1.5 V) when working. The goal here is to see if reducing the energy consumption of the node when it is working will make the node survive the whole winter period. The reduction in energy consumption will lead to a total energy consumption of: 50 mA for 10 minutes:

$$\frac{250mA}{60mins} \times 10 = 8.33mA$$

1 mA for 50 minutes:

$$\frac{1mA}{60mins} \times 50 = 0.833mA$$

Total energy consumption:

$$8.33mA + 0.83mA = 9.16mA$$

Giving an estimation with optimal conditions:

$$\frac{42000mAh}{9.16mA} = 4585hours \approx 191days$$

At 50 mA the effect of temperature is also a lot less significant, only suffering a loss of about 25% at temperatures close to -40°C.

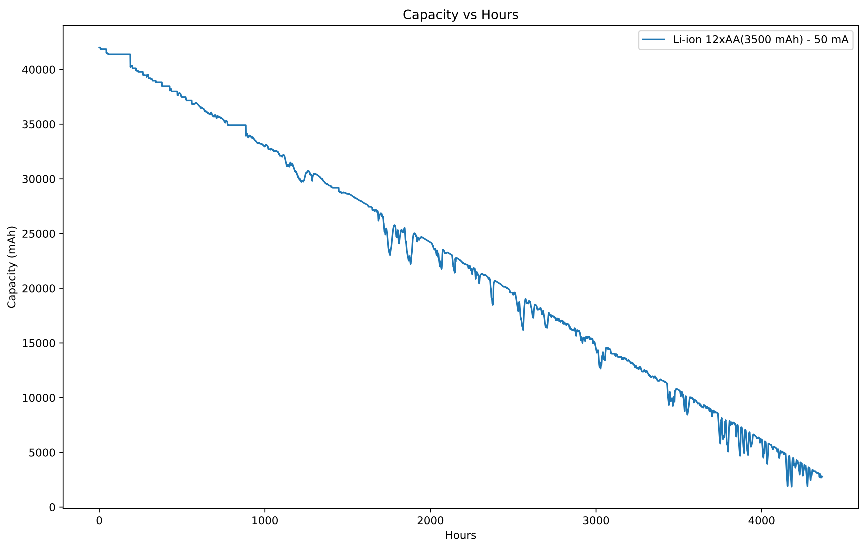


Figure 5.7: Node 50mA - 182 days in Karasjok

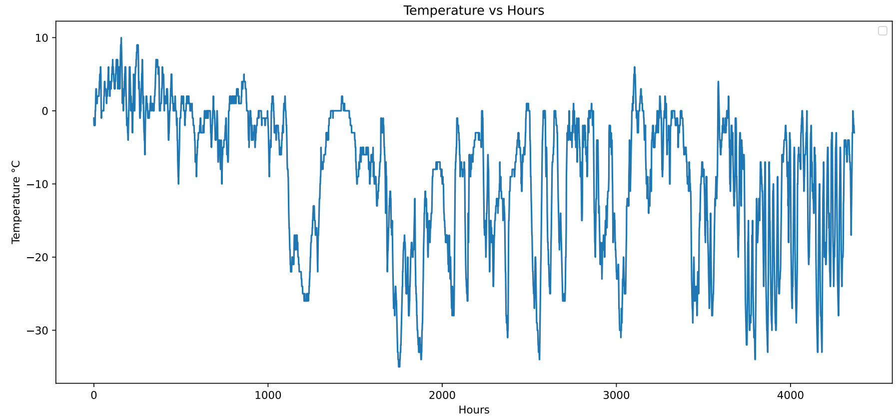


Figure 5.8: Temperature for the 182 days

The simulation ended at hour 4367 ≈ 182 days. The final remaining capacity was 2782 mAh at a temperature of -3.3°C. The final capacity of this experiment ended up at 31 945 mAh. Making the consumption and loss of capacity total:

$$42000mAh - 2782mAh = 39218mAh$$

The consumption expected for this simulation:

$$4367hours \times 9.16mA = 40001mAh$$

Making the inaccuracy:

$$40001mAh - 39218mAh = 783mAh$$

This would mean rate of inaccuracy per hour of :

$$\frac{783mAh}{4367hours} \approx 0.18mA$$

Even with the small imperfections and inaccuracies the experiments show interesting results to what one can expect from batteries at realistic weather conditions with low temperatures. Comparing the experiments to the deployed systems, the real OUs would be somewhere in between these experiments, with the energy consumption of 70-120 mA when not sleeping. This would potentially lead to a loss of total capacity of at least 25%

6

Discussion

This section discusses and evaluates the battery plugin and its prototype. Looking into weaknesses and possible future improvements.

6.1 Evaluation of the prototype

From the experience designing and implementing the prototype of the battery plugin, and also from testing and experimenting with it, it seems clear that this is both possible and useful for a simulator to include. The challenges are apparent, as systems and the conditions they situate in become more complex, so do the simulation and variables to recreate these scenarios. The aim should be to provide a typical and general recreation. Creating a simulator that is accurate on a fine-grained level is not very realistic. This prototype does provide a decent insight into how temperature can affect a system, even if it is not completely accurate. Being able to test systems of nodes with different temperatures or temperatures from real weather data is valuable.

6.2 Design decisions

When it comes to the chosen design decisions, it is mostly a result of what was available of data and information regarding how batteries are affected by

temperature. The effect is widely acknowledged and known, but finding good data in the form of detailed numbers proved to be difficult. It is a challenging effect to measure. Despite no guarantee of accuracy, the results from using the battery plugin will give a rough outlook on what it could look like.
Improving the accuracy and validity of the temperature effect is possible. It would need better and more concrete data to be simulated more accurately. Collecting data for this would require a lot of equipment and work. It could be done by having freezers at different temperature levels, discharging fresh batteries at a constant current and comparing it to the battery's stated capacity. This would have to be done more than once to compute average results or ensure that results are similar enough for the data to be valid.
Another way to calculate the new capacity of the battery could be to have set points mapped in a dictionary, where for example -40°C would be mapped to 50% capacity and -30°C to 60%. In between values could be calculated by using the rate of increase.

$$\frac{\Delta Capacity}{\Delta Temperature} = \frac{60\% - 50\%}{(-30°C) - (-40°C)} = 1$$

So a value in between these set points could be computed by the rate of increase times the difference in temperature. For example -35 °C would be 55% with this method.
The problem is the lack of data and the ability for this effect to be described accurately with functions. As it is the result of a chemical reaction, it does not necessarily follow predictable patterns that are easy to express as a function and therefore to simulate accurately.

6.3 Future Work

There are still many aspects missing from having the impact of the environmental condition fully simulated and there are more variables to the temperature effect on the battery.
The way voltage works and behaves has not been properly simulated. In reality when a battery is discharging, the voltage will slowly decrease over time. Voltage also decreases with low temperatures.[fig: 6.1]

The internal resistance of the battery will also increase while it is discharging. This behavior is different depending on the battery chemistry and is challenging to calculate or estimate.
What is possible with this battery plugin is to control and change the voltage manually by updating it during the simulation.

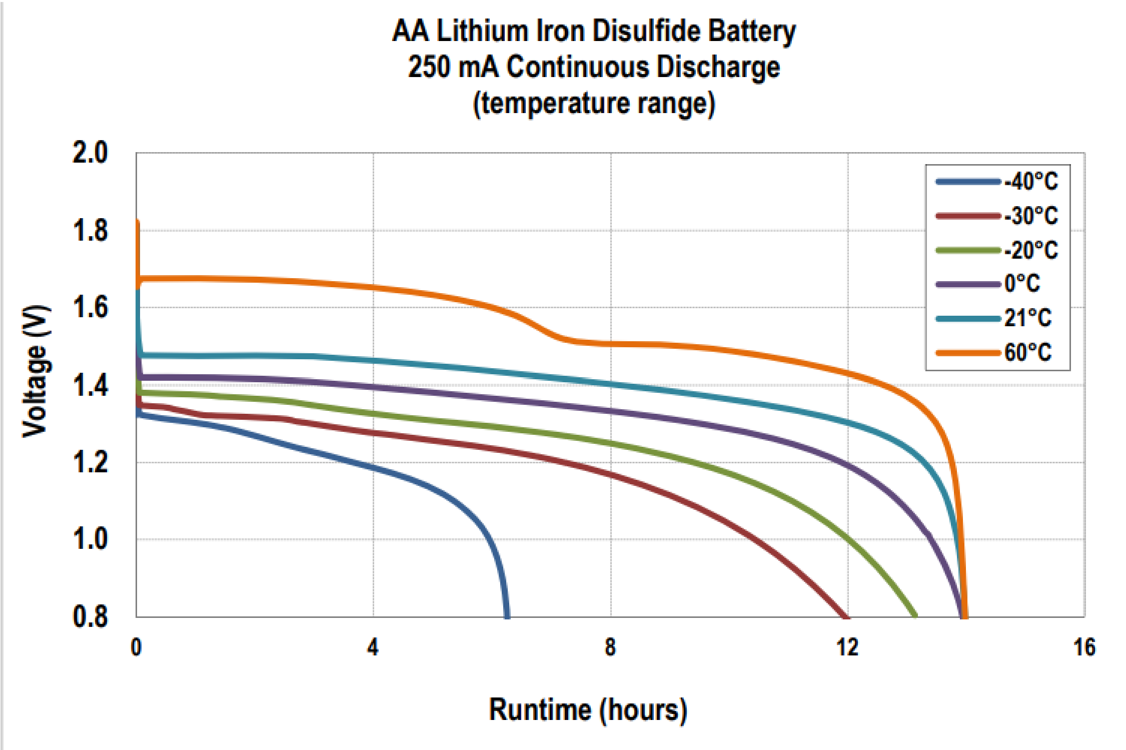


Figure 6.1: Voltage dropping over time when battery is discharging vs temperature [5]

Another interesting feature that could be added is the simulation of recharging batteries. Recharging batteries is also affected by temperature, where the time it takes to charge will increase when the temperature gets lower. For each recharge cycle the battery will lose capacity and its lifetime will be reduced.

Weather data is plentiful and accessible, so there are many things to potentially use for simulation. Humidity can lead to leakage or corrosion on batteries and do damage to other hardware on a node. Precipitation like snow or rain could be harmful to nodes, by either flooding the node or completely covering and isolating it. Forecast weather can be used to simulate a system in or close to a deployment location before deployment to get even closer to predicting the outcome of a deployment plan.

The Battery plugin is also lacking the full range of constant current options, posing difficulties when trying to simulate nodes with energy consumption with intermediate values. For example the real OU from [19], stating a power draw of 70-120 mA.

6.4 Key discoveries

This thesis describes the great harm that environmental conditions, especially when it comes to low ambient temperatures, can cause to cyber-physical systems and in particular their batteries if no precaution has been taken. Sub-zero temperatures and lower is a reality of the Arctic Tundra. From researching this subject and performing simulations, the takeaway is that at least one or more of these conditions need to be considered when planning for a deployment of cyber-physical systems:

1. Ensure batteries are isolated well to keep temperature as close to optimal as possible, also keep batteries encased well to protect against flooding and humidity.

2. Have enough overhead capacity to plan ahead and expect the potential reduction that the cold climate will have. Expecting batteries to perform according to their specification sheet and under-estimating the need capacity can be fatal for the system.

3. Making sure the system is as energy-efficient as possible will mitigate a lot of the worst effects that temperature have. If energy consumption is kept below 250 mA or even 50 mA, the loss of capacity diminishes greatly. At 25 mA Li-ion is able to provide the full capacity at -40 °C [5]

7 Conclusion

The aim of this thesis was to extend the functionality of the simulator ESDS, by identifying the missing features to be able to simulate a cyber-physical system in an environment like the Arctic Tundra. This feature built on the idea of simulating the impact of weather on such a system. To attempt to simulate how cold weather with extremely low temperatures would affect this system; a battery plugin was made. The battery plugin gives the ability to experiment with different variables related to energy, power, voltage and capacity to simulate how a real battery would act. This battery plugin also features the ability to simulate the temperature effect of sub-zero temperatures, bringing the weather conditions to the simulator.

In the context of simulating cyber-physical systems in the arctic tundra with all its different challenges, there's a definite value in simulating the weather conditions with focus on temperature. This thesis has shown the value and need for simulating battery conditions and its exposure to the cold temperatures. Energy consumption and battery preservation is proven to be a very important consideration before deploying a system in the real world.

8

Appendix A

Included in the appendix are all the points describing the relation between capacity and temp at different current discharge levels and their respective approximated functions. These are all the functions available and used to determine the loss of capacity from temperature.

	x-axis	y-axis
1	-40	0
2	-35	0.05
3	-30	0.05
4	-25	0.1
5	-20	0.1
6	-15	0.15
7	-10	0.2
8	-5	0.25
9	0	0.35
10	10	0.7
11	20	0.9
12	25	1

Figure 8.1: Points derived from Alkaline 250 mA curve

$$f(x) \approx 0.00026293x^2 + 0.0194854x + 0.387411$$

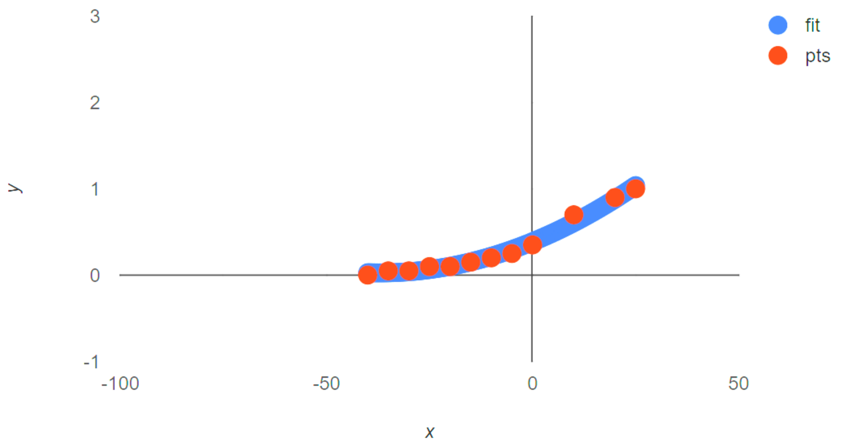


Figure 8.2: Function approximated from Alkaline points

$$f(x) \approx 0.000625541x^2 + 0.0515216x + 1.06485$$

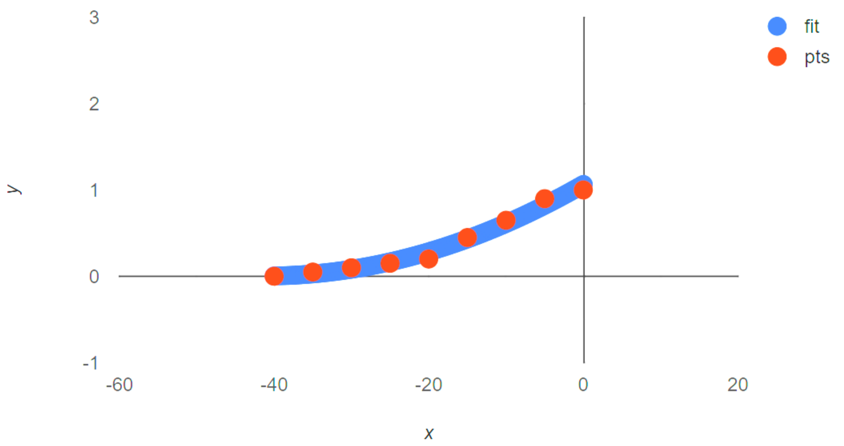


Figure 8.3: Points derived from NiMH 250 mA curve

$$f(x) \approx 0.000625541x^2 + 0.0515216x + 1.06485$$

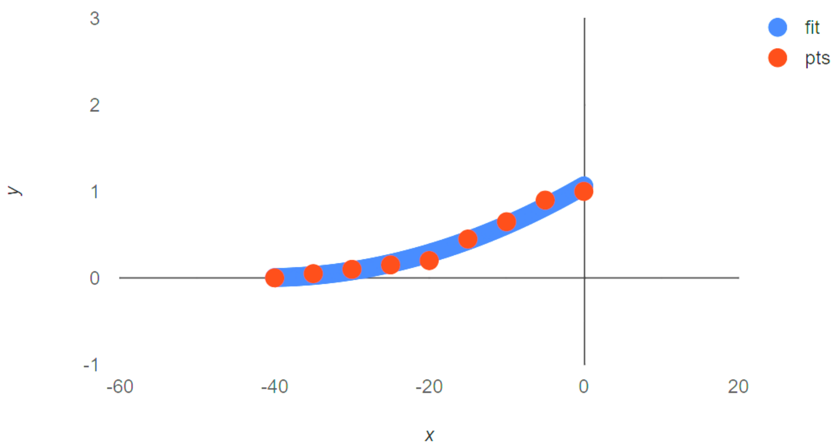


Figure 8.4: Function approximated from NiMH points

	x-axis	y-axis
1	-40	0.45
2	-35	0.65
3	-30	0.8
4	-25	0.9
5	-20	0.95
6	-15	0.97
7	-10	1
8	-5	1
9	0	1
10	...	...

Target and Calculation Method

Affine/Linear using Curve Fitting

Parabola/Hyperbola using Curve Fitting

Figure 8.5: Points derived from Li-ion 250 mA curve

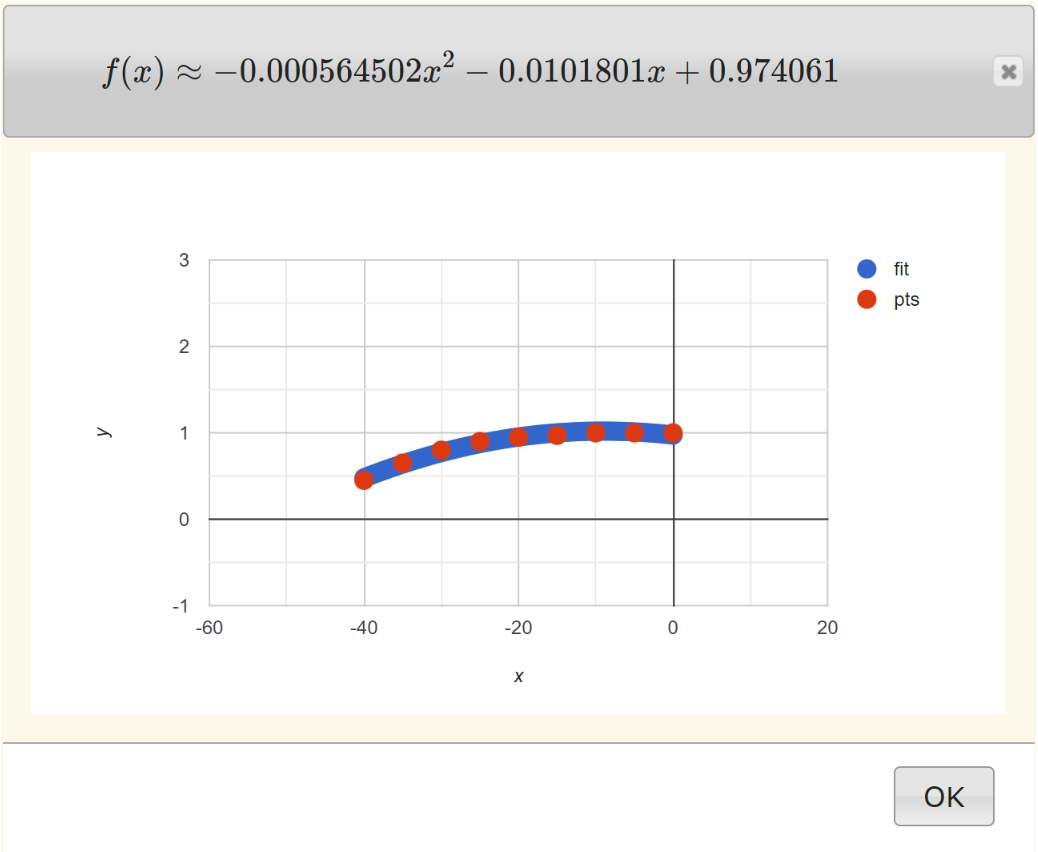
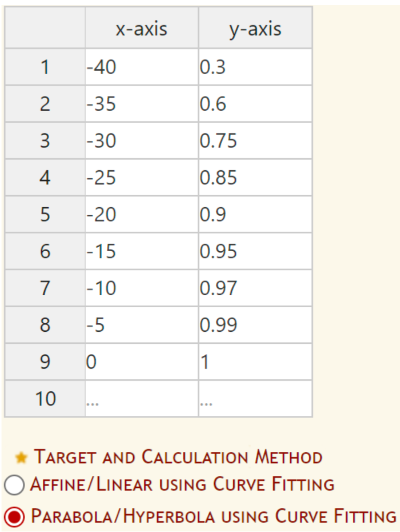


Figure 8.6: Function approximated from Li-ion 250 mA points



	x-axis	y-axis
1	-40	0.3
2	-35	0.6
3	-30	0.75
4	-25	0.85
5	-20	0.9
6	-15	0.95
7	-10	0.97
8	-5	0.99
9	0	1
10	...	...

Target and Calculation Method
Affine/Linear using Curve Fitting
Parabola/Hyperbola using Curve Fitting

Figure 8.7: Points derived from Li-ion 500 mA curve

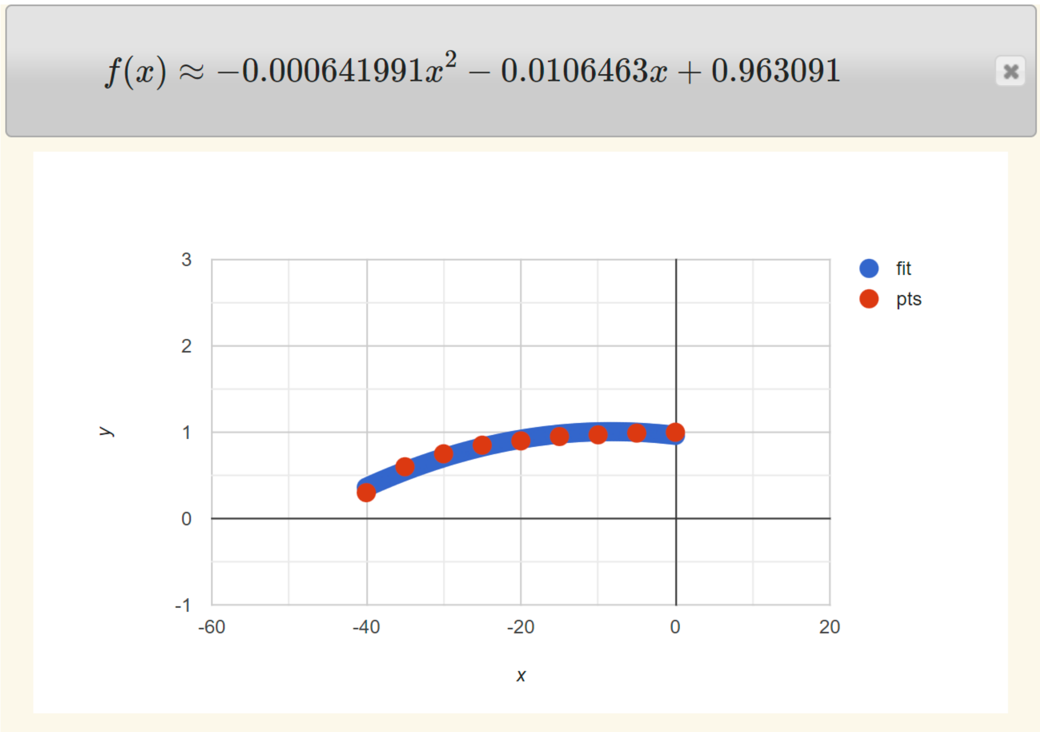


Figure 8.8: Function approximated from Li-ion 500 mA points

	x-axis	y-axis
1	-40	0
2	-35	750
3	-30	1500
4	-25	2100
5	-20	2500
6	-15	2700
7	-10	2900
8	-5	3000
9	0	3200
10	...	...

TARGET AND CALCULATION METHOD

AFFINE/LINEAR USING CURVE FITTING

PARABOLA/HYPERBOLA USING CURVE FITTING

Figure 8.9: Points derived from Li-ion 1 A curve

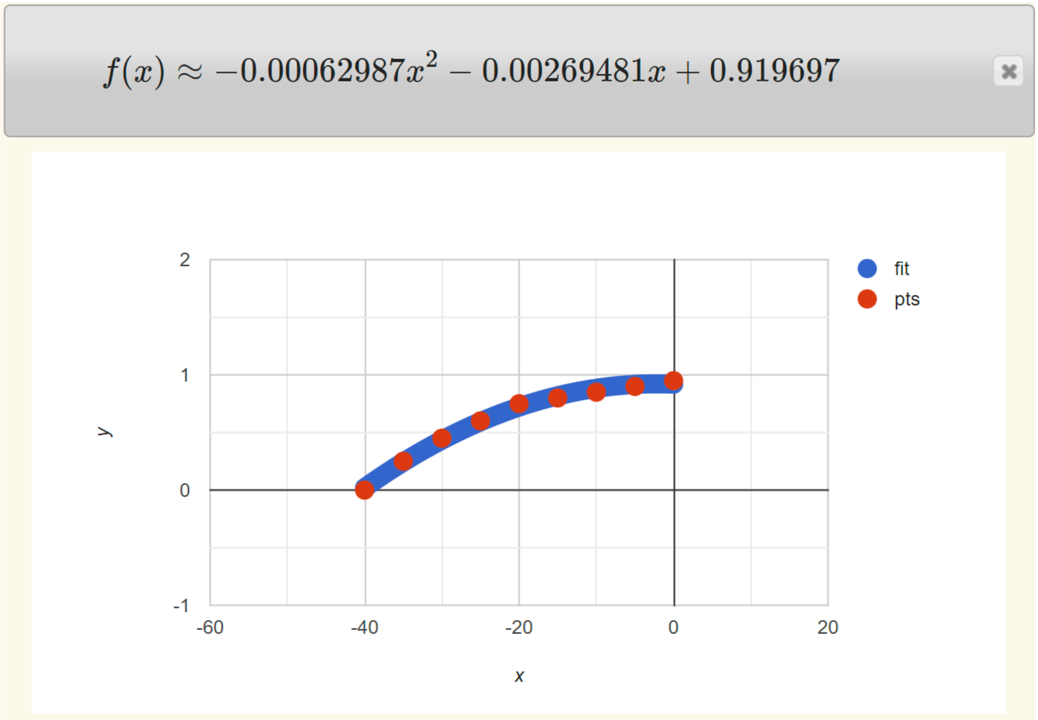


Figure 8.10: Function approximated from Li-ion 1 A points

	x-axis	y-axis
1	-40	0.9
2	-30	0.95
3	-20	1
4	-10	1
5	-5	1
6	0	1
7	...	...

Figure 8.11: Points derived from Li-ion 50 mA curve

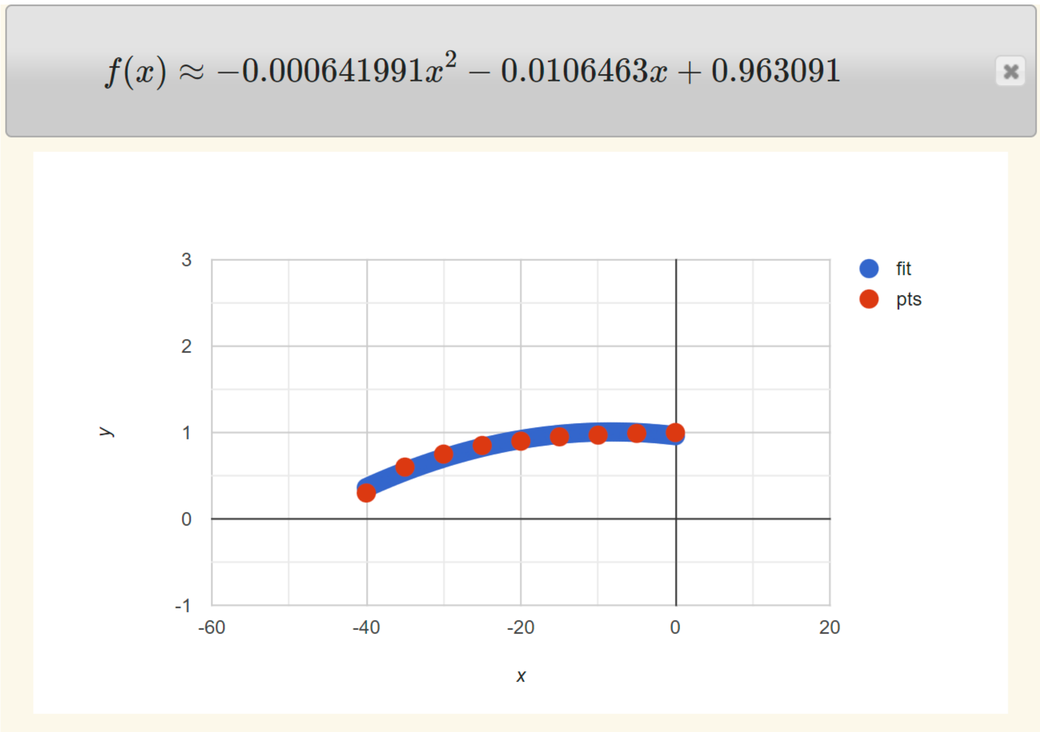


Figure 8.12: Function approximated from Li-ion 50 mA points

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