



Energy Modeling of System Settings: A Crowdsourced Approach

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Battery consumption of mobile devices

- Mobile device's limited battery capacity is a common problem
- How to **save energy** instead of restricting usage?





Energy efficient configuration?





Energy efficient configuration?

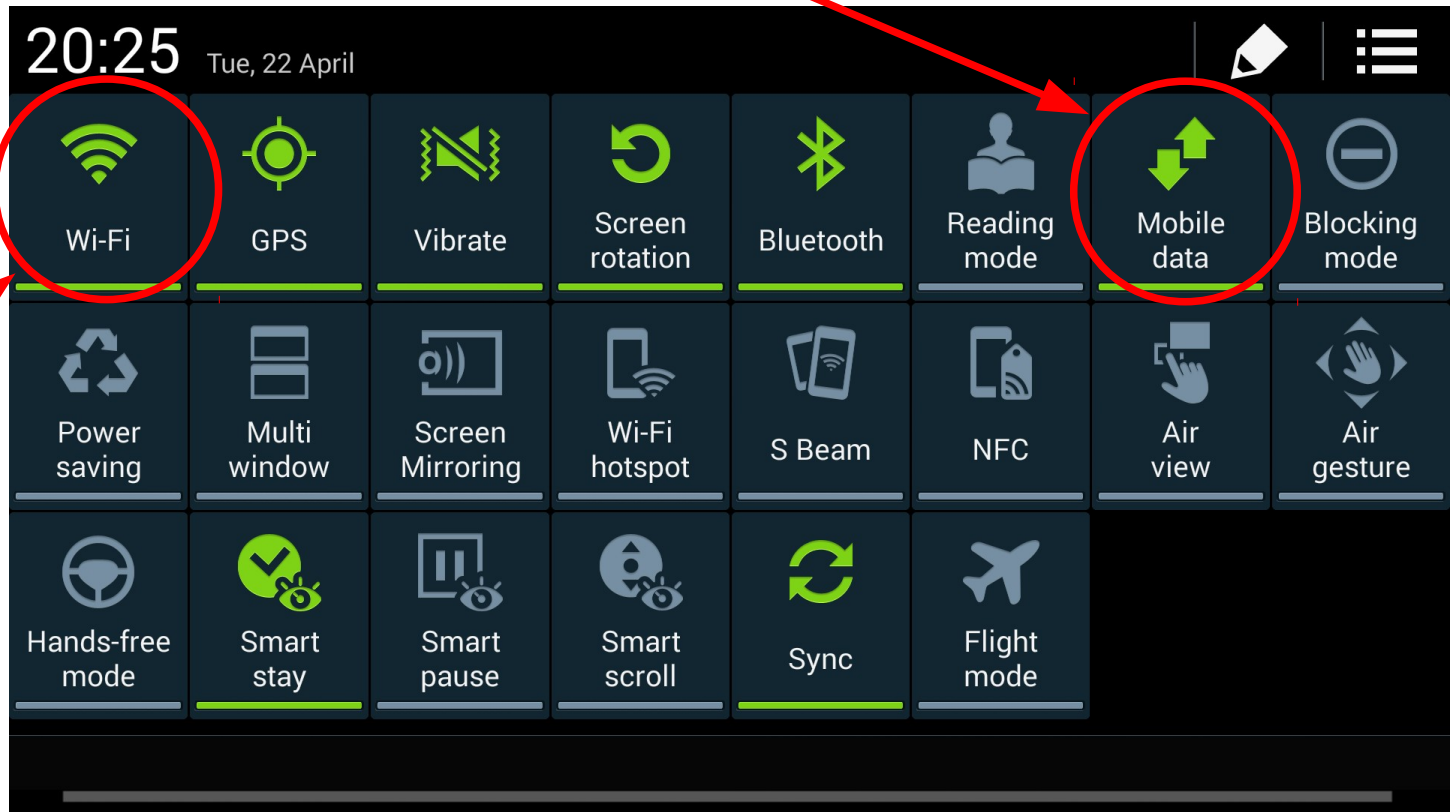


Network type



Energy efficient configuration?

Mobile settings



Network type

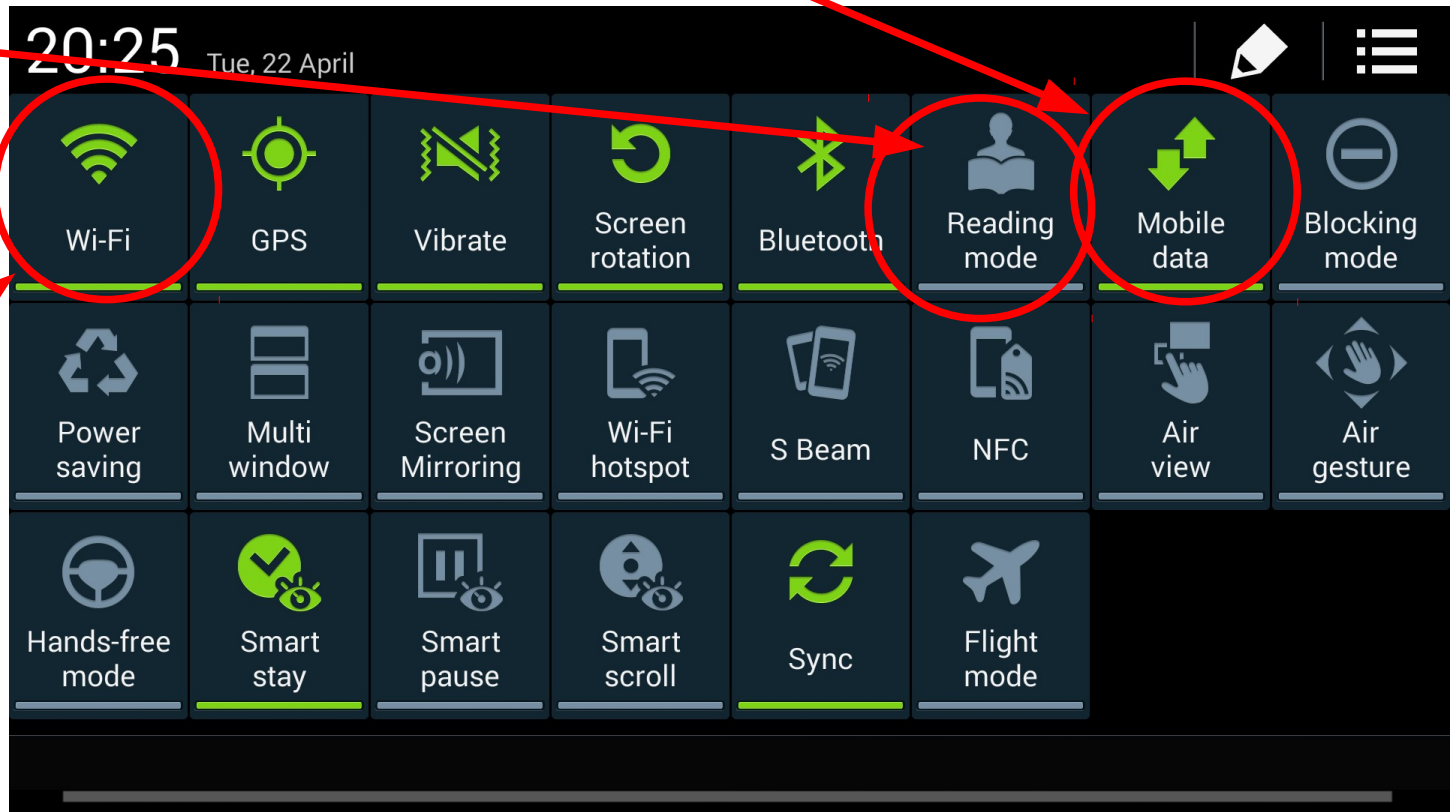


Energy efficient configuration?

Mobile settings

Screen
Brightness

Network type





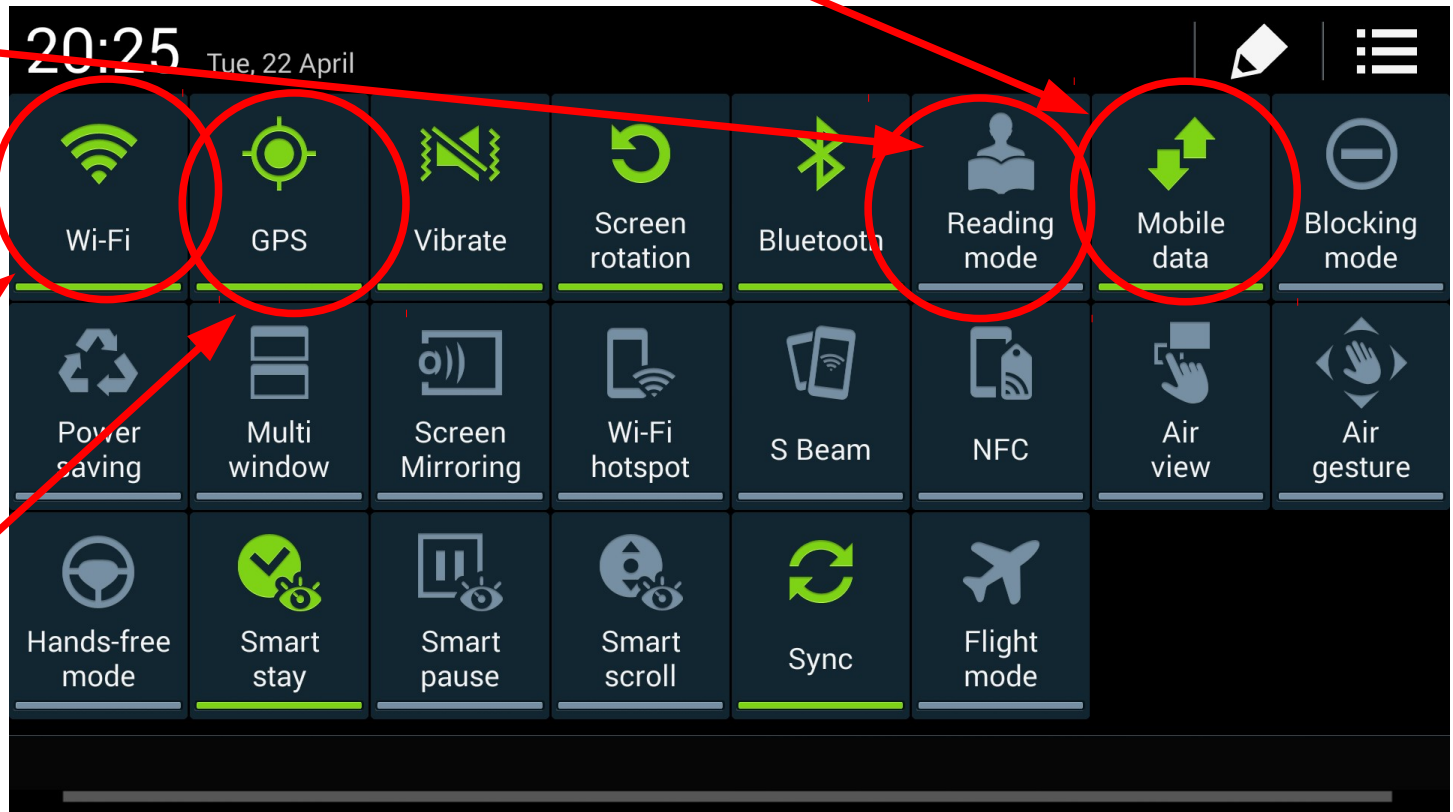
Energy efficient configuration?

Mobile settings

Screen
Brightness

Network type

Moving or not?





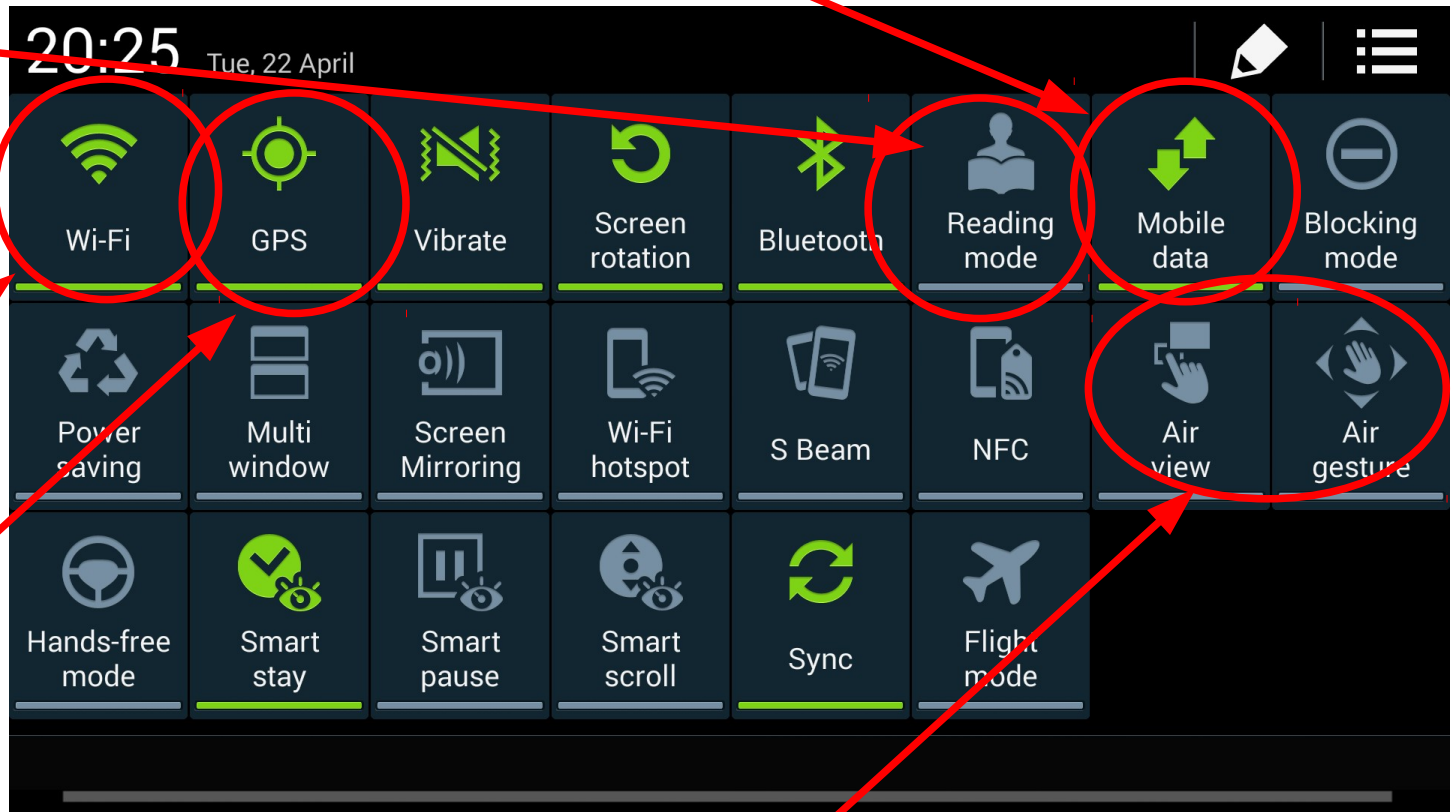
Energy efficient configuration?

Mobile settings

Screen
Brightness

Network type

Moving or not?



Sensing something?



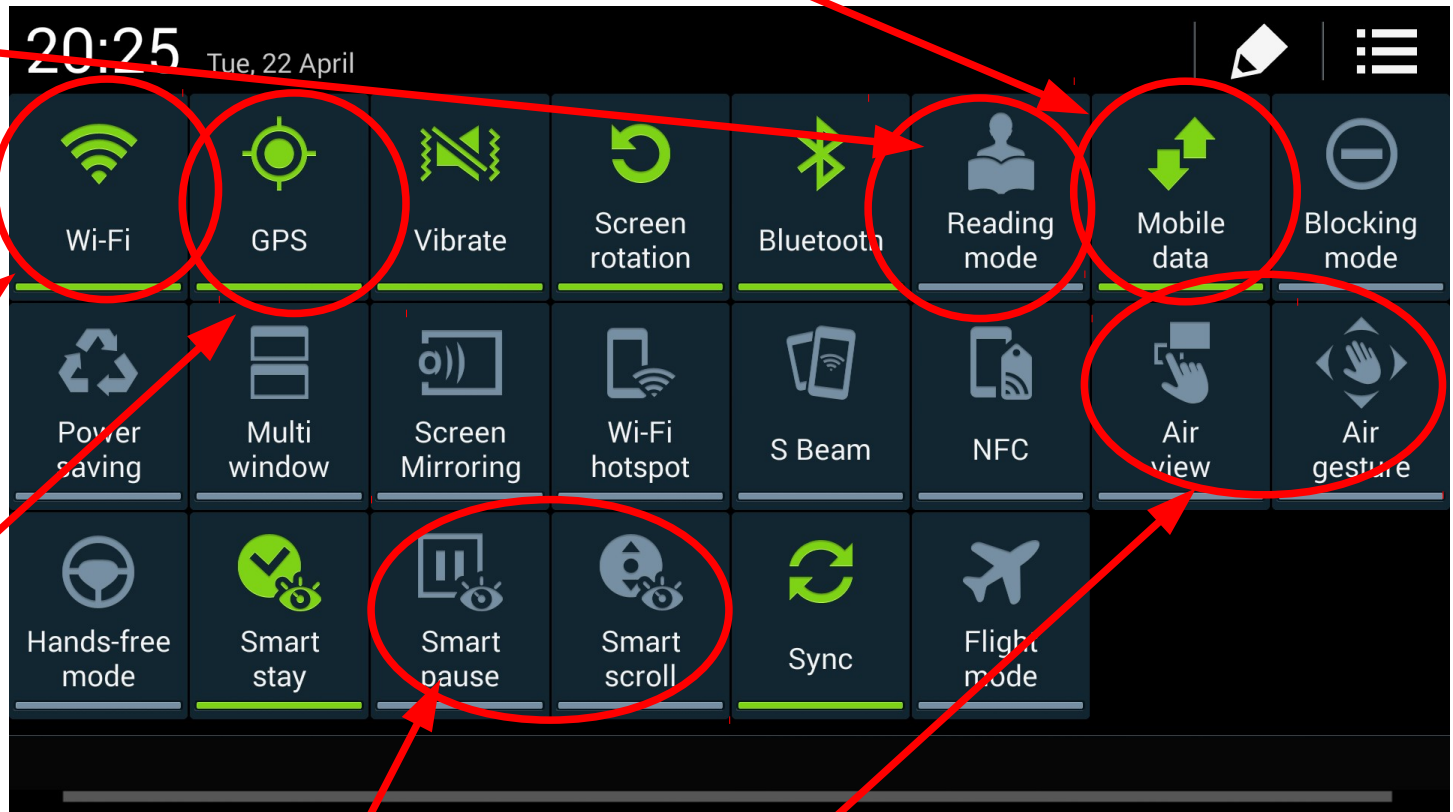
Energy efficient configuration?

Mobile settings

Screen
Brightness

Network type

Moving or not?



Advanced functions

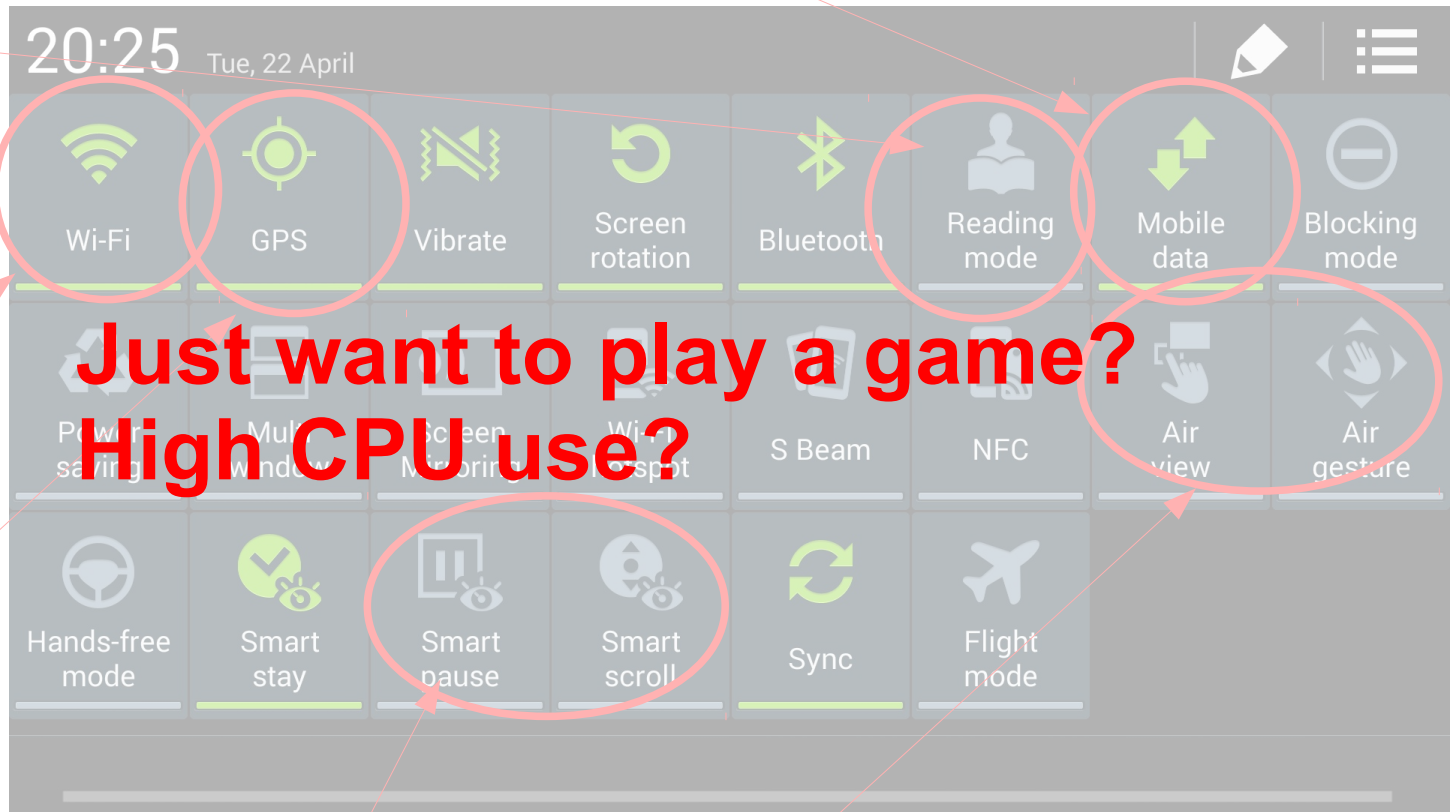
Sensing something?



Energy efficient configuration?

Mobile settings

Screen
Brightness



Network type

Moving or not?

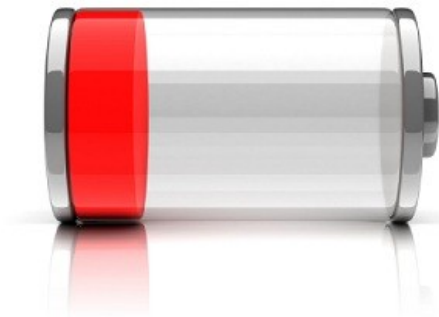
Advanced functions

Sensing something?



Energy consumption of system settings

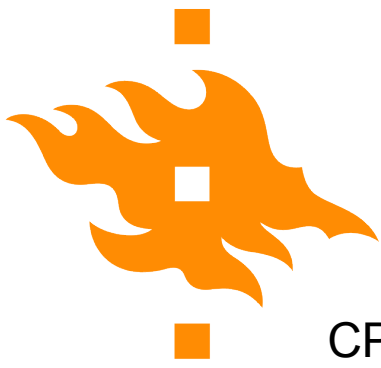
- **Complex interdependencies** between the different features of the mobile devices
- Previous research has focused on single attributes, instead of the **system setting combinations**
- **Energy models** for understanding energy impact and transitions of system settings





Contributions

- Novel approach to construct **energy models** to combine energy impact of system settings
- **Crowdsourced approach** captures a system state cost-effectively from real life, and reveals new and more complex insights to battery consumption
- We make available a large-scale dataset of 11.2 million data points from 150,000 Android devices
 - <http://carat.cs.helsinki.fi/research/>



Features of mobile devices

CPU

Mobile settings

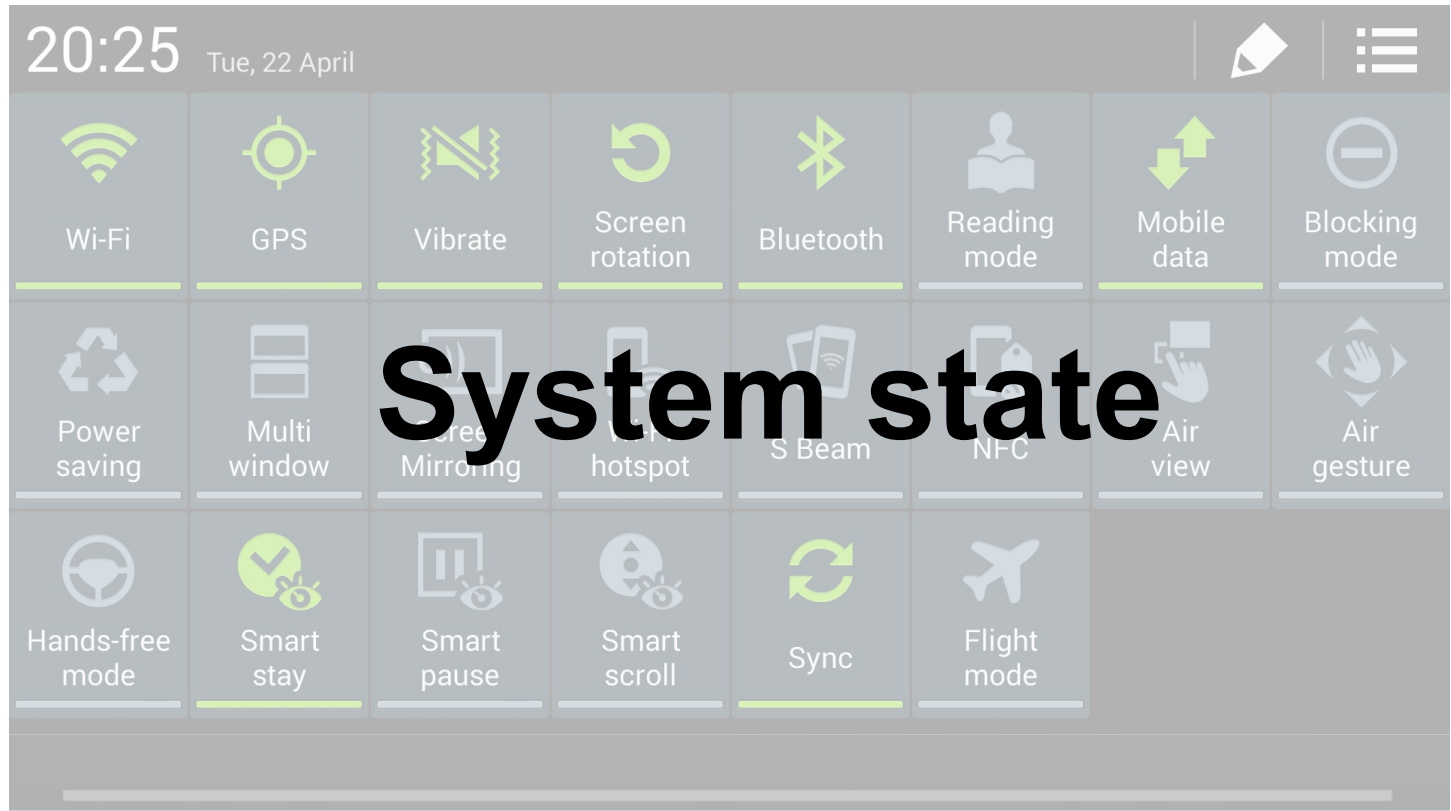
Applications

Screen
brightness

Memory

Network type

Location



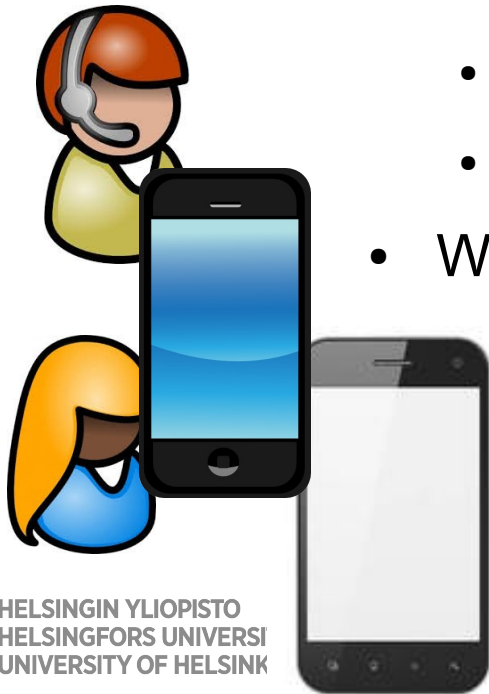
Sensors: camera,
microphone, infrared...

Energy saving modes



Features of mobile devices

- Understanding relationships between system state and **usage context**
- Complex dependencies between mobile devices' features are hard to model in laboratory
 - Tens of thousands of applications
 - System settings and all their possible values
- We need data from **real-life situations**





Crowdsourced approach

- Learn from many mobile devices
 - 150,000 individual users in this work
- **Cost-effective way** to collect data: only install a mobile application
- Build **energy models** from real-life usage of mobile devices





Carat, large-scale mobile dataset

- Measurements from 750,000 mobile devices
 - Battery level, applications, system settings...
- In this work, we used a subset of 11.2 million samples from 150,000 **active Android devices**
 - Constantly sending data
- This anonymized Context Factor Dataset will be available for research use in <http://carat.cs.helsinki.fi/research>





Carat, large-scale mobile dataset

- Data values are from Android API
- Samples made every time when there is change in the battery level
- Samples are sent to the cloud when user opens the application – no background data





Attributes

Battery information
*battery level, voltage,
health, temperature*

Screen brightness
*automatic or manual,
numeric value, on/off*

Subsystem variables
*CPU load, memory,
distance traveled*

Network settings
*network type, signal strength,
mobile technology*



Energy rate



- **Energy rate** as a unit of energy consumption
- Battery level change divided by time change
 - Energy rate = $\Delta \text{battery} / \Delta \text{time}$
- Percents per second
- Expected battery life with a given attribute combination, in hours (without idle)
- Validated in Oliner et al: *Carat: Collaborative energy diagnosis for mobile devices*, SenSys'13



Methodology



- Battery life gain
 - Difference between two energy rates
 - Presents **absolute differences** and helps to compare combinations
- Mutual information (MI) and conditional mutual information (CMI)
 - Attributes' influence on energy rates
 - Presents **correlations** of attributes and energy rates and helps to rank them



Energy of individual attributes

- We validated our approach by looking at individual attributes using mutual information
- Crowdsourced data give similar results than previous studies of battery monitoring





Energy of individual attributes

- Crowdsourced data can capture phenomena that CPU use has the clearest impact to the energy rate

Context factor	MI
CPU use	1.330
Distance traveled	1.069
Battery temperature	0.143
Battery voltage	0.099
Screen brightness	0.030
Mobile network type	0.019
Network type	0.018
Wi-Fi signal strength	0.014
Wi-Fi link speed	0.014
Mobile data status	0.013
Mobile data activity	0.005
Battery health	0.004
Roaming	0.0002



Energy of individual attributes

- Some attributes seems to have lower impact than in previous research, e.g., screen brightness

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Energy of combinations

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Combinations of factors		CMI
Battery voltage	CPU use	4.29
CPU use	Screen brightness	2.17
Battery temperature	CPU use	2.07
CPU use	Distance traveled	1.81
CPU use	Wi-Fi signal strength	1.69
Battery voltage	Distance traveled	1.53
Battery temperature	Distance traveled	1.28
Distance traveled	Screen brightness	1.26
CPU use	Wi-Fi link speed	1.12
Battery voltage	Screen brightness	1.08
Wi-Fi link speed	Wi-Fi signal strength	0.99
Mobile data status	Network type	0.95
Network type	Wi-Fi signal strength	0.85
CPU use	Mobile network type	0.80
Battery temperature	Screen brightness	0.79
Distance traveled	Wi-Fi signal strength	0.75
Network type	Wi-Fi link speed	0.64
Mobile data status	Wi-Fi signal strength	0.60
Battery temperature	Battery voltage	0.56
Distance traveled	Wi-Fi link speed	0.54
Battery voltage	Wi-Fi signal strength	0.53

When looking screen brightness combined impact with other attributes...



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Attribute combinations give more accurate view to energy consumption



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Attribute combinations give more accurate view to energy consumption



Selected findings

- Wi-Fi signal strength dropping one bar can loss battery over 13%
- High temperature can cause even 50% battery loss, and high temperature is not always related to high CPU load
- Automatic screen brightness is, in the most cases, better than manual setting
- In addition to CPU, battery temperature and distance traveled together offer a good prediction to battery lifetime



Evaluation of results

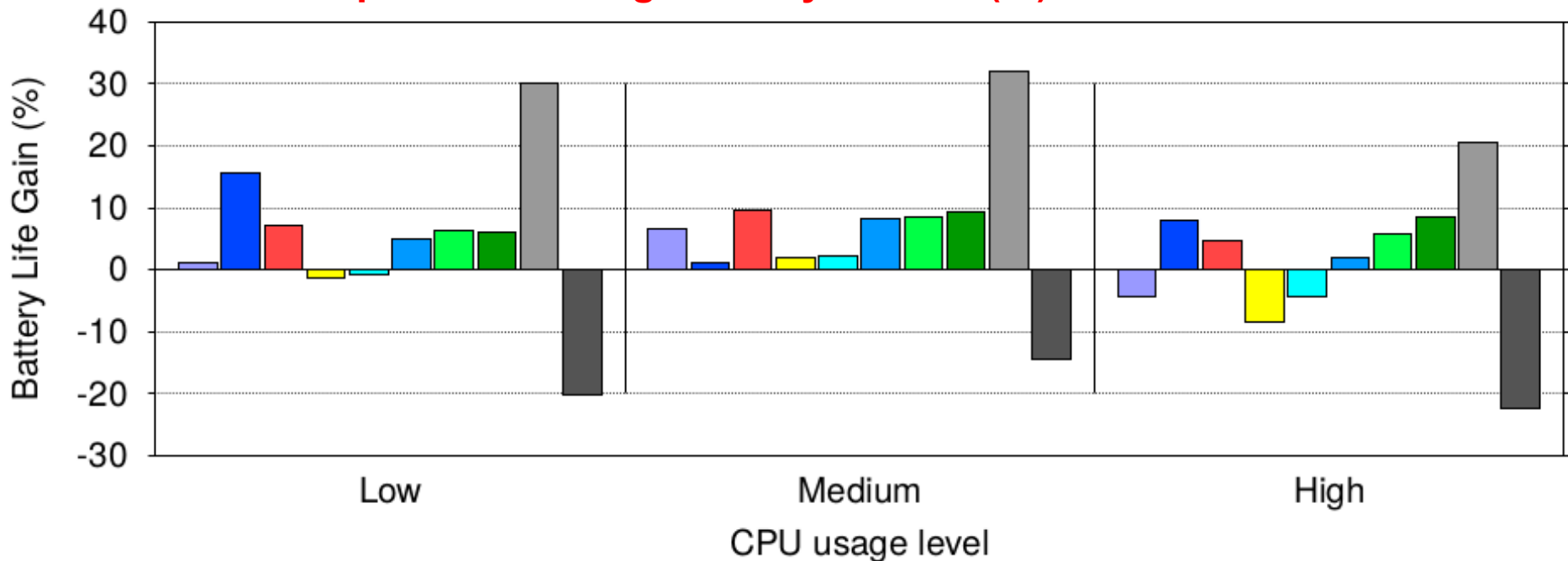
- We choose some combinations that have the highest impact to energy consumption
 - CPU use + movement
 - CPU use + screen brightness
 - CPU use + Wi-Fi signal strength
 - CPU use + battery temperature
- We tested these cases both in crowdsourced data and laboratory



Results from data

Battery life gain of different combinations compared to average battery lifetime (%)

- Stationary
- Movement
- Screen Auto
- Screen Manual
- Signal Bad
- Signal Average
- Signal Good
- Signal Excellent
- Under 30C
- Over 30C



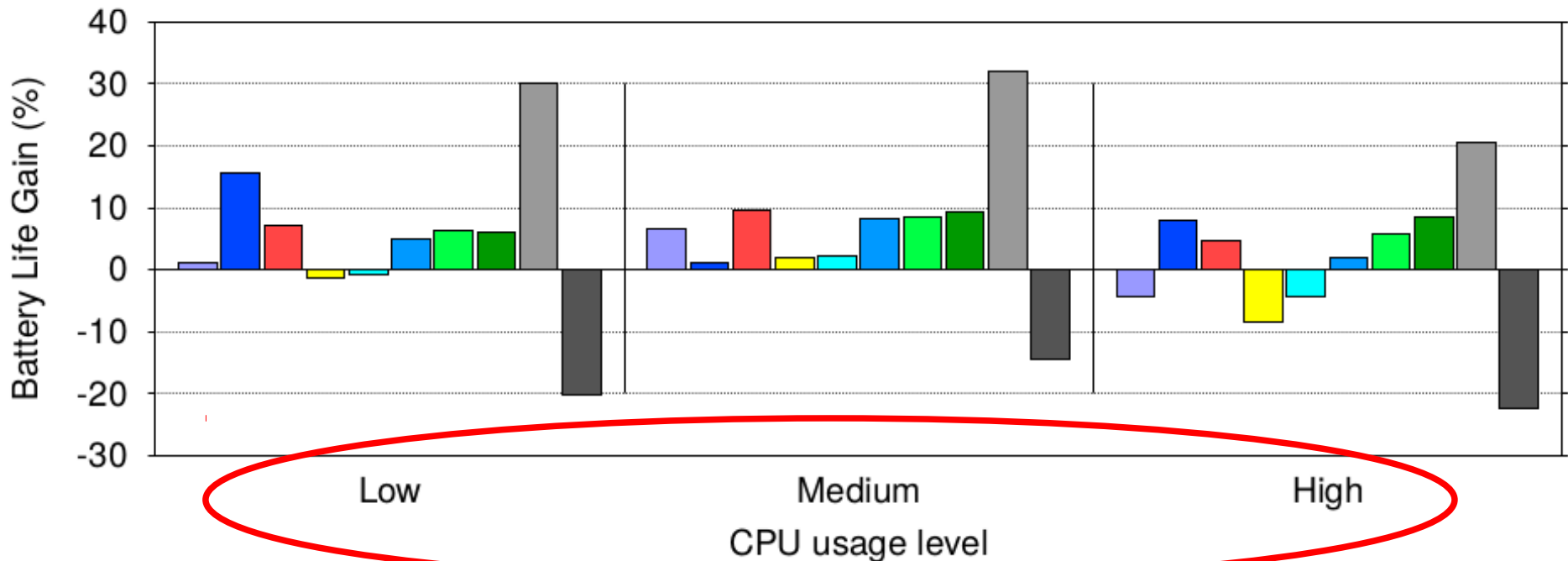
Battery Life Gain = Battery lifetime difference compared to average



Results from data

CPU levels are separated

- Stationary
- Movement
- Screen Auto
- Screen Manual
- Signal Bad
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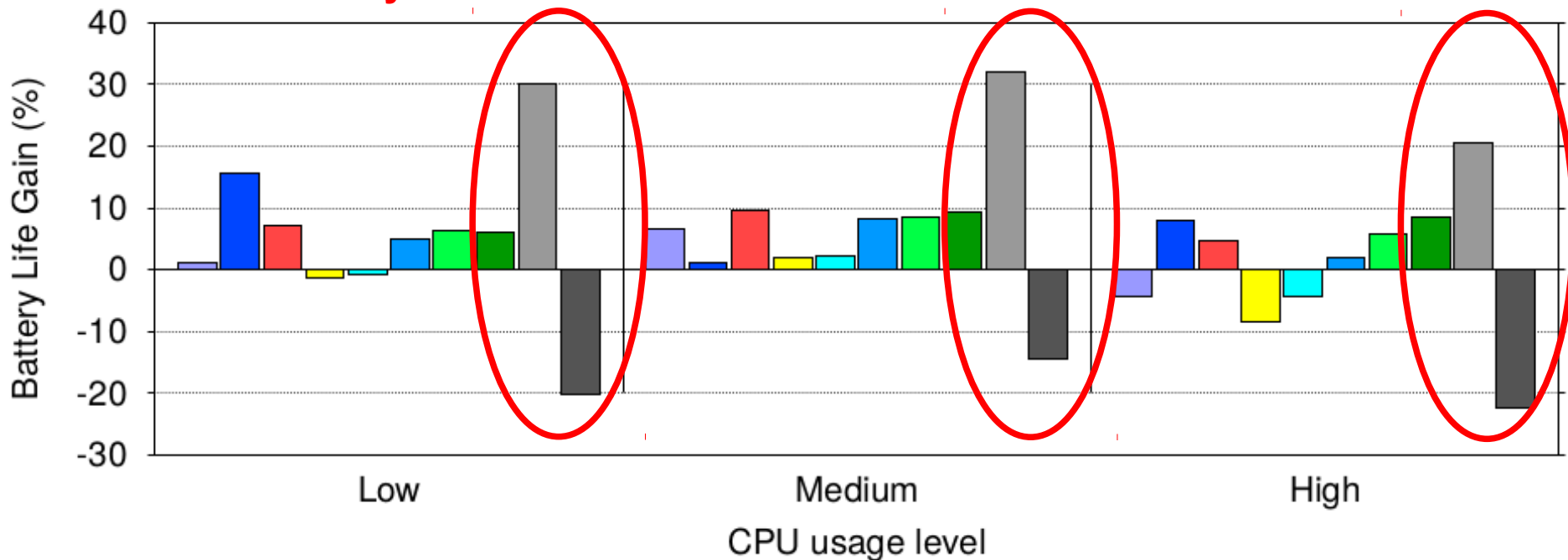
Battery Life Gain = Battery lifetime difference compared to average



Results from data

High battery temperature decreases battery life

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- Movement
- Screen Auto
- Screen Manual
- Signal Bad
- Signal Average
- Signal Good
- Signal Excellent
- Under 30C
- Over 30C



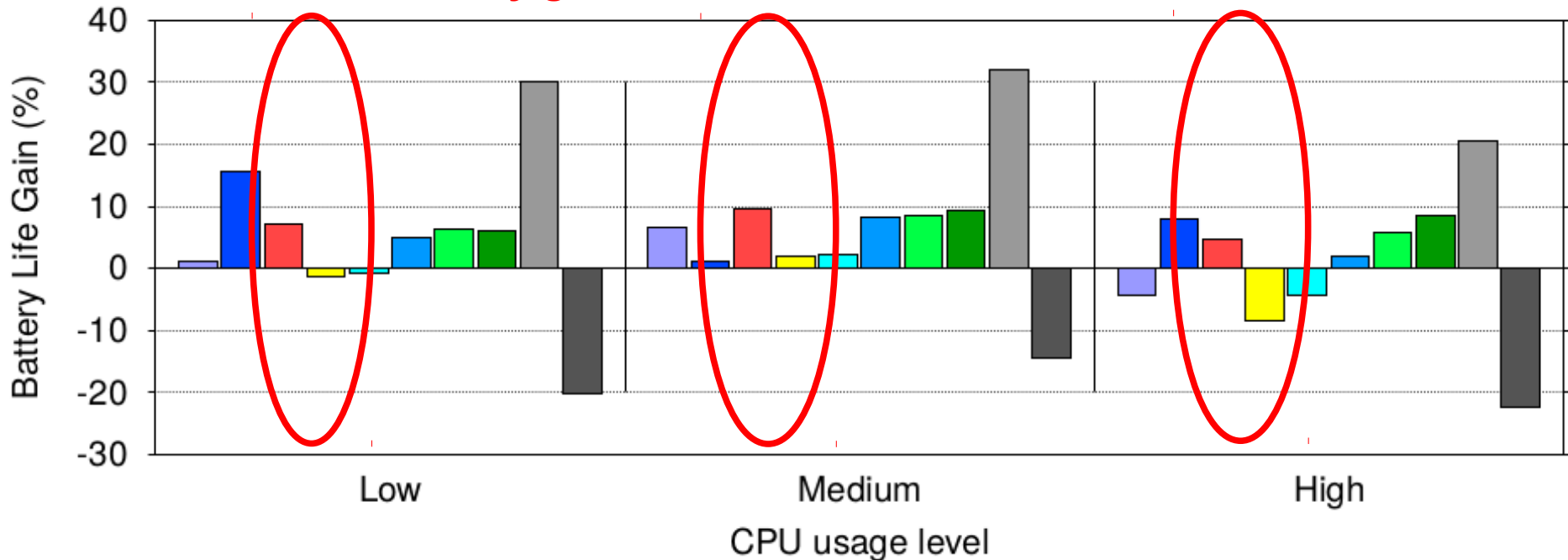
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Results from data

- Stationary
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- Screen Auto
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- Under 30C
- Over 30C

Automatic screen brightness has better battery gain than manual



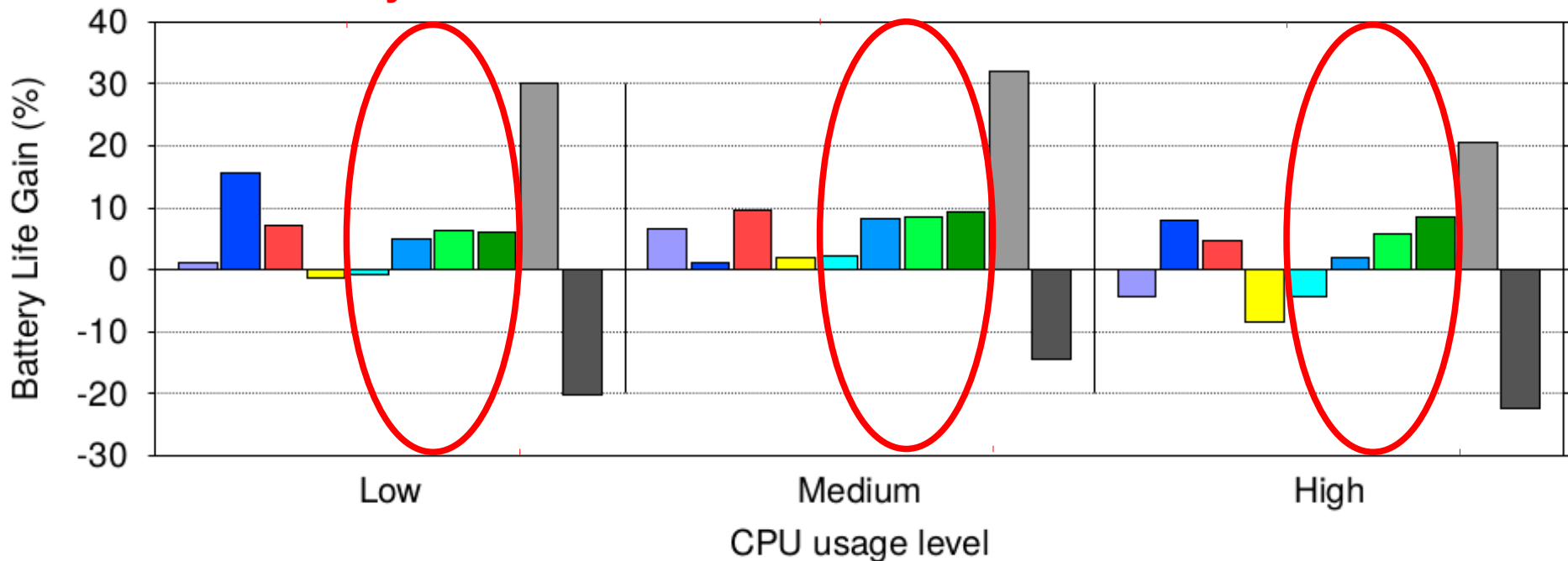
Battery Life Gain = Battery lifetime difference compared to average



Results from data

Better Wi-Fi signal strength improves battery life

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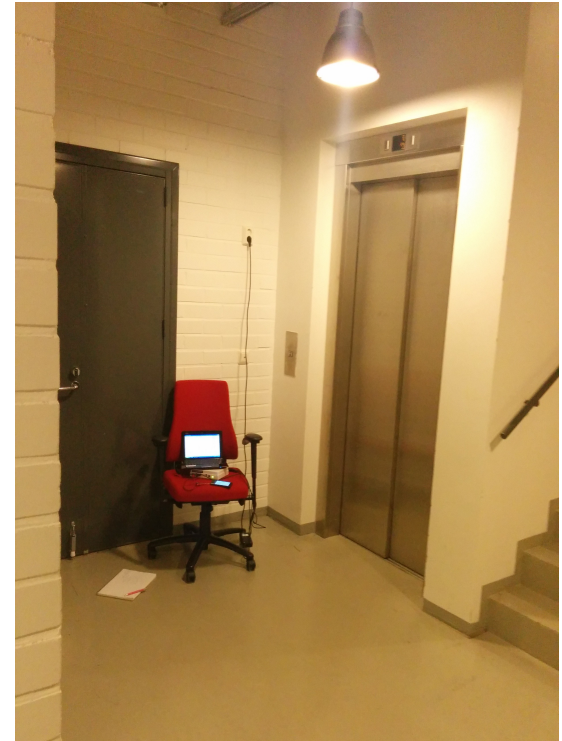


Battery Life Gain = Battery lifetime difference compared to average



Power meter validation

- We used Monsoon power monitor to evaluate our data-driven results
- *Mobile Energy Measurement Platform (MEMe)*





Power meter validation

Average battery life in hours, with the indicated configuration active

CPU use	All	Low	Medium	High
<i>All Wi-Fi</i>	2.60 h	4.77 h	2.23 h	1.90 h
<i>Bad Wi-Fi</i>	2.51 h	4.52 h	2.20 h	1.93 h
<i>Average Wi-Fi</i>	2.60 h	4.99 h	2.27 h	1.91 h
<i>Good Wi-Fi</i>	2.53 h	4.82 h	2.21 h	1.87 h
<i>All screen br.</i>	2.69 h	5.40 h	3.27 h	1.92 h
<i>Manual screen br.</i>	2.60 h	4.99 h	2.27 h	1.91 h
<i>Auto screen br.</i>	2.78 h	5.89 h	2.50 h	1.92 h



Power meter validation

Differences between the combinations, e.g. screen brightness:

CPU use	All	Low	Medium	High
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Power meter validation

In low CPU use, difference is clear:

CPU use	All	Low	Medium	High
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Power meter validation

But in high CPU, power monitor loss information:

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Power meter validation

Generating recommendations based on the power meter does not make sense:

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Power monitor versus data

- In power monitor measurements
 - CPU dominates results
 - Provides **limited information** from other attributes of system state
- Data results are averages from **real-life situations**
 - They give more realistic estimates
 - Averages from real usage, instead of fixed attributes
 - They can be use as practical energy recommendations



Battery lifetime – an example

Battery Temperature	Distance Traveled	CPU Use Level	Screen Brightness	Estimated Battery Life (h)
Under 30°C	>0	Low	Automatic	8.83 – 9.12
Under 30°C	>0	Low	Manual	8.49 – 8.82
Under 30°C	>0	High	Automatic	8.09 – 8.24
Under 30°C	>0	Medium	Automatic	7.65 – 7.89
Under 30°C	>0	Medium	Manual	7.34 – 7.60
Under 30°C	>0	High	Manual	7.27 – 7.41
Under 30°C	None	Medium	Automatic	6.57 – 6.64
Under 30°C	None	Low	Automatic	6.28 – 6.35
Under 30°C	None	Medium	Manual	6.13 – 6.20
Under 30°C	None	Low	Manual	5.88 – 5.96
Under 30°C	None	High	Automatic	5.78 – 5.82
Over 30°C	>0	Low	Automatic	5.08 – 5.22
Under 30°C	None	High	Manual	5.00 – 5.04
Over 30°C	>0	Low	Manual	4.73 – 4.88
Over 30°C	>0	High	Automatic	4.62 – 4.69
Over 30°C	>0	Medium	Automatic	4.59 – 4.70
Over 30°C	>0	Medium	Manual	4.28 – 4.39
Over 30°C	None	Medium	Automatic	4.25 – 4.29
Over 30°C	>0	High	Manual	4.08 – 4.14

**Just want to play a game?
High CPU use?**



Battery lifetime

Keep high CPU level constant

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Over 30°C	>0	Medium	Manual	4.28 – 4.39
Over 30°C	None	Medium	Automatic	4.25 – 4.29
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Battery lifetime

Try to keep your phone relatively cold

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Over 30°C	>0	Medium	Automatic	4.59 – 4.70
Over 30°C	>0	Medium	Manual	4.28 – 4.39
Over 30°C	None	Medium	Automatic	4.25 – 4.29
Over 30°C	>0	High	Manual	4.08 – 4.14



Battery lifetime

→ 78% more
expected battery life

Battery Temperature	Distance Traveled	CPU Use Level	Screen Brightness	Estimated Battery Life (h)
Under 30°C	>0	Low	Automatic	8.83 – 9.12
Under 30°C	>0	Low	Manual	8.49 – 8.82
Under 30°C	>0	High	Automatic	8.09 – 8.24
Under 30°C	>0	Medium	Automatic	7.65 – 7.89
Under 30°C	>0	Medium	Manual	7.34 – 7.60
Under 30°C	>0	High	Manual	7.27 – 7.41
Under 30°C	None	Medium	Automatic	6.57 – 6.64
Under 30°C	None	Low	Automatic	6.28 – 6.35
Under 30°C	None	Medium	Manual	6.13 – 6.20
Under 30°C	None	Low	Manual	5.88 – 5.96
Under 30°C	None	High	Automatic	5.78 – 5.82
Over 30°C	>0	Low	Automatic	5.08 – 5.22
Under 30°C	None	High	Manual	5.00 – 5.04
Over 30°C	>0	Low	Manual	4.73 – 4.88
Over 30°C	>0	High	Automatic	4.62 – 4.69
Over 30°C	>0	Medium	Automatic	4.59 – 4.70
Over 30°C	>0	Medium	Manual	4.28 – 4.39
Over 30°C	None	Medium	Automatic	4.25 – 4.29
Over 30°C	>0	High	Manual	4.08 – 4.14



Battery lifetime

Switch screen
brightness to
automatic

Battery Temperature	Distance Traveled	CPU Use Level	Screen Brightness	Estimated Battery Life (h)
Under 30°C	>0	Low	Automatic	8.83 – 9.12
Under 30°C	>0	Low	Manual	8.49 – 8.82
Under 30°C	>0	High	Automatic	8.09 – 8.24
Under 30°C	>0	Medium	Automatic	7.65 – 7.89
Under 30°C	>0	Medium	Manual	7.34 – 7.60
Under 30°C	>0	High	Manual	7.27 – 7.41
Under 30°C	None	Medium	Automatic	6.57 – 6.64
Under 30°C	None	Low	Automatic	6.28 – 6.35
Under 30°C	None	Medium	Manual	6.13 – 6.20
Under 30°C	None	Low	Manual	5.88 – 5.96
Under 30°C	None	High	Automatic	5.78 – 5.82
Over 30°C	>0	Low	Automatic	5.08 – 5.22
Under 30°C	None	High	Manual	5.00 – 5.04
Over 30°C	>0	Low	Manual	4.73 – 4.88
Over 30°C	>0	High	Automatic	4.62 – 4.69
Over 30°C	>0	Medium	Automatic	4.59 – 4.70
Over 30°C	>0	Medium	Manual	4.28 – 4.39
Over 30°C	None	Medium	Automatic	4.25 – 4.29
Over 30°C	>0	High	Manual	4.08 – 4.14



Battery lifetime

→ 5% more expected battery life

Battery Temperature	Distance Traveled	CPU Use Level	Screen Brightness	Estimated Battery Life (h)
Under 30°C	>0	Low	Automatic	8.83 – 9.12
Under 30°C	>0	Low	Manual	8.49 – 8.82
Under 30°C	>0	High	Automatic	8.09 – 8.24
Under 30°C	>0	Medium	Automatic	7.65 – 7.89
Under 30°C	>0	Medium	Manual	7.24 – 7.60
Under 30°C	>0	High	Manual	7.27 – 7.41
Under 30°C	None	Medium	Automatic	6.57 – 6.64
Under 30°C	None	Low	Automatic	6.28 – 6.35
Under 30°C	None	Medium	Manual	6.13 – 6.20
Under 30°C	None	Low	Manual	5.88 – 5.96
Under 30°C	None	High	Automatic	5.78 – 5.82
Over 30°C	>0	Low	Automatic	5.08 – 5.22
Under 30°C	None	High	Manual	5.00 – 5.04
Over 30°C	>0	Low	Manual	4.73 – 4.88
Over 30°C	>0	High	Automatic	4.62 – 4.69
Over 30°C	>0	Medium	Automatic	4.59 – 4.70
Over 30°C	>0	Medium	Manual	4.28 – 4.39
Over 30°C	None	Medium	Automatic	4.25 – 4.29
Over 30°C	>0	High	Manual	4.08 – 4.14



Battery lifetime

Go cooler place AND
switch screen to
automatic

Battery Temperature	Distance Traveled	CPU Use Level	Screen Brightness	Estimated Battery Life (h)
Under 30°C	>0	Low	Automatic	8.83 – 9.12
Under 30°C	>0	Low	Manual	8.49 – 8.82
Under 30°C	>0	High	Automatic	8.09 – 8.24
Under 30°C	>0	Medium	Automatic	7.65 – 7.89
Under 30°C	>0	Medium	Manual	7.34 – 7.60
Under 30°C	>0	High	Manual	7.27 – 7.41
Under 30°C	None	Medium	Automatic	6.57 – 6.64
Under 30°C	None	Low	Automatic	6.28 – 6.35
Under 30°C	None	Medium	Manual	6.13 – 6.20
Under 30°C	None	Low	Manual	5.88 – 5.96
Under 30°C	None	High	Automatic	5.78 – 5.82
Over 30°C	>0	Low	Automatic	5.08 – 5.22
Under 30°C	None	High	Manual	5.00 – 5.04
Over 30°C	>0	Low	Manual	4.73 – 4.88
Over 30°C	>0	High	Automatic	4.62 – 4.69
Over 30°C	>0	Medium	Automatic	4.59 – 4.70
Over 30°C	>0	Medium	Manual	4.28 – 4.39
Over 30°C	None	Medium	Automatic	4.25 – 4.29
Over 30°C	>0	High	Manual	4.08 – 4.14



Battery lifetime

→ **98% better
expected battery life**

Battery Temperature	Distance Traveled	CPU Use Level	Screen Brightness	Estimated Battery Life (h)
Under 30°C	>0	Low	Automatic	8.83 – 9.12
Under 30°C	>0	Low	Manual	8.49 – 8.82
Under 30°C	>0	High	Automatic	8.09 – 8.24
Under 30°C	>0	Medium	Automatic	7.65 – 7.89
Under 30°C	>0	Medium	Manual	7.34 – 7.60
Under 30°C	>0	High	Manual	7.27 – 7.41
Under 30°C	None	Medium	Automatic	6.57 – 6.64
Under 30°C	None	Low	Automatic	6.28 – 6.35
Under 30°C	None	Medium	Manual	6.13 – 6.20
Under 30°C	None	Low	Manual	5.88 – 5.96
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Over 30°C	>0	High	Automatic	4.62 – 4.69
Over 30°C	>0	Medium	Automatic	4.59 – 4.70
Over 30°C	>0	Medium	Manual	4.28 – 4.39
Over 30°C	None	Medium	Automatic	4.25 – 4.29
Over 30°C	>0	High	Manual	4.08 – 4.14



Impact



- Crowdsourced data allows modeling real-life system setting combinations
 - With enough data, we can average out the bias
- Our results show novel findings and also agree with previous work
 - Battery temperature, Wi-Fi signal strength, automatic screen brightness
- Models provide practical energy recommendations



Takeaways

- Attribute combinations give more complex insight to energy consumption than single system settings
- Crowdsourced data can be used to model a large number of system states cost-effectively
- Laboratory measurements provide information from scenarios that might not represent the real world





Thank you!

- Contact us carat@cs.helsinki.fi
 - Or firstname.surname@cs.helsinki.fi
- Read more about the Carat project in <http://carat.cs.helsinki.fi/>

