OPQ Cloud: A scalable software framework for the aggregation of distributed power quality data

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Abstract

Power quality issues can be caused in a variety of situations. Voltage fluctuations, frequency fluctuations, and harmonics are all power quality issues which can be caused by weather, high penetration of renewables, man-made issues, or other natural phenomena. We designed a software framework which can aggregate crowdsourced distributed power quality measurements in order to study power quality issues over a dense geographic area.

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1 Introduction and Motivation

According to the Office of Electricity Delivery & Energy Reliability, the electricity that we consume in the United States has a frequency of 60 Hz and a voltage of 120 V [2]. Power quality (PQ) issues arise whenever there is a deviation from these standards or when other harmonics get introduced into the power.

Common PQ issues include voltage sag, voltage flicker, and harmonics. [5]. For our current OPQ project, we're only measuring voltage and frequency. However, we plan to study the affects of harmonics through total harmonic distortion (THD) in the future.

We're initially focusing our research efforts on the state of Hawaii. Hawaii is currently in a state of transition changing its electrical grid from its current 90% fossil fuels / 10% renewables to 60% fossil fuels / 40% renewables by 2030 [1]. Consumers and businesses are installing photovoltaics at increasingly high rates [3]. Common issues that can occur with renewables on the grid include undervoltage, overvoltage, output power fluctuation, harmonic distortion, and frequency fluctuation [6]. Because of this, consumers are running into roadblocks by way of the utility companies due to possible grid instabilities that can arise with renewable energy sources [4] being introduced to the power grid.

A major problem is that there is no data that consumers can point to that says "hey, the power quality in our neighborhood is good, so we should be able to install photovoltiacs. Instead consumers only know what they're told by the utilities. Even then, utilities are not mandated to report on PQ information.

On the flip side, distributed PQ data does not exist for the utilities either, and they have to force consumers to wait until their neighborhood can be studied by utility engineers to ensure that the addition of renewables is not going to harm the grid.

Power quality also has an effect on large industries' bottom lines. Laskar et al. found that voltage fluctuations can damage sensitive electronic equipment and can cost companies quite a lot of money. For example, a semiconductor production plant will lose over 5 million USD per power event. Financial trading companies will lose over 8 million USD an hour during power events [8]. It's important to note that these are just power events, not power outages. It's important for companies to understand the PQ that is coming into their plants and to also understand the PQ of the neighborhoods around them and how that PQ can affect their bottom line.

2 A Software and Hardware Diagnostic Framework

Our project contains a hardware devices for measuring voltage and frequency and also a software framework for aggregating distributed PQ measurements and events. The software framework is the focus of this paper.

The OPQ project provides a software solution which aggregates crowd sourced distributed PQ data. We provide real time monitoring and alerts for users when PQ events occur. We also provide a simple wizard style sign up which allows users to connect to their OPQ hardware devices with ease. Users can manage their PQ data in an intuitive and anonymous way. Users can also receive alerts via email or SMS.

Our project is built using a large selection of open source technologies. For a full list of software and libraries used in our project, see section A.

We believe that our system can provide crowd sourced distributed PQ data to consumers, businesses, and utilities alike. We hope to provide a transparent way of collecting and distributing PQ data. We want to empower consumers to understand the quality of the power feeding into their homes and to understand the PQ of the neighborhood they reside in. Businesses should be able to safeguard their electrical assets by assessing the possible threats to their company due to PQ. We want utilities to have a better understanding of PQ so that they can work with correcting PQ issues. Utilities can also use our data to stand out-of-the-way

of renewables when there aren't PQ issues. We believe that the OPQ project is a step closer to realizing a smarter grid.

One of the main tenants of our project is openness. We provide openness in three ways. Our software is built on top of open source libraries. Our software is itself released under an open source license (GPL v3), and our data is open so that other researchers and the public can make informed decisions about PQ.

3 Software Implementation

3.1 Obtaining the Software

All software and related documentation for our project can be found at OPQ's github page <https://github.com/openpowerquality/>.

3.2 Grid Map

A useful tool when working with geographically distributed data is a dynamic map to visualize PQ events and other PQ related information. We're using the Leaftlet Javascript library to provide a mapping interface. For the actual map imagery, we're using the open licensed OpenStreetMap tiling images.

Leaflet provides utilities for placing markers and icons, and we heavily used this early on to display the location of PQ events. We realized that this approach caused several issues. First, we do not want to compromise our users' privacy by displaying the exact location of their OPQ device on a map. Second, if multiple PQ events happen near each other, the map would become cluttered with icons.

We came up with an approach that allows users to select their own level of anonymity while still providing useful and easy to parse visual information.

The Leaflet library allows the for creation of polygon layers where the points of the polygon can be encoded in JSON. We created a Javascript grid-map library which utilizes Leaflet's polygon layer and splits the map up into a series of evenly divided grid squares (similar in idea to a checker board). We wrapped this functionality up into a library using the Javascript module pattern to separate the public API from the back end code. This library allows us to use our map interface in separate locations in our cloud service.

3.2.1 Generating the Polygon Points

To generate an evenly spaced grid, we identified the NW and SE latitude and longitude points of the bounding box (BB) that contains the area of interest our grid should cover. The BB we chose for Hawaii is outlined in table 1.

Table 1: Hawaii Grid Square Bounding Box

BB Point	Location	Latitude	Longitude
North West	NW of Niihau	22.534353	-161.004639
South East	SE of Big Island	16.719592	-151.853027

We can calculate the latitude (ϕ) and longitude (λ) of a point (ϕ_2, λ_2), given a starting point (ϕ_1, λ_1), bearing (Θ), distance (d), and angular distance ($AD = \frac{d}{radius\ of\ earth}$) with the following formula which uses the distance over a great arc circle as an approximation for the shape of the earth.

$\phi_2 = asin(sin(\phi_1 * cos(AD) + cos(\phi_1) + sin(AD) * cos(\Theta))$
$\lambda_2 = \lambda_1 + atan2(sin(\Theta) * sin(AD) * cos(\phi_1), cos(AD) - sin(\phi_1) * sin(\phi_2))$

With the above formula, we start with the NW point of the BB, and generate all points due South of the starting point within the BB with a given distance interval. This process generates the first point for each of the row in our point matrix. Then for each starting point, we generate all points due East within the BB. The result of this process is a matrix of evenly spaced points which can then be used to create polygons of evenly spaced grid squares. It should be noted that we optimize our library so that only polygons within the current browser window viewing area are generated.

3.2.2 Dynamic Sizing of Grid

Grid scale is defined as the length of each square polygon in the grid. That is, a grid scale of 256 kilometers contains grid squares which each are 256 kilometers by 256 kilometers. The coarsest grid scale that we support is 256 kilometers and the finest grid scale is $\frac{1}{8}$ kilometer.

We designed our grid-map library so that when the map is zoomed out, it displays the coarsest grid of 256 kilometers. As the map is zoomed in, each grid square is recursively divided into four smaller squares, each with a grid-scale that is exactly one-half of its parent's. This process continues until the map is at max zoom and each grid square represents $\frac{1}{8}$ of a kilometer.

The location of any grid is invariant to both zoom and pan as long as the NE BB starting point is not changed. This makes it easy to associate ids with individual grid squares so that devices can then be associated with individual grid squares.

3.2.3 Grid Square Naming

In order to associate OPQ hardware devices with locations on the grid, we developed a naming scheme that stores the parent information of each grid in the name itself. Grids at the coarsest grid scale (256 kilometers) are simply named by their row (r) and column (c) using the format $r, c :$. We show an example of how the coarsest grid squares would be named in figure 1.

For each level that the grid becomes more fine, each square recursively divides into four squares. We can name each of these child squares by its location in the parent square. For each finer level, we simply append this location id onto its parent's id.

Table 2: Naming of Child Grid Squares

Position in Parent	**ID**
Top Left	0
Top Right	1
Bottom Right	2
Bottom Left	3

Figure 2 shows the ids of the first level of children under the parent grid square.

We can then recursively use the same naming scheme for each level of children in the grid. For example, a grid id of "0,0:13" represents the following information. At the coarsest level, the location "0,0:" represents the top left 256x256 kilometer grid square. The following "1" represents that the 128x128 kilometer child of the coarsest level is located at the top right of its parent square. The following "3" represents that the

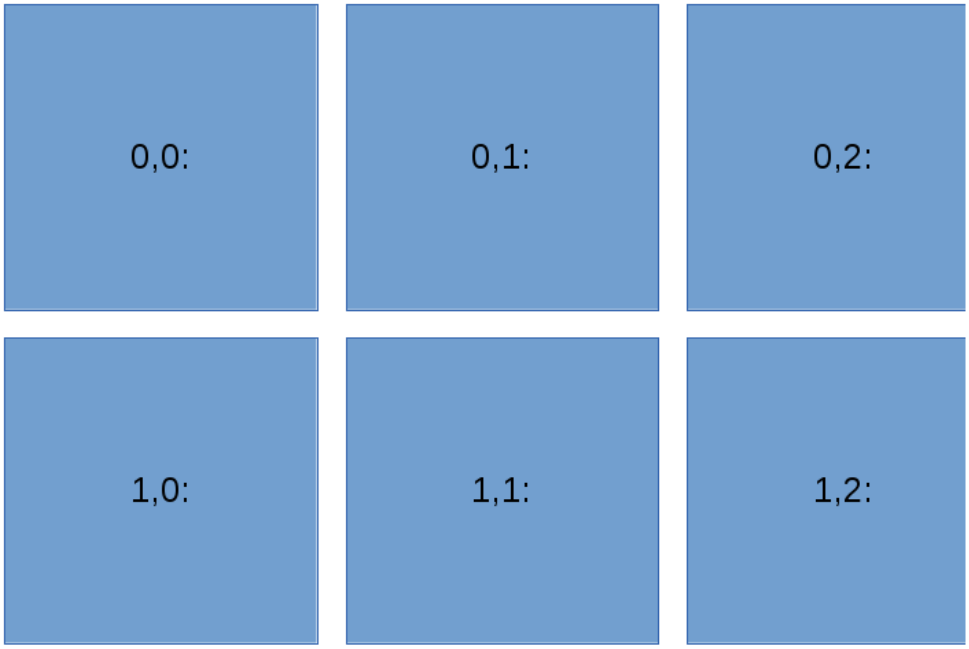


Figure 1: Naming Convention for Coarsest Grid Layer.

Figure 2: Naming Convention for First Children.

grandchild of the coarsest square is in the bottom left of the child's square. To illustrate the concept of recursive ids, please refer to 3.

3.2.4 Importance to OPQ

We want our users to feel comfortable sharing their PQ information. We want to empower our users to select the amount of anonymity they require when sharing the location of their OPQ hardware device. Our grid system allows users to select any grid square at any grid scale for the location of their device. This means that if a user is comfortable giving away the relative location of their home, they can select a $\frac{1}{8}$ kilometer grid square which contains their device. If they are not as comfortable with such an accurate location, they can choose a larger grid square, perhaps $\frac{1}{2}$ kilometer, 2 kilometers, 4 kilometers, etc.

We can also use the user's defined location to determine their local PQ neighborhood. A user is said to be part of a neighborhood if they've selected their location with a grid scale of less than or equal to 4 kilometers. Their neighborhood is all parent grid squares up to and including 4 kilometers.

3.3 OPQ Cloud Features

3.3.1 Sign-Up

Our sign up process collects information about the owner of an OPQ hardware device as well as information about the device itself. We use a custom wizard style dialogue provided by Fuel UX to make it easy for users to set up their device(s).

After collecting the user's contact information, the wizard associates the user's account with their OPQ hardware device(s). To do this, we ask for the provided id number of the OPQ device(s). After the device is associated with the user's account, we allow the user to opt-in to our data sharing program by selecting their approximate location on our grid-map. This feature makes it possible to anonymously share your PQ data with the community. Finally, we collect the user's SMS and preferred contact email so that users can be alerted by email, SMS, or both when PQ events take place.

Examples of our sign up wizard can be found in the attached screenshots as figures 6, 7, 8, 9, 10, and 11.

3.3.2 PQ Measurements

Our measurements section shows 20 voltage and frequency measurements per page. The measurements are ordered by most recent. The user is able to select which of their devices they want to show PQ measurements for. Users can also filter measurements by the last minute, hour, day, week, month, year, or all.

An example of our measurements page can be found in the attached screenshots as figure 12.

3.3.3 PQ Events

The PQ events page is the first page a user is redirected to after logging in. This page shows 20 PQ events per page from all the user's devices. The events are ordered by most recent first. This page shows the type of PQ event (frequency, voltage, or device), the value of the event (i.e. 65 Hz), the timestamp of the event, and the duration of the event (i.e. 2000 milliseconds). Users can also filter events by the last minute, hour, day, week, month, year, or all.

This page also allows users to tag PQ events with an external cause. For instance, possible tags might include "downed power line", "tropical storm Flossie", or "refrigerator condenser".

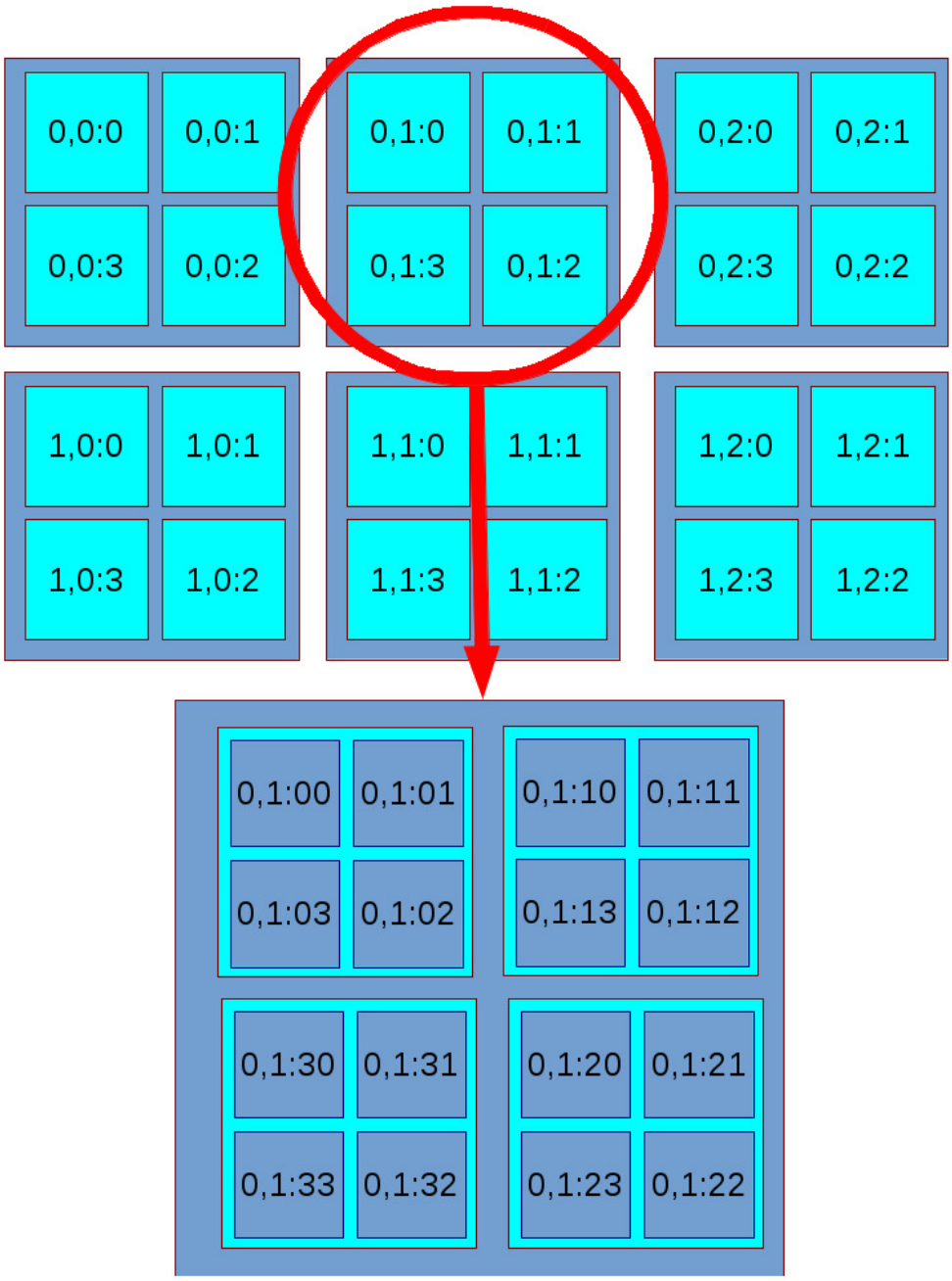


Figure 3: Recursive Naming of Children.

An example of the PQ Events page can be found in the attached screenshots as figure 13.

3.3.4 Data Sharing

OPQ users are able to share their PQ information by opting in to our community data sharing program. In order for a user to share their data, they simply select the finest grid scale their comfortable with that their OPQ device resides in. When users share their data, they also get access to nearby PQ events from other users sharing their data within the same neighborhood. Users may complete this process during sign up, or opt-in (or out) at any later time.

3.3.5 Nearby PQ Events

OPQ users in the same neighborhood can receive alerts about PQ events within their neighborhood. A neighborhood is chosen by the user when they select to share their data and select the appropriate grid square for their device. A neighborhood is defined as the user's selected grid square and all parent squares up to 4 kilometers.

An example of our device administration page can be found under the attached screenshots as figure 14.

3.3.6 Device Administration

With our device administration page, users can easily add more OPQ devices to their profile or update details about existing devices that they own. Users can give nicknames to devices such as "lab", "garage", or "warehouse #3" so that they don't have to memorize the id number of each device. Users can also customize the types of PQ alerts they receive during PQ events for each device. They can define the e-mail and SMS number for alerts per device.

An example of our device administration page can be found under the attached screenshots as figure 16.

3.4 OPQ Cloud Infrastructure

3.4.1 Database Design

We're using the Ebean ORM for persistence throughout our cloud service. Ebean is backed using a MySQL database. The persisted entities in our software are described in table 3.

Table 3: Persisted Entities

Entity	**Description**
Alert	User defined e-mail or SMS alert.
Event	A PQ event.
ExternalCause	A user tagged external cause (i.e. tropical storm).
Measurement	A single frequency and voltage measurement.
OpqDevice	A single OPQ hardware unit's information.
Person	A single owner of an OPQ hardware device.

The table structure is described as a Crow's Foot ER diagram in figure 4.

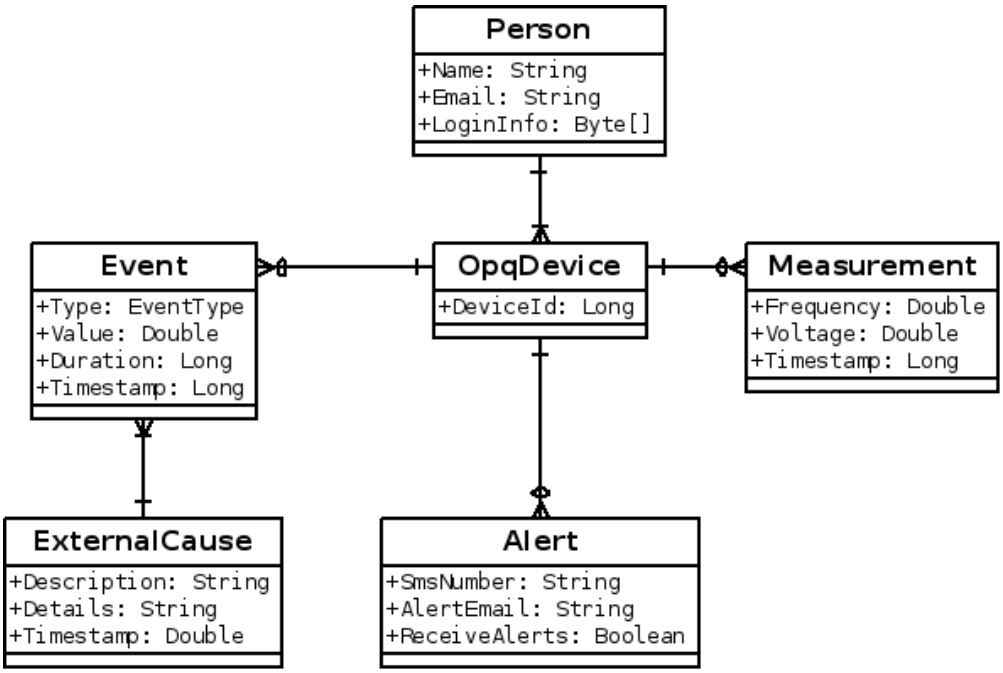


Figure 4: Crow's Foot DB ER diagram.

3.4.2 Asynchronous 2-Way Communication

Not only can OPQ hardware devices send information to the OPQ cloud service, but the OPQ cloud service also has the infrastructure to send or request information from OPQ devices. In order for the cloud service to send or request information from OPQ devices, the OPQ devices first have to ping the cloud service to tell the cloud service that that device exists and is online.

This is achieved when the cloud service receives a ping packet from an OPQ device, and then creates a mapping from that device's ID to the WebSocket handler associated with that device.

When the cloud service needs to contact the device, it looks up the appropriate WebSocket handler from the map, and then uses that WebSocket handler to communicate with the device.

Devices are pruned from the mapping if they have not sent any data for over an hour.

3.5 OPQ Protocol

We've created a custom communication protocol between OPQ devices and our OPQ cloud service. Our OPQ simulator also makes use of our OPQ communication protocol. Our protocol utilizes a fixed length header with a variable sized payload. The layout of the protocol is described below.

3.5.1 Magic Word Header

The magic word header is simply 4 bytes which signify the start of an OPQ data packet. The four bytes will always be 0x00C0FFEE.

Table 4: Protocol Layout

Description	Size (bytes)	Start Byte	End Byte
Magic Word Header	4	0	3
Type	4	4	7
Sequence Number	4	8	11
Device Id	8	12	19
Timestamp	8	20	27
Bitfield	4	28	31
Payload Size	4	32	35
Reserved	16	36	51
Checksum	4	52	55
Payload	Variable	56	56 + P

3.5.2 Type

The type field specifies the type of OPQ packet being sent. The types and their values are specified below.

Table 5: Packet Types

Type	Value	Description
Measurement	0	Frequency and voltage measurement.
Frequency Event	1	This packet contains frequency PE data.
Voltage Event	2	This packet contains voltage PE data.
Device Event	3	This packet contains device event data.
Ping	4	Establishes connection with OPQ cloud (no payload).

3.5.3 Sequence Number

The sequence number is a 4 byte field which maintains the ordering of packets in multi-packet transmissions. This way, if packets are received out-of-order, they can be reassembled in the correct order.

3.5.4 Devive Id

This field represents a positive 64-bit integer which uniquely identifies each OPQ hardware device.

3.5.5 Timestamp

This field is a 64-bit integer which represents the number of milliseconds since the epoch of when this packet was sent.

3.5.6 Bitfield

This is a 4-byte bitmask where each bit represents one of 32 options depending on the type of packet. This is currently not being used, but it's use is planned for future expansion.

3.5.7 Payload Size

A 32-bit integer which stores the size of the payload for each packet.

3.5.8 Reserved

These 16-bytes are reserved for later use.

3.5.9 Checksum

The checksum of each packet is a 4-byte field that is computed by summing every field in the packet except for the checksum field itself. In other words, the checksum C is computed as $C = sum(all\ bytes) - sum(bytes[52 - 55])$.

3.5.10 Payload

The payload is a variable length field which contains different data depending on the type of packet being sent. The three types of payloads are described below.

If the packet is a measurement type, the payload is 16 bytes where the first 8 bytes represent an IEEE 754 floating point number of the frequency and the last 8 bytes represent an IEEE 754 floating point number of the voltage.

If the packet is a frequency event type, the payload is 16 bytes where the first 8 bytes represent an IEEE 754 floating point number of the frequency and the last 8 bytes represent the duration of the event as a 64-bit long integer. The duration represents the number of milliseconds since the epoch.

If the packet is a voltage event type, the payload is 16 bytes where the first 8 bytes represent an IEEE 754 floating point number of the voltage and the last 8 bytes represent the duration of the event as a 64-bit long integer. The duration represents the number of milliseconds since the epoch.

If the packet type is a ping packet, the payload remains empty.

3.6 Reference Implementation of Protocol

A fully tested reference implementation of our protocol has been written as a standard Java library. We're currently using this implementation of the protocol is both our OPQ simulator and our OPQ cloud service.

The reference implementation provides many utilities which aid in the construction of OPQ packets. For example we provide convenient getters and setters that accept decimal inputs for frequency, voltage, device id, event duration, timestamp, etc.

The setters convert the decimal values into the appropriate array of bytes and stores them at the correct location in the protocol. The setters also make sure that the payload section of the protocol is structured correctly.

The getters select the correct subarray of bytes from the protocol and converts them into a readable decimal value.

The library itself is resilient against inadvertently creating invalid packets. The library contains a wide range of custom exceptions which are thrown when an OPQ packet is put into an invalid state.

3.7 OPQ Simulator

We designed an OPQ hardware simulator so that we could try out new ideas without needing to deploy actual hardware right away. Our OPQ simulator can act as a proxy for a real OPQ hardware device or as a proxy for many OPQ devices. Utilizing our reference implementation of the OPQ protocol, the OPQ simulator simulates actual OPQ data packets.

We provide a GUI designed using the JavaFX framework which allows for fined grained control over sending a single OPQ packet, or for the implementation of various distributed simulations.

3.7.1 Single Packet Simulation

When testing our OPQ Cloud service, we found that we needed the ability to send single OPQ packets to the cloud service where we could control all details of the packet being sent. We provide an interface that makes it easy to construct a single OPQ packet and then send it to cloud service for evaluation. We also provide the functionality to alter your values in both decimal and hexadecimal notations at the same time.

Users of the simulator can alter the fields described in table 6.

Table 6: Single Packet Simulation Fields

Field	**Details**
Websocket URL	URL of cloud service.
Device Id	The simulated OPQ hardware device id.
Type	One of the available OPQ packet types.
Sequence Number	Sequence number for simulated multi-packet data.
Timestamp	The number of milliseconds since the epoch.
Bitfield	Bitfield options for the simulated packet.
Frequency	The frequency of the simulated packet.
Voltage	The voltage of the simulated packet.
Alert Duration	The duration of the simulated event.

The GUI makes it difficult to create invalid OPQ packets. For example, when the type of packet is “Event Frequency”, the fields for modifying the voltage become uneditable and set to 0. If the type of packet is “Event Voltage”, the frequency fields become uneditable. When the type of packet is “Measurement”, then the duration field is made uneditable. If the type of packet is “Ping”, then only the device id and timestamp fields remain editable. An example of the single packet simulation can be seen in figure 17.

3.7.2 Distributed Simulations

Our OPQ simulator also provides a simulation for performing single-source, large-data testing on our OPQ cloud service. The simulation allows for a variable number of devices which continually send measurements and generate PQ events a definable percentage of the time. For a more accurate simulation, a thread is generated for each device, so that their packet timing is independent of other devices.

A description of the editable fields are provided in table 7.

Table 7: Distributed Simulation Fields

Field	Details
Websocket URL	URL of cloud service.
Device Ids	List of OPQ device ids to send packets from.
Packet Types	Any available OPQ packet types (except ping).
Packets/second	The number of packets each device sends per second.
Event Frequency	Percentage between [0.0 - 1.0].

Note that the "Event Frequency" field determines how frequency a PQ event should be generated by each device. A value of .5 would say that each device should generate a PQ event 50% of the time, whereas a value of .1 says that each device should only generate PQ events 10% of the time. An example of this simulation can be seen in figure 18.

4 Evaluation and Results

4.1 Using the OPQ Simulator

We used the OPQ simulator to send simulated measurements and PQ events to the OPQ cloud service. We tested that the measurements and events received by the cloud service were the same ones sent by the simulator. We did this for multiple users and multiple simulated devices.

Users that were set up to receive SMS and/or email alerts received those alerts when PQ events were generated by the simulator. Users who opted to share their PQ data also received alerts that were generated within their neighborhood.

4.2 Performance and Scalability

Our hosting provider Cloudbees provides a service called New Relic which provides application performance management. In other words, New Relic is an online service attached to Cloudbees which can perform profiling on our OPQ cloud service. We found the following metrics for our cloud based service to be the most telling at our current stage of the project.

4.2.1 Response Time

There are three categories for response times that developers need to concern themselves with. Less than 0.1 seconds feels instantaneous to users. Less than 1.0 second is the limit for a user's flow of thought to go uninterrupted, and less than 10 seconds keeps the user's attention [7].

In order to calculate response time, we navigated all sections of our cloud service under normal simulated load from OPQ devices.

Our software when selecting a link and seeing an updated page has an average response time of 289 milliseconds with the largest response time being just under 750 milliseconds. Our response time falls just between the two categories of instantaneous and keeping the user's train of thought. As long as our response

times remain less than a second, then no large architectural changes need to made to accommodate faster response times.

The 750 millisecond response time is generated when loading the page that describes PQ events. The reason for the high response time is due to database calls which access all power events associated with all devices for the particular user. Even though the events page causes the highest response time, since the response time is less than a second, we're currently not concerned with it. Further analysis on the database response time is discussed in the next section, database profiling.

The response time for both our web service and for our database are described in figure 5.

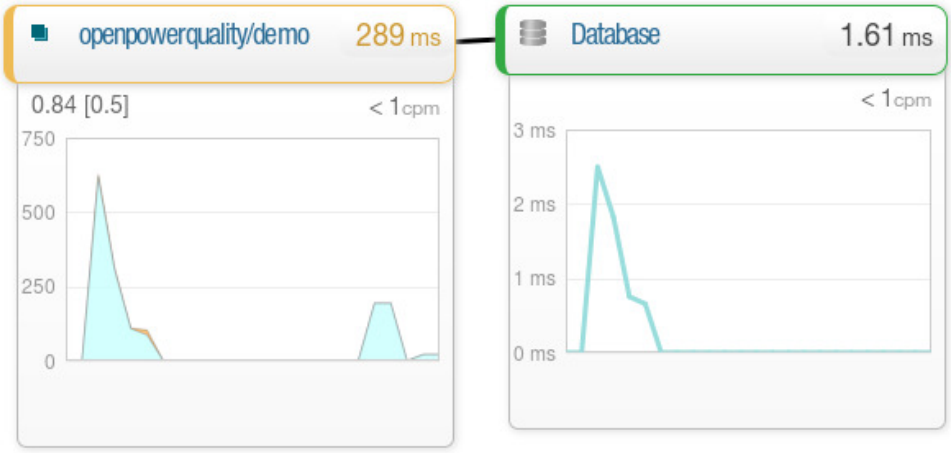


Figure 5: Web Service and DB Response Times.

4.2.2 Database Profiling

We stress tested our Cloudbees database using our OPQ simulator with a simulation of 20 OPQ devices each sending either measurements or PQ events five times a second. In other words, our webservice and database was responding to and storing 100 OPQ packets per second. We chose this for our initial stress testing as it's our aim for our initial pilot deployment of devices.

We found that stress testing the database with the above parameters would use about 5 megabytes of data in half an hour. Extrapolating this data, our service will consume about 240 megabytes a day, 1.7 gigabytes a week, and 6.7 gigabytes per month. This number can be greatly reduced if we only send occasional measurements and PQ events when they occur instead of multiple measurements per device per second.

When profiling the database we can provide several metrics.

The top five most time consuming database operations are outlined in table 8.

Even though querying OPQ devices takes up the largest amount of time in the database, the average response time is still less than 0.1 seconds which is well within the responsive zone that we're aiming for.

Table 8: Database Profiling

DB Field	Operation	Total % of Time	Avg. Response Time (ms)
OPQ Device	Select	52.4	2.41
Person	Select	19.9	3.82
Event	Select	19.4	8.18
Measurement	Select	7.16	3.78
OPQ Device	Insert	0.66	1.4

5 Future Work

5.1 External Causes

Users have the ability to tag PQ events with external causes if the user knows what caused the PQ event. Currently, users can tag events for their own records, but this feature could lead us to some interesting analytics.

We hope utilize this feature with possibilities of crowdsourcing common tags to diagnose an entire neighborhood containing PQ events. One example would be if there is a bad storm and the PQ fluctuates in the area under that storm. Users could tag their PQ events as related to the storm, and we could basically track the path of the storm by following the tags.

Eventually, we would like to employ machine learning to infer information from user defined tags. If a user sees that they have a power event every time their refrigerator turns on, they can tag the event with their refrigerator model and machine learning can learn to associate that PQ signature with the turning on of that particular compressor. With that learned fact, we can filter and identify these signatures in all homes. In this way, we could classify PQ event signatures with the help of crowdsourcing.

Once we're able to classify power events through machine learning, we can provide recommendations to users on how they can mitigate their PQ issues that we diagnosed. If we can determine what constitutes as sustained PQ issues, we might be able to recommend when to call the utilities, or when they might benefit from installing power conditioning equipment, or perhaps we can alert users to unplug their electronics if we can forecast poor PQ.

5.2 Public PQ Monitoring

We currently only support a rudimentary map interface for displaying public PQ events. If a PQ event occurs, the grid square that it's located in and all parent grid squares will change to a red coloring.

We would like to add the ability to reflect how many power events have happened within in area but using multiple colors indicating the density of PQ events in a particular area.

We would also like to perform aging on PQ events so that only the most recent (being user defined) events would show up on the public map.

Finally, we would like to provide an animated map interface that would should cascading PQ events. The inspiration behind this is similar to weather maps which can show the animated path of a storm, we would like to show an animated path of PQ events.

5.3 Security and Privacy

The Play framework provides built-in support for SSL encryption. We are currently not encrypting our traffic, but as soon as it can be implemented in hardware and implemented in the OPQ simulator, we can enable SSL on the cloud service as well.

We believe that our grid-map approach is a step in the right direction to protecting user privacy, but we also see the need for a privacy study which will determine the amount of information that can be obtained from our OPQ project and our OPQ data. We need to determine if there are problems with our approach in terms of privacy, and if so, how can we address them?

5.4 Usability Testing

Our software has not undergone any usability testing. We need to perform usability testing and make changes based on those tests. We hope to begin basic usability testing as soon as we start our pilot program once we're ready to deploy our OPQ hardware devices.

5.5 Other Event Types

We are currently only monitoring voltage and frequency. We believe that our hardware is capable of monitoring other useful PQ metrics as well. One area that we plan on focusing on in the near future is the measuring of harmonics through total harmonic distortion (THD). We would like to study the affects of renewable power sources on the grid and how they contribute to adding harmonics on top of the power on the grid.

5.6 Integration with Other Sources

We would like to integrate our PQ data with power generation and consumption data by gaining access to the users utility account information.

We would also be interested in partnering with utilities and solar distribution companies to gain access to the PQ data.

5.7 Data Analytics

Finally, we believe that there is a myriad of data analytics that can be performed using the crowdsourced PQ data. We need to investigate the types of analytics that are possible, and then implement them. Examples of analytics that we are interested in include average neighborhood PQ, correlation of PQ with weather systems, and PQ prediction and forecasting.

6 Conclusion

We designed a framework of software technologies that allow for the aggregation of crowd sourced distributed PQ data. We created a cloud based service for aggregating and displaying PQ information. We created a communications protocol that we hope can become an open standard for smart meter devices. We created a grid interface that allows users to share PQ data while still remaining anonymous. We created a hardware device simulator which can be used as an analogue to a real OPQ hardware device for testing purposes. Most importantly, we laid out a solid foundation for further research.

A Appendix: Software Used

Our application stack uses a variety of technologies and libraries in order to provide a cohesive environment for aggregating distributed power quality data. Our software is developed using Java, Scala, Javascript, and markup languages for display (CSS, HTML). We make heavy use of asynchronous communication by using the WebSocket protocol and use Twitter Bootstrap to provide a consistent and reactive user interface.

A.1 Development Environment

The OPQ Cloud software was developed on Debian GNU/Linux using version 7 of the OpenJDK. The software is shared under version 3 of the GPL license and all sources are shared on Github.

A.2 Cloudbees

Our OPQ Cloud application is hosted on Cloudbees which provides a platform as a service (PaaS) for building, running, and managing web applications. Cloudbees provides a continuous deployment environment which allows us to push changes to Github and Cloudbees will automatically build, run static analysis on the software, and deploy the software to the cloud. The Cloudbees web service can be found at <http://www.cloudbees.com/>.

A.3 Play Framework

The Play Framework is a modern open source model, view, controller (MVC) framework which allows developers to write web applications in either Java or Scala. The Play Framework provides facilities for asynchronous communication between clients using the built-in WebSocket standard. The Play Framework can be obtained at <http://www.playframework.com/>.

A.4 Ebean ORM

The Ebean object-relational mapping (ORM) is provided by the play framework and allows us to easily persist Plain Old Java Objects (POJOs) to the database of our choosing. Specifically, we are using MySQL as our database back end. Information about Ebean can be found at <http://www.avaje.org/>.

A.5 Twitter Bootstrap

Twitter Bootstrap is a library which consists of pre-rolled CSS, HTML, and Javascript templates for rapidly creating reactive and consistent user interfaces. Bootstrap allows us to create an interface that is consistent across multiple devices from desktops, to laptops, tablets, and mobile phones. Bootstrap can be downloaded at <http://getbootstrap.com/>.

A.6 Fuel UX

Fuel UX is a set of extensions built on top of Bootstrap that add extra functionality to Bootstrap driven websites. We're specifically using Fuel UX for the sign-up wizard in our OPQ cloud service. Fuel UX can be found at <http://exacttarget.github.io/fuelux/>.

A.7 Leaflet

Leaflet is an open source, mobile ready, Javascript library for creating interactive maps. We use Leaflet to display distributed PEs as well as for allowing users to select the location of their device as well as to allow users to select their neighborhood. We built an anonymous grid layer on top of Leaflet so that consumers can feel comfortable sharing their PQ data. Leaflet can be obtained at <http://leafletjs.com/>.

A.8 OpenStreetMap

OpenStreetMap provides a mapping service similar to Google Maps, but uses crowd sourced information to generate their maps and releases their map tiling images as open data. OPQ makes use of OpenStreetMap by using their tiling API within the Leaflet library. More information about OpenStreetMap can be found at <http://www.openstreetmap.org/about>.

A.9 Java Websocket

Java Websocket is an open source library which provides access to the Websocket Standard. This library is used by our OPQ Simulator to act as a client device. This library was not needed in the OPQ Cloud software as the Play framework handles all WebSocket communications for us. Java Websocket can be found at <http://java-websocket.org/>.

A.10 JavaFX

JavaFX is a graphical user interface (GUI) framework which provides tools from developing GUIs seamlessly across multiple different platforms and architectures. JavaFX makes integration with web technologies such as CSS and embedded HTML easy. We use JavaFX as the GUI back end to our OPQ simulator. JavaFX can be obtained at <http://www.oracle.com/technetwork/java/javafx/overview/index.html>.

A.11 Static Analysis

We use a variety of static analysis tools to spot bugs in our source code. JUnit <http://junit.org/> is used as a unit testing framework for our software. FluentLenium <http://fluentlenium.org/> is used for writing acceptance tests for our software. We use FindBugs <http://findbugs.sourceforge.net/> to perform further static analysis and to enforce coding standards. Finally, we use Emma <http://emma.sourceforge.net/> to perform unit test coverage over our source code base.

B Appendix: Screenshots

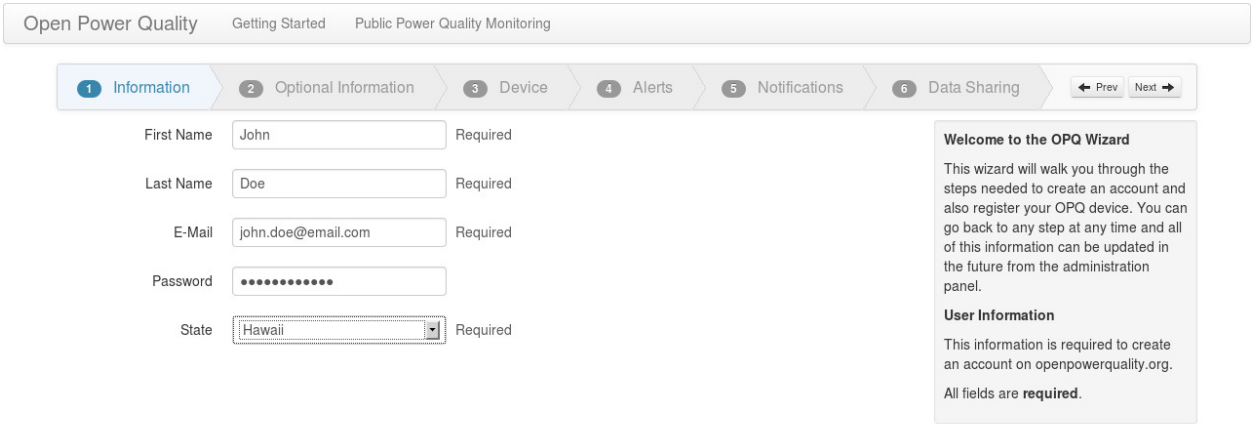


Figure 6: OPQ Wizard Screenshot.

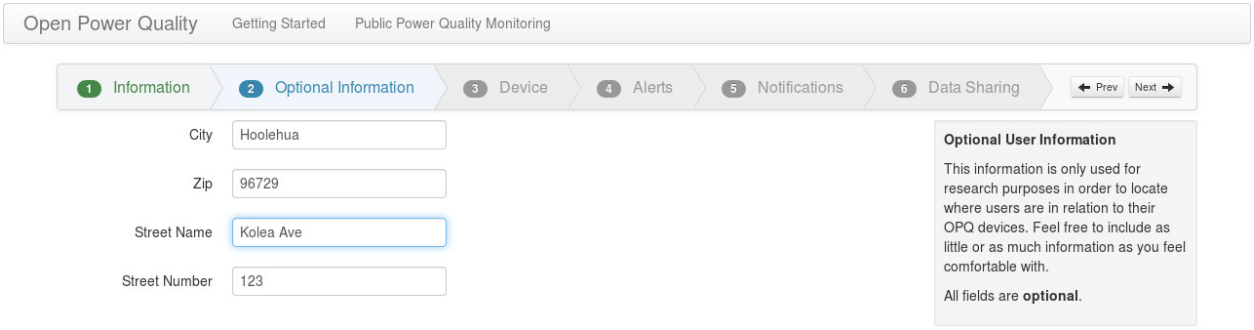


Figure 7: OPQ Wizard Screenshot.

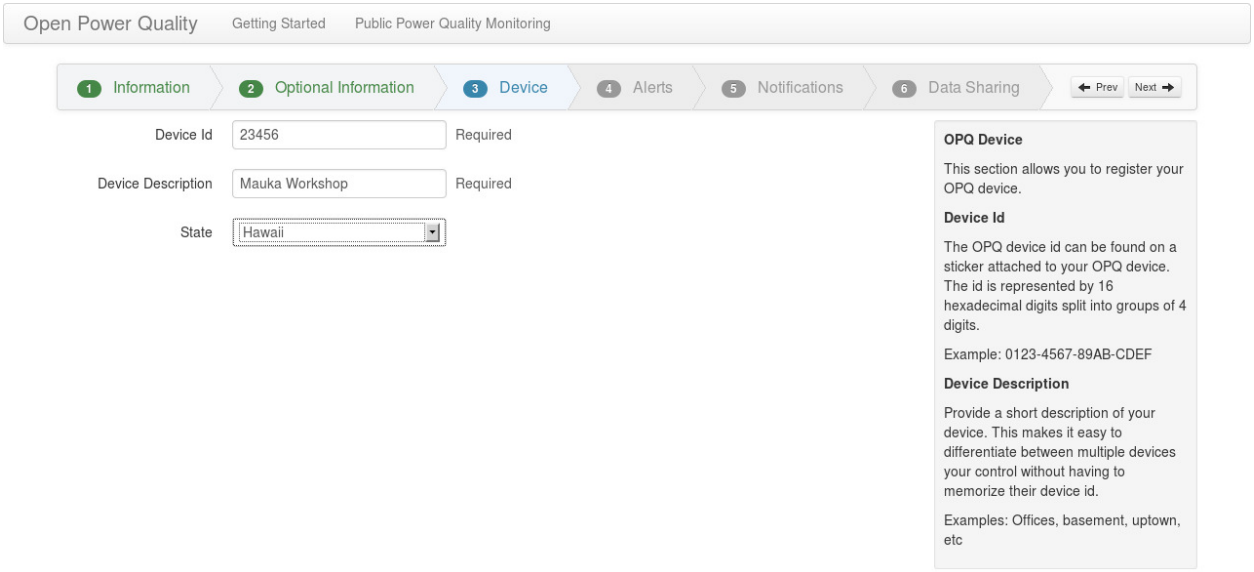


Figure 8: OPQ Wizard Screenshot.

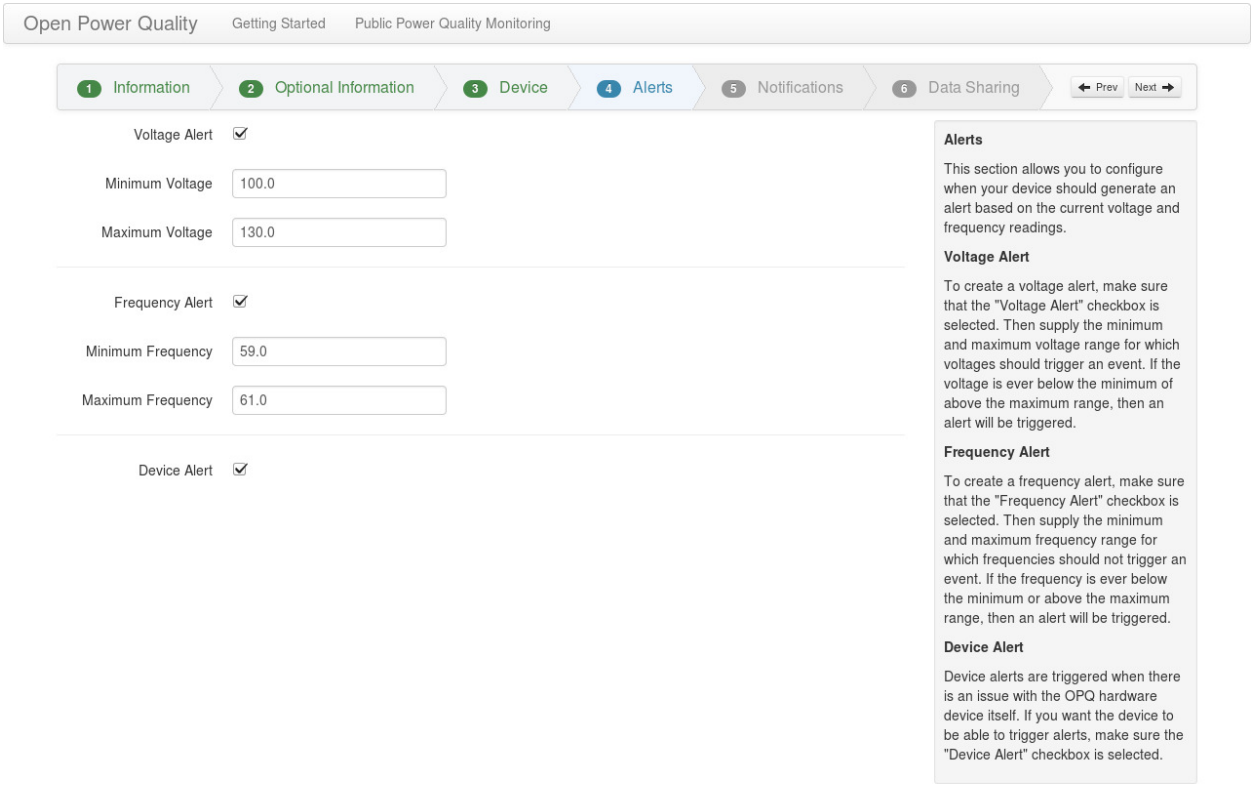


Figure 9: OPQ Wizard Screenshot.

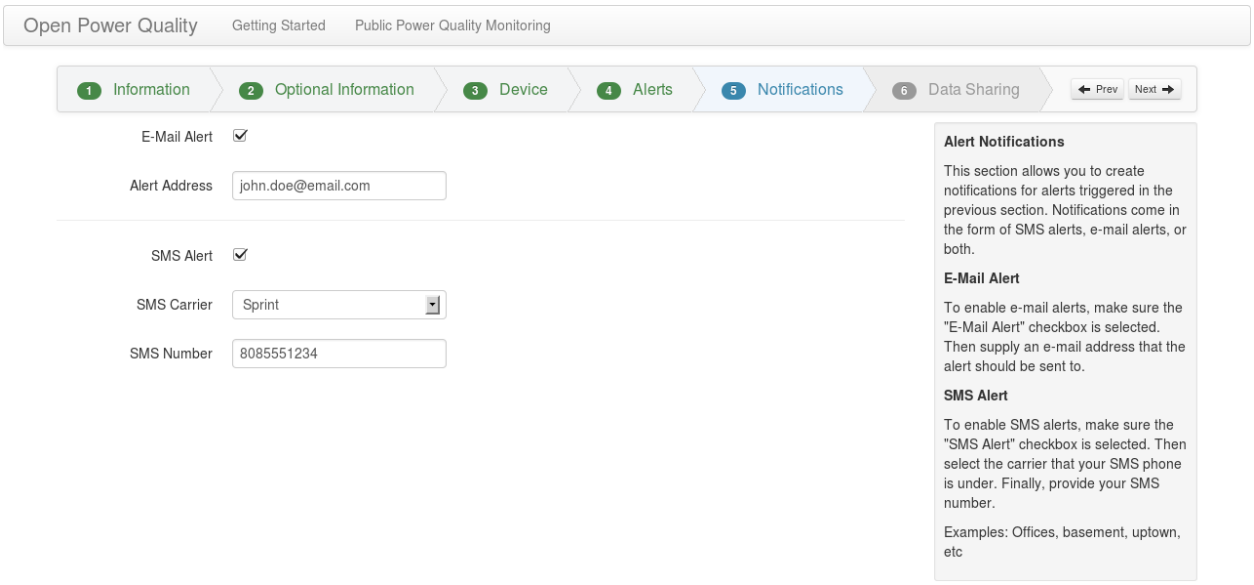


Figure 10: OPQ Wizard Screenshot.

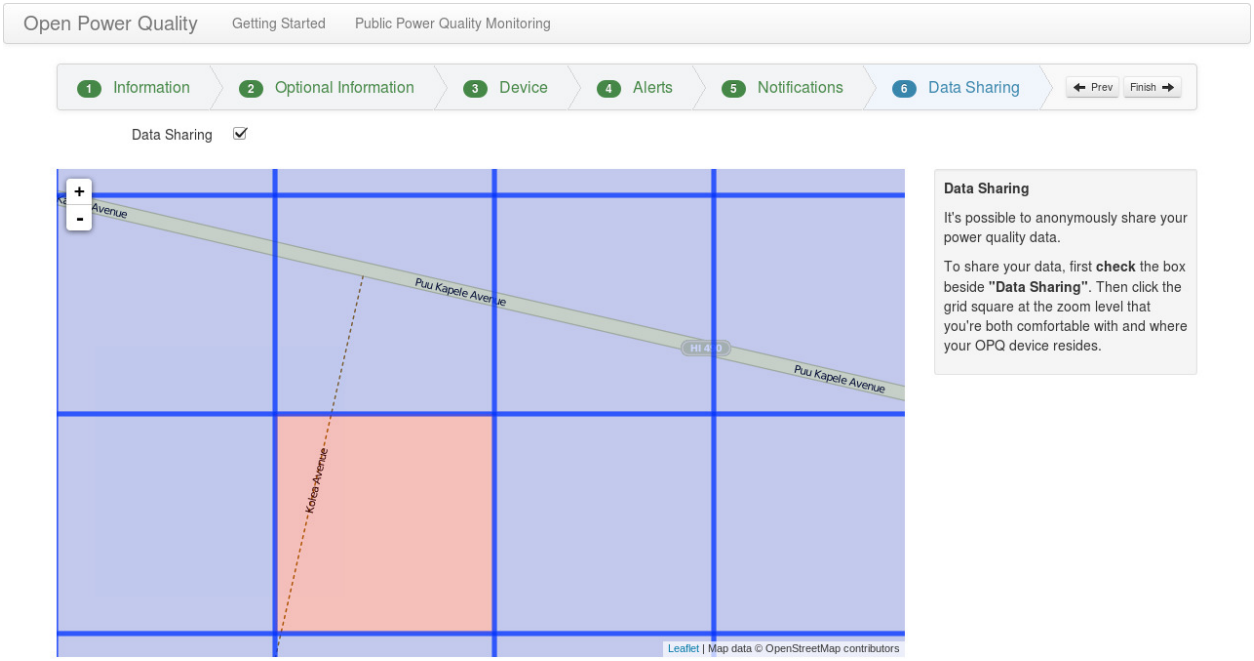


Figure 11: OPQ Wizard Screenshot.

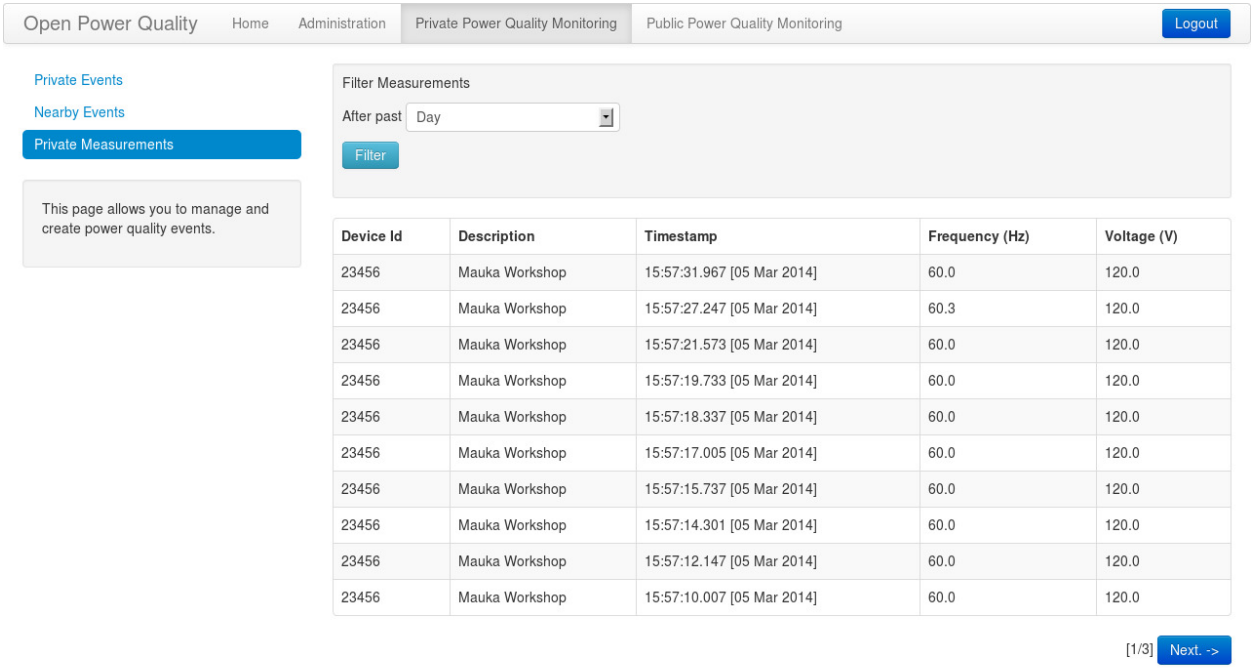
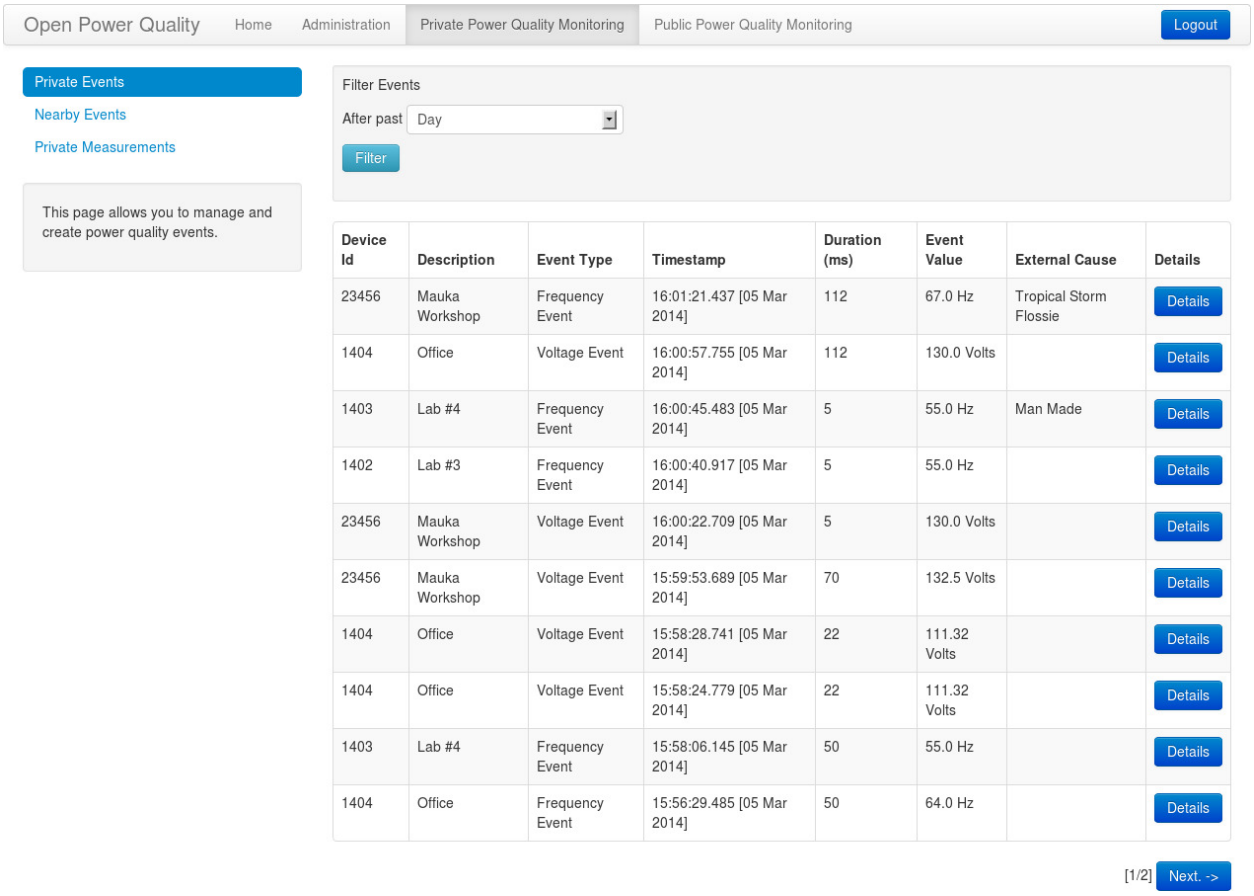
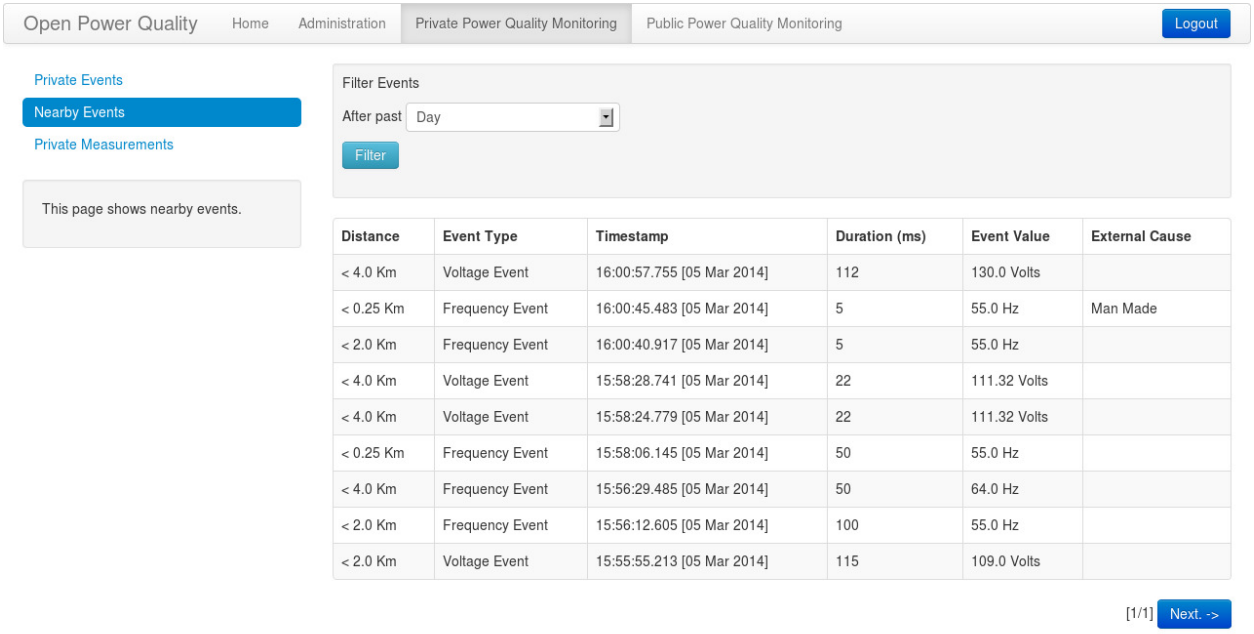


Figure 12: Private PQ Measurements.


Open Power Quality
Home
Administration
Private Power Quality Monitoring
Public Power Quality Monitoring
Logout
Private Events
Nearby Events
Private Measurements
This page allows you to manage and create power quality events.
Filter Events
After past
Day
Filter
Device Id
Description
Event Type
Timestamp
Duration (ms)
Event Value
External Cause
Details
23456 Mauka Workshop Frequency Event 16:01:21.437 [05 Mar 2014] 112 67.0 Hz Tropical Storm Flossie Details
1404 Office Voltage Event 16:00:57.755 [05 Mar 2014] 112 130.0 Volts Details
1403 Lab #4 Frequency Event 16:00:45.483 [05 Mar 2014] 5 55.0 Hz Man Made Details
1402 Lab #3 Frequency Event 16:00:40.917 [05 Mar 2014] 5 55.0 Hz Details
23456 Mauka Workshop Voltage Event 16:00:22.709 [05 Mar 2014] 5 130.0 Volts Details
23456 Mauka Workshop Voltage Event 15:59:53.689 [05 Mar 2014] 70 132.5 Volts Details
1404 Office Voltage Event 15:58:28.741 [05 Mar 2014] 22 111.32 Volts Details
1404 Office Voltage Event 15:58:24.779 [05 Mar 2014] 22 111.32 Volts Details
1403 Lab #4 Frequency Event 15:58:06.145 [05 Mar 2014] 50 55.0 Hz Details
1404 Office Frequency Event 15:56:29.485 [05 Mar 2014] 50 64.0 Hz Details
[1/2]
Next. ->
Figure 13: Private PQ Events.


Open Power Quality
Home
Administration
Private Power Quality Monitoring
Public Power Quality Monitoring
Logout
Private Events
Nearby Events
Private Measurements
This page shows nearby events.
Filter Events
After past
Day
Filter
Distance
Event Type
Timestamp
Duration (ms)
Event Value
External Cause
< 4.0 Km
Voltage Event
16:00:57.755 [05 Mar 2014]
112
130.0 Volts
< 0.25 Km
Frequency Event
16:00:45.483 [05 Mar 2014]
5
55.0 Hz
Man Made
< 2.0 Km
Frequency Event
16:00:40.917 [05 Mar 2014]
5
55.0 Hz
< 4.0 Km
Voltage Event
15:58:28.741 [05 Mar 2014]
22
111.32 Volts
< 4.0 Km
Voltage Event
15:58:24.779 [05 Mar 2014]
22
111.32 Volts
< 0.25 Km
Frequency Event
15:58:06.145 [05 Mar 2014]
50
55.0 Hz
< 4.0 Km
Frequency Event
15:56:29.485 [05 Mar 2014]
50
64.0 Hz
< 2.0 Km
Frequency Event
15:56:12.605 [05 Mar 2014]
100
55.0 Hz
< 2.0 Km
Voltage Event
15:55:55.213 [05 Mar 2014]
115
109.0 Volts
[1/1]
Next. ->
Figure 14: Nearby PQ Events.

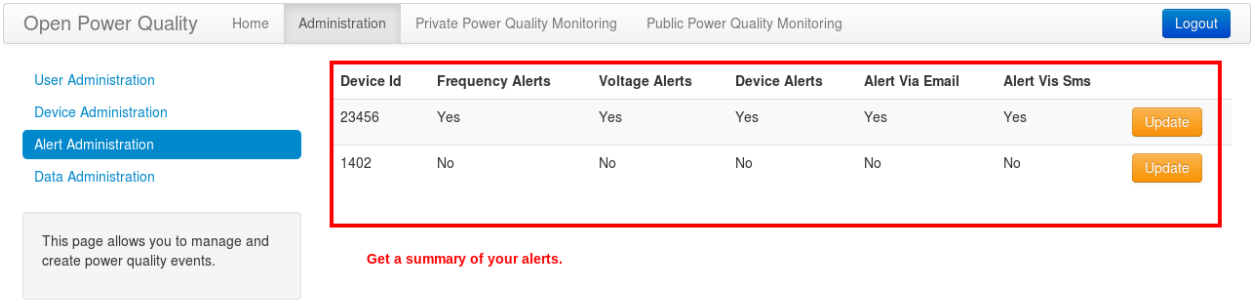


Figure 15: Alert Administration.

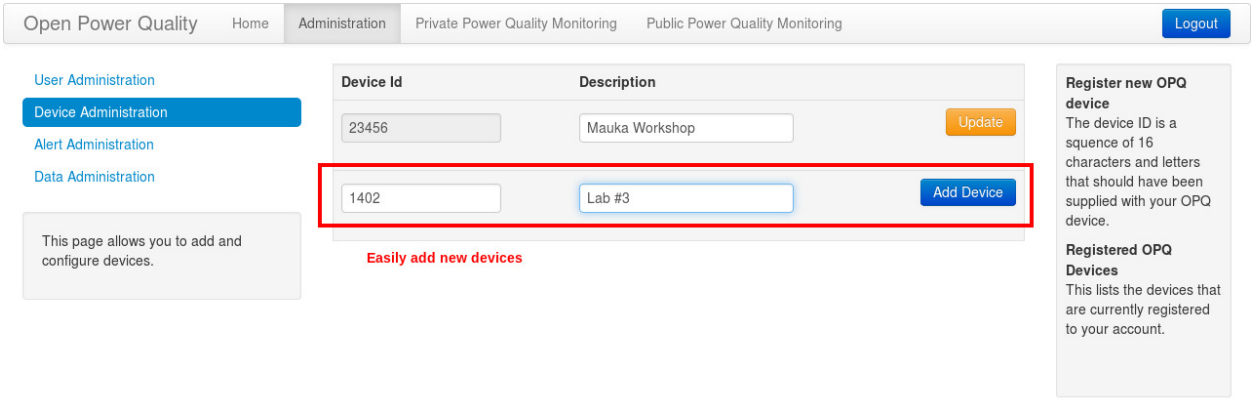


Figure 16: Device Administration.

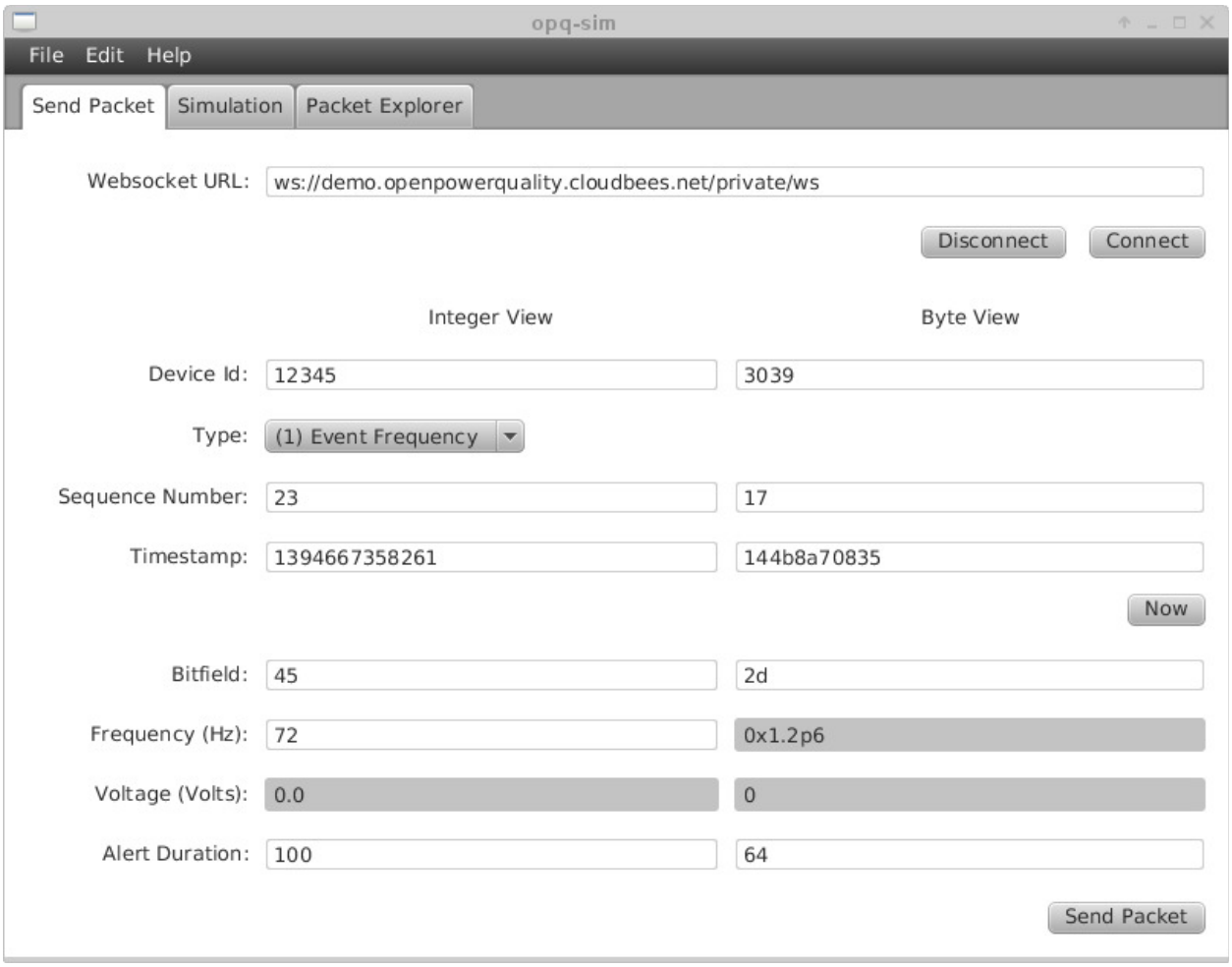


Figure 17: OPQ Simulator Single Packet

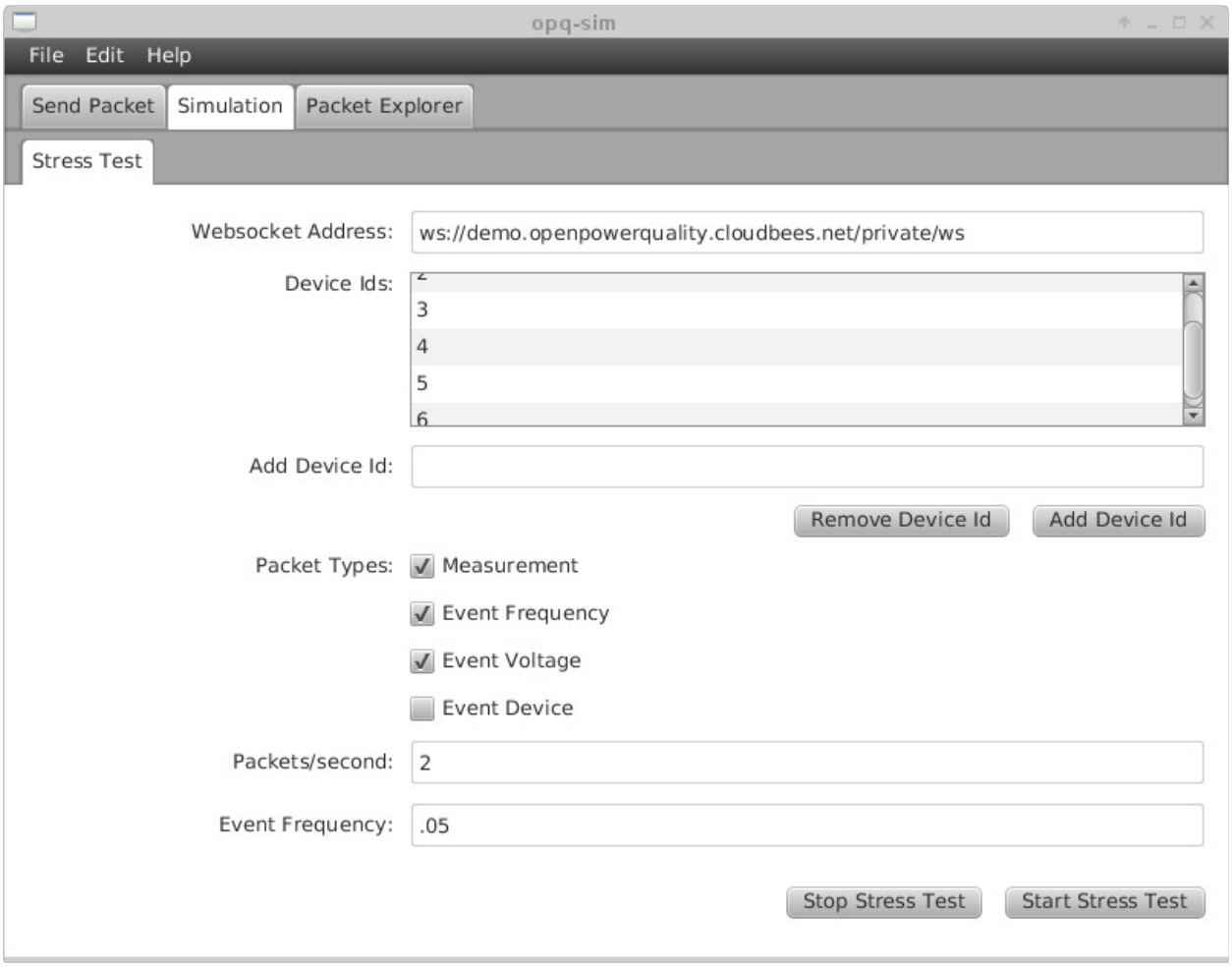


Figure 18: OPQ Simulator Stress Test Simulation

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