Towards Real-time, Fine-grained Energy Analytics in Buildings Through Mobile Phones

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Abstract

In this paper we present a system called the Energy Lens – a system that provides deeper, real-time visibility of plug-load energy consumption in buildings. Our initial work focuses on plug-load power metering, display, and real-time aggregation, presented to the user through a mobile phone. We discuss the three main, non-trivial challenges that must be addressed to provide real-time energy analytics in buildings through mobile phones and our initial approach towards addressing each challenge.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous

General Terms

Distributed Consistency, Mobile application

Keywords

Disconnected operations, network access, energy, power, plug loads

1 Introduction

The United States leads the world in per-capita energy consumption. Our electricity use has consistently increased over the last 40 years [3] and other parts of the world are rising all too rapidly. With the specter of climate change and the increasing cost of energy, we must explore new ways for individuals to gain visibility and insight into their energy consumption in order to optimize and reduce it. With the increasing penetration of embedded sensors in the environment and the continued rise in smartphone adoption, we see an opportunity for smartphones to bridge the physical world to our computational infrastructure and provide an 'energy lens' on the physical world.

We use mobile phones to construct an entity-relationship graph of the physical world and combine it with streaming sensor data in order to perform detailed energy-attribution. We limit the scope of the world to a single building domain. We have designed and implemented a real-time, mobile energy auditing application, called the 'Energy Lens', that allows us to collect information about things throughout the building and how they are related to each other. For example, computer X is inside room Y and connected to meter Z. Then, we use these relationships to guide our data look-up and analytical calculations. For example, the load curve of room Y consists of the sum of all the power traces for loads inside room Y. We use the mobile smartphone as the main input tool. Our work examines *three main challenges* in setting up and deploying a real, whole-building infrastructure to support real-time, fined grained energy analytics.

The first challenge is related to tracking and mobility. The use of mobile phones presents classical, fundamental challenges related to mobility. Typically, mobility refers to the phone, as the person carrying it moves from place to place. However, in the energy-attribution context, we are also referring to the movement of energy-consuming objects. Tracking their relationships to spaces and people is as important as tracking people. We describe how we deal with *both moving people and moving objects* and show that these historically difficult problems can be addressed relatively easily, if the proper infrastructure is in place.

The second challenge is about capturing the inter-relationship semantics and having these inform our analytics. We adopt the general notion of physical tags that identify objects in the world. Our system uses *QR codes* to tag things and locations in the physical world. However, *any tag that provides a unqiue identifier for an object could serve the same purpose*. Once tagged, there are three types of interactions – registration, linking, and scanning – which establish important relationships. Registration is the act of creating a virtual object to represent a physical one. Linking captures the relationship between pairs of objects. Scanning is the act of performing an item-lookup. Each of these interactions requires a set of swiping gestures. Linking requires two tag swipes while the other two actions require a single

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tag swipe. Internally, we maintain a *entity-relationship graph (ERG)* of things, people, and locations, that gets updated through these sets of gestures.

The third challenge is about indoor network connectivity and access. In order to connect these components, we rely on having 'ubiquitous' network connectivity. However, in practice, network *availability* is intermittent and our system must deal with the challenges of intermittency. We discuss how caching and logging are used to address these challenges. Moreover, when connectivity is re-established, we must deal with applying updates to the ERG, as captured by the phone while disconnected.

2 Related Work

Our work touches on several areas from logisticsto context-aware mobile applications [6]. In the building space, there has been some interest in building various kinds of energy-related visualization and control applications. HBCI [4] proposes a high level archiecture that also relies on QR codes, mobile phones, and ubiquitous network access. HBCI introduces the notion of object capture through the mobile phone and individual services provides by the object, accessible via an object lookup. The proposed service model is *object-centric*, such as individual power traces or direct control accesss. Their "query" service is a tag lookup mechanism realized through QR code scanning of items. The 'Energy Lens' also embodies the "query" via a tag lookup, however we focus on context-related services rather than object-centric services. We build and maintain an entity-relationship graph (ERG) to capture the inter-relationships between items. The ERG informs our analytical processing. We use an eventual-consistency model to maintain the inter-relationship graph over time. HBCI does not address the challenges faced in realizing an indoor, interactive application that relies on ubiquitous network connectivity. Our architecture directly addresses this challenge, as we observe that indoor connectivity characteristics do not comply with the ubiquitous connectivity requirement for this class of application.

3 Challenge 1: Tracking People and Things

The Energy Lens app consists of a web application that displays timeseries data and an Android-based smartphone app. The android app is relatively simple; consisting of a menu with only two options: Update deployment state, scan to view services. Swipe gestures manipualte a local portion of the entity-relationship graph – local with respect to a user's current location. Since each location (room, floor) has a QR code attached to it and items are associated with those locations, we can identify the location by name (`/buildings/SDH/spaces/4F/toaster`).

The first set is called a 'registration' swipe and we use it to register new items. The user scans a QR code and the item it is attached to. This creates an 'attached-to' link between them. Adding, removing, binding, and attaching items is done with a pair of swipes. A lookup is done with by swiping the QR code attached to an item.

We have designed a set of heuristics for setting the location during an update, that piggybacks on the swipe gesture. The following is a list of rules for automatically setting the location of people and things:

- When a user swipes at a location L, they are presumed to be at L for fixed period τ. An "association timer" is set to release this association after τ seconds.
- If the user swipes anything that is associated with a location l at time $t \leq \tau$, and $l(t) \neq$ L, then we set the new location of the *thing* they swiped to l(t) and reset the association timer.
- If the user swipes anything at location l at time $t \geq \tau$, we set the location of the *person* to l(t). We reset the association timer to τ.
- If a user registers a new location, they are presumed to be at that location.

For each of these, we provide an interactive option to ask for location-change confirmation from the user. So if we think the user/item has moved but they have not, the preset action can be overridden. The guiding principal we follow in our design is to leverage the swipe gesture for as much contextual information as possible. Furthermore, we do not explicitly track users. Context is only set on the phone and used in operations sent to the server.

We construct the entity relationship graph through naming in StreamFS. StreamFS uses filesystem constructs, such as symbolic links and hierarchical naming which are useful for expressing an acyclic graph structure (StreamFS checks for cycles when symlinks are created). Registered meters are placed in the device path, `/dev`. Items are stored in `/inventory`. QR codes are stored in `/qrc`. When an item is registered a symbolic link is created from the specific qr code directory to the item. `/spaces` contains a hierarchy of floors, rooms, and sub-spaces. `/users` contains the list of usernames. We also have a `/tax` directory, where we construct an device hierarchy for access by plug-load category. Placement (location) is also captured with symbolic links.

4 Challenge 2: Consistency Management

We use an eventual-consistency model for maintaining the ERG over time. Naturally, the spatial inter-relationships change over time as items are moved and replaced. In order to deal with this we offer two options: 1) we periodically re-scan the items and their locations, essentially re-capturing the inventory collection portion of the audit or 2) we allow building occupants to participate as auditors, capturing their own personal items and shared items. This should provide at least as much value as a periodic energy audit and can be completed in a fraction of the time [7].

5 Challenge 3: Disconnected Operation

Although connectivity is ubiquitous, network access is not. This occurs due to dead zones, idle-disconnect and failed hand-off between access points. When encountered in practice, especially while editing deployment state, it can be quite frustrating and discourage use of the application. We designed a mechanism that does smart caching, not only to improve performance, but also to allow for disconnected operation.

The process is demonstrated in Figure 1. The components shown are the *ERG cache*, the *operation log (OpLog)*, and the *prefetcher*. We separate the steps in the figure as a READ sequence and a WRITE sequence. All reads go to the cache (steps 1 and 2 on the left hand side of the figure). Writes go through the OpLog (steps 1 - 5 on the right side of the figure). For writes, the application makes a write request (1) and it is forwarded to StreamFS (2). If StreamFS is reachable and the write is successful (3), the operation is applied to the ERG cache (4) and the response is sent the application (5). If the operation is not successfuly, step 4 is skipped. If StreamFS could not be reached, step 3 is skipped, and the opera-

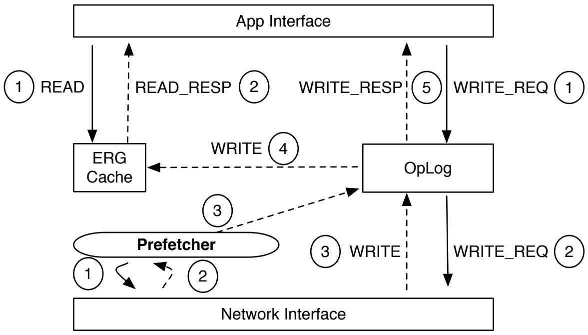

Figure 1. Standard mechanisms for consistency management on the phone. All READ request go to the local cached version of the ERG. All WRITES must go through the OpLog.

6 Deployment Experience

We deployed 20 ACme power meters [5] on a single floor of a building on campus. The data was made available through sMAP [2] and forwarded to our processing and data management layer, StreamFS [1]. We distributed the ACmes throughout a single floor in our building and registered various plug loads as being measured by them. We also tagged hundreds of items and locations throughout the entire building. In total we tagged 20 meters, 20 metered items, 351 un-metered items, and 139 rooms over 7 floors. Figure 2 shows three screen shots of power traces obtained from the ACme deployment, and displayed through the Energy Lens.

In our initial deployment we found that the use of our tracking scheme to be effective, especially in conjunction with interactive confirmation. The ERG was effective at capturing deployment state, although highly mobile items, such as laptops, were particularly difficult to keep track of. Finally, our disconnected operation mechanism was effective at masking intermittent connectivity. For future work we will baseline the floor's energy consumption before and after the deployment and measure if more visibility and analytics indeed motivates occupants to use less.

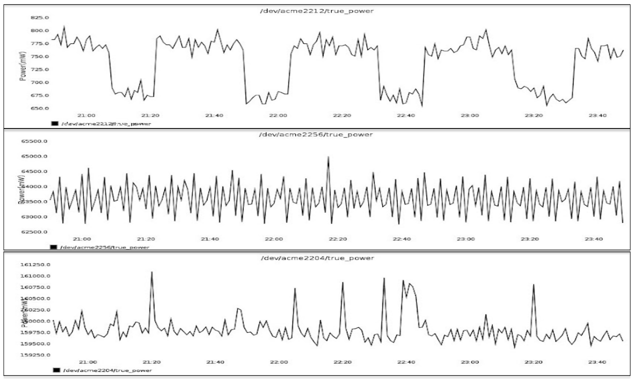

Figure 2. Power traces obtained from power meters attached to various plug load on one of the floors of a building on campus. These show screen shots of the Energy Lens timerseries data display.

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