Micro-Blog: Sharing and Querying Content Through Mobile Phones and Social Participation

Shravan Gaonkar
Dept. of CS
University of Illinois
gaonkar@uiuc.edu

Jack Li
Dept. of ECE
Duke University
jack.li@duke.edu

Romit Roy Choudhury
Dept. of ECE
Duke University
romit@ee.duke.edu

Landon Cox
Dept. of CS
Duke University
lpcox@cs.duke.edu

Al Schmidt
Verizon Inc.
Boston, USA
al.schmidt@verizon.com

ABSTRACT

Recent years have witnessed the impacts of distributed content sharing (Wikipedia, Blogger), social networks (Facebook, MySpace), sensor networks, and pervasive computing. We believe that significant more impact is latent in the convergence of these ideas on the mobile phone platform. Phones can be envisioned as people-centric sensors capable of aggregating participatory as well as sensory inputs from local surroundings. The inputs can be visualized in different dimensions, such as space and time. When plugged into the Internet, the collaborative inputs from phones may enable a high resolution view of the world. This paper presents the architecture and implementation of one such system, called *Micro-Blog*. New kinds of application-driven challenges are identified and addressed in the context of this system. Implemented on Nokia N95 mobile phones, Micro-Blog was distributed to volunteers for real life use. Promising feedback suggests that Micro-Blog can be a deployable tool for sharing, browsing, and querying global information.

Categories and Subject Descriptors

C.2.4 [**Computer Communication Networks**]: Distributed Systems – *Distributed Applications*; C.2.4 [**Computer Communication Networks**]: Network Protocols; H.4.3 [**Information Systems Applications**]: Communications Applications – *Information Browsers*; H.5.3 [**Information Interfaces and Presentation**]: Groups and Organization Interfaces – *Collaborative Computing*

General Terms

Design, Experimentation, Measurement, Performance, Human Factors

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Keywords

Mobile phones, participatory sensing, blogging, social networks, energy-aware localization, location privacy, context-aware search, geotagging

1. INTRODUCTION

Wireless sensor networks export information about the physical environment to computer systems by forming ad-hoc topologies and aggregating or streaming thousands of local observations to a central location [1–4]. This model has been most successful in scientific and military settings such as wildlife surveillance [2], volcano monitoring [5], vehicle tracking [6], and environment sensing [7]. These networks are practical because sensor nodes such as Crossbow motes provide an attractive price-performance ratio [1]. Motes' low cost makes installations of hundreds or thousands of observation points feasible. The affordability of such large networks allows deployments to cover large geographic areas and creates redundancy for overcoming the high failure rate of individual nodes. Yet despite being relatively inexpensive, motes' computational and communication technologies are powerful enough to support a wide range of complex distributed applications.

Mobile computing hardware is approaching a similar price-performance moment in which powerful, low-cost commodity devices will enable a new generation of *participatory sensing* applications [8]. In particular, commodity mobile phones with a variety of sensors (cameras, GPS, accelerometers, health-monitors) are already widely deployed and becoming more ubiquitous each year. Each phone can be viewed as a "virtual lens", capable of focusing on the context surrounding it. By combining the lenses from billions of active phones, it may be feasible to build a "virtual information telescope" that enables a high-resolution view of the world. This vision is illustrated in Figure 1 – Micro-Blog aims to translate this vision into a widely deployable service. The central idea is as follows:

Mobile phone users are encouraged to record multimedia blogs on-the-fly, enriched with inputs from other physical sensors. The blogs are geotagged and uploaded to a remote server that positions these blogs on a spatial platform (e.g., Internet

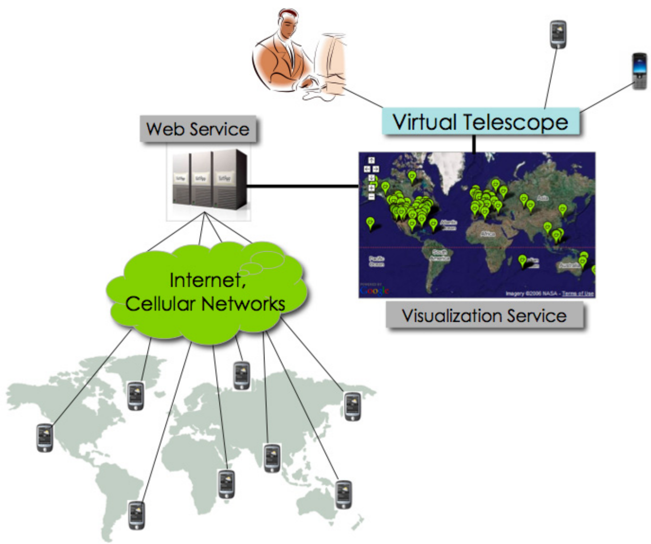

Figure 1: A high level view of the virtual information telescope. User generated/sensed content are posted on a location-based map. Internet users browse and query this content. Queries are resolved through participatory or automatic sensing.

maps). Internet users can zoom into any part of the map and browse multimedia blogs at those locations. Moreover, users may query selected regions for desired information. Queries are serviced either through explicit human participation, or automatic physical sensing.

One of the key technological challenges faced by Micro-Blog is that the application needs to resolve a tension between localization accuracy and battery lifetime. Devices often have access to multiple localization services, and reasoning about each of their tradeoffs is non-trivial. For example, GPS can be accurate to within several meters, but can drain a mobile phone's battery within seven hours. WiFi based localization [9] can improve battery lifetime at the expense of higher localization error, and is limited to dense war-driven urban areas. GSM localization is widely available and extremely energy efficient, but is accurate to hundreds of meters. Micro-Blog addresses this challenge by switching between different schemes with the aim to achieve an application-specific balance between accuracy and battery life.

We have evaluated our Micro-Blog prototype using energy and localization experiments, trace-based simulations, and a small-scale deployment among 12 volunteers. Our localization benchmarks and simulations demonstrate that our scheme is feasible, while feedback from the user study was positive. As a result, we believe that Micro-Blog represents a promising new model for mobile social collaboration.

The rest of this paper is organized as follows. Section 2 describes the Micro-Blog framework with potential future applications that may be feasible. Section 3 discusses related work, followed by architectural considerations in Section 4. The system implementation is presented in Section 5, with evaluations in Section 6. Section 7 discusses limitations and ongoing work, and Section 8 concludes with a brief summary.

2. MICRO-BLOG SERVICE DESCRIPTION AND APPLICATIONS

Figure 1 illustrates the technological overview of Micro-Blog. Taking advantage of phone sensors, users are encouraged to record multimedia blogs on-the-fly. Blogs may be enriched with a variety of sensor inputs, such as accelerometer vibrations, health sensors, WiFi SSIDs. The phone application associates the blog with the time and location of the device, creating what we call a "microblog". The microblog is transported over an available wireless network such as WiFi or cellular, to a web-accessible database. The microblogs are then positioned on a spatial platform, such as Google Maps or Microsoft SensorMap [10]. A variety of web services can be used to mine, group, and correlate blogs based on interests, themes, and social networks. An Internet user can zoom into any part of this world map, and browse streaming content originating from that region.

Querying in Micro-Blog:
When specific content is not available on the map, users can mark out a geographic location and direct queries to phones located near it. Human responses to these queries can be placed on maps as well, facilitating a platform for location-aware content sharing over mobile devices. The responses may also be stored in a database, and later used to answer new queries that seek similar information. Since the query-response interaction occurs in human languages, it can be sophisticated and often subjective in nature. Issues such as incentives and privacy are also pertinent challenges for the Micro-Blog platform.

Importantly, not all queries may warrant explicit human participation: (i) One category of queries may require the phone to automatically sense and dispatch events. Accelerometer readings from phones of automobile riders [12, 13], or open WiFi SSIDs near a street cafe are two examples. (ii) A slightly different category may require a very low level of individual participation. In this category, a query might have a long expiry time, and may suffice if at least one among many people replied to it over a large time window. The quality of tourist experience at an island could be one example. Micro-Blog enables the entire range of location-aware querying, without any guarantees on whether the queries will be serviced. Live case studies with Micro-Blog suggest that users are cognizant of the lack of guarantees and are yet interested in asking questions to different parts of the world.

Micro-Blogs at Physical Locations:
In addition to superimposing them on virtual space (Internet maps), microblogs may also be superimposed on physical space. An individual's microblog about a restaurant may "float" near the restaurant, and can be pushed to other people's phones when they arrive at that physical location. A general publish/subscribe system can evolve that automatically sifts through floating microblogs, and draws user-attention to those of interest. Further, the database of floating microblogs can be queried, modified, or updated through the interface of mobile phones and social participation.

2.1 Micro-Blog Applications

In this section, we describe several potential applications that may emerge on the Micro-Blog platform.

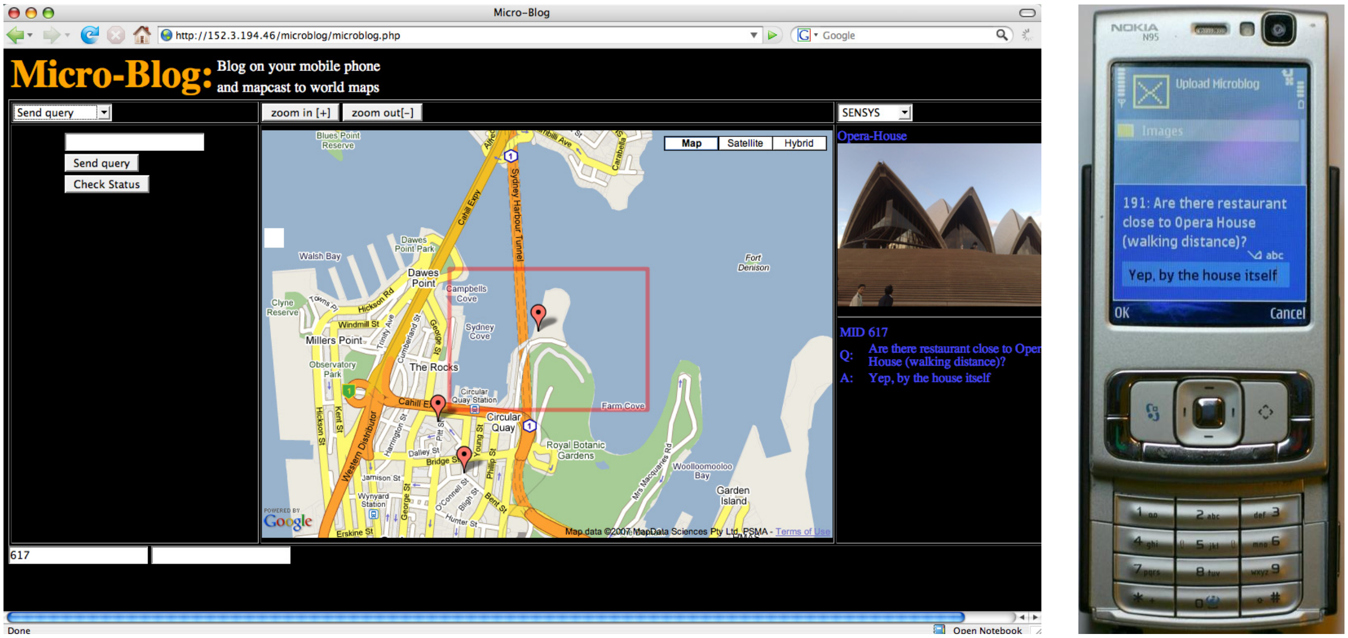

Figure 2: Micro-Blog screenshot and phone query: A microblog of the Opera House in Sydney, Australia, shown on the map. The multimedia blog plays on the right panel. The Internet user selects a region (shown by a square box on the map), and sends a query to phones in that region. The phone on the right, physically located in Sydney, receives the query. The user replies to it, and the reply is transmitted back to the server. The query and reply are associated to the blog, as shown in the right panel. This microblog was created during our demonstration of Micro-Blog at ACM Sensys 2007 [11] held in Sydney, Australia.

Tourism: Imagine an internet map (e.g., Google Maps) punctuated with numerous icons, each having a "Play" button. An Internet user, Jack, planning a vacation to a beach, navigates to *Carolina Beach, USA*, and clicks on one of the "Play" buttons. An audio-visual microblog is played that describes an anonymous tourist's experience at the beach while she was there a few weeks back. Although useful, Jack decides to browse a few other blogs located around the same geographical region. Unfortunately, none of the blogs he played discussed parking facilities near the beach, an important criterion in Jack's beach selection. Therefore, Jack records his query on his laptop's microphone, marks out a destination region around the beach, and sends the query to phones in that region. Since he wants to finish planning soon, he specifies the query to be valid for 1 hour.

Tourists located within the marked region of the beach, those that have Micro-Blog services turned on, find a pop up query on their mobile phones. Only a few people respond by recording their replies into their phones and adding pictures of the parking spots (a new microblog). Soon, Jack sees the visual details about parking at the Carolina Beach and is happy with the situation. While nearly convinced, he directs just one more query to phones on the beach, requesting information about availability of WiFi access points. WiFi interfaces on some phones resolve this query and return the scanned SSIDs and signal strengths – the phone user does not participate in generating this reply. Satisfied with the outcome of his research, Jack proceeds to search out a good hotel using Micro-Blog.

Figure 2 shows a screenshot of a microblog interaction, and the corresponding activities on the phone. We describe the details of our system later in Section 5.

Micro-News: It might be feasible to develop a news service in which citizens play the role of journalists, reporting audio-visual events in the context of their lives. News may also be derived from automatically sensed information from mobile phones, such as the air quality of a region of interest. Subscribers to such news channels can search extremely high resolution news about any place/topic/event of interest. The spontaneity of capturing information with phones, and the ease of publishing them, can make such a news service different from Internet based blogging sites.

Micro-Alerts: Superimposing microblogs on physical space can act as location-aware alerts. When walking paths in a university campus are not available on Internet maps, microblogs can be virtually placed at different spots with instructions to reach different department buildings. A lost user, trying to reach Building X in the university, can download pre-recorded walking directions from her current location to building X. Metaphorically, micro-alerts are like virtual sticky notes floating on physical space.

Social Collaboration: In general, applications on Micro-Blog may connect those who need services to those who can offer them. (1) We envision the possibility of on-the-fly car pooling where ride-takers can dynamically establish a connection to nearby ride-givers, reducing fuel consumption. (2) Rural healthcare may benefit from Micro-Blog. Surveys have shown that villagers have a high financial/logistic cost of visiting doctors, and often underplay their illnesses as an excuse to postpone medical visits. Even slight indications about the potential gravity of a disease can be effective in arresting a train of mistakes [14]. Micro-Blog can be a platform for providing low-cost, preliminary, health-indications. Medical practitioners can browse microblogs posted from villagers of the world, and offer preliminary indications (e.g. "you need to see a doctor immediately"). In contrast to unavailable Internet access, the widespread adoption of mobile phones may be particularly amenable to Micro-Blog. (3) Similar applications may also be feasible in the context of education, where students from rural regions post their queries, and one among many qualified users, respond.

3. RELATED WORK

Recently, a new wave of research is focusing on developing participatory platforms for people-centric mobile computing applications. The vision is engagingly articulated in [8] and [15]. We present some of the related work in this broad direction.

Project Satire [16] aims to develop smart clothes that will monitor human activity and trigger alerts in specific situations. Using accelerometer-equipped sensor motes, authors have shown the possibility to discriminate between human actions based on their accelerometer signatures. Project BikeNet [17] has demonstrated an application in which biking experiences of humans can be monitored and shared within a social circle. Through a variety of sensors attached to bikes, bikers are characterizing the experiences of bike riding over a given path. Several other applications closely relate to human activity, such as PeopleNet [18], MAX [19], SenseWeb [20], MyExperience [21], MetroSense [17, 22]

More recently, the widespread adoption of mobile phones, and the tremendous growth in their computing/communication power, have made them an attractive platform for sophisticated applications. The vision of a sensor network of mobile phones, the potentials, and underlying challenges were articulated in [15, 23]. Several systems have begun to emerge. In [13, 24], authors demonstrated the possibility of estimating traffic congestion using accelerometer readings and GPS traces from mobile phones. A range of projects are attempting to aggregate on-body health data into mobile phones [25] with the end goal of building a health monitoring and emergency response system. Project MetroSense [22, 26, 27] is developing a generic platform for urban sensing through a combination of mobile phones and sensor motes. In [28], the population of mobile phones, combined with user inputs, have been used to dynamically estimate the demographics of a region. Authors describe applications in which the visitor frequency of a tourist spot, or the spatial contour of certain gasses, can be visualized by combining the inputs from multiple phones. Several other systems and platforms are assembling mobile phone based systems that will enhance our view of of the physical/biological world we live in [15, 17, 22].

While many systems are oriented toward sensing the physical/chemical/biological surrounding, a concurrent trend in social computing and networking is becoming distinctly visible. Recently referred to as Web 2.0, this trend is exhibiting the power of combining human participation with mobile technology [29]. Authors in [30] have revealed the possibility of video communication as one way of sensing the urban environment. They suggest the possibility of performing streamed video blogging, directly from public mobile phones to content subscribers on the Internet. In [31], authors study the prospects of using mobile computing to facilitate participation and social adoption of networking technology. The study highlights interesting insights on how collaboratively participating in technology impacts the social relationship and community formation in developing regions of the world. Nokia has launched *Lifeblog* [32] that allow users to create a timeline of their activities (photos, sms, video, etc.) – a type of digital recording of one's own life. Web services such as Twitter [33], Dodgeball [34], etc. are enabling people to explicitly communicate their status to others within social networks. A slightly different type of service [35, 36] enables users to find other people of similar likings around them, and invite them to meet up on physical or virtual space.

When injected with location awareness, many of these applications are becoming even more interesting. Project AURA [37] demonstrates a prototype in which mobile phones read bar-codes from on-shelf products, and query Internet search engines to obtain product ratings and information. On similar lines, project Cooltown [38] summarizes its objective as *allowing everything to have a web page*. In another interesting project [39], messages are pushed to phones once they arrive at a location. For example, Socialight allows users to go to different places in the downtown New York, and receive memos about neighborhood activities. Authors in [40] propose a similar location-aware reminder system – users schedule reminders on their phones that are triggered only when they reach a location.

Micro-Blog is a generalization of the above ideas, augmented with the ability to query mobile phones, or their human owners. Responses to these queries can contain a mix of quantitative and qualitative information, often useful for decision making. Moreover, human participation may facilitate "distillation" of raw sensor data by combining it with the context in which they are generated. The framework to exploit human processing [41] as an instrument to overcome the limitations of device-based sensing, can potentially lead to a new paradigm in information technology. Micro-Blog attempts to facilitate such a paradigm.

4. ARCHITECTURE AND DESIGN

Figure 3 presents the client-server architecture of Micro-Blog. Recorded blogs are labeled with the locations and access permissions. A localization service is consulted to obtain a reasonable location estimation. As mentioned earlier, even when GPS is available, its continuous use may not be energy-efficient. Hence, the localization service selects one among several localization schemes (WiFi, GSM, GPS, or combinations thereof) that meet the application's accuracy/energy requirements. The location-tagged blog is transported to an application server over a WiFi or cellular connection, which in turn forwards it to a back-end database. The blogs are organized/indexed appropriately, based on blog originators, access permissions, themes, or other keys. When a client wants to access a microblog, it contacts a web server to retrieve it. The web server provides only those blogs that the user has permissions to access.

Phones periodically update the Micro-Blog server with their own locations, which maintains per-phone location in its lo-

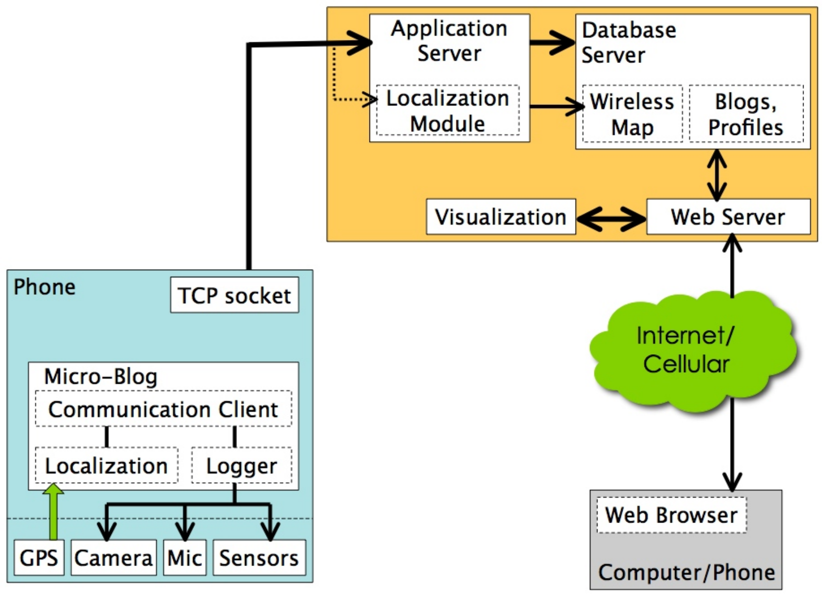

Figure 3: Block diagram of the Micro-Blog software architecture

calization database. When a user sends a query to a specific region, R, the server first determines if the query can be serviced from the database of blogs. If feasible, the server retrieves all microblogs that match the time, location, and permission attributes, and returns them to the user in reverse chronological order. Otherwise, the server selects phones located in the region R (that have declared themselves available) and forwards the query to them. Phones that arrive later at R also receive the query. When some phone responds to this query, the response is linked to the query and placed on the map as a new, interactive microblog. Queries are active for a pre-specified lifetime, configured by its originator. Upon expiry, they are removed from the server.

To achieve content distribution in physical space, the Micro-Blog server also "pushes" location-specific blogs to phones that arrive at that location. The push operation is triggered when the phone updates the server with its location. Of course, not all microblogs are pushed to phones – only channels that have been subscribed to by the respective user.

4.1 Design Considerations

Several technological challenges and social concerns underlie mobile phone based applications. Examples include (1) exhausted battery in times of need, (2) efficient localization-accuracy, (3) incentives for participation, (4) privacy, (5) spam, and several others. Some of these issues exhibit inherent tradeoffs and must be addressed in a manner that suits the application. This section presents a pertinent range of design issues and tradeoffs and discusses proposed approaches applicable in Micro-Blog. System evaluation, through measurements and user study, is discussed in Section 6.

4.1.1 Energy-Aware Localization

Issue: Location information is central to Micro-Blog. Not only is content tagged with locations, phones too must periodically report their own locations to the remote server such that they can be suitably queried. While GPS based localization provides good accuracy (around 8 meters), our measurements in Figure 4 demonstrate an unacceptable battery life of less than 7 hours, when GPS is used continuously. Even if Assisted-GPS (AGPS) is used, the improvement is only marginal. Clearly, energy-aware localization services need to be designed to balance the energy and accuracy demands of practical mobile phone applications.

Proposed Approach: Alternate localization schemes have been well studied and are widely available. Research from Place Lab [9] has proposed a variety of solutions using WiFi based or GSM cell tower based localization. However, energy-accuracy tradeoffs apply to these techniques as well. Energy consumption with WiFi based localization, although better than GPS, is significantly worse than GSM schemes. A judicious selection needs to be performed based on the application needs, residual battery power, and a phone's mobility characteristics.

Instead of choosing a static localization scheme, it might be beneficial to switch between different schemes to achieve a better energy-accuracy tradeoff. New schemes may also be designed that offer new operating points in this tradeoff space. For instance, if collaboration between mobile phones can be incentivized, it may be possible to opportunistically localize one phone using GPS beacons from others. Schemes may further adapt to residual battery power by switching to aggressive localization when the phone is predicted to get recharged soon, and vice versa. While a host of possibilities exist, we develop a simple energy-aware extension of Place Lab to suit Micro-Blog applications.
In Place Lab [9], authors create a wireless map of a region by war-driving in the area. The wireless map is composed of sampled GPS locations, WiFi access points audible at these locations, and their corresponding signal strengths. This wireless map is then distributed to phones. When a phone travels through the mapped area, it estimates its own location by matching its list of audible WiFi APs to the wireless map. Several matching schemes have been proposed, including (1)

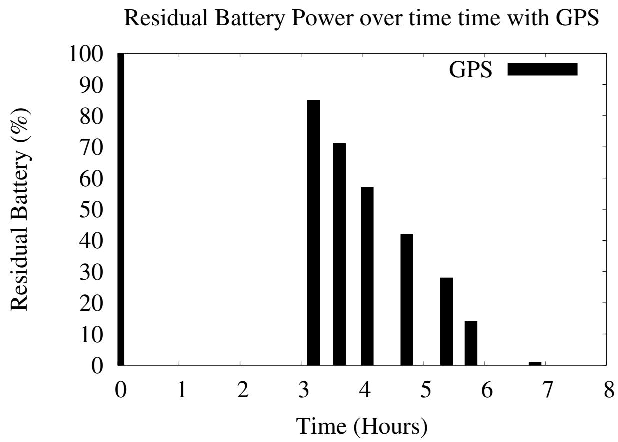

Figure 4: Energy consumption with GPS based localization for Nokia N95 phones.

Centroid Computation, where the centroid of all overheard APs is assumed to be the position of the phone, (2) *Signal Strength* based estimation, where signal strengths are used as weights in computing the weighted average of the audible APs, and (3) *Fingerprinting*, where the location of the phone is assigned to a point in the wireless map which is closest in terms of an euclidian metric. Experiments show that Place Lab is capable of achieving a median positioning error of 13 to 40m. Employing a similar technique with GSM cell towers increases the localization error range from 94 to 196m, but provides a greater service area. The experiments were mostly performed in the downtown area of Seattle with reasonable WiFi and GSM coverage.

Micro-Blog augments Place Lab with an energy-aware optimization. The basic idea is as follows. A phone switches between multiple localization schemes, such that the localization accuracy can benefit from the more accurate scheme, while battery life can improve due to the more energy-efficient scheme. Without loss of generality, we explain the strategy using WiFi and GPS only.

Using our scheme, a phone remains in the WiFi mode by default, and periodically computes its estimated location. When it finds that the WiFi fingerprint is not changing over time (an indicator of no macro movement), it determines its GPS location once, and uses it for subsequent blogging functions. The location error is expected to remain minimal while the node is stationary[1]. However, once the phone detects movement (inferred from changes in audible WiFi SSIDs) it begins estimating the distance it has moved and the approximate velocity. When the distance moved becomes greater than a particular threshold, δ, the phone records its GPS location once again, and computes the current error in WiFi localization. Let t_0 denote any time instant at which the phone takes a GPS reading. In subsequent time steps, t_i, the phone estimates its location through a simple linear interpolation using the precise GPS location from the past, $L_g(t_0)$, and its WiFi-estimated location, $L_w(t_i)$. The weights of the linear interpolation is derived from the estimated velocity, v_{est}. More precisely, at time t_i, the interpolated location is computed as $L_{w+g}(t_i) = L_g(t_0) + i \times v_{est}$ along the straight line joining $L_g(t_0)$ and $L_w(t_i)$. The interpolation is performed for τ time steps, after which the phone does not utilize the knowledge of its past GPS measurement. When the phone has moved greater than δ distance since time t_0, it samples its GPS location again. Figure 5 shows the proposed interpolation scheme. The same idea can be applied for switching between GSM and WiFi. Each of these combinations will lead to a new operating point in the energy-localization tradeoff space, offering the application to select one that suits it best.

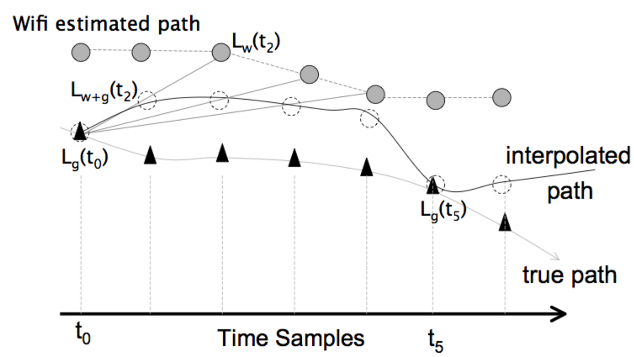

Figure 5: Interpolation between two localization schemes to achieve the advantages of both.

Of course, this simple interpolation scheme does not achieve optimality by any means. Moreover, if users take sharp turns in their movement path, it may not trigger a change in the WiFi-estimated location for a long duration. As a result, the proposed scheme will continue to extrapolate the original direction of movement, potentially resulting in greater inaccuracy. The correction will occur only when the WiFi fingerprint is itself updated (i.e., $L_w(t_i)$ changes). Furthermore, the parameters of δ and τ need to be carefully chosen, based on mobility patterns, desired localization accuracy, and energy budget. We believe energy-aware localization in mobile phones is an open research problem, and merits individual research attention. Developing optimal, application-aware solutions is a part of our ongoing research.

4.1.2 Energy-Aware Applications

Issue: Energy-aware decisions are often influenced by the application requirements. From the end-user perspective, some operations may be sacrificed for improved energy-efficiency, while others may be critical for acceptable performance.

Proposed Approach: We have incorporated two simple forms of energy awareness in Micro-Blog.

(1) When a blog is created by the user, the application records the current GPS location to maximize the accuracy of blog placement (on Google map). However, when a phone periodically reports its location to the Micro-Blog server, it uses a WiFi or cell-based localization, or combinations thereof. Since the exact location of the phone may not be critical for spatial querying, lower accuracy is tolerable.

[1] In the absence of a better localization scheme, we assume that GPS location is the ground truth.

(2) Micro-Blog delays uploading blogs if it finds that the residual battery power is below some threshold. The blog is transported only after the phone has gained sufficient charge, such that the residual energy does not go below the threshold even after expending the blog-transmission energy. The default threshold is set to 72% of the battery life, and is a parameter that can be changed by the user. The transmission energy is calculated as a function of the blog-size. While postponing blog transmission increases the delay of posting blogs, it assures users that the phone retains energy for unforeseen emergencies. User feedback show that the facility to set this threshold was a valued feature.

4.1.3 Incentives

Issue: As described, querying Micro-Blog assumes that users respond to queries even when they are generated by strangers. A natural question to ask is *why would anyone agree to reply to a stranger's queries when replying costs battery power and the user's attention?*

Proposed Approach: We propose to handle incentives through two mechanisms: social networks and explicit incentive mechanisms.

(1) Queries could be restricted to within social networks. In such cases, users may not need a well defined incentive to reply to queries from friends. While this approach facilitates participation within a social group, it does not encourage communication between strangers, confining content distribution only within social clusters.

(2) In the absence of an underlying social network, Micro-Blog can apply a "give and take" approach to incentives. Initially, a user would be registered with a pool of n free query credits. Every time she initiated a new query, her count would be decremented, while every response she generated would increase her count by K ($K \geq 1$). The value of K can vary based on the global balance of queries and responses. In the worst case, K could be 1, requiring each user to respond to one query before initiating a new query. However, if the system exhibits healthy participation, K could be increased.

Unfortunately, colluders could also initiate bogus queries and responses to artificially inflate their query totals. We draw upon existing graph theoretic approaches to address this problem. A directed link between two nodes, (i, j), can denote a query; the cost of the link can represent the number of queries from i to j. If a clique of nodes are identified such that the cost over all the links are greater than a threshold, then these users will be under suspicion of misbehavior. These users can then be penalized either through a reduction in their query credit, or by some other mechanism.

Incentives are also necessary to cope with the financial costs of using Micro-Blogs. Mobile phone service providers typically charge for data transmission/reception, and microblogging multimedia content can incur non-marginal costs. However, with commoditization of mobile phones, applications and services will play a critical role in customer retention. Trends show that services will be offered free to customers, as a value added package to basic voice communication. Micro-Blog is envisaged to be one of the applications included in such a package.

4.1.4 Location Privacy

Issue: Placing blogs at its location of creation reveals the whereabouts of the blog's originator. This presents several location-privacy challenges.

Proposed Approach: Since users periodically transmit their location to a central server, they must trust server administrators to manage this data properly. This appears to be a fundamental drawback of the Micro-Blog architecture, although techniques from related work that allow clients to securely exchange locations through a mutually untrusted intermediary may be applicable [42].

Nonetheless, we currently assume that users are willing to trust the Micro-Blog service. In the simplest case, a Micro-Blog client operates in three modes: *private*, *social*, and *public*. The private mode can be restricted to individual viewing only – e.g., microblogs about a user's honeymoon trip may be tagged private, meaning that it can only be viewed by the user. The social mode could only be visible to members in the user's social network, while the public mode can be open to all Micro-Blog users. A user's current location can be tagged similarly. A user that wishes to be "social" may be forwarded queries from members in her social networks. If the user is willing to be "public," anyone may send her a query. When in the public mode, a user may choose to assume a pseudo-identity such as a nickname. In addition, a user can obfuscate her location through her localization service. For example, switching a device into cell tower localization intentionally introduces uncertainty about a user's whereabouts. Micro-Blog provides a GUI on the mobile phone that allows users to control these privacy preferences.

4.1.5 Spam

Issue: The problem of unwanted queries or spam is similar to the incentives problem described in Section 4.1.3. We apply a similar solution.

Proposed Approach: We allow users to regulate the type of query traffic that they are willing to receive. While a user is in social mode, she may wish to receive at most Q_{ss} queries per day from members of her social network only. Of course, Q_{ss} can be zero. In the public mode, she may wish to receive at most Q_{ps} queries from her social network, and at most Q_{pp} queries from the public. We set the default values as: $Q_{ss} = 5$, $Q_{ps} = 5$, and $Q_{pp} = 2$. The values can be configured at any time. When a user activates Micro-Blog or changes these configurations, the phone updates the server with these parameters. The server blocks queries in accordance.

4.1.6 Content Inaccuracy

Issue: Because microblogs can be generated without any centralized oversight, their content can reflect (intentionally or not) inaccurate information.

Proposed Approach: In public mode, users can be assigned reputations, based on the ratings other browsers assign to her microblogs. If a user's microblogs continue to receive low ratings from others, then her reputation will decrease. The reputation of the user is translated into a confidence value reflecting the server's confidence in that blog. When a user is below a threshold reputation, microblogs from that user is not published. While this scheme cannot immediately identify a false content, over time, a misbehaving user can be identified. Of course, Micro-Blog has no way of preventing users from exploiting a strong reputation to make an inaccurate microblog more believable.

5. SYSTEM IMPLEMENTATION

The Micro-Blog phone client, implemented on Nokia N95, is approximately 6,000 lines of code using the Carbide C++ compiler supported by the Symbian OS platform[2]. The server is approximately 7,500 lines of code across C++, PHP, Ajax, and MySQL. We present the details next.

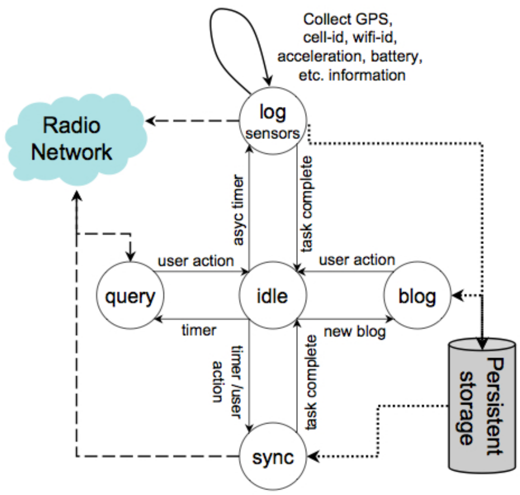

Figure 6: Finite state machine of the Micro-Blog client operation.

5.1 Phone Client

The Micro-Blog phone client has been developed using Nokia's Carbide C++ (version 1.2) in the Windows environment. The software requires access to the location services, network services, and the file-system on the phone. The Nokia S60 3^{rd} edition SDK provides the necessary APIs for this. However, Symbian applications need to be signed with appropriate certificates. We obtained a developers certificate based on the phone's IMEI identifier.

The Micro-Blog client is designed to minimally interrupt the normal operations of the phone. Figure 6 presents the state diagram for the software. By default, the client is in the *Idle* state. When the user initiates a new blog, the client makes a transition to the *Blog* state and tracks all the user-generated content being added to the file system. Once completed, the content is tagged with the phone location. To allow offline blogging, e.g., blogging about a vacation while driving back home, Micro-Blog allows users to explicitly modify the location of a blog. The user can visit a map on the phone, determine the location of where the pictures/videos were taken, and assign these coordinates to the microblog. Once the user clicks the send button, the client switches to the *Sync* state, and transports the blog to the server over a TCP connection. The software then returns to the *Idle* state.

[2]Initially we implemented a large part of Micro-Blog in the Java J2ME platform, but were unable to access some of the lower level information such as multiple WiFi MAC IDs, signal strength information, cell tower IDs, etc.

Micro-Blog implements a periodic polling mechanism to monitor inputs from phone sensors. The application transfers to the *Log* state whenever a poll returns a new result, or if some of the asynchronous sensors trigger an alert. Sensor data, including location, WiFi SSIDs, GSM tower IDs, and signal strengths, are logged on the phone's file-system. Upon completion, the client returns to the *Idle* state.

When a user configures the phone to be visible on the map, the client application initiates and maintains a persistent TCP session with the remote server. Location coordinates are periodically uploaded to the server, along with requests for new queries. If the phone qualifies for some pending queries (depending on permissions, social memberships, etc.), the queries are forwarded to the phone. The client transitions to the *Query* state, displays the query on the phone, and waits for user action. Once the reply is created, the phone transports it back to the server and returns to the *idle* state. A few screenshots of the phone display are presented in Figure 7.

Figure 7: Screenshots from the phone display main blogging functions, permission configuration, and sensor logs.

5.2 Web Infrastructure

Data from phones is received at a Micro-Blog application server. The server accepts TCP connections from phones, and forwards all received data to a back-end MySQL (5.0) database server. Depending on whether the data contains blogs, localization information, or user profile configuration, it is appropriately stored in relational tables. If the arriving blogs prove to be replies to some earlier query, then they are suitably associated to the query, and forwarded to the visualization service.

We have installed an Apache (2.0) web server to offer HTTP access to Micro-Blog over web browsers. Users login into our service, and can request blogs for any region of the world. The request for that region is received at the web-sever, and communicated to the database server through PHP (5.0) and Javascripts. Microblogs associated to that region are returned

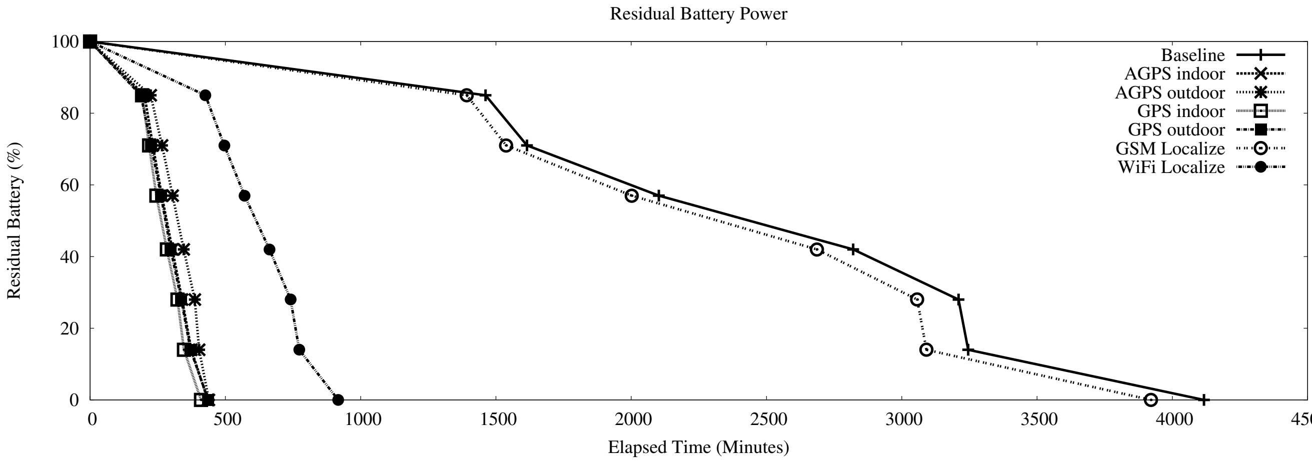

Figure 8: Energy consumption due to GPS, AGPS, WiFi, and GSM based localization in comparison to a baseline scheme. Experiment performed on Nokia N95 phone platform.

to a visualization service that displays the blogs on Google maps through Ajax programming with the JMaki toolkit. The webpage is returned for the user to browse. A user query is transported to the server, along with the corner locations of the marked (square) region (see Figure 2). The query is executed to obtain all phones that are available to service this query. It is then routed to all these phones over the active TCP connections. Phones that do not have a live connection to the server cannot be contacted. When the query is persistent, it is held at the server for the specified lifetime. When new phones connect to Micro-Blog, the database checks if the phone satisfies the constraints, and accordingly pushes the query to them. Once a response arrives for a query, the database associates the response to the query, and sends it back to the query-originator (if the HTTP connection is still open). The response is also recorded in the database; the user can view the responses to her queries when she logs in later.

6. EVALUATION

Micro-Blog was evaluated using off-the-shelf Nokia N95 phones. The tradeoff between energy awareness and localization error is of interest. We characterize this tradeoff for WiFi, GSM, and GPS based localization schemes.[3] We also characterize the tradeoff when using our proposed scheme of switching between WiFi and GPS, as well as GSM and WiFi.
To understand social aspects of Micro-Blog (e.g., willingness to participate, incentives, privacy concerns), we performed case studies with volunteering university students. We report interesting comments and feedback from questionnaires and exit interviews.

6.1 Battery Life and Location Accuracy

To measure the maximum battery life of the phone, we monitored the rate of energy consumption when no applications were running on it. We call this the *Baseline* scheme as shown in Figure 8. We then measured the battery life for GPS and AGPS services[4], also shown in the same figure. Evident from the graph, the battery life of GPS and AGPS were far below the maximum. Even when GPS was invoked less frequently (every 1 minute and 2.5 minutes), the lifetime proved to be less than 10 hours. Future mobile phone applications will frequently require location updates, and using GPS-based localization will be an energy-inefficient solution.

To understand the energy profile of alternate schemes, we implemented WiFi and GSM based localization, originally proposed in Place Lab [43]. The Place Lab algorithms (centroid, signal strength based, and fingerprinting) demonstrated comparable energy consumptions, and we report only the fingerprinting scheme in Figure 8. Evidently, GSM required least energy resulting in a lifetime of more than 60 hours. In contrast, WiFi achieved around 16 hours of continuous localization. Improvements of around 30 minutes were visible when WiFi localization was invoked less often (once in 10 seconds).

While battery life improved with alternate localization schemes, there was a proportional reduction in location accuracy. Figure 9 characterizes the localization error from the WiFi-based fingerprinting scheme, which proved to be the best alternate to GPS in our university campuses. A similar experiment with GSM resulted in a a much larger error of around 600m. Table 1 briefly summarizes this energy-accuracy tradeoff.

	GPS	WiFi	GSM
Approx. Life	7.8 hours	20 hours	63 hours
Approx. Error	8m	25m	600m

Table 1: Energy-accuracy tradeoffs for different localization schemes evaluated at the Urbana-Champaign and Duke University campus. Both campuses exhibited similar trends.

[3]We admit that our performance analysis is specific to the hardware platform in use, and may not accurately reflect other platforms.

[4]In AGPS, a phone's GPS receiver gathers the signals from GPS satellites, and sends them to the cell tower. The tower computes the location of the phone, and sends it back to the phone, saving computation energy at the phone. The AGPS location is often more accurate than GPS because the cell tower may be equipped with local terrain information that impacts the reception of satellite signals.

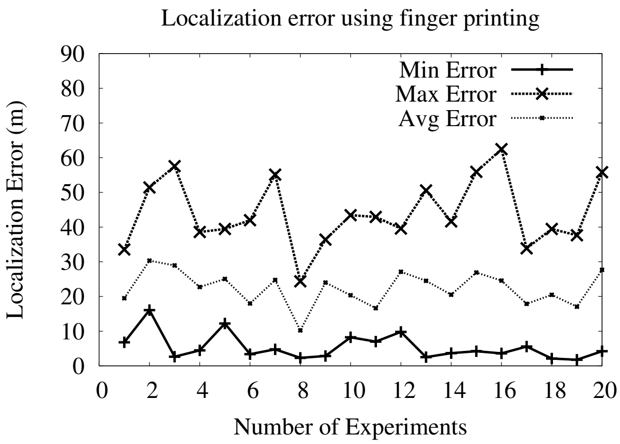

Figure 9: Minimum, Maximum, and average error based on localization using WiFi fingerprinting.

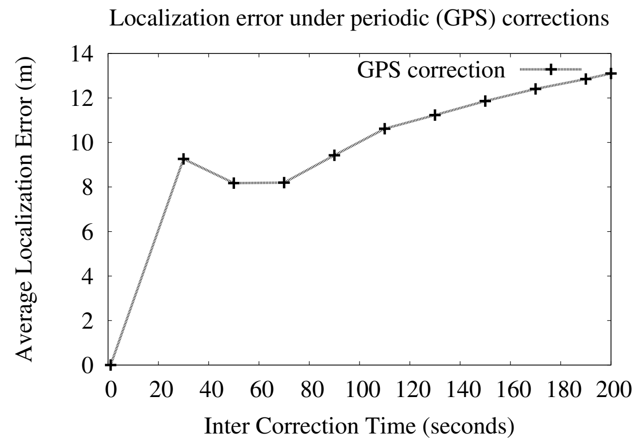

Figure 10: Localization error with a combined GPS and WiFi scheme. Standard deviation in the experiment was 7.2132m.

We evaluated the proposed multi-mode localization scheme using two combinations: (1) WiFi with periodic GPS corrections, and (2) GSM with periodic WiFi corrections. The evaluations were performed on real traces collected by war-driving around the university campuses (for calibration), and then walking/driving as a Micro-Blog user (for location estimation). The simulator was written in Java. Figure 10 shows the error when WiFi localization was used as default, and GPS measurements were invoked at increasing intervals (on the X axis). The graph is an average of 514 path segments of the phone, each moving in random directions for 50 meters over the entire campus. Evidently, interpolation between WiFi and periodic GPS measurements improves accuracy over WiFi alone. Except for one anomaly, the accuracy is greater for higher GPS frequency. However, the battery life of this interpolation scheme decreases due to frequent GPS readings. The tradeoff is characterized in Figure 11. The graph shows that the overall improvement in the WiFi+GPS scheme appears minor. The curve displays a knee at around 17 meters on the x axis. For localization errors less than 17 meters, the WiFi measurements do not contribute much because WiFi-based fingerprinting cannot distinguish between movements within that resolution. As a result, the WiFi energy is mostly wasted. As the localization accuracy decreases, WiFi fingerprinting plays a more important role in the interpolation, and hence, the benefits become visible.

We performed the above experiments with a combination of GSM (as default) and WiFi fingerprinting (being measured periodically). Figure 12 shows the results from the experiments. Clearly, when battery life is of interest, the GSM+WiFi scheme offers a useful spectrum of tradeoff. Tolerating a localization error of 125m can lead to around 25 hours of battery life. In certain applications, including Micro-Blog, such an error may be acceptable, especially in light of obfuscating the actual location of a user for privacy purposes. In view of this, we adopt the GSM+WiFi localization scheme in Micro-Blog, permitting the phone to survive for longer than one full day. Of course, users are offered the option to modify this setting, if they intend to improve their localization accuracy.

To understand the overall energy performance of Micro-Blog,

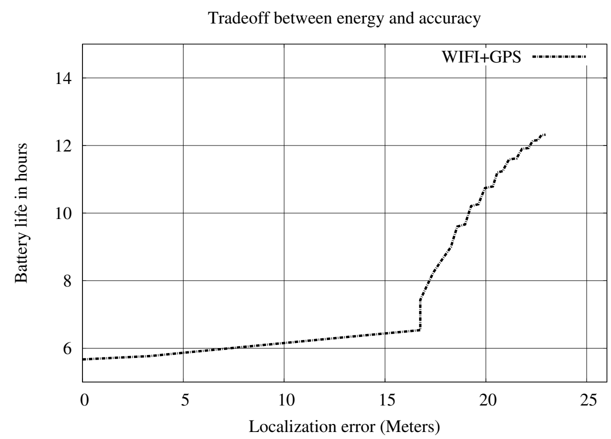

Figure 11: Energy accuracy tradeoff with proposed WiFi + GPS interpolation heuristic.

we requested a student to blog in the university campus. The energy logger recorded the residual energy and all blogging activity, including camera, GPS, audio recordings, and WiFi based data upload. A combination of GSM and WiFi was used, with the desired localization accuracy set to 50m. The sum of all Micro-Blog activity lasted for 5 hours 40 minutes. This included uploading of 18 multimedia blogs and replies to 4 text queries for a total of 24 MB, and continuous reporting of the phone's current location. After 5.6 hours of activity (at 6:00pm), localization and transmission activity was stopped because the residual battery power dropped to 28%. We recorded substantial power consumption due to the camera flash, and some due to voice calls made during the day. The battery lasted for around 21 hours before draining out completely in the night.

6.2 Case Studies

Nokia N95 phones were distributed to a set of 12 volunteering students. Students were trained with the Micro-Blog interface, and told that their "social" blogs would be protected by a password that they will be allowed to choose. Blogs cre-

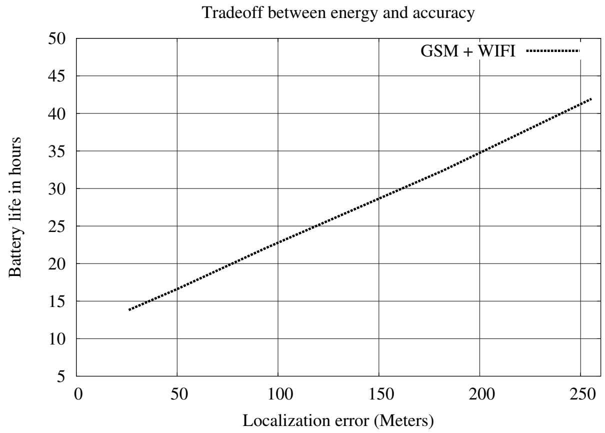

Figure 12: Energy accuracy tradeoff with proposed GSM + WiFi interpolation heuristic.

ated in the "public" mode would be open for global viewing. Queries were sent when phones were observed at a location of interest; some of the members in this project volunteered to send queries when they identified an opportunity. Students were guaranteed that their blogs would remain fully confidential. Each student was also given a questionnaire, and was requested to fill it out only after he/she had performed a few microblogs. When students returned the phone, we performed an exit interview. We summarize the user experiences and feedbacks from this study.

Fun activity for idle time, but needs to have "cooler" GUI: Most students agreed that it was fun to "capsule" events, especially when they were idle/free (e.g., waiting for busses, or on Friday nights). However, since it was near the end of the semester, students found it difficult to find excess free time. This resulted in fewer blogs than expected. They also complained about an unfriendly user interface – in several occasions, the phone had to be rebooted while trying to send a large picture. Some students also forgot to take the additional phone, and was unable to blog for long durations.

Privacy control vital, and replies more interesting: Most blogs were tagged private. While it appeared that students were protective about their content, opinions from the exit interview were surprising. Students expressed that "*everyday events did not seem exciting to be posted to a global forum*". Since most blogs were meaningful only to the individual, and his/her social circle, they were tagged private. Rather interestingly, one comment was "*replying queries would be easier because it reflects specific interests of an outsider about my surrounding*". There was unanimous agreement that privacy control configuration was vital, especially for location tracking.

Incentives not an issue if its fun: Except 3 users, all others were enthusiastic about the idea of replying to queries, as long as the traffic could be controlled. The 3 concerned users were skeptical of receiving queries that did not match their interests. Also, users were sometimes annoyed that the query reached them when they had already left the relevant location. They also expressed the need to buffer queries to be replied later.

When asked about the lack of certainty in receiving replies, there was wide agreement that Micro-Blog will not be used for critical operations. One of the responses was "*I would use it mostly to satisfy my curiosity*".

Voice is personal, text is impersonal: There was a strong correlation between text blogs and public modes. When interviewed, students expressed that text appeared to be impersonal, and possible to correct. Recording a well delivered voice blog seemed harder. In the social mode, students were "*not concerned about being correct or formal*".

Evenings are good times: Most blogs were after 3:00pm, with a large density of blogs between 5:00 and 9:00pm. This can be attributed to the end of a work day. When we asked if they were concerned about battery, most of them said that they did not care because their own mobile phones was not loosing charge. When asked if they would care with their own phones, few students mentioned that they were comfortable in the evening because they know recharging is imminent. One student only added "*except on a Friday evening*".

7. LIMITATIONS AND ONGOING WORK

Mobile phone based participatory sensing is an emerging platform; several issues need to be addressed across multiple disciplines. This section discusses several limitations with Micro-Blog, with some references to our ongoing work.

Location-Privacy in General Public: Our user study was performed with university students who may not be representative of the broader population. General users may not be willing to expose their real-time locations to a global forum. Schemes need to be developed that effectively obfuscate individual user locations, while maintaining the population statistics. Hence, one should be able to know the number of people in Manhattan, without knowing any individual's location. Even the service provider should not be able to locate an individual. Micro-Blog currently does not support such standards of location-privacy.

Exploiting Accelerometers for Localization: Our multi-modal localization scheme exploits a user's movement patterns to address the energy-localization tradeoff. For instance, in the absence of macro movements for a threshold time, the phone invokes a GPS measurement. In this paper, user movements have been estimated through changes in WiFi or GSM based locations. These are low-accuracy indicators. Utilizing accelerometer readings from a phone, as well as an user's mobility profile, can lead to improvements. We are designing an energy-aware localization scheme that takes advantage of both these opportunities. Kalman filtering techniques may be particularly applicable in this context [44].

Integration with a Social Network Application: Several attributes of Micro-Blog rely on a pre-established social network. It may not be practical to initiate a new social network for Micro-Blog users. Integrating Micro-Blog with Facebook or similar services is perhaps a better option. We are making progress towards this direction.

Identifying False Content: Reputation based schemes have been used in the past to identify false information [45]. However, such schemes have a high latency to converge on a misbehaving user. An intelligent attacker can always operate below the threshold of detection, and may be successful in misleading others with false data. Since Micro-Blog may be employed for real-time decision making (e.g., whether to take a side-street to avoid traffic congestion), potential security concerns may need to be addressed.

How Conclusive is User Study? The enthusiastic response from our user study, while indicative, may not be conclusive about Micro-Blog's appeal to public. Our study was performed on a set of 12 individuals. It is possible that these volunteers are early adopters of technology and services, and are in the suitable age group for embracing Micro-Blog. More exhaustive study may be necessary to understand the reaction of a larger cross-section of the population. Towards this goal, we plan to develop Micro-Blog for more popular phones, and make it available for download.

8. CONCLUSION

In this paper, we presented the design and implementation of a participatory sensing application called Micro-Blog, which allows smartphone-equipped users to generate and share geotagged multimedia called microblogs. This data can be browsed or queried through either an Internet map service such as Google Maps or in physical space as a user moves through a location. In addition, Micro-Blog allows an Internet user to directly send queries to a set of phones located in a region of interest. Phone users in the specified region that receive these queries can then reply at their discretion.

One of the key technical challenges addressed by this work is the need to balance the competing goals of accurate location coordinates and long battery life. Because microblogs are geotagged, user experiences depend on accurate matches between data and a location. On the other hand, accurate localization cannot come at the cost of unacceptably short battery lifetimes. Micro-Blog addresses this issue by infrequently using more accurate, but power-hungry localization services such as WiFi to offset the error introduced by less accurate, but more power-efficient localization services such as GSM localization.

We evaluated Micro-Blog by building and deploying a prototype implementation. Preliminary experience with users has been highly promising; while challenges such as non-academic user psychology, incentives, and privacy remain unmet, users' overall experience with the system was positive. As a result of this feedback and our energy-efficient localization scheme, we believe that Micro-Blog represents a promising new model for mobile social collaboration.

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