Are Apps Going Semantic?
A Systematic Review of Semantic Mobile Applications

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Abstract. With the wide-spread availability of cheap but powerful mobile devices and high-speed mobile Internet, we are witnessing an unprecedented growth in the number of mobile applications (*apps*). In this paper, we present a systematic review of mobile apps which use Semantic Web technologies. We analyzed more than 400 papers from proceedings of important conferences on Semantic Web and other venues. We give a brief overview of the 36 semantic mobile apps we identified by grouping them based on their specific functionalities. Our results show that usage of Semantic Web technologies on mobile devices is on the rise and there is a need for development of more tools to facilitate this growth.

Keywords: Semantic Web, semantic mobile applications, Android

1 Introduction

Mobile devices (such as smartphones and tablets) have been fast replacing other stationary devices as de facto medium for online browsing, social networking, and other applications. The widespread availability of high-speed mobile Internet and lowering prices of smartphones has accelerated this change. In fact, the most popular mobile application (*app*) stores crossed the one million apps mark in 2013. By using semantic technologies, applications on mobile devices can benefit from the advantages of the Semantic Web. For example, apps can use information from the Linked Data cloud, publish as well as subscribe to various data sources without worrying about app or device specific schemas, and reason over information to derive non-explicit facts.

The use of semantic technologies on mobile devices has been subject of interest from the early stages of the Semantic Web [1] and it has been recently invigorated with efforts to test and even port existing semantic technologies to mobile devices [2–5]. However, how many of the existing apps are using Semantic Web technologies is still unknown. Recently, Ermilov et al. performed a study on the field [6] by analyzing 172 relevant papers and coming up with guidelines for designing and developing effective semantic applications for ubiquitous devices.

However, the focus of their work was to find "the existing approaches for development of ubiquitous semantic applications" and thus slightly different from the goal of discovering how many semantic mobile apps have been presented.

In this paper we present a systematic review of semantic mobile applications which covers the breadth of semantic mobile apps and the depth of semantic data management. To this end, we analyzed more than 400 papers extracted from Google Scholar as well as proceedings of important Semantic Web conferences. From this set of studies we found 36 papers presenting semantic mobile apps for which we have extracted a brief summary with the focus on identifying "what" and "how" of semantic technology usage in these apps. We present information about common platforms and operating systems for mobile apps, Semantic Web technologies being used (locally on the device or in servers), and domains of the apps. We also outline some of the challenges and problems faced by researchers while developing semantic mobile apps. Our results show that number of semantic mobile apps has been steadily increasing over the years.

The rest of the paper is organized as follows. In Section 2, we present the methodology followed in performing this systematic review. In Section 3, we overview the semantic mobile apps we discovered grouped by specific domains. In Section 4, we answer the research questions proposed in our methodology. Finally, in Section 5, we discuss about findings of the review and outline future work.

2 Methodology

In this section we explain the methodology followed for the systematic review performed (based on the guidelines proposed in [7]).

Research Questions. The goal of this review is to find evidence to answer the following questions:

RQ1: How many semantic mobile applications have been developed?

RQ2: Is the increase on the number of mobile devices and their features motivating the development of more semantic mobile apps?

RQ3: Which domains are more suited for Semantic Web in mobile apps?

RQ4: What are the most used platforms and operating systems for semantic mobile apps?

RQ5: What are the most used Semantic Web technologies on mobile devices?

RQ6: Are Semantic Web technologies being used locally on mobile devices?

RQ7: What challenges/problems (specific to mobile devices) are researchers facing when developing semantic mobile apps?

Search Strategy and Study Selection Criteria. To find the studies to analyze we used the Google Scholar[3] web search engine which indexes millions of research papers (and thus, includes documents from the major electronic libraries

[3] `https://scholar.google.com`

–such as ACM, IEEE, and Springer–). We also went through the proceedings of the following Semantic Web conferences: the International Semantic Web Conference (ISWC) from 2002 to 2014 (last edition available), the Extended Semantic Web Conference (ESWC) from 2004 to 2015, and the International Conference on Semantic Systems (I-SEMANTICS) from 2009 to 2014. To query Google Scholar we used combinations of the following keywords: "Semantic Web", "Mobile device", "Android", "SPARQL", "RDF", "OWL" and selected the first 400 results. Regarding the proceedings of the conferences we manually checked the title and abstract of each paper to select those focusing on mobile computing.

After this step, we manually went through each paper to check if there was a semantic mobile system described in it. We use the definition of ubiquitous semantic application as an app which is designed and developed for ubiquitous devices and uses semantic data in any way during it's execution by Ermilov et al. [6]. We excluded papers which only presented an architecture or an ontology but did not describe an implementation of a semantic mobile app.

Data Extraction Strategy. For each paper remaining after the selection process we extracted the following information required to answer the research questions explained earlier: year, app functionality, mobile platform, local vs. remote handling of semantic data, Semantic Web technologies, and specific challenges related to development of the app.

3 Semantic Mobile Apps

In this section we give a brief overview of the 36 semantic mobile apps identified in the selection process. We have grouped the selected apps into disjoint domains. Therefore, even though many of the apps can be classified as Location-Based Services, we have chosen a more specific functionality for the purpose of this classification.

Map based and Augmented Reality. *mSpace Mobile* [1] provides information about topics of chosen interest to mobile users related to their location. The client app accesses the knowledge about topics and the location based information by calling remote web services. The server queries RDF KBs, using RDQL (RDF Data Query Language) [8], and returns the results to the client app. *DBpedia Mobile* [9] extracts information about POIs in the surroundings of the user from DBpedia [10] and displays them on a map. The client app, developed as a web app, displays the information obtained by a server which queries DBpedia using SPARQL. *PediaCloud* [11] displays tag clouds with information related to the user geographical location. The app executes SPARQL queries against the DBpedia endpoint to obtain POIs around the user and computes the tag cloud with the information retrieved. The app presented in [12] offers nearby POIs (e.g., cultural attractions) which match a user request or user interests. The app uses a semantic matchmaker (using non-standard reasoning services) on the device to match POIs (extracted from OpenStreetMap and enhanced semantically by a back-end) with given requests.

LOD4AR [13] displays POIs around the user by using augmented reality (AR). The client app, developed as a web application, obtains POIs as JSON by querying a server and displays it using an AR library. The server manages an OpenRDF Sesame RDFS store with information gathered from several sources (DBpedia, LinkedGeoData.org, Romanian Government Open Data portal). *Alive Cemeteries* [14] combines AR with Semantic Web to navigate through a cemetery in Hungary. The client app uses Androjena[4] to handle the POIs returned by executing SPARQL queries against a knowledge base (it is not clear whether the KB is stored in the device or in a server). *ARSemantic* [15] offers personalized POIs using AR considering the user profile. The app uses a semantic reasoner (Mini-ME [16]) to infer POIs which might be interesting for a user regarding her profile. The reasoning tasks of subsumption, satisfiability, concept abduction, and concept contraction are used on the mobile device with enhanced OpenStreetMap data to do the matching between services and profile.

Disaster, Health Management and Collaborative. *WeReport* [17] allows people to report the situation during an emergency and relief workers to obtain continuously disaster feed. *Donate-N-Request* [17] (Android) matches requests for resources with their availability in the context of disaster scenarios. Both apps use a ported version of Jena to manage semantic data (reports or requests near the user) retrieved from an external server by executing SPARQL queries. Also, the app semantically annotates user generated reports and requests and sends them to the server. *VGSAndroidApp* [18] allows users to submit and browse volunteering requests. The client app uses the Triploid API, realized on top of Androjena, to parse the information returned by a RESTful web service. The web service executes SPARQL queries against the Jena triplestore in the server.

Patient Self-Management App [19] helps patients to develop self efficacy to overcome barriers for the self-management of cardiac risk factors. The app uses an OWL ontology to model the patient profile but it is not explicitly mentioned whether the app manages the OWL ontology directly or not. *Rafiki* [20] helps community health-workers in remote areas in the diagnosis of diseases. The app manages OWL ontologies on the device which are defined using the OWL API[5]. The app also uses SWRL rules and a DL reasoner (HermiT [21]) on the device to infer the most probable diseases for a patient given her symptoms and context.

ParkJam [22] helps users to find parking using crowdsourced geographic data (from external sources and users of the system). The client app gets the parking information from a back-end system on a server which integrates information from Linked Data sources (such as OpenStreetMap). *Urbanapoly* [23] uses Human Computation (minigames to engage users) to enrich and validate geo-spatial Linked Data (POIs). The client app obtains information about POIs around the user and the server validates information received from multiple users and publishes it. *FaceBlock* [24, 25] allows users to define their context-aware privacy policies regarding pictures taken by others (e.g., “do not allow strangers to take

[4] `https://github.com/lencinhaus/androjena`

[5] `http://owlapi.sourceforge.net`

my picture") and implements it on devices around. The app, which has been tested on smartphones and Google Glass, uses the OWL API to handle OWL ontologies for the representation of the user context and SWRL rules for the definition of the policies. The app also uses a DL reasoner (JFact[6]) to infer the policy to be executed depending on the user context. *csxPOI* [26] enables the collaborative creation, sharing, and modification of semantic POIs. The client app receives POIs from the server, which stores them in a triplestore, and allows users to modify them or create new ones.

Semantic Web Browsers and Endpoints. *mSWB* [27] is an effort to develop an endpoint-agnostic mobile Semantic Web browser which can connect to any of the available endpoints to retrieve maximum information. The client app allows user to perform keyword based search and visualize the results in table and map view. The federated middleware, on an external server, takes care of running semantic queries in parallel on different endpoints and returning the results to the app. *OntoWiki Mobile* [28] is a mobile version of the free and open-source semantic wiki application "OntoWiki" which facilitates knowledge acquisition in a collaborative manner. The app is a HTML5 application which uses RDFauthor[7] (Javascript-based system) for data authoring and utilizes HTML5 cache functionality to support offline work. Persistence of data is provided at the server which has advanced conflict resolution and replication features built-in which allows concurrent editing of same resources.

RDFBrowser [29] is an RDF browser which provides a generic layer for accessing device information making it independent of specific application schemas. The app uses Androjena to manage RDF data on the device and there is a remote RDF server which exposes the device information for outside world consumption. *RDF On the Go* [30] is an RDF storage and SPARQL query processor for Android devices allowing them to query data collected on the devices locally. They have adapted Jena and ARQ toolkits for mobile to handle RDF data and the app stores the triples from LinkedGeoData collection. The data is indexed using R-trees to support spatial SPARQL queries. The app presented in [31] makes it possible for mobile devices to publish the information from applications and sensors on them through a SPARQL endpoint. This data can be gathered by applications by querying the endpoints and federation through SPARQL queries. The app includes an RDF store and SPARQL endpoint based on the Sesame library (adapted to Android). *Linked Sensor Middleware* [32] provides wrappers for sensors on mobile device for the purpose of data collection and publishing. Through their web interface users can annotate and visualize the real world sensed data. They have also linked this sensor stream data to other Linked Data sources and the unified dataset can be queried through a SPARQL endpoint. *SHERLOCK* [33, 34] enables devices to automatically exchange knowledge about Location-Based Services in the geographic area of the user (e.g., a service to find taxis or to obtain pictures of monuments around). The

[6] `http://jfact.sourceforge.net/`
[7] `http://aksw.org/Projects/RDFauthor.html`

app manages OWL ontologies using the OWL API. Also, it uses a Description Logics reasoner on the device (JFact) to infer services which might be interesting for the user.

Social Networks and Recommendation. *Person Matcher* [35] obtains FOAF profiles from persons around the user (via Bluetooth) and calculates a "compatibility" score with the user for each profile discovered. The app handles RDF data using the MicroJena library[8]. *Mobile Social Semantic Web* [36] offers a distributed social network based on Semantic Web technologies. The app queries various triple stores (e.g., FOAF) and transforms the RDF, by using the Androjena, into a format that is suitable for social applications such as contact information based and FOAF based. *Who's Who* [37] enables users to access and visualize Linked Data by linking physical world with virtual with the help of contextual information (e.g., location). To address the potential latency problems due to low bandwidth or no network connection, the app includes a light weight triple store on the device, using the RDFquery library[9], which stores knowledge from the remote RDF server.

Mobile Wine agent [38] offers descriptions of wines and dishes, and recommendations to the user regarding her location. The app manages an ontology and supports partial reasoning on the device and exhaustive reasoning over the information collected is performed on the Jena server. *Cinemappy* [39] computes contextual movie recommendations for users by using their spatial and temporal position. The app executes SPARQL queries against the DBpedia endpoint to obtain information related to movies which is combined with information from semistructured sources. *Krishi-Mantra* [40] offers suggestions and alerts to farmers to improve productivity regarding the crops being cultivated. The client app sends information introduced by the user in forms to the server through RESTful web services and displays the results. The server translates the information to SPARQL and queries the KB with information about cotton. *RealFoodTrade* [41] allows farmers and fishermen to sell their products directly to the end-buyer. The client app sends user keywords (related to a particular type of fish) to the server which obtains a matching product in its ontology and finds announcements regarding fishermen selling it.

Travel. *GetThere* [42] provides users from rural areas with details about public transport (buses). The client app invokes web services which execute SPARQL queries against the dataset managed by the back-end. The server integrates information from Linked Data points with crowdsourced locations of buses shared by the clients. *LinkedQR* [43] enables users to scan QR codes attached to pieces of art in a museum to obtain further information. The client app creates and executes a SPARQL `DESCRIBE` query against the server using the URI contained in the QR code. The returned RDF is parsed by the app, using the Sesame library, and shown to the user. The server manages a KB with information about an art

[8] `http://poseidon.ws.dei.polimi.it/ca/?page_id=59`
[9] `https://code.google.com/p/rdfquery`

gallery enriched with information from DBpedia. *HDTourist* [44] helps tourists visiting a foreign city by displaying urban data from DBpedia. The app executes SPARQL queries against a local RDF/HDT file (which contains information extracted from DBpedia) using a Java library[10]. *Touristguide* [45] offers personalized tourist information to users after profiling them through questions. The client app obtains the information from a server which maintains the information about places in an ontology. *CURIOS* [46] offers personalized information to tourists based on their preferences and activity history. The client app uses RESTful services to obtain the information from the KB (generated by their previous system CURIOS CMS from Hebridean Connection dataset). Additionally the client also provides semantic (semantic relevance) and location-based (euclidean) caching to overcome connectivity issues. *Mobile Cultural Heritage Guide* [47] helps in finding interesting cultural material for a tourist using her location. The client app sends user information (location, heading, and facets) to the server which queries the KB (containing data from the Eculture data cloud, LinkedGeoData.org, and DBpedia, among others) and returns POIs.

4 Results

In this section, we answer the research questions posed in Section 2:

RQ1: How many semantic mobile applications have been developed? At least *36* semantic mobile apps have been presented in the literature based on our survey of publications over the last 10 years. Given that there is no central repository for authors to publish their semantic mobile apps, the process of finding them relies on quality of indexing mechanisms, appropriateness of keywords used in the search, and effectiveness of the selection of the studies. In our effort to avoid a possible bias, the studies were evenly split between the authors for the purpose of reviewing them.

RQ2: Is there an increase on the number of semantic mobile apps? Figure 1(a) shows the number of papers presenting a semantic mobile app per year (the figure do not include one app published in 2015[11]). Notice that there is a gap between 2005 and 2009, we believe that this might be related to two milestones: the release of the iPhone in June 29, 2007, and the release of the first commercial version of Android in September 23, 2008. With the more powerful and affordable devices, high speed Internet, and better tools available, the number of mobile semantic web apps doubled in 2010 and 2014 whereas it remained stable in between.

[10] `https://github.com/rdfhdt/hdt-java`

[11] This study has been finished in May 2015 so more semantic mobile apps might be presented in 2015.

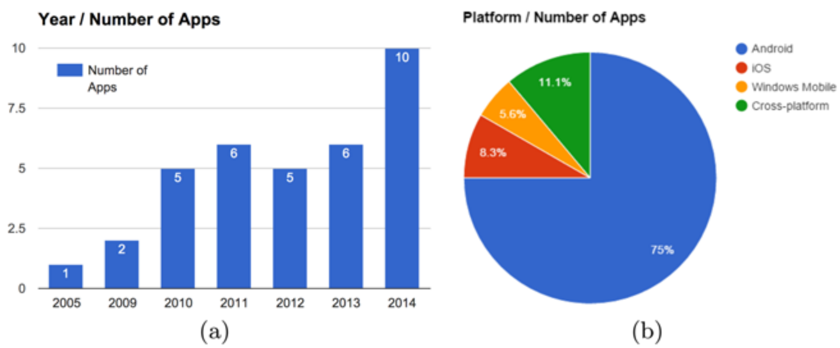

Fig. 1. Number of semantic mobile apps per year (a) and number of semantic mobile apps per platform (b).

RQ3: Which domains have the most number of Mobile Semantic Web apps? The majority of the apps reviewed, 27 apps out of 36 (i.e., [1, 9, 11–15, 17, 18, 20, 22, 23, 25, 26, 34, 35, 37–42, 44–47]), can be classified as Location-Based Services (LBSs). This was as expected as mobile devices are equipped with sensors which are able to obtain the location of the user in real-time. Among these LBS apps, the most common functionality is providing information about Points Of Interest (POI), 14 apps (i.e., [1, 9, 11–15, 23, 26, 37, 44–47]).

RQ4: What are the most used platforms and operating systems? In general all the apps are deployed on smartphones, except for [1, 35] which were deployed on Personal Digital Assistants (PDAs), as they were developed when PDAs where the most popular mobile devices. Figure 1(b) shows the distribution across different operating systems with Android being the most common choice for semantic mobile apps [11, 14, 15, 17, 17, 18, 20, 22, 23, 25–27, 29–32, 34, 36, 37, 39–46] (27 out of 36). 3 of the apps were developed for iOS [19, 38, 47] whereas 2 are Windows Mobile apps [1, 35]. Also, there are 4 apps that have been developed as web applications [9, 12, 13, 28] and thus are cross-platform. The dominance of Android could be attributed to two factors: (1) it has the most number of users worldwide and it is based on Java as most of the popular semantic tools.

RQ5: What are the most used Semantic Web technologies? Figure 2 shows a wordcloud generated with the different semantic technologies that the apps reported using. For management of semantic data on the device, the most common libraries used are: Androjena (in [14, 18, 29, 36]), OWL API (in [20, 25, 34]), and Sesame API (in [31, 43]). Regarding Linked Data endpoints, apps use mainly the DBpedia (in [9, 11, 13, 39, 43, 44, 47]) and OpenStreetMap/LinkedGeoData (in [12, 13, 15, 22, 30, 47]) KBs. With regards to semantic reasoning, the following reasoners have been reported: Mini-Me (in [15]), JFact (in [25, 34]) and Hermit (in [21]).

Fig. 2. Wordcloud with the semantic technologies used by the different apps.

RQ6: Are Semantic Web technologies being used locally on the device? Most of the apps, 23 out of 36 (i.e., [1, 9, 13, 14, 17, 18, 22, 23, 26–28, 32, 37, 38, 40–47]), use a client-server approach in which the mobile app itself acted as an interface to present the results returned by the server. These type of client apps were also reported to be majority in [6] (where they were called "thin client apps"). However, 9 of these 23 apps (i.e., [14, 17, 18, 28, 37, 38, 43, 44]) processed Semantic Web languages on the device. 13 apps (i.e., [11, 12, 15, 19, 20, 25, 29–31, 34–36, 39]) do not follow the client-server approach and manage semantic data on the device (which can obtain from other devices or directly from Linked Data sources). Also, just 6 apps (i.e., [12, 15, 20, 25, 34]) use a semantic reasoner/matcher on the device to infer facts.

RQ7: What challenges/problems (specific to mobile devices) are researchers facing when developing semantic mobile apps? The challenges reported by apps can be broadly categorized into two: general Semantic Web challenges and those specific to mobile apps. In the first category we have long term issues such as helping users to define content in RDF or integrating information from different source. While the challenges specific to mobile apps include: the need for efficient mobile RDF triplestores [44], scalability issues from the perspective of storage and processing while increasing number of triples (e.g., [43] reported that increasing the number of triples in 20 multiplied the processing time almost by 4), lack of semantic reasoners for certain mobile operating systems (such as iOS), better local storage to minimize bandwidth and battery consumption for retrieving and processing semantic data [34, 46].

5 Conclusion and Next steps

The results of our systematic review, with more than 400 papers analyzed, show that mobile semantic apps have been presented since the early days of the Semantic Web, 2005. However, it was not until 2009 that the number of mobile semantic apps started to steadily increase. The increment seen in 2014 motivates us to believe that in the following years this number will continue growing with the adoption of new mobile devices (such as smartwatches, smartglasses, and even "smart cars"). However, Semantic Web research should focus on dealing with the problems related to this new scenario (e.g., devices with limited capabilities which generate large amounts of highly-dynamic data) to popularize the use of semantic technologies in apps on these existing and future devices.

Our results show that most of the apps act as clients which rely on external servers for the handling of semantic data. This means that although they consume data which comes from Linked Data points and ontologies, this data is preprocessed on a server which returns the data in a semistructured format (JSON) or just as strings. However, this has been changing recently with few apps exploiting the capabilities of current mobile devices to handle semantic data locally. We believe that this trend would continue with work performed in porting existing semantic technologies (such as the Jena port Androjena, and semantic reasoners [2–4]) or creating new technologies specifically for mobile devices (e.g., semantic reasoners such as Mini-Me [16]).

Finally, based on the results and apps discovered in this review, we think it would be useful to formally define what a "semantic application" is, irrespective of whether it is mobile or not, by further studies. This would help in coming up with methodologies for systematic reviews and recommendations for semantic app development. The different scenarios presented in this paper, such as apps consuming data from a server in a non-standard format while the server obtains this information from the Linked Data cloud, apps handling data in a semantic format (i.e., RDF and OWL) on the device, or apps using a semantic reasoner to handle the data, would have to be studied to determine an specification of semantic apps.

In future, we want to extend this work by considering semantic mobile apps published in app stores (such as Google Play or Apple App Store). Based on a preliminary look at the Google Play Store[12] we found that number of commercial semantic mobile apps are indeed meager. Also, we are planning to build a website which can act as central repository of mobile semantic apps which would be updated periodically to keep track of all the latest apps.

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