Personalizing the Internet of Things Using Mobile Information Services

Dmitry G. Korzun
Department of Computer Science
Petrozavodsk State University
Petrozavodsk, Russia
e-mail: dkorzun@cs.karelia.ru

Sergey I. Balandin
ITMO National Research University
St. Petersburg, Russia
FRUCT Oy
Helsinki, Finland
e-mail: sergey.balandin@fruct.org

***Abstract*—A smart space enables semantics-oriented information sharing in a networked computing environment, including the case of mobile settings. In this paper, we consider the emerging case of Internet of Things (IoT) environments. We introduce our study on personalization of such environments using mobile information services within a smart space. Such advanced services are defined now as "smart" or "intelligent". Their construction and delivery are provided by participants themselves, following the concepts of multiagent systems, peer-to-peer networks, and autonomic computing. This study identifies the key properties of a smart space to serve its mobile users and to provide them with all needed information assistance.**

Keywords–Smart Spaces; Internet of Things; Information Services; Personalization; Mobile OS.

I. INTRODUCTION

We consider the emerging case of Internet of Things (IoT) environments [1]. An IoT environment is associated with a physical spatial-restricted place equipped with and consisting of a variety of devices personal mobile devices, multimodal systems, etc.). In addition to local networking, the environment has access to the global Internet with its diversity of services and resources. Evolving from the world of embedded electronic devices, an IoT environment includes many mobile participants, each acts as an autonomous decision-making entity: a smart object in the IoT terms [2] or agent in the multiagent system terms [3]. In these IoT settings, the role of personalized mobile information services becomes growing.

Smart spaces form a programming paradigm for creating a wide class of ubiquitous computing environments [4]–[8]. Nowadays, smart spaces become more and more closely integrated with IoT. More precisely, a smart space enables information sharing in a given IoT environment, supporting construction of advanced information services by the participants themselves. Such services are often referred as "smart", emphasizing the new level of service recognition (detection of user needs), construction (automated preprocessing of large data amounts) perception (derived information provision to the user for decision-making). In this paper, we study personalization of IoT environments using mobile information services constructed within smart spaces.

Our study essentially exploits the known opportunities of M3 architecture [1], [9], [10], which represents a particular approach to creation of smart spaces [11]–[13]. Participants are software agents that act as Knowledge Processors (KPs) over the information of the entire given IoT environment. The central component is a Semantic Information Broker (SIB). It maintains a knowledge corpus cooperatively collected and produced by the KPs themselves, following the concept of Peer-to-Peer (P2P) networking and implementing an information hub of the environment. We characterize mobile information services by their ability (i) to find a proper information fragment (e.g., a situation-aware recommendation) in the knowledge corpus over the information available in the whole IoT environment and (ii) to deliver the result to the mobile end-user with effectively perceived visual representation on the personal mobile device (e.g., a widget on smartphone).

The M3-based approach achieves semantic interoperability even in the challenging IoT settings when the large number of mobile participants are involved as well as a lot of surrounding devices and remote Internet services are used in computations. Service construction can be personalized for a mobile user based on recognition and own interpretation of the collected information by the KPs resided on the user's personal mobile device. Service delivery and consumption by a mobile user essentially depends on processing and visualization methods supported on the user's personal mobile device and its mobile Operating System (OS).

The rest of the paper is organized as follows. Section II introduces mobile information services constructed within smart spaces. Section III discusses the properties of service construction and delivery in the case of IoT environments. Section IV studies the role and opportunities of mobile operating systems to form our approach to service-oriented personalization of IoT environments. Section V motivates the value offering of personal smart spaces that virtually accompany the users providing them advanced mobile information services. Finally, Section VI concludes the presented study.

II. MOBILE INFORMATION SERVICES

The amount of information is growing in the Internet such that users cannot efficiently manage the existing multitude of resources. The observable lack of mechanisms for information exchange between Internet services results in high fragmentation, i.e., information collected in one service is rarely accessible in another. In this section, we consider the M3-based approach to mobile information services constructed within smart spaces. Such services are called "smart" aiming at intelligent use of all available information in various situations that the mobile user can get [5], [6], [8].

The first property is an information service, i.e., the service provides the information fragment appropriate to the user in the current environment. The user—not the service—applies this fragment for situational decision-making. Consequently, such services provides a kind of informational and analytical support. The intellectual role of human is not replaced but auxiliary assistance is performed, similarly as it has happened in automated and autonomic computing [14]. The key challenge is information search, construction of the appropriate information fragment, and its visualization to the user.

The second property is a mobile service. The mobility essentially increases the number of situations which the users can get in. Consequently, such services are acting as a mobile assistant that accompanies the user. The latter follows the style “make everything from my personal mobile device”, and the user may have no idea which other devices (surrounding or remote) are involved into the service construction and delivery. The key challenge is making the participation easy and transparent, as well as the service delivery becomes essentially aware of the visualization capabilities of the user’s device.

Smart spaces support provision of advanced information services [12]. A smart space is created in a given computing environment, which is typically localized by being associated with a physical spatial-restricted place (office, room, home, city square, etc.). The environment is equipped with a variety of devices, including the essential share of mobile ones. Smart spaces aim at supporting cooperation of all devices in the environment in order to provide its users with convenience, safety, and comfort. The underlying computing environment is enhanced to handle the growth of the number of mobile devices and the amount of multi-source information to be processed.

The required cooperation of devices is supported by establishing a shared view of resources in the environment. Every device can join and leave the space dynamically. Software part of a smart environment includes two sides:

1) Agents to make autonomous information processing,
2) An information hub to provide a shared view on all available information.

Participation of a device is determined by its software agent running on the device. The users participate using their personal mobile devices as primary means to consume services. Each agent produces its share of information and makes it available to others via the hub. Similarly, the agent consumes information of its own interest from the hub. That is, a hub is a server that realizes a shared information space (i.e., an associative memory for agents) for the required cooperation.

The M3 architecture provides a particular approach for creating smart spaces [1], [9]. Rather than promoting the compatibility within one specific service-level solution in terms of protocols or software stacks, the M3 architecture addresses information-level compatibility and the collaboration between different producers and consumers of information on more abstract level [5], [8]. Agents interact on a semantic level, utilizing (potentially different) existing underlying services.

Smart-M3 platform [13], [15] is open source middleware for implementing smart spaces that follow the M3 architecture and take the mobile settings into account; see Fig. 1. The key architectural component is SIB that implements an information hub for agents of a given environment. Agents act as KPs running on devices of the environment. Some of them act on behalf of external data sources, resources, and services. Network communication between a KP and its SIB uses Smart Space Access Protocol (SSAP) or other M3-aware protocols [16] for information access and exchange.

Each KP communicates with a SIB using the blackboard interaction model [17]. This SIB maintains semantic information of the environment and its applications. The information is represented in accordance with the Resource Description Framework (RDF); see [18]. The basic data unit is a triple. A set of such RDF triples is considered as a graph, allowing representing semantics as relations. As a result, a shared knowledge corpus is formed in an RDF triplestore.

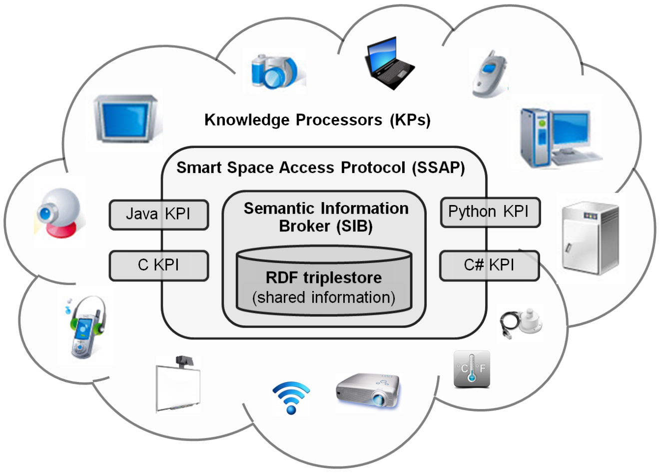

Figure 1. Smart-M3 concept model of a smart space.

Communication between KPs is indirect, it occurs through the insertion and removal of triples into or from the SIB. This blackboard model is complemented by the Pub/Sub model [7], [17], which allows KPs to subscribe to specific triples. A subscribe operation creates a persistent query that is stored in the SIB and is re-evaluated automatically after each change to the shared content. Every subscribed KP is notified when the specified triples are added, removed, or updated.

The content representation in the form of RDF graph makes the ability to reason existing knowledge and infer new knowledge by means of ontologies. The Web Ontology Language (OWL) from the Semantic Web is used for creating ontologies [18]. Following [19], let us formally define a smart space as (I, O), where I is factual data (smart space content) and ontology O provides their logical representation structure. Ontology provides a tool to make use of the shared data and their semantics. Thus, the KPs can focus on the semantics of processed information.

In the multi-agent case, the notion of common ontology for the entire smart space becomes more or less virtual. Explicit maintenance of a space-wide large ontology O is impractical. Each KP may use own ontology o, though partially agreed with others. The partial ontology o describes the structure of content accessible by this KP (or a group of KPs). This property leaves freedom for a mobile KP to make own interpretation of the shared knowledge corpus, e.g., depending on the local user’s context observed on the personal mobile device.

Operations on shared content I are essentially based on semantic search: any operation with an information fragment i first requires finding i in I. Table I shows basic smart space access primitives. SIB supports search queries using SPARQL query language. The result of the query is a list of all triples that match the query. In fact, it makes any SIB a SPARQL endpoint [18]. If the ontology-oriented type of interaction is used then the smart space access primitives are enriched with ontology, e.g., for $q = q(o)$ the search query becomes subject to the given logical structure of factual data in I.

TABLE I. SMART SPACE ACCESS PRIMITIVES.

Primitive	Notation	Description	Search factor
join, leave	—	KP initiates a session establishing a network connection to SIB. KP may use own ontology o for structural representation of exchanged information between KP and SIB.	Scope determination: part of I that the given KP may access.
insert	$I := I + x$	Insertion of new facts. A set of triples x is added to I on the assumption that no triple of x already exists in I.	Existence check: I does not contain x.
remove	$I := I - x$	Remove existing facts. A set of triples x is deleted from I on the assumption that x already exists in I.	Existence check: I contains x.
update	$I := \langle I + x \rangle$	Update of existing facts. A set of triples x is updated in I (non-interrupted remove and insert) on the assumption that the triples already exist in I.	Search: triples x to update.
query	$x := [q \to I]$	Instant content retrieval. The query returns all existing in I triples x specified by q.	Search: triples x matching to the specification q.
subscribe, unsubscribe	Await $x := [q \to I]$	Persistent content retrieval. Whenever the specified by q content in I is changed the query returns the affected triples x	Search: appearance of triples x matching to the specification q.

In summary, construction of an information service requires iterative search-and-process manipulations of several KPs on the shared content. Eventually, a needed information fragment becomes derivable by a KP on the user side.

III. SERVICES IN INTERNET OF THINGS ENVIRONMENTS

An IoT environment is a computing environment associated with a physical spatial-restricted place. The surrounding "things" are Internet-enabled devices that can perform computations. In addition to local networking, the environment has access to the global Internet with its diversity of services and resources. In this section, we formalize construction and delivery of mobile information services in smart spaces deployed in a given IoT environments.

Although the term IoT was initially proposed to refer to uniquely identifiable interoperable connected objects with Radio-Frequency IDentification (RFID) technology, now the most common view of IoT refers to a dynamic global network infrastructure for the ubiquitous connection of numerous physical objects (e.g., everyday things equipped with RFIDs, various sensors and actuators, embedded and mobile electronic devices, low capacity and powerful computers) that rely on advanced wireless communication and information processing technologies. Furthermore, IoT aims at fusion of real (physical) and virtual (information) worlds. As a result, IoT is evolving to service-oriented information interconnection and convergence on the global level [2], [20], [21].

Involvement of many surrounding devices of the IoT environment is one of the essential properties that the smart spaces approach has to take into account in service development. Even low-capacity devices act in service construction on the equal basic with more powerful computers. As a result, it opens the services for data coming from the physical world (embedded and other IoT devices) and from such an overlapped area of the physical and information worlds as human-related and social activity [22] (smartphones and other personal mobile computers, various carried and wearable devices). Many edge IoT devices become responsible for a significant part of system computations, in accordance to the vision of smart objects in IoT [2], [23] and of human-centered information systems in edge-centric computing [24].

The interoperability becomes one of the key issues. For a smart space deployed in an IoT environment, the interoperability is defined as the ability for software agents (written in different programming languages, running on different devices with different operating systems) to communicate and interact with one another (over different networks). In the previous section, we showed that having a shared view on available resources an information service can be considered as information search and knowledge reasoning over the content I with subsequent delivery of the result to the end-users. Let us formalize conceptual steps of the service construction.

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Require: Ontology $o$ to access information content $I$ of the smart space. The set $U$ of available UI devices.
1: Await $[q_{\text{act}}(o) \to I] = \text{true}$ {event-based activation}
2: Query $x := [q_{\text{info}}(o) \to I]$ {information selection}
3: Select $d \in U$ {target UI devices}
4: Visualization $v_d := v_d + x$ {service delivery to end-user}
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Figure 2. Information service construction for the end-user.

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Require: Ontology $o$ to access smart space information content $I$. The set $U$ of available UI devices.
1: Await $[q_{\text{act}}(o) \to I] = \text{true}$ {event-based activation}
2: Query $x := [q_{\text{info}}(o) \to I]$ {information selection}
3: Decide $y := f(x, o)$ {formulation of processing action}
4: Update $I := I + y$ {new shared information}
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Figure 3. Content search & processing in the smart space.

The algorithm in Fig. 2 defines construction of an information service for the end-user. Step 1 detects when the service is needed based on the current situation in the smart space. Step 2 makes selection of knowledge x to deliver to the user. Step 3 decides which UI elements are target devices for the service delivery. Step 4 updates recent visualization v_d to include x on device d.

The algorithm in Fig. 3 defines construction of an information service responsible for eventual production of appropriate information fragments in the smart space. Step 1 analyzes the space content to detect when a processing action is needed. Steps 2 and 3 are reasoning in context of the current situation, and the service decides what updates (possibly without human intervention) are needed in the recent system state. The updates become available to the participants.

Therefore, KPs of the smart space apply available knowledge in constructing and delivering the services, without necessarily identification who finds and provides the knowledge. Algorithms 2 and 3 of generic services assume that some part of available knowledge is shared in the smart space and the other part is kept locally by KPs themselves (i.e., non-shared). To make a further step in the service design we need to clarify the structure of I. In the extreme case, all data a service needs are accessed via its smart space, which provides search query interfaces to reason knowledge over I and its instant structure.

Based on the ontological modeling approach, one can consider I consisting of various information objects and semantic relations among them [1], [11], [25]. Its basic structure is defined by problem domain and activity ontologies (OWL classes, relations, restrictions). Factual objects in I are represented as instances (OWL individuals) of ontology classes and their object properties represent semantic relations between objects.

For modeling IoT objects (their resources and processing activity), P2P methods can be applied for representing the inferred knowledge [19]. Any object $i \in I$ is treated as a peer. Each i keeps some data (values of data properties) and has links to some other objects j (object properties). Therefore, a P2P network G_I is formed on top of I. Contributions to the smart space (insert, update, remove) change the network of objects, similarly as it happens in P2P due to peers churn and neighbors selection. This P2P model extends the notion of ontology graph (interrelated classes and instances of them) kept implicitly in I and in ontologies o at the KPs to a dynamic self-organized system. That is, content I is considered as interacting objects, which are active entities (make actions) on one hand and are subject to information changes (actions consequence) on the other hand.

Consequently, service construction can be formulated in terms of flows of information changes. Given a starting object $s \in I$ and its initial change. Let $D(s)$ be a graph routable from s in G_I. Construction of a service corresponds to a routing path $s \to^* d$. Injection of the change starts the service (like a P2P node starting a lookup query). The sequence of changes flows in G_I. Note that parallel paths are possible. Any point when an agent reads an object can be considered a final step of the service construction since the agent consumes an outcome.

In summary, the service construction in an IoT environment needs virtualization of all related processes and resources. In addition to the straightforward virtualization, the semantics are shared to describe relations observed by involved participants in ongoing processes and available resources. The shared content is a knowledge corpus represented as a semantic network (represented objects and their relations). It becomes a dynamic evolving system with properties similar to P2P networks. A service construction process is reflected in the smart space as routes in the semantic network.

IV. PERSONALIZATION APPROACH

The users are more and more interested in context-aware, situational, and personalized services. In this section, we study the opportunities of mobile devices and mobile operating systems in the proposed service-oriented personalization of IoT environments On one hand, the personalization approach is based on the smart space properties, which we described in the previous sections. On the other hand, the role of mobile operating systems is crucial for customizing a service to the user's needs in the current situation.

Nowadays, the personal mobile devices are seen as the primary tool for accessing services in the smart space [13]. Moreover, in the near future personal handheld devices could become not just an interface to the mobile and Internet services, but the master devices for personalized management of IoT environment, and play in the world of devices the same role as browsers play in the world of Internet services. In fact a modern smartphone is the closest and very powerful device that can manage surrounding IoT environment, so creating a personal smart space around the user. The personal mobile device shall not be anymore seen as a pure service consumption point. In fact it is the best source of situational and other personal information that can be used in delivery or even personalized construction of various services.

Our work on smart spaces-based development has already indicated the distinctive role of smartphones and tablets for such emerging IoT application domains as collaborative work systems [26], e-Tourism recommendation services [27], and mobile healthcare assistance [28]. Many studied use cases of the smart spaces based applications for IoT consider smartphone as a device for handling processing of the most personal data, which is done by the corresponding KPs that are executed on the device [29].

Consider the personal smart spaces created by placing the smartphone in the center to take role of the SIB host. This architectural change enables a number of benefits for the end-users, which we discuss in the next section. At the same time the use case is quite demanding for the smartphone. Let us study whether the new architecture can be supported by the available smartphone ecosystems. Even the quick analysis of the iOS and Windows ecosystems illustrated that they are not properly suitable, as it is not possible to get required access to the low-level interfaces and functions.

The next considered candidate is the Android ecosystem. One can find a number of studies that use KPs on Android devices in M3-enabled smart spaces, e.g., see [30], [31]. Moreover, it is possible to make SIB working on Android devices. Unfortunately, Android sets too many restrictions on the use of low-level functions. Due to these restrictions the implementation of a personal smart space cannot be done efficiently. The Android ecosystem provides insufficient processing power for proper management of a smart space by SIB installed even on the most powerful Android smartphones.

Another candidate is Tizen OS ecosystem [32]. Since the last two years it has become one of the leaders OS for IoT devices, which is important advantage for programming smart spaces. Moreover, Tizen is an open source platform that enables efficient implementation of SIB. The only strong disadvantage of the current Tizen OS ecosystem is that it is too much focused on compatibility with resource-restricted devices and they pay less attention to OS optimization for the high-end smartphone devices. As a result, although Tizen OS is a very promising candidate, it is impossible to find powerful enough high-end smartphone on Tizen OS.

Finally, Sailfish OS [33] is yet another ecosystem for personal mobile devices in IoT. This OS can be seen as a close "relative" of Tizen OS, as the root of both systems is in MeeGo OS. Nevertheless, Sailfish OS focuses on smartphones as a primary target device with setting the key goal in optimization of the system performance. As a result, Sailfish OS provides currently the most efficient and fast mobile OS ecosystem. The system is based on Linux kernel and includes most of required basic primitives for accessing low-level functions and interfaces. The open architecture enables us to develop and integrate the missing primitives to the system core. Moreover, other key priorities of Sailfish OS are privacy and usability. These are exactly the "bonus" features that this mobile OS we are expected to provide to the smart spaces. Nowadays, the

Sailfish OS ecosystem is supported by half a dozen of high-end smartphones. Although these smartphones are not well-known among regular users so far, one can get Sailfish OS devices and even have a few options.

In summary, this preliminary study of mobile operating systems indicates that potentially the Sailfish OS provides the best-suited candidate for implementing personalized M3-enabled smart spaces.

V. VALUE OFFERING BY PERSONAL SMART SPACES

The personal smart spaces aim at automatic dynamic personalization of the whole virtual and physical environment around the user. The personalization is done based on the individual preferences as well as on physical location and other relevant context information available for the smart space. The idea is that the smart space makes continuously monitoring of all services and devices that are available for the user at any moment of time and automatically forms environment management requests to maximize comfort and safety of the user. In particular, the personal smart space provides a middleware to help the user to most efficiently interact with the surround IoT environment.

Consider an example of user interaction with physical environment. When the user enters to the shopping mall the personal smart space can check what large interaction screens are available. As a result, when the user is passed by, she/he can take control over the available screens as a temporarily interface for more comfortable interaction with services provided by the shopping mall.

The example can be continued for the user interaction with the virtual environment. While the user interacts with the shopping mall services, the personal smart space makes monitoring what is searched by the user, request for personal discounts from the shops of interest, and build the optimal path for visiting places of interest.

The mixed user interactions with virtual and physical environment are also possible. When the user is done with search the personal smart space activates navigation services on the smartphone plus available visualization. Other appropriate tools can also be activated, e.g., to highlight the path in the shop or to call elevators.

By the above illustrative example we describe our idea of the new type of value offering delivered by the personal smart spaces. Everyone can imagine a number of other use cases for various application domains. Importantly that such use case scenarios fully fit to the basic reference model of smart spaces [4], [5], with assumption that SIB could be fully operational on the personal mobile device.

The definition of personal smart spaces creates a new problem of collaborative personalization, as multiple users will interact with IoT environments in public places. The environment has to adopt itself to the multiple users at the same time. As a result, we come with definition of a new key parameter—the size of the gravity field of the personal smart spaces. In other words, the individual gravity field shows the influence level of the user to the collaborative decision making and control in the IoT environment.

An interesting case study for collaborative personalization is the microphone service of SmartRoom system [26], [30]. Each user can use her/his smartphone as a microphone collaboratively working in multimedia equipped room during a conference session, work group meeting, or seminar. The audio system in the room is a shared resource with mutual exclusion. User access to this resource is subject to personalization, which, in turn, depends on the situational role and interests of the user.

In summary, defining the optimal size for each individual gravity field is an open research topic for our further work, which we are planning to accomplish within the scope of studying collaborative use of the personal smart spaces.

VI. CONCLUSION AND FUTURE WORK

This paper elaborated the fundamental concept of mobile information services that are constructed and delivered within smart spaces. We introduced the theoretical properties of such services that enable personalization of the IoT environment. The properties are essentially based on semantic-driven multi-agent iterative search-and-process manipulations on the shared knowledge corpus with virtualization of IoT environment processes and resources. The important direction of our further theoretical research is new data mining and knowledge reasoning methods for effective service personalization in the large-scale IoT settings. Such methods need to be implemented as cooperative activity of many KPs with knowledge sharing support from SIB. In particular, it needs extending the function of SIB, which is recently limited with information access and exchange mediation.

From the applied research and development point of view, a promising option for applications is personal smart spaces when the user's smartphone is placed in the center. We considered the main available mobile OS ecosystems and concluded that most of them cannot provide the required support for the personalized smart spaces. Nevertheless, the Sailfish OS seems a suitable ecosystem for creating personal smart spaces with the M3 architecture. This option provides the most straightforward solution to enable personalization of IoT environments based on the user's preferences. At the same time, we are faced with a new research problem of collaborative personalization when the IoT environment adapts itself to multiple users. Its solutions need extending the SIB with the gravity field support for the personal smart spaces. In particular, definition of an optimal size for each individual gravity field is an important research topic of our future work.

As the next development step we are planning to implement a full version of Smart-M3 SIB for Sailfish OS. Then, a set of reference use cases will be created and experimentally evaluated on top of the personalized smart spaces.

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