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The Social Internet of Things (SIoT) – When social networks meet the Internet of Things: Concept, architecture and network characterization ☆

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ABSTRACT

Recently there has been quite a number of independent research activities that investigated the potentialities of integrating social networking concepts into Internet of Things (IoT) solutions. The resulting paradigm, named *Social Internet of Things* (SIoT), has the potential to support novel applications and networking services for the IoT in more effective and efficient ways.

In this context, the main contributions of this paper are the following: (i) we identify appropriate policies for the establishment and the management of social relationships between objects in such a way that the resulting social network is navigable; (ii) we describe a possible architecture for the IoT that includes the functionalities required to integrate *things* into a social network; (iii) we analyze the characteristics of the SIoT network structure by means of simulations.

1. Introduction

There are scientific evidences that a large number of individuals tied in a social network can provide far more accurate answers to complex problems than a single individual (or a small group of – even knowledgeable – individuals) [38]. The exploitation of such a principle has been widely investigated in Internet-related researches. As a consequence, several schemes have been proposed that use social networks to search Internet resources, to route traffic, or to select effective policies for content distribution, e.g., [27,11,31,39,8,29].

The Internet of Things (IoT) integrates a large number of technologies and envisions a variety of things or objects around us that, through unique addressing schemes and standard communication protocols, are able to interact with each others and cooperate with their neighbors to reach common goals [36,1].

Recently the idea that the convergence of the "Internet of Things" and the "Social Networks" worlds is possible, or even advisable, is gaining momentum, as it will be discussed in the following. This is due to the growing awareness that a "Social Internet of Things" (SIoT) paradigm would carry many desirable implications into a future world populated by intelligent objects permeating the everyday life of human beings.

In fact, applying the social networking principles to the IoT can lead to several advantages:

- the SIoT structure can be shaped as required to guarantee the network navigability, so as that the discovery of objects and services is performed effectively and the

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scalability is guaranteed like in the human social networks;
- a level of trustworthiness can be established for leveraging the degree of interaction among things that are *friends*;
- models designed to study the social networks can be re-used to address IoT related issues (intrinsically related to extensive networks of interconnected objects).

Even if the idea of a Social Internet of Things (SIoT) has been already discussed, as we will explain in Section 2, in this paper we go beyond the state of the art in several ways:

- we identify appropriate policies for the establishment and management of social relationships between objects in such a way that the resulting social network is navigable;
- we describe a possible architecture for the IoT, which includes the functionality required to integrate *things* into a social network;
- we study the characteristics of the SIoT network structure. To this purpose we present some interesting results obtained through the SWIM mobility simulator [28].

A further major contribution of this paper is the provision of an overview (the first one, to the best of our knowledge) of the research activities aimed at the integration of social networks and the Internet of Things.

The paper is organized as follows. In Section 2 we provide a survey of the research activities that focus on the integration of social networking concepts into the Internet of Things. In Section 3 we present the basic idea of the SIoT and propose a classification of the types of social relationships that can be established between objects. In Section 4 we describe our proposal for a SIoT architecture and relevant functionalities, while in Section 5 we illustrate some examples of how the SIoT can be exploited. The structure of the resulting SIoT network is the subject of the analysis reported in Section 6. Finally, in Section 7 some concluding remarks are drawn.

2. State of the art

The collective intelligence emerging in social networks is an extremely interesting phenomenon that has been described in fascinating ways (e.g., [38]). This has been pointed out by many researchers – quoting the words by the DARPA Director Regina Dugan during her keynote speech at IEEE Globecom 2010 – as the key factor of a "*new era of wonder for science*". In fact, the incredible success of social networking websites, such as Twitter and Facebook, and the availability of data about the structure and dynamics of social networks collected through these websites, have attracted the attention of a large number of scientists from several areas [21]. In the context of communication and networking, for example, schemes have been proposed that exploit the similarity in the interests of friends – the so called *homophily* – to enhance the Internet search [31] or to optimize the peer-to-peer networks [11]. Also, schemes have been proposed that use social relationships to establish higher levels of trust and, thus, improve the efficiency and effectiveness of security solutions (e.g., [27,39]). In the mobile computing domain the intuition that individuals who are connected by social relationships are likely to meet more often than people who do not have any connection has been exploited. As a consequence, schemes have been proposed, which base the policy for data diffusion in opportunistic networks on the above property (see [8] or [29], for example).

A first idea of socialization between objects has been introduced by Holmquist et al. [17]. In that paper, the focus was on solutions that enable smart wireless devices, mostly wireless sensors, to establish temporary relationships. The authors also analyze how the owners of the sensor nodes should control such a process. However, that work is dated 2001 and both the concepts of the IoT and the online social networks were in their infancy.

More recent literature reports several researches and experimental applications based on a new generation of objects. These enter into humans' daily activities with a new attitude and a greater awareness of the fact that they are designed as "smart" objects with a potential for interaction with each other previously inconceivable.

In [3] the "things" connected to the Internet are clearly distinguished from the "things" participating within the Internet of social networks, which are named with the neologism Blogject, that is, "objects that blog". The theoretical concept of Embodied Microblogging (EM), introduced in [32], also challenges the current vision of IoTs. Rather than focusing on thing-to-thing or human-to-thing interactions, it proposes two novel roles that the augmented everyday objects will play: (i) mediate the human-to-human communication and (ii) support additional ways for making noticeable and noticing activities in everyday life. Also the authors of [23] show how to empower physical objects to share pictures, comments, and sensor data via social networks. They also discuss about the implications of the so called "socio-technical networks" in the context of the IoT.

Last but not least, the work in [30] introduces the idea of objects able to participate in conversations that were previously reserved to humans only. Those envisioned are objects aware of dynamic community structures; thus, they are able to develop a spontaneous networking infrastructure based on the information to be disseminated other than the information on the objects themselves.

Recently, the idea that the IoT and the social networks are two worlds not really that far apart from each other as one might think, has begun to appear in the literature. It is the case of the papers [33,10], for example. More specifically, in [33] the authors envision the future of the Internet as being characterized by what they name Ubiquitous IoT architecture, which resembles the social organization framework (SOF) model. That work provides an insightful overview of the expected IoT network structure. However, it does not aim at exploiting the characteristics of the social networks into the IoT. Analogously, the research activities reported in [10] consider that, being things involved into the network together with people, the social networks can be built based on the Internet of Things and are meaningful to investigate the relations and evolution of the objects in the IoT. Finally, the convergence of IoT and social networks has been considered in [14]. In that work, an individual can share the services offered by her/his smart objects with either her/his friends or their things. Accordingly, in [14] the reference social network is a social network of humans and it is utilized by things as an infrastructure for service advertisement, discovery, and access. That remarkable contribution somehow violates the IoT vision in which the objects should interact spontaneously to offer value-added services to humans.

An important step in the direction of the SIoT has been accomplished in [23]. There, the implications of the integration between the IoT and the social networks have been investigated and a few interesting exemplary applications are described. That paper, however, does not describe how the social relationships should be established by objects and does not propose any solution regarding the required architecture and protocols.

Finally, in a recent paper [25] social attributes, which reflect the social relations of nodes, have been analyzed. There a sort of quantification of the social relationships among mobile nodes is also performed by means of parameters such as an interaction factor and a distance factor. Besides, the authors study the behavior of mobile nodes by applying the typical theory of the social networks. In [25], however, it is assumed that there is a one-to-one correspondence between persons and objects. On the contrary, in the IoT, several objects can be carried by the same person while a large part of the objects will remain either static or embedded in the environment.

As a logic consequence of the studies described above, recently the name *Social Internet of Things* began to appear in official documents and published papers. This happens in form of either simple statements of objectives to be achieved within the activities of Strategic Research Agendas [12], or interesting attempts to explore the social potentialities of the Internet of Things building blocks [4].

3. A Social Internet of Things

The cited literature, however, still lacks in some basic aspects which should be addressed to fully achieve an actual "social networks of intelligent objects". In fact, in analogy with the social networks of human beings we need: (i) the definition of a notion of social relationship among objects, (ii) the design of a reference architectural model implementing a Social Internet of Things based on the codified inter-object relationships, and (iii) the analysis of the social network structure, which derives from the objects interactions based on the defined social relationships. Only a thorough investigation of these three issues will allow for effectively extending the use of models designed to study social networks of humans [20] to social networks of things.

The definition of a kind of social behavior of objects has been addressed in our previous works. More specifically, the definition of the novel paradigm of Social Internet of Things (SIoT) and the initial studies on the relevant social structures have been the focus of our initial investigations in [2]. Also an embryonic idea of architecture has been suggested, by starting from an appropriate revision of those utilized by the major existing social networking websites [5].

Although in this paper we aim at addressing the items (ii) and (iii), a brief review of the introduced concepts relevant to the potential social links among objects is given in the rest of this section. This will ease the comprehension of the concepts introduced later and make the illustrated research self-consistent.

One can start from the idea that, in the future, things will be associated to the services they can deliver. Thus, within a given social network of objects, a key objective will be to publish information/services, find them, and discover novel resources to better implement the services also through an environmental awareness. This can be achieved by navigating a social network of "friend" objects instead of relying on typical Internet discovery tools that cannot scale to the trillions of future devices.

The choice of the best basic set of social relationships can be made by observing sample typologies of application and the inter-object interactions that these foresee. The next step is to bring social behaviors of objects back to the widely accepted four elementary relational models of the Friske's theory [13,16] summarized in Table 1.

We claim that these patterns of interaction among human beings are directly applicable to possible social behaviors of typical objects that implement pervasive applications. There is no doubt that many applications and services should in the future be associated with groups of objects whose individuality will be "sacrificed" to the overall interest of providing services to users (as it is the case, for example, of applications involving the use of swarm intelligence and swarm robotics). It is equally true that many applications will involve an interaction among objects that will be performed "au pair", i.e., where each object will be the bearer of its specific service to the community. In addition, several services are already available, which involve the use of multiple objects that establish asymmetric relations (as, for example, in services based on Bluetooth, Zigbee, 6LoWPAN networks of sensors/actuators or RFID identification systems). In other services, the objects condition their relationship of "friendship" to the achievement of mutual benefits (this is the case, for example, of cooperative services designed to reduce the energy consumption of wireless devices). Those described above are merely examples of services that will surely find a placement in the future social network of smart objects and that rely on the same cited relational structures that Fiske has theorized for human beings.

From the analysis of possible service and application typologies, built upon the envisaged Social Internet of Things (more details will be given in a following section), one can also derive some basic relationships onto which relationship profiles will be defined within the reference system architecture. The kinds of relationships we define are those here summarized:

- *"Parental object relationship"* (POR): established among objects belonging to the same production batch, i.e., usually homogeneous objects originated in the same period by the same manufacturer.

Table 1
Basic relational frames

Relational model	Brief description
Communal sharing	Equivalence and collectivity membership emerge against any form of individual distinctiveness
Equality matching	Egalitarian relationships characterized by in-kind reciprocity and balanced exchange
Authority ranking	Asymmetrical, based on precedence, hierarchy, status, command, and deference
Market pricing	Based on proportionality, with interactions organized with reference to a common scale of ratio values

- *"Co-location object relationship"* (C-LOR): established among objects (either homogeneous or heterogeneous) used always in the same place (as in the case of sensors, actuators, and augmented objects used in the same environment such as a smart home or a smart city). Observe that, in certain cases, such C-LORs are established between objects that are unlikely to cooperate with each other to achieve a common goal. Nevertheless, they are still useful to fill the network with "short" links.
- *"Co-work object relationship"* (C-WOR): established whenever objects collaborate to provide a common IoT application (as in case of objects that come in touch to be used together and cooperate for applications such as emergency response, telemedicine, etc.).
- *"Ownership object relationship"* (OOR): established among heterogeneous objects which belong to the same user (mobile phones, music players, game consoles, etc.).
- *"Social object relationship"* (SOR): established when objects come into contact, sporadically or continuously, because their owners come in touch with each other during their lives (e.g., devices and sensors belonging to friends, classmates, travel companions, colleagues).

Please note that the establishment and management of such relationships should occur *without human intervention*. This is not in contrast with a future vision of a "fully networked human". This latter is responsible only to set the rules of the objects, social interactions and then enjoys the services resulting from such interactions. This is a clear paradigm shift from other proposals, according to which the objects/devices just participate in the human social network built by their owners.

By following an approach inspired by human "social relationships" and "relational models" things mimic the human behavior just to effectively interact with each other. A clear advantage lies in the fact that, in so doing, models and principles, which already proved to be effective for the study of the human social networks, can be extended to the object communities. Accordingly, the results shown in the last section of this paper demonstrate that it is possible to create social networks of objects that are easily navigable, like the ones created by humans.

In Section 6 of this paper we analyze the network structure arising from the above types of social relationships through numerical examples.

4. The SIoT system

In this section we provide an overview of a possible implementation of the SIoT. More specifically, in Section 4.1 the envisioned reference architectural model is described, in Section 4.2 the major functions required to run the SIoT are illustrated, and in Section 4.3 the advantages and disadvantages of the proposed architecture are analyzed.

4.1. The architecture

To describe the proposed system we resort on the simple three-layer architectural model for IoT presented in [40]. It consists of: (i) the sensing layer, which is devoted to the data acquisition and node collaboration in short-range and local networks; (ii) the network layer, which is aimed at transferring data across different networks; and (iii) the application layer, where the IoT applications are deployed together with the middleware functionalities.

Fig. 1 shows the resulting three-layer architecture. The three basic elements of the proposed system are: the SIoT server, the gateway, and the object.

4.1.1. SIoT server

The SIoT server does not encompass the sensing layer but only the Network and the Application Layers. The Application Layer consists of three sublayers. The Base Sublayer includes the database for the storage and the management of the data and the relevant descriptors. These record the social member profiles and their relationships, as well as the activities carried out by the objects in the real and virtual worlds. Data about humans (object owners as well as visitors) are also managed.

The relevant ontologies are stored in a separate database and used to represent a semantic view of the social activities. Such a view is extracted through appropriate semantic engines. Indeed, ontology and semantic services are necessary to provide a machine interpretable framework for representing functional and non-functional attributes and operations of the IoT devices. In this context, several works have been already conducted, which could be a starting point for the definition of an ontology to be used in the SIoT system. One solution is to adopt the Ontology Web Language for Services (OWL-S) model that provides both rich expressive descriptions and well-defined semantics. This has already been used as the basis of a semantic service modeling framework for the IoT [9]. In this framework, services are used as an interface that represents the IoT resources (i.e. the physical world devices) and provide an access to the functions and capabilities of these resources. Also in [18], an ontology is considered as a fundamental attribute of the IoT with the role of supporting the agent (man or machine) who reads an electronic tag to understand the information in it. Ontologies to manage and control heterogeneous systems have been

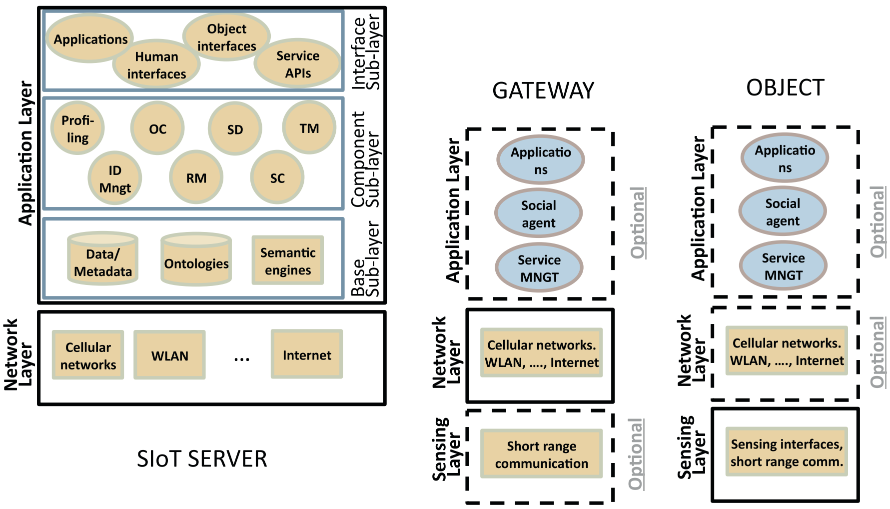

Fig. 1. Proposed system architecture following the three-layer model made of the sensing, network, and application layers. The main SIoT components belong to the application layer, wherein the relationship management (RM), service discovery (SD), service composition (SC), and trustworthiness management (TM) functionalities are located. The lines represent the optional layers in both the object and the gateway architecture.

investigated in [19]. Here the authors foresee that without ontological classification and semantic annotation processes an automatic discovery will be impossible. In [6] the importance of the ontology has been analyzed from a social network perspective as a format to represent the object information which is relevant to end users.

There are several other approaches for creating semantic service descriptions [15], including: Semantic Annotations for WSDL (SAWSDL), Unified Service Description Language (USDL), Web Service Modelling Language (WSML), Web Service Modelling Ontology (WSMO), and Semantic Annotations for Representational State Transfer SA-REST [37]. All these models are good bases that can be exploited to describe the social objects in our model. In this context, it is also worth mentioning the Friend-of-a-Friend project (FOAF; www.foaf-project.org), which is aimed at creating a web of machine-readable pages describing people, the links between them, and the things they create. The results of this project are of particular interest for the description of the objects' social links.

With reference to Fig. 1, the Component Sub-layer includes the tools that implement the core functionality of the SIoT system. The *ID management* is aimed at assigning an ID that universally identifies all the possible categories of objects. The *profiling* is aimed at configuring manually and automatically a (static or dynamic) information about the objects. The *owner control* (OC) is the module that enables the definition of the activities that can be performed by the object, the information that can be shared (and the set of objects which can access such information), as well as the type of relationships that can be set up. The *relationship management* (RM) is a key module in the network since the objects have not the intelligence of humans in selecting the friendships; thus, this intelligence needs to be incorporated into the SIoT. Main task of this component is to allow objects to start, update, and terminate their relationships with other objects (on the basis of the owner's control settings).

The *service discovery* (SD) is a fundamental component [34], which is aimed at finding which objects can provide the required service in the same way humans seek for friendships and for any information in the social networking services. The *service composition* (SC) component enables the interaction between objects. Most of the time, the interaction is related to an object that wishes either to retrieve an information about the real world or to find a specific service provided by another object. In fact, the main potential we see in deploying SIoT is its capability to foster such an information retrieval. Leveraging on the object relationships, the service discovery procedure finds the desired service, which is then activated by means of this component. Last but not least, the *trustworthiness management* (TM) component is aimed at understanding how the information provided by the other members shall be processed. Reliability is built on the basis of the behavior of the object and is strictly related to the relationship management module. Trustworthiness can be estimated by using notions well-known in the literature, such as centrality and prestige, which are crucial in the study of the social networks.

The third sub-layer, that is the Interface Sub-layer, is where the third-part interfaces to objects, humans, and services are located. This sub-layer may be mapped onto a single site, deployed in a federated way by different sites, or deployed in a cloud. Herein, we are not proposing any specific implementation solution.

4.1.2. Gateway and objects

As to the gateway and objects systems, the combination of layers may vary mainly depending on the device characteristics. The following three scenarios can be foreseen. In a simple one, a dummy object (e.g., a RFID tag or a presence sensing device) that is equipped with a functionality of the lowest layer, is only enabled to send simple signals to another element (the gateway). The gateway is equipped with the whole set of functionalities of the three layers.

In another scenario, a device (e.g., a video camera) is able to sense the physical world information and to send the related data over an IP network. The object would then be set with the functionality of the Network Layer other than that of the Application one. Accordingly, there is no need for a gateway with Application Layer functionality. An Application Layer in a server, somewhere in the Internet, with the gateway application layer functionality would be enough.

According to a third scenario, a smart object (e.g., a smartphone) may implement the functionality of the three layers so that the gateway is not needed, but for some communication facilities targeted to maintain the Internet connectivity of the object. This is the case of a smartphone, which has enough computational power to perform all the three-layer operations and that may need a gateway for ubiquitous network connectivity.

Whatever the scenario implemented, the Application Layer encompasses the SIoT applications, as well as the social agent and the service management agent, which are presented below. The social agent is devoted to the communication with the SIoT servers to update its profile, to update friendships, and to discover and request services from the social network. It also implements the methods to communicate directly with other objects when they are geographically close or when the service composition needs direct communications between objects. Finally, the service management agent is responsible for the interfaces with the humans that can control the behavior of the object when communicating within their social network.

4.2. Main SIoT processes

The main components of the proposed architecture are located in the Component Sub-layer. In fact, the SIoT is not intended as a solution for the sensing and networking in IoT, but to make the world of trillions of things manageable when facing the problem of service and information discovery. Additionally, it aims at laying the ground for autonomous interactions among objects (mainly through service discovery and composition) for the benefit of the human user.

In order to describe the interactions among the SIoT architectural elements, in Fig. 2 we provide an overview of the processes related to four main SIoT activities, namely: entrance of a new object, service discovery and composition, new object relationship establishment, and service provisioning. In the figure, the square blocks represent the tasks involved in the analyzed activity (e.g., account creation, profiling, parental control). These have a label associated *i2j* that identifies the two elements that communicate to carry out the task ($i, j = H, S, A, O$, which stand for human, SIoT server, object agent, and object, respectively). Notice that herein the gateway is not mentioned, even if it may take part in these processes when the agent is involved. This is because, in this context, the agent is defined as the software entity that implements the application functionalities of either the object or the gateway. On top of the task blocks we cite the main architectural components (see Fig. 1) involved to carry out the relevant operations.

For what concerns the **entrance** of a new object into the system, the relevant activities are mostly carried out by the object owner, who communicates with the servers to create the account, insert the object profile data, and set the control parameters though the ID management and object profiling components. The ID scheme should be interoperable with the main identification schemes already in use in this area, such as: IPv6 addresses, Universal Product Code (UPC), Electronic Product Code (EPC), Ubiquitous code (Ucode), OpenID, URI. The profiling adds relevant information about the capabilities and history of the object to its relevant ID. Given the heterogeneity of the IoT nodes, SIoT members are organized in classes. Each class is defined on the basis of the main object features.

- *Class1* is assigned to mobile objects with large computational and communication capabilities. Examples of objects belonging to this category include smartphones, tablets, and vehicle control units.
- *Class2* is assigned to static objects with significant computational and communication capabilities; to this class belong objects such as: displays, set top boxes, smart video cameras.
- *Class3* is assigned to objects with sensing capabilities only, that is objects capable of providing a measure of the environment status.
- *Class4* is assigned to the RFID- or NFC-tagged objects.

Each class is then characterized by specific attributes, such as: *object category*, which further specifies the object typology within its class; *owner ID*; *object position*, which can be changing over the time depending on the object mobility features[1]; *power supply status*, that defines whether the object is either battery-powered (and the battery power level is provided), socket-connected (and whether is currently connected or not), or harvests power from the environment; *amount of traffic* generated in terms of number of connections and overall bit-rate.

Once the object profiling procedure is completed, then the agent (which may be running either on the object itself or in a separate system, depending on the object characteristics) completes the process by looking for friends in the SIoT servers. During this phase the object establishes the main relationships that are triggered by its profile as well. Such relationships include parental object and ownership object relationships. Other relationships are established afterwards, during the entire lifetime of the objects, and mainly depend on the objects' movements and service/information exchanges over the SIoT.

Service discovery and composition are triggered by the application running either on the SIoT servers or in close relationship with the agent (in the gateway or in

[1] Position of an object should be given in absolute terms and can be estimated directly (by the objects itself) or indirectly (it is provided to the object by some other elements in the system, which can estimate its own position). Obviously, in the latter case, the estimation of the position is not very accurate. However, note that accurate positioning is not required by the SIoT operations.

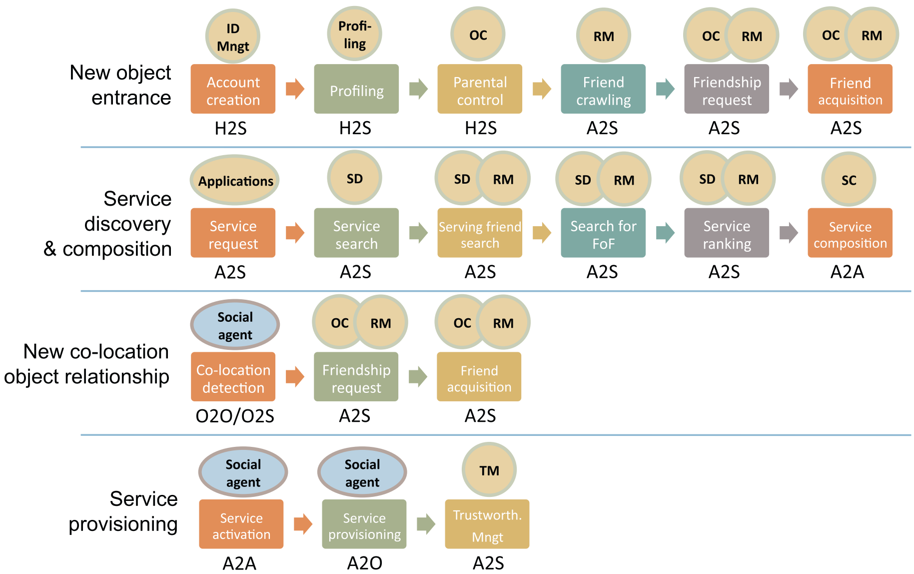

Fig. 2. Processes related to four main SIoT activities: new object entrance; service discovery and composition; new object relationship; service provisioning.

the object). The application can be one of those mentioned in Section 5. The way in which this process is performed depends on the type of service that the application is looking for. Examples are: the provisioning of information about the surrounding environment, the status of an object and the activities carried out by the object owner, as well as the activation of a specific action from another object.

Once the service request has been triggered by the application, the process continues with one of the most innovative and crucial task of the designed system, that is, the serving friend search. This is related to the procedure of looking at the “friend” object’s profiles to see whether the required service is provided by one or more of them. In this process, the different types of relationships have not the same relevance to any application. For instance, if the requested service is of a “best practice sharing” type, then the parental relationship is the most important. In fact, the same problem has probably been addressed in the past by objects belonging to the same production batch. In the case of need of an information about the surrounding environment, co-location and co-work relationships are those that should be exploited. In fact, the corresponding friends are those that most probably had occasion to acquire an information on the surroundings. In case a friend able to provide the service has not been found, then, the graph of friendships is also crawled. Since more than a single service may be found, a ranking is required. The ranking can be executed according to different rules, among which: the serving object trustworthiness, the credit/debit relationship of the interacting objects, the object resources (in terms of residual battery power, bandwidth, communication and computing reliability, and so on). Several approaches can be adopted in this context to rank the potential service providers, as those described in [35].

When the described activity ends, the service composition is triggered, which consists of interfacing the requesting service with the required one. Note that the service composition involves A2A communications, while A2S communications are required during other tasks.

In the **new object relationship activity**, two objects become aware that they are neighbors for a period of time long enough to trigger friendship. In this scenario we are referring to the co-location, co-work, and social relationships, which are triggered in case of geographical proximity of the objects. The detection of this event is enabled by the use of short range communication facilities (e.g., NFC, Bluetooth, or ZigBee interfaces) that allow two objects to detect that they are within communication range of each other. There are other possibilities to detect this event. One is the use of the localization facilities (WiFi/Bluetooth triangulation, INS systems, or even GPS) already available within the objects to track their position over the time. During an upload of location information into its profile (in the SIoT server), an object can detect the co-location relationship with other objects. Whatever the way the object detects the co-location event, the object agent then requests the friendship, which may be accepted according to the owner control rules.

The **service provisioning process** consists in delivering the service previously discovered and composed with the requesting service. As an example, let us consider the scenario of a smartphone that is looking for information about radio signal coverage in the areas surrounding its current position (this is the fourth example discussed in the next section). To accomplish its target, the smartphone drives a service discovery and composition process to look for smartphones and personal computers that have already visited the areas of interest (and are then aware of the signal strength). Once the service has been composed, the requesting agent (installed in the smartphone itself) communicates with the agents providing the relevant information to activate the service. All the way through, the service requesting agent is able to extract important information about the trustworthiness of objects that provide the services. This information is uploaded to the SIoT server and thus is available to the whole community.

4.3. Analysis of the proposed SIoT system

The IoT domain is characterized by a significant fragmentation and by the presence of heterogeneous systems based on dissimilar architectures. This makes a synergistic integration process difficult to be carried out. The need for a clear reference architectural model that will allow the different systems to cooperate is, thus, strongly felt. As such a model is still missing, we tried to adhere to the following principles: define an architecture that could foster the interoperability with existing IoT components, protocols, interfaces, and functionalities; include mechanisms for the efficient integration of this architecture into the service layer of the Future Internet networking infrastructure.

The resulting architecture is expected to provide the following advantages:

- A separate layer devoted to the sensing of the physical world allows for an easy integration of the existing and widespread standards for short distance communication technologies, such as: RFID, UWB (Ultra-Wide Band), NFC (Near Field Communication), and WSN (Wireless Sensor Networks).
- A layer devoted to the data transport functionalities allows for interconnecting the separate networks involved in the IoT. In this context, we follow the successful structure of the current Internet architecture centered around the Internet Protocol (IP), which can be seen as the narrow waist between connected devices on the one side and applications and services on the other.
- The service discovery module is surely one of the key functionalities in the IoT arena and is present in most of the proposed IoT architectures [24]. It addresses the issue of handling queries that contain a semantic information through a kind of declarative language. In this way, pointers refer to objects that can provide the related service (i.e., provide the information that satisfies the initial query). In our architecture, we have defined a separate module devoted to this functionality to foster interoperability with external systems. Therefore, queries that require the access to entities that are not part of the SIoT, can be sent to external architectures where the equivalent module can handle the process. Obviously, the discovery will rely on different principles with respect to the social-oriented approach we propose.
- The service composition module enables mashup interaction models (e.g., browsing, linking, bookmarking), which are pillars of the Internet of Services, to be extended to the real-world. This fosters an open ecosystem of digitally augmented objects on top of which applications can be created (i.e., it promotes the integration of the Internet of Service with the Internet of Things).
- As proposed in most of the other relevant architectures (e.g., [14]), the gateway is a key component to allow objects with limited communication and/or computing capabilities to take part in the IoT. This is another strong point we wanted to keep in our architecture.

On the other hand in the proposed solution we identify the following two potential weaknesses:

- The relationship management functionality in our solution is implemented only into the Server, without a collaboration of the gateway and the objects. We decided for this solution to allow "non SIoT-enabled" devices and relevant gateways to take part in the SIoT without the need for updating their systems. This approach, however, has the disadvantage of requiring a continuous communication with the servers for the creation and the update of the relationships. In particular, it is necessary to send information about the activity of the owner monitored by the objects (e.g., position, use of the Internet connection, movements), so that the co-location, co-work, and social relationships can be detected.
- The discovery process in our approach is driven by the relationship links among objects, which are followed to find the target service providers. Once these are found, their trustworthiness levels are evaluated to select the most reliable ones. The amount of interaction between the service discovery and the relationship management modules is limited; for this reason, we have decided to keep these two modules separate. However, if the discovery is performed by following the links involving trusted nodes only (i.e., there is a need for navigation across "trusted" areas), then the number of interactions between the two above components may increase significantly. This may reduce the efficiency in resource discovery.

5. Sample applications

Several applications can benefit from the availability of social relationships between things interconnected to a network composed of trillions of nodes. While a few interesting applications can be already defined, many others will show up in the years to come according to the increase in the number and categories of objects able to connect to the Internet. Fig. 3 provides a sketch of some sample applications, which are described in the following:

1. Giacomo has just bought a new notebook. It is a Mac this time, because of the influence of the Mac closed-community of colleagues at his work premises. At the beginning, this new world is a jumble for him because of the difficulties in connecting to some network equipments (e.g., printers, faxes, and smartcard readers) that indeed appear to him not to be exactly Mac-friendly. By exploiting social relationships with other Mac computers in the same local area network, Giacomo's Mac can find a mate that has already addressed the same configuration issues and fix the problems. Looking for potential sources of information through its social network (and exchanging best practices) is quite straightforward. In fact, features such as geographical location, class of object, brand, and typology, allow for identifying the right friends in the community. Note that Apple's Bonjour already provides the functions required for Apple devices to discover other Apple devices in the

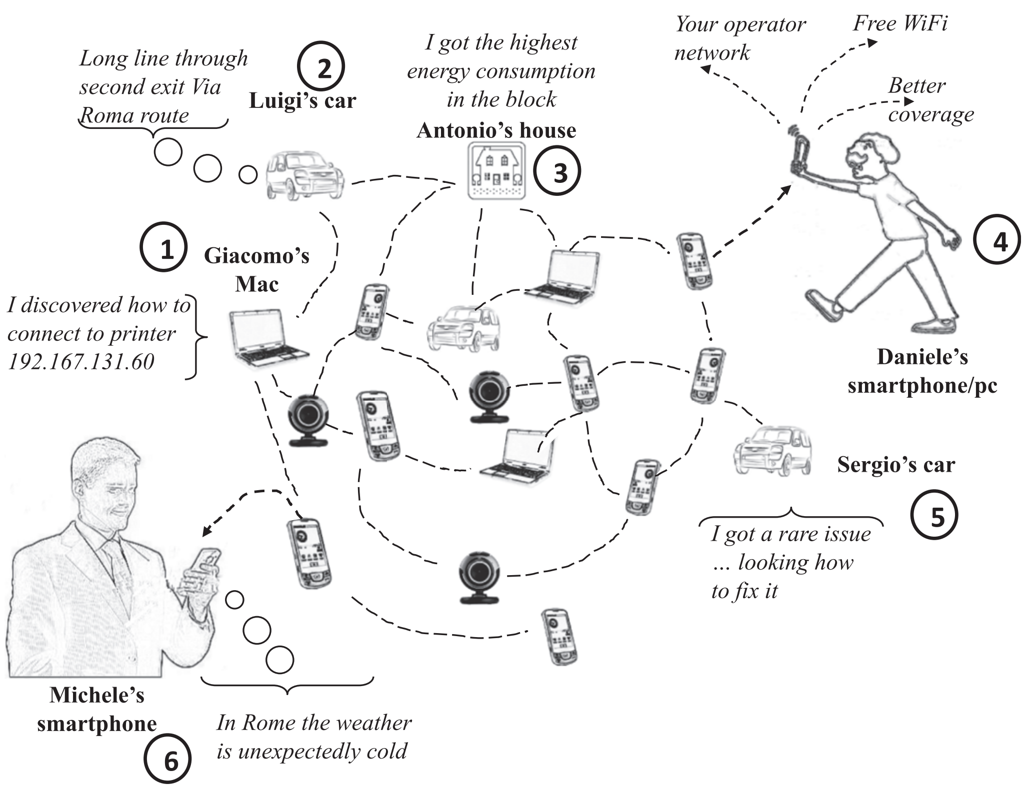

Fig. 3. Sketch of the sample applications in the Internet of social things.

same network and share resources with them. However, Bonjour is a service/resource discovery solution which cannot satisfy the need described above. In other words, you can print using a printer shared by another Mac device, but you cannot use that printer if the latter Mac device is not active.

2. Luigi is a sales representative that frequently moves by car around the city to meet his customers. Unfortunately, the traffic has increased during the last year; this making his tour more and more problematic. However, by exploiting the social network, his car is able to gather information in advance about traffic congestion along possible routes and to choose the best path to get to the meeting in the scheduled time. Finding the right source of information in the IoT social network is easy for the car by contacting "friend" devices acquired by means of co-location relationships. By this we mean those cars with which Luigi's car shared some routes in the past but which belong to drivers that Luigi might not even know.
3. Antonio has bought a new house in a block recently built according to advanced eco-friendly principles. Each flat is equipped with controllers and sensors able to manage and measure energy consumption and production (photovoltaic and solar cells) during the whole day. By means of their IoT social network, the domestic controllers are able to exchange information on the energy usage with reference to: consumption and production of energy to perform local benchmarking, identification of the energy providers that best match the house needs (in terms of cost profiles), identification of the household appliances with the highest efficiency levels. A light in any house changes the color according to the energy saving level obtained by its owner, which differs from other houses in the block. Ownership and co-location relationships are exploited in this scenario.
4. Daniele is a frequent traveler for work and needs the network to connect to his colleagues, customers, and family. His smartphone is a member of the IoT social network and is able to get information about the places in his surroundings that are covered by a stronger signal, by less congested UMTS cells, by its operator base stations (for free data service), and by free WiFi. Again, the right "friend" devices in this scenario are found by looking for specific member categories (smartphone and PCs) and geographical locations.
5. During the last year, Sergio's new car is having frequent problems, which seem to be difficult to fix. On the basis of the information collected by the junction box through the sensors located in the car, a profile of the problem and of the car is built. This profile is then exchanged within the IoT social network to look for similar problems that have already been addressed by other cars in the network (it is again a best practice exchange scenario). The search for the node that may help in fixing the issue is driven by the problem profile and mainly exploits parental relationships among cars.
6. There are several sensors that are going to be installed more and more numerous in any environment. These provide information about the status of environments

Table 2
Characteristics of the sample applications of Fig. 3 in terms of popularity and geographical extension.

	Local	Universal
Niche	1: Giacomo's Mac 3: Antonio's house	5: Sergio's car 6: Laura's closet
Popular	2: Luigi's car	4: Daniele's smartphone/pc

in terms of temperature, crowdedness of the ambient (rooms, theaters, discos, and others), identity of the people, humidity level, and other parameters about the weather. All these objects may exchange friendship with the controller of Michele's closet. He is preparing for his next travel and automatically acquires the list of clothes to be used for a comfortable travel.

Some of the above applications are of interest for a large part of the social network members (we refer to these as *popular* applications), while others are of interest for only a restricted part of the objects community (we refer to these as *niche* applications). Additionally, the applications are classified into those that have a geographical relevance, that is, mainly involve the objects that are located in a specific area (*local*), and those that do not have a geographical relevance (*universal*).

In Table 2 we provide a classification of the mentioned applications. Example 1 is local and of the niche category since the interest is limited to the LAN area and to only a restricted subset of the computer categories. Example 2 mainly involves the vehicles in a geographical area, thus it is local but is of interest for the entire car category and can be considered universal. Example 3 is clearly local and belongs to the niche category. In Example 4, even if the exchanged information refers to a specific location, the scenario is that of a smartphone that travels all around the world so that it is not geographically restricted; and it is popular since it involves entirely the smartphone and the computer categories. Example 5 is surely the case of an application of interest for a restricted group of SIoT members (the cars of a specific category) and universal since there is no connection with the geographical location of the cars. For the same reasons, Example 6 is universal and it can be considered as belonging to the niche category.

The popularity is for sure an important aspect to consider when developing an application, since the expected popularity can justify the high costs for designing and building it. However, in our vision, the social component sub-layer should be considered as a middleware that can be used by any application, both popular and of niche. The geographical connotation is, instead, important to understand whether the co-location and co-work relationships are important or not.

6. SIoT network characterization

In order to characterize the SIoT network, we will study the probability distributions of the geographical distance between nodes that are connected with each other as well as the probability distribution of the length of the shortest path between a pair of nodes randomly selected.

In order to estimate such a probability distribution, we would need the mobility data traces of a large number of objects. Unfortunately, such a data is not available to date. Therefore, we have exploited the *SWIM* simulator [22,28], which is able to capture the impact of social behavior in the mobility of humans. Logically, we have modified it to focus on the mobility of things rather than on the mobility of their owners.

Accordingly, this section is organized as follows. Firstly, we briefly describe the SWIM mobility model and the modifications introduced (Section 6.1); secondly, we analyze the numerical results obtained (Section 6.2).

6.1. Simulation environment

To produce mobility traces of objects we have used the mobility model called *Small World In Motion* (SWIM) as a starting point [22,28]. Our choice is motivated by the ability of SWIM to take the impact of social behaviors on the movement of human beings into account. In fact, it has been proven that an appropriate tuning of the parameters of the SWIM mobility model allows to obtain accurate matching between the output of the model and the most popular mobility traces available in CRAWDAD [26].

The basic intuition under the construction of the SWIM mobility model is that humans choose their destinations depending on the distance from their *home* and the popularity of such destinations. In other words, if we assume that the area of our interest is divided into smaller areas called *cells* and that each user u is assigned a home $h(u)$, then in the selection of her next destination a given user u will assign a *weight* $w(C)$ to cell C equal to

$$w(C) = \alpha \cdot \text{distance}(h(u), C) + (1 - \alpha) \cdot \text{seen}(C) \tag{1}$$

where $distance(h(u), C)$ is a function of the distance between the home of user u and the cell C and decays as this distance increases, while $seen(C)$ keeps the popularity of the cell C into account. Indeed, this represents the number of users that have been observed by u the last time she visited cell C. In this context, we assume that at any time a user can *see* all the users within a certain distance, which we call *user perception radius*.

The parameter α is in the range $[0; 1]$ and is used to determine whether the users prefer to visit popular sites rather than nearby ones. Once the destination is selected, the user moves in a straight line towards it and with a constant speed proportional to the distance to travel.

We have chosen the parameter setting that matches the Cambridge scenario [26]. More specifically, we consider a scenario characterized by the parameters reported in Table 3, in which we have assumed that the area of interest is a unitary square.

However, the output of the original SWIM is a trace of the position of humans. In this paper, instead, we are interested in the mobility of things. Accordingly, we have extended the SWIM simulator as follows.

We assume that each user possesses a set of things connected to the SIoT. The number of owned things is selected

Table 3
Configuration parameters.

Users	2000
User perception radius	0.0067
Simulation time	11 days
α	0.8

randomly according to a normal distribution with average equal to 10 (such as: one or more smartphones, a tv, a personal computer, a car, a digital camera, a digital frame, one o more sensors at home, and a number of RFID objects). Furthermore, we assume that at any time the user carries a certain number of objects, that vary according to a normal distribution with average equal to the objects she posses and leaves the others at home.

In this way, it is possible to simulate the movements of all the objects in the SIoT and post-process them.

6.2. Numerical results

In the following we show and analyze the numerical results obtained as explained in the previous section. More specifically, we study the characteristics of the random variable $X^{(A)}$. This is defined as the random variable representing the distance between two nodes that are tied by a social relationship of type A (in our case $A \in \{POR, C-LOR, OOR, SOR, \ C-WOR\}$). We are interested in the probability density function of $X^{(A)}$.

More specifically, we first focus on parental object relationships and co-location object relationships, that is, we consider $X^{(POR)}$ and $X^{(C-LOR)}$. Results of such an analysis are given in Section 6.2.1 Then, we move the focus on OOR (Section 6.2.2), SOR (Section 6.2.3), and C-WOR (Section 6.2.4).

Finally, in Section 6.2.5 we will briefly discuss the navigability of the resulting SIoT network.

6.2.1. POR and C-LOR

Parental Object Relationships (POR) are independent (in the scales of interest) from the specific positions of nodes. In fact, in most cases objects tied by POR are distributed uniformly in the area of interest. Accordingly, we do not focus on the distribution of $X^{(POR)}$. Here, we only stress that POR can be utilized to build long links in the SIoT.

The distribution of $X^{(C-LOR)}$ is obvious as well. In fact, in this case, a link exists between two objects only if their distance is very small. Accordingly,

$$f_{X^{C-LOR}}(x) \approx \delta(x) \tag{2}$$

Observe that relationships of C-LOR type can be utilized by the applications to explore the environment surrounding a given object and, therefore, are extremely important in the context of smart environment applications.

6.2.2. OOR

In Fig. 4 we represent the probability density function in case of Ownership Object Relationship, that is, we show $f_{X^{(OOR)}}(x)$ versus the value of the distance x. In the same figure, we also show the probability density function of the exponential and Gamma distributions that have average

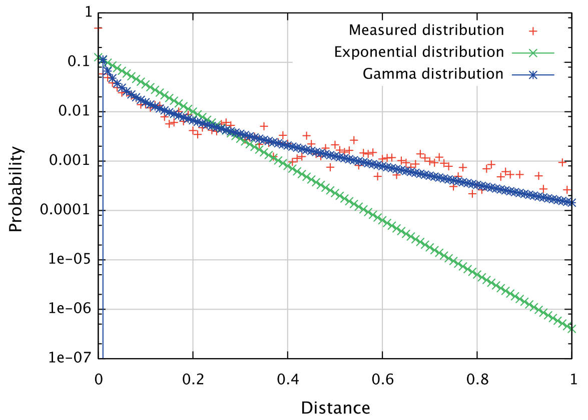

Fig. 4. Probability density function of the variable $X^{(OOR)}$. In the figure we show the pdf of the exponential and Gamma distributions with the same average value and variance.

value and variance equal to those of $X^{(OOR)}$. In the figure it is evident that the exponential distribution does not provide an accurate approximation of $X^{(OOR)}$.

To better assess the accuracy of the approximation provided by the Gamma distribution, we need to clean the measured $f_{X^{(OOR)}}(x)$ and to this purpose we filter it. Specifically, we define the operator $\Phi(f)$ which can be applied to any sequence f of values and that returns another sequence $\{\Phi(f)\}$ such that its i-th value is the sum of the first i values in the sequence f, that is

$$\{\Phi(f)\}_i = \sum_{j=1}^{i} \{f\}_j \tag{3}$$

In Fig. 5 we show $\{\Phi(f_{X^{(OOR)}}(x))\}$ and $\{\Phi(f_\Gamma(x)\}$ where $f_\Gamma(x)$ represents the Gamma distribution that approximates $f_{X^{(OOR)}}(x)$. In Fig. 5 it is evident that the Gamma distribution does not provide an accurate approximation of $f_{X^{(OOR)}}(x)$. In the same figure it is also evident that $\{\Phi(f_{X^{(OOR)}}(x))\}$ has a linear behavior when represented in log–log scale, which means that $f_{X^{(OOR)}}(x)$ is power-law. To demonstrate this, in Fig. 5 we show the line which approximates

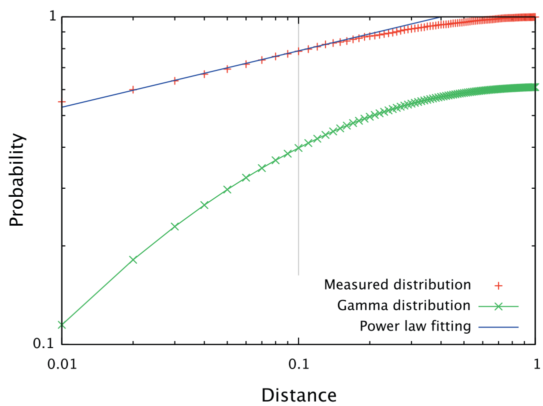

Fig. 5. Values of $\{\Phi(f_{X^{(OOR)}}(x)\}$ and filtered pdf of the Gamma distributions with the same average value and variance.

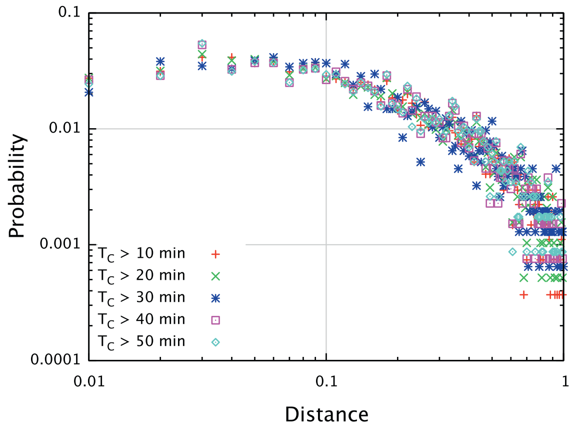

Fig. 6. Probability density functions, $f_{X^{(SOR)}}(x)$, obtained for different values of T_C.

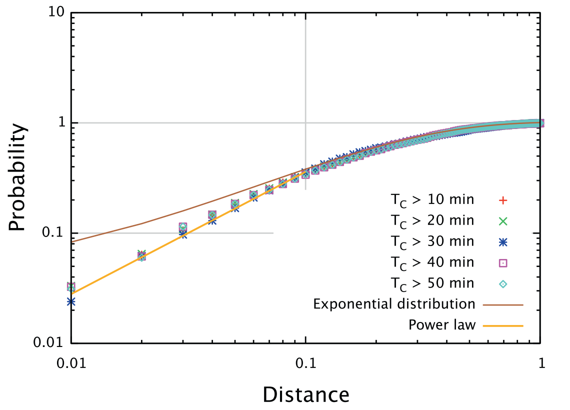

Fig. 7. "Filtered" probability density functions, $f_{X^{(SOR)}}(x)$, obtained for different values of T_C, and filtered exponential distribution that approximates them.

$\{\Phi(f_X^{(OOR)}(x))\}$ in the log–log scale. In other words it is possible to approximate

$$f_{X^{(OOR)}}(x) \propto x^{\beta_{OOR}} \tag{4}$$

For example, in the case discussed above, we have that β_{OOR} is equal to -0.827.

6.2.3. SOR

In Fig. 6 we represent the probability density functions, $f_{X^{(SOR)}}(x)$, of the distance between nodes connected by Social Object Relationships for different values of the parameter T_C. We have assumed that a relationship of the SOR type is established between objects if their owners meet at least N_C times, if successive meetings occur at intervals of duration longer than T_I, and if each of the meetings lasts longer than T_C. More specifically, in Fig. 6 we assume that $N_C = 2$ and $T_I = 8$ h. In order to "clean" the figure, we represent the values of $\{\Phi(f_{X^{(SOR)}}(x))\}$ in Fig. 7. In the same figure we show the filtered pdf of the exponential distribution and the power law distribution which approximate $f_{X^{(SOR)}}(x)$. By observing the figure, one notices that the probability density function of $X^{(SOR)}$ is not significantly impacted by the specific value of T_C. Additionally, it arises that the exponential distribution provides an accurate approximation of $X^{(SOR)}$ for large values of x, while the power law distribution is more accurate for small values of x. Accordingly, $f_{X^{(SOR)}}(x)$ can be approximated as follows:

$$f_{X^{(SOR)}}(x) \propto \begin{cases} x^{\beta_{SOR}}, & \text{if } x < x_{\text{thresh}}, \\ e^{-\gamma_{SOR} \cdot x}, & \text{if } x > x_{\text{thresh}}. \end{cases} \tag{5}$$

In our case, for example, $\beta_{SOR} = 0.12, \gamma_{SOR} = 3.87$, and $x_{\text{Thresh}} = 0.1$.

This dichotomy in the behavior of $X^{(SOR)}$ – that is, it is power-law for low values of x and exponential for high values of x – is in line with what has been recently demonstrated in [7].

In Fig. 8 we show the number of SOR relationships established versus the value of T_C. As expected, the number of relationships decreases as the value of T_C increases.

Same discussions can be done by observing Fig. 9 where we show the probability density function $f_{X^{(SOR)}}(x)$ for different values of T_I. In this case, we have assumed that $N_C = 2$ and $T_C = 30$ min. Also in this case the number of relationships established decreases as the value of T_I increases.

Finally, similar observations can be done by considering Figs. 10 and 11 which are analogous to 6 and 7, respectively, but have been obtained by using different values of N_C.

6.2.4. C-WOR

In Fig. 12 we show the pdf of $X^{(C-WOR)}$ obtained when we impose that a co-work social relationship is established only when the objects "meet" in a certain set of locations (offices, fabrics, laboratories, etc.) and that such meetings last for longer than T_C. More specifically, in the figure we represent the results obtained by considering different values of T_C; furthermore we show the Gamma distribution that approximates the above pdfs. By observing Fig. 12, we notice that the value of T_C does not have a significant impact on the probability distributions $f_{X^{(C-WOR)}}(x)$ and that the Gamma distribution provides an accurate approximation of such pdfs. Indeed, we have

$$f_{X^{(C-WOR)}}(x) = x^{k-1} \frac{e^{-x/\theta}}{\Gamma(k)\theta^k} \tag{6}$$

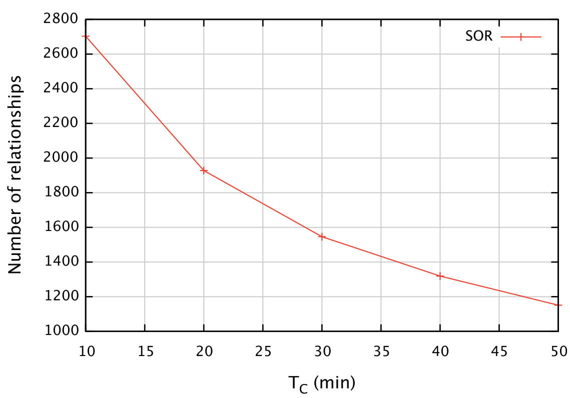

Fig. 8. Number of SOR relationships established versus the value of T_C, when $N_C = 2$ and $T_I = 8$ h.

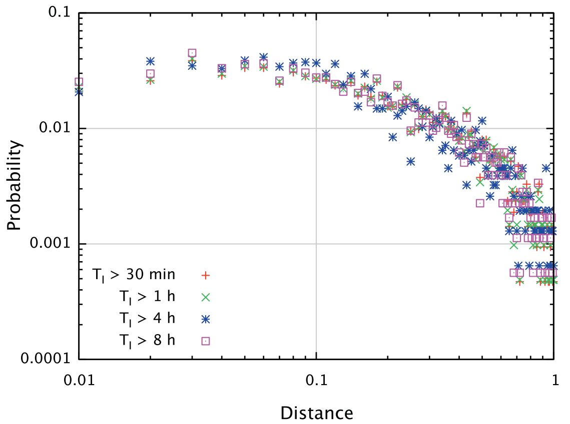

Fig. 9. Probability density functions, $f_{X^{(SOR)}}(x)$, obtained for different values of T_I.

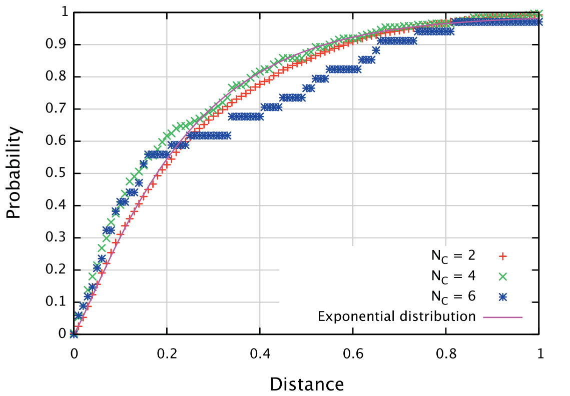

Fig. 11. "Filtered" probability density function, $f_{X^{(SOR)}}(x)$, obtained for different values of N_C, and filtered exponential distribution which approximates them.

where $\Gamma(k)$ is defined as follows:

$$\Gamma(k) = \int_0^\infty t^{k-1} e^{-t}\, dt \tag{7}$$

and $\theta = 15.93$ whereas $k = 2.11$.

In Fig. 13 we show analogous curves when there are no predetermined locations in which co-work object relationships can be established.

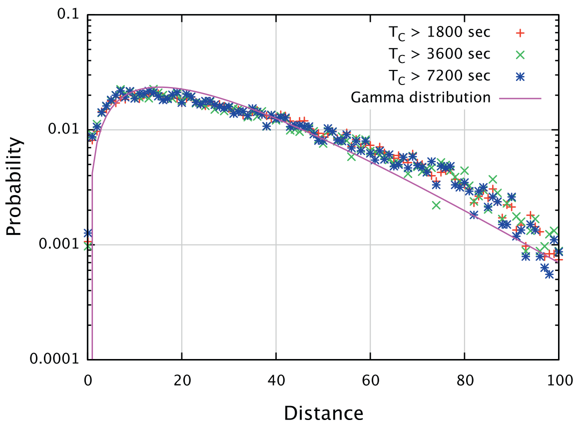

Fig. 12. Probability density functions, $f_X^{(C-WOR)}(x)$, obtained for different values of T_C, and Gamma distribution which approximates them.

6.2.5. SIoT network navigability

In Fig. 14 we show the probability distribution of the minimum path length between a pair of randomly selected objects of the SIoT. In the above figure we observe that the network diameter is 6 and that the average path length is equal to 2.85. For the sake of comparison, in Fig. 14 we show the distribution of the minimum path length between a pair of randomly selected nodes for a random network with the same number of nodes and edges as the SIoT. We observe that the average path length is 3.03 (almost equal to the one we found for the SIoT), however, the network diameter is 11 and 4% of the nodes are isolated. We summarize such results in Table 4.

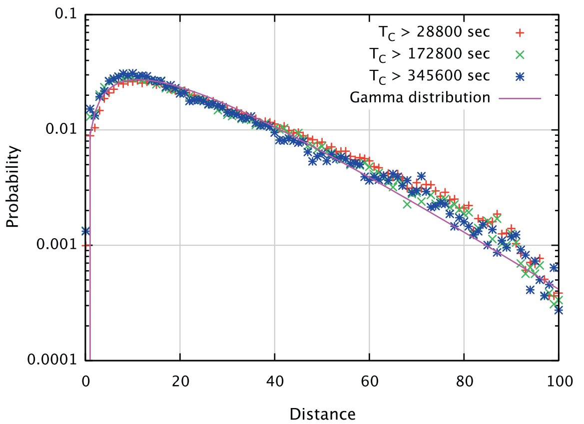

Fig. 13. Probability density functions, $f_{X^{(C-WOR)}}(x)$, obtained for different values of T_C, and Gamma distribution which approximates them.

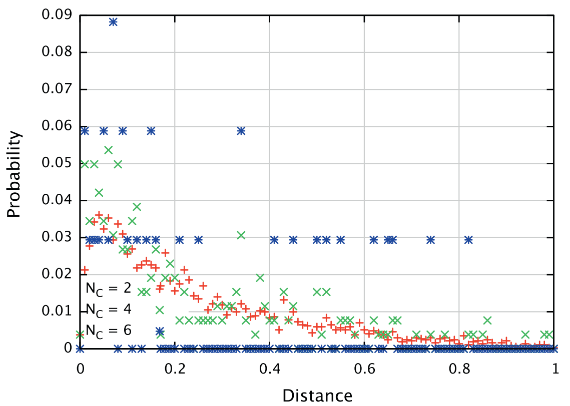

Fig. 10. Probability density functions, $f_X^{(SOR)}(x)$, obtained for different values of N_C.

The average value of the minimum path length has been evaluated by considering pairs of randomly selected objects. Instead, we expect that in most application scenarios

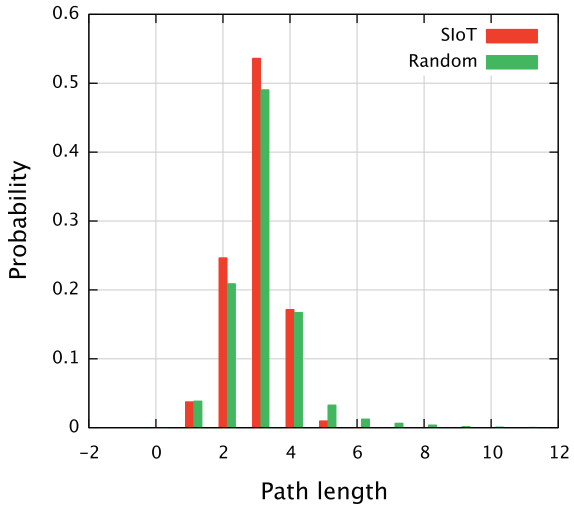

Fig. 14. Probability distributions of the minimum path length between a pair of randomly selected objects in SIoT and in random network cases.

Table 4
Comparison between the SIoT and a random network.

Parameter	SIoT	Random network
Average path length	2.85	3.03
Diameter	6	11
Isolated nodes (%)	0	4%

interactions will occur preferably between nodes that have already interacted in the past and/or have a high degree of homophily. This would further reduce the average path between *interacting* nodes.

7. Conclusions

In this paper we have focused on the integration of social networking concepts into the Internet of Things, which leads to the so called "Social Internet of Things" (SIoT) paradigm. Recently, the SIoT has been the subject of several independent research activities as it promises to achieve scalable solutions in networks interconnecting trillions of nodes and to support new interesting applications. More specifically, in this paper we have identified the types and the characteristics of the social relationships that can be established by objects in the SIoT. Furthermore, we have proposed a system architecture and the required basic functionality for an implementation of the SIoT. Finally, we have statistically analyzed the structure of the SIoT network.

Our analysis has been based on the output of the SWIM mobility simulator. Results of such an analysis show that the probability distributions of the distance between nodes that are linked by a social relationship depend on the type of relationship. More specifically,

- For OOR relationships, such a distribution is characterized by a powerlaw behavior.
- For SOR relationships, such a distribution is characterized by a power law behavior for small distances and exponential behavior for large distances.
- For C-WOR relationships, such a distribution is characterized by a Gamma behavior. Furthermore, it is obvious that, for C-LOR relationships, the distances between connected nodes must be small. Whereas, for POR relationships, the existence of a relationship between two nodes is independent of their distance.

It follows that the above types of social relationships offer the possibilities to set long as well as short links and, therefore, their weight can be tuned in the SIoT in such a way that the resulting network structure offers the desired features in terms of navigability and scalability. We leave the detailed definition of the procedure to be executed for the establishment and maintenance of the above relationships, along with the relevant parameters, for future research.

Also, we are now planning to assess the results of our analysis versus the most popular mobility data traces – those stored in CRAWDAD, for example – and to verify that the resulting networks are navigable and provide short paths between any pair of nodes.

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