Dynamic Social Structure of Things: A Contextual Approach in CPSS

The Dynamic Social Structure of Things (DSSoT) is proposed in this article as a cyber-physical-social systems (CPSS) smart services framework, aiming to boost sociality and narrow down the computational and networking contextual complexity based on situational awareness. Essentially, DSSoT monitors spatiotemporal situations and, depending on users' individual goals preferences, and various other social aspects, induces and structures relevant social objects and smart services in a spontaneous social network of relationships and interactions. As a proof of concept, an application that uses DSSoT is provided, called Airport Dynamic Social.

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Cyber-physical-social systems (CPSS) regard humans and their interests, needs, and motives as part of the broader system, not as additional aspects lying on its boundaries.[1,2] In this sense, intelligence and reasoning about the social aspects of humans – including their activities, preferences, emotional states, and various other subjective elements embedded from human communities – act as the core for realizing the integration between virtual, physical, and social worlds. CPSS goes beyond the vision of cyber-physical systems (CPS), in which the latter aim to realize the integration between abstract computational artifacts with communication, monitoring, and control facilities;[3,4] CPSS further incorporate and reason about extracted knowledge hidden in human behavior with the goal of bridging human-to-device perceptions. However, many challenges arise in CPSS that hinder its realization and deployment in our daily lives, including the complexity arising from its heterogeneous nature and the large scale of contextual data handled within its environment.

Recently, a paradigmatic class of CPSS emerged, referred to as the *social Internet of Things* (SIoT),[5,6] which provides a vision for handling heterogeneity in CPSS as well as boosting sociality. SIoT builds on the emerging technology of social objects,[7] in which smart objects become exposed to the Web, allowing command and control-based interactions with people and other objects. The goal is not only to interact with one object at a time but to use mashup capabilities between devices, services, and Web applications to generate a new user experience, which we refer to as *smart services*. The SIoT establishes

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social structures among objects and people for the goal of improving network navigability, by using social objects' discovery and search mechanisms to narrow down the scope of discovery to a manageable network of relationships and interactions resembling social network services (SNS).[5]

Another big challenge revolves around how to handle the variety of contextual data in CPSS as well as SIoT (as its subclass) for intelligent decision making. Situational awareness (SA) would be an approach capable of addressing this challenge. That is, combining the objective context (which represents the physical environment, such as location, time, device status, and available services) along with the subjective context (which captures the internal sociality aspects such as relationships, preferences, trust, and preferred services) is proposed as a core for intelligence generation. Achieving SA would contribute to characterizing users' situations and goals for adaptive services' provisioning in CPSS; additionally, it narrows down the scope of social objects' and smart services' visibility beyond the suggested SIoT structures, where heterogeneity is dealt with within the narrow scope of spatiotemporal situations.

Thus, in this article we build on the notion of social structures as a practical solution to manage the complexity coming from the diverse entities interacting within CPSS. However, with the ultimate goal of reaching efficient, situational-based integration among the social, cyber, and physical worlds of CPSS, we establish dynamic and goal-driven social structures in our framework, which we call Dynamic Social Structure of Things (DSSoT). DSSoT utilizes a reasoner to determine users' short-term situational goals, and incorporates available social objects and smart services to meet these goals. Accordingly, DSSoT groups social objects and the smart services they provide in a temporal social structure, with the aim of direct service provisioning and interactions. Additionally, from a technical perspective, we build on Internet Protocol version 6 (IPv6) to develop an application scenario and a prototype (called Airport Dynamic Social) to allow direct interactions with things in the physical world via DSSoT.

CPSS: From Challenges to Solutions

In their discussion of CPSS, Amit Sheth and his colleagues[8] use the term *computing for human experience* (CHE) to refer to personal and social activities, decision making, interaction with physical and social worlds, and any human-centric role. In this sense, CHE, when enabled within a CPSS environment, can shift its paradigm from search-based to solution-based.[8] Accordingly, reasoning about knowledge generated by observing human activities can eventually improve the user experience in CPSS.

Similarly, Zhong Liu and his colleagues[1] argue that the integration among CPSS entities shouldn't focus solely on physical aspects; rather, human-driven mental elements of commands controls which should provide the core for this proposed integration. In this sense, advanced intelligence mechanisms should be utilized for achieving the integration among CPSS worlds and eventually reaching the full potential of CPSS.

Fei-Yue Wang[2] argues that CPSS can achieve intelligence when smart spaces are able to autonomously observe what's happening inside them, and construct a model of relationships and interactions with smart space inhabitants and act according to the decisions made. Researchers could actualize this concept by accessing a large infrastructure of sensors, actuators, appliances, and other devices with embedded processors that are capable of communicating with humans as well as forming an integrated global information network.

In short, the two most challenging aspects for realizing the future shape of CPSS are boosting sociality as well as the intelligence represented in proactive decision making. Thus, CPSS should be equipped with reasoning methods to actively monitor and model situations and activities for the goal of providing relevant services anywhere at any time, with the aim of enhancing users' experience.

On the other hand, context-awareness in ubiquitous and pervasive environments is a widely tackled topic aimed at improving intelligent decision making.[9,10] Context is typically dealt with in the literature with a separation between social and physical aspects. However, achieving contextual intelligence in CPSS doesn't necessarily involve realizing new kinds of awareness; rather, it's more of a reinvention of the wheel by combining social and physical aspects to characterize users' situations and needs and utilize it for the process of intelligent decision making and adaptive services provisioning.

Using SIoT to Fulfill Emerging Requirements

The SIoT paradigm exhibits sociality benefits from SNS. These benefits include the rich profiling system that manages contextual data about various social aspects, such as relationships,

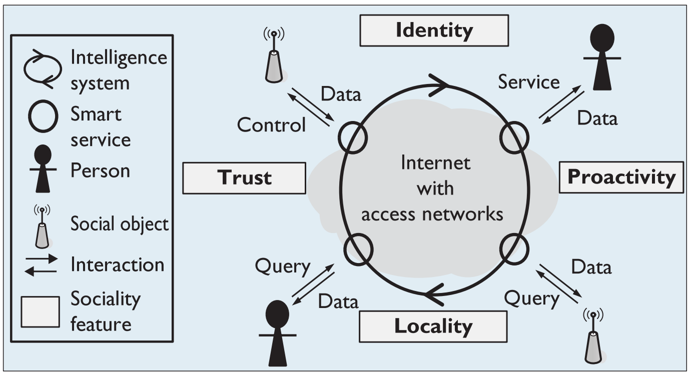

Figure 1. The social Internet of Things (SIoT) framework with its sociality features exhibited from social network services (SNS).

trust, interests, and so on. However, the notion of sociality in SIoT is expanded beyond humans to include social objects equipped with the computational and networking capabilities needed to become conscious elements.[6] For instance, my coffee machine realizes my time of arrival to the office and prepares my favorite coffee at that time. As Figure 1 shows, the abstract framework of SIoT builds on the social structure to provide and consume smart services, where an intelligence system manages such social structures. This intelligence system operates on top of the Internet and is accessible via platforms with various access networks. People and social objects interact proactively for providing and consuming services.

In Figure 1, we present the main sociality features (deduced from the literature) that characterize social behavior within the SIoT framework, as well as in the wider CPSS environment. First, personality is the main characteristic of social entities that enable them to carry out their own social role[5,11] — that is, initiating relationships, interacting, sharing, granting, or revoking access to resources based on preferences. Second, proactivity, which refers to entities that exhibit a goal-driven manner[12,13] — in which, entities interact with the aim of providing or receiving services to meet their own expectations. In this sense, social objects might have goals to meet that other entities could schedule, infer, or directly request. Third, the locality feature allows social entities to follow small-world phenomenon, denoting that human beings are all linked by means of short chains of acquaintances through a local network of relationships and interactions.[11] Finally, trust allows social entities to provide and consume data, and react, generate, and maintain social relationships based on the preset or acquired level of trustworthiness.[5,12]

Toward a Solution

CPSS boost sociality by understanding day-to-day human behavior. This implies reasoning about wide social and physical context. We propose building dynamic social structures that break down contextual complexity into the narrow scope of situations, and thus maintain user privacy and adaptability to their needs. Figure 2 provides two scenarios to highlight the static social structure (again, as deduced from the literature), and the dynamic structure that we propose (DSSoT).

Scenario a: static social structures of everything. Nadia is in the airport to catch her flight. She sends a platform-based search request to allocate available social objects and smart services around her. Accordingly, a list of available objects and services in the airport is processed and sent to Nadia. Now she can select objects to add to her network as social nodes, forming a social structure for direct interaction and service provisioning (see Figure 2a). Later, Nadia can revoke these nodes' access to her profile manually for each object or service.

Scenario b: DSSoT. In the airport, when Nadia sends a request to allocate social objects and smart services around her, an event gets triggered and the airport services provider sends a request asking for permission to access Nadia's profile. The DSSoT framework then applies reasoning about Nadia's situation and short-term goals, including her check-in counter, maps service, a favorite restaurant, the closest reading or work area, and so on. The DSSoT is then induced with a list of social objects and smart services around Nadia that meet her goals. Once she approves it, a temporal social network of social objects and smart services gets established, which expires by the end of the situation (see Figure 2b).

Toward a Contextual Approach in CPSS

The major challenges for realizing DSSoT involve the integration and reasoning about context-awareness coming from CPSS worlds for intelligent and proactive decision making. DSSoT acts as a practical method to achieve SA, in which a temporal social structure meets users' goals anywhere at any time.

DSSoT

Reasoning about spatiotemporal situations takes place once a user triggers an event, or by

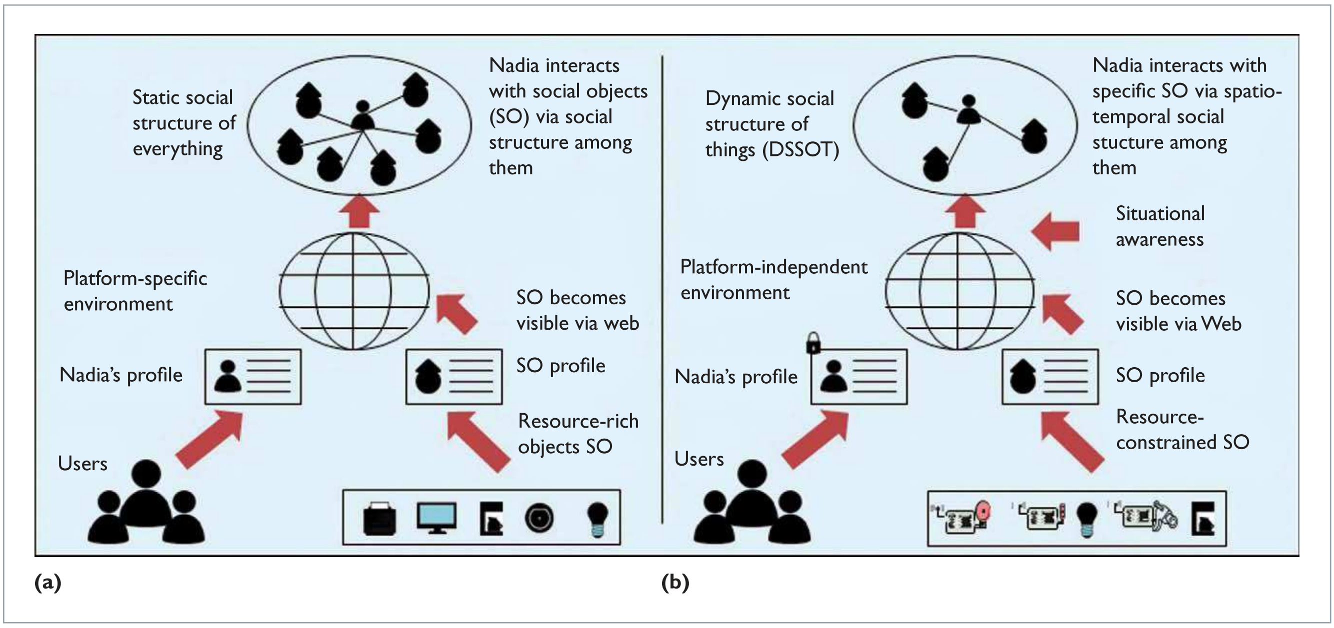

Figure 2. Comparison of social structures. (a) Static versus (b) dynamic.

something stored in the user's profile (for example, something stored in the schedule). Then, the framework sets about determining relevant smart services and social objects. In this sense, the framework maps smart services (SS) to a certain social object (SO) — for example, it correlates and annotates a self-check-in machine in an airport with the service it provides (self-check-in). It can map various SS to multiple SOs; for example, detecting a spot suitable for reading might include detecting and comparing the light conditions inside and outside a building. Additionally, some services could be Web applications not mapped to a SO, such as information and maps services. After applying a ranking algorithm that considers services' ratings, user preferences, authorization, and trust, DSSoT can establish social structures based on services' and objects' relevance (see Figure 3a). Figure 3c shows the semantic data model upon which the main entities interact for DSSoT generation. We base DSSoT on three types of contextual reasoning (see Figure 3b):

- *event retrieval* — related to the user's spatio-temporal physical environment;
- *service relevance* — related to user requirements, preferences, interaction history, trusted services, authorization restrictions, and services ratings; and
- *object relevance* — related to objects available to meet goals.

A Novel Service Framework in CPSS

As Figure 4 shows, we can realize the DSSoT approach through a service-management framework, allowing goal-driven interactions among a diversity of entities for providing and consuming services in CPSS environments. The intelligence generation initiates when an event is triggered, which could be via

- real-time requests for services or event initiation, where facts are extracted from the requests using a natural language processor (NLP);
- the users' condition, users' surrounding environment, and device status update, where the context management conducts the acquisition and storage of contextual data; or
- stored events in user profiles — such as schedules where the profile management (PM) capability extracts and handles facts about an event.

To perform situational reasoning, the Semantic Service Relevance assessment Rules Engine (SSRRE) carries out semantic rule-based matching (see Figure 3c), which can eventually scale down the scope of service and object discovery. Based on the filtered list of matching objects and services extracted from SSRRE, the service controller (SC) can generate DSSoT and manage it. When the service itself is provided, DSSoT uses an NLP model to allow direct interactions between users and objects. Finally, the framework

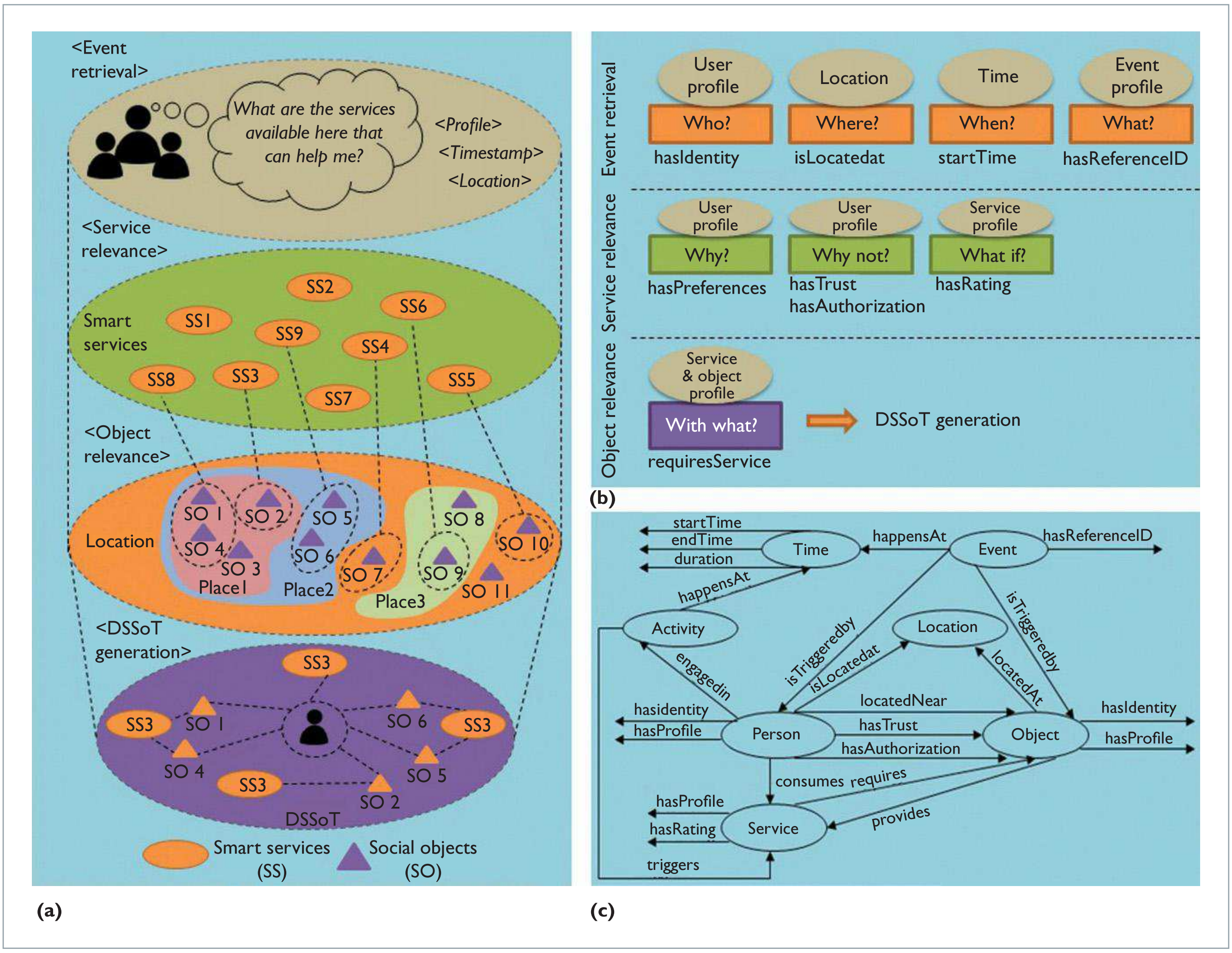

Figure 3. Dynamic Social Structure of Things (DSSoT) generation model. (a) Goal-based services restriction in DSSoT. (b) Context-reasoning model for DSSoT generation: Event retrieval restricts the discovery scope of social structure generation to object entities, such as things that are matched with the generated event. The service relevance refines the discovery scope based on a ranking algorithm to create a personalized network of services that matches users' individual requirements, trust, ratings, and so on. The object relevance provides a list of objects capable of undertaking the required services and tasks to finally meet the goals. (c) DSSoT semantic data model.

uses a feedback loop to provide essential contextual data for the adaptive service learning conducted by the CPSS service management.

Application Scenario: Lost in an Unfamiliar Airport

Now that we detailed the framework's underpinnings, let's look at a service procedure to be built on top of this framework.

Imagine this scenario: Nadia is on a trip abroad and going back home, but she's lost in an unfamiliar airport. Once she approaches the airport's main directory, she sends a request from her mobile device asking for help. Her identity is detected, along with a request to access her profile. Upon her approval, an application uses her schedule to detect Nadia's purpose of traveling. The app computes the sequence of activities needed to meet Nadia's triggered event, and for each activity the app checks the services associated with it against their relevance to her. Then, it sends a notification to Nadia's mobile device informing her of the flight status and gate number. After that, Nadia's mobile generates a list of nearby objects associated with the services she needs. After Nadia's approval, the app establishes a temporal network, including relevant objects and services. Nadia now can receive logistics

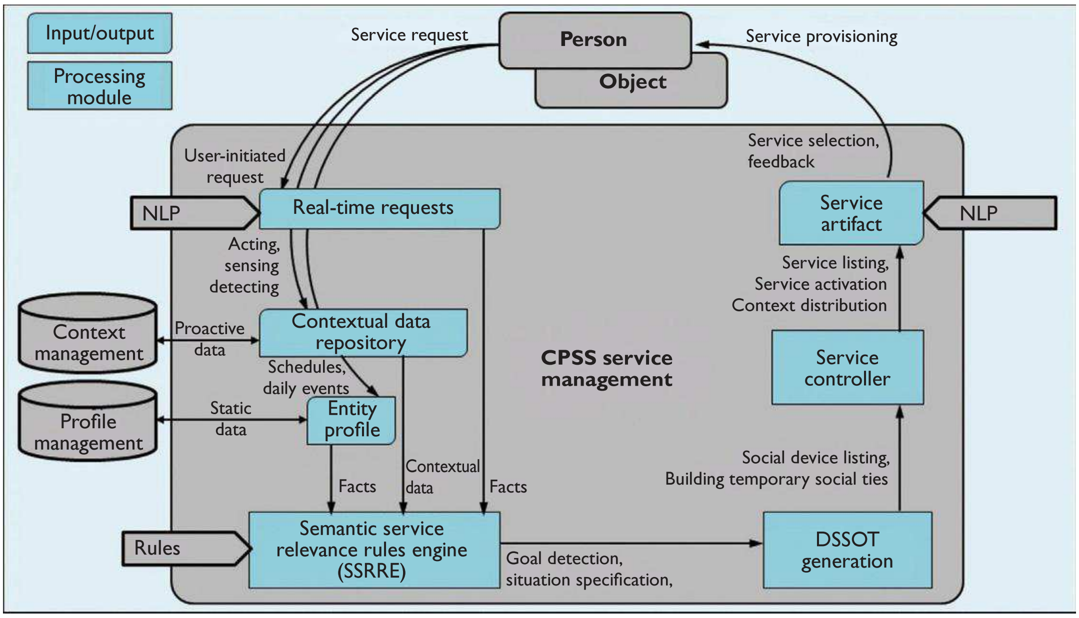

Figure 4. DSSoT service framework. (NLP stands for natural language processor.)

information, and she can send information to her favorite coffee shop in the airport, asking them to prepare her coffee. She can also receive updates from the objects in her network, with information regarding how crowded her flight boarding gate is, or if there's any change in the flight boarding time. Nadia decided to grab her coffee and go directly to the gate and spend some time reading; she sends a request to the boarding gate asking about the lighting condition there. Before boarding, she sends a request to see the temperature on the plane.

As Figure 5 shows, when the passenger enters the airport, her mobile device connects to the locally available wireless network. The interface (IN) running on the passenger's mobile device advertises her identity and location. The SSRRE and SC components running on the airport servers coordinate to determine event-related activities. Then SSRRE component coordinates with a PM instance on the passenger's device to match event activities against preferences, and then return the list of preferred activities. Again, the SC component coordinates with SSRRE to determine the filtered activity's related services; SSRRE then coordinates with the PM capability to match services against restrictions and ratings existing in the passenger profile. A list of filtered relevant services is then returned from SSRRE to the SC. Next, a request to fetch the services' corresponding devices is sent to the PM instance in the airport servers. When the devices' identities return from PM to the SC, the SC can interact directly with social objects (SO) to receive objects' status and updates. Then a final list of active objects is sent to the passenger IN awaiting her approval. Once the user approves the list, direct interaction can occur between the user and objects via the NLP in the airport servers. The NLP module detects user commands and natural-language interactions with devices. This NLP uses each device's profile at the setting-up phase to obtain keywords related to device's functions. The NLP also applies a set of rules to obtain the meaning in an English-language context. Output from the NLP is then converted into a semantic format and processed by SSRRE.

Application Scenario: Airport Dynamic Social

The testbed setting of Airport Dynamic Social benefits from IPv6, to accommodate the huge number of smart objects increasingly being introduced to the Internet. IETF and other standardization bodies are making great efforts to reduce the IPv6 footprint for resource-constrained devices. IPv6 over low-power wireless personal area networks (6LoWPAN) is designed to add wireless sensor connectivity to the IPv6 protocol. It enables the use of IPv6 in low-power

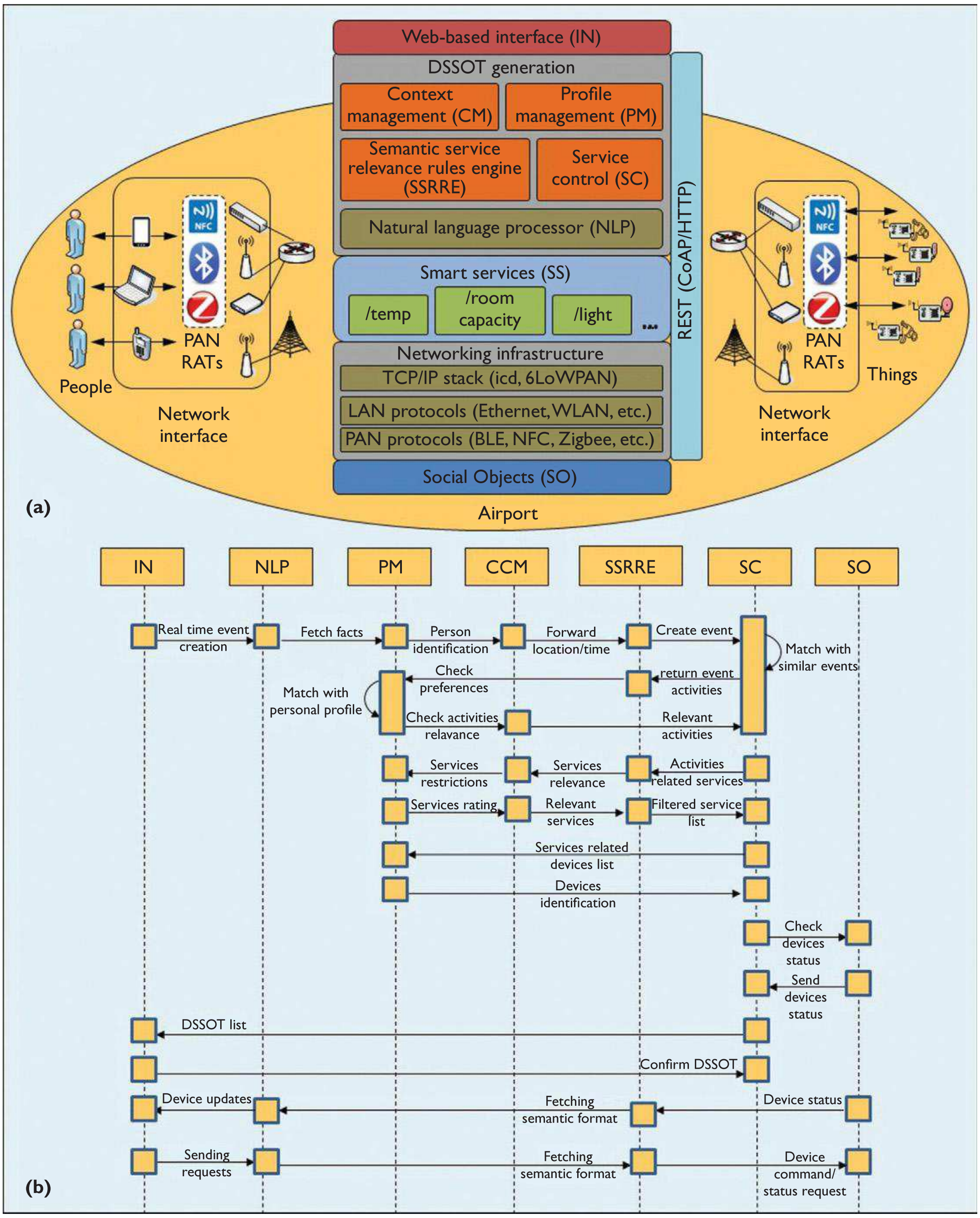

Figure 5. DSSoT service interaction procedure. (a) DSSoT abstraction modules layers. (b) DSSoT interaction flow diagrams.

and lossy networks (LLNs), such as those based on IEEE 802.15.4. In addition, the Routing Protocol for LLNs (RPL) and the Constrained Application Protocol (CoAP) in the application layer are key IP networking protocols that seamlessly integrate resource-constrained smart objects into the Internet. DSSoT has been designed so that it benefits from these advances, offering an effortless deployment of such systems without the need for a protocol translation gateway or an intermediary server to cope with device heterogeneity.

We developed the Airport Dynamic Social prototype with some sensor nodes, a router, and a smartphone application for Android operating systems using IPv6 and related networking stacks for smart objects to illustrate how DSSoT works. We

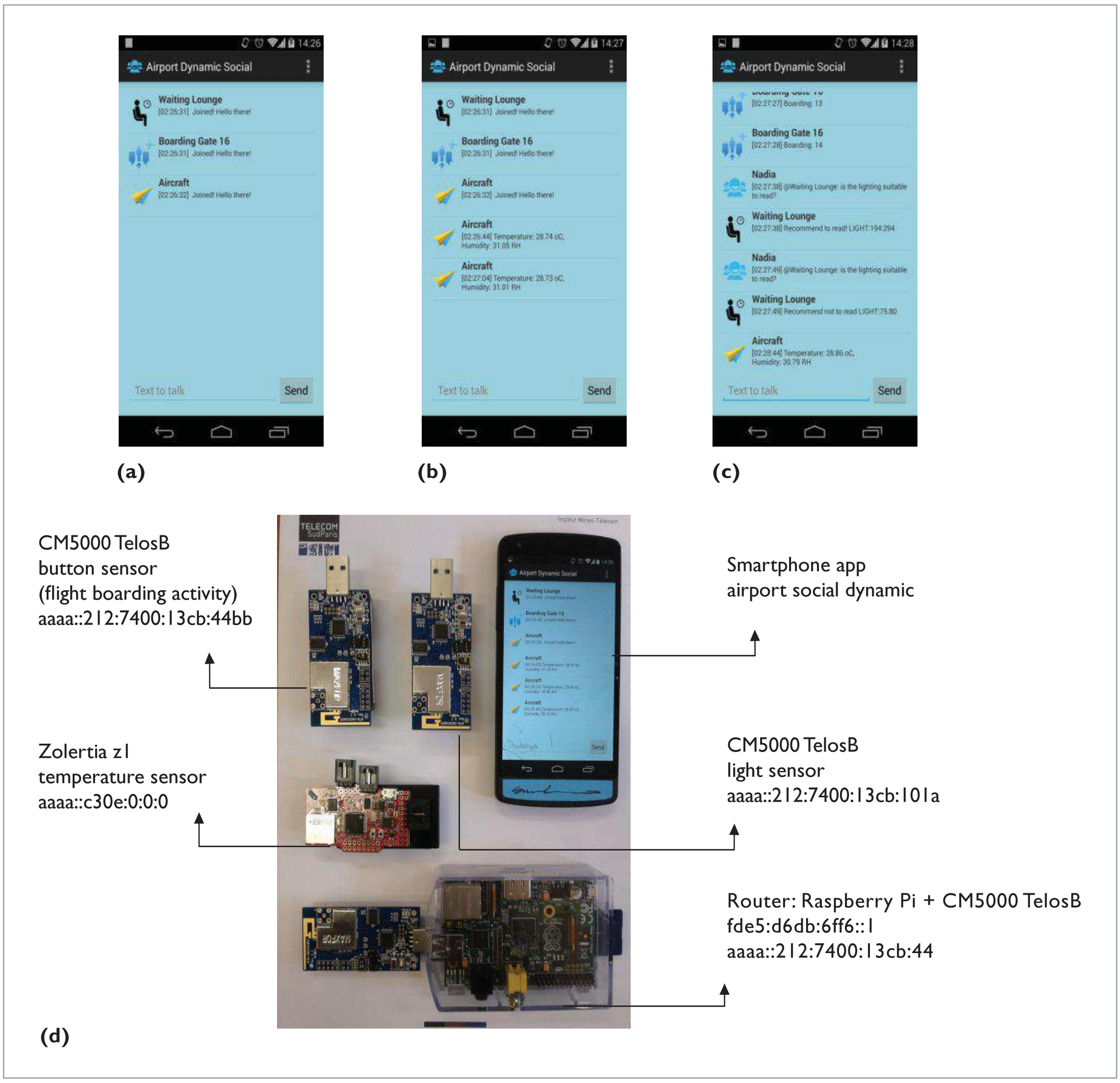

Figure 6. Airport Dynamic Social application and implementation. When a passenger logs onto the app, the application detects the passenger's event and configures information on service relevance. (a) The application then sends the passenger a list of devices selected to match the event's goals, after the passenger approves the devices list. Next, the devices on the passenger's DSSoT network will push notifications about any status updates; for instance, (b) the aircraft might send updates about current temperatures, and (c) the boarding gate will send notifications about the number of passengers boarding, so that the passenger can select an optimum boarding time with shorter lines. The passenger can also interact directly with the boarding gate, for instance, to ask if the lighting is suitable for reading. (c and d) An embedded NLP fetches the request and transfers it to the boarding gate; after checking the lighting level, the status is sent to the user, in this case with the recommendation not to read.

used one Zolertia Z1 WSN mote (a wireless sensor network node) for temperature sensing inside the airplane, one CM5000 TelosB node for sensing the lighting level in the waiting lounge, and another CM5000 node to track boarding. A network device called Border Router, developed with a Raspberry Pi computer board combined with a CM5000 TelosB as an IEEE 802.15.4 radio device, acts as a router between the IPv6 IEEE 802.15.4 network and the users' IPv6 Wi-Fi phone network. Each sensor provides its service via a CoAP endpoint that users' smartphone applications can subscribe to in order to receive updates, such as the airplane's interior temperature or the number of boarded passengers. Users can also request specific information, such as whether the lighting level in the waiting lounge is bright enough for reading a book; light sensors deployed there can reply directly to the user. Figures 6a through 6c show examples of the application and implementation. Figure 6d shows the equipment we used in the prototype, with IP addresses.

DSSoT is a contextual approach that operates on top of a novel CPSS service framework. Given the heterogeneous nature of CPSS, intelligence and proactive decision making should be handled within the scope of spatiotemporal situations. This notion of proactive and dynamic reasoning not only contributes to handling heterogeneity in CPSS, but also leverages privacy by limiting access to resources based on preferences, trust, and various social aspects, including users' short-term goals. This work represents the backbone of a wider project, which aims to build a social-based framework of interconnected nodes of people, devices, and services. Future work includes integrating DSSoT with security supports to address privacy issues, a crucial obstacle to leveraging DSSoT's adoption in trusted CPSS environments.

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