

# SCAMPI: Service platform for soCial Aware Mobile and Pervasive computing

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## ABSTRACT

Allowing mobile users to find and access resources available in the surrounding environment opportunistically via their smart devices could enable them to create and use a rich set of services. Such services can go well beyond what is possible for a mobile phone acting alone. In essence, access to diverse resources such as raw computational power, social networking relationships, or sensor readings across a set of different devices calls for distributed task execution. In this paper, we discuss the SCAMPI architecture designed to support distributed task execution in opportunistic pervasive networks. The key elements of the architecture include leveraging human social behavior for efficient opportunistic interaction between a variety of sensors, personal communication devices and resources embedded in the local environment. The SCAMPI architecture abstracts resources as service components following a service-oriented model. This enables composing rich applications that utilize a collection of service components available in the environment.

## Categories and Subject Descriptors

H.4 [Information Systems Applications]: Miscellaneous

## Keywords

Opportunistic Computing, Opportunistic Communications, Social Behavior, Service Architecture

## 1. INTRODUCTION

Mobile users carry ever increasingly powerful mobile devices that feature substantial processing power and memory

along with a wide range of sensors. Moreover, these devices offer several wireless networking interfaces to access network infrastructure, to communicate directly with one another, and to interact with a multitude of external sensors. These capabilities can be used stand-alone but, more importantly, they may also be harnessed to support resource sharing: powerful smart devices can dynamically instantiate ephemeral mobile clouds within which they communicate spontaneously and efficiently to tackle a problem at hand—from cooperative sensing to content sharing to distributed data mining. Indeed, it is appealing to exploit the richness of diverse social, contextual, content, software, and hardware resources in these devices to create distributed applications that extend beyond the capabilities of any single device. It is precisely this opportunity that we capture in our design of a service delivery platform, SCAMPI (Service platform for social-aware mobile and pervasive computing).

The SCAMPI architecture builds on premises set by opportunistic communications research, which has enabled communication between collocated devices in networks characterized by intermittent connectivity. This work is often also referred to as pocket switched networking [7] or opportunistic networking [3]. Rather than viewing the population of devices as a mere communication platform, *opportunistic computing* [3, 4] research views the cooperation of devices as a significant execution platform for providing richer functionality by sharing and composing distributed resources, so as to unleash rich mobile services.

Existing solutions for distributed task execution on smartphones [1] illustrate that their powerful capabilities constitute an appealing platform for distributed computing. However, using a smartphone simply as a replacement for a computing node overlooks the many contextual properties that can be leveraged in a personal mobile device. The rich collection of sensors in the users' mobile phones can enable novel classes of applications that sense the node's environment [10] and provide a unique view on the surrounding world. While previous work has considered Internet-based clouds for the analysis of the complex sensor information [10, 15], we propose that such offloading can also be done into the immediate environment.

Research supports that social relationships [15] and the

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user's context [10] define the communication properties and by extension the reachability of resources in the opportunistic networks. Extending the opportunistic service provisioning from simple message forwarding to access to rich set of resources brings up challenges in the design of security and incentives.

Indeed, a design based on social and context awareness can support novel security mechanisms for the opportunistic computing platform.

The SCAMPI architecture combines the distributed task execution with social and context-aware opportunistic networking to enable opportunistic computing in pervasive networks characterized by a rich set of resources. The contribution of the present paper is threefold. First, we present the key properties of the service-oriented SCAMPI platform. Second, we summarize several key research results that have guided the design of the platform. Third, we synthesize our results to motivate the key design choices in the SCAMPI architecture for distributed computing in opportunistic pervasive networks.

## 2. RELATED WORK

SociableSense [15] presents an approach for users to quantify their sociability and illustrates how computationally intensive sensing tasks can be offloaded to cloud in fixed network to trade increased latency and bandwidth costs to energy savings in the mobile devices.

A survey on mobile sensing [10] discusses a system where sensory data from multiple users is collected to cloud to enable sensing collective behavior of groups of people. The survey also discusses various architectural challenges and approaches to ensure privacy of sensor data collected by the users.

Shankar et al. [17] propose a system that collects and indexes updates in mobile social networks. Their design illustrates how the users' interaction with places and social networks can be used to produce a service at a lower cost than their online counterparts.

Zhou et al. address the challenge of securing data in mobile clouds [18]. They propose a system that uses service providers in the fixed network to perform the resource intensive security operations on behalf of the mobile devices while maintaining the critical secrets on the possession of the mobile user only.

Research conducted in Delay-tolerant networking Research Group (DTNRG) serves as input to the opportunistic messaging architecture used in SCAMPI. The DTNRG architecture [2] proposes packaging application data in self contained messages. This allows any network node to act on a message unit that is meaningful for applications, for example, to open a complete view of webpage that is in transit. To support rich services beyond message oriented communication, SCAMPI supports data streaming to directly connected nodes.

## 3. SCAMPI ARCHITECTURE

We now explain how the features of opportunistic pervasive network guide the design of the SCAMPI architecture and motivate the main building blocks. We go over specific examples of the building blocks in Section 4.

Figure 1 presents a layered view on the SCAMPI architecture.

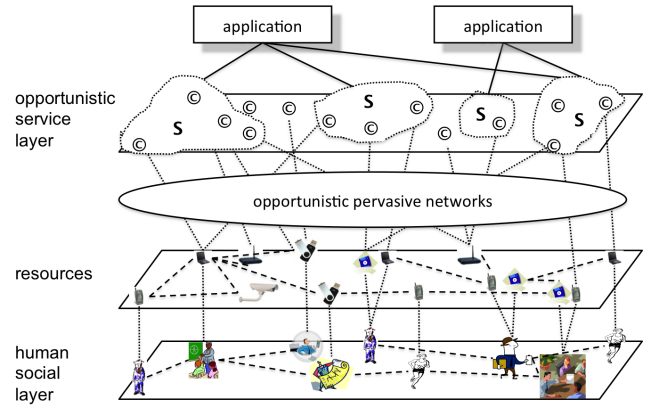


Figure 1: View on the SCAMPI environment.

Fundamentally, all applications, services and communications require physical *resources*. These resources can be fixed installations in the environment (e.g., a wireless access point) or contributed opportunistically by nearby users' personal devices (e.g., a mobile phone's CPU). This characteristic phenomena of user-contributed resources means that the set of available resources is intrinsically tied to the behavior of the people carrying the devices, or the *human social layer*. The human social layer includes social relationships among the SCAMPI users, which further translate to relationships between the physical resources. Enabling interactions between the disparate resources is the job of the *opportunistic pervasive network* layer. These interactions allow the *opportunistic service layer* to abstract the dispersed resources into service components, which are used to form complex services required by the applications.

The key focus of SCAMPI is in the opportunistic service layer, i.e., on how to abstract service components from the resources available in the environment through opportunistic networking. And further, how to enable complex services to be composed from these abstracted components.

The following subsections motivate the SCAMPI design starting from understanding the key properties of the opportunistic computing environment.

### 3.1 Modeling Service Provisioning

To guide the architectural design, the SCAMPI investigates the pervasive opportunistic environment by means of analytical modeling. The objective of this step is a clear understanding of key parameters that define the opportunistic computing environment. From the point of view of modeling, the resources are seen as service components that have probabilistic reachability and can be opportunistically accessed. The aggregate of service components can be used to compose a rich service. The composition problem comprises three stages [16]: i) selecting an appropriate service sequence set out of available services; ii) forwarding service inputs to the device hosting the next service in the composition; and iii) routing final service outcomes back to the requester.

Properties such as contact and inter-contact characteristic of the underlying opportunistic pervasive network define how the tasks can be distributed in the network and their results retrieved, and what kind of performance can be expected. As composing services from a number of remote service providers is one of the key SCAMPI concepts, the

capability of the network to execute the given set of services is crucial. Therefore, a key task is to understand which key metrics (service load, service location, contact properties, ...) serve as fundamental parameters for decisions on service composition. Section 4.1 discusses how such modeling has led to design choices in the SCAMPI architecture.

Modeling in SCAMPI is also used to understand other properties of the opportunistic service layer. For example, it is used to understand optimal service invocation policies [12], which optimize resource use while minimizing the expected response time for the user. Other modeling activities include modeling the mobility of users as precisely as possible [6], or modeling the behavior of key components of the SCAMPI environment, such as data dissemination [19] or inter-contact time properties [11].

### 3.2 Resource Stability

Opportunistic computing requires the ability to access resources across a heterogeneous network in spite of the underlying challenges posed by its topology. In wireless networks, the topology depends on the node layout and the wireless link dynamics; the former is time-varying due to relative node mobility, while the latter is time-varying as a baseline due to the vagaries of RF propagation, primarily multipath fading. Mobility and link instability result in scarce predictability.

While mobility may easily cause dramatic changes in the network, stationary wireless link dynamics are also of interest, mainly because it is easiest and most advantageous to access external resources in (temporary) conditions of relative stationarity. Owing to social behavior of humans, SCAMPI nodes can be expected to group together for non-negligible blocks of time in which they remain stationary with respect to one another.

### 3.3 Distributed Recommendation

Content sharing is a service that users might naturally expect over opportunistic networks. Indeed, delivering content to mobile users using an opportunistic (or peer-to-peer) system is a promising alternative to centralized infrastructure. It can leverage high bandwidth available locally between the nodes. Moreover, it presents a unique opportunity to exploit social relationships between users – as manifested through proximity – to discover and promote more relevant content. In the context of recommender systems, these two advantages might seem contradictory: recommender systems can leverage locality of interest and user profile, but they appear to require either centralized databases and computation, or significant communication exchanges. This has prevented their use in a constrained opportunistic mobile environment. In the context of SCAMPI, however, these two advantages can be combined. We have proposed a new distributed rating prediction and recommender system that takes advantage of any peer-to-peer exchange opportunities. This algorithm incorporates users feedback implicitly, and does not require for users to provide interests a priori, or for content to be classified beforehand. The algorithm is further discussed in Section 4.3.

### 3.4 Relation to Online Social Networks (OSNs)

Studying social relations and physical contacts at the same time is difficult due to limited availability of fitting data sets. Wide scale data sets such as provided by mobile cellular net-

work signaling data do not include rich data of social ties and are a matter of privacy. On the other hand, experimental user studies are often limited in terms of number of test participants and often capture only a few real-world scenarios. In SCAMPI, emphasis is put on the design of experiments dedicated to the analysis of social relations, physical meetings, and network communication happening.

The SCAMPI design supports integration with identities that users have established in the existing online social networks. This is possible, for example, by using public Open Authentication protocol (OAuth) interfaces and supports efficient bootstrapping of social context. The approach leads to the following benefits. First, linking identities cryptographically to existing social network identities such as Facebook allows users to initialize social graph information, which can be used to infer social relations at time of opportunistic encounters. Second, the unique identities enable to relate actions to specific users in the OSNs, for example, a message may use a gateway to pass towards an existing OSN user account.

## 4. KEY RESEARCH RESULTS

This section highlights key results that cover the modeling, design and experimentation work outlined in the previous section. The results illustrate importance of the chosen research topics in designing effective opportunistic computing systems.

### 4.1 Modeling Service Provisioning

Two key issues have been tackled up to now with respect to service execution and composition. On the one hand, we have studied the optimal operating point of invocation of service components [12]. On the other hand, we have defined distributed algorithms to compose complex services starting from individual components [16]. In the latter case, optimal invocation policies are used to invoke the selected individual components.

With respect to the first issue, the challenge is how to decide the *replication policies* when a seeker (node requiring a service component) invokes executions on encountered providers (nodes providing the component). As component execution may take time, in general it is possible that a seeker and a provider are not anymore in contact when the component execution terminates at the provider. If the seeker encounters another possible provider, the replication policy decides whether a new execution should be spawned or not. Considering that computation and bandwidth resources are limited, a trade-off exists between the performance experienced by the seeker in terms of component execution delay, and the associated resource consumption.

On the one hand, seekers could replicate execution requests as widely as possible, as the experienced delay will be the minimum across the spawned replicas (components results will be retrieved upon encountering the first seeker that has terminated an execution). On the other hand, if all seekers replicate greedily, then providers will be saturated, and the expected execution time will thus grow to infinity. We have studied [12] through an analytical model the optimal replication policy, which guarantees the minimum expected execution delay for seekers, by driving the overall network to optimally use the providers' computational resources. We specifically show that the policy is self-adaptable to various parameters, including the number of seekers and providers,

the computational load of the components, the components' request generation rate. The optimal policy replicates aggressively when "a lot" of resources are available, while self-controls itself when resources are scarce, up to generating a single request only in case of congestion.

With respect to the second issue, we propose [16] and evaluate through simulation models algorithms to select components available on various nodes, in order to obtain a composed service in opportunistic networks. Specifically, each node builds and maintains a *service graph* where nodes represent components provided by nodes of the networks, while an edge exists between two nodes if the output of the first component is compatible with the input of the second. The cost of edges includes both the expected time to encounter (or reach through a multi-hop opportunistic path) the second node, and the estimated load at the node. Costs are estimated through gossiping algorithms and by monitoring inter-contact times between nodes, in a completely distributed fashion (note that this may result in partial knowledge about available components). Compositions are found by computing shortest paths on the graph. In the paper we study the performance of service composition by considering different levels of awareness and the possibility of using multi-hop opportunistic paths to route components requests and results. We find that distributed algorithms using partial information well approximate algorithms having perfect knowledge, and that exploiting multi-hop forwarding provides a significant advantage. This is confirmed by testing the algorithms both on synthetic mobility models and in real traces.

## 4.2 Resource Stability

To properly make sense of node interaction, we have built a framework for the characterization of the network-wide impact of link dynamics [14], whose centerpiece is the Expected Network Delivery (END) metric.

The key idea behind the END metric is to decouple the impact of the network topology from the performance of whatever is running on the network. In other words, the END serves to gauge whether the network is likely to thwart anything we might wish to do with the network. The END is computed based on basic control traffic measurements *in vivo*, i.e., as the network is being used. This is in sharp contrast with an *in vitro* approach whereby the state of the network is measured in a vacuum, which does not work in the presence of unstable link dynamics. The END can be viewed as a metric that characterizes the network from the point of view of the network user. It can also be interpreted as a measure of the component of the QoE of the network user induced by the network itself as opposed to what is running on it.

One key application of the END metric is the fair comparison of different network solutions. Network conditions may vary significantly over time, impacting experimental results in different ways at different times. Comparing results from different experiments may be next to impossible due to fundamentally different connectivity conditions that have fundamentally different impacts; indeed, even a single experimental run may be affected in different ways over time. In [14], we show how the END can be employed to compare different data collection protocols accounting for the impact of the topology.

Aside from a physical topology, SCAMPI networks also

have a service/resource topology: when a service seeker issues a request, the object of its request may be located at any other node in the network, or at various nodes, in the case of service composition. To determine the applicability of any opportunistic computing scheme, it is extremely critical to gauge the network topology in both its physical and service/resource-oriented dimensions. Our current work is tackling the extension of the END framework beyond connectivity to resource availability.

## 4.3 Distributed Recommendation

Next, our model [8] is summarized to show feasibility of distributed recommendation system in an opportunistic setting. The system consists of a set  $\mathcal{U}$  of mobile users. A subset  $\mathcal{N} \subseteq \mathcal{U}$  of all the mobile users, whom we call producers, generate a stream of items that they exchange opportunistically with other users. For example, producers could maintain a blog, a news-feed or a twitter-feed on their devices. Occasionally, a producer may generate new blog entries or new tweets that are added to his locally-maintained feed and subsequently shared with other users encountered. We denote by  $\mathcal{N} \subseteq \mathcal{U}$  the set of users who receive content; we call users in  $\mathcal{M}$  consumers. Note that  $\mathcal{M}$  and  $\mathcal{N}$  may intersect, as a user may both produce and consume content.

Our model aims at describing networks with arbitrary connectivity constraints, and thus we assume a very general process of contacts between users. To make the model tractable, we include some independence assumptions: opportunistic contacts over different timeslots occur independently, even for the same pair of users. However, we do not assume that contacts are independent between different pairs. This is essential because groups of mobile users tend to have correlated behaviors: two consumers Alice and Bob are in a group and hence if Charlie is a producer that meets Alice, he is much more likely to meet Bob in the same timeslot. In addition, contacts created by mobility exhibit locality: if we assume that Alice is both a producer and a consumer, the fact that Charlie meets Alice and that Alice meets Bob in the same timeslot makes it likely that Charlie meets Bob. This latter correlation exists even if Alice and Bob follow independent trajectories.

Although producers may generate diverse content and although consumers' interests may vary, in many applications there exists a small number of characteristics or features that influence how consumers perceive the content. As such, content should be grouped by similarity with respect to these features into categories. The categories are relevant to how producers generate content: a producer may exhibit a bias towards generating content of a certain category. However, categories may also arise due to shared features that are harder to characterize with a simple label. For example, blog posts may form a category that spans several topics (e.g., news and technology) and be additionally defined by their credibility, whether they are humorous or not, etc.

Our algorithm is very appealing for opportunistic mobile networks because of its completely distributed nature. Consumers and producers carry their own profiles, and only exchange them for rating predictions upon opportunistic encounters. We have applied our algorithm to the Netflix dataset, with good results - depending on how parameters set, our algorithm obtains a root-mean-square error of more than 0.85.

## 4.4 Social Network Experiments

A Facebook application termed *Stumbl* has been developed and deployed [5]. The Facebook application allows to capture existing, real-world social relations and communication habits using Facebook communication channels such as 'Wall posts' containing posts of messages, photos, videos, etc. To capture physical meetings, a reporting interface is integrated used to report actual meetings with persons once per day. Therefore, a subset of Facebook contacts was selected (max. 20 persons). For this subset, not only meetings are reported but also the relations are classified by the user into friends, family members, and colleagues.

A crucial aspect in designing an long-term experiment is the motivation of the test users, first, to start participating, and, second, not to loose interest in participating. *Incentives* are usually introduced to motivate test users including material incentives such as fees, hardware access, free 3G connectivity, etc. or incentives targeting social and psychological behaviors such as winning during a competition, gaining respect, etc. In the experiments conducted for Stumbls, a raffle was introduced where chances of winning were increased if the application was frequently used and the number of Facebook friends signing up as Stumbl users are high.

The Stumbl experimental study lasted for three weeks, overall 39 persons participated (on the average, 22 reported ongoing during the study). Preliminary results of the analysis show that indeed different contact patterns can be found depending on the type of social relation in terms of contact frequency and contact duration. For example, physical meetings with family members were frequent and long lasting, while meetings with colleagues were shorter. The results are compatible to intuition and can be exploited in social-aware DTN (Delay Tolerant Network) routing protocols. A detailed description of the experiments and results can be found in [5].

## 5. CONCLUSIONS

We have discussed several research results that support the SCAMPI architecture as an approach to opportunistic computing. The discussion illustrates how combination of analytical modeling, low level mechanisms and learnings from experimentation in social networks are valuable factors in realizing a rich service platform for mobile users. We believe that such design can enable new set of rich social and context-aware services that will empower flexible application development with modern smartphones.

The proposed approach motivates further research, for example, on cooperation dynamics when some nodes participate with only subset of available resources [9] or when the nodes can discover only subset of services due to practical limitations in used devices [13].

Initial experience from building applications on top of the SCAMPI architecture supports our view that the users can conspire to create a service cloud without any infrastructure support. The social and contextual properties that are available from the rich smartphone APIs provide good fit for supporting applications on individual devices. This offers interesting avenues for application developers to design opportunistic applications beyond communication or content sharing purposes. Yet, cooperations of such devices

will form complex ecosystems that offer challenges for future research.

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