Research Strategy
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Abstract

This document provides a perspective of the evolution of my research strategy around the topic of human-centric networking and computing. It is divided into three time periods, corresponding to the research of mobile networking systems (2003 to 2007), and user-centric cooperative networking (2008 - 2013), as well as the current research plan on human-centric pervasive systems (2014 - 2020).

Contents

1 Introduction

The Internet has been going through a radical transformation to support the needs of a society in transformation. From a technological perspective, such needs concern supporting communication services adaptable to users' daily routine.

Therefore, people become the main focus in the way mobile communication systems should be engineered. This user-centric perspective of mobile networking is supported by the boost in the usage of mobile devices (e.g. smartphones and tablets) with augmented sensing capability. This trend started by requiring mobile operators to adapt their access networks to support IP based multimedia mobile services, and later led to the investigation of methods to integrate cellular and user-centric networks.

Smartphones and tablets are just an initial enabler of a truly human-centric pervasive communication and computing system. The next wave of computing is still being defined. Wearable computers, embedded sensing devices and robotics are only some of the systems to come. In a future Internet of everything, such pervasive devices will be able to collect and share smart data, with the intention to improve the day-to-day living of today's society.

In the future, people will expect an augmented daily life experience by taking advantage of a large set of services derived from the pervasive integration of networking and computing functions. For the past 20 years, the pervasive computing community has developed technology that allows sensing, computing, and wireless communication to be embedded in everyday objects, from smartphones to clothes, enabling a range of context-aware mobile applications. In the future, mobile communication systems are expected to be engineered based on a deeper awareness about people context and behavior. Such human-centric pervasive systems will be able to provide intuitive services by learning and adapting continuously to user's habits, routines, and preferences.

The realization of this vision toward a human-centric pervasive system has been pursuit since 2003 by means of the following three research streams.

2 Research stream #1 (2003-2007): Multimedia Mobile Networking

The fourth generation of mobile systems (4G) aimed to provide multimedia communications to mobile users with distinct requirements. For this propose, the QoS architecture for multi-user mobile multimedia (Q3M) framework [5] (2007) was developed to control of the quality level of multimedia sessions shared by a large number of mobile users, who could operate as receivers or sources of data. Such control was achieved by the integration of three components: the Multi-User Session Control (MUSC) [4] (2007), the Multi-service Resource Allocation (MIRA) [1] (2008) and the Cache-based Seamless Mobility (CASM) [16] (2007). The Q3M architecture was engineered to take into account the number of satisfied users into the operation of the mobile access network.

- Outcome: 3 PhD Thesis; 2 MSc Dissertations; 1 Book; 2 Book chapters; 12 Patents; 5 Journal papers; 25 conference papers

3 Research stream #2 (2008 - 2013): User-centric Cooperative Networking

To achieve a fully pervasive low-cost communication system, there is the need to reduce the number of those who are socially excluded (e.g. due to their geographic location) and to increase the quality of wireless communications. To solve the former problem the Internet Engineering Task Force (IETF) has been working on an architecture for delay-tolerant and disruption-tolerant networks (DTN), allowing the expansion of mobile communication systems to isolated areas based on user-centric cooperative forwarding schemes. A recent trend is looking at a social design of communication systems [15] (2012), aiming to use inference about the social nature of human mobility to bring messages closer to the destinations. This challenge has been pursuit based on two approaches: dLife [12] (2012), a cooperative forwarding algorithm able to capture the dynamics of the network represented by time-evolving social ties; SCORP, a social-aware content-based forwarding approach that considers the people social interaction and their data interests to implement a low-cost data delivery system in urban, dense scenarios [13] (2013). While dLife is part of the SocialDTN Android implementation [6] (2014) tested in the Amazon region in Brazil, the SCORP proposal is a component of the Information and Context Oriented Networking (ICON) cross platform implementation [2] (2013). The development of user-centric cooperative networking schemes showed that entities participating in pervasive wireless systems need to continuously reacting to changes in the surround environment as well as in social interactions [11] (2014). This observation raise several issues in what concerns the development of self-organized pervasive systems.

Pervasive systems benefit from good and stable wireless communications. Therefore there is the need to reduce the impact that unstable propagation conditions and mobility of devices have on the performance of wireless system. In face of multi-path propagation and low data rate stations, cooperative relaying is able of achieving gains in performance and reliability [7] (2014). The proposed solution, called RelaySpot [8] (2007), removes the need for estimation and broadcast of channel conditions, and improves the utilization of spatial diversity, minimizing outage and increasing the transmission capacity of wireless networks, even in the presence of interference and mobile devices.

Independently of the used cooperative networking strategy, the deployment of user-centric communication systems requires an incentives model to motivate users to share services and resources, as well as to avoid selfish nodes to hinder the functioning of the entire system. Virtual currency and reputation mechanisms are commonly adopted in online communities to boost participation, but their joint application has not been deeply explored, especially in the context of pervasive systems, where the enabling infrastructure is opportunistically built by community members. Hence, user-centric wireless networks [14] (2008) need to encompass a hybrid model that combines the usage of virtual currency and reputation-based incentives in the specific context of a community of users with Wi-Fi enabled devices capable of establishing ad-hoc connections [3] (2012).

- Outcome: 2 PhD Thesis, 1 Patent application; 6 Book chapters; 5 Journal papers; 1 IETF draft; 2 Prototypes; 17 conference papers.

4 Research stream #3 (2014 - 2020): Human-centric Pervasive Systems

As for the future, the plan is to use the devised user-centric cooperative networking approaches to investigate the best methods to support the creation of human-centric pervasive systems.

In order to be classified as human-centric, technology should be intuitive for the user. This means that technology should be able of creating interventions that are aligned with activities in people's everyday lives. For that, there is the need to understand how technology affects people's behavior or awareness.

With this propose in mind, a pervasive sensing framework, PerSense [10, 9] (2014), is being developed to allow the engineering of human-centric pervasive systems. Such framework aims to be able to sense, learn, visualize and share information, augmenting the understanding that pervasive systems have about the needs, desires, and behaviors of people and specially communities.

In order to engineer truly pervasive human-centric systems, there is the need to ensure a significant level of autonomy. For this propose, **self-awareness** properties of complex systems is being studied concerning the availability, collection and representation of knowledge that a node can get about itself.

A first challenge in devising a self-aware sensing system is its accuracy. However, the differences among people cause the accuracy of classification to degrade quickly – the sensing diversity problem. To address this problem, **affinity networks** can be incorporated into pervasive sensing systems to address the challenge of robust classification caused by the sensing diversity problem. The conventional classification approach is to use the same classification model for all users: all users perform sensor-data collection and data labeling. This is both burdensome to the user and wasteful as multiple users often collect nearly identical data but the training of each model occurs in isolation of each other. By using affinity networks, we may mitigate user and context diversity by sharing training data and classification models based on social similarities. Affinity networks provide weighted similarity graphs that represent different forms of social network information (e.g. proximity, online, conversational), and provide an indication of the probability of nodes to share training data or complete classification models.

While self-awareness aim to allow devices to have an accurate knowledge about themselves, it is clear that there is still much to understand about how to characterize system-level behaviour that emerges from the interactions of self-aware nodes. Namely, in a pervasive sensing system there is the need of **coordinating multi-agents** to reach three important goals: **i) consensus** on a single sensing value to represent the environment of the complete system; ii) **influence** that an user can have on others; iii) **synchronization** to support complex activity recognition.

One research issue is raised by the fact that most research in consensus problems assumes that the final consensus value to be reached is inherently constant. This may not be the case, since the information state of each agent may be dynamically evolving in time according to some inherent dynamics: this happens in some human-centric sensing systems where agents self-awareness is evolving through time, due to changes in people's behavior or awareness. Hence, it is important to study **dynamic consensus problems** where the final consensus value evolves over time as a function of environmental dynamics or sources with variable reliability. One open research issue is the impact that the **small-world networking** model may have on the creation of fast consensus algorithms.

In order to have a consistent system representation over time (e.g. to perform complex activity recognition, based on the combination of several simple activities), it is necessary to insure that all involved sources are **synchronized in time**. The study of synchronized networks of dynamical entities has a lot to offer for the understanding of emergent behavior in complex systems. Its study helps to explain how non-identical entities, such as the sensing multi-agents, can adjust their rhythms exclusively due to interactions. In a similar way as other forms of collective behavior, synchronization depends on the properties of the oscillators and on the structure of the network of interactions.

In what concerns interaction modeling, there are still several open questions such as the characterization of the basins of attraction among entities. For instance, how is the **influence model** stablished between individuals in a social system, even when the network of interactions is unknown? One open issue is the development of methods for better understanding the effect that networked interactions have on the spread of social behaviors and outcomes over time. The influence model may also enable the inference of interactions and dynamics when the network structure is unknown—all that is needed is information about signals from individual observations, which lead us again to the need to develop systems with accurate self-awareness.

The most challenging task in using sensing data to devise influence models, is the correct inference of a causal process from observable data. If we find that behavior between two individuals is correlated, it could be due to influence, but it could also be due to selection or to contextual factors. These mechanisms are generically correlated, so we should carefully consider alternative mechanisms that may underlie correlated behavior. One aspect to be tackle is the exploitation of time data to test causal ordering based on the asymmetries found in network relationships.

As a summary, the future of technology passes by becoming truly pervasive and human-centric. This means that services must rely on networking sensing devices able to self-organize allowing the creation of large-scale systems that are aligned with activities in people's everyday lives. The self-organization property of human-centric pervasive systems can be achieve by following four core research lines: self-awareness; consensus; influence and synchronization.

5 Summary and Future Plans

This documents shows how the applied research strategy interplay real world applications, technology and theory, aiming to produce an impact on society. It started by looking at graph theory (e.g. social graphs, small-world networks) to create opportunistic forwarding algorithms able to support data sharing among pervasively deployed systems, even in the presence of intermittent connectivity. In order to increase the impact of the devised technology, an IETF draft was produced and an implementation was deployed in a real world setting in the amazon region in Brazil.

The devised opportunistic networking algorithms are being used to investigate human-centric pervasive sensing based on complex system theory (self-awareness, self-organization, synchronization) and networked control system aspects of multi-agent technology. This effort is being used to develop a framework, PerSense, aiming to augment the understanding that pervasive systems have about the needs, desires, and behaviors of people and specially communities.

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