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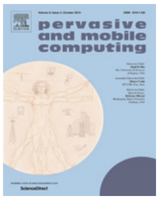

Review

Power management techniques in smartphone-based mobility sensing systems: A survey

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The rapidly enhancing sensing capabilities of smartphones are enabling the development of a wide range of innovative mobile sensing applications that are impacting on everyday life of mobile users. However, supporting long-term sensing applications is challenging because of their key requirements for continuous access to embedded sensors for gathering raw data, which can deplete the device's battery in a few hours. This problem is expected to remain in the near future because the improvements on the capacity of batteries are coming at a slower pace than those advances in computing and sensing capabilities. The research community has highlighted the need for power-aware and context-aware sensing techniques deployed at different levels of mobile platforms for making a more efficient use of energy resources. Previous studies have analyzed the optimization of power consumption in mobile devices over different critical axes, like data transmission, computing, and hardware design. However, a comprehensive study focused in the challenges of power-aware smartphone-based sensing and strategies for addressing them has not been produced yet. This survey aims to fill this void with a particular focus on mobility sensing systems (e.g., human activity recognition, location-based services), presenting a comprehensive review of relevant strategies aimed at solving this issue. Also, this survey defines a taxonomy for such solutions, highlighting their strengths and limitations. Finally, most relevant open challenges and trends are discussed for providing insights for future research in the field.

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1. Introduction

The great popularity of smartphones is drastically changing our daily lives by providing an increasingly powerful set of tools as a result of significant advances in the field. In particular, the capabilities and platform complexity of smartphones are continuously improving, becoming truly system-on-chip (SoC) devices able to adapt their operation over three distinguishing dimensions, namely communication, sensing, and computation, as conceptually shown in Fig. 1. The advances on these dimensions are enabling the *context-awareness* paradigm in mobile and pervasive computing, opening the path for a myriad of applications and services, both for individuals and for communities. The implementation of large-scale sensing systems can be tailored by using such smartphone-based sensing, which aim to collect data from sensors embedded on smartphones distributed along a geographical area [1–3]. This large-scale collection of data originates mobile crowd-sensing systems, which typically involve the elements depicted by the scenario shown in Fig. 2.

Important issues of mobile crowd-sensing as a whole have been analyzed in the literature, covering important high-level aspects such as privacy [1,4], trust management and reputation [5,6], incentive mechanisms [7,8] and quality of information [9]. Scientific efforts have also been conducted for reducing the energy consumption of mobile crowd-sensing systems, producing different strategies and mechanisms for the distribution of tasks and for adapting the operation of mobile devices over their dimensions. However, these mechanisms are particularly focused on the communication axis [10–13], which is essential for crowd-sensing systems due to the amount of sensed data sent to the server or cloud side, leaving the sensing and computation dimensions partially studied. Because of this reason, a comprehensive study of the techniques for reducing power consumption in the sensing and computation dimensions in the mobile crowd-sensing scenario is still needed.

In this survey, we concentrate on the analysis of the different solutions for performing continuous access to sensors in a power efficient way, as well as the scientific background behind them. More specifically, we focus on the different power-aware strategies employed for building mobility sensing systems, understanding mobility as the different aspects that express the motion in user behavior. Hence, mobility is a concept that can range from fine to coarse grain motion detection. Fine grain mobility could be exemplified in a HAR (Human Activity Recognition) system that identifies whether user is walking or running, etc., typically by employing accelerometer and other inertial sensors. On the other hand, coarse grain mobility could be of interest, for instance, in LBS's that focus on user traversing along places in a large geographical zone rather than in detecting activities; such task is usually performed through energy hungry location providers, like the GPS. It is noteworthy that, as it will be described in Section 3, several of the proposed solutions employ fine grain mobility techniques for aiding the coarse grain ones, producing power savings since the access to location providers is avoided.

As a result of the advances on the sensing dimension, modern smartphones include a set of low-cost and specialized embedded sensors such as accelerometer, digital compass, gyroscope, GPS receiver, microphone, and camera, among others. These sensors have rich capabilities for creating mobile sensing applications at different spatial and temporal scales and with different levels of accuracy and energy costs [14–16]. For this class of applications, the core requirements are the background and continuous sensors' data acquisition, as well as associated on-device computations for extracting useful information for the user [14,17]. As user interaction can be required for collecting data, two sensing paradigms have been proposed in the literature [14]. The *opportunistic paradigm* tries to determine the most appropriate moment for automatically collecting data from sensors without user participation at all. On the other hand, the *participatory paradigm* leverages on the abilities of user, requiring his/her participation to label data and choose the moment for collecting them. Given its autonomy, the opportunistic paradigm represents the preferable choice for continuous mobile sensing, and hence it is the main focus of this article.

1.1. Smartphone-based sensing characteristics

Regardless of the sensing paradigm, the internal operation of mobile sensing applications commonly involves a set of stages that describe the closed loop shown in Fig. 3, consisting in: (a) *Sensor reading* that involves selecting, configuring, and requesting data to sensors, (b) An *optional pre-processing* for discarding uninteresting data like outliers or reducing noise, (c) *Feature extraction* for obtaining features, i.e., more computationally efficient representations of data, (d) *Classification* of extracted features into classes of special interest, for example human activity aspects that might feed machine learning strategies, and (e) *Post-processing* for offering feedback to user, launching network communication, triggering another sensing-classification chain with the outcome of classification acting as feedback information for a more precise operation of sensors, or for performing further processing. In Fig. 3, from left to right, each stage increases the level of context-awareness of the mobile platform, requiring more specialized algorithmic solutions to perform the above described functions. The design of such solutions is not straightforward, as there are a number of factors that impact the operation of each stage. This is the case of the dynamics of user's context which depends on changes produced in the environment, the existing constraints in mobile platforms, and privacy concerns of personal data manipulation that, as a whole, compromise the sensor readings,

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