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Mobile Crowd Sensing Architectural Frameworks: A Comprehensive Survey

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***Abstract*— Mobile Crowd Sensing has emerged as a new sensing paradigm, efficiently exploiting human intelligence and mobility in conjunction with advanced capabilities and proliferation of mobile devices. In order for MCS applications to reach their full potentials, a number of research challenges should be sufficiently addressed. The aim of this paper is to survey representative mobile crowd sensing applications and frameworks proposed in related research literature, analyze their distinct features and discuss on their relative merits and weaknesses, highlighting also potential solutions, in order to take a step closer to the definition of a unified MCS architectural framework.**

Keywords—mobile crowd sesning; architectures; challenges; survey

I. Introduction

THE proliferation of mobile devices in conjunction with the advancement in their communication, computing, storage and multi-modal sensing capabilities gave rise to a new sensing paradigm, the so called Mobile Crowd Sensing (MCS) or People / Human Centric Sensing [1]. MCS leverages on the power and wisdom of crowd, exploiting human intelligence, ubiquity and mobility features. To this respect, people are empowered to contribute data sensed or generated from their mobile devices, enabling efficient (in terms of cost and time) monitoring of large-scale phenomena that cannot easily be measured or would otherwise need costly investments (in terms of hardware and software). MCS applications employ proper data mining algorithms in order to analyze data, identify spatio-temporal patterns, generate models and make predictions on physical or social phenomena being observed [1].

MCS has recently attracted the attention of researchers with designed applications ranging from environmental monitoring (e.g., air quality [2]) to traffic planning [3], public safety [4] to smart parking [5-6]. However, a number of critical issues and challenges should be adequately addressed in order for MCS to reach its full potentials. Without being exhaustive, aspects that should be carefully considered and adequately solved are mainly related, first, to the highly dynamic conditions experienced by the set of mobile devices as well as the limitations imposed in terms of energy, bandwidth and computing resources, second, security, privacy and data integrity in conjunction with proper incentives that should be in place.

Current MCS applications are based on different practices with quite different assumptions, adopting different underlying architectures and system models, aiming to provide solutions to different sub-problems at hand. Our view is that a coherent and unified architectural framework, including all key elements related to MCS processes and taking into account their inter-dependencies could constitute a step forward to enabling the unimpeded advancement of MCS. Even though there is a number of related research works that endeavor to define an architectural framework (e.g., [1], [7], [8], [9]), shedding more light to the underlying issues, balancing their inter-play and accounting for and systematically addressing all challenges in a generic, concrete, reliable and robust manner could enable MCS systems to achieve their full potentials. To this respect, in the current work, having as a starting point the MCS unique characteristics and open challenges posed, we comprehensively and critically survey recent MCS systems, models and architectures proposed in related research literature, while analyzing their distinct features and discussing on their relative merits and weaknesses.

The rest of the paper is structured as follows. Section II discusses on MCS characteristics, indicating the research challenges that should be considered and adequately addressed. Section III overviews 10 architectural frameworks

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proposed in related research literature. Section IV discusses on our findings concerning the focal aspects of mobile crowd sensing system design identified, while section V concludes the paper and highlights our future plans.

II. Mobile Crowd sensing Characteristics and Challenges

MCS presents a number of unique characteristics. First, humans are involved in the loop for data collection, processing, analysis and sharing, which brings unprecented opportunities [10]. Concerning data collection, MCS involves both implicit and explicit user participation with *opportunistic sensing* (which does not require users to actively act in order to perform a specific task) to *participatory sensing* (that necessitates the active involvement of users in order to complete a sensing job) at the two ends [1]. Concerning data transmission, users may adopt the *opportunistic transmission paradigm*, adopting a store-carry-forward behavior, relaying information to other devices in case a new forward opportunity is identified or the *infrastructure-based transmission*, utilizing a communication system (i.e., cellular networks, WLAN, WiMAX) in a centralized or a distributed manner [11], [10]. Data are collected both from the physical world (sensed data from mobile devices) as well as from online communities (mobile social network services related data) [7]. Data from different communities present different characteristics, being often complementary. To this respect, in [7], the authors advance the exchange of data across online and offline communities in order to identify and fully integrate their complementary features and merits. Additionally, as noted in [7], human involvement and participation in the collection, processing and sharing of data will necessitate and ultimately lead to a combination of human and machine intelligence. The optimization of this mixture is considered by the authors as a significant design issue for MCS systems, while they claim that their combination should be application centric.

Numerous research challenges arise from the MCS paradigm. The set of mobile devices, their sensing, computation, storage and communication capabilities can vary significantly due to the device mobility, variations in their energy levels, the conditions of the communication channels as well as to owners' preferences. Thus, identifying and scheduling sensing tasks across multiple devices with diverse sensing capabilities and resource availabilities / limitations imposed is a quite complex and challenging issue to address.

In this context, one should also take into account the fact that devices' current abilities and context of operation may lead to a higher or lower data quality in terms of accuracy and confidence as well as latency (with the latter applying to the case of delay tolerant applications). Additionally, different type of sensed data may be produced and used for serving the same purpose, each one with different data quality and necessitating different resource consumption levels. Thus, improving on the data quality level, while minimizing the consumption of resources necessitated is another challenging issue to solve. Current solutions adopt low duty cycling for sensors producing high quality data (requiring to this respect high energy levels) and deciding on the sensors to be employed each time on the basis of the available energy levels of the devices. The proposed solutions, however, should take into account the fact that a multitude of different MCS applications that require the same data types may concurrently co-exist. Thus, it is of outmost importance to identify common data needs, allow data sharing across different applications and even prioritize data collection on the basis of the number and priorities of the requesting applications.

Local processing of the collected data on mobile devices, prior to their aggregation and processing at the backend in order to reach a form suitable for consumption by applications, may also be a solution to devices' resource limitations, as produced intermediate results necessitate lesser energy and bandwidth for their transmission. The underlying challenge to this respect is to design proper algorithms and identify common local processing requirements across different MCS applications.

Additionally, MCS architecture should take into account and efficiently address the case of potentially inaccurate/erroneous data. MCS applications could suffer from inaccurate data provisioning due to their inherently open nature. This type of data can be produced intentionally and/or unintentionally. Unintentional inaccurate data provisioning covers the cases of obsolete / noisy data due to the time period that has elapsed from the point data are sensed till the time data are processed, faults, low resource levels, potential low quality of the wireless link and environmental uncertainties. Intentional inaccurate data provisioning refers to erroneous data provided in purpose in order for malicious and/or selfish parties to disgrade the usefulness of the collected data and/or take advantage of certain situations (e.g., minimizing the effort put / resources consumed for required contributions at the cost of acquiring and sharing low quality data, being entitled, however, to the reward entailed). Thus, maintaining collected data integrity is an important problem in the context of MCS. The authors in [11] propose a number of trust-based data analysis approaches in order to preserve trustworthiness in the context of MCS. Specifically, users' contributions are observed over a period of time in order to evaluate his/her trustworthiness. Users' trustworthiness may be exploited in order to identify the most trustworthy users to be involved at specific sensing tasks. However, trustworthiness evaluation may contradict users' security and privacy considerations. Thus, mechanisms are required for providing some form of '*accountable anonymity*', linking users to their actions, without revealing their identity [8]. In general, as noted in [11], MCS systems should be adaptive and robust in order to identify on one hand inadequate user participation and on the other hand obsolete, redundant, inconsistent and/or inaccurate data collection.

The manner in which the goals of MCS are succeeded contradicts (at least to some extent) to some of the end-users preferences and requirements. Privacy concerns are raised, considering, understanding, choosing and controlling the information users share, with whom and for how long [8]. For example, users would like to have access to a smart parking service, but they are reluctant in disclosing sensitive information (such as users' current location, point of interests or personal activities). As noted in [8], sensed data, tagged with spatio-temporal information, could be exploited in order to infer even users' daily routines and habits. Thus, it is imperative to preserve the privacy of the individuals. A generic privacy / security framework should be in place independently of the MCS application considered or the nature of the data shared. At this point it should be noted that privacy is user specific and to this respect privacy schemes and techniques should take into account and efficiently address variations in users' willingness to share data in the risk of other people acquiring/inferring private information. A potential solution would be to adopt a fully decentralized privacy preserving architecture, enabling users to fully control their own personal data (e.g., decide with whom they are going to share them and when [8], [7]), with the risk however of acquiring potentially low quality data. [8] advances the adaptive combination of centralized solutions that allow for identity management and accountability and decentralized architectures that enable the dissemination of selected information in a peer to peer manner.

As aforementioned, users involved in MCS applications contribute either to data collection or to data relaying in an opportunistic manner. To do so, users may incur energy and computational related resource consumption, monetary cost or are required to spend their time and put explicit effort in order to complete successfully their mission. In order for MCS applications to reach their full potentials and allow their unimpeded advancement, appropriate incentive mechanisms need to be in place so as to promote users cooperation and retain their engagement to accurate data collection or generation and sharing, while also protecting and preserving user privacy. Thus, incentives should be provided in a privacy-preserving manner [8]. User incentives may be broadly categorized in the following three categories [7]: financial incentives, interest and entertainment, social and ethical reasons (e.g., users' recognition, socialization), while attributing service quotas and enhancement of reputation [8] may be considered.

III. Mobile Crowd sensing Architectures

In [1], the authors bring to the forefront the necessity of defining a unifying architecture in order to address current limitations concerning developing and deploying MCS applications. To their view, architecture should enable application developers to specify their data needs in a high level language, identify common data needs across different MCS applications in order to avoid unneeded sensing and processing activities, properly schedule tasks to the most suitable set of mobile devices, ensure the desired data quality in a dynamic setting through proper reconfigurations and reuse the same local processing activities across different device platforms. In [7], a reference MCS framework is provided, composed of a) *a crowd sensing physical layer* with access control being an important function at the local side enabling users to decide with whom their data can be shared, b) *data transmission*, exploiting a multitude of mobile networking techniques (including both transmission in an opportunistic manner and transmission utilizing existing infrastructure), c) *data collection infrastructure*, collecting data and catering for users' privacy protection, d) *crowd data processing*, applying a machine learning techniques in order to find patterns, generate models and make predictions, offering added value to end-users and e) *applications*. In [8], the authors derive a generic architectural design (including stakeholders) in order to capture all key MCS features. In [9], in an attempt to efficiently address identified challenges concerning MCS scalable application development (related mostly to the heterogeneity and incompatibilities of hardware and mobile platforms, the willingness and the rate at which users install applications on their devices and the increasing bandwidth demands), the authors propose an architectural solution advancing the following three principles: a) *separation of data collection and sharing from application specific logic*, b) *decentralization of data processing and aggregation near end-user* and c) *removal of application installation from MCS application deployment*. The proposed system architecture consists of three layers. The first one is composed of the mobile devices. The second one comprises distributed cloud infrastructure deployed close to the end-users, consisting of *proxy virtual machines* (*proxy VMs*), handling all the requests for sensor data on behalf of the mobile devices, being in essence an extension of the mobile devices in the cloud with each proxy VM being associated with a single mobile device and *application virtual machines* (*application VMs*) performing data processing for each crowd-sensing application. The application VM is coordinated by the application server located at the third layer, consisting of centralized cloud infrastructure. This architecture takes into account user-defined policies, enforcing user preferences on data collection and sharing, may require explicit permission from the user, or a mobile device may automatically join crowd-sensing tasks in case pre-defined criteria are met.

Currently, there is little consensus on the underlying system architectures with different MCS applications adopting different models, aiming to provide solutions to different problems at hand. In the following, we critically survey recent MCS systems and architectures of state-of-the-art related research efforts, in an attempt to identify open research issues and challenges and indicate potential ways of addressing them.

A. McSense

In [12], the authors present McSense, a mobile crowdsensing platform, which enables task design and assignment, exploiting information about potential workers, regions and their context to efficiently and effectively perform the task assignment process. In particular, McSense, for each geo-localized sensing task, estimates the time required and the number of workers that are necessitated to complete it with a specific probability. To this end, it leverages information on the profile of users / region along with task related data. They have defined three different task assignment policies (i.e., random, attendance and recency) based on the time spent by workers in the task area in the past, and the time period since they have been in the area in the past. They have incorporated in their framework an incentive mechanism based on monetary rewards and additionally they exclude from the set of potential workers for a specific task the workers that have limited battery resources in their mobile device. In a nutshell, McSense puts task description, task assignment, and mobile sensing in a closed loop that allows more efficient and effective usage of all socio-technical resources involved.

B. Pick-A-Crowd

[13], discusses on a push-based software architecture for efficiently assigning tasks to potential workers based on the profiles of workers and tasks. Workers' profiles contain information on skills and interests and are constructed based on social networking information extracted concerning workers' preferences as well as on past performance concerning task completion in previously assigned tasks. Specifically, the liked pages of each user in Facebook are stored in an external database and used to create workers' profiles including their interests. Each task is associated with a difficulty degree that is predicted on the basis of workers' profiles and tasks descriptions (e.g., a score computed on the basis of how many workers could successfully and with the required accuracy perform a specific task based on their skills and interests perform). The platform incorporates monetary reward for the completion of a specific task, splitting the available budget to identified micro-tasks with 'difficult' micro-tasks receiving higher reward. The authors describe three task assignment models (i.e., category-based, expert profiling, semantic-based) in order to automatically assign tasks to the most suitable workers for their completion. The performance of the task assignment techniques are evaluated and compared against pull-based techniques.

C. MEDUSA

In [14], the authors propose an extensible and robust programming framework for specifying in a high level manner and managing the execution of crowd sensing tasks between mobile devices and the cloud. Specifically, a high-level programming language called *MedScript* provides abstractions for intermediate steps in a crowd sensing task (referred to as *stages*). Medusa runtime incorporates a cloud and mobile device component, minimizes the task execution state on mobile devices, while it supports the following characteristics: a) multiple concurrent tasks may be performed by a single worker, whereas stage execution is not necessarily synchronized across workers, b) each worker may specify resource usage policy on his/her mobile device, which should be respected by the system, c) task description may incorporate deadlines, after which a task instance fails and data collected are not valid, d) failure recovery mechanism, which considers transient errors (due to battery exhaustion or user-related actions), resulting to task instance failure after specific internal time-outs. Upon failure, stages may be retried, e) results are returned to the requestor only after all defined steps have been successfully completed, f) monetary incentives are provided to motivate users to participate in tasks, while reverse incentives may also be exploited in order for the workers to pay the requestor for the privilege in contributing to specific tasks, g) data privacy and subject anonymity with respect to the requestors are supported, while users must explicitly permit access to their data before uploading them to the cloud, can also view the privacy policy of the system presenting in a detailed manner how collected data can be used and have the ability to select whether or not to participate in data collection.

D. VITA

Vita is a mobile cyber-physical system, which supports efficient development, deployment and management of multiple crowd sensing applications and tasks [15]. It is a flexible architecture, integrating service-oriented design principles with a resource optimization mechanism in order to allow for intelligent task allocation as well as for dynamic collaboration of services between mobile devices and cloud computing platform during run-time. Specifically, application-oriented service collaboration model is introduced for intelligently allocating human-based tasks among users and computing tasks between mobile devices and the cloud computing platform efficiently and effectively. The system takes into account different parameters and criteria, such as computation power, communication capacity, remaining battery time, the number of similar tasks users have competed in the past, the number of remaining tasks, user preferences, requirements and constraints, and so on. Social related information may also be utilized in order to quantify the distance / relationship of two entities (either physical or virtual) in order to facilitate the development of human and computing tasks according to different application scenarios. The authors leverage on two intelligent computing techniques in order to provide optimized solutions for the task allocation process: genetic algorithm and K-means clustering. A service state synchronization mechanism is incorporated so as to handle potential service failures, ensure service consistency and collected data correctness. In a nutshell, Vita leverages on service computing, cloud computing and social computing, proposing a comprehensive and flexible architecture, supporting both application developers and users in the context of mobile crowd sensing.

E. CAROMM

In [16], the authors propose and develop a context-aware real-time open mobile miner (CAROMM) framework to support efficient and scalable data collection for mobile crowd sensing. CAROMM integrates and correlates sensory data with social-related data from Twitter and Facebook and delivers real-time information to mobile users, answering queries pertaining to specific locations of interest. CAROMM leverages on resource-aware and energy-efficient local analytics and processing of data on the mobile device along with the relevant contextual information associated with them, reducing, thus, the amount of data being sent to the cloud and the amount of energy consumed on the mobile devices, supporting however quite accurate data collection in comparison to models of intermittent / continuous sensing and sending of information. Specifically, mobile data stream mining is employed and resource-aware clustering on sensed data is used to identify significant changes in the current context of operation in order to reduce the frequency and the amount of data transferred to the cloud, ensuring at the same time that significant information will not be lost. The sensitivity of change detection can be controlled by CAROMM framework. Finally, the cost of sending raw sensor data at pre-specified intervals to the cloud for processing vs. data aggregation and processing on the mobile devices and subsequently sending to the cloud is evaluated in terms of data transfer, energy consumption and accuracy.

F. effSense

In [17], the authors propose an energy-efficient and cost-effective data uploading framework, *effSense*, targeting crowd sensing tasks that do not require real-time data uploading. effSense considers both data plan users (mostly concerned with energy consumption) and non-data-plan users (sensitive to data cost), utilizes adaptive uploading schemes within pre-defined and fixed time intervals called cycles, while participants are enabled at each cycle to select the most appropriate time and network to upload data. effSense framework leverages on the predictability of users' activities and mobility in order to identify critical events and select the most appropriate uploading strategies for both user types by means of lightweight algorithms that are executed locally on mobile devices (e.g., use zero-cost network such as WiFi or opportunistically select another device in proximity to relay data to the server with reduced cost or energy consumption for NDP users in addition to piggybacking data uploading task on a 3G voice call for DP users), allowing however for a certain amount of time delay between data sensing and data uploading.

G. PRISM

Platform for Remote Sensing using Smartphones (PRISM) is presented in [18]. PRISM endeavors to efficiently address the challenge of easy development and deployment of MCS applications, combining and balancing characteristics of generality, security and scalability. PRISM enables re-usage of existing code modules, adopts a push-based model sending application tasks out automatically to an appropriate set of mobile devices based on a pre-specified set of criteria, while for preserving security, untrusted applications run in a software sandbox enhanced with novel features such as *sensor access control* for controlling access to sensitive sensor data, forced amnesia so as to wipe out a PRISM application's state periodically and resource (in terms of energy and bandwidth) metering in avoid resource depletion.

H. Crowd-sourced sensing and collaboration using Twitter

In [19], the authors propose Twitter to serve as the infrastructure for sensors and smartphones to collaborate / coordinate in the context of crowd-sourced sensing applications. The open publish / subscribe Twitter system enables users to assign tasks to several nodes in a specific region in order to acquire the data required, search the data published by several nodes and integrate data in various ways in order to offer value-added services. Twitter social networking aspects provide also easy provisioning of incentives for participating in crowd sensing tasks. In the proposed system, Twitter acts as middleware for publish / subscribe and search / discovery data. The system as a first step tries to answer accepted questions by using data on Twitter. If this is not possible, the system finds experts, potentially exploiting information retrieval techniques, to obtain answers to reply to the requestors. The authors evaluated the performance of the proposed system via a crowd-sourced weather radar and a noise mapping application.

I. Sensarena

Sensarena is a three-tiered architecture presented in [20]. The first tier is the presentation tier and comprises the participants that provide collected sensor data and the requestors that submit sensing requests, equipped with SensarenaP and SensarenaR android applications, respectively. The second-tier is the business-logic tier and the third is the data tier that stores separately all user-related information, sensing task details and collected data. Sensarena platform focuses on energy-aware task assignment by excluding participants that their energy resources are below a pre-defined threshold, not allowing participation in sensing tasks and by allocating tasks to the closer participant(s) to the point of interest / measurement. The users should be registered and authenticated in order to use Sensarena platform, while they are enabled to denote their preferences on which sensor data shall be contributed.

J. oneM2M Architecture Based IoT Framework for Mobile Crowd Sensing in Smart Cities

The authors in [21], propose an IoT enabled MCS framework based on the oneM2M standard architecture. Additionally, they present a power-aware mobile application framework, allowing the development of self-adaptive mobile applications, which dynamically adjust their behavior based on current mobile device's battery levels and context of operation. The proposed framework is composed of a) *battery and context monitoring engine*, b) *analyzer engine*, which evaluates battery and context information with respect to certain rules in order to decide on the adaptation profile that should be applied (i.e., light, medium, strong adaptation profile) and c) *self-adaptive features*, including hardware resource adaptation, software resource adaptation, user features adaptation and additional optimization features. Sensor meta-data originating from heterogeneous sources and domains are treated through semantic web technologies in order to efficiently address inherent incompatibilities and allow for the combination of data, reasoning, collaboration between applications and deduction of new information of interest / intelligence. The processing on data can be performed on a cloud or edge platform on M2M gateways.

IV. Discussion

After surveying the systems / architectural frameworks proposed and adopted in recent related research efforts, it is found that the different approaches lack unity. Each system / application is based on quite different assumptions, while the architectural framework considered varies significantly in many aspects. Without being exhaustive, we could refer to the following: a) pull vs. push model assumed, with the first one requiring users to retrieve the list of active tasks and select the ones they wish to join, whereas the second one diminishes user control, pushing tasks to mobile devices if specific requirements and criteria are met, b) centralized vs. distributed model adopted for data collection, c) design of the sensing campaign, task specification and the overall task assignment process, d) data pre-processing on mobile devices and its related implications, e) incentive mechanism design for encouraging and retaining user participation in MCS tasks, f) addressing inconsistent / inaccurate data provisioning, considering the highly dynamic MCS environment in the presence of selfish and malicious users, g) user privacy, h) energy efficiency in different sub-problems (e.g., which sensors should be employed, at which frequency data should be collected, when data should be uploaded, where and in which manner), i) types of data collected and integrated (data sensed from the physical world and social networking related data collected from online communities), j) MCS application collaboration (data collected should be available for integration, analysis, reasoning and inferring new knowledge / intelligence by different MCS applications).

The presented frameworks address in a quite different manner a sub-set of the aforementioned issues, while, to the best of our knowledge, a comprehensive list identifying all critical aspects, their implications to the design of an MCS system and proposed solutions is missing from related research literature. Even though there is a number of related survey papers [1], [7], [8], [9], [10], [11] they either focus on a specific group of challenges or do not – at least to our opinion – cover every MCS key element and their interplay. The MCS architecture should be general, flexible, robust, scalable, secure (from both end-user's and system's side), energy efficient, context-aware and self-adaptive with advanced cognitive capabilities, defer the heterogeneity of hardware and software platforms, enable the collaboration of different MCS applications, allow the easy development and deployment of MCS applications in a generic way, allowing for code re-usage. The authors' view is that each problem / challenge should not be addressed independently, but in relation and taking into account potential inter-dependencies of MCS key features, while context-awareness, self-adaptivity in conjunction with advanced cognitive capabilities will introduce significant improvements in various aspects.

V. Conclusion

In this paper, a representative set of mobile crowd sensing systems proposed in related research literature are surveyed, while their distinct features and relative merits and weaknesses are discussed. The authors conclude that the proposed schemes lack unity, while a comprehensive list of critical aspects and their implications to the design of a mobile crowd sensing system is missing from related research literature. We plan to continue our work towards that direction, which could hopefully form the basis for defining a unified framework in the future.

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