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Context-Aware Computing for Mobile Crowd Sensing: A Survey

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Abstract

Today, the distribution of people with smart mobile devices has provided the opportunity for mobile crowd sensing. Several mobile crowd sensing systems have led to the collection of valuable information with a low infrastructural investment. These types of information have been used in context-aware systems to provide high-level services. In this paper, a comprehensive reference framework is proposed to investigate context-aware mobile crowd sensing systems from three viewpoints of concepts, context-awareness, and functionalities. Each of these aspects has one or more parameters, which investigate and classify the existing works. To this end, the paper characterizes domain and cooperation type, context-awareness, incentive mechanisms, data sharing, local analysis and global aggregation of mobile crowd sensing systems. The aim is to thoroughly review the existing works, foster the dissemination of state-of-the-art research, and present future research directions.

Keywords—Mobile crowd sensing, Context-awareness, Functionalities, Survey

Introduction

With the spread of mobile devices (like smartphones and tablets) that are equipped to a collection of sensors (like camera, GPS, and accelerometer), and their ability to connect to the internet, an opportunity for crowd sensing has been created. People can use these devices and their built-in sensors to collect and share the sensed data of a population [1]. In fact, Mobile Crowd Sensing (MCS) is a form of people's volunteered cooperation in collecting and sharing various information [2]. The information produced from a crowd sensing system can be used in applications of different fields such as urban monitoring [3], road surface assessment [4] [5] [6], environmental monitoring [7] [8], intelligent transportation systems [9] [10] [11] [12], task allocation systems [13], and healthcare [14] [15] [16].

A significant part of crowd sensing information is used in context-aware systems. "Context is any information that can be used to characterizes the situation of an entity. An entity can be a person, a place,

Declarations of interest: none

or an object" [17]. "A context-aware system is one that uses this information in providing services to users" [17]. A context-aware application can change its behavior to adapt it with the user's context [18] [19]. Context-awareness is one of the most important features of pervasive computing systems, which increases our control and awareness of the surrounding environment [20] [21].

Context-aware applications may use the contextual information produced by crowd sensing systems. Previously, several review studies in different fields of MCS have been conducted including, privacy and security [22] [23] [24], Internet of Things [25], concepts [26], data mining [27], providing incentive mechanisms to users [28] [29], and practical fields [30] [31] like music [32], disaster management [33], water management [34], and healthcare [35]. According to our best knowledge, not any study that investigates crowd sensing from the context-awareness perspective has been conducted yet. Context-awareness is an important characteristic that can help crowd sensing systems reach a better understanding of the situation of an entity. This understanding will help to identify any changes in the situation of that entity. Hence, a better response to this dynamic nature of the environment will take place. Therefore, investigating these systems from a context-awareness perspective is much important.

As several MCS systems have been proposed in previous years and the lack of a comprehensive survey for investigating them, this paper aims to study context-aware MCS systems according to various aspects that are necessary for a typical MCS system. To this end, we have used the keywords of "Crowd sensing" or "Crowd sourcing" plus "Context-aware" in the Google Scholar as the most comprehensive research paper indexing database. Afterwards, we have filtered out retrieved papers in two steps. In the first step, papers that have been published by unknown or unpopular publishers have been eliminated. Since Google scholar mostly performs the search in a keyword matching manner, in the second step the papers have been semantically investigated and unrelated papers to the subject of the survey have been ruled out.

To systematically perform the review, a conceptual framework is proposed (figure1), which aims to investigate MCS systems from three viewpoints including concepts, context-awareness, and functionalities. These aspects correspond to the main steps for specifying a computer system in software engineering, which involve general specification as well as determining functional and non-functional requirements. In this regard, concepts (including domain type and type of user cooperation) are related to the general purpose and main usage of the system. After this overall specification, context-awareness is regarded as the main characteristic or non-functional requirement of MCS systems. To fulfill the investigation, the functional requirements (including incentive mechanism, data sharing, local analysis, and aggregation) of these systems are also explored. It should be noted that these parameters are rather independent. There is not any straightforward mutual influence between any pairs of them. Finally, the results obtained and the lessons learnt are discussed and the new directions of research are elaborated.

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The rest of the paper is organized in the following way. Section 2 reviews related research studies and investigates them from the concept perspective. In section 3, the existing studies are investigated from the context-awareness viewpoint. Section 4 aims to investigate MCS systems from the functionalities perspective. After reviewing previous research, section 5 provides an overall discussion and proposes a reference architecture. Finally, section 6 concludes the paper and provides future research directions.

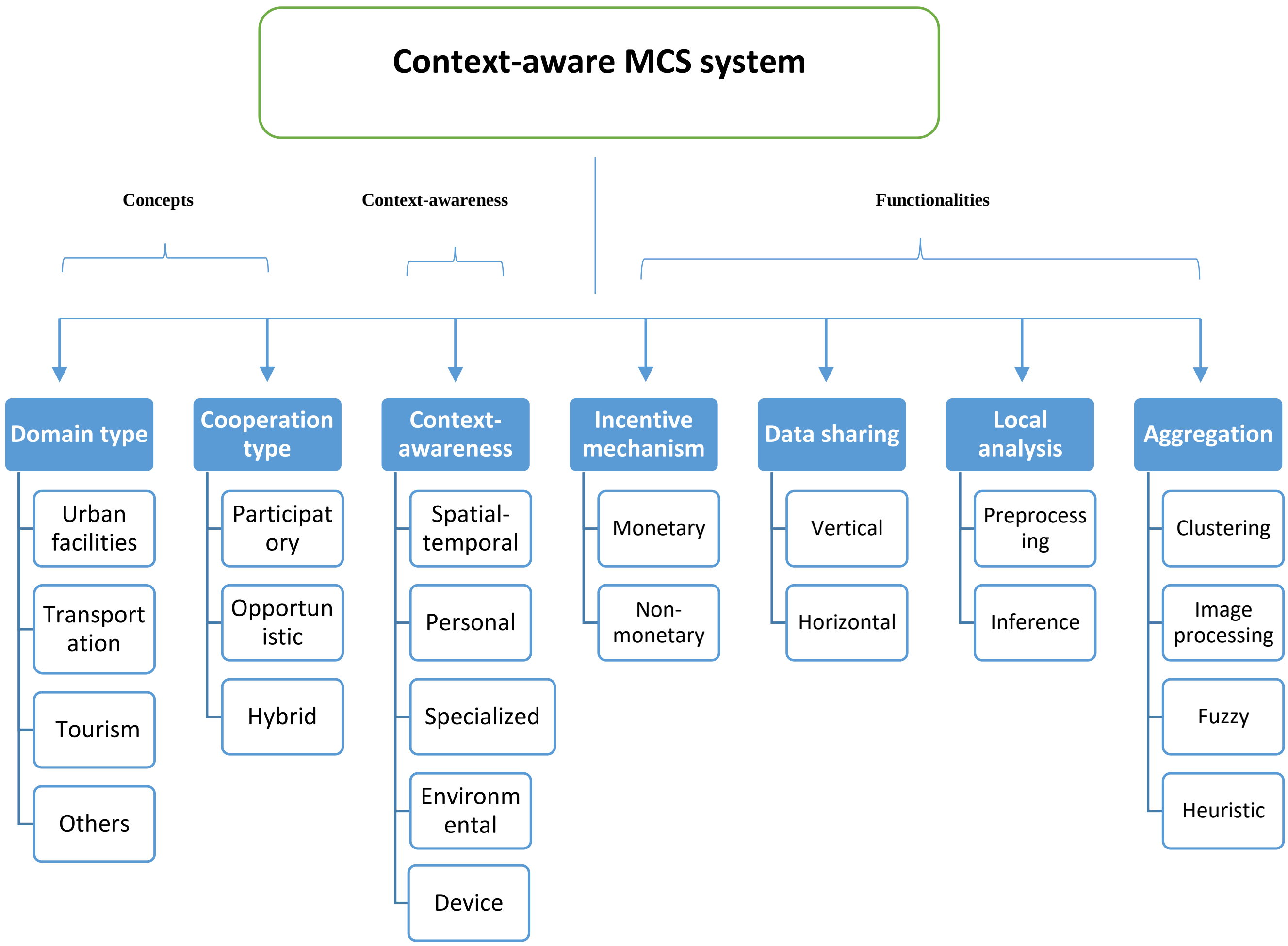

Figure 1. The proposed framework for reviewing context-aware crowd sensing systems

2: Overview of MCS projects

In this section, context-aware crowd sensing systems are reviewed from the concept perspective including domain type and method of user cooperation. Figure 2 shows the geographic distribution of these projects in different continents. In terms of numbers, most of these projects have been carried out in the continents of Europe, America, Asia, and Australia, respectively.

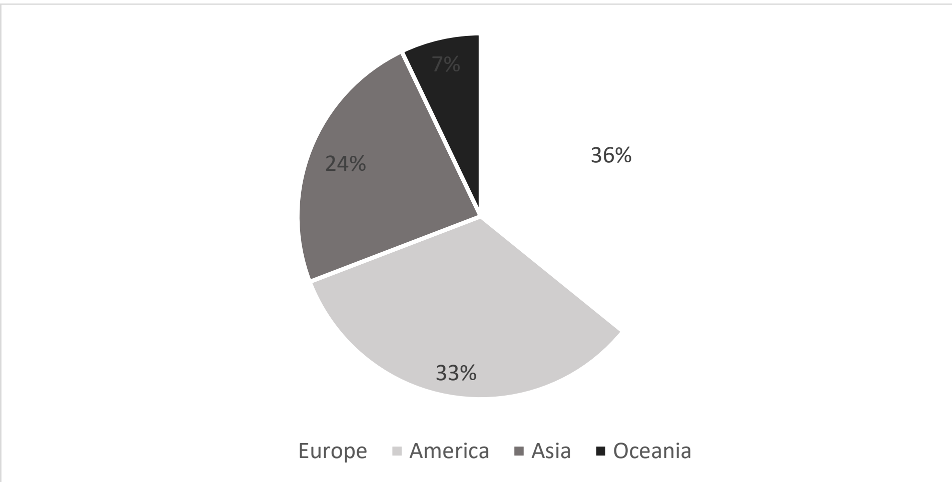

Figure 2. Continental distribution of related studies

2-1: Domain type

The domain type shows the target field of deploying crowd sensing systems. Generally, according to domain type, the existing context-aware crowd sensing systems can be classified into the categories of urban, transportation, tourism, and others. In the following, these categories are elaborated.

- **Urban facilities:** The data produced from crowd sensing can be used for urban life automation. Most of the investigated studies belong to this category. For instance, the PAN360 project [36] produces a panoramic map of the user's points of interest and presents it to him, so that user can acquire more comprehensive information of their surroundings. The CMC project [37] provides the means of obtaining communicative obstacles between people and government, and quickly informs statesmen of these problems. The Here-n-now project [38] provides a service to the user in order to inform them of the situation of different places. For example, if a user decides to go to a park, a restaurant or any desired place, they can gather information about the noisiness or security conditions of that place.

Declarations of interest: none

- **Transportation:** Data produced by crowd sensing on a network of vehicles can be used in various applications of transportation. In this respect, the CANS project [39] [40] collects the local traffic information of various vehicles through crowd sensing, aggregates the global traffic information and uses that information for dynamic navigation. Also in the FEV system [41], an optimal route between the point of departure and the destination is selected, and electronic vehicles share the traffic information with one another using vehicle-to-vehicle communications.

  Using this traffic information, in case of traffic jams in certain routes, another routes with less traffic congestion are replaced. This action leads to lower energy consumption in these vehicles. The VSN project [42] also proposes a model for crowd sensing in the social network of vehicles, which can be useful in improving safety and managing traffic. In the Beacon system [43], by installing a proprietary application on smartphones that receives position through GPS and with the help of crowd sensing, users can be notified of the location of different buses and their approximate time of arrival to the station.

  Studies show that playing music that fits the mood of the driver can considerably help in reducing crashes [44]. The NCC project [45] plays the music that best fits the current mood of the driver by detecting their condition. For this purpose, it uses crowd sensing to discover which music fits each mood.

- **Tourism:** Today, the tourism industry has gained much significance and the number of tourists has increased. In this domain, the FCC project [46] [47] collects contextual information (like location) for those users who go to Saudi Arabia for the pilgrimage. According to their location, it provides a collection of healthcare, housing, and transportation services in order to better organize the travelers.
- **Others:** A number of crowd sensing projects have been carried out in miscellaneous domains. For instance, the CSP system [48] collects the privacy preferences of users, which can be used for implementation of context-aware applications. Also in the C3P project [49]**,** mechanisms for better protection of cloud-stored data are proposed after the sensitivity of users about their sensed information is determined through answering some questions about privacy.

  Some projects consider MCS generally, and propose mechanisms for generic environments. trustworthy is one of concerns of most MCS systems. In order to prevent user's abuses in general MCS environments, the WSC system [50] proposes a mechanism for identifying dishonest users, preventing their activities, and selecting reliable users. Through MCS, the AWI project [51] detects the requirements of the users' devices to help designers develop more efficient and cost-effective browsers. In the projects of Matador [52], CATA [53], MCSP [54], CAPR [55], and CARROT [56]**,** the crowd sensing system relegates its sensing task to those users who are more suitable for doing it.

2.2: Cooperation type

In MCS, the process of data gathering is possible with the cooperation of users. In this subsection, the relevant research will be reviewed from the perspective of user cooperation type in crowd sensing. Generally, the type of cooperation in investigated MCS systems can be categorized to the participatory, opportunistic, and hybrid groups:

- **Participatory**: This category of systems need the active cooperation of individuals. They are classified into the following subgroups:
  - ✓ Mobile photography**:** In this subcategory, the type of data being sensed is an image. By taking pictures using smartphones and sending them to the server, individuals take part in crowd sensing. For instance, in the PAN360 project [36], individuals cooperate in creating panoramic maps by taking pictures and sending them to the server.
  - ✓ Questionnaire: In MCS systems, the data is gathered from individuals through questionnaires. Individuals cooperate in crowd sensing by answering a series of questions and benefiting from its resulting facilities. For instance, in the C3P system [49], Amazon employees take part in crowd sensing by answering questions about privacy. In the Curios project [57] [58], some questions about a particular subject are asked from users. Then, according to the answers given by them, the system acquires knowledge, which it uses for producing information related to that subject. For example, when a user goes to a particular place, the system asks questions about that location from the user. Through the answers, it acquires knowledge about that place and can provide interesting and useful information to other users who later visit that place.
- **Opportunistic:** This category relies less on active user cooperation in the process of sensing and sending information, and the data is automatically sensed and sent. The process of sensing without user intervention occurs by portable sensors accompanying the user. With respect to the type of these sensors, these systems are further categorized into the following subgroups.
  - ✓ Mobile Sensors: In these systems, the built-in sensors in the smartphone of users automatically gather and send data relevant to crowd sensing. For example, in the Here-n project [38], the information of the environment, which the users are located in, is automatically sensed through built-in smartphone sensors and sent. Also the FCC project [46] [47] automatically senses the information related to the location of pilgrims through built-in smartphone sensors. Finally, in the Beacon system [43], the information related to the location of individuals and buses is automatically sensed and sent through the sensors of users' smartphones.
  - ✓ Body Sensors: Much of the information related to the individuals' health is automatically sensed by sensors placed on their body. For example, in the FCC project [46] [47], the information related to the health of pilgrims is automatically sensed by wearable sensors and sent.

Declarations of interest: none

✓ Vehicular Sensors: In the domain of transportation, the sensors installed on the vehicles automatically sense the data relevant to crowd sensing. For example, in the CANS [39] [40] and FEV [41] projects, the traffic information is calculated and sent through vehicular sensors.

• **Hybrid**: This category of systems provides both of the possibilities for participatory or opportunistic cooperation to users. For example, in the CSP project [48], the users can manually or automatically cooperate in crowd sensing through smartphone sensors and with respect to their privacy preference.

Table 1 provides a general overview of research studies related to the context-aware crowd sensing.

Table1: General overview of research studies related to context-aware MCS

Project Name	**Reference**	**Domain type**				**Cooperation type**						**Implementation status**	**Publication type**
						Participatory		*Opportunistic*		*Hybrid*	*Unknown*		
		Tourism	*Urban*	*Transportation*	*Others*	M-photography	Questioner	Mobile sensor	Vehicular sensor				
FCC	[46] [47]	✓						✓				Implemented	Conference
MAC	[59]				✓					✓		Deployed	Magazine
Matador	[52]		✓			✓	✓	✓				Implemented	Conference
MCSP	[54]				✓	✓						Designed	Report
TMS	[60]		✓					✓				Designed	Conference
Curios	[58] [57]				✓		✓	✓				Implemented	Journal
CMC	[37]		✓					✓				Prototyped	Conference
Here-n	[38]		✓					✓				Designed	Conference
PAN360	[36]		✓			✓						Deployed	Journal
CARROT	[56]				✓	✓						Designed	patent
FEV	[41]			✓					✓			Simulated	Magazine
CADE	[61]				✓			✓				Simulated	Workshop
CATA	[53]				✓			✓				Simulated	Conference
D-cloc	[62]				✓			✓				Simulated	Conference
CAPR	[55]				✓	✓						Simulated	Journal
VSN	[42]			✓							✓	Designed	Conference
AWI	[51]				✓			✓				Designed	Conference
PCAM	[63]				✓			✓				Deployed	Workshop
WSC	[50]				✓						✓	Prototyped	Conference
LBSC	[64]				✓	✓						Designed	Conference
NCC	[45]			✓				✓				Implemented	Conference
CSP	[48]				✓					✓		Implemented	Journal
C3P	[49]				✓		✓					Designed	Symposium
COM	[65] [66]				✓			✓				Designed	Conference
CANS	[40] [39]			✓					✓			Simulated	Journal
Beacon	[43]			✓				✓				Designed	Workshop

3: Context-awareness: project review

In this section, related research studies are investigated from the context-awareness perspective. Each of the existing systems makes use of one or several context elements. In the past, general classifications for context-awareness have been proposed [17], [67], but in the crowd sensing domain, these classifications need to be reconsidered. In this domain, spatial-temporal, personal, specialized, device and environmental context types are of much interest. Therefore, the same classification is proposed, which is investigated in the following:

- **Spatial-Temporal***:* In crowd sensing applications, information related to time and location is especially significant. Location is mostly accessed through GPS, Wi-Fi, or cellular networks. Almost all of the systems reviewed use this category of information for two purposes, as follows:

  Providing location-based services: Many of the reviewed crowd sensing projects use the location of the user for providing intelligent services. For example, the CARROT [56], D-CLOC [62], MCSP [54], and CMC [37] projects, detect the user's current, future, or commonly visited locations by tracing his/her location. Then, the system assigns its sensing needs (like going to a place and taking photos or videos) to those users who visit the intended areas. Also in the PAN360 project [36], when a user enters a new place, the information about his direction of travel is received through the compass and accelerometer and the map of the user's surrounding is provided to him for guidance. In the Beacon project [43], the user is notified of the location of different buses and their approximate time of arrival to the station through the mobile application that senses their location through GPS. The Curious project [57] [58] uses the GPS coordinates of the user's cell phone for extracting the location, direction, and the time interval the user stayed at his visited location. This application uses the obtained knowledge to provide interesting and useful information to the user about the places they visit.

  *Map creation***: S**ome of the crowd sensing systems use the sensed information of location for creating maps. For example, in the PAN360 project [36], the users take pictures of the places they are located at and help the server in creating panoramic maps.

  Since location is considered to be a sensitive context element, in some cases [68], individuals are not inclined to disclose it [48]. For this reason, in the PCAM project [63], the user's location is obscured using location perturbation techniques, such that another location within a certain radius of the original point is replaced.

- **Personal context:** This category of contextual information contains the user's personal information [69]. Personal context has been widely used for general applications. Among crowd sensing systems, in the CATA project [53], the manager shares a few of the sensing tasks with a user and the user chooses one of these tasks. Then, similarity between user (according to personal context like profile and current state) and the selected task is calculated. If the calculated similarity is higher than the threshold, the user will perform that task. The CMC system [37] uses personal context like the user profile (age and gender) to recommend a particular task such as participation in voting or filling a questionnaire. The MAC project [59] obtains a

Declarations of interest: none

comprehensive understanding of the users' interests and behaviors from their activities (like sleeping, walking, sitting, movement patterns, etc.). It helps in understanding their needs to be used in various applications. Finally, the NCC system [45] uses age and gender to recommend the music that is suitable to the driver's current situation.

- **Specialized context:** Some of the applications of crowd sensing are designed for a particular domain like healthcare, transportation, etc. As a result, they use the specialized context information of that domain. For example, in the FCC project [46] [47], the health situation of an individual can be determined from his pulse count, heartbeat and blood pressure, which are collected through the network of available active sensors. Similarly, in the domain of transportation, the CANS system [39] [40] approximates traffic density using the speed and the average absolute value of vehicles' acceleration. FEV [41] proposes a solution for recharging electrical vehicles using traffic data and average speed.
- **Environmental context:** This category of context describes the state of the user's environment. For instance, in the Here-n project [38], environmental information like noise and population density are used in gaining an awareness of that environment's commotion and security. For example, when a user wants to go to a restaurant, she can find out whether that place is busy or not. In the CADE project [61], the environment's noise level is measured under various conditions. Then, the values attained are compared with one another to determine the factors that have affected the quality of them.
- **Device context:** This category of information is related to the device that is used for crowd sensing. For instance, the CADE project [61] studies the quality of sensed data with the help of mobile device contextual information (like phone brand, sensor model, and calibration level). Furthermore, the CATA system [53] studies the effect of different devices contextual information (like device hardware) on energy consumption. This system seeks to improve the energy efficiency of crowd sensing applications.

Table 2 summarizes the contextual information used in context-aware MCS systems.

Declarations of interest: none

Table 2: Contextual information used in context-aware MCS systems

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Project Name	Spatial-Temporal context	Personal context	Specialized context	Environmental context	Device context
FCC [46] [47]	Location	Historical activities, User's points of interest	Pulse rate, Heart beat Blood pressure, ECG	-	-
MAC [59]	Location	User activity, Mobility- pattern, Social relationship	Heartbeat, Blood, Pressure, ECG, Stress level	Temperature, Humidity, pollution	-
Matador [52]	Location, Time	User activity, age, gender	-	-	-
MCSP [54]	Location, Type of location, Time of day	Workers current activity, User task	-	-	Current-device status
TMS [60]	Geo-location	-	Mobile network topology	-	-
Curious [57] [58]	Place where the user stays, Time of visit, Duration of stay, Path	-	-	-	-
CMC [37]	Geographical coordinates (latitude, longitude), Temporal data	User activity User task, age, gender	-	-	Battery consumption
Here-n-now [38]	-	User activity	-	Noise level, Light intensity, Crowd intensity	-
PAN360 [36]	Location	-	-	-	Smart phone orientation, Smart phone GPS error
CARROT [56]	-	User preference, User task, User cost	-	-	-
FEV [41]	Time of travel	-	Average speed, Cost of energy	-	-
CADE [61]	-	Human behavior factors	-	Noise Level	Hardware factors (e.g. phone brand)
CATA [53]	Location, Time	Activity, Gender, Age	-	-	Battery level Built-in sensors
D-CLOCK [62]	Future location	User task, User cost	-	-	-
CAPR [55]	Location	User task, User cost	-	-	-
VSN [42]	Location, Delay	User task	Identities of neighbors and objects, Network overhead	-	Battery consumption
AWI [51]	-	-	Size and position of web site elements	-	-
PCAM [63]	Location	-	-	-	-
WSC [50]	-	-	Type of task	-	-

Declarations of interest: none

			Reward amount of task		
LBSC [64]	Location, Time	User task	-	-	-
NCC [45]	-	User mood	Traffic	-	-
CSP [48]	Location	-	-	-	-
C3p [49]	-	-	Data features, Information extracted from data analysis	-	-
COM [65] [66]	Spatial temporal interaction	User social Information	-	-	Device type
CANS [39] [40]	-	-	Mean absolute acceleration, average speed	-	-
Beacon [43]	Location	-	-	-	-

4: Functionalities

Typical MCS systems have various functionalities including providing incentive mechanisms, local analysis, and data aggregation and sharing. In this section, existing MCS systems are reviewed according to each of these cases.

4-1 Incentive mechanism

Individuals often participate in crowd sensing using their smartphones. This participation has costs for them, since it consumes resources like battery, memory, bandwidth, and sometimes their time [28]. Besides, since the sensed data usually contains private information about location, the participation of individuals may lead to revealing their location; therefore, they may not be willing to participate in crowd sensing. As a result, mechanisms for encouraging users should be considered. Generally, incentive mechanisms used in previous studies can be classified into the following categories:

- **Monetary incentive mechanisms:** In this category, participants receive financial rewards for their participation in crowd sensing tasks. Mason and Watts [70] demonstrate that the higher the amount of reward, the faster the tasks are accomplished. These rewards are divided into two categories including fixed and dynamic. In the dynamic incentive mechanisms, users set the price they have in mind for their own sensed data [71]. This approach to pricing leads to increase in prices and higher income for sellers. So in many projects, the reverse auction approach is used CARROT [56], D-CLOC [62], CAPR [55] [72] [73] [74] [75] [64] in such a way that each user offers a price to the system in exchange for the crowd sensing task that they perform. According to the prices offered by users, the system decides to accept or reject the offer. Then, the system chooses selected users from bidders for task assignment and removes others. In this auction, individuals who are removed from the system cancel their participation CAPR [55]. In order to encourage individuals removed from the system, mechanisms for long-term individual participation in crowd sensing are proposed CAPR [55] [76] [77] [78]. The procedure for these mechanisms is such that, those users who were removed in the previous round, have an increased chance of selection in the current round.

In the fixed rewarding mechanism, there are prices already set for different sensing tasks, which are static and do not change until the task's completion. For example, in the MCSP project [54], the system pays a fixed price for each task that a worker does. Also, in another system [79], the students of a university are asked to take pictures from the contents of trash cans and put tags on the photos pointing out the contents of the garbage. In exchange for sending each valid photo, each person receives a fixed amount. The collected data is used for improving the placing of trash cans.

- **Non-monetary incentive mechanisms:** This category is not in the form of giving cash or non-cash rewards, but brings about a good feeling. These mechanisms can be further categorized into providing entertainment and public services, as follows:
  *Entertainment***:** In this subcategory, crowd sensing tasks are turned into a game, meaning individuals can participate in sensing while playing a game [80]. These games need to be sufficiently engaging for individuals to enjoy doing them [28]. for example, In a research [81] a maps including various locations is provided to users. This game is played by going to the specified locations, taking pictures and sending them. These pictures are later used for making 3D models of objects. Whoever goes to more locations and takes more pictures, obtains a higher score. In the TMS project [60], the Open Mobile Network [82] which is a conceptual model for the mobile network topology uses smartphone applications for collecting information related to the network. For this purpose, a game called Jewel Chaser, which has a map with specified places is released. Players should go to these places and collect virtual jewels. The more jewels are obtained, the higher the ranking of the user is. After arriving at these places, the users collect mobile network's data and this data is transferred to the server.

  Public service: This category of non-monetary mechanisms includes sensing activities whose benefit is for all individuals participating in crowd sensing. For example, participating in air pollution sensing programs will allow the authorities to adopt reasonable approaches for controlling air pollution. In this regard, in some projects [83] [84] [85] [86], users collect data related to air quality using air pollution measurement sensors. This data, along with information of the user's location, is sent to a database. This data is used for creating air pollution maps and these maps will be provided to those individuals who have participated. Some systems help customers in making informed decisions for shopping. For example in some projects [87] [88], users take pictures of products and their price tags using their smart cameras. Then, these pictures and their location information (using GPS) is sent to a central server and stored in a database. Whenever a

Declarations of interest: none

user, who has participated in the sensing process, requests the price of a product, that request, along with user's location is sent to the server. Afterward, the server provides a list of products that are available in nearby shops with their prices to the user. After comparing prices, the user chooses her desired product.

Some of the crowd sensing systems provide health related services to their users. Health is a subject that most people are very concerned about. Thus, they are after eliminating causes that may endanger their health. For example, obesity causes many illnesses and many people are willing to go on a diet and lose weight. In this regard, a participatory sensing program called W8Loss [89] is introduced, where participants register their activities and this program helps them at losing weight.

Table 3 summarizes the incentive mechanisms used in previous studies.

Table 3: Incentive mechanisms used in previous studies

Incentive / Ref	Monetary		Non-monetary	
	Dynamic	Static	Entertainment	Public Service
[62]	✓			
[56]	✓			
[55]	✓			
[64]	✓			
[72]	✓			
[73]	✓			
[74]	✓			
[75]	✓			
[54]		✓		
[79]		✓		
[60]			✓	
[81]			✓	
[83]				✓
[84]				✓
[85]				✓
[86]				✓
[87]				✓
[88]				✓
[89]				✓

4-2 Data sharing

Since crowd sensing deals with data collection and presentation, the way in which data is shared is important. Generally, sharing is done either vertically or horizontally, as follows:

- **Vertical**: In vertical data sharing, which is supported by many systems, the aggregation component directly provides the information to consumers [90]. Since the aggregation component and users are positioned in different layers, this mechanism is regarded as top-down or vertical. To this end, two sharing approaches including the social media and queries are generally used. In this regard, in a study [91], the server infers the presence status of the individual (e.g. dancing at a specific party) using the information resulted from sensors such as noise and accelerometer. Then, it shares that information on social media such as Facebook with their friends. After logging in to the social network, the user has control on filtering the list of friends that he is willing to share this status with. In the query-based approach, information is provided to users according to their requests. In this regard, people take pictures of advertisements on bulletin boards in different areas (like workplace or the street) and send them to the server of FlierMeet [92]. The server classifies and tags the photos based on the type of advertisement, such as a general concert ad, a professional academic ad, etc. In the end, users are able to request their intended advertisements through the provided query mechanism. For this, the users can specify their required tags within the intended class of advertisements. The server processes the query and responds with the conforming advertisements. Finally, in the Micro-Blog system [93], a map is provided to users so that they can issue query for demanding information and status of each place on the map. The server processes the query and responds with the requested information that has been gathered via crowd sensing.
- **Horizontal***:* In horizontal sharing, the users share the sensed data directly with each other [90]. Horizontal sharing usually occurs through social networks or device-to-device communications. Social networks provide a suitable basis for sharing information between people at the same level. For this purpose, social networks like Facebook are used for individuals to share crowd sensing tasks by leaving a post for their friends [94]. People, who are willing, perform these tasks and send the result to that individual. Moreover, the social network is used for people to share parking related events together with the geographical information of the location. These events include leaving a parking lot, availability of parking spots, and searching for a parking spot [95]. The aim is to help drivers to find a nearby free parking space.

If device-to-device communication is supported, it can be used for horizontally sharing data. In this regard, in the VANET domain, vehicles can communicate via vehicle-to-vehicle communication [96]. For example, vehicles can collect traffic information and share that information with nearby vehicles [97]. As a result, each vehicle will augment its dynamic traffic information and can use it for finding a suitable route to the destination.

4-3: Local analysis

Various sensors, like GPS, accelerometer, microphone, and camera in smart devices are used for data collection in crowd sensing. Since the amount of data collected by mobile phones is enormous, continuously transferring all the data to the server causes network congestion as well as a massive workload for the server. As a result, in some crowd sensing systems, local analysis is performed on mobile phones [8]. Generally, local analysis consists of preprocessing and inference, which are discussed below.

- **Preprocessing:** The data sensed by sensors is usually raw, and sometimes needs to be preprocessed [98]. In some crowd sensing systems, preprocessing is done for noise elimination [99] and data filtering [100]. For instance, in CenseMe [101] that aims to detect the presence of an individual, at first the sound of the environment is recorded. Then, for accurate voice detection, the background noise is eliminated using low pass filters [101].
- **Inference:** Inference is an approach for data analysis that leads to acquiring high level information [102]. [103] [104]. In this regard, CenseMe [101] infers high-level information of users (such as stationary or mobile, physical activities, including sitting, standing, using mobile phone, walking, running, or stair climbing) from a variety of continuously sensed data provided by user's smartphone. To this end, it exploits the J.48 decision tree classification algorithm. Inference is commonly carried out by heuristic or intelligent algorithms. In SoundSense [102], the mobile phone component classifies the sensed sound into either speech, music, or Ambient sound type. To this end, it uses a two-step classifier. The first step consists of a J.48 decision tree algorithm. To improve the accuracy, output of the first step is processed by a first-order Markov model via the second step. In the Here-n project [38], the activity of the user is inferred with the help of neural network and then is handed over to the server. In another research [101], the mobile phone analyzes and infers [105] user's activity (sitting, walking, visiting friends), psychological state (happy or unhappy), interests (presence in a sports gym, coffee shop), and the environmental conditions (noisiness) by receiving the user's contextual information (like location and the speed of movement) and making use of voice and conversation detection algorithms.

In the VANET domain, a crowd sensing system for monitoring and managing transport fleet has been introduced [106]. This system conducts local processing using statistical algorithms in order to control the vehicle's performance, fuel, and the driver's behavior. Also, in the CANS project [39] [40], each vehicle infers its local traffic level using speed, absolute value of acceleration, and a fuzzy reasoning algorithm.

4-4: Aggregation

Performing crowd sensing with the help of many individuals leads to the collection of a large amount of data. This data should be aggregated and processed to be converted into high-level information before being utilized by users and systems. Sometimes, the volume of the generated data is so huge that big data techniques should be leveraged for processing it in a scalable manner. In this regard, Hadoop [107] and Spark [108] are utilized for processing huge amount of data. Hadoop is a platform for storage and processing of a large volume of data. It is exploited for evaluating the quality of sensed data using the MapReduce parallel programming model [109]. Similarly, truth discovery from the huge volume of users' provided data is a sophisticated and time-consuming process. To this end, MapReduce is utilized to efficiently evaluate the big data received on the server component [110].

Spark is a parallel processing framework that extends Hadoop MapReduce. It has been used for prompt processing of the vast volume of data provided by people in festivals and city events [111]. The aim is to quickly detect any minor panic to be able to perform quick and targeted interventions. Similarly, Spark is used to perform deep learning on a huge amount of data generated by users [112]. The aim is to discover high-level information in a reasonable time.

In MCS, the servers located at the top layer make use of various techniques for data aggregation. Among the previous research, the types of data processing done on servers for data aggregation can be classified into the following groups:

- **Clustering:** One of the most important techniques for aggregation in MCS is to use clustering algorithms for categorizing the massive amount of data sent by users [113]. In this regard, the NCC project [45] performs clustering on various songs reported by users' mobile devices. In another research [114], the GPS and accelerometer data are locally processed by users' smartphones in order to discover roughness of road surface. Then, information related to roughness points are transferred to the server. Using the Linear Programming Chunking (LPC) algorithm [115], the server at first filters out faults like fake acceleration signals (caused by engine vibration). Then it aggregates the received points by clustering. For this purpose, all reported points that are close to each other and fall within a circle with a particular radius are identified and the average of these points is considered as a roughness. Finally, a map including all identified uneven points is produced.
- **Supervised learning**: Classification of the data generated by users is another important processing technique of the aggregation server. It yields to useful information from a mass of raw data. In this regard, the central server of FlierMeet [92] uses supervised classification scheme to categorize user's images of fliers into either of ad, academic, notice, or recruitment fliers. Similarly, neural network is used [116] [117] for classifying the digit segments extracted from images of gas stations' price list. Besides, random forest is used in SmartRoad [103] to identify the type of intersections (i.e. presence/absence) and the type of traffic regulators. To this end, driver's smartphones send sensed data to the server. Afterwards, the server represents each intersection by a vector of statistical features and performs supervised classification.

- **Image processing:** Considering that in many crowd sensing applications images are taken and sent to the server, image processing is one of the common methods of aggregation. In this regard in the PAN360 project [36], the cloud server uses a hash algorithm, which is based on the contents of the image, to find images related to the one sent by the user. Then, with the help of image processing, it places the related pictures next to each other and creates a panoramic map. Also, in another project [116] [117], a MCS system takes pictures of gas stations' price list using cameras installed inside the users' vehicles. These pictures, along with coordinates of location, fuel station brand, and time, are sent to the central server. The server scans the picture and extracts the fuel price using image processing and computer vision algorithms. Finally, the users can search for the cheapest refuel option in their proximity. The server will send them the location, fuel price, and brand name of the station that is close to them.
- **Fuzzy:** Fuzzy systems also have applications in aggregation of information produced by sensors. For example, the fuzzy system is used for validating individual's cooperation in crowd sensing [94]. For this purpose, the server uses a fuzzy inference system including both parameters of the quality of contribution and the trustworthiness level of participant to calculate the person's contribution validation score. Then, this score is compared with a threshold value to be used as a measure for accepting or rejecting the contribution. In case of acceptance, the data sent will be used; otherwise, it will be dropped.

  In the Here-n project [38], the cloud component receives four parameters of light intensity, noise level, activity level, and crowd density. Then, using fuzzy logic, it discovers either of three states of lively (noisy and bright), noisy (crowded and having high user activity), and quiet (low noise and activity).

- **Heuristic:** Heuristic algorithms have also been proposed for the data aggregation. In this regards, the vehicles of the CANS system [39] [40] send local traffic information to the urban server through vehicle-to-infrastructure communications. The urban server uses a weighted heuristic formula to aggregate this information and to generate the global traffic map. Also, in a task allocation system, the workers send their sensed data to a cloud-based server [118]. Since this data is usually unreliable, a confidence-aware truth discovery method is proposed for discovering facts from data. For this objective, a weight is assigned to each worker using weight determination approaches. The weight of each worker is proportional to the degree of reliability of their data. The degree of reliability is proportional to the inverse difference between actual data and the data received from that worker. Then, the data from workers with higher weights are used for acquiring aggregated results.

Table 4 summarizes the investigated research according to data sharing, local analysis, and aggregation.

Table 4. Summary of MCS Systems according to data sharing, local analysis, and aggregation

Reference	**Data sharing**				
	Vertical		Horizontal		
	Social network	Query-based	Social network	V2V	
[91]	✓				
[92]		✓			
[94]			✓		
[95]			✓		
[96]				✓	
	Local Analysis				
	Preprocessing		Inference		
	Noise elimination	Filtering			
[99]	✓				
[100]		✓			
[101]		✓	✓		
[102]			✓		
[104]			✓		
[38]			✓		
[39] [40]			✓		
	Aggregation				
	Clustering	Supervised learning	Image processing	Fuzzy	Heuristic
[45]	✓				
[113]	✓				
[114]	✓				
[92]		✓			
[103]		✓			
[36]			✓		
[116] [117]		✓	✓		
[94]				✓	
[38]				✓	
[39] [40]					✓
[118]					✓

5. Discussion

Declarations of interest: none

Most of the considered research projects have not been developed; that confirms the challenge of deploying MCS systems. In MCS systems, the location information of people is usually used, so they are unwilling to participate as a matter of privacy violation. This issue is one reason that makes the deployment of these systems difficult. Moreover, the existing incentive mechanisms have not been able to solve this problem. Therefore, more realistic and appealing incentive mechanisms need to be invented to further encourage individuals to participate. Providing high-level information or a services based on that information can be used for creating such incentive mechanisms.

Despite the fact that the objective of crowd sensing is data collection and sharing, many projects lack mechanisms for information distribution. This subject emphasizes that MCS has a long way to become operational and also interactions between users face some challenges. Therefore, mechanisms enabling more cooperation and sharing between individuals should be much more investigated.

Data created using sensors has much redundancy and sometimes low accuracy that can reduce the performance of crowd sensing systems. Therefore, it is required to eliminate these redundancies and increase data quality. In previous systems, filtering and noise elimination are mostly performed on servers, whereas inventing techniques for controlling redundancies and eliminating poor quality data on mobile devices could reduce bandwidth consumption and server workload.

To conclude the paper, figure 3 proposes a reference architecture for MCS systems 3. The proposed architecture illustrates and summarizes the position of discussed components in a comprehensive MCS system.

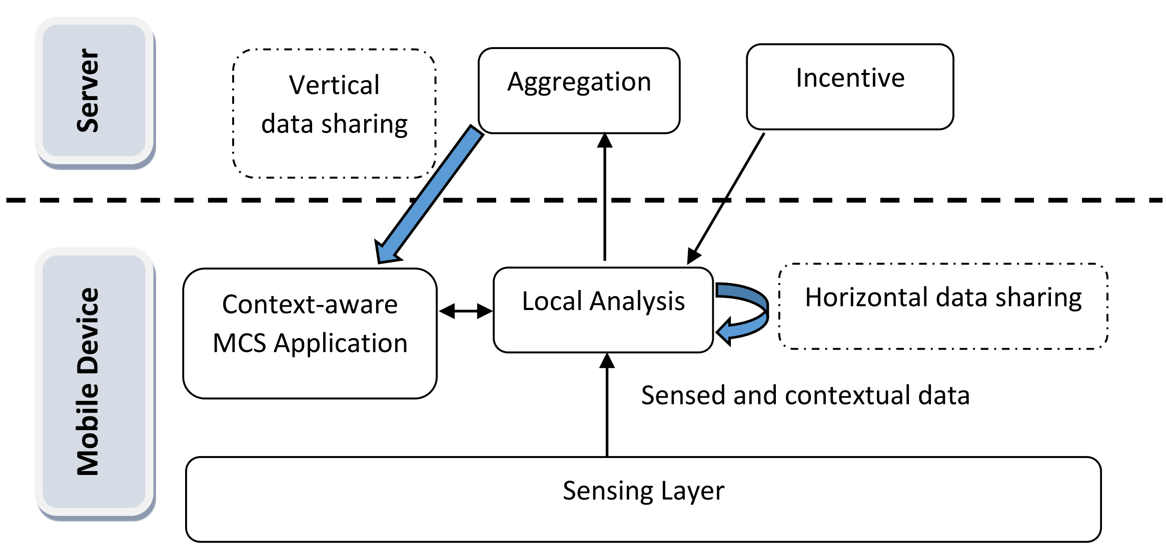

Figure 3. Reference architecture of the MCS system.

Declarations of interest: none

In general, MCS systems consist of two tiers including mobile device and server. In the bottom of mobile device tier, there is sensing layer, which is responsible for gathering data from the environment. Afterwards, the sensors hand over the data to the local analysis component, which is responsible for processing data. The processed information can be shared horizontally among different smartphones. Besides, context-aware applications resided on users' devices can utilize this information. The main component of the server is aggregation, which is responsible for receiving information from users' devices and processing and aggregating it. Afterwards, it provides vertical data sharing mechanism for MCS-based applications. The server tier should also provide incentive mechanisms to motivate users for participating in the sensing process.

6. Future research directions

In this paper, context-aware MCS systems have been investigated from various aspects including domain type, sensing cooperation type, context-awareness, incentive mechanism, data sharing, local analysis method, and aggregation approach. In crowd sensing, a huge amount of data is created continuously, which is difficult to be stored and processed by traditional servers. Cloud is commonly used as a massive storage and computational resource. The main problem lies in high communication delay of cloud, and as a result, the inability to execute interactive and real-time applications. To solve this problem, a comprehensive architecture for real-time crowd sensing systems can be introduced with the help of edge or fog computing.

MCS has commonly entered general domains while it can have many applications in specialized branches like medicine, geography, archeology, engineering, linguistics, social sciences, and others. The use of MCS systems in various specialized domains for collecting and processing information is one of the main open directions for next research. In this regard, disasters like earthquakes are one of the important domain applications for MCS systems. One of the challenges for managing and responding to disasters is information gathering. More particularly, after a disaster old map of streets is not valid and a new map of open roads is required. Besides, rescue teams require real-time information regarding people needing urgent help in collapsed buildings, or even animals in need of help in countryside. In summary, various types of real-time information should be obtained, aggregated and sent to different parties and rescue groups. Traditional approaches cannot handle this situation well. Context-aware MCS systems are appropriate solutions for managing such situations.

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Declarations of interest: none

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