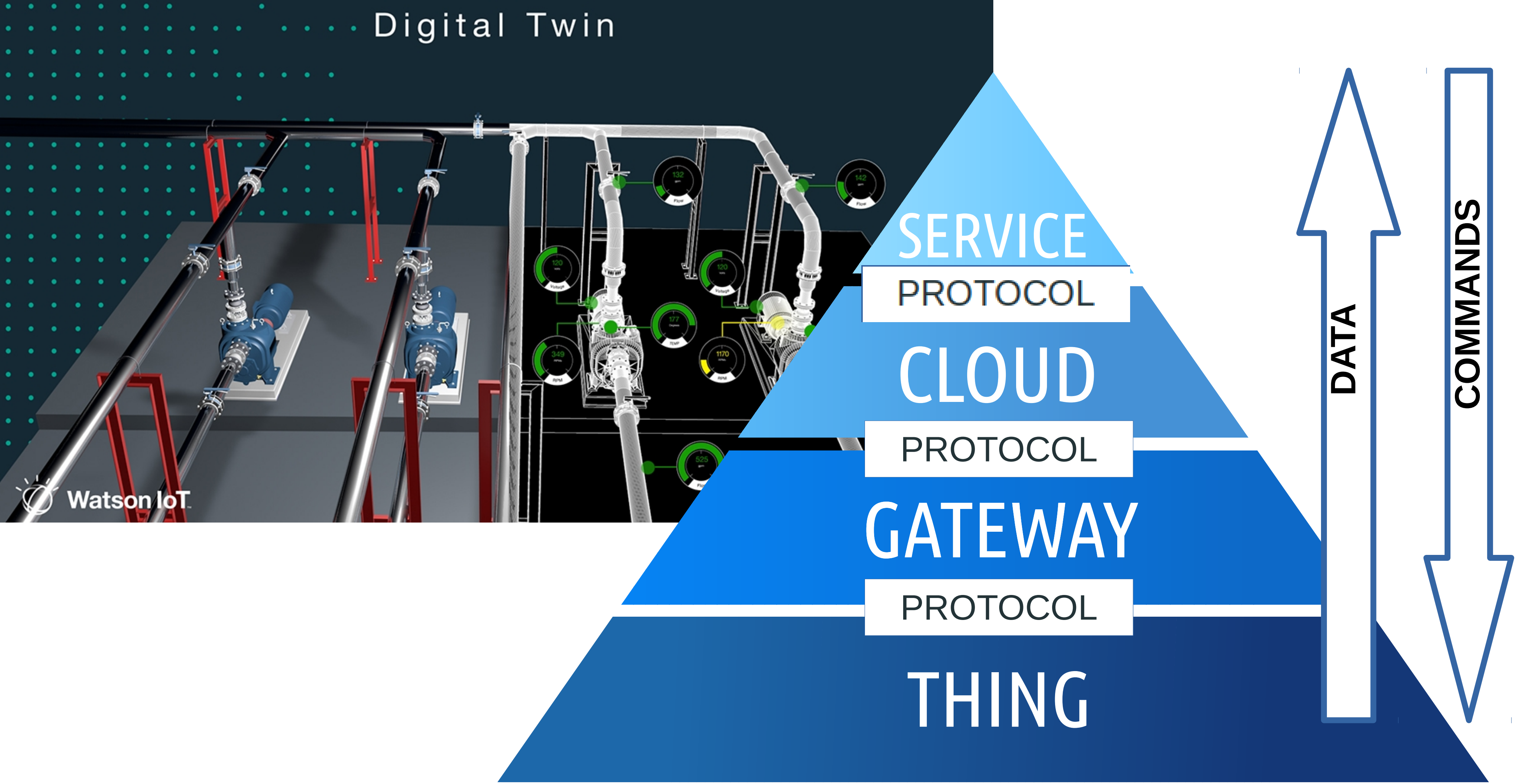
Crowd Sensing

Andrea Vitaletti

Agenda

- Context
- Motivation
- Crowd Sensing
- Privacy
- No fixed communication infrastructure (next lectures)
  - MANET
  - DTN
- Hands-on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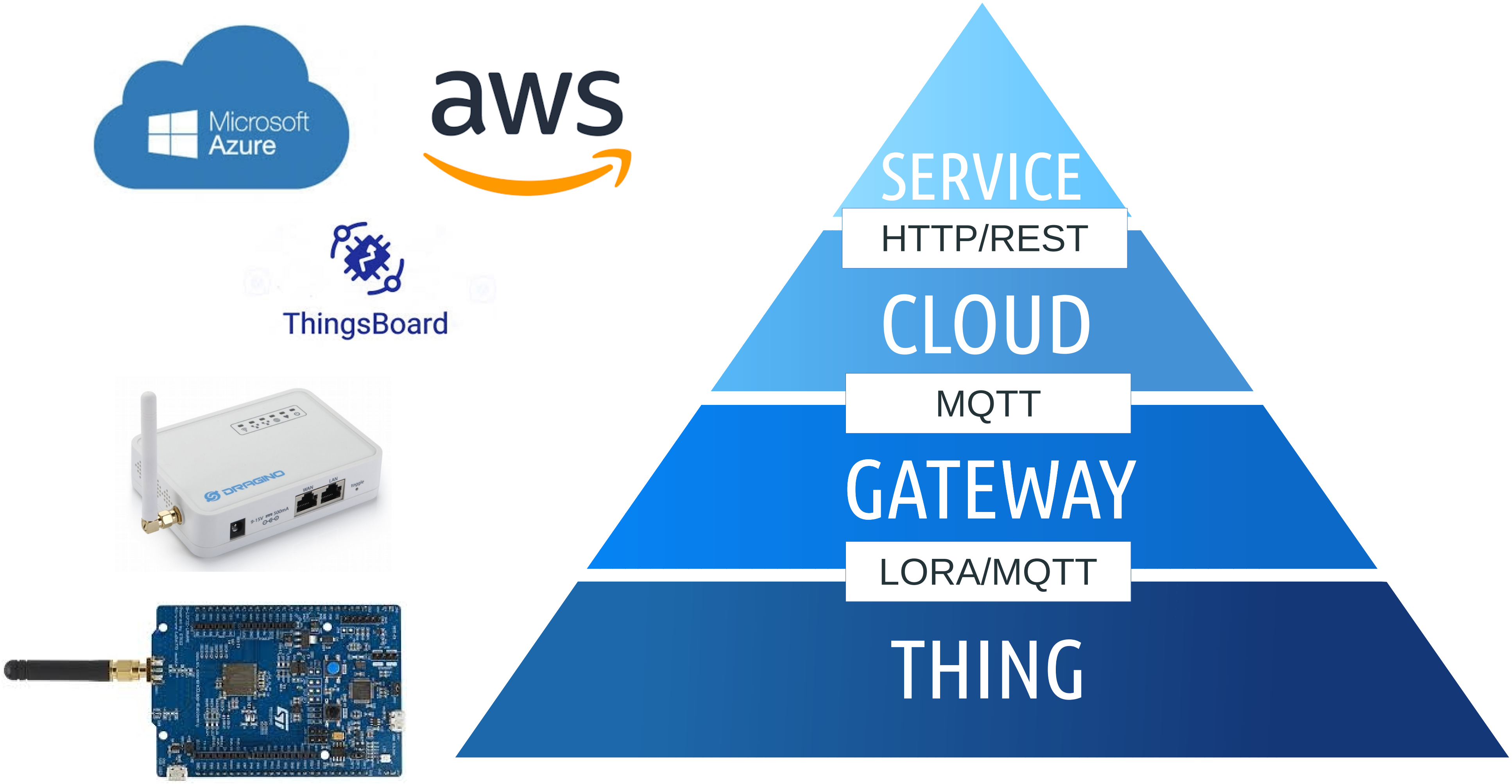
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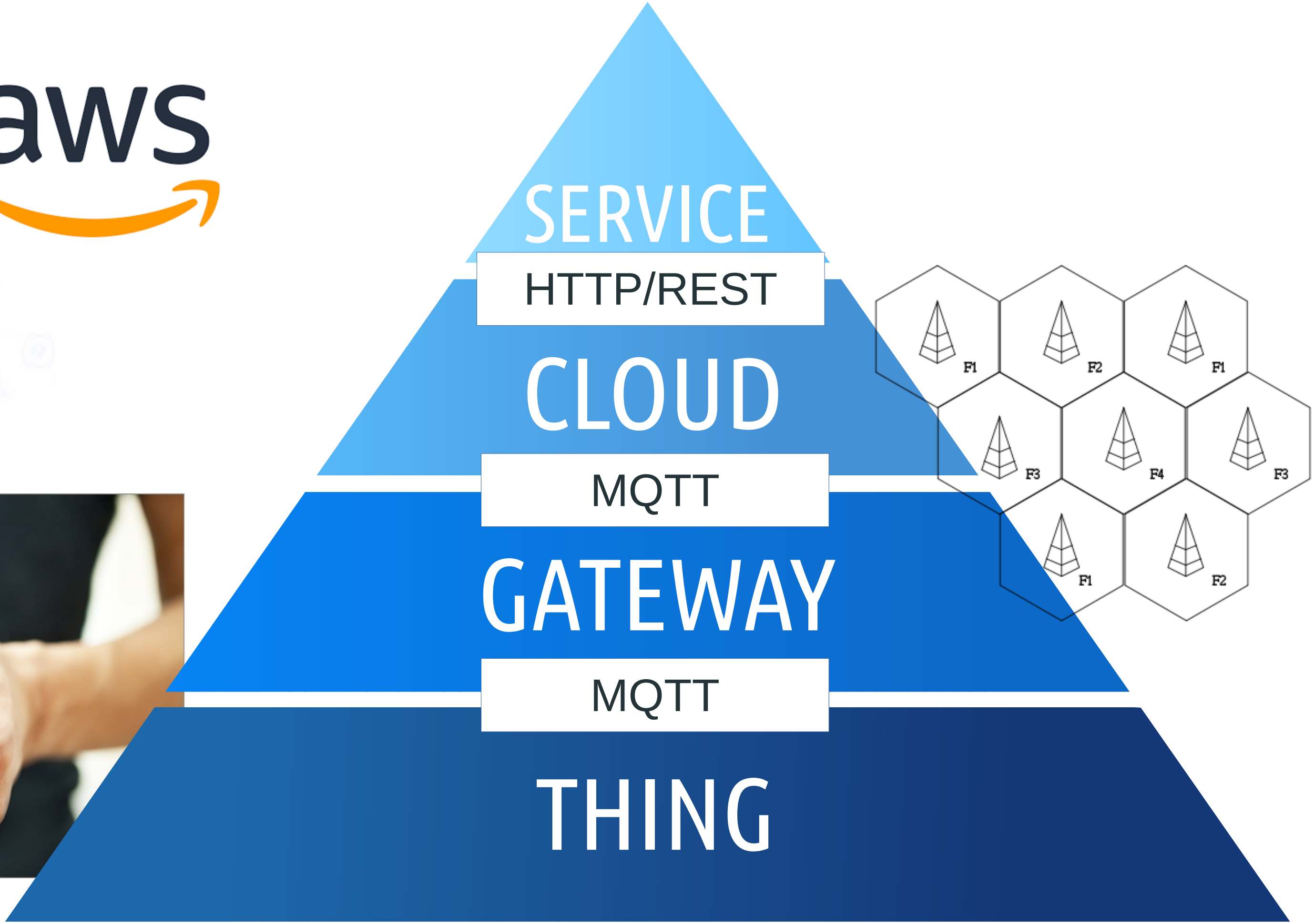
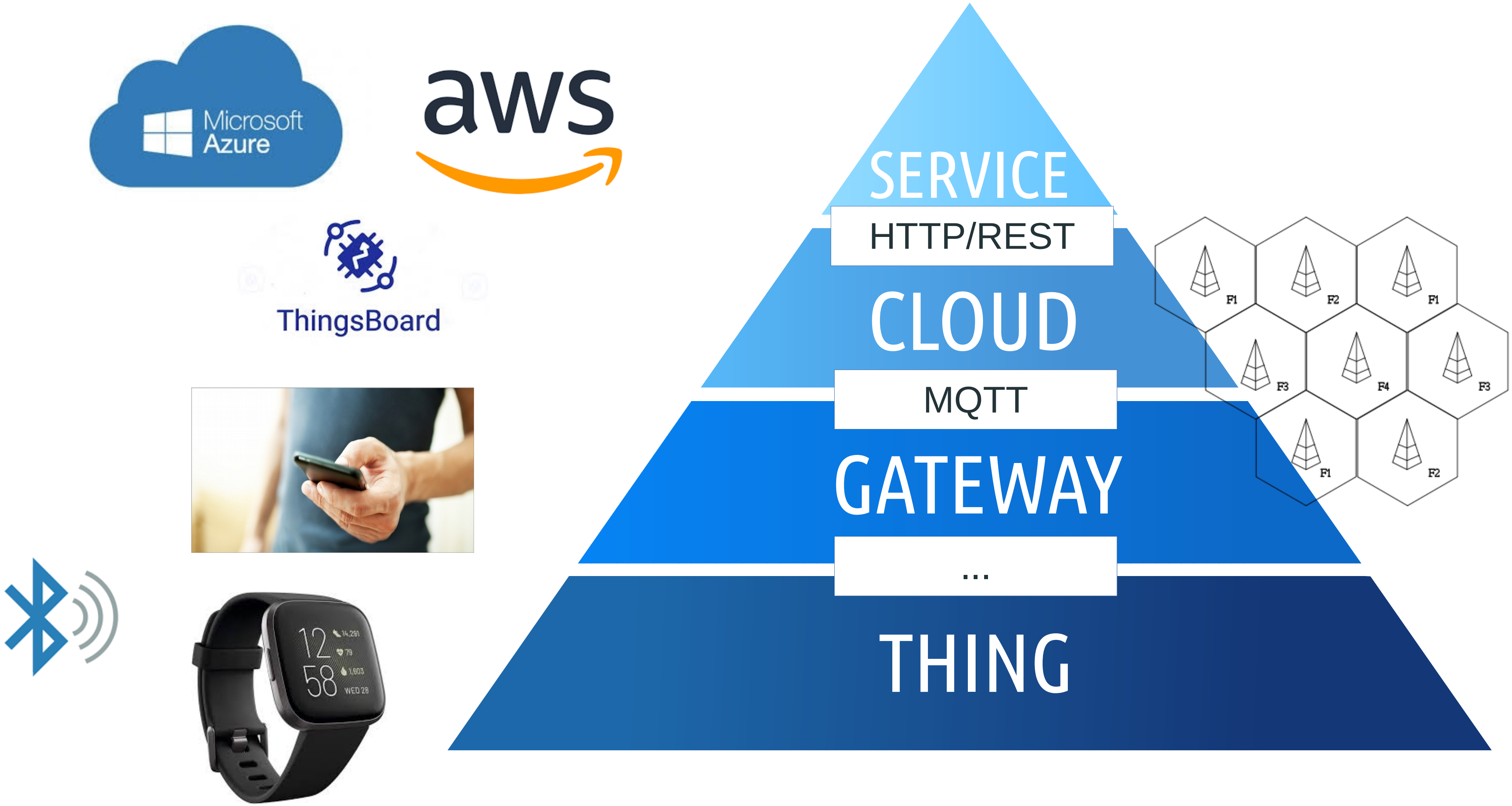
ThingsBoard

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Motivations

The larger and most cost-effective sensor network available

https://ourworldindata.org/internet

https://www.gapminder.org/tools/

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

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A Survey on Mobile Crowd-Sensing and Its Applications in the IoT Era

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ABSTRACT Mobile crowd-sensing (MCS) is a new sensing paradigm that takes advantage of the extensive use of mobile phones that collect data efficiently and enable several significant applications. MCS paves the way to explore new monitoring applications in different fields such as social networks, lifestyle, healthcare, green applications, and intelligent transportation systems. Hence, MCS applications make use of sensing and wireless communication capabilities provided by billions of smart mobile devices, e.g., Android and iOS-based mobile devices. The aim of this paper is to identify and explore the new paradigm of MCS that is using smartphone for capturing and sharing the sensed data between many nodes. We discuss the main components of the infrastructure required to support the proposed framework. The existing and potential applications leveraging MCS are laid out. Furthermore, this paper discusses the current challenges facing the collection methodologies of the participants' data in task management. The recent issues in the MCS findings are reviewed as well as the opportunities and challenges in sensing methods are analyzed. Finally, open research issues and future challenges facing MCS are highlighted.

INDEX TERMS Mobile crowd-sensing, smartphone, data sensor management, Internet of Things, location privacy.

I. INTRODUCTION

Smart phones are ubiquitous mobile devices expected to proliferate rapidly, and their penetration is estimated to be in the order of billions worldwide. Delivery applications such as mobile application stores (Apple AppStore, Google Play Store, etc.) and social media have transformed mobile phones into intelligent computing devices using the instant download of applications [1]. Smartphone vendors are continuously increasing the number of built-in sensors, a fact that makes them an excellent contextual information provider. Thus, smartphones can be used for large scale sensing of the physical world at low cost by leveraging the available sensors on the phones. With the proliferation of smartphones, several sensing approaches have emerged such as mobile phone sensing [2]. To enhance the user experience, many of the applications that come installed or can be downloaded from the online application delivery platforms take advantage of sensors available on the phone. The fixed sensors on the smartphone offer the chance to develop innovative applications in many sectors such as environmental monitoring, healthcare, and transportation [3]. In such applications, smartphones play the role of base sensor nodes and gateways depending on the availability of the mobile phones within a region of interest. Similarly, sensors deployed in today's smartphones are witnessing a continuous improvement of their hardware and software capabilities Smartphones can

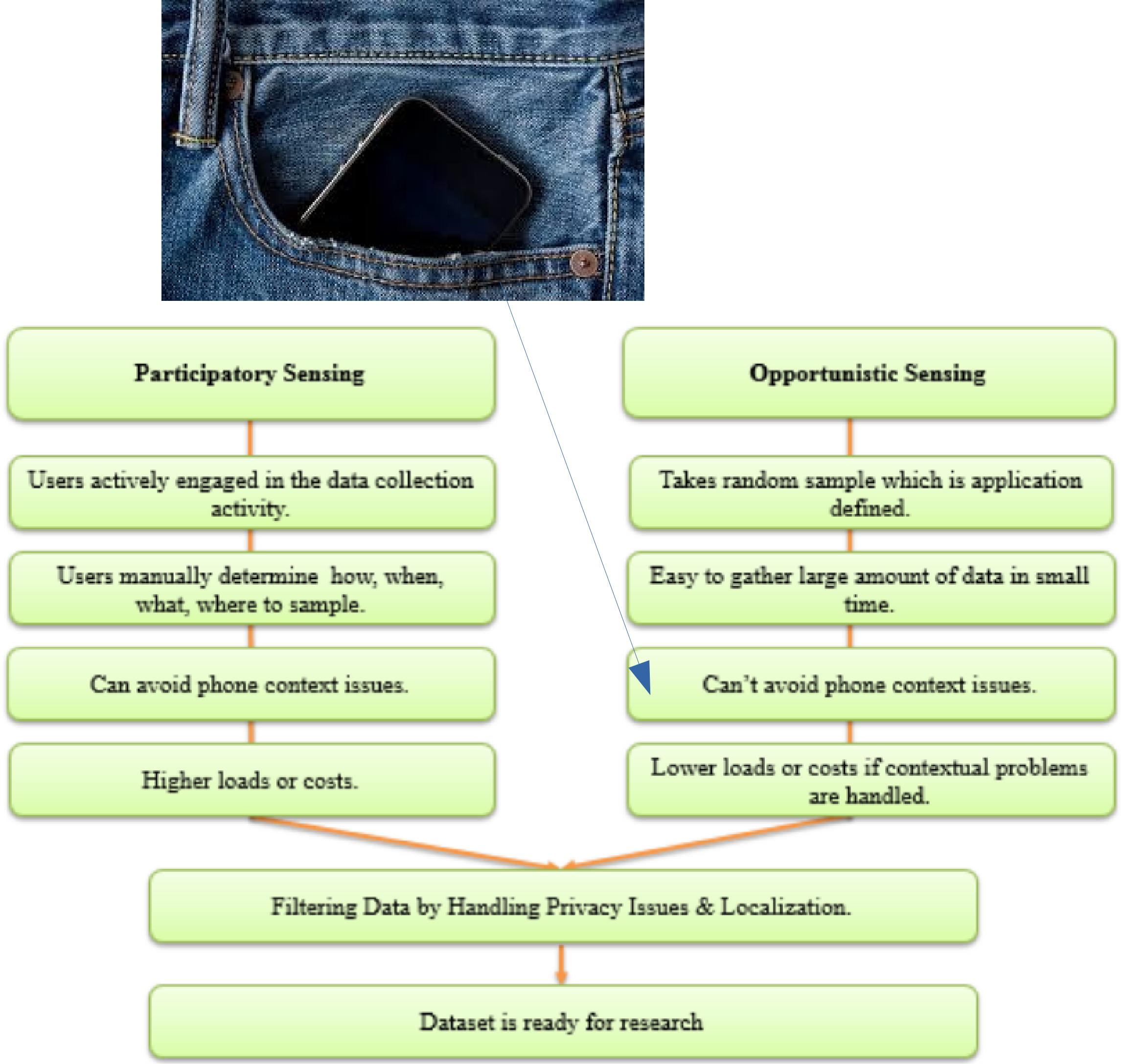

FIGURE 2. MCS paradigm for participatory and opportunistic sensing [15].

A Survey on Mobile Crowdsensing Systems: Challenges, Solutions, and Opportunities

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***Abstract*—Mobile crowdsensing (MCS) has gained significant attention in recent years and has become an appealing paradigm for urban sensing. For data collection, MCS systems rely on contribution from mobile devices of a large number of participants or a crowd. Smartphones, tablets, and wearable devices are deployed widely and already equipped with a rich set of sensors, making them an excellent source of information. Mobility and intelligence of humans guarantee higher coverage and better context awareness if compared to traditional sensor networks. At the same time, individuals may be reluctant to share data for privacy concerns. For this reason, MCS frameworks are specifically designed to include incentive mechanisms and address privacy concerns. Despite the growing interest in the research community, MCS solutions need a deeper investigation and categorization on many aspects that span from sensing and communication to system management and data storage. In this paper, we take the research on MCS a step further by presenting a survey on existing works in the domain and propose a detailed taxonomy to shed light on the current landscape and classify applications, methodologies, and architectures. Our objective is not only to analyze and consolidate past research but also to outline potential future research directions and synergies with other research areas.**

***Index Terms*—Mobile crowdsensing, urban sensing, opportunistic sensing, participatory sensing.**

I. Introduction

MOBILE crowdsensing (MCS) has gained popularity in recent years becoming an appealing paradigm for sensing and collecting data. MCS systems rely on sensors and communication interfaces embedded in commonly used mobile devices such as smartphones and wearables. Nowadays, mobile devices are essential for our daily activities, including business, communication, and entertainment [1], [2]. According to Gartner statistics, the number of worldwide smartphones sales in 2018 was 1.55 billion units [3], and the number of wearable devices shipped in 2018 was 178.91 million, which is projected to reach 453.19 million in 2022 [4]. Smart watches, glasses, rings, gloves, and helmets are the most popular wearable devices currently available on the market corresponding to a highly increasing revenue that is estimated to rise up to USD 95.3 billion by 2021 [5]. Furthermore, the crowd analytics market is predicted to reach USD 1 142.5 million by 2021 raising from USD 385.1 million of 2016 at a compound annual growth rate of 24.3% [6].

The term *mobile crowdsensing* was first introduced by Ganti *et al.* to indicate a more general paradigm [7] than mobile phone sensing [8], [9]. Guo *et al.* [10] give a definition that clearly highlights this difference: *"MCS is a new sensing paradigm that empowers ordinary citizens to contribute data sensed or generated from their mobile devices, aggregates and fuses the data in the cloud for crowd intelligence extraction and people-centric service delivery"*. To operate efficiently, MCS systems require the participation and contribution of a large number of users. Although entire communities can potentially benefit from such a contribution, a singular person may be reluctant to participate, being selfish or having privacy concerns. To ease this burden, in the last years the research community has put lots of effort in developing proper incentive mechanisms [11]–[14] and in investigating privacy issues [15], [16].

The capillary spread of smartphones and wearables along with the rich set of built-in sensors are certainly the main key enablers leading to the success of MCS paradigm. Accelerometer, gyroscope, GPS, microphone, and camera are only a representative set of sensors that facilitated the development of several applications in a wide range of scenarios, including health care, environmental, and traffic monitoring. Many applications using smartphone sensors have been already developed and are currently in use. To illustrate representative examples, HealthAware [17], MPCS [18], and DietSense [19] foster healthy eating by collecting images of consumed food and inspect daily user-activity by extracting context information such as time and location where food was consumed. For this purpose, both applications use the accelerometer, GPS, and microphone. Nericell [20]

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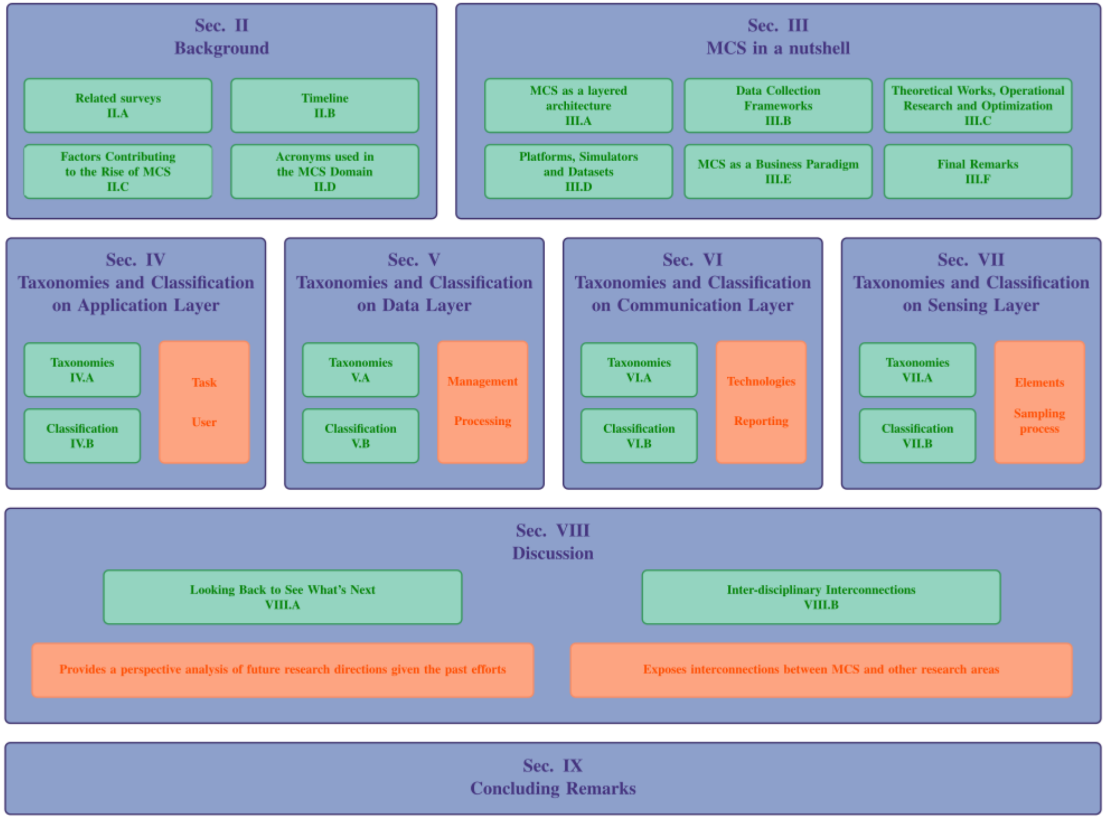
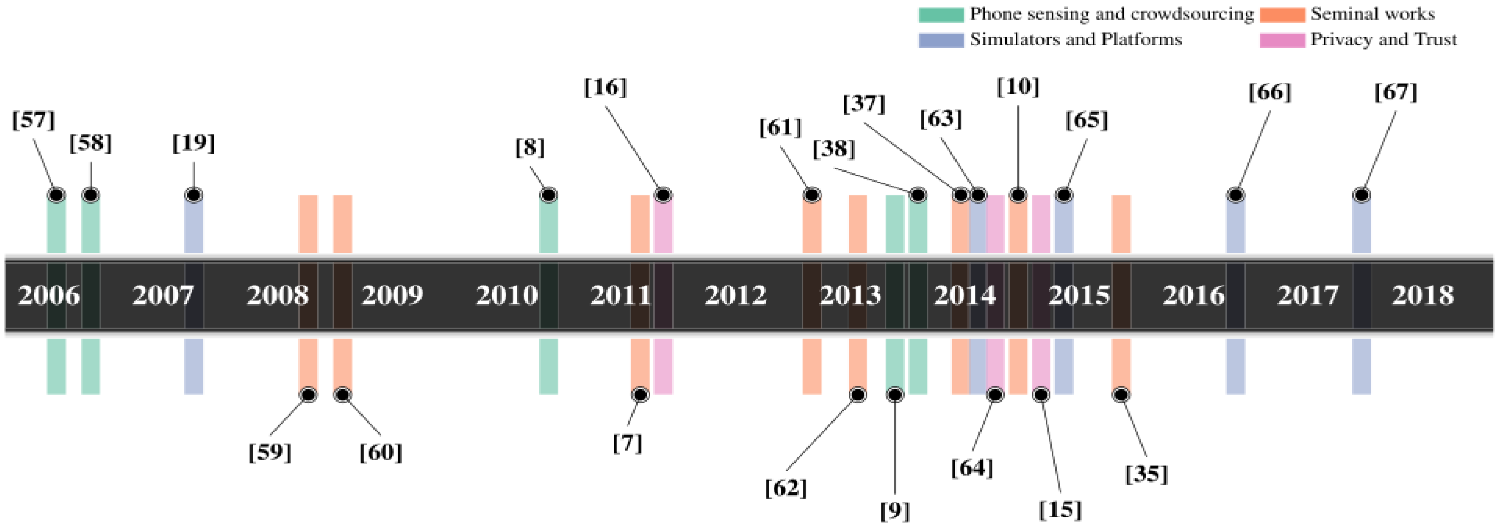


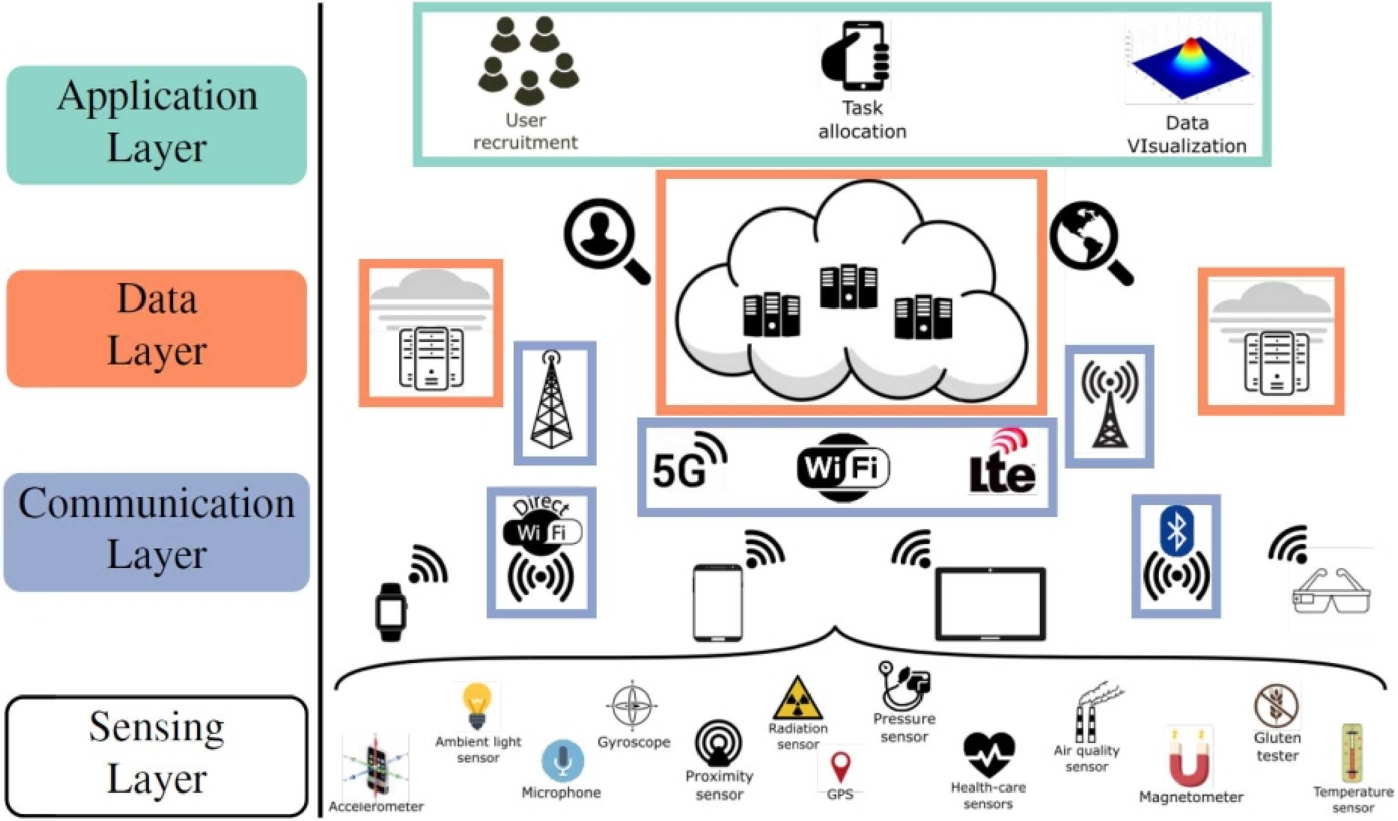
Fig. 2. Survey organization. Section II provides a background on MCS literature. Section III presents the four-layered architecture, and discusses theoretical and practical works. Sections IV–VII propose taxonomies and classification on the four layers, i.e., application, data, communication, and sensing layers. Section VIII discusses future directions and interconnections with other research areas. Finally, Section IX concludes the survey.

TABLE I
RELATED SURVEYS

TOPIC	DESCRIPTION	REFERENCES
Mobile Crowdsensing	Include works that survey crowdsensing architectures, frameworks and data collection techniques	[35], [40], [41] [42]–[44]
Sensors & Sensor Networks	Describe generic sensing equipment when employed by crowdsensing applications, sensor networks, and platforms in different domains.	[45]–[49]
Mobile Phone Sensing	Describe methodologies of employment of sensing equipment embedded in mobile devices for non-crowdsensed applications.	[8], [9]
Anticipatory Mobile Computing & Networking	Describe techniques like machine learning to predict the context of sensing and network state.	[50], [51]
User Recruitment	Survey techniques to recruit users for sensing campaigns and describe existing incentive mechanisms to promote participation.	[12], [13], [52], [53]
Privacy	Present the threats to users and privacy mechanisms that are exploited in existing crowdsensing applications to address these issues.	[15], [16]



Layered architecture of MCS systems



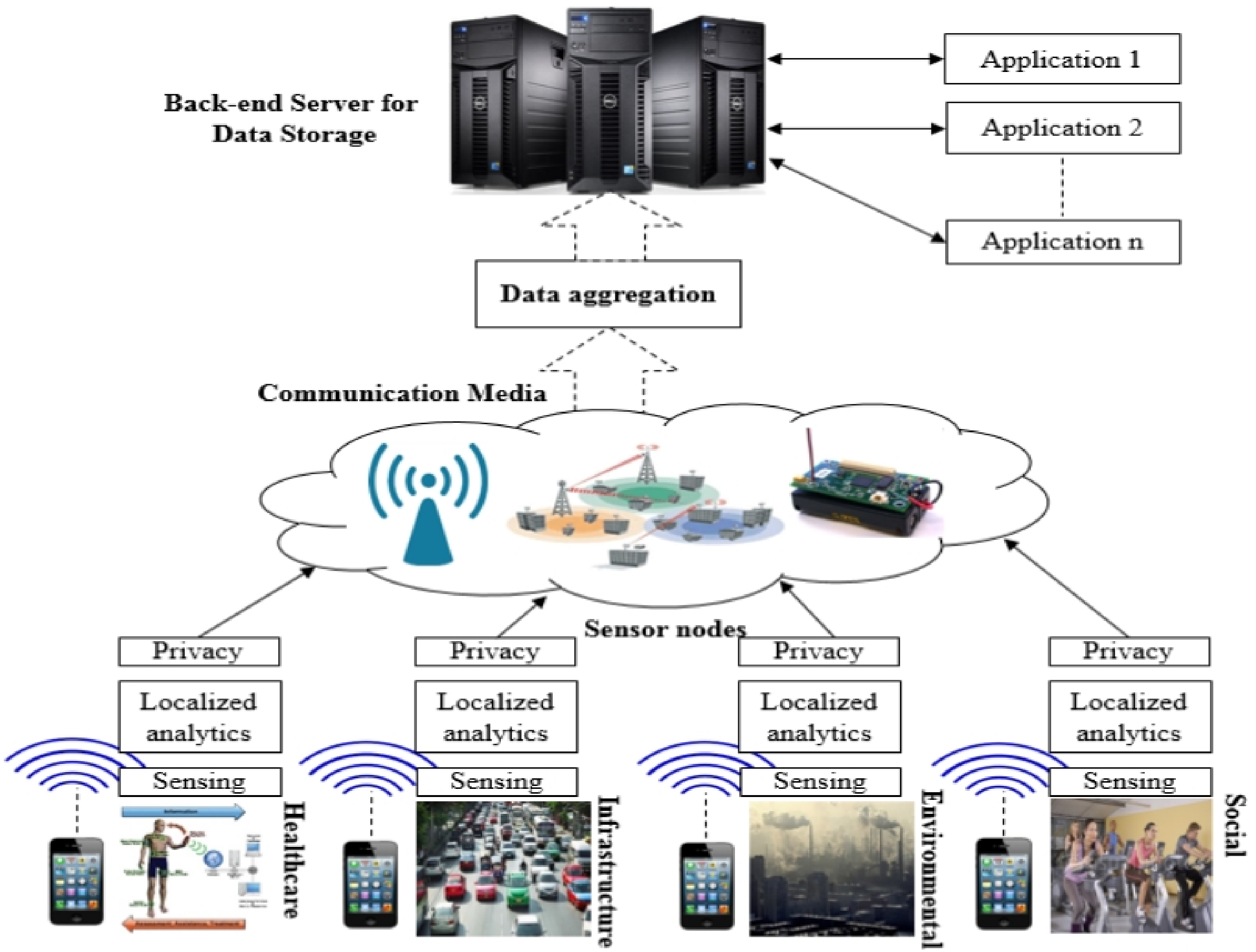


FIGURE 4. **Infrastructure required to support the MCS framework.**

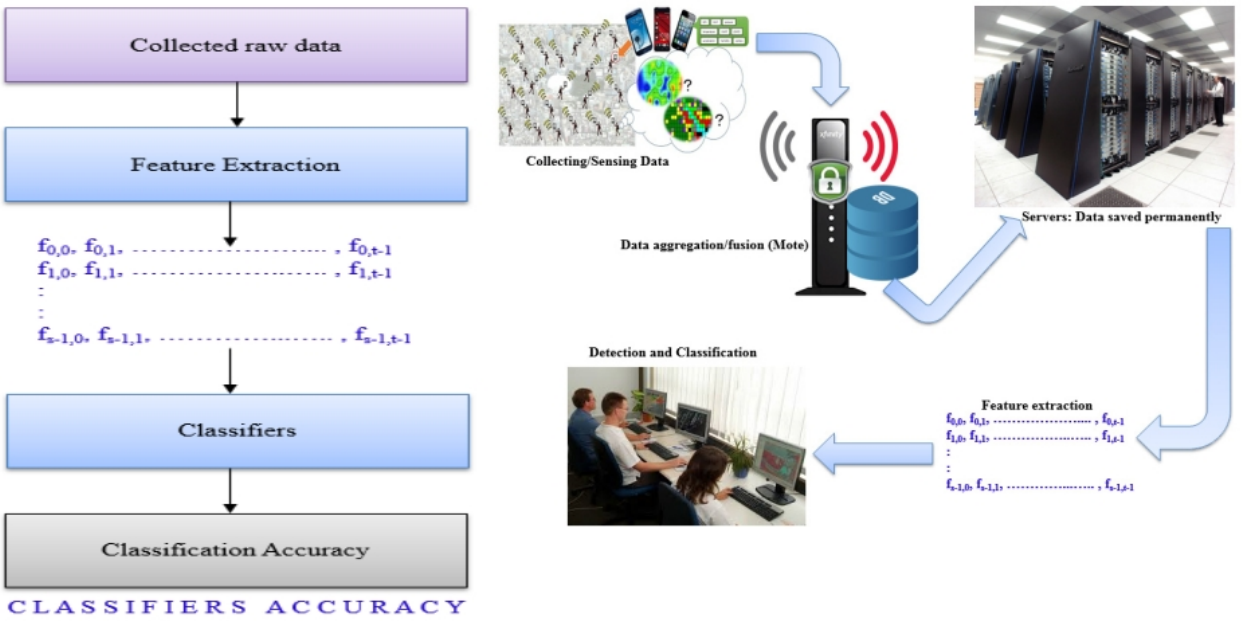


FIGURE 5. Feature extraction and classification.

TABLE 5. Crowd-sensing types of measured phenomena [32], [66], [69].

MCS applications	Used in	Examples
Healthcare	Measuring the healthcare vital signs	Measure heart rate, EEG, ECG
Environmental	Measuring the parameters of the natural environment	Water levels, air pollution, wildfire habitats
Infrastructure	Measuring the status of the public infrastructure	Traffic congestion, road conditions, bridge faults, structural health monitoring
Social	Measuring data about individual social life	Cinemas visited by an individual, daily exercise or sports

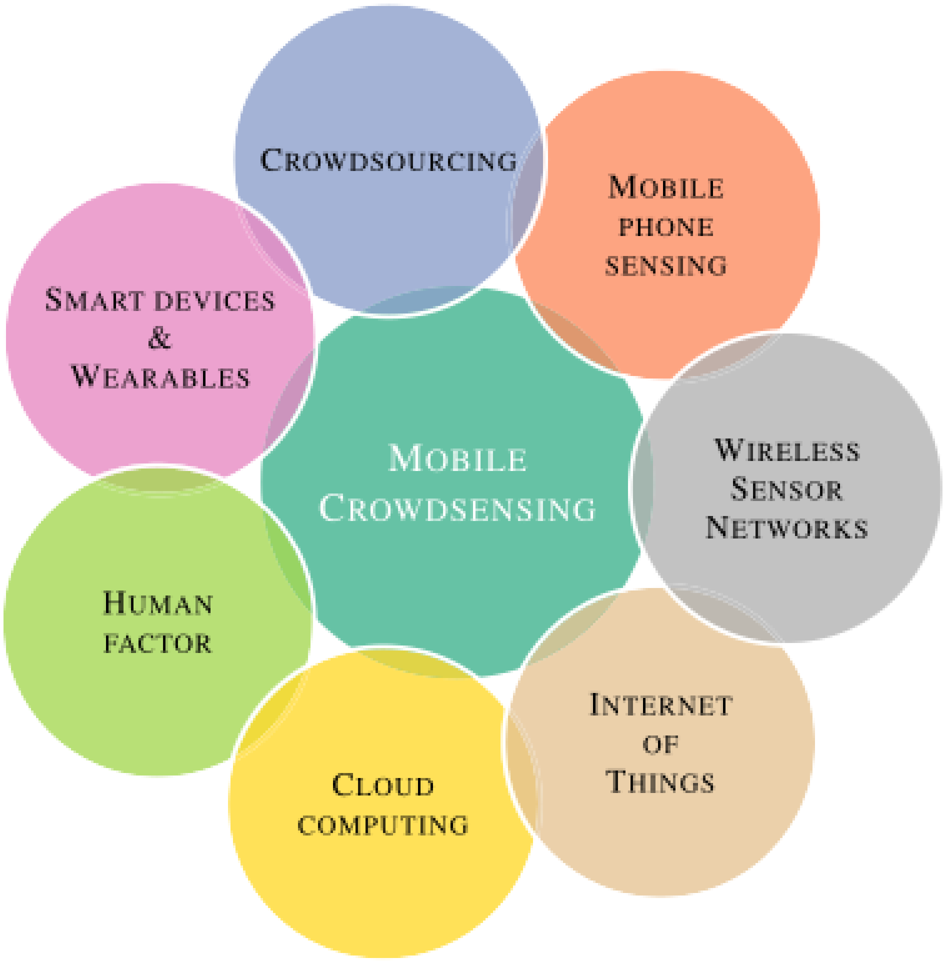


Fig. 4. Factors contributing to the rise of MCS.

TABLE 7. Summary of challenges realted to MCS and their diffrences/similarities with IoT challenges.

Challenge Area	MCS versus IoT
A. USERS PARTICIPATION	Both MCS and IoT applications motivate users' participation in many applications through incentive strategies.
B. PRIVACY AND SECURITY	Although this challenge is shared between IoT and MCS, the bulk of this challenge in MCS is concerning anonymization and privacy, while the challenge of trust is shared between the two areas.
C. DATA SIZE	Data size is a challenge that is common to IoT and MCS. Mobile devices and smartphones having data traffic split over different available wireless networks presents a major challenge. With MCS, an additional challenge is the generation of unexpected data due to human participation (as opposed to sensor data in IoT).
D. DATA ACCURACY	Data accuracy is a challenge that is common to IoT and MCS. However, MCS faces additional challenges, such as the compromise of data accuracy by malicious users and less control over the type of used devices.
E. OTHER CHALLENGES	Battery consumption and several other uncategorized challenges constitute a mixture of IoT/MCS challenges.

TABLE 2. **Comparisons between sensing groups.**

Sensing Group	Sensor Type	Communication Environment	Applications
Healthcare Sensing	Accelerometer, EEG/ECG/ EMG, Pulse Oximetry, Heart rate, Blood pressure, Blood Glucose, and Temperature Probe	ZigBee, Bluetooth, cable, WiFi, WiMAX	Body move, Skin/Scalp, Electrodes Oxygen Saturation, Pulse oximeter, Arm cuff based monitor, Strip-based glucose meters, Body and/or skin temperature
Industry/public Sensing	Accelerometer, flex, power, Vibration, hall, ultrasound, sound, bend, strain, stress	ZigBee, Bluetooth, cable, WiFi, WiMAX	Solar Panel and Inverter, Gas Pressure, Proximity detection, Water Level Sensing, Heating oil tanks.
Environmental Sensing	Air pollution, Water quality,	ZigBee, Bluetooth, cable, WiFi, WiMAX	Physical sensors, Chemical sensors, and Biological sensors
Military Sensing	Security detection	ZigBee, Bluetooth, cable, WiFi, WiMAX	Electromagnetic, pressure, light, energy/signals, explosions, sound,
Mobile Sensing	Touch screens, accelerometers, gyroscopes, GPS, cameras, etc.	WiFi, 3G, NFC, Bluetooth	Traffic monitoring, leisure activities and air pollution control, rich and growing set of social networking applications

TABLE 3. **Impact of Zigbee, Bluetooth, Wi-Fi, and GSM/GPRS on MCS.**

References	ZigBee	Bluetooth	Wi-Fi	Cellular	Comments
[70, 71, 72]	✓				Not used in MCS due to the lack of ZigBee integration into mobile devices.
[75, 76, 77, 78, 79]		✓			Bluetooth has a very short range that requires higher participants' density for same sensing accuracy requirements.
[78, 81, 86]			✓		Wi-Fi is the most common technology available on mobile devices; however, the infrastructure mode is more technologically developed compared to the Ad Hoc mode. Whereas Ad Hoc mode is typically more suitable for MCS especially in areas not covered by Wi-Fi access points.
[82, 85, 86]				✓	Even though cellular is costly, it is the most widely used technology.

TABLE III
DOMAIN-SPECIFIC DATA COLLECTION FRAMEWORKS (DCFS)

DOMAIN OF INTEREST	DESCRIPTION	REFERENCES
Emergency prevention and management	Prevention of emergencies (e.g., monitoring the amount of water in the river bed) and post-disaster management (earthquakes or flooding)	[24], [115]–[118]
Environmental monitoring	Monitoring of resources and environmental conditions, such as air and noise pollution, radiation	[21], [22], [56], [113], [119]–[127]
E-commerce	Collection, sharing and live-comparison of prices of goods from real stores or specific places, such as gas stations	[128]–[131]
Health care & wellbeing	Sharing of users' physical or mental conditions for remote feedback or exchange of information about wellbeing like diets and fitness	[17], [19], [114], [132]–[134]
Indoor localization	Enabling indoor localization and navigation by means of MCS systems in GPS-denied environments	[135]–[137]
Intelligent transportation systems	Monitoring of citizen mobility, public transport and services in cities, e.g., traffic and road condition, available parking spots, bus arrival time	[20], [138]–[143]
Mobile social networks	Establishment of social relations, meeting, sharing experiences and data (photo and video) of users with similar interests	[62], [144]–[153]
Public safety	Citizens can check, share and evaluate the level of crimes for each areas in urban environments	[154], [155]
Unmanned vehicles	Interaction between mobile users and driver-less vehicles (e.g., aerial vehicles or cars), which require high-precision sensors	[156]–[158]
Urban planning	Improving experience-based decisions on urbanization issues, such as street networks design and infrastructure maintenance	[30], [159], [160]
Waste management	Citizens help to monitor and support waste-recycling operations, e.g., checking the amount of trash or informing on dynamic waste collection routing	[25], [26]
WiFi characterization	Mapping of WiFi coverage with different MCS techniques, such as exploiting passive interference power, measuring spectrum and received power intensity	[161]–[163]
Others	Specific domain of interest not included in the previous list, such as recommending travel packages, detecting activity from sound patterns	[145], [146], [164]–[167]

TABLE IV
GENERAL-PURPOSE DATA COLLECTION FRAMEWORKS (DCFs)

TARGET	DESCRIPTION	REFERENCES
Context awareness	Combination of data mining and activity recognition techniques for context detection	[170], [171]
Energy efficiency	Strategies to lower the battery drain of mobile devices during data sensing and reporting	[172]–[176]
Resource allocation	Strategies for efficient resource allocation during data contribution, such as channel condition, power spectrum, computational capabilities	[177]–[179]
Scalability	Solutions to develop DCFs with good scalability properties during run-time data acquisition and processing	[180], [181]
Sensing task coverage	Definition of requirements for task accomplishment, such as spatial and temporal coverage	[182]–[185]
Trustworthiness and privacy	Strategies to address issues related to preserve privacy of the contributing users and integrity of reported data	[186]–[191]

Privacy protection in mobile crowd sensing: a survey

Yongfeng Wang [1,2] · Zheng Yan [1,3] · Wei Feng [1] · Shushu Liu [3]

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Abstract

The unprecedented proliferation of mobile smart devices has propelled a promising computing paradigm, Mobile Crowd Sensing (MCS), where people share surrounding insight or personal data with others. As a fast, easy, and cost-effective way to address large-scale societal problems, MCS is widely applied into many fields, e.g., environment monitoring, map construction, public safety, etc. Despite the popularity, the risk of sensitive information disclosure in MCS poses a serious threat to the participants and limits its further development in privacy-sensitive fields. Thus, the research on privacy protection in MCS becomes important and urgent. This paper targets the privacy issues of MCS and conducts a comprehensive literature research on it by providing a thorough survey. We first introduce a typical system structure of MCS, summarize its characteristics, propose essential requirements on privacy on the basis of a threat model. Then, we survey existing solutions on privacy protection and evaluate their performances by employing the proposed requirements. In essence, we classify the privacy protection schemes into four categories with regard to identity privacy, data privacy, attribute privacy, and task privacy. Besides, we review the achievements on privacy-preserving incentives in MCS from four viewpoints of incentive measures: credit incentive, auction incentive, currency incentive, and reputation incentive. Finally, we point out some open issues and propose future research directions based on the findings from our survey.

Keywords Mobile crowd sensing · identity privacy · attribute privacy · data privacy · task privacy · incentive mechanism

This article belongs to the Topical Collection: *Special Issue: Trust, Privacy, and Security in Crowdsourcing Computing*
Guest Editors: An Liu, Guanfeng Liu, Mehmet A. Orgun, and Qing Li

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TABLE V
THEORETICAL WORKS ON OPERATIONAL RESEARCH AND OPTIMIZATION PROBLEMS

TARGET	OBJECTIVE	REFERENCES
Trade-off data vs. energy	Maximization of the amount and quality of gathered data while minimizing the energy consumption of devices	[36], [193]–[197]
Sensing coverage	Focus on how to efficiently address the requirements on task sensing coverage in space and temporal domains	[196]–[203]
Task allocation	Efficient task allocation among participants leveraging diverse techniques and approaches	[204]–[214]
User recruitment	Efficient user recruitment to meet the requirements of a sensing campaign while minimizing the cost	[215]–[224]
Context awareness	It consists in exploiting context-aware sensing to improve system performance in terms of delay, bandwidth, and energy efficiency	[225]–[232]
Budget-constrained	Maximization of task accomplishment under budget constraints or minimization of budget to fully accomplish a task	[111], [233]–[237]

TABLE VI
PLATFORMS, SIMULATORS AND DATASETS

	WORKS	DESCRIPTION	REFERENCE
PLATFORMS	ParticipAct Living Lab	It is a large-scale crowdsensing platform that allows the development and deployment of experiments, considering both mobile device and server side	[239]
	APISENSE	It enables researchers to deploy crowdsensing applications by providing resources to store and process data acquired from a crowd	[240]
	SenseMyCity	It acquires geo-tagged data acquired from different mobile devices' sensors of users willing to participate in experiments	[241]
	CRATER	It provides APIs to access data and visualize maps in the related application to estimate road conditions	[242]
	Medusa	It provides high level abstractions for analyzing the required steps to accomplish a task by users	[243]
	PRISM	Platform for Remote Sensing using Smartphones that balances generality, security and scalability	[244]
	MOSDEN	It is used to capture and share sensed data among distributed applications and several users	[38]
	MATADOR	It aims to efficiently deliver tasks to users according to a context-aware sampling algorithm that minimizes energy consumption of mobile devices	[245]
SIMULATORS	CrowdSenSim	It simulates MCS activities in large-scale urban environments, implementing DCFs and realistic user mobility	[67]
	NS-3	Used in a MCS environment considering mobility properties of the nodes and the wireless interface in ad-hoc network mode	[65]
	CupCarbon	Discrete-event WSN simulator for IoT and smart cities, which can be used for MCS purposes taking into account users as mobile nodes and base stations	[246]
	Urban parking	It presents a simulation environment to investigate performance of MCS applications in an urban parking scenario	[247]
DATASETS	ParticipAct	It involves in MCS campaigns 173 students in the Emilia Romagna region (Italy) on a period of 15 months using Android smartphones	[63]
	Cambridge	It presents the mobility of 36 students in the Cambridge University Campus for 12 days	[248]
	MIT	It provides the mobility of 94 students in the MIT Campus (Boston, MA) for 246 days	[249]
	MDC Nokia	It includes data collected from 185 citizens using a N95 Nokia mobile phone in the Lake Geneva region in Switzerland	[250]
	CARMA	It consists of 38 mobile users in a university campus over several weeks using a customized crowdsourcing Android mobile application	[251]

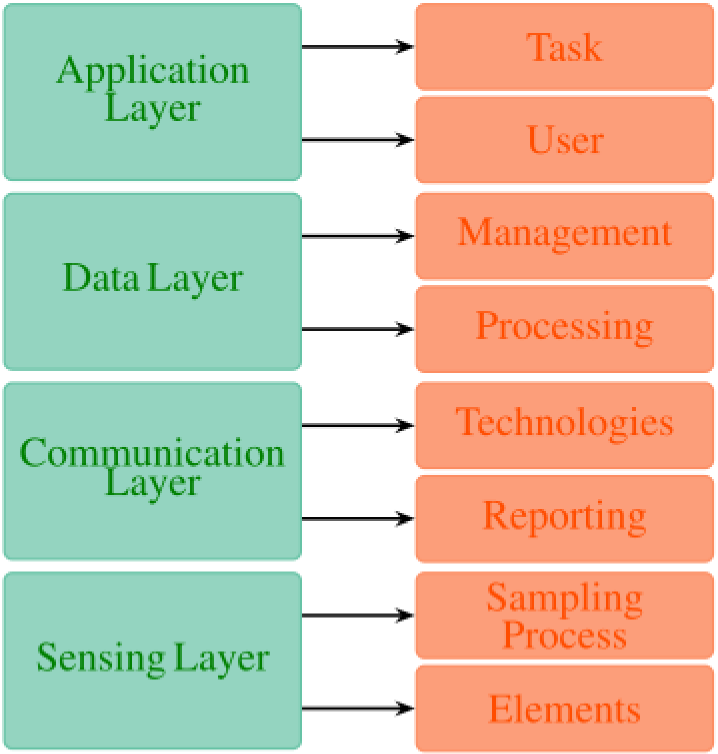

Fig. 9. Taxonomies on MCS four-layered architecture. It includes sensing, communication, data, and application layers. Sensing layer is divided between sampling and elements, which will be described in Section VII. Communication layer is divided between technologies and reporting, which will be discussed in Section VI. Data layer is divided between management and processing, and will be presented in Section V. Application layer is divided between task and user, which will be discussed in Section IV.

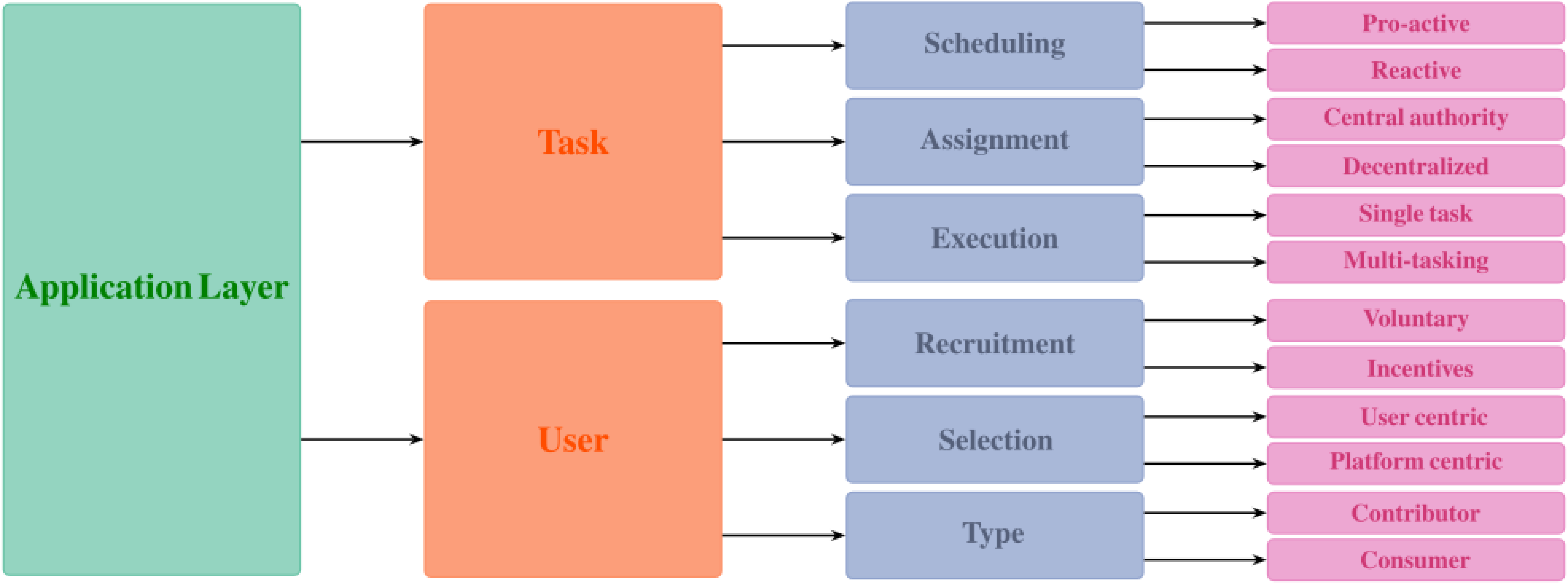

Fig. 10. Taxonomies on application layer, which is composed of task and user categories. The task-related taxonomies are composed of scheduling, assignment and execution categories, while user-related taxonomies are divided into recruitment, selection and type categories.

TABLE VII

Classification Based on Task Taxonomies of Application Layer

Project	Reference	Scheduling		Assignment		Execution	
		Pro-active	Reactive	Central Aut.	Decentralized	Single task	Multi-tasking
HealthAware	[17]	x		x			x
DietSense	[19]	x		x			x
Nericell	[20]		x	x			x
NoiseMap	[113]		x	x		x	
GasMobile	[21]		x	x		x	
NoiseTube	[121]		x	x		x	
CenceMe	[59]	x			x		x
MicroBlog	[60]	x			x		x
PEIR	[119]		x	x			x
How long to wait?	[140]	x			x		x
PetrolWatch	[129]		x		x	x	
AndWellness	[134]	x			x		x
Darwin	[153]	x			x		x
CrowdSense@Place	[145]		x	x			x
ILR	[166]	x			x		x
SoundSense	[164]		x	x		x	
Urban WiFi	[162]		x	x		x	
LiveCompare	[131]	x			x	x	
MobiClique	[148]		x		x		x
MobiShop	[130]	x			x	x	
SPA	[132]	x			x		x
EmotionSense	[147]		x	x			x
ConferenceSense	[165]		x	x			x
Travel Packages	[167]	x			x		x
Mahali	[127]		x	x		x	
Ear-Phone	[120]		x	x		x	
WreckWatch	[141]	x			x		x
VTrack	[143]		x	x			x
Social Serendipity	[149]	x			x		x
SociableSense	[150]	x			x		x
WhozThat	[151]		x		x	x	
MoVi	[152]		x	x		x	

TABLE VIII
CLASSIFICATION BASED ON USER TAXONOMIES OF APPLICATION LAYER

		Recruitment		Selection		Type	
Project	Reference	Voluntary	Incentives	Platform centric	User centric	Consumer	Contributor
HealthAware	[17]	x			x	x	x
DietSense	[19]	x			x	x	x
Nericell	[20]	x		x			x
NoiseMap	[113]		x		x		x
GasMobile	[21]		x	x			x
NoiseTube	[121]	x		x			x
CenceMe	[59]	x			x	x	x
MicroBlog	[60]	x			x	x	x
PEIR	[119]	x		x		x	x
How long to wait?	[140]	x			x	x	x
PetrolWatch	[129]	x			x	x	x
AndWellness	[134]	x			x	x	x
Darwin	[153]	x			x	x	x
CrowdSense@Place	[145]		x	x			x
ILR	[166]		x		x		x
SoundSense	[164]	x			x		x
Urban WiFi	[162]	x		x			x
LiveCompare	[131]		x	x		x	x
MobiClique	[148]	x			x	x	x
MobiShop	[130]	x		x		x	x
SPA	[132]	x			x	x	x
EmotionSense	[147]	x			x		x
ConferenceSense	[165]	x			x		x
Travel Packages	[167]		x		x	x	x
Mahali	[127]		x	x			x
Ear-Phone	[120]	x		x			x
WreckWatch	[141]	x			x		x
VTrack	[143]	x			x	x	x
Social Serendipity	[149]	x			x	x	x
SociableSense	[150]		x		x	x	x
WhozThat	[151]	x			x	x	x
MoVi	[152]		x	x		x	x

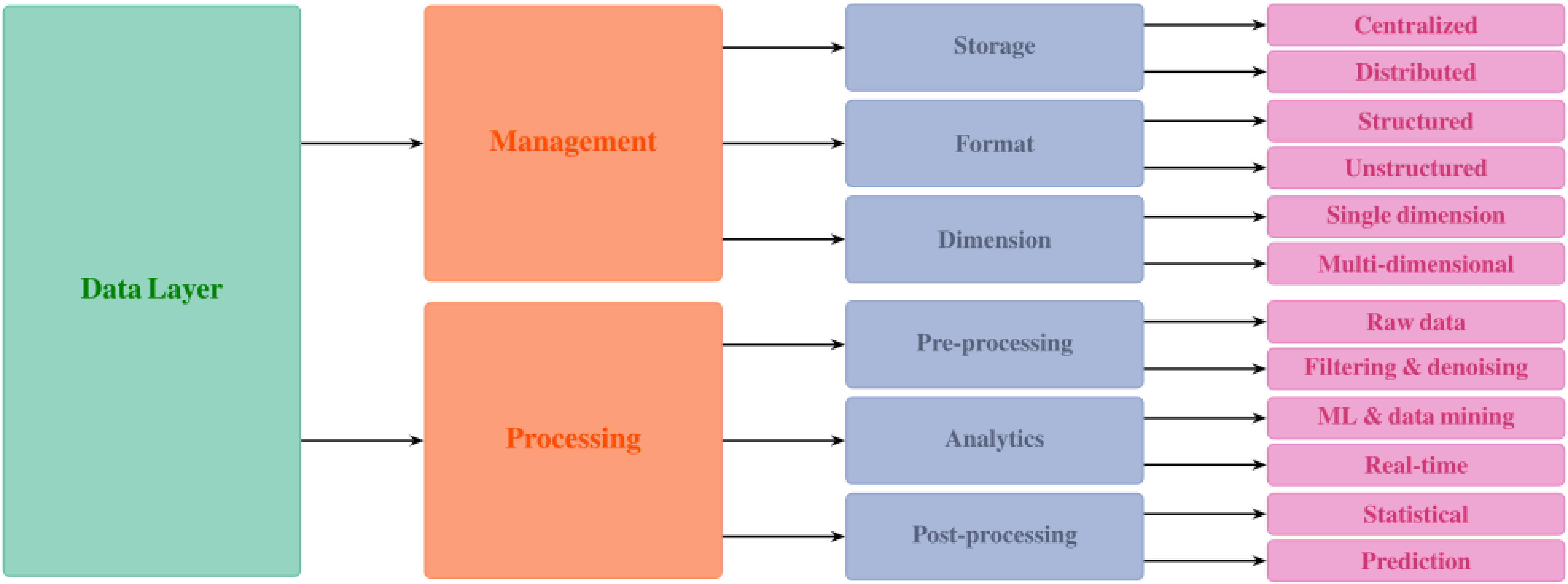

Fig. 12. Taxonomies on data layer, which includes management and processing categories. The management-related taxonomies are composed of storage, format, and dimension classes, while processing-related taxonomies are divided into pre-processing, analytics, and post-processing classes.

TABLE IX
CLASSIFICATION BASED ON MANAGEMENT TAXONOMIES OF DATA LAYER

		STORAGE		FORMAT		DIMENSION	
PROJECT	REFERENCE	Centralized	Distributed	Structured	Unstructured	Single dimension	Multi-dimensional
HealthAware	[17]		x		x		x
DietSense	[19]	x			x		x
Nericell	[20]	x			x		x
NoiseMap	[113]	x		x		x	
GasMobile	[21]	x		x		x	
NoiseTube	[121]	x		x		x	
CenceMe	[59]		x		x		x
MicroBlog	[60]	x			x		x
PEIR	[119]	x			x		x
How long to wait?	[140]	x			x		x
PetrolWatch	[129]	x		x		x	
AndWellness	[134]	x			x		x
Darwin	[153]		x		x		x
CrowdSense@Place	[145]	x			x		x
ILR	[166]		x		x		x
SoundSense	[164]		x	x		x	
Urban WiFi	[162]		x	x		x	
LiveCompare	[131]	x		x		x	
MobiClique	[148]		x		x		x
MobiShop	[130]	x		x		x	
SPA	[132]		x		x		x
EmotionSense	[147]		x		x		x
ConferenceSense	[165]		x		x		x
Travel Packages	[167]		x		x		x
Mahali	[127]	x		x			x
Ear-Phone	[120]	x			x	x	
WreckWatch	[141]		x	x			x
VTrack	[143]	x		x			x
Social Serendipity	[149]		x		x		x
SociableSense	[150]		x		x		x
WhozThat	[151]		x		x		x
MoVi	[152]	x			x	x	

TABLE X
CLASSIFICATION BASED ON PROCESSING TAXONOMIES OF DATA LAYER

		PRE-PROCESSING		ANALYTICS		POST-PROCESSING	
PROJECT	REFERENCE	Raw data	Filtering & denoising	ML & data mining	Real-time	Statistical	Prediction
HealthAware	[17]		x		x	x	
DietSense	[19]		x	x		x	
Nericell	[20]		x	x		x	
NoiseMap	[113]	x			x	x	
GasMobile	[21]	x		x		x	
NoiseTube	[121]	x		x		x	
CenceMe	[59]		x		x	x	
MicroBlog	[60]		x	x		x	
PEIR	[119]		x	x		x	
How long to wait?	[140]		x		x		x
PetrolWatch	[129]		x		x	x	
AndWellness	[134]		x	x		x	
Darwin	[153]		x	x		x	
CrowdSense@Place	[145]		x	x		x	
ILR	[166]		x	x		x	
SoundSense	[164]		x	x		x	
Urban WiFi	[162]	x		x		x	
LiveCompare	[131]	x			x	x	
MobiClique	[148]		x	x		x	
MobiShop	[130]	x		x		x	
SPA	[132]		x	x		x	
EmotionSense	[147]		x	x		x	
ConferenceSense	[165]		x	x		x	
Travel Packages	[167]		x	x		x	
Mahali	[127]		x	x		x	
Ear-Phone	[120]	x		x		x	
WreckWatch	[141]		x		x	x	
VTrack	[143]		x		x		x
Social Serendipity	[149]		x		x	x	
SociableSense	[150]		x	x		x	
WhozThat	[151]		x		x	x	
MoVi	[152]	x		x		x	

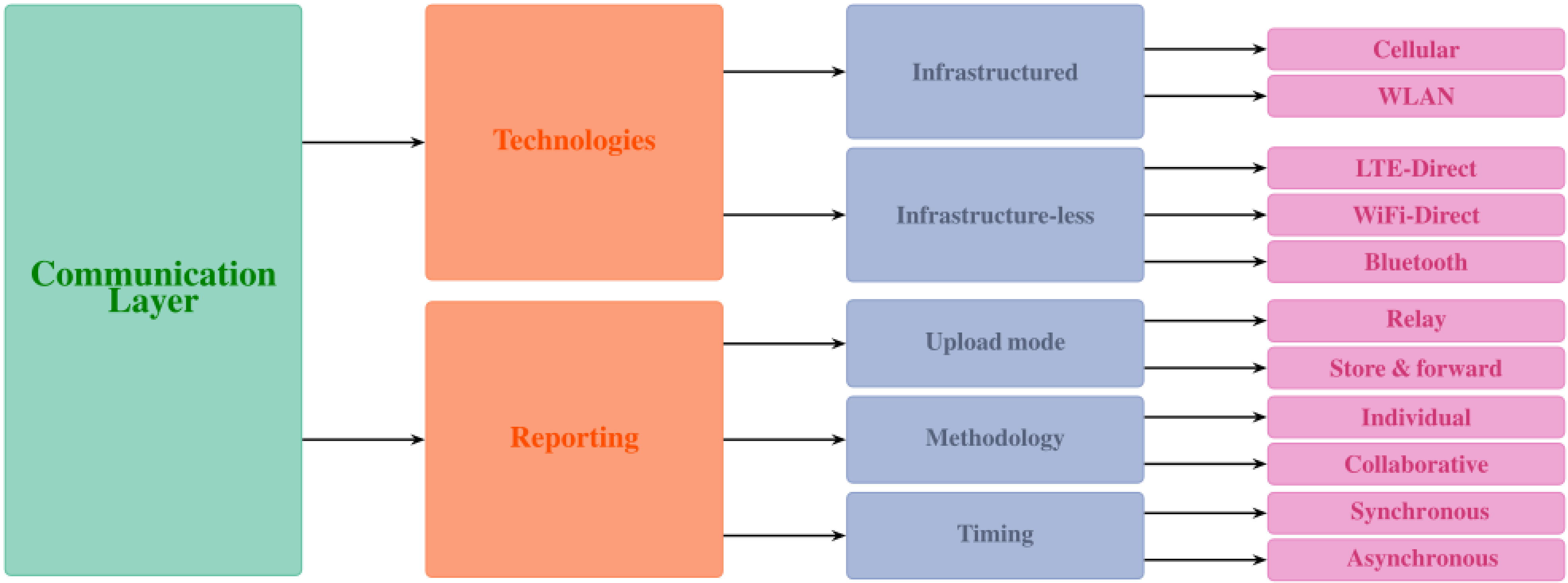

Fig. 13. Taxonomies on communication layer, which comprises technologies and reporting categories. The technologies-related taxonomies are composed of infrastructured and infrastructure-less classes, while reporting-related taxonomies are divided into upload mode, methodology, and timing classes.

TABLE XI
CLASSIFICATION BASED ON TECHNOLOGIES TAXONOMIES OF COMMUNICATION LAYER

PROJECT	REFERENCE	INFRASTRUCTURED		INFRASTRUCTURE-LESS		
		Cellular	WLAN	LTE-Direct	WiFi-Direct	Bluetooth
HealthAware	[17]		x			x
DietSense	[19]	x	x			
Nericell	[20]	x				x
NoiseMap	[113]	x	x			
GasMobile	[21]	x	x			
NoiseTube	[121]	x	x			
CenceMe	[59]	x	x			
MicroBlog	[60]	x	x			
PEIR	[119]	x	x			x
How long to wait?	[140]	x				
PetrolWatch	[129]	x				
AndWellness	[134]	x	x			
Darwin	[153]	x	x			x
CrowdSense@Place	[145]		x			
ILR	[166]	x	x			x
SoundSense	[164]	x	x			
Urban WiFi	[162]		x			
LiveCompare	[131]	x	x			
MobiClique	[148]	x	x			x
MobiShop	[130]	x	x			
SPA	[132]		x			x
EmotionSense	[147]	x	x			x
ConferenceSense	[165]		x			x
Travel Packages	[167]	x	x			
Mahali	[127]	x	x			
Ear-Phone	[120]	x	x			
WreckWatch	[141]	x				
VTrack	[143]	x	x			
Social Serendipity	[149]	x	x			x
SociableSense	[150]	x	x			x
WhozThat	[151]	x	x			x
MoVi	[152]	x	x			

[a] Note that the set of selected works was developed much before the definition of the standards LTE-Direct and WiFi-Direct, thus these columns have no corresponding marks.

TABLE XII
CLASSIFICATION BASED ON REPORTING TAXONOMIES OF COMMUNICATION LAYER

		UPLOAD MODE		METHODOLOGY		TIMING	
PROJECT	REFERENCE	Relay	Store & forward	Individual	Collaborative	Synchronous	Asynchronous
HealthAware	[17]		x	x			x
DietSense	[19]		x	x			x
Nericell	[20]	x		x		x	
NoiseMap	[113]	x		x		x	
GasMobile	[21]		x	x			x
NoiseTube	[121]		x	x			x
CenceMe	[59]		x	x			x
MicroBlog	[60]		x		x	x	
PEIR	[119]		x	x			x
How long to wait?	[140]	x			x	x	
PetrolWatch	[129]		x		x		x
AndWellness	[134]	x		x			x
Darwin	[153]		x	x		x	
CrowdSense@Place	[145]		x	x			x
ILR	[166]		x		x		x
SoundSense	[164]		x	x			x
Urban WiFi	[162]		x	x			x
LiveCompare	[131]	x			x	x	
MobiClique	[148]		x		x	x	
MobiShop	[130]	x			x	x	
SPA	[132]		x	x		x	
EmotionSense	[147]		x	x			x
ConferenceSense	[165]		x	x			x
Travel Packages	[167]		x	x		x	
Mahali	[127]		x		x	x	
Ear-Phone	[120]		x	x			x
WreckWatch	[141]	x		x		x	
VTrack	[143]	x		x			x
Social Serendipity	[149]		x		x	x	
SociableSense	[150]		x	x			x
WhozThat	[151]		x		x		x
MoVi	[152]	x			x	x	

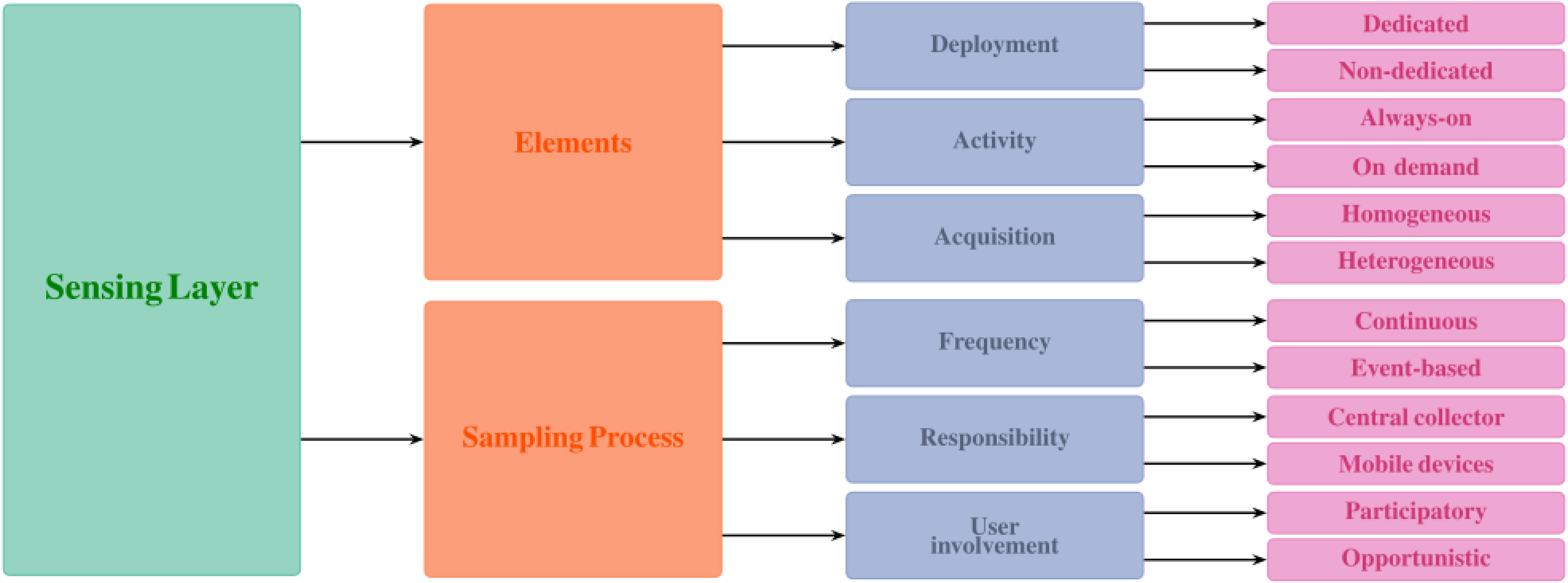

Fig. 14. Taxonomies on sensing layer, which comprises elements and sampling process categories. The elements-related taxonomies are divided into deployment, activity, and acquisition classes, while sampling-related taxonomies are composed of frequency, responsibility, and user involvement classes.

TABLE XIII
CLASSIFICATION BASED ON ELEMENTS TAXONOMIES OF SENSING LAYER

		DEPLOYMENT		ACTIVITY		ACQUISITION	
PROJECT	REFERENCE	Dedicated	Non-dedicated	Always-on	On demand	Homogeneous	Heterogeneous
HealthAware	[17]		x		x		x
DietSense	[19]		x		x		x
Nericell	[20]		x	x		x	
NoiseMap	[113]		x	x			x
GasMobile	[21]	x			x	x	
NoiseTube	[121]		x		x	x	
CenceMe	[59]		x		x		x
MicroBlog	[60]		x		x		x
PEIR	[119]		x	x			x
How long to wait?	[140]		x		x		x
PetrolWatch	[129]		x		x	x	
AndWellness	[134]		x		x		x
Darwin	[153]		x		x		x
CrowdSense@Place	[145]		x	x			x
ILR	[166]		x	x		x	
SoundSense	[164]		x		x		x
Urban WiFi	[162]		x	x		x	
LiveCompare	[131]		x		x		x
MobiClique	[148]		x		x		x
MobiShop	[130]		x		x	x	
SPA	[132]	x		x			x
EmotionSense	[147]		x	x			x
ConferenceSense	[165]		x		x	x	
Travel Packages	[167]		x		x		x
Mahali	[127]	x		x			x
Ear-Phone	[120]		x	x		x	
WreckWatch	[141]		x	x			x
VTrack	[143]		x	x			x
Social Serendipity	[149]	x		x			x
SociableSense	[150]		x		x		x
WhozThat	[151]		x		x		x
MoVi	[152]		x	x		x	

TABLE XIV
CLASSIFICATION BASED ON SAMPLING TAXONOMIES OF SENSING LAYER

PROJECT	REFERENCE	FREQUENCY		RESPONSIBILITY		USER INVOLVEMENT	
		Continuous	Event-based	Mobile Dev.	Central Coll.	Participatory	Opportunistic
HealthAware	[17]		x	x		x	
DietSense	[19]		x	x		x	
Nericell	[20]	x		x			x
NoiseMap	[113]	x		x		x	
GasMobile	[21]	x		x		x	
NoiseTube	[121]	x		x		x	
CenceMe	[59]		x	x		x	
MicroBlog	[60]		x	x		x	
PEIR	[119]	x			x	x	
How long to wait?	[140]		x	x			x
PetrolWatch	[129]		x	x			x
AndWellness	[134]		x	x		x	
Darwin	[153]		x	x		x	
CrowdSense@Place	[145]	x			x		x
ILR	[166]	x			x	x	
SoundSense	[164]	x		x		x	
Urban WiFi	[162]	x			x		x
LiveCompare	[131]		x	x		x	
MobiClique	[148]		x	x		x	
MobiShop	[130]		x	x		x	
SPA	[132]	x			x		x
EmotionSense	[147]	x			x		x
ConferenceSense	[165]		x	x		x	
Travel Packages	[167]		x	x		x	
Mahali	[127]	x			x		x
Ear-Phone	[120]	x		x			x
WreckWatch	[141]		x	x		x	
VTrack	[143]	x			x		x
Social Serendipity	[149]	x		x		x	
SociableSense	[150]	x			x	x	
WhozThat	[151]	x		x		x	
MoVi	[152]		x		x	x	

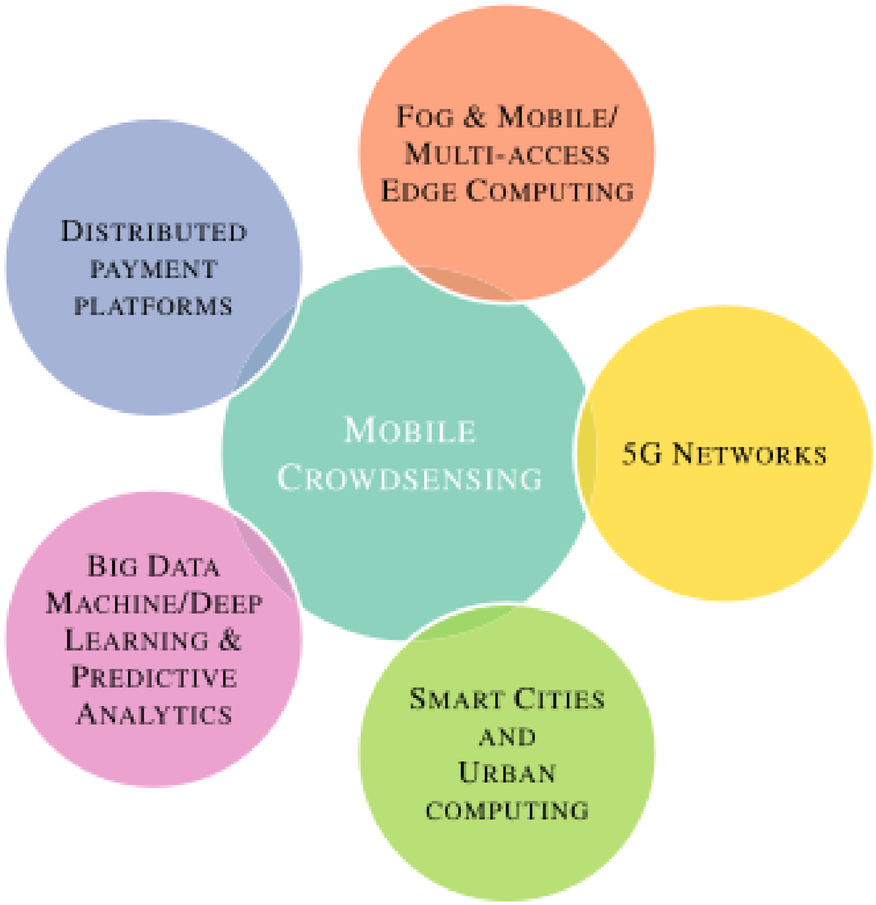

Fig. 15. Connections with other research areas.