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Crowdsensing Solutions in Smart Cities towards a Networked Society

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Abstract

The goal of the paper is to give an overview of the most relevant aspects of mobile crowdsensing that are already utilized by the society. The paper focuses on best practices applied in smart cities today, how these applications can be motivated (incentives), and how they rely on technology enablers of today's vertical silos and future's horizontal approaches. We introduce a path for transforming the vertical silos of today containing separated solutions in various domains into a horizontal, unified ecosystem, giving a way to novel technology and business opportunities.

Keywords: crowdsourcing, mobile crowdsensing, smart city, networked society

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1. Introduction

At the early stage of the evolution, mankind discovered that cooperation can help people solving more complex tasks than one can do alone. They hunted, constructed buildings, carried goods together with success. Co-working remained significant, nowadays more complex tasks are solved based on this principle. IT-related tasks with enormous computational power needs are often outsourced to many users with different hardware and computational power. The performance of collaborators in solving a complex problem often exceeds the power of today's supercomputers.
Crowdsourcing is a form of cooperation of a big group of users (so called crowd) where single users are solving small subtasks of a greater job, so complex problems can be handled more efficiently with many co-working users involved (e.g. Seti@home [1]). Cooperation is also useful when the user can add something beside the computational power. With modern mobile phones equipped with various sensors (accelerometer, GPS, gyroscope, etc.) the cooperation between the members of the crowd is possible in large sensing tasks, as well. Mobile phones can not only provide access to their sensors, but there is also a possibility to manually send information about the owner's surroundings through a mobile application. This way, people provide information which is already processed by their mind, so it is more valuable for the community sensing service.
Crowdsensing is a subtype of crowdsourcing where the actual outsourced job is a complex sensing task. One example is the operation of thematic web logs (blogs), where users provide their sensed information of the same phenomena. This particular example belongs to social crowdsensing applications, where participants share their produced data through a central server with each other. The database created this way provides a better understanding of problems and helps to make decisions and prepare community-based solutions together which are not only better grounded, but will satisfy more individuals. Microblogs [2] also belong here, which is a universal platform for cooperation between users. People can share information on touristic areas, not only different experiences but also real-time questions, at a certain venue within the location-based application. Another aim

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of the platform is to help spreading news and other interesting information in a short timescale among the users. Another example of social crowdsensing applications is Flysensing [3], which relies on flight passengers carrying electronic devices and presents a diverse collection of use cases including health monitoring, safety and surveillance, scientific discovery and business analytics.

To map a phenomenon or to discover a territory, sensors in different places in or around the area of interest should send their data so the crowdsensing application could have a clear vision of what is happening there. These sensors can be immovable ones, deployed in advance, like in wireless sensor networks (WSNs) or moving ones. Static sensor placement has disadvantages of insufficient coverage of the area of interest, high costs of deployment and maintenance and it is not scalable as well. A novel approach is the usage of sensors that are carried by people on their daily routes. They represent a variant of mobile sensor networks which rely on people's smartphones utilizing the sensors integrated in these devices. Smartphones are uncontrolled mobile sensors as their mobility is not restricted as of those sensors, which are deployed in advance (e.g. on public vehicles). They move along with their owner and collect the information about speed, acceleration, connected cell towers, Wi-Fi hotspots in sight, etc.

Utilizing moving sensors in crowdsourcing is called mobile crowdsensing (MCS). That is, MCS differs from the deployed sensor networks in involving people who are moving, and accordingly, collecting data from different places and routes. People are not only carrying sensors integrated to their mobile devices like smartphones, but are able to provide information about the surroundings manually, as well. Advantages of MCS over other types of sensor networks include a) high computing capacity of smartphones for pre-processing of data, b) connectivity to cloud supporting data processing and c) individuals are able to provide useful information about the surroundings that is hard to monitor by sensors [4]. Humans can contribute deep, qualitative knowledge; they can analyze fuzzy or incomplete data; and they can act in ways that digital systems often cannot [5]. However, the evaluation of sensed data can be biased by the variance of available sensors and their accuracy in different smartphones. Reliability of the sensed information is also a question as it depends on the number of sensing received about a certain phenomena. Phone owners cannot be forced to run the crowdsourcing application or to provide manual sensing, so the critical size of the crowd has to be maintained with various types of incentive mechanisms. They help the system in getting just the right quantity and quality of information needed for the actual sensing use-case.

The way how members of the crowd provide information can be divided into two categories, participatory [6] or opportunistic, whether the owner of the sensing device plays an active role in sensing or not. In participatory sensing the user helps the sensing process with manual intervention, for example indicating when he/she gets on a public vehicle, naming the traffic line and the stop where the sensing event happened. In automated or opportunistic sensing the user plays a passive role in the process as the sensing tasks are carried out automatically, e.g. by an application running in the background. Although participatory sensing can lead to more exact data, opportunistic sensing can be more reliable, because it can provide continuous and large scale data feed, which can eliminate the bias of human factor.

In general, the created sensor data goes through the following typical processing steps in case of mobile crowdsensing: data collection and mediation, data storage and distribution, data analytics and any service specific use case logic, service exposure. The mediation layer is responsible for collecting the data from the individual data sources and then forward it to the data layer, tagged with appropriate meta-information. These information may originate from the active help of participatory crowd or automatically learned from similar measures received in the past. The data layer has the functionality of storing information in an appropriate storage model and of distributing the data among consumers. These consumers can be the service specific use cases hosted by the service layer and creating value from the sensed data. The service layer is also responsible for exposing the results either via creating new data / knowledge or by offering services. The target of the exposure can be both the source of the sensor data (even the individual) and the connected society.

The goal of the paper is to give an overview of the most relevant aspects of mobile crowdsensing that are utilized already by the society. The paper focuses on best practices applied in smart cities today, how these applications can be motivated and rely on technology enablers of today's vertical silos and futures horizontal approaches. The rest of the paper is organized as follows. First, the practical applications of crowdsensing in smart cities are detailed in Section 2. These applications focus on urban transportation, public safety and environmental applications. In order to facilitate data creation, it is important to actively involve people both in participatory and opportunistic crowdsensing: incentive mechanisms are discussed in Section 3. Finally, Section 4 provides an outlook for next generation crowdsensing supported by technology evolution via more generic horizontal solutions.

2. Crowdsensing in Smart Cities

Researchers of the United Nations reported in 2014 [7] that more than half of the human population lived in the urban/city areas and this number is already about 80% in North America and Latin America, and this proportion is on the rise. This fact calls for smart operation of these cities by applying all the new technologies that recent development of information and communication technologies can bring us. Among similar concepts of digital cities, intelligent and ubiquitous cities, so called smart cities can adopt the collaborative aspect of operation between different role-players of the town, including citizens. This initiative is actually the recognition of the importance of using digital technologies for a sustainable future [8]. All smart applications rely on collecting available information from sensor networks in and around the city and make the operation of public services (like lighting, heating, garbage collection, etc.) intelligent. As discussed crowdsensing is a novel way for data collection, particularly in densely populated areas where insuring the appropriate number of sensing users is easier. Therefore its application in smart cities is beyond dispute.

Crowdsensing has use-cases in smart city concepts alone and alongside with sensor networks as an additional technology that involves moving (carried) sensors and human intelligence into the sensing process. Many crowdsensing applications address tasks related to urban transportation systems, which include the tracking of public vehicles (buses, trams, subways and rentable bikes) or others like mapping bumps on the road to quickly inform authorities where to intervene. Public safety is another category of applications where the power of the crowd is used to indicate unusual/abnormal behavior of people, extreme situations like riots, demonstrations and similar. Tracking the urban environment is also of interest and of help in maintaining and improving the quality of life in cities. Although it is a typical use-case for fixed sensors, the development of new smartphone sensors makes them able to participate in monitoring and the manual sensing can indicate phenomena that are not discernible by fixed sensors.

Further smart city scenarios are emerging every day, the CityPulse [9] project has identified 101 smart city scenarios and related use cases, developing an evaluation metric to measure the requirements for a smart city framework. The scenarios include examples for facilitating transportation such as a real time travel planner or a service predicting public parking space availability, and other applications belong to public safety for example e-Neighborhood and Smart events.

2.1. Crowd-assisted urban transportation

2.1.1 Bike Sharing Systems

As the population in urban areas is growing significantly, new solutions are needed to cope with growing traffic and air pollution. The problem of growing traffic can be solved by diverging people among different means of transportation. To cut air pollution down, we can think about using alternative fuel in engines or maybe we can simply replace engines with our physical abilities. Using bicycles in short distances could significantly decrease air pollution caused by cars, meanwhile the impact on daily commuting time is rather positive. To motivate more people to use bicycles in cities, establishing bike sharing systems seems to be a good solution. These systems already exist in many cities around the world, where the main idea is that people can rent a bicycle in the streets at certain stations and after the ride leaving them at another station which is close to their destination.

Beyond finding the optimal location of the stations (the distance is normally not bigger than 500 meters between two arbitrary stations), the number of docks in each station and the number of bicycles in the whole system need to be planned carefully. When the system starts operating the main challenges become the maintenance of the equipment and the redistribution of bicycles among the stations.

In all of these bike sharing systems, the bicycles have a built-in GPS sensor which enables them to be tracked. Knowing the location of bicycles helps not only in preventing theft, but it can also be used for route planning or facilitating redistribution through crowdsensing.

For being capable to run such BSS systems, there are several problems to be solved. The optimized number of bicycles should been determined in the system, examining the effect of redistribution vs. the performance of the whole system from the business point of view. The redistribution is crucial in bike sharing systems, therefore in order to improve it, users can be motivated and rewarded to alter the actually unfavorable bicycle distribution. For example, two stations are offered, one of them is clearly closer to the destination. The other is slightly farther, which results in a longer walk from the end station to the destination, but it helps the redistribution from the system point of view. To motivate people helping redistribution in this way pricing incentives are used, i.e. choosing the less ideal station in terms of additional walking distance will cost less for the individual than the other option. For example the above mentioned problems were addressed in Singapore's bike sharing system, where they want to replace short train routes (maximum three stops in the popular train network of the city) [10] and in [11], where the authors propose that if an individual starts a ride in the system he/she is asked to give his/her destination. The incentive schemes will be introduced more thoroughly in Section 3.

Major challenge is to involve public and personal bikes of daily commuters into public transportation. For example, suburban buses and trains have very limited capacity for carrying bikes. Official bike locking stations would let accept people that their bikes are safely stored. Here the free space availability and tracking are essential basic features. Moreover, capacities should be harmonized with weekly needs of people. Examples of Dutch trains stations with massive and large scale bike storages are a first idea.

2.1.2 Transport tracking

Mobile Crowdsensing applications in transportation include measurement of traffic conditions on roads (e. g. traffic congestion), mapping parking place availabilities in garages and in the streets, furthermore collecting maintenance spots on different facilities causing outages and traffic diversions.

In large cities traffic can often be unpredictable (especially during rush hours), therefore most traffic-influenced public transit lines can bear shorter or longer delays. Weather conditions like a rainstorm or an extreme snowfall can seriously influence the traveling speed of all the vehicles in the city. To public transport passengers it is important not to wait too long at the stations in extreme weather conditions. This challenge was addressed in [12], where a naming scheme for a content-centric crowdsourcing network as an effective way of describing the entities of a crowdsourced public transit network (locations, and vehicles) was presented. It is a hierarchical nomenclature which can easily express even some properties of a station inside a city, in an area. The interconnections of route parts can be expressed how they are connected in real life or by a particular transit line (including the places of stops, traffic lights, etc.). The solution firstly records GPS and accelerometer data. Field tests showed losing the GPS signal on average 18.4% of the travel time, thus the conclusion is that GPS cannot be relied entirely. Network localization (GSM) were foreseen as Wi-Fi hotspots are not so widespread in India, where the tests took place, so they cannot be used for localization. They always collect historical data so if the CS system could not provide sensed data then it can be substituted with older sensing. Fuzzy-intersection and fuzzy-union are used to find bus stops and traffic lights automatically from sensor readings. It turns out this is a tough problem to solve even if they raise the number of considered journeys.

To overcome this challenge, [13] proposed a system, which monitors public transport vehicles with a crowdsensing application running on traveling users' mobile phones and detects the stopping places of the vehicles. As stopping places are timestamped, they can be compared with the fixed timetable. This means that possible delays can be reported to the members of the crowd-community, enabling the development of geo-dependent online services that can check the updated arrival times at the current stop of every transit line belonging there. In this way waiting too long for public vehicles without notifications can be prevented. The method relies on accelerometer readings of the smartphones and it uses a progressive localization technique comparing Wi-Fi SSIDs sensed at different stopping places.

Public transport companies often seek the opportunity to synchronize the public transport network of a big city with the habits and lifestyles of the inhabitants to reach higher efficiency. Another challenge is to satisfy customer (passenger) needs and desires when using their service. Crowdsensing can provide help by collecting data through many sources including mobile phones and smartphones. The anonymous data helps tracking the movements of thousands of people from place to place and correlating this information with time and the speed of travel. The system understands the mode of transportation people are using and knows where they are traveling to and from. This all facilitates optimizing public transport routes and reduction of costs and pollution which overall results in a healthier environment (example for this is the project started in 2011 called 'Istanbul in motion' [14]). Apart from automated, opportunistic sensing, other applications which concentrate more on increasing customer experience usually require participatory sensing as the collected data is often subject to personal opinions. Tranquilien [15] alleviates train transportation by not only helping to reduce delays, but also giving commuters more comfort, easing peak hours by spreading passenger load across more trains, and generally increasing the overall efficiency of the network. The optimization algorithm is able to predict how many people will be boarding and disembarking from the trains at each station throughout the day up to a week in advance. The model aggregates many available data resources besides user data such as app check-in information and search queries. Crowdedness of vehicles determine general comfort level, but passengers are often interested in many other qualities of vehicles such as cleanliness, availability of air conditioning, power outlets and accessibility with wheelchairs. Applications like Moovit [16] and Tiramisu [17] support these challenges; however, their basic function is also to facilitate route planning with public transportation in big cities around the world by incorporating possible GPS data of the vehicles.

Not only passenger behavior but also road conditions and congestions have severe impact on the efficiency of a transportation network. Real-time traffic-condition monitoring solutions already exist, which use only GPS traces and nothing else, requiring low bandwidth when transferring recorded traces via wireless networks. Since only a single sensor is activated and a small amount of data is transmitted, energy efficiency is a key advantage of the application. Saving energy is essential when users are to be encouraged to use such an application on their smartphones with quickly draining batteries. After data collection and traffic visualization, road segments and similar characteristics on different roads can be defined. The computed results are distributed amongst the contributors, taking into consideration the real-time traffic conditions when planning their route. A fine example for this is the Surface application [18]. Cities of the developing world have to cope with some additional challenges. Besides route planning, rich sensing application helps detecting traffic conditions utilizing the accelerometer and the microphone of the smartphones. Rich sensing is critical in the context of cities concerned, because road conditions tend to be variable (e.g. a lot of potholes), vehicle types are heterogeneous, and the flow of traffic is chaotic (e.g. a lot of braking and honking). For instance, the accelerometer is used to detect potholes and the microphone to detect honking. Energy efficiency should be also addressed, by using triggered sensing, wherein a sensor that is relatively inexpensive from the energy viewpoint is used to trigger the operation of a more expensive sensor when needed. For example, the accelerometer is used to detect a high incidence of braking, which then triggers microphone-based sensing to check for honking. Another challenge arises in the context of an accelerometer that is disoriented because the phone is at an arbitrary orientation with respect to the vehicle. The orientation of the disoriented accelerometer should be determined, so that the measured accelerations along its x, y and z axes could be mapped to accelerations along the true X, Y and Z axes [19].

Users are easier to be motivated to use an application when they can have direct advantage as they use the collected data. One of the key advantages can be saving fuel, which not only cause them saving money but it also contributes to our environment by decreasing pollution. E.g., using community-shared fuel prices helps to navigate to the cheapest petrol station on the way to save money [20]. A solution could be to concentrate on traffic hotspots (high volume traffic with lower average speed) detection, after aggregating data from the users to offer such routes for them, which avoid hotspots not only to decrease travel time, but also to reduce fuel consumption [21]. When finding a fuel-efficient route for the users, the mobile phones can connect to a standard interface in cars that provide data related to fuel consumption. Aggregating data from many vehicles on roads allow the system to suggest suitable directions for the drivers. However, it does not take the driving style and real-time traffic conditions into account [22].

The above mentioned challenges are combined in a crowdsensing platform called Waze [20], which helps drivers to get real-time information on road conditions, namely accidents, potholes, police safety cameras, breakdowns and many more relevant details. Being a versatile platform explains its popularity. After it had been incorporated into Google Maps, Waze became the world's largest community-based traffic-outsmarting navigation app. Data is collected opportunistically and manually as well to warn drivers when they approach police, accidents, road hazards or traffic jams. To improve routing around the world, users can report/edit changes in maps to keep them up-to-date. For this purpose many national Waze-communities were formed (the very first one in Hungary) to deal with local map issues: closures, diversions, speed cameras by connecting the announcements of the national police and road maintenance services.

All the above solutions are focusing to one or several use-cases. However there is a wider initiative for these challenges which is called Cooperative Intelligent Transportation System (C-ITS) [23]. To support special applications like crowdsensing in the ITS domain, advanced mobile networking schemes and optimization techniques (e.g. [24]) are becoming more and more essential also in vehicular communication architectures.

2.1.3 Urban mapping

The power of the crowd is discovered by governments all over the world and involving citizens to map their surroundings and provide these information to the authorities is more and more common. This kind of data harvesting can rely besides the sensor reading also on the intelligence of the sensing users which is called manual sensing. However automated sensing (or so called pull-based sensing, as the server/app pulls the data from the sensors) has the advantage of continuous data supply from the sensed area which is often valuable than using the often less reliable manual sensing. Street Bump [25] application is one of those, which are automatically collecting the data from the phone sensors to map potholes in the streets of Boston. It was developed by the Boston authorities and in 2013 it received The Digital Government Achievement Awards (DGAA). It detects bumps on the roads while the users are travelling with the application running on their mobile phones. As the phone analyzes accelerometer data and detects possible places of potholes. Findings are reported to the city authorities so the road can be repaired before it causes serious damage in the cars.

Urban mapping crowdsensing applications can not only be used for problem-solving but also providing up-to-date information on maps not only for drivers but also for pedestrians. Map++ addresses this challenge, which helps digital maps to improve with automated sensing [26]. It uses standard smartphone sensors to automatically enrich digital maps with different road semantics like tunnels, bumps, footbridges, crosswalks and road capacity. The application emphasizes energy-efficiency (uses only common sensors with low energy consumptions, which are anyway active normally on a smartphone while in use), but still provides high accuracy both for in-vehicle and pedestrian traces. The data is captured by a cloud-based architecture which feeds useful conclusions back to high number of users after data processing.

Most urban mapping applications rely on manual sensed data or push-based sensing, as users note their observations when they want to by pushing the information to the central server. Users’ sensory organs provide much richer data source then sensors: people can easily conclude from their surroundings if there are issues on the road or if they are in a dangerous situation. The following applications are working on the same principle: CitySourced [27] is a civic engagement platform offering the possibility for residents to report quality of life, public safety and environmental issues directly to the local government. The application is operational in most of the neighborhoods around the United States. The type of data collected is referred to as volunteered geographic information (VGI) as users upload geotagged photos of the discovered issues noting the category of the problem. A geographic information system server, ArcGIS is receiving the issues so the governments of the cities can determine trends and typical hotspots (graffities concentrated to abandoned neighborhoods) of the issues so they can react with action plans [28]. Another reporting interface, called FixMyStreet [29] is available for the citizens of the United Kingdom. There is an interactive map that allows reporting potholes, streetlight outages, and other street-related problems. These problems are brought to the appropriate council which is responsible for maintenance and repair. As the individuals' reports appear on a shared public map it aggregates valuable information on the state of the streets. One of the newest examples from September 2014 is the application of Budapest's XII district's Government with similar goals: to collect, map and flick off landfills, potholes and abandoned cars in their neighborhood [30]. Another co-working, data harvesting application, targeting groups of people with special interests is Cyclopath [31]. It creates an interactive map for cyclists in the Minneapolis area that enables users to find bicycle-friendly routes in the region. It not only contains road surface conditions, off-road paths but also location of coffee shops. Compared to the generic Google Maps bicycle road planning service Cyclopath relies on a place-based community to contribute local knowledge and its existence and use is a point of pride for the local bicycling community.

A challenging application for future would be a map service covering special limitations. E.g., routes without stairs for disabled people and mothers with small children; or even providing a route for kids and young pupils where all the crossroads have lamps.

2.2 Crowdsensing for public safety

In growing cities and mass events like festivals, peaceful or violent demonstrations, authorities have to find new data sources to track masses of people and happenings in the society. Crowdsourcing can not only provide real-time information from the streets through comments, pictures or videos taken at the spot by the crowd-members but can also offer the feeling of being safe and listened to. Public safety supervision requires user and sensor data for early fire-, earthquake- and other natural disaster-alerts, for maintaining public utility services, for planning safe routes for pedestrians across the city and for many other use-cases. Several applications target to solve these problems, others are still unaddressed.

Crowdsensing applications can help e.g. rescue teams with real-time information in the event of an earthquake to estimate the situation and reduce the time needed to prepare for an intervention [32].

A mobile application uRep is developed for users to see how utility companies are proceeding with solving outages in their systems (electricity, water, etc.). The companies and users can both provide location based information on the level of parts of cities, sections of roads. Developers foresee extension of their app for offering assistance to people in need and gathering data to help prevent damages in future events.

Route planning inside a city is not a new task and is solved by numerous apps/services but taking into account the notorious city districts, bad-security streets is something new to deal with. A solution is offered by SafetyRouter [33], which is a map-based route planner and it offers the safest path between two points of the city, according to crowdsensed live data stream, and stored historical crime entries. Shortest and safest paths can be combined to give the "best path" for the users. This is described by a simple summarizing-minimization formula. Shortest path is determined with Dijkstra or A* search method. Crime analytics is also given by this app by determining crime hotspots and clusters in a city which can be of serious help to the authorities. A density-based method is used to generate crime heatmap. Crime clusters are determined by k-means and DBScan clustering algorithms. These two outcomes of the app are demonstrated and visualized by a mobile platform for crowdsourcing of crime incidents. In the app, data from crowdsourcing is ranked along three models: 1) vector model for relevance-investigation between textual queries and search results, 2) spatial ranking based on Euclidean distance, 3) timeliness: decreasing a sensing's weight as time passes by. A weighted linear combination of the 3 rankings is provided as the outcome.

The impact of crowdsourcing through social networks (which are also operated by a crowd) like Usahidi, Facebook, Twitter and similar in disaster-management [34] helped state services to find troubled people in Haiti earthquake, Japanese Tsunami and other disasters as well by providing geotagged pictures and localized emergency calls. Everyday security is targeted with the AlertID [35] application in the US, which is a secure social network for neighborhoods providing local crime information, alerts in case of extreme weather and of course the possibility to the citizens to help each other by providing useful information about their surroundings. In Hungary a new smartphone application is aiming to offer a danger reporting system that unites all the public authorities (ambulance, police, and firefighters) who are listening to the calls of help through this application [36]. Users can also see their family members' calls and can help in emergency situations happened near to them as the application can navigate them to the spot.

Machine learning-based decision-making with artificial intelligence can be also used to increase public safety in crisis situations. In SmartRescue application [37], a framework is defined for data collection, decision and communication to users who are provided with necessary instructions regarding evacuation in case of an emergency situation. The system uses a publish-subscribe mechanism which enables flexible data collection and transmission amongst real-time users.

Among several research projects, the European Union also recognized the importance to address problems related to data harvesting, social sensing, managing crowds of people not only for collecting data but to maintain safety. An EU FP7 running project [38] is focusing on management of complex evacuation operations according to current conditions: number and placement of people to evacuate. Aims also include to help the civil protection authorities, but they are basically trying to rely mostly on CCTV cameras, Wireless Sensor Networks and so called “people-sensors” utilizing the well-known data harvesting method, crowdsensing. INSIGHT [39] is an EU-financed project ending in 2015, which utilizes diverse deployed sensors, social networks and smartphones to map the surroundings and, accordingly, to offer a better social management of disaster monitoring involving citizens. They can participate in data-collection and also in decision making. They aim to develop a system which can handle real-time processing of the incoming datasets coming from sensors and the crowd. SafeCity [40] is a public-safety enhancer project of the European Commission which involves all possible data sources to detect events happening in the cities in real-time, makes smart decisions automatically to reduce the reaction time of the first responders in hazardous situations, relying on citizens, but also using CCTV cameras and sensor networks of different types.

2.3 Environmental monitoring

Environmental applications concentrate on measuring and mapping large-scale phenomena happening in the natural environment around us, such as natural disasters or pollution level. People nowadays are keen to store data (mainly photos and videos) on their smartphones which reflect their personal experience and memories. The data produced like this can be easily transferred to mobile crowdsensing applications that can, for example help in maintaining the air quality in big cities where it can be a serious question. Activating particular sensors of smartphones will not require such manual activities of users to upload data for the applications as they can be produced automatically with the consent of the user. These sensor-based applications can provide location-based information on air pollution level and on weather situations including temperature, humidity and light conditions. Processing information retrieved from these applications can support our decision-making process when choosing appropriate clothing for a day or when planning our route in a city (especially when using outdoor transport facilities or bicycles and the quality of the air is a concern). The iMAP [41] is a cellphone-based indirect sensing application which estimates the pollution level in streets. Compared to other crowdsensing problems where a dense set of sensors is available this problem addresses a sparsely sensed phenomenon, concentrating on air-pollution. Deploying fewer sensors provides a more feasible approach compared to direct sensing, but challenges data processing. The paper identifies Land Use Regression (LUR) as a suitable modelling solution. When the sensed data is captured, local traffic, population, and weather characteristics measured at regional air monitoring stations are taken into consideration to provide estimated pollutant concentrations for each user.

According to a recent discovery, ‘space weather’ is a useful sensor to predict many types of Earth- and space-based phenomena such as earthquakes and tsunamis. Disaster prevention is recognized to rise public safety in urban areas. The Mahali project [42] facilitates this goal by monitoring ionospheric electron density with the help of mobile crowdsensing that helps to increase the number of sensors and to expand data transport capabilities through participating devices acting as relays. Mahali uses GPS signals that penetrate the ionosphere not for positioning but for science this time. First the data is collected by GPS receivers which have a line of sight to several GPS satellites. This information is fed in a cloud-based environment by internet-connected mobile phones (solving the last mile connectivity problem) to make further calculations.

3. Incentive mechanisms

Mobile crowdsensing can outsource sensing tasks to mobile phone users, who are willing to collaborate. However people and their willingness to take part in crowdsensing are not reliable enough for most of the applications that aim to map phenomena of high interest. Some of the sensing tasks are interesting and sometimes a good way to spend time for the users who are travelling on public transport and have nothing to do in the meantime. But if they have, the crowdensing platform can easily be left without enough number of sensings from the users. In this case users should be motivated in some way to continue providing information and these methods are called the incentive mechanisms. So crowd-cooperation could and should be rewarded in one or several ways, possibly including monetary payments, and gamification or by offering the sense of security: as a reward of their work the actual city will be a safer place to live.

Monetary rewards are the most common way of incenting. Users can be rewarded according to the number of smartphone sensors they enable for the platform to use user for crowdsourcing purposes. Different sensors can result in different payout depending on their energy consumption and the type of the sensing task they are taking part in. An example for this is Apisense, a mobile sensing platform that uses a multi-cloud architecture with a trusted central node, enabling scientists to run sensing tasks on a widespread crowdsensing system [43]. Monetary rewarding is not an option for single researchers thus authors strongly believe in gamification-type incentives.

The article of [44] describes and tests two different incentive methods: micro payments (MP) (5 dollars for five small sensing tasks) and weighted lottery (WL), where for the same amount of tasks completed, participating users receive a ticket and at the end of day tickets are drawn to decide who gets the 50 dollar reward. They use three performance metrics to evaluate their methods: recruitment, the ability to attract participants, compliance, to which extent participants complete the task assigned to them and user-effort to measure how hard sensing users work, because there are big differences between automated and manual tasks. They carried out a test at a conference/exhibition in two days, challenging the two incentive methods mentioned.

They found the following: *recruitment* - they measured a 16% higher compliance rate with Weighted Lottery than Micro-Payments; *compliance* - MP reached higher compliance rates than WL. There were no correlations between the popularity of the area where the task should be carried out and the compliance rate; *user effort* - MP significantly outperform WL for participating users with regards to active session times.

They observed the larger area covered and with greater density by participants given MP than WL. Authors concluded that WL attracted more users due to higher possible payouts, but MP-incented users were more productive, probably because the guaranteed payment, not regarding the more than two times higher expected payment from WL. From the crowdsourcer’s side users with MP carried out almost the same amount of tasks than those with WL with a total payout 4 times lower than for WL-incented users.

Similar payment-based incentives are compared in [45]. The effects of three micro-incentive mechanisms are examined where subtasks of the crowdsensing process are rewarded in different ways. First one is the Uniform-reward method (similar to MP of the previously discussed work) which is used as baseline to examine the effectiveness of the other two. In this case sensing users get the same reward for every accomplished sensing task. It is used because of easy implementation and because it is a first step from bulk payments to other, more complicated micro incentives. The Variable scheme uses changing monetary incentives for every task which helps to determine how the changing reward influences the quality of sensing. It can also remerge the decreased interest of the sensing user by temporarily raising rewards. The Hidden scheme is analogous to WL where the user finds out the value of reward only after completing the actual sub-task. This is similar to gambling where the user has the possibility to acquire high income in a short time. Of course, high rewards are much rarer than lower ones, but their occasional winning encourages the users to continue participating. Results show that the three micro incentive mechanisms have similar efficiency although it can be concluded that people favor the more predictable uniform and variable cases over the gambling-like hidden scheme.

Also an interesting approach is the one presented in [46] which introduces a new attitude: if there are not enough users for the particular sensing task then some of the not-working members of the crowd are rewarded beside the actively participating ones with a small amount of money to get them ‘back to business’ in the coming rounds. Of course the aim is also to sustain diversity of sensing users so the ‘free’ rewards always go to the groups which are not well represented in the base. The quality of sensing is maintained by the SPREAD algorithm [47], by getting enough sensing users and supervising their diversity. The algorithm gives a graph representation of the active sensing users and a geometric coverage algorithm (Set Cover), which is utilized to select the potential candidates from the area of interest in the most diverse way. The second part of the algorithm acquires a sample set in each sensing round while staying inside a previously set monetary limit for the job.

The idea of linking the CS application to social networks can be of help because we are more motivated to help people who we know but it restricts the number of sensing users in the app. [2] tries to answer the question why would somebody answer to any popup question or complete a task in a crowdsensing application if it takes his/her time and could deplete the phone’s battery? Another solution they have proposed is to use a credit system to avoid that some users only ask for help but they do not want to provide anything by charging every question and reward every answer with credits.

The incentives needed for extensive user participation, quality of sensing and privacy-aware incentives should be differentiated [48]. The privacy-aware incentive is actually the degree of security that the crowdsensing framework can offer the users: at location-based application users are willing to know that their data is in absolute anonymity. Number of users can be maintained by using the Vickrey-Clarke-Grooves bidding mechanism [49], [50]. It also assures that sensing users are giving reasonable price-bids as their demand for doing a sensing task with reverse-auction model defined by the three scientists. The quality of sensing is often also closely connected to the number of sensing users. An incentive platform for parking information systems is presented in [51] which gets the adequate number and quality of sensing from the users that are not trustworthy at default. First they stimulate users’ participation with a credit-system where every new parking availability information (PA) is rewarded with a static credit amount and - depending if the PA led to a successful parking action or not - a bonus, which can be much higher than the static reward and can be varied by the TruCentive platform to keep the quality of sensing high. The PA-buyers are refunded if the reported parking place has been filled up in the meantime. Honesty of the role-players of the crowdsensing platform is maintained by a game theoretic approach that guarantees that they can obtain the highest value in the ‘game’ (the TruCentive platform) if they are honest.

An online incentive mechanism is presented in [52] where the task is to select the appropriate users from the crowd who play their role in a game theoretic way (they are ready to provide false information about their capabilities to obtain higher revenues from the crowdsourcer). It is modelled as an online auction problem, as a realistic case is considered where the users are arriving one-by-one continuously in a random order and their availability changes over the time. In this way it is harder to decide whether to accept a user's bid (price) for a task or not, based on the knowledge to the present moment while staying inside a budget constraint for all the tasks together. The method uses a maximization function for the value of the work done by the sensing users covering the region of interest all the time, satisfying six properties: computational efficiency (algorithm runs in real-time), individual rationality (all users have positive utility), budget feasibility (staying inside a cost limit), truthfulness (sensing users have to report their true costs), consumer sovereignty (users are handled equally, depending only to their power and costs) and constant competitiveness which means that the algorithm has to have almost the same performance like the offline solutions which have the knowledge of every users' details before they arrive to the region of interest. Their mathematical solution to the problem with the mentioned desired properties is well evaluated with simulations and it is shown that it can run in real-time, enabling it to use as an online decision mechanism which results in value of sensing that highly outperforms random user-selection methods.

Users are entering an optimal reverse auction each time the service provider (crowdsourcer) receives a new sensing job to be done [53]: users report their perceived costs for a unit amount of sensing work which includes all the costs starting from the energy cost of sensing, processing (computational power), battery level and charges of transmitting data to the provider and also the discomfort of the user while he/she provides manual sensing through the smartphone. Their incentive mechanism aims to minimize the total cost of user compensation for the delivered sensed data and to motivate users to participate in sensing jobs. The actual user-side costs are private data so they would have a strong motivation to misreport it to obtain higher payments. To solve this and user-side costs are handled through Bayesian game among the users, which results in Bayesian Nash equilibrium which means that users declare realistic costs (because they are not rewarded otherwise) and are motivated to participate because their utility for doing it is always greater than zero. Maintaining the guaranteed quality level of sensing services is done by neglecting the employment of sensing users who are consistently providing less accurate data with the crowdsourcing system.

Table 2 gives a classification of the above presented incentive mechanisms, considering the type of incentive, the goal of providing incentives and the reward allocation method. As we may think that the monetary rewarding is dominant, however from the table it can be seen that in several cases other type of incentives are also utilized, like a service as a reward, in some cases supported by a game theoretic approach. Rewarding the participation of the users in the process in not always sufficient, the quality of the sensing should be also provided by the incentives system.

Table 3.1. Incentives

Incentive mechanism	Incentive type	What is incented?	Reward allocation method / idea
[43]	monetary	participation	number of sensors dedicated to CS
[44]	monetary	participation	micro payments or weighted lottery
[45]	monetary	participation	per task: uniform or variable or hidden scheme (like gambling)
[46]	monetary	participation	per task + for non-working as well if reinforcement is needed
[47]	diversified user enrollment	quality of sensing	reverse auction-based
[2]	credit-system (service as reward)	participation	credit reward for answering, credits needed for asking
[51]	credit-system (service as reward) + game theoretic	participation + quality of sensing	credit for reported parking place (PA) + bonus credit for successful parking accordingly
[52]	online auction model + monetary	participation + quality of sensing	auctions result in prices that are payed for users for sensing
[53]	game theoretic	participation + cost minimization for the service provider	Bayesian Game for Nash-equilibrium for user truthfulness and willingness to collaborate

4. Moving to a horizontal architecture

Many applications for Smart Cities are developed independently and invites participants on per application basis. In this section we summarize what are the common features in these applications.

We show how these applications are built in a vertical manner today. We also present the most impressive activities and solutions towards more efficient horizontal architectures. These applications can share the participants and the sensed data, as well.

Finally we give an example how current individual applications could be organized in a "single" horizontal system.

4.1 Common features in Smart City applications

Most of smart mobile devices can provide data from a number of sensors that resemble IMU-like sensors (mIMUs). Typical available sensors include:

- GPS
- gyroscope
- accelerometer
- magnetometer
- proximity sensor
- temperature sensor
- humidity sensor
- ambient light sensor
- barometer
- gesture sensor
- microphone
- camera (images, video)

Nevertheless, there are other data sources that can be considered as sensors, like the social feeds [54], [55]. Such feeds like Twitter or Facebook posts are the most beneficial when many people recognize something important for the society, especially when correlating with other data sources. E.g., the change of taste of water and pressure in the water pipelines indicates that some dust already entered the water system.

Not all devices have all the sensors, most devices only contain a subset of the above, while there are some high-end devices that contain all of them. However, the basic tuple of GPS + accelerometer + magnetometer are generally available, thus they can provide basic location and movement information. All device makers provide APIs and SDKs through which the sensor data can be read and gathered programmatically in a custom application. Several application examples were presented for the major application areas in smart cities in Section 2.

Table 4.1 collects the main types of these applications and their impact on people's life. The solutions were first classified based on the type of data sources they use, as this feature heavily affects the energy consumption of the devices and the completeness of the crowd's database. Further classification aspects were the periodicity of data access and the way how members of the crowd provide information. The place of the computation is in the majority of the cases at a central server. There are also cases when the users preprocess the data, reducing the data transfer overhead, which is not negligible when involving large number of users.

In spite of the various available data sources only a limited set is used today. Beyond manual reports, mostly accelerometer and GPS data are popular, which are really the basic information sources. The data report is typically done via periodic reports or pushed occasionally. Roughly half of the examples are opportunistic or participatory; meanwhile the computation is done on the server side; and the individuals and society benefit from the information provided by these applications.

4.2 Architectures

Most of the solutions available today are based on the vertical principle. That is, today's solutions typically answer particular questions for one service provider focusing on a given use case and service upon this use case. As a result, many aspects of the vertical solution rely on application-specific or proprietary solutions. This limits the widespreadness of the services in case of the tiniest difference in the vertical silo if a service provider would like to move to a new market. New solutions might be needed if a new market is targeted or new sensors / devices are introduced. This vertical concept is illustrated in Figure 4.1a.

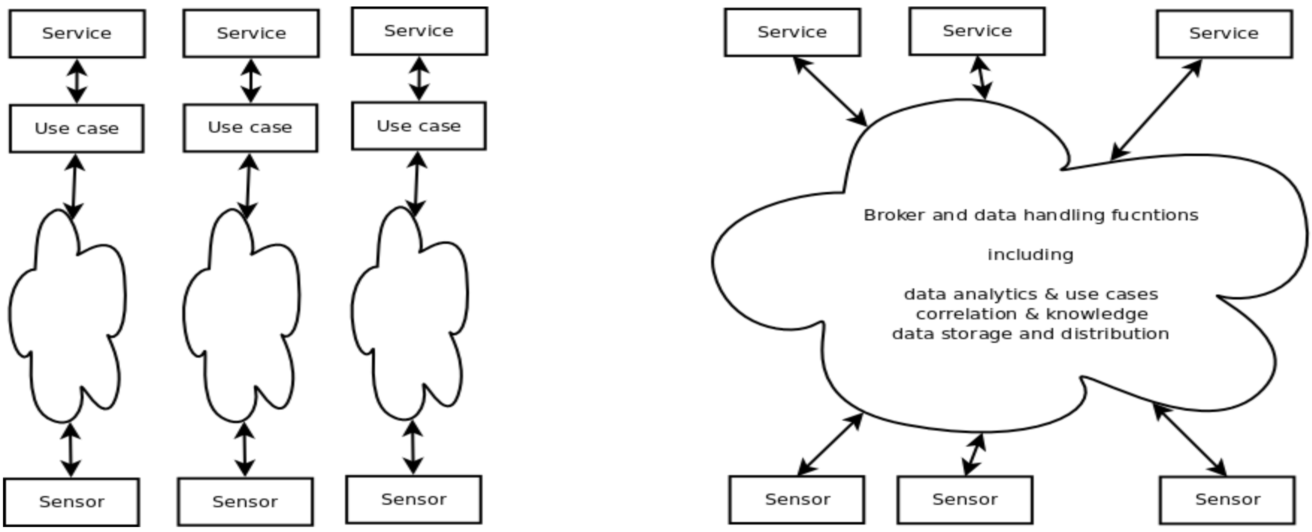
Early platforms like mCrowd [56] already provides possibility to share questions (tasks) with other user connected to the app and rely the answers on the community or even by artificial intelligence connected to the task distribution proxy of the system. In [57], a framework is proposed for recruitment in participatory sensing, especially interesting to organize campaigns, qualify the collected data/replies and review the progress.

There are platforms giving a complete framework for crowdsensing applications. Medusa [58] provides abstractions and programming framework to build crowdsensing tasks, which are distributed among smartphones and the cloud. To prove Medusa's generality, authors have implemented ten different use-cases working with cameras, accelerometers, GPS, audio and network sensors. McSense [59] provides a distributed architecture complementing Medusa in a sense to exploit information about the potential users of the app and their mobile execution context (e.g., processing power, battery, level, and so on).

Based on the above platforms and the great similarities of the major smart city use cases summarized in Table 4.1, one can imagine that a new horizontal principle and architecture could merge and connect various crowdsensing jobs at the same time. That is, all job requests, volunteers to collect data to answer the question and an interface for the results. That is, transition towards

Table 4.1: Major characteristics of crowd sensing application areas and reference solutions

	Referenced Solution	Type of sensor / data source	Data access paradigm	Participatory / Opportunistic	Place of computation	Direct benefit
Bike Sharing Systems	BSS Singapore [10]	GPS	periodic	n/a	server	private company
	BSS Redistribution [11]	GPS	periodic	n/a	server	individual, private company
Transport tracking	Improving Public Transport Through Crowdsourcing [12]	GPS, accelerometer	periodic	opportunistic	server	individual/ community
	Event Detection in Public Transit Tracking [13]	accelerometer, Wi-Fi	periodic	opportunistic	server	Community
	Istanbul in motion [14]	GPS	periodic	opportunistic	server	individual, society
	Tranquilien [15]	n/a	push	participatory	server	Individual
	Moovit [16]	GPS	push	participatory	server	individual, community
	Tiramisu [17]	GPS	push	participatory	server	individual, community
	Surface Street Traffic Estimation [18]	GPS	periodic	opportunistic	server	Individual
	Nericell [19]	microphone, accelerometer	stream	opportunistic	server	Individual
	VTrack [21]	GPS, WLAN	periodic	opportunistic	server	Individual
	GreenGPS [22]	GPS	periodic	participatory	server	Individual
	Waze [20]	GPS	push	participatory	server	individual, community
Urban mapping	Streetbump [25]	GPS, accelerometer	periodic	opportunistic	server	individual, community
	Map++ [26]	accelerometer, gyroscope, magnetometer, RSSI	periodic	opportunistic	server	individual, community
	Citysourced [27]	GPS, camera	push	participatory	server	individual, community
	FixMyStreet [29]	reports	push	participatory	server	individual, community
	Hegyvidek [30]	reports	push	participatory	server	community
	Cyclopath [31]	reports	push	participatory	server	individual, community
Public safety	AlertID [35]	reports+ weather services, crime databases	push	participatory	user + data providers	community
	HelpyNet [36]	report	push	participatory	user itself	small community
	eVACUATE [36]	reports, localization, accelerometer + sensor networks	push + periodic	participatory + opportunistic	server	community
	INSIGHT [39]	diverse sensors +reports+sensor networks	push + periodic	participatory + opportunistic	server	community
	SafeCity [40]	reports + sensor networks	push + periodic	participatory	user itself	community
Environ-mental monitoring	iMAP [41]	GPS	periodic	participatory	server	Society
	The Mahali project [42]	WLAN	poll	opportunistic	server	society



a) vertical b) horizontal

Figure 4.1 Vertical and horizontal architectures

a more flexible architecture focuses on a multi-purpose solution adopting open or standard solutions where it is not business-critical to use the proprietary solutions. However, even proprietary solutions might be limited to the service exposure phase and the rest of the analytics, distribution, storage and collection of data could be hosted in a cloud-based architecture as illustrated in Figure 4.1b.

For example, projects like e-LICO [60] have already proposed solutions supporting analysis workflows in such a horizontal environment, and provide general-purpose and application-specific services and related toolkits. One of the first large-scale real-world experiments covering the entire horizontal spectrum is the ParticipAct Living Lab testbed [61]. This is an ongoing experiment at the University of Bologna involving 300 students for one year in crowdsensing campaigns that can passively access smartphone sensors and also require active user collaboration.

Within such horizontal systems, it would be much easier for people to join initiatives for the good, social community or simply business solutions of their personal interest. The differences between the vertical and horizontal solutions could be well summarized similarly to the foreseen evolution from the traditional M2M principle towards the IoT principle [62] as shown in Table 4.2 [63].

4.3 Transformation of application into horizontal solutions

In order to illustrate the strength of the horizontal solutions, let us introduce an example of the transport tracking application areas containing most of the methods developed individually. Realization of horizontal solutions needs more than the above technical functionalities.

Table 4.2: Vertical vs. horizontal solutions [63]

Aspect	Vertical solutions	Horizontal solutions
Applications and services	Single application - single device	Multiple applications - multiple devices
	Communication and device centric	Information and service centric
Business	Closed business operations	Open market place
	Use case driven	Participatory community driven
Technology	Vertical system solution approach	Horizontal enabler approach
	Specialized / generic devices	Generic devices
	De facto and proprietary	Standards and open source
	Closed data formats	Open API

An important additional function is the service broker. It is responsible to agree with the participants about:

- Which sensor data or information is shared
- In what format and how often the data is reported
- With whom to share the data
- What incentive(s) the participants get

Using the broker, the participants can contribute to a much larger eco-system or limit their activity to a given service, which makes much comfortable to join a crowdsensing community. Meanwhile it provides complete control of the participants' data asset. The compound of the transport tracking use cases is illustrated in Figure 4.2.

As mentioned above, the most important functionalities in a horizontal system are the broker and related data handling functionalities. These are highlighted in Figure 4.2 with light grey boxes. The data handling functionalities include i) the data storage; and ii) the use case related correlations & analytics of the different data sources. The data sources are highlighted with dark grey boxes in Figure 4.2.

The users/participants of the horizontal system are in connection with the broker and their corresponding data sources are reported towards the data handling function. With the control of the broker function, the data handling function forwards the processed data towards the applications presented in the top of Figure 4.2. According to the functionality, there are two main types of connections between the elements of the horizontal system. The dashed lines represent the logical connections, e.g., about the negotiations between the users and the broker; and between the broker and the data handling functions.

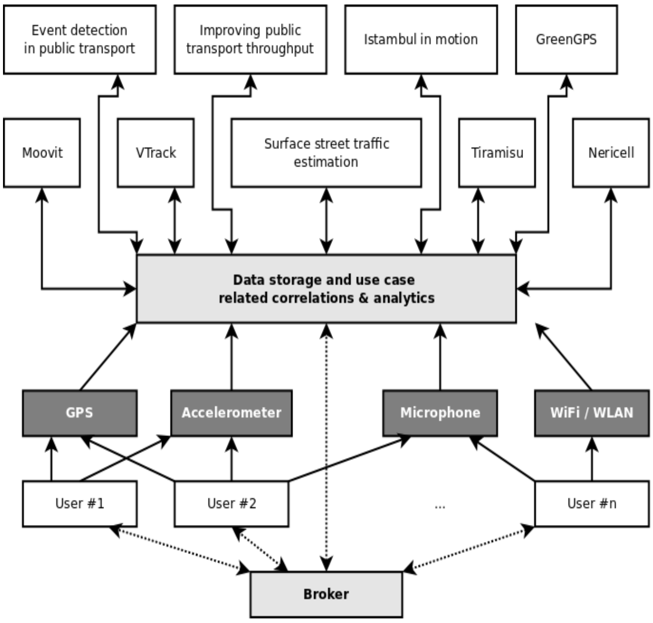


Figure 4.2. Illustrating transport tracking use cases in a single horizontal architecture

The single-ended solid lines represent the sensed data flows from the users' sensors towards the data handling function.

The double-ended solid lines represent the preprocessed data flows and the mediations of broker functionalities towards the services on the top of the architecture.

As you can see, in such a horizontal architecture all presented applications can be efficiently connected together in a single system. This system can greatly improve the quality of the individual application via the involvement of much more wide basis of possible participants for crowd sensing applications and services.

Similar framework can be defined for the most applications by the strong cooperation of partners of the cities including the municipalities, the citizens, the utilities and private companies, as well. Thereby, smart operation of cities could be provided for the happiness of the entire community.

CONCLUSION

In this paper we gave an insight into the applications of crowdsensing in Smart City-related use-cases like public transport tracking and urban mapping. Public safety and environmental monitoring are new areas and also promising examples of crowdsensing applications. We proposed a way forward in the field by transforming the vertical silos of today containing separated solutions in different domains into a horizontal architecture. The proposed ecosystem enables fruitful interaction between crowdsensing entities and supports the networked society.

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