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Adopting incentive mechanisms for large-scale participation in mobile crowdsensing: from literature review to a conceptual framework

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Abstract

Mobile crowdsensing is a burgeoning concept that allows smart cities to leverage the sensing power and ubiquitous nature of mobile devices in order to capture and map phenomena of common interest. At the core of any successful mobile crowdsensing application is active user participation, without which the system is of no value in sensing the phenomenon of interest. A major challenge militating against widespread use and adoption of mobile crowdsensing applications is the issue of how to identify the most appropriate incentive mechanism for adequately and efficiently motivating participants. This paper reviews literature on incentive mechanisms for mobile crowdsensing and proposes the concept of SPECTRUM as a guide for inferring the most appropriate type of incentive suited to any given crowdsensing task. Furthermore, the paper highlights research challenges and areas where additional studies related to the different factors outlined in the concept of SPECTRUM are needed to improve citizen participation in mobile crowdsensing. It is envisaged that the broad range of factors covered in SPECTRUM will enable smart cities to efficiently engage citizens in large-scale crowdsensing initiatives. More importantly, the paper is expected to trigger empirical investigations into how various factors as outlined in SPECTRUM can influence the type of incentive mechanism that is considered most appropriate for any given mobile crowdsensing initiative.

Keywords: Mobile, Crowd sensing, Monetary, Incentive, Incentive mechanism, Participatory sensing, Urban sensing, Smartphone, Mobile crowdsensing, Community sensing

Background

With rapid growth in mobile technologies, smart devices such as mobile phones, smart vehicles and wearables are fast becoming powerful sensing units used at a societal scale for monitoring the surrounding environment and for understanding complex urban and community dynamics [1]. These devices come equipped with a broad range of sophisticated embedded sensors such as an accelerometer, gyroscope, GNSS, digital compass, GPS, microphone, light intensity sensor and camera [2]. The phenomenal growth in the richness and diversity of sensors on smart devices [3], combined with the inherent

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mobility of mobile device users provide a unique opportunity to harvest large-scale sensing data with fine-grained spatio-temporal coverage [1, 4]. The process for doing this is commonly referred to as *mobile crowdsensing*, a socio-technical concept facilitated by a growing number of software applications that are fast becoming indispensable tools for active urban intervention [1].

Mobile crowdsensing can be formally defined as a large-scale sensing paradigm in which spatially distributed participants with sensing and computing devices capture and collectively share data in order to measure and map phenomena of common interest [3]. Unlike the traditional static infrastructure-based sensing method, mobile crowdsensing does not require the deployment of expensive fixed infrastructure assets, potentially making it a cheaper solution [1]. Basically, the key drivers of mobile crowdsensing are the ubiquitous mobile device users, whose geographical distribution allows for an extensive acquisition of spatially-oriented data in a scale that steers various smart-city applications [1].

Applications of mobile crowdsensing cut across a wide range of areas that are critical for sustainable urban development and for improvement to quality of life for citizens, in terms of convenience, comfort, safety and security [1]. Typical application areas include environment monitoring, community healthcare, surveys with embedded geotagged photos [5], traffic monitoring and transportation planning, garbage classification, infrastructure management, disaster management, public safety and so on [1, 6, 7]. With the recent surge in the application of these socio-technical systems in city management, mobile crowdsensing has been recognised as an important technological enabler for smart cities [1]. In this sense, successful societies are increasingly incorporating data and insight from mobile crowdsensing solutions into their planning process, decision making and policy formation activities [1]. Consequently, this burgeoning phenomenon has attracted significant attention from major industry players and academic research communities, seeking to address the key challenges militating against widespread use and adoption of mobile crowdsensing systems [1].

One of the key challenges that must be adequately tackled in order to harness the full potential of mobile crowdsensing is the issue of how to identify the most appropriate incentive scheme for sufficiently motivating individuals to participate in large-scale sensing campaigns [8]. For any crowdsensing initiative to be successful, an efficient incentive mechanism is required to adequately compensate participants for the time, effort and resources invested in the process of capturing, processing and transmitting sensed data [9]. Typically, different sensing tasks will cause each participant to incur varying level of direct and indirect costs arising from the use of network bandwidth, memory, CPU, battery usage, personal time, travel and special skills [10]. Hence, without strong incentives to meet the varying expectations of different participants, the problem of poor motivation and unwillingness of individuals to participate in the crowdsensing process abounds [1].

Several incentive mechanisms (e.g. [11–16]) have been proposed to address this problem, many of which are designed to suit the crowdsensing context and specific requirements of the underlying sensing initiative. Despite the proliferation of these technical solutions, Restuccia et al. [17] draw attention to the fact that it is yet unclear what is the most appropriate incentive to adopt in motivating users to participate in mobile

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crowdsensing. As a first step towards simplifying the process of identifying suitable incentives, several studies (e.g. [17–20]) have surveyed existing incentive mechanisms in the literature. While these studies report valuable and significant contributions, they have not explicitly provided a comprehensive guide that can be useful in inferring the most appropriate type of incentive for any given crowdsensing initiative. Hence, this paper synthesises relevant literature, with the primary focus of inferring a broad range of factors that can influence and therefore guide the decision to adopt an appropriate incentive mechanism for any given mobile crowdsensing initiative.

Contributions

Drawing primarily on the literature on incentive mechanisms for mobile crowdsensing, this study contributes to the body of knowledge on how to effectively incentivise citizens to participate in large scale crowdsensing in the following ways:

- The paper reviews over 130 relevant articles and presents a comprehensive view of mobile crowdsensing, its various types, and the different kinds of incentive mechanisms that nurture the crowdsensing experience. It clearly differentiates between the concepts of crowdsensing and crowdsourcing, which are sometimes misused interchangeably in the literature.
- Based on synthesis of literature, the concept of "SPECTRUM" is proposed to shape thoughts and guide decision making relevant to the selection of an appropriate incentive scheme for any given crowdsensing initiative. More specifically, a broad SPECTRUM of factors is presented that covers the various aspects which should be considered when adopting incentive mechanisms for mobile crowdsensing initiatives. Although an attempt is made to report on the appropriateness of different incentive mechanisms as influenced by the factors outlined in SPECTRUM, the overall goal is not to be strictly prescriptive in recommending various incentives for specific purposes.
- An exemplary discussion of a case study is presented to show how a combination of factors outlined in SPECTRUM could influence the choice of incentive used in real-world mobile crowdsensing applications.
- The paper lays the groundwork and motivation for empirical investigation into how different factors outlined in SPECTRUM may influence the type of incentive mechanism adopted for mobile crowdsensing.
- The paper also discusses and highlights research challenges and areas where further studies relevant to the different factors outlined in the concept of SPECTRUM are needed to improve citizen participation in mobile crowdsensing.
- In terms of contribution to practice, it is envisaged that the wide range of factors covered in SPECTRUM will enable smart cities to broaden the opportunities of adopting the most appropriate incentive mechanism in order to effectively incentivise users and improve participation in large-scale crowdsensing applications.

The remainder of this paper is organised as follows: the next section presents the various types of mobile crowdsensing activities currently being practised, followed by "Types of incentive mechanisms" section which then summaries the different types of

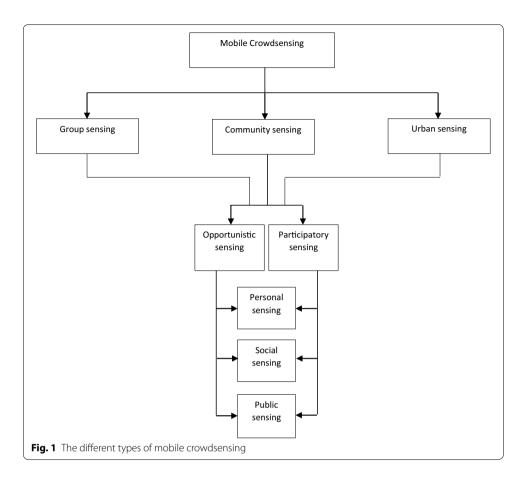Ogie *Hum. Cent. Comput. Inf. Sci.* (2016) 6:24

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incentive mechanisms that nurture the crowdsensing experience. In "Conceptual framework" section, the concept of SPECTRUM is proposed based on synthesis of literature and used in "Adoption of incentive mechanisms in real-world mobile crowdsensing applications" section to show how a combination of factors could influence the choice of incentive used in real-world mobile crowdsensing applications, including an exemplary discussion of a case study. "Discussions" section further discusses the practical implications, research opportunities and challenges. Finally, "Conclusion" section concludes the paper and makes suggestion for future research.

Types of mobile crowdsensing

Before differentiating between the various types of mobile crowdsensing activities, it is important to first provide clarity to avoid ambiguity in the use of the terms crowdsensing and crowdsourcing. In crowdsourcing, a top-down approach is adopted and the aim is to source the solution to a complex problem by splitting it into smaller tasks that can be executed by individual members of the public [10, 21]. Often times, the crowdsourcer has an idea of what to expect and the geographical location of participants is not a barrier. Whereas in crowdsensing, a bottom-up approach is adopted and the aim is to understand or sense a complex problem of interest by splitting the responsibility of harvesting relevant information to the crowd and then aggregating the results to obtain an emergent outlook of the phenomenon [10, 21]. In the case of crowdsensing, geographical location of participants is critical and there is often no knowledge about what to expect, hence the need for sensing to obtain an output that approximates the opinion of the whole crowd [10].

In broad terms, crowdsensing can be divided into three main categories namely *group, community,* and *urban sensing* (see Fig. 1). Group sensing occurs when an ad hoc group formed loosely and opportunistically (e.g., spatially nearby phones) collaboratively contribute sensed data to address a localised shared problem [1]. A typical example is *SignalGuru*, a crowdsensing solution that enables vehicles passing through an intersection to sense and share the traffic signal information and adjust their driving speed accordingly [22]. Community sensing occurs when the participants in the crowdsensing tasks come from a strongly bonded community, with established social ties and trust amongst members [1, 23]. The output of community sensing is usually of very high quality as participants are more committed towards contributing to solving a common problem of interest to the community [1, 23]. Urban sensing on the other hand is a broader crowdsensing campaign targeting participants at city-scale level to contribute data from the urban landscape [1, 24]. In this case, any citizen can participate, including strangers and visitors who may not have vested interest in the phenomenon of concern [1]. Hence, the quality of output is usually not as good as those obtained in group or community sensing, and the presence of fake data is also eminent [1].

Based on the awareness and degree to which the custodians of sensing devices are involved in the architecture, each of these three types of mobile crowdsensing, i.e., group, community, and urban sensing, can be further subdivided into *opportunistic sensing* and *participatory sensing*. Opportunistic sensing is a mobile crowdsensing paradigm, wherein mobile devices are automatically used to sense data without users' knowledge or explicit action [25]. In opportunistic sensing, user involvement is minimal and the

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Fig. 1 The different types of mobile crowdsensing

mobile device itself makes decisions according to the sensed and stored data [24]. A typical example of opportunistic crowdsensing is *CrowdSense@Place*, an application that opportunistically capture images and audio clips from smartphones in order to classify places into a variety of categories such as store, restaurant, etc. [26]. However, in participatory sensing, the active involvement of device custodians is required and it is often the case that most community and urban sensing initiatives are participatory in nature [25].
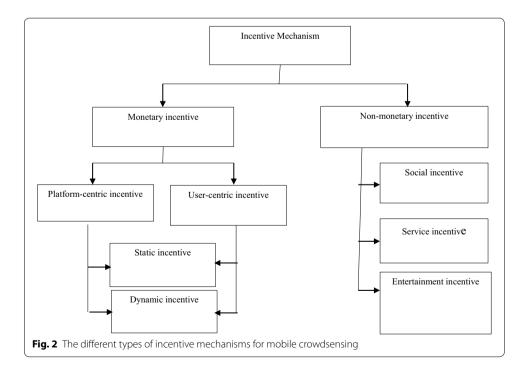
Lastly, based on those to whom crowdsensed data is shared, both opportunistic and participatory sensing can be further subdivided into three categories namely *personal, social* and *public sensing* [27]. Personal sensing involves personal monitoring and focuses on vital information such as daily life patterns and physical activities, social contacts and personal location, health vitals (e.g. heart rate, blood pressure and sugar level), etc. [24]. By aggregating data from different personal sensing activities, it is possible to detect patterns in physical and health outcomes in a given group or community. When an individual shares social information gathered from personal sensing activities with friends or other members of a social group or community, the process is referred to as social sensing [24]. On a broader scale, when mobile crowdsensing data (e.g. environmental, traffic, safety, or security related data) is shared with everyone for public good, the process is referred to as public sensing [24].

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Types of incentive mechanisms

Broadly two types of incentives can be used in mobile crowdsensing applications namely *monetary incentives* and *non-monetary incentives* as shown in Fig. 2 and described in the following subsections.

Monetary incentives

Monetary incentives are the real money or any other financial commodity such as virtual cash, redeemable credit, etc. that the users consider valuable [28]. Depending on who sets the price for a sensing task, monetary incentives can be either *platform-centric* or *user-centric* [28]. In the platform-centric model, sometimes referred to as *crowdsourcer-centric* incentive mechanism [29], the initiator of the sensing task sets the price and aims to maximize the platform's profit [30]. In the user-centric model, the reverse is the case as the price is defined by the participants [30]. Furthermore, the platform-centric and user-centric models can either operate as *static* or *dynamic* incentive mechanisms. In static incentive, the price for a task is estimated in advance and stays the same whereas in dynamic incentive, the price changes based on the minimum amount of money a participant is willing to accept to do the task [31]. In addition to participants' preference, incentives for mobile crowdsensing can also be designed to dynamically change depending on factors such as the time of day, number of available participants, location and type of data captured as demonstrated in a participation-aware incentive mechanism known as *SenseUtil* [32, 33]. Similarly, Biswas et al. [34] proposed *PISCES*, a closed-loop incentive framework that considers the sensing demand and changing availability and reporting behaviour of participants in order to compute rewards that dynamically converge to a minimum value after several trials.

Fig. 2 The different types of incentive mechanisms for mobile crowdsensing

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Non-monetary incentives
Non-monetary incentives are rewards which do not involve money or financial commodities. In broad terms, non-monetary incentives can be divided into three categories namely *entertainment, service,* and *social* incentives.

Entertainment incentives
Entertainment incentives cover rewards that motivate users based on interestingness (i.e., where users are willing to participate because they think the task is interesting and important) and enjoyment (i.e., where users find the task entertaining and enjoyable, e.g. game). Entertainment incentives such as gamification often work better in certain types of mobile crowdsensing applications, particularly those involving environment monitoring and location services [1]. The idea of gamification is to make the crowdsensing task as entertaining and engaging as possible so that users meticulously perform tasks that would ordinarily be challenging [28]. The use of games as incentive in mobile crowdsensing has certain drawbacks that need to be adequately addressed in future research. For instance, how can user-generated metadata from gaming be better managed to preserve privacy? How can the difficult task of designing games for incentivising users in mobile crowdsensing be simplified in order to increase applications in a wide range of crowdsensing contexts? Similarly, how can complicated or boring crowdsensing tasks be turned into a game that is actually enjoyable or fun to play? There is also need for research to develop standardised approach for quantitatively measuring the effect of gamification on mobile crowdsensing systems [28].

Social incentives
The use of social incentives in mobile crowdsensing applications is based on the idea that people could be motivated to participate in sensing tasks for social and ethical reasons [1]. Typical factors that drive social incentives include the need to socialise with others, reputation and social recognition [1]. People may sometimes engage in mobile crowdsensing tasks due to the good feeling they derive from doing that. This is called altruism [31]. Other factors that drive social incentive include mental satisfaction derived as result of engaging in crowdsensing tasks, self-esteem and love of the community in which a crowdsensed task is being performed [28]. For example, *CachedSensing* is a game-based incentive built on the principles of geocaching, wherein service providers interested in monitoring the environment write sensing tasks on NFC tags, hide the tags, and publish their coordinates, with the intention of exploring the altruistic nature and the spirit of competition between users who go searching and performing the defined sensing tasks [35]. Another example of social incentive mechanism is social trust assisted reciprocity (STAR) [36, 37]. STAR exploits the synergistic marriage of social trust, which is an important aspect of social relationship, and the reciprocity to stimulate mobile crowdsensing [36, 37]. Such incentive models are suited for community-based sensing where strong social ties exist and people are motivated to contribute to a common good. Jaimes et al. [38] describe such motivation to contribute to social good as *collective incentives.* Social psychological factors can also be used as non-monetary incentive mechanism to promote mobile crowdsensing activities. In this sense, some people may engage better with crowdsensing tasks when there is someone else watching

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and facilitating the process than when they are alone [28]. Just like gamification, there is also need for research to develop standardised approach for quantitatively measuring the effect of these social incentive factors on mobile crowdsensing systems [28].
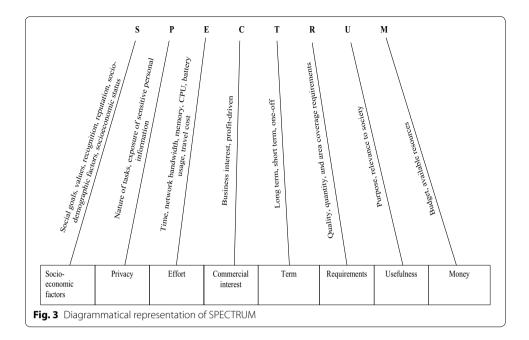
Service incentives

Service incentive is a non-monetary reward system wherein participants in mobile crowdsensing systems are asked to contribute sensed data in return for service usage [1]. Such service may be one that is offered using the aggregated crowdsensed data as demonstrated in [39–41]. In other cases, a service that provides utility to a broad gamut of society is used as incentive, not one that necessarily derives its value from the crowd-sensed data. For example, a telecommunication provider could offer users services such as free texting, free calls, mobile internet data, discounts, etc. in order to motivate them to contribute sensed data to be utilised for market research or network improvement purpose [42]. However, this type of incentive suffers certain limitations. For example, mobile phone users that are not within the service area might not be inclined to partici-pate. There might also be a problem of poor area coverage when users of the given service are not uniformly distributed across the area of interest for data capture.

Conceptual framework

Mobile crowdsensing applications are of no value if they are not adequately used by the crowd to sense phenomena of interest. The fact that today's mobile crowdsensing applications rarely scale up to more than 1000 participants is an issue of concern, particu-larly for densely populated urban areas [3]. Based on synthesis of relevant literature, this section presents a SPECTRUM of factors that broadly covers the various aspects that should be considered before adopting or designing incentive mechanisms for mobile crowdsensing applications. SPECTRUM is an acronym for a number of factors, i.e., socioeconomic factors, privacy, effort, commercial-interest, term, requirements, useful-ness, and money, which are described in the following subsections and represented dia-grammatically in Fig. 3. It is envisaged that the concept of SPECTRUM will help shape thoughts and decision making related to improving the use and adoption of mobile crowdsensing applications. It can also help to facilitate understanding and highlight areas where additional actions can be taken to improve participation in existing mobile crowdsensing applications.

Socioeconomic factors

In adopting an incentive mechanism for mobile crowdsensing applications, it is impor-tant to consider the social and economic makeup of participants in the target com-munity. From an economic perspective, people are more inclined to participate in crowdsensing if they perceive that the outcome will improve their economic status. From a social perspective, mobile users are considered to have social goals, values and rela-tionships that strongly influence their behaviour to participate in crowdsensing activities [37, 43, 44]. These values and goals vary from one individual to another. For some it is a desire for cleaner and safer cities [10]; for others it is the need to socialise, gain reputa-tion, or receive the recognition of their community [1]. Understanding people's social values is therefore an important step towards adopting the most appropriate incentive

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Fig. 3 Diagrammatical representation of SPECTRUM

to motivate them to engage actively in mobile crowdsensing. This view is consistent with previous studies (e.g. [45, 46]) which have shown that citizens' sociodemographic characteristics influence their participation in city-wide urban development initiatives.

In addition, Wu and Luo [8] have also highlighted the need for incorporating socioeconomic factors into the design and implementation of incentives for citizen engagement in civic service. Such socioeconomic factors can sometimes influence and lead to preference for certain types of incentive mechanisms. For example, if a community is mainly dominated by students and low income earners, the preference for monetary incentive is easily justified in terms of efficiency and veracity compared to if the community members were predominately people of affluence and enviable socioeconomic status. Similarly, Talasila et al. [47] noted that for a social category and age group that is young and vibrant, gamification stands out as a powerful incentive that can be used to motivate a small number of participants to cover the mapping of a large region with sensor readings. In addition, social recognition incentives that make participants feel appreciated and their contributions valuable are considered to be key priorities in cases where people's interest to participate in civic service have been negatively affected by their poor socioeconomic status and the resultant low self-esteem [48]. It is therefore important to consider socioeconomic factors and to characterise participants into different social groups or networks based on demographic composition, values, ties and motives in order to accurately adopt an incentive that is most appropriate for each group.

Privacy

Privacy is an important factor that should be considered when adopting incentives to facilitate participation in mobile crowdsensing. The privacy issue associated with mobile crowdsensing applications arises from the potential to incidentally collect sensitive data about participants [25]. For example, community sensing applications that collect and

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aggregates sensed data in large-scale run the risk of accidental leakage of personal information such as sensitive images and health-related outcomes [2, 49]. RFID sensor tags in wearable devices can be used to uniquely identify and track users [50]. GPS sensor readings can reveal sensitive information about an individual's daily commutes, including routes to home and work locations [25]. Understandably, people are sensitive to how sensor data is captured and utilised, and would be reluctant to contribute to crowdsensing campaigns if they are not reasonably convinced that their privacy will be adequately protected in the process [51]. Service providers are also aware that the breach of privacy protection legislation can attract significant compliance liability in most organised societies [52]. As a result, privacy-preserving mechanisms that ensure personal information cannot be gleaned from mined patterns have become key priority requirements in designing incentives for mobile crowdsensing [1].

Several of such privacy-preserving mechanisms have been proposed in the literature. For example, anonymization and pseudonymity are popular privacy-preserving mechanisms, which obscure personally identifying information in sensed data [53]. The limitation though, is that anonymization leads to false perception of privacy protection because the use of reverse address lookup technique on GPS sensor readings can still reveal frequently visited locations of individuals and therefore derive their personal details [25, 53]. This issue of location-based privacy is mostly addressed by mechanisms based on k-anonymity [53]. The idea behind k-anonymity is to build groups of k participants that share a common attribute (e.g., k participants living in the same neighbourhood), such that it becomes difficult to distinguish one from another [53]. In addition, privacy-preserving mechanisms based on cryptographic techniques have been suggested, but such solutions lead to high energy consumption and scalability is often an issue [25]. Similarly, perturbation based approaches, which carefully add artificial noise (e.g. Gaussian noise) to sensed data in a manner that does not affect the accuracy of statistical trend has been proposed as one of the viable solutions for preserving user privacy in mobile crowdsensing applications [25, 53]. These aforementioned privacy-preserving mechanisms as well as other privacy-aware sensing model and architecture already described extensively by Khan et al. [24] (e.g. Secure SocialAware, SmokeScreen, and Prisense) provide real opportunities to address privacy concerns and improve the efficacy of different types of incentive schemes used for facilitating large-scale mobile crowdsensing campaigns.

However, given that these privacy-preserving mechanisms can sometimes incur significant implementation overhead, it is important to understand the triad relationship between the nature of the sensing task, privacy criticality and the different types of incentive mechanisms in order to adopt the most appropriate incentive for motivating data contributors. Gustarini et al. [54] demonstrated that the nature of sensing task can influence participants concern about privacy and therefore the type of incentive required. For example, sensing tasks that allow citizens to provide evidence for prosecuting criminals require high level of privacy to ensure the safety of participants, particularly when the underlying incentives are purely social (e.g. desire for safer cities). The Boston Marathon bombing, wherein tens of thousands of images and videos were contributed by citizens for analysis, presents a real-world experience to substantiate the above example [55]. However, if monetary incentive was to be used instead in the Boston

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Marathon bombing case, privacy preservation or anonymization becomes really difficult, particularly because of the need to accurately identify and reward users who have contributed relevant data. Krontiris and Maisonneuve [56] describe this phenomenon as the tension between social translucence and privacy. For similar reason to accurately identify and incentivise citizens with monetary rewards, the *CityZen* crowdsensing solution requires registration and authentication of users, potentially minimising the level of privacy protection anonymous participants would otherwise enjoy [57]. In this sense, an inverse relationship between privacy and monetary reward can be gleaned i.e. the higher the money involved, the greater the need to collect personally identifiable information of participants and hence, the lesser the privacy. This is further supported by evidence from a previous study [58] suggesting that money can quickly incentivise people to forgo their privacy. More specifically, the study found that people are willing to provide sensitive information about themselves for as low as 1 Euro [58]. Understanding how the criticality of privacy changes with different sensing tasks and with the use of different incentives is therefore important when adopting incentive mechanisms for mobile crowdsensing initiatives.

Effort

In designing an appropriate incentive scheme for mobile crowdsensing applications, it is important to consider the anticipated effort required by the user to perform the sensing tasks. This is crucial because failing to offer incentives that are worth performing the sensing tasks can lead to poor adoption of mobile crowdsensing systems [1]. One can think of effort in terms of the time and resources (e.g. network bandwidth, memory, CPU, battery usage etc.) consumed in performing sensing tasks [10]. Occasionally, other indirect costs (e.g. the cost of travelling to a specified sensing location) may also be incurred [59]. The effort required in performing sensing tasks varies as different crowdsensing practices place varying demands on users' mobile devices. For instance, *piggyback crowdsensing*, wherein the tasks of capturing and uploading sensed data are performed in parallel with phone calls, helps to save energy consumption on participants' mobile devices [60–62]. Whereas, *peer-to-peer (P2P) mobile crowdsensing* that allows storage and computational functions to be performed on user devices, tend to consume more resources in participant's gadgets [63]. Depending on the sensing tasks, each participant will incur varying level of direct and indirect costs. Hence, accurately estimating the appropriate effort required for each participant and monitoring how that will change with time and context is vital in order to efficiently incentivise citizens to actively engage in mobile crowdsensing. Gao et al. [64] reported that rewarding participants according to their actual contributions is more likely to result in increased participation compared to a strategy that pays a blanket amount to all data contributors. Based on observations of previous studies, they noted that offering more rewards does not necessarily translate to an overall increase in total aggregated data received if the same amount of reward is paid to all participants [64]. This implies that the "one-size fits all" reward mechanism is not a robust option and more intelligent approaches that consider the actual effort of data contributors are required. In designing incentive mechanisms to reward the actual effort of participants, consideration is sometimes given to the work done in introducing or recruiting new users into the crowdsensing system [65]. The

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adoption of this type of incentive mechanism by the winning team of the 2009 DARPA Red Balloon Challenge, i.e., the team from Massachusetts Institute of Technology, clearly demonstrates its effectiveness [66]. Such reward mechanisms, often known as geometric incentive schemes, compensate users with additional passive incentive or a proportion of the rewards earned by participants they introduced/recruited to the crowdsensing system and those of every other participant that has joined under that referral tree [65]. However, the free riding behaviour of participants who earn large passive rewards means that the huge number of individuals recruited through geometric incentive mechanisms does not always translate to a proportionate effort and the budget required to compensate participants can be quite high [65].

Based on available budget, Angelopoulos et al. [67–69] recommend several strategies to reward the effort of data contributors in mobile crowdsensing, including proportional incentive policy, participation-aware incentive policy, behavioural-aware incentive policy, location-aware incentive policy, mobility-aware incentive policy, thrifty incentive policy and quality-aware incentive policy. Proportional incentive policy advocates that for each task segment, incentive proportionate to the expected utility and the current residual budget be allocated, from which the effort of participants who have contributed data to the task segment can be rewarded accordingly [69]. Participation-aware incentive policy recommends that the efforts of data contributors be initially rewarded with high incentives in order to stimulate the crowd and attract a minimum percentage of participating agents [67]. Afterwards, the efforts of data contributors should be rewarded in a more conservative manner that is good enough to retain` existing participants, not necessarily attracting new ones [69]. Behavioural-aware incentive policy rewards participants based on historical records of their trustworthiness and commitment to the crowdsensing initiative [68]. Location-aware incentive policy selects participants by virtue of their locations or rewards participant's effort according to the cost associated with the given location where data is captured while mobility-aware incentive policy rewards participant's effort according to the frequency with which the user moves around the area of interest to capture data [68, 70]. Thrifty incentive policy aims at rewarding participants in such a way that ensures available budget is used prudently and resourcefully. Quality-aware incentive policy seeks to reward the efforts of participants in a manner that is proportionate to the quality of data contributed. The rationale for the quality-aware incentive policy is to attract high quality participants by offering higher amounts of incentive [67]. However, Jin et al. [71] and Wang et al. [72] propose quality-aware incentive mechanisms (QIMs) that strike a balance between quality and cost of data. These QIMs, which are based on reverse auctions, do not reward participants on the basis of just the quality of their data, but rather optimise the selection of participants by taking into consideration both the quality and the price of their data [71, 72].

The amount and type of incentive to be adopted can also depend on the nature of the sensing task [47]. The underlying assumption is that tasks that are more difficult and demanding would require greater effort and therefore higher amounts of incentive. In principle, monetary incentives are considered to be more suitable for sensing tasks that require significant manual effort while gamification is more appropriate when the sensing task does not have tight time constraints and its requirement can be easily translated into an enjoyable game action [47].

Commercial interest

With the rapid growth in the Internet of Things and the advancement in big data and cloud-based technologies, combined with the increasing sensing and processing power of ubiquitous mobile devices, the concept of sensing as a service has emerged to fully maximise the commercial opportunities in mobile crowdsensing [73, 74]. In this regard, mobile crowdsensing has been described as a new business model, wherein the sensing platforms are designed to be profit-oriented, e.g., [75–77] and the difference between the value derived from the crowdsensing based services i.e. sensing revenue and the total rewards paid to participants i.e. sensing cost [78], is the service provider's profit, not taking into account other operating costs [9, 79]. However, as observed with the traditional crowdsourcing market, the maturing of the commercialisation of mobile crowdsensing applications can potentially cause users' expectations about incentives to shift significantly towards monetary rewards. Typically, one would expect that users' motives and rationalisation for participation will be driven by the desire to have a share in the profit generated from the business venture. Hence, in adopting a suitable incentive mechanism for a crowdsensing initiative, it is important to consider that the presence of commercial-interest can cause a bias towards monetary incentives. Commercial interest as discussed here does not refer to profit made through advertisement in the platform but rather focuses on income that directly accrues from the use of the collected data.

Term

In designing incentives for mobile crowdsensing applications, an important factor that is often ignored is term. Term, otherwise referred to as *shelf life*, is the period for which the crowdsensing initiative is intended to last [80]. Some crowdsensing applications, by virtue of the purpose they serve are only active seasonally, e.g., the *PetaJakarta* system used during the monsoon seasons for crowdsensing flood conditions in Jakarta [81]. Other crowdsensing applications may operate in short term, e.g., a one-off initiative, sometimes lasting just few hours [82] or long term basis [64, 83]. Sun [84] and Sun et al. [85] noted that it is important to consider the term when designing profitable and sustainable incentive mechanisms for mobile crowdsensing. The incentive mechanisms to keep participants in the crowdsensing loop on long-term basis are more complicated than those required for short term sensing activities [64]. For example, in long-term or ongoing sensing campaigns, users may find the sensing tasks repetitive and boring over time. Incentives may become undervalued or inadequate as a result of significant improvement to the socio-economic conditions of participants. In addition, Salim and Haque [86] noted that when participation in mobile crowdsensing is required for a long term, incentives are considered to be highly relevant compared to when it is for short term.

Similarly, Gao et al. [64] noted that short-term sensing incentive may not sufficiently guarantee the long-term continuous participations of users. This is usually the case when the receipt of the short term incentive is irregular in the long term. For instance, if a user observes that the receipt of an acceptable incentive has suddenly become irregular due to low success rate in an auction based incentive mechanism, the user may lose interest and eventually drop out of the sensing loop [64]. One solution to this problem though is an incentive mechanism that automatically lowers the bids of users who were unsuccessful in the previous round of auction, in order to increase their chances of winning in

future auction rounds [64]. Similarly, Nan et al. [87] and Guo et al. [88] recommend paying well-performed losers a minimal amount that is encouraging enough to keep them in the sensing loop.

Furthermore, the duration of a sensing task plays an important role in determining the most appropriate incentive mechanism to adopt [47]. For long term sensing tasks, the gaming approach is considered not suitable because the game design for strong in-game incentives to keep players engaged over a long time is extremely difficult and in many cases defiling the essence of the sensing task [47, 89]. For such long term sensing efforts (e.g., 1 year) where gamification cannot continuously sustain participants' motivation, it is speculated that monetary incentives would be more effective because man's want for money is insatiable [47, 89]. Money is a strong influence on people and still remains the most appropriate incentive for crowdsensing tasks that impose tight constraints on participants, including strict timing of sensing event [47]. Monetary incentives should therefore be prioritised over social and entertainment incentives when it is crucial to quickly lure citizens into participating in sensing tasks that have strict timing requirement [47].

Requirements

Requirements as defined here refer to the specification of the mobile crowdsensing application in terms of quality, quantity, and area coverage. Reddy et al. [90] highlighted these three factors as the key performance metrics of any mobile crowdsensing system. Every mobile crowdsensing initiative is unique and the requirements in terms of quality, quantity, and area coverage vary. Hence, in order to adopt the most appropriate incentive to help attain the specific requirements of the sensing tasks, it is important to understand which type of incentive mechanism works best for each of these factors, i.e., area coverage, quality and quantity of crowdsensed data. This can be a challenging task, especially when the associated cost or affordability of the incentive mechanism is taken into consideration. Zhang et al. [91] relate to this as the "4A" requirements, which are affordability, accuracy (i.e. quality), availability (i.e. coverage) and adequacy (i.e. quantity). The need to satisfy these requirements is driving new crowdsensing paradigms, including the concept of *sparse mobile crowdsensing* [92]. Sparse mobile crowdsensing, which aims to reduce the overall sensing cost without compromise of data quality, functions by allocating sensing tasks for only a small portion of the target area to be covered while inferring the data of the remaining unsensed area based on the spatial and temporal correlation among the data captured from different sub-areas [92]. An obvious limitation of sparse mobile crowdsensing is that it may not be ideal for applications in which data quantity is as important as data quality.

The quantity of crowdsensed data can be increased in many ways, including monetary rewards and gamification incentives [93]. In using monetary reward to increase the quantity of crowdsensed data, Sarma et al. [94] recommend that the budget be optimally split, such that one portion is allocated to advertisement targeted at attracting participants while the remaining portion is used for actual compensation of participants' effort. The basic assumption behind the use of monetary incentives for increasing the quantity of crowdsensed data is that participants are motivated by the desire to increase financial gains and so tend to engage more in crowdsensing activities [1]. This strategy

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of rewarding participants according to their level of contribution is described by Sarma et al. [94] as *proportional incentive*, which is different from *equal incentive* where the same amount is paid to all participants irrespective of the quantity of data contributed [94]. The downside of proportional incentive is that the desire to gain more money may cause some participants to contribute fake data as evidenced in a recent experimental study where monetary reward was used to incentivise citizens [47]. The results of the study show that though the quantity of data received increased by 15 %, there were also plenty of fake data submitted mostly by the top 20 high earners [47]. For this reason, gamification is sometimes used instead as a viable incentive for increasing the quantity of data in mobile crowdsensing [93]. When used as an incentive, gamification can help to motivate users to increase the quantity of data contributed, both in terms of diversity and amount of data [8].

Data quality in mobile crowdsensing can also be increased by both monetary rewards and gamification incentives [93]. A recent study by Talasila et al. [47] demonstrated that by increasing the monetary reward assigned to crowdsensing tasks, the quality can also be improved. Sun and Ma [95, 96] and Micholia et al. [97] show how improvement to the quality of crowdsensed data can be achieved while still constraining the monetary incentive mechanism to work with a fixed budget. In improving the efficacy of monetary incentives as means of enhancing data quality, Guo et al. [89] proposed several strategies implemented in *TaskMe*, including dynamic budgeting, data quality evaluation metrics (e.g. completion ratio, quality indicator), competitive worker selection and quality check that occur after users complete tasks and submit their data along with bid price, and a multi-payment system that rewards not just the winner, but also a few high ranking losers as determined by available budget. Importantly, this strategy of competitively selecting workers at the completion of tasks can potentially eliminate the issue of uncertainty about the eventual participation and contributions of users as discussed in [98]. Furthermore, Kawajiri et al. [93] demonstrated that the quality of crowdsensed data can be directly increased through gamification. This is an important step forward from the traditional idea of indirectly improving the quality of data by increasing the quantity [93]. Few other studies that have used gamification in urban-scale crowdsensing initiatives include [98, 99].

In most urban-scale crowdsensing initiatives, area coverage is a major requirement, which if not adequately addressed can undermine the robustness of the system. The problem of area coverage occurs when the regions of interest have geographically unbalanced number of participants (i.e., plenty of participants in some areas and little or none in others) or when the data of interest have geographically unbalanced prices (i.e., very expensive in some areas and cheap in others) [45]. Based on analysis results from a recent study, Talasila et al. [47] suggest that gaming is the most appropriate incentive for attaining uniform area coverage because it is a cost-effective solution that has great potential to motivate participants to capture data from both popular and unpopular regions. Example of such mobile crowdsensing solutions designed based on gamification incentives to achieve fast and efficient area coverage are *Alien vs. Mobile User* and *Crowd Soft Control* proposed in [100] and [101] respectively. Nevertheless, Albers et al. [102] opine that the use of monetary incentives such as location-dependent coupons that are only redeemable in a certain part of a city (i.e., target area) can effectively steer users to collect data from the target area. Similarly, Mendez and Labrador [103] proposed the

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concept of *density maps* to generate the number of participants and the locations that should be covered in the data collection exercise so that incentive mechanisms can be properly oriented to satisfy the crowdsensing requirements in a cost effective manner.

Usefulness

Usefulness relates to the purpose for which the crowdsensed data is being collected. The usefulness of a crowdsensing initiative has an inherent ability to positively or negatively influence user participation. If the usefulness of the crowdsensing campaign is considered a public good and has a broader appeal and relevance to the target community, people will be more inclined to participate based on ordinary social incentives. Typical crowdsensing activities that appeal to the broader community include those related to public safety and security [1]. For example, the city-scale participation in the Peta-Jakarta.org system, a mobile crowdsensing solution used for producing open, real-time situational overview of flood conditions in Jakarta is mostly driven by users' motivation to contribute to public good and safer communities [81]. In rare situations where the crowdsensing initiative is highly useful and provides unique benefits or opportunities to the participants (e.g., submission of auditioning videos for actor/actress roles), a *reverse incentive* scheme, in which the participants pay the service provider instead, may be adopted as demonstrated with the crowdsensing application known as *Medusa* [104]. Similarly, when the crowdsensing application is considered very useful to participants, Tomasic et al. [105] show that simple incentives such as the *quid pro quo* (QPQ) approach can be effective. The QPQ approach reminds users to contribute data without which they are denied access to the system [105]. QPQ is ideal for highly useful crowdsensing applications and it is again the basis for the incentive adopted in [106]. Importantly, Tham and Luo [107] noted that such highly useful crowdsensing applications, in which users are both contributors and consumers of service, require deeper investigation of issues bothering on social welfare and fairness of incentive mechanisms. Conversely, when the purpose of a crowdsensing initiative does not appeal to the broader community, a stronger incentive such as monetary reward is required to be provided by the service provider in order to sufficiently motivate users to participate in sensing data. It is therefore important to consider the usefulness of the crowdsensing initiative when deciding on the most appropriate incentive for a crowdsensing campaign.

Money

Money refers to the financial budget and other resources available for implementing the crowdsensing project. From an economic standpoint, it is important to carefully consider the available resources, including financial and non-financial assets such as technological infrastructure, human resources, skillsets etc. and adopt the most economically viable incentive mechanism that would yield maximum pay-off from the crowd [67]. Depending on the scale of the sensing campaign, monetary rewards can be far more costly than social and game incentives because of the payments involved [108]. Hence, when the available fund for the crowdsensing project is little and impracticable for motivating large-scale participation, monetary incentives should be discouraged and social ones adopted where feasible.

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Adoption of incentive mechanisms in real-world mobile crowdsensing applications

Numerous incentive mechanisms (e.g. [11–16]) have been proposed in the literature, but not many of them have been applied in real-world crowdsensing applications. Viewed with the lens of SPECTRUM, Table 1 shows how a combination of factors could influence the choice of incentive used in real-world mobile crowdsensing applications. The real-world mobile crowdsensing applications listed are those which have specifically considered incentive options for motivating participants. Crowdsensing initiatives that collect data on an ongoing basis are classified as long term. Examples include NoiseMap [111], NoiseTube [112] and NoiseSPY [113] that collect data on an ongoing basis in order to monitor noise pollution in the urban environment.

In Table 1, the classification of privacy and effort into "high", "low", or "moderate" is based on the nature of crowdsensing task. Tasks that have high likelihood of personal information been exposed are considered to have high privacy risk. Similarly, tasks that demand greater usage of network bandwidth, memory, CPU, battery, personal time and participant's skills are considered to require high effort. Furthermore, when compared with evidence from literature, it is observed that only an insignificant number of real-world crowdsensing applications have discussed money or budget as a constraining factor in adopting incentive mechanism. However, from an economic standpoint to minimise cost, it can be assumed that the role of money or budget as a constraining factor in adopting incentive mechanism is implied.

From Table 1, it can be seen that most real-world mobile crowdsensing applications prioritise the adoption of non-monetary incentives such as social, service and entertainment (e.g. gamification) incentives over monetary ones. This is usually the case (e.g. [109, 111–113, 116, 117]) when the crowdsensing initiative is considered useful to the general public and participants' socioeconomic needs can be met in the process. However, except for Waze [110] that provides strong social incentives, it is observed that when the crowdsensing initiative is motivated by a commercial or business interest to make financial profit (e.g. [114, 115]), monetary incentive is often used instead to reward participants. These opt for monetary incentive is justified, considering that users' motives and rationalisation for participation may be influenced by the desire to have a share in the profit generated from the business venture.

Applying SPECTRUM in real world: the case of PetaJakarta

Using the PetaJakarta system as a case study, this section presents an exemplary discussion of how the concept of SPECTRUM (i.e., socioeconomic factors, privacy, effort, commercial-interest, term, requirements, usefulness, and money) can be applied in adopting the most appropriate type of incentive mechanism for real-world crowdsensing applications. The PetaJakarta system is selected for this discussion based on the author's experience and familiarity from working on the project. The PetaJakarta system is a crowdsensing application that harnesses the power of social media and the ubiquitous nature of mobile devices to gather, sort, and generate real-time maps of flood conditions in various parts of coastal mega-cities such as Jakarta, Indonesia [81]. Developed by the SMART Infrastructure Facility of the University of Wollongong, Australia in collaboration with the Jakarta Emergency Service (well known as BPBD DKI Jakarta) and Twitter

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Table 1 SPECTRUM applied to real-world mobile crowdsensing applications

Mobile crowd-sensing application	Socioeconomic factors Will participants' social or economic needs be met?	Privacy Is there high privacy risk?	Effort Is the effort required generally considered to be high, low, moderate?	Commercial-interest Is there a business interest or motive to profit financially?	Term Is the term long, short, or seasonal?	Requirements Is there a strict requirement in terms of data quality, quantity, or area coverage?	Usefulness How beneficial is the collected data to the general public?	Money How well is money or other available resources a limiting factor?	Type of incentive adopted
BudBurst Mobile [109]	Yes, social interactions with other users	Moderate	High	No	Seasonal	Area coverage	Understanding the effects of global climate change	Not discussed; implied	Gamification i.e. floracaching game; altruistic contribution to scientific knowledge of plant's life cycle
Waze [110]	Yes, social needs are met through gaming entertainment; economic through time and gas money savings in traffic	High	Low	Yes	Long term	No	Helping citizens save time and gas money on their daily commute through road traffic	Not discussed; implied	Gamification; other social incentives such as increased reputation in community, savings on fuel when commuting
NoiseMap [111]	Yes, need for a serene urban environment; social interactions with other users	Moderate	Moderate	No	Long term	Quality and quantity	Monitoring of urban noise pollution	Not discussed; implied	Social i.e. ranking of participants according to contributions
NoiseTube [112]	Yes, need for a serene urban environment	Moderate	Moderate	No	Long term	No	Monitoring of urban noise pollution	Not discussed; implied	Social i.e. altruistic contribution to local environment

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Table 1 continued

Mobile crowd-sensing application	Socioeconomic factors — Will participants' social or economic needs be met?	Privacy — Is there high privacy risk?	Effort — Is the effort required generally considered to be high, low, moderate?	Commercial-interest — Is there a business interest or motive to profit financially?	Term — Is the term long, short, or seasonal?	Requirements — Is there a strict requirement in terms of data quality, quantity, or area coverage?	Usefulness — How beneficial is the collected data to the general public?	Money — How well is money or other available resources a limiting factor?	Type of incentive adopted
NoiseSPY [113]	Yes, need for a serene urban environment	Moderate	Moderate	No	Long term	No	Monitoring of urban noise pollution	Not discussed; implied	Social i.e. altruistic contribution to local environment
Crowdsignal and Algosnap [114]	Yes, economic reward	Low–High	Low–High	Yes	Short–long term	Quality, quantity and area coverage	Data for academic research	Reward is based on budget and task	Monetary
Premise [115]	Yes, economic reward	Low–High	Low–High	Yes	Short–long term	Quality, quantity and area coverage	Data used by private companies and partners	Reward is based on budget and task	Monetary
GasMobile [116]	Yes, need for cleaner city	Moderate	Low	No	Long term	Quality	Monitoring of urban air pollution	Not discussed; implied	Service i.e. Information feedback
Ikarus [117]	Yes, through paragliding sport.	No	Moderate	No	Long term	Not a necessity	Sensed data is used to create thermal map for the paragliding community	Not discussed; implied	Social i.e. increased reputation in the paragliding community
LiveCompare [118]	Yes, grocery shoppers save money on purchase	Moderate	Moderate	No	Long term	No	Only participating grocery shoppers save money on purchase	Not discussed; implied	Service i.e. grocery bargain hunting

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Inc., the PetaJakarta system relies on citizens with mobile devices to report the locations of flood events by posting geotagged "tweets", preferably with an embedded image and text description of flood conditions (e.g. water height) in their localities [81]. Based on the aggregated geo-located tweet data, a publicly accessible city-scale map of real-time flood conditions is generated, thereby facilitating swift assessment, emergency response and management of flood hazards [81]. Interestingly, this system has been deployed in the city of Jakarta without explicit recourse to any viable mechanism for incentivising citizens. Hence, the steady dwindling of tweet reports from citizens has put the discussion around a potential incentive mechanism on the front burner of priority research challenges. Here, the role of SPECTRUM in guiding that decision to select an appropriate incentive mechanism is discussed.

Socioeconomic factors constitute an important element of SPECTRUM. In the context of Jakarta, a densely populated city with many underprivileged citizens seeking to improve their economic well-being [119], one would think that low-priced monetary incentive will be effective in motivating people to engage in the crowdsensing process. However, given the terrain in which citizens are expected to collect data, i.e., flood conditions, there is a tendency that the use of monetary incentives will strongly influence the urban poor struggling to acquire enough earnings for daily survival to engage dangerously with flood hazards, potentially creating ethical and legal risks for the service provider. Similarly, gamification has entertaining and strong influences on people and one can hardly justify the appropriateness or rationality in engaging citizens with games while flood disasters unfold, with risk of harm to people's property and loved ones. Nonetheless, when the social perspective is taken into consideration, a unique opportunity emerges- the citizens of Jakarta have strong social values as reflected in their engagement with social networks and are rated the "biggest tweeting" city in the world [120]. Many Jakarta citizens already share values in (safely) exchanging real-time flood information using social media. These social values combined with altruism and the desire for a safer city have so far contributed to some meaningful activities in the PetaJakarta system. It is therefore important that the introduction of a concrete incentive mechanism reinforces these social values, not destroy them as a monetary incentive could potentially do when introduced [28]. On the basis of socioeconomic factors, a well-designed social incentive, which poses no ethical and legal concerns is considered a better option than monetary or gamification rewards.

Privacy is the second element in SPECTRUM. In the context of Jakarta, privacy concerns exist, particularly for the urban poor living in informal settlements or slums situated along the watersides [119]. These people may be reluctant to contribute geo-located tweets because of fear that they will be traced by the government and punished for living in illegal settlements. Though money can quickly incentivise people to forgo their privacy [58], the issues raised above with monetary incentives remain a concern in that context. Rather, it is argued that societal recognition of slum dwellers and their role in community building be strongly emphasised in PetaJakarta campaigns and endorsed by government authorities as an aspect of social incentive to motivate contributions from the millions of Jakarta's citizens residing in slums. Anonymity should also be encouraged as possibly permitted through the twitter user account.

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In terms of effort, tweeting can be considered "effortless" and enjoyable for active users of social media. However, to compensate for the resources consumed on user devices, outstanding contributors should be identified and given social incentives such as community recognitions and awards. These awards or prizes could include coupons, which are still safer than traditional monetary incentives that pay a price for each relevant data contributed.

When commercial interest as an element of SPECTRUM is considered, the ground for monetary incentive is again weak in the case of PetaJakarta because the system is not profit-driven or designed with the intention to make economic returns. Citizens' expectation of monetary rewards is therefore low in such a system that is designed for common good. A social or collective incentive is considered more appropriate in this case to motivate citizens to contribute to social good [38]. With regards to term as a component of SPECTRUM, the PetaJakarta system is used seasonally in Jakarta during the annual monsoon period, typically between November and March [121]. The period between each consecutive monsoon season provides sufficient time to instigate or rekindle citizens' motivations for data contribution by embarking on social programmes for flood preparedness, including campaigns and advertisements for PetaJakarta, community recognition and celebration of citizens who were outstanding in their contributions during the last crowdsensing regime.

Requirement as an element of SPECTRUM refers to the quality, quantity and area coverage needs of the crowdsensing system. These three factors are vital for the success of the PetaJakarta system, but the quality of tweets (e.g. accuracy of GPS location, quality of embedded image, etc.) is most important for decision making. A fair and well-designed social incentive scheme that highlights and recognises outstanding contributors based on the quality and quantity of data submitted is an important step in the right direction. Admittedly, area coverage is better addressed with gamification or monetary incentives and social rewards will have very limited effect. To address area coverage in PetaJakarta, a social incentive can be complemented with the concept of sparse mobile crowdsensing [92], previously discussed in "Requirements" section, by inferring missing data from poorly sensed areas based on the spatial and temporal correlation among the data captured from areas that are adequately covered.

Usefulness is a key element of SPECTRUM, which influences the type of incentive that should be adopted for mobile crowdsensing. PetaJakarta finds its usefulness in improving public safety from flood hazards and can be considered a public good, with broader appeal and relevance to the citizens of Jakarta. Citizens would therefore be inclined to participate in the use of PetaJakarta, based on social incentives that encourage altruistic behaviours and the desire for safer communities. Furthermore, money as an element of SPECTRUM is a key factor that determines if monetary incentive is appropriate for a crowdsensing initiative or not. In Jakarta, the shortage of funding and the meagre budget available for disaster management demands that low cost approaches such as social incentives be adopted for incentivising data contributors to the PetaJakarta project [119]. In a nut shell, by consideration the various elements in SPECTRUM in relation to the unique context of the PetaJakarta system, one can infer that social incentives are most appropriate for motivating citizens of Jakarta to participant in the crowdsensing process. Other real world application scenarios may present their unique characteristics

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and constraints, but SPECTRUM will still be found useful in shaping thoughts and guiding decision making to adopt the most appropriate incentive scheme. More importantly, the use of SPECTRUM would ensure that decision makers do not miss out on any of the key factors that would influence the choice of incentive mechanism for their specific mobile crowdsensing initiative.

Discussions

This study has presented the concept of SPECTRUM to represent the range of factors, namely socioeconomic factors, privacy, effort, term, requirements, usefulness and money, that should be carefully considered in order to adopt the most appropriate incentive for mobile crowdsensing applications. The intuitive premise behind the concept of SPECTRUM is that decision makers can make more robust decisions that consider exhaustively the key factors that significantly influence the choice of incentive for motivating large-scale participation in mobile crowdsensing. When considered together, these factors presented in "Conceptual framework" section and represented diagrammatically in Fig. 3 do not prescribe any particular type of incentive, but rather give decision makers sufficient information to make more balanced and robust decisions based on how each of the factors relate to the crowdsensing context and any specific objectives.

Although SPECTRUM is a conceptual framework, the factors upon which it is established have been strongly recommended as key attributes influencing the choice of incentives in mobile crowdsensing [47, 108]. For instance, Talasila et al. [47] recommend that the designers of mobile crowdsensing systems consider key factors such as the desired spatio-temporal properties of the data (i.e. accounting for area coverage and timing requirements), the level of data reliability required (i.e. accounting for quality and quantity requirements), the monetary cost, the user privacy, the user effort and the resource consumption on mobile devices. They added that going forward, all these factors need to be considered by designers when building systems and choosing an appropriate incentive for a particular crowdsensing situation [47]. Similarly, Zaman et al. [108] recommend that when determining the reward for participants in mobile crowdsensing, several factors should be considered including, spatio-temporal characteristic of the event (i.e. again accounting for area coverage and timing requirements), privacy valuation, fairness (i.e. accounting for users' effort in terms of adequacy of reward), purpose of sensed data (i.e. addressing usefulness) etc. The concept of SPECTRUM addresses all of the aforementioned factors. It is hoped that by proposing the concept of SPECTRUM and highlighting the state of knowledge in relation to the outlined factors, the groundwork is laid for empirical investigation into how various factors may influence the type of incentive mechanism that is considered most appropriate for any given crowdsensing task.

In terms of practical implication, the outlined conceptual framework, i.e., SPECTRUM, can enable urban computing professionals and researchers consider a broader range of factors and consequently adopt the most appropriate incentive mechanism to attain large scale participation and citizen engagement in mobile crowdsensing. This implies that cities can get smarter and better equipped to develop new intelligence in monitoring, understanding and responding to a wide range of urban problems.

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Research opportunities and challenges

With the introduction of the outlined conceptual framework come new research opportunities and challenges that need to be further investigated in order to fully explore the potential of SPECTRUM in improving citizen participation in mobile crowdsensing. While the adoption of the most appropriate type of incentive as facilitated by SPECTRUM is a crucial step towards improving citizen participation in mobile crowdsensing, actual engagement of participants will also depend strongly on whether the right incentive has been properly designed and implemented. Hence, in highlighting research challenges and areas where further studies are needed to improve citizen participation in mobile crowdsensing, it is important to consider design and implementation issues relevant to the different factors outlined in the concept of SPECTRUM.

For a start, the concept of human grouping which has emerged as a way to simplify the process of understanding and utilising socioeconomic factors in selecting an appropriate incentive is yet to be fully explored in the context of mobile crowdsensing [1]. The idea behind human grouping, for purpose of designing effective incentive mechanisms, is that participants in each group will share similar social and economic goals, different from other groups and hence would be motivated differently. The importance of incorporating human grouping into mobile crowdsensing, a process described by Lane [122] as *community-aware sensing*, has been emphasised in several studies, including [123, 124]. *GroupMe*, proposed in [124] is a giant stride in this direction to help facilitate the discovery of groups within mobile crowdsensing systems. However, several research challenges still need to be adequately addressed in order to fully maximise the potential of using human grouping to improve the outcomes of decision making related to appropriateness of incentive mechanism. A typical example is how to accurately design robust solutions to automatically identify and characterize mobile users into virtual communities and social networks in a way that is both dynamic and privacy-friendly.

Privacy is a reoccurring term in mobile crowdsensing research and also the second factor in the concept of SPECTRUM. As earlier highlighted in this study, a key priority requirement that must be considered when designing incentives for mobile crowdsensing is the need for privacy-preserving mechanisms that ensure personal information cannot be gleaned from mined patterns [1]. Unfortunately, the design of privacy-preserving mechanisms is hampered by the fact that there is a trade-off between privacy guarantees and sensing fidelity [53]. The enforcement of privacy-preserving measures often degrades the quality of sensed data, thus also potentially decreasing its utility [30]. Worse still, individual perception of privacy and data sensitivity varies and strongly depends on socio-cultural and contextual differences - factors that are difficult to accurately measure in urban scale [53]. Furthermore, privacy of mobile crowdsensing systems is still in its infancy and requirements may vary slightly depending on the area of application [24]. For example, in designing crowdsensing applications for use in emergency conditions, there may be additional requirement to allow the specified privacy settings to be overridden when necessary (e.g. by paramedics or doctors). These factors combine to make the design of privacy-preserving mechanisms difficult. Further studies that demonstrate how privacy-preserving mechanisms can be incorporated into the design of different types of mobile crowdsensing incentives are therefore required.

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In the context of monetary incentives, several privacy-friendly solutions have emerged upon which future studies can build. For example, APISENSE is a mobile crowdsensing application based on monetary incentive that enforces user privacy by allowing participants to control access to the sensors on their mobile devices. The user chooses whether to participate or not depending on the perceived threat to privacy. In return, the system rewards the user with redeemable credit based on the quantity and quality of data contributed [30]. The reward system is a weighted approach that allocates more credit to sensors that are more privacy-invading [30]. The user therefore enjoys the flexibility to disable some of the sensors for privacy reasons. This solution is quite useful because it gives a fair chance to both the users that are profit-driven and those that are privacy-conscious to maximise the outcome of their participation in a way that does not appear exploitative. In a similar monetary incentive scheme based on reverse auction mechanism, users' privacy was guaranteed by enabling them to bid and claim their reward anonymously, while at the same time ensuring high quality output is delivered [125]. These aforementioned privacy-friendly solutions, as well as other existing privacy-aware monetary incentive systems [e.g. 126–128] provide real opportunities and the foundation knowledge upon which future studies can expand.

Monetary incentive and its relationship with the quality of crowdsensed data is another key area that needs to be further investigated in order to fully explore the potential of SPECTRUM in improving citizen participation in mobile crowdsensing. It is argued that once money is involved in crowdsensing, the participants are more likely to deceive or cheat the system to increase financial gains [1]. Such cheating might involve the submission of fake data. The situation is further complicated when one considers the distributed nature of participants [28]. Participants are likely to submit sensing data of diverse quality due to difference in their spatial–temporal contexts and personal effort levels [9]. There is even strong evidence that monetary incentives do not affect quality of work, but rather merely affect the number of times a worker is willing to do a task [28]. This position is in contradiction to a recent study by Talasila et al. [47] demonstrating that by increasing the monetary reward assigned to crowdsensing tasks, the quality can also be improved. This situation calls for further studies to empirically investigate the relationship between monetary incentives and the quality of crowdsensed data.

In terms of implementation, another challenge associated with quality requirement is how to design a relevant incentive mechanism that facilitates honest and efficient contributions and also avoids unnecessary rewards to low quality crowdsensed data [1]. In other words, the key issue is how to technically estimate the quality of sensing data without pre-existing knowledge of the specific sensing behaviour of each participating user and the corresponding ground truth information at the time of data capture to independently verify the correctness of the data [9]. This area of research is still grossly under-investigated and only a few studies exist. For example, by extending the well-known Expectation Maximization algorithm that combines Bayesian inference and maximum likelihood estimation to determine the quality of crowdsensed data, and further applying the classical Information Theory to quantify the effectiveness of crowdsensed data, Peng et al. [9] inferred fair and proper rewards for participants using the estimated values of quality and contribution. However, a major limitation of the abovementioned solution is

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the lack of a standardised approach based on which both participants and service providers can accurately estimate cost of participation.

Determining the right amount that participants expect to receive for their efforts in contributing crowdsensed data is a complex challenge. Typically, the expectation of each contributor is different and their opinion on the perceived cost of their participation varies, depending on personal judgement of resource utilisation and the unique context or current situation they are involved in at the time [112]. Accurately estimating the appropriate amount for each participant and monitoring how that will change with time and context is an increasingly difficult task that requires deeper investigation [129]. A common practice is to avoid this problem of estimating the expected amount for rewarding participants' efforts by using the reverse auctions technique, where the need for the requester to set or guess a reasonable amount for users is eliminated and the participants are allowed to set the amount themselves [125, 130]. For example, Koutsopoulos [14] proposed an incentive mechanism based on a reverse auction model that uses a negotiation process to reduce sensing cost while ensuring the quality of sensed data. However, an inherent limitation of this approach is that time-delays from the underlying negotiation process may degrade the purpose for which the data is collected, particularly if the data is meant to serve a real-time solution such as weather forecasting, urban parking, etc. [93]. Users might also find the negotiation process too cumbersome [93]. Further research is required to thoroughly address these challenges.

Another issue associated with rewarding the effort of participants is that which may occur if the ease of the sensing task renders the participation cost low and as a result, the reward amount is also fixed low. It has been demonstrated that the number of users participating in crowdsensing initiatives reduces when tasks are split into subtasks of lower rewards [131, 132]. In this case, even though the reward amount might be deemed appropriate based on the participation cost, motivation to participate will still be weak if the number of sensing tasks to which a participant is engaged is not large enough to amount to a significant sum [93]. Future research in monetary incentives needs to provide for this kind of scenario when considering the effort of participants.

Furthermore, it is important to consider that in certain situations the reward amount attached to a crowdsensing task cannot sufficiently motivate some participants, particularly if they are driven by intrinsic motivations and not necessarily financial gains. Anawar and Yahya [133] noted that the interpretation of incentives in crowdsensing literature is still loose, mostly focusing on monetary incentives and poorly addressing situations in which participants are mostly driven by intrinsic motivation, which is also known as the "third drive". In such situations where reward amount is not a factor, the use of monetary incentives may destroy pre-existing intrinsic motivations in a process known as "crowding out" [28]. Crowding out can also occur when the situation is reversed i.e. when some users expect monetary reward in a scheme that only promotes social rewards. A conventional approach to minimising the problem of crowding out is to use hybrid incentive mechanisms that combine both monetary and non-monetary reward models. For example, Jaimes et al. [31] recommend a combination of monetary rewards and other types of incentives such as intrinsic and social-based incentives, etc. in order to increase user participation. *CityZen* is a crowdsensing platform for citizen engagement in smart city management that incentivises participants with monetary

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rewards, civic recognitions and discounted tickets to zoos, museums, etc. [57]. Similarly, QuaCentive is a quality-aware incentive framework for mobile crowdsensing, implemented by appropriately integrating one monetary (i.e. reverse auction) and two non-monetary (i.e. reputation and gamification) incentive mechanisms [28]. The *NAIST Photo* participatory sensing system proposed by Ueyama et al. [134] also provides option for a combination of monetary and gamification incentives. To sum it up, D'Hondt et al. [135] express their conviction that large-scale crowdsensing can be achieved through an incentive scheme that carefully balances altruism with a form of direct or indirect remuneration, not necessarily of monetary nature.

With the complexities and implementation overhead associated with monetary incentives, there are possibilities that some of today's mobile crowdsensing systems running on monetary incentives will be translated or complemented with non-monetary incentives in the future, e.g., increased social recognition and other task-related awards issued by hosting communities [10]. The robustness and sustainable use of such socio-technical systems driven by hybrid incentive mechanisms will depend on the ability to understand and resolve potential issues bothering on ethics and fairness [136]. Hence, there is need for a deeper investigation into the implications of allowing both monetary and non-monetary incentive mechanisms to co-exist and be used concurrently to reward participants in the same mobile crowdsensing system.

Mobile crowdsensing initiatives that have strict area coverage requirements can also pose significant challenges when the adopted incentive must be designed in such a way as to steer participants contribution towards meeting the specific requirements [31]. A few studies (e.g. [31, 93]) have proposed incentive mechanisms that aim to address the problem of poor data capture in some areas and data redundancies in others. Prominent amongst these solutions is SPREAD, a monetary incentive designed to select the lowest cost participants that are best distributed spatially to cover the area of interest within a defined budget [31]. This implementation is based on a combination of the Greedy Set Cover algorithm, the Weighted Variance Maximization algorithm and the well-known Reverse Auction Dynamic Price with Recruitment (RADP-VPC-RC) mechanism [31]. Similarly, the concept of "steered crowdsensing" has been proposed as a viable solution to address the issue of poor area coverage. In this approach, different redeemable credit points are assigned to various locations and users motivated by these incentives can choose to make it to the locations of interest to capture data samples [93]. While the aforementioned solutions have made significant research contributions, further studies are required to address the problem of poor area coverage along various directions, such as the use of mobility profiles as one of the selection criteria when recruiting participants [65]; recruiting participants with high demographic diversity [66]; increasing the coverage area by understanding the mobility patterns of different groups [67]; involving participants with broad and diverse social interaction patterns [68]; and the use of density maps to estimate the number of participants in a given area [25]. It is also important to investigate the problem of poor area coverage from the perspective of unequal representation of various community stakeholders and interest groups in the participatory sensing process and how that influences the fairness and reliability of the crowdsensed data for urban decision making.

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Conclusion

The design and selection of an appropriate incentive mechanism is critical to the success of any mobile crowdsensing initiative. This study has offered the concept of SPECTRUM as a comprehensive guide for inferring the most appropriate type of incentive suited to the unique characteristics or requirements of any given crowdsensing task. No doubt, the broad range of factors covered in SPECTRUM will enable smart cities to efficiently incentivise users and improve participation in large-scale crowdsensing applications. Furthermore, the paper has highlighted research challenges and areas where additional studies related to different factors outlined in the concept of SPECTRUM are needed to improve citizen participation in mobile crowdsensing. One limitation of this study is that the proposed concept of SPECTRUM is short of concrete realization through empirical validation. Future studies will therefore seek to empirically validate the significance of each factor covered in SPECTRUM in the context of different types of mobile crowdsensing activities and incentive mechanisms.

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