Sensing Data Market: Architecture, Applications and Challenges

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Abstract

With the rapid development of the Internet and various form of wireless communication technologies, information-on-demand has become a reality, e.g. people today routinely receive news items, stock prices etc. via their mobile phones or RSS feeds. We believe there is a real demand from users for all kind of information and especially sensing data. This paper proposes a new network based service called *Sensing Data Market* (SenseMart). The defining characteristic of SenseMart is that users share their sensing data among themselves. In other words, SenseMart facilitates the *exchange* (in the sense of a marketplace) of sensing data and can be viewed as the "Napster" of sensing data. This paper discusses possible architectures for SenseMart and the research challenges to realise it.

1 Introduction

Wireless sensor networks (WSNs) [2,3] — which consists of many low-cost, miniature, wireless communication enabled embedded computers — have been labelled as a disruptive technology by many technology and business analysts. A common assumption among nearly all the current research in WSNs is the deployment of *dedicated* WSNs for a particular technological purpose, e.g. the structural health of building in an earthquake-prone area can be monitored by deploying a network of dedicated wireless sensor nodes equipped with accelerometers on the buildings to be monitored. Although these dedicated WSNs can fulfil many technological and business needs, their deployment requires capital investment of sensing and possibly communication infrastructure.

Recently, an alternative paradigm has emerged for WSNs wherein the key idea is to leverage the existing sensing and communication infrastructure [13]. The key driver of this new paradigm is the near ubiquity of mobile phone handsets in many countries. Mobile phones, though not built specifically for sensing, can in fact be used as sensors. The cameras on mobile phones can be used as video and image sensors. The microphone on the mobile phone, when it is not used for voice conversations, can be doubled up as an acoustic sensor. A few recent projects that have been proposed in this new paradigm are Participatory Sensing [4] , MetroSense [5] and CarTel [14]. Participatory Sensing aims to leverage sensors in mobile phones in collecting data (e.g. noise measurement) with the networks "proving" authenticity of data via location and time services. The MetroSense project aims to build a metropolitan scale WSN by exploiting mobile devices via opportunistic sensing and opportunistic data collection. The aim of the CarTel project is to design and deploy a mobile distributed sensor computing system for vehicular platforms, with a particular focus on developing an API for enabling new applications ranging from road traffic monitoring to on-board automative diagnostics. This paper proposes an exciting new dimension to sensor networking called *Sensing Data Market* (SenseMart). Similar to Participatory Sensing etc., SenseMart will leverage the existing sensing and communication infrastructure. The defining characteristic of SenseMart (which also sets it apart from projects such as Participatory Sensing etc.) is that users are encouraged to share their sensing data among themselves to accomplish a higher level task. In other words, SenseMart facilitates the *exchange* (in the sense of a marketplace) of sensing data and can be viewed as the "Napster" of sensing data. The high level idea in SenseMart is to provide appropriate incentives to users to encourage sharing of data so that the sensing application meets the desired information quality, and monitor the quality of user contributions to maintain data integrity. SenseMart can be more directly compared to the BitTorrent file sharing application in its objective of rewarding users proportionate to the resources they contribute. We believe that SenseMart will have far ranging impact in the world of sensor networks in the same way that peer-to-peer networks have revolutionised the landscape of content distribution in the Internet.

2 SenseMart: Concepts and Applications

The Internet and wireless communications (e.g. cellular phones, WiFi etc.) have made information-on-demand a reality, e.g. people today routinely receive news items, stock prices etc. via their mobile phones or RSS feeds. We believe there is a real demand from users for all kind of information and especially sensing data. We can classify information and its mode of delivery according to:

- *Type of information* can be real-time or historical.
- *Mode of collection and distribution* can be client-server or peer-to-peer.

The "cross-product" of the above two classifications gives rise to four different categories of data services:

- *Historical & Client-server*: e.g. various web sites offer historical data of weather [1] and currency exchange rates [2].
- *Historical & Peer-to-peer*, e.g. various travel web sites [3] provide reviews on hotel services based on customers' own experience. The hotel customers are in fact "sensors" and share their "sensing data" with the community.
- *Real-time & Client-server*: e.g. real-time delivery of sports results [4], stock prices [5], flight information etc.
- *Real-time & Peer-to-peer*: Services in this category does not appear to exist currently [6].

The aim of SenseMart is to fill in the missing gap of providing real-time sensing data to the community via peer-to-peer communication. By using SenseMart, useful real-time sensory information such as real-time traffic condition, actual bus arrival time etc. can be made available to the community at low cost. We will now discuss two applications that motivate and can be enabled by SenseMart in detail.

2.0.1 Application 1: Real-time road traffic flow information distribution

It is now commonly acknowledged that cars in the not too distant future will more and more resemble state-of-the-art computers, equipped with wireless interfaces, GPS navigation systems, storage disks, audio/video entertainment systems and a large array of sensing devices. In fact, GPS based navigational units are already being adopted in the newer automobile models. However, the current generation of systems compute the driving directions based on a static road map that is independent of the prevailing road conditions. The availability of real-time traffic information such as congestion hot-spots, accident notification, or water floods is likely to lead to a better selection of the route by the navigators but unfortunately such information is not currently available. A direct but expensive solution to this problem involves deploying sensing and communication infrastructure along the roadways for continuous monitoring. A cost-effective and viable alternative is provided by SenseMart, which leverages on the existing sensing and communication infrastructure. Firstly, the on-board car electronics such as the GPS navigator and other on-board sensors (which is the existing sensing infrastructure in this case) can readily compute the local traffic condition, e.g.,

[1] http://www.wunderground.com/
[2] http://xe.com
[3] http://www.tripadvisor.com/, http://travel.yahoo.com/
[4] http://www.cricinfo.com
[5] http://www.iqchart.com/
[6] Although Skype (http://www.skype.com/) fits both real-time and peer-to-peer labels, it does not deliver real-time sensing data.

the average speed and direction of movement, vehicular density in the neighbourhood. Secondly, this local traffic information can be distributed to other road users using the existing communication infrastructure, e.g. mobile phone networks, WiFi, WiMax, the Internet, or possibly inter-vehicular communication networks [15] in the future. Note that the actions of information collection and dissemination can be performed automatically without human intervention by an intelligent agent inside the navigator.

The traffic information collected will not only benefit road users at that time but can be archived and integrated with a Global Information System (GIS) for future use by road users, web services and town planners. Road users can use the historical data to plan their journey. A travel web services can use the data to give their clients a good estimate to how much time to spare to get to the airport. Town planners can use the data for modelling and simulation to improve the transport network. Note that some of the interfaces that we need are already in place, e.g. Google earth can be integrated to provide real-time data information. Also, a recent effort by Microsoft [12] aims to create a sensing information portal for searching and dissemination of sensor data. △△△

2.0.2 Application 2: Collaborative radio sensing for cognitive radio application

Traditionally, most commerical radios are hardware-based with predetermined operating parameters, i.e., they always operate at a particular power and frequency. Over the years, as engineers built radios in cheaper and smaller packages, it is becoming possible to build intelligence into them, making the idea of sharing frequencies dynamically a reality. Moreover, the traditional method of allocating radio spectrum by governing authorities has resulted in a very low utilisation of radio spectrum, in fact, measurement shows that less than 20% of the licensed spectrum is used at any one place at a given time [9]. Both of these factors motivate a new paradigm of wireless communication called *cognitive radio* [10] that enables a wireless node to change particular transmission or reception parameters (such as frequency, power, modulation scheme, etc) based on observations of various environmental factors such as the radio spectrum, user behaviour and network state. Even though in theory, every possible observable parameter can be taken into account to influence the node decision, most of the current research activities focus on *Spectrum Sensing Cognitive Radio*, wherein the goal is to allow a radio to utilize any unused *white space* in the radio spectrum (e.g. TV bands). A key problem that needs to be solved to enable this is the design of high quality spectrum sensing devices and algorithms for exchanging spectrum sensing data between nodes. Consider a scenario where two wireless nodes wish to communicate with each other. Before they can do so, they first need to pick an available frequency band, which is not being currently used. It has been shown in [11] that a simple energy detector cannot guarantee accurate detection of signal presence. This calls for more sophisticated spectrum sensing techniques and requires that information about spectrum sensing must be exchanged between neighbouring nodes reguarly. SenseMart is an ideal candidate for such collaborative spectrum sensing tasks. Nodes in the vicinity of the transmitter and receiver can distributedly sense parts of the complete radio spectrum and report back their readings to the communicating nodes. This will allow the nodes to judiciously pick a suitable frequency band with the least interference for communication. Note that the communication of spectrum information can be broadcast on pre-determined channels.

Note that there are a few features in this SenseMart application that are not found in many current sensor network examples. Firstly, in this application, the radio is used both as a sensor and communication device. Secondly, the sensing dimension can be large. A sensor network that monitors temperature has a singular dimension for sensing, since only one sample is needed at each location at any given time. On the contrary, in this application, the power spectral density at a temporal-spatial point is in-principle infinite dimensional. The sensing dimension can be finite if we are only concerned about a finite number of frequency bands. In any case, the sensing dimension will be large and it therefore makes sense for the nodes to sense the network collaboratively to achieve faster sensing response. △△△

3 Architecture and research challenges

3.1 Comparison with peer-to-peer file sharing

The above sample applications showcase the features of the SenseMart framework. SenseMart leverages the existing sensing and communication infrastructures to enable the *exchange* of sensing data in a large geographic area. The communication infrastructure that SenseMart users can use include the Internet, cellular and mobile networks, various form of access technologies (e.g. WiFi, WiMax), mobile ad hoc networks, inter-vehicular networks and many other future communication technologies. With the rapid development of communication technologies, we believe that bandwidth will be plentiful in the future for mobile users and reliable real-time delivery of streaming data to mobile users will no longer be a technical barrier. With this assumption, SenseMart is effectively a peer-to-peer network whose goal is to deliver real-time sensory data collected by sensory data sources (the data producers) to the users who are interested in the data (the data consumers). Although much work has been done on peer-to-peer file sharing, the problem of peer-to-peer real-time sensory data sharing has a number of new features:

- *Real-time streaming data*: In addition to placing demand on communication resources to enable timely delivery of sensing data, the data consumers must be able to locate their desired data producers within a time-limit since the utility of real-time data diminishes with time.

- *Dynamic consumer-producer relationship*: Consider the traffic information application as an example, a data consumer may need the data from different data producers at different part of his journey. The consumer-producer relationship can be highly dynamic and changes many times within a user session. This dynamic imposes constraint on the delivery of data and how the producers can be matched to consumers.

- *Heterogeneity and time-dependence in benefits*: Sensory information that is of benefit to one person at a given time may not be of equal benefit to someone else, e.g. the traffic information at one location may not be relevant to those users who will not be travelling past or near to that location.

- *Critical number of data producers*: A user may only derive reasonable benefit if a critical or minimal number of users contribute sensory data, e.g. a user in the traffic information application will want to know the traffic information on all the possible routes that he will take to reach his destination. Therefore, the utility of this user critically depends a minimal number users from a certain geographic area contributing.

- *Quality of information*: An user, in addition to deciding whether to contribute data or not, can also choose to contribute data of different quality of information. Since sensory data is essentially the spatial-temporal sampled data of a phenomenon, the user can choose to sample at different rates. A higher sampling rate will inevitably give a more accurate picture of the sampled system dynamics but will require more bandwidth for delivery. In addition, the user may also be able to control the resolution of sensing, for example, by modifying the zoom and/or pixel resolution of images. For the collaborative radio sensing application, quality of information manifests itself in a different way, e.g., a user can choose to aggregate spectrum sensing information at different level of resolutions in both the time and frequency domains. For a user who operates its radios in a narrow frequency band, spectrum information that spans a wide frequency band will only provide little information.

  Another dimension that Quality of Information manifests itself is due to the time-sensitive nature of real-time sensory data whose utility diminishes over time. Thus, if a user holds onto the sensory data and releases it only when the sampled phenomenon has changed significantly, the information is of diminished utility to the other users.

- *Legality of data*: This deal with the questions: Is the data genuine or fake? Can the data be trusted? How can we know that the data has been sampled at the given location at the given time?

3.2 Architecture

The system architecture for SenseMart must take into consideration all the above new features. We will look at three different architectures: a centralised, hierarchical and distributed architecture.

In a centralised architecture, a central data server is used to collect all user contributed data and disseminate the data to the users. Before disseminating the data to the interested users, the data server may aggregate and process the data to an appropriate temporal-spatial resolution. Each piece of data is tagged with its spatial and temporal information. The users (or their agents) who are interested to receive the data should register with the data server. In specifying the type of data required, users should also indicate their desire temporal-spatial attributes. Note that the types and attributes of the data that a user wants may vary with time. Therefore, SenseMart includes mechanisms that a user can use to add, change or remove previous requests of sensing data. Depending on the amount of data and request to be processed, the centralised architecture may not be able to meet the processing and delay requirements of the users. The scalability of the centralised data server can be improved by using a hierarchy of data servers distributed over a geographic area. In addition to distributing the processing load among multiple data servers, the hierarchical approach can also reduce the communication load by exploiting overlay multicast.

In addition to collecting and distributing data, the data servers will need to ensure the legality of the contributed data so that other receivers will trust the received data. The location and time stamp of the user contributed data can be verified by the communication network. In addition, the data server can check whether the data is consistent with the data contributed by the nearby users or other independent measurements. Since SenseMart may be dealing with real-time data, extensive checking of large number of continuous data streams may not be feasible. A possibility is to perform some basic checks for data before disseminating it and to perform more extensive checks later on. Such *a posteriori* checks may be used to assign a reputation measure to the contributing users. Another function of the data servers is to ensure that the Quality of Information is maintained and we will discuss this further in Section 3.

To encourage data sharing, the data servers will also need to calculate incentives to reward data producers depending on the utility of their contribution. These incentives can be as simple as assigning points to data producers analogous to frequent flier miles. These points can be redeemed by the producers to request the data that they might be interested in. The points can be assigned proportional to the number of requests for data from that location or time, the fidelity of contributed data, the availability of alternative or replacement data producers etc. In a hierarchical system, each data server may be assigned a certain quota of points that it can award. Incentives are discussed in detail in the next subsection.

In a distributed architecture, the data producers and data consumers form ad-hoc groups to exchange data without using data servers. In order to realise this, there must be efficient ways for data consumers to identify the users who can contribute the desirable data. In this architecture, data consumers can broadcast their rankings for various data producers based on whether they found the data useful subject to solving the whitewasher [6] problem. The aggregated rankings provide a peer-based mechanism that may be used to rate which data producers are more trustworthy. The transport of data can be realised by a concast tree rooted at the data consumer or a multicast tree sourced at the data producer leveraging the earlier work in multicast wireless in ad hoc networks.

Note that whether a SenseMart application should use the hierarchical or distributed architecture depends strongly on the processing, transport and application requirements. For the traffic information distribution application, we expect that the hierarchical architecture will be easier to implement than a distributed architecture due to the potentially large number of users, constantly changing requirements of data consumers for traffic information, mobility of users, as well as a possible lack of correlation between the locations of the data producers and data consumers. In particular, the time varying nature of both networks and changing data requirements make a distributed solution very challenging. In particular, one may ask whether the dynamic hash table techniques for searching in peer-to-peer networks will be competitive in this very dynamic scenario or will we need new search techniques if the distributed architecture is to be used. By contrast, a business entity managing the traffic flow application, can install infrastructure nodes at strategic locations to be data servers or act as relays to data servers. These nodes can collect data from passing cars, summarize data for roads over much wider areas, and disseminate data to all passing vehicles.

However, for the collaborative radio sensing application, a user is likely to be interested in the local spectrum usage which means that the data consumers are likely to be close to the data producers. Such clearly defined correlation means that a distributed SenseMart is ideal since only local or near local communications will be needed.

3.3 Incentives to contribute high quality data

Since SenseMart relies on users contributing sensing data to be shared among the users, a very important issue is that there must be an incentive to share. Otherwise, it is well known from the "Tragedy of the Commons" [8] that most users will tend to be free-riders rather than contributors. The free-rider problem has been empirically observed in file-sharing in the Guntella peer-to-peer networks where it was found that 25% of users share no files at all [1].

The literature on incentive-based mechanisms to encourage sharing in peer-to-peer networks is immense [7]. These include making the file sharing an *excludable* good and reward those users who contribute more files. These ideas can also be used in SenseMart to encourage the sharing of sensing data. However, the SenseMart incentive problem has a number of new features that are not found in the peer-to-peer file sharing problem.

In SenseMart, the utility that the an user can derive from the contributed data depends on the temporal-spatial distribution of the contributing users. These requirements induce the following research questions:

- How can incentive schemes be designed to ensure that the aggregate data collected from the network is of high utility to the users?
- How can the incentive scheme ensure that a minimum number of users contribute?

The analysis of the existence and properties of Nash equilibiria will be a challenging task in view of the large number of users and heterogeneity of the user preferences and requirements. In addition, since the user utility depends on a minimum number of users contributing, it will have a shape similar to a sigmoid (or other similarly shaped) functions, the non-convexity of the utility function means the existent of multiple Nash equilibria which can make the analysis difficult.

In contrast to the peer-to-peer file sharing systems where users main decision is to contribute files or not, a user in SenseMart can decide on the quality of information of the data to be contributed in addition to deciding whether to contribute data or not. This gives rise to the following important research questions: How can we quantify the quality of sensing data? How can an incentive mechanism be designed such that the users are motivated to share high quality sensing data? Would it be possible to exploit mechanism design to encourage users to "reveal" high quality sensing data? How can the incentive mechanism take into account the heterogeneous requirement of different users? How can the incentive mechanism take the time-sensitive nature of the data into account?

The incentives to be provided can be barter-liked, i.e. data in exchange for data. It is also possible to use monetary incentives, either real or virtual, to motivate the users to share sensing data. If monetary incentives are to be used, how can such a scheme be designed? How can such a scheme take into account the quality of information, heterogeneous user requirements etc?

3.4 Quality of information

Assuming that the incentive problem can be solved and users are happy to contribute high quality data, it will be important for SenseMart to maintain a good quality of information.

Since SenseMart relies on user contribution and we do not have control over the distribution of users, we will not be able to ensure that all the locations of interest may not be covered. For example, in the traffic flow application, it may not be possible to obtain an accurate measure of traffic flow rates on a desolate road. Some relevant questions are:

- How do we deal with missing data?
- How do we deal with sparse or insufficient data at the locations of interest?
- How do we adjust and negotiate data sampling rates with individual data producers in response to users entering and leaving the network?

Instead of missing or insufficient data, SenseMart may also face with the problem of having redundant data. To understand this, let us consider the traffic flow application as an example. In order to obtain a reasonably accurate measure of traffic flow rates on certain main arteries, a sufficient number of samples must be collected from the participating road users. If the number of samples is too few, the traffic flow information will not be accurate enough and additional queries must be triggered. On the other hand, a high sampling rate will consume enormous bandwidth with only a marginal gain in the quality of information. For the traffic information application, the locations of interest are also the congested places with many vehicles. We therefore expect many potential sensing data contributors from the locations of interest but the data will be highly redundant with little gain in additional information. Some important research questions are:

- How can the data server efficiently balance the quality of information and communication resources needed to transmit high quality data?
- If only some of the users at a location of interest need to contribute data, how can the data server do this in a fair and efficient manner?
- Further, in a distributed architecture how do we effectively manage the quality of information?

3.5 Distribution of the sensing tasks amongst the collaborating nodes

We discussed earlier that a distributed architecture is well suited for the collaborative radio spectrum sensing application. This application differs from many other sensor network application in that the phenomenon to be sensed — power spectral density – is in fact a continuous quantity at any location in time. However, in practice, we are not interested in the entire spectrum but whether radio energy is detected in a number of spectrum bands, in this case the measurement of interest is in fact a vector. Subsequently, when employing SenseMart, it is important that the sensing task is distributed amongst the cooperating nodes, whereby each node only senses a part of the desired spectrum. There are several reasons for this; the primary being reducing the energy expended in the sensing task. Additionally, this will keep the response time to a minimum. Finally, not all sensors may have the same capabilities, which calls for a distribution that takes this into account. Resorting to a simple un-coordinated randomised division policy, may result in some parts of the desired spectrum being neglected. Thus, the key research questions are: How can collaborative strategies be designed to distribute the sensing task in an effective manner among the cooperating nodes? How can heterogeneous node capabilities be taken into account?

3.6 Security and privacy

Security is of paramount importance to ensure the success of SenseMart and related applications. Active participation of users in contributing the sensed data adds a new dimension to the security issues that are prevalent in traditional sensor networks. Several critical research challenges need to be addressed: How do we tell that data is reliable? How do we know whether the data is credible since malicious users may intentionally contribute false data? Another aspect of security, which is important is data integrity, i.e., ensuring that the sensed data is not modified by intermediate relayers if relayers are to be used. Symmetric and public-key cryptography may solve some of these problems. The challenge, given the limited resources of the mobile devices is computational complexity and code efficiency. Another approach is to assign reputation rankings to contributors based on the quality of their contribution, as is common in many Web 2.0 sites, such as Youtube [7] and Web 2.0.

Privacy of the users contributing data is critical for encouraging participation. For certain applications, it would be desirable for users to hide personal details such as identity, precise location, time of day, etc, while contributing data. Certain details such as identity may be easier to conceal as compared to other information such as location without having an adverse effect on the resolution of the contributed data. There should be mechanisms that allow users to mask out these details and enable control over the resolution of the divulged data. Policies could be implemented wherein the producer can dynamically adapt the resolution depending on the level of trust associated with the consumers. The key is to balance the privacy of producers while still guaranteeing high quality of information.

4 Conclusions

We have proposed *SenseMart* to facilitate peer-to-peer sharing of sensor data among people. The major research challenge in SenseMart hinges in achieving a certain Quality of Information for the application to be useful. We believe that this can potentially be realized through incentives for rewarding contributing users, and reputation rankings to maintain data integrity.

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