Quality-of-Information Aware Data Collection for Mobile Sensor Networks

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***Abstract*— Quality-of-information (QoI) in sensor networks measures attributes such as accuracy, timeliness, completeness and usefulness of data ultimately delivered to users. It is a challenge to provide the required QoI in mobile sensor networks given the large scale and complexity of the networks with heterogeneous mobile and sensing devices. In this paper, we provide a comprehensive study on major QoI metrics for mobile sensor networks and the effect of mobility. Three different mobility scenarios are studied including mobile sensors, mobile sinks and mobile "mules" carrying data between sensors. We conclude that mobility both can improve as well as degrade the QoI metrics. We then discuss how QoI can be optimized through coordination among heterogeneous devices. We also suggest a ubiquitous publish/subscribe system for mobile sensor networks.**

I. Introduction

Recent studies have revealed vast usage of Wireless Sensor Networks (WSNs) for different applications such as transportation, health care and environmental monitoring [1], [2]. Wireless sensors can also be integrated into an innovative and large-scale information infrastructure, called Internet of Things (IoT), which connect various physical devices and objects in an intelligent and autonomous manner. From the users' point of view, their ultimate concern is the Quality-of-Information (QoI) that they can obtain from the sensing data received. Common QoI metrics such as accuracy, timeliness, completeness, usefulness and security of data also apply for mobile sensing applications. Unfortunately, existing approaches generally design the transmission of sensing data and the movement of mobile sinks simply based on traditional networking metrics without considering the QoI or the context for its use.

Mobility in sensor networks can take many forms and challenges the common QoI metrics. A sensor node could be mobile by itself and senses different locations while on the move. The sensor network sink could be mobile which means that a sensor system needs to reroute all sensed data to the current location of the sink. A sensor node could also act as a data collection mule, obtaining sensed data while it is passing by a sensor and dropping the data to the sink or to other mobile sensor nodes when coming into their communication ranges.

Mobile sinks and data mules have been suggested for data collection in sparse sensor networks, typically when the network is not fully connected to the sink [3]. For example, with the popularity of smart phones, mobile users can participate in a wide range of participatory sensing and urban sensing applications [4]. These phones can act as mobile sinks in sparsely distributed stationary sensors and forward data over 3G or WiFi when such connectivity is available or encountered. For example, BikeNet [5] utilizes an opportunistic mobile sensing platforms where data are collected and carried by cyclists with uncontrolled mobility. It also operates in a delay tolerant sensing mode, where cyclists go on trips, collect sensed data, and upload their data when they return to home. With the increasing popularity and diversity of sensing applications, however, the sensing context and detailed data sharing strategies with both stationary sensors and mobile phones remain to be further explored.

Mobile sensor networks pose a number of new challenges to achieve QoI-aware data collection due to the mobility, varying and temporal and spatial sensing coverage, the large scale and heterogeneity of nodes. The achieved QoI is affected by the availability of mobile devices, the location and coverage of wireless sensors, the network connectivity and capacity, etc. Furthermore, sensors and mobile sinks are constrained by limited resources such as batteries, computational power, memory and communication range. It is important to fully utilize the capabilities of different devices in order to maximize the QoI under these constraints.

In this paper we explore the QoI metrics with respect to the different forms of mobility and present our preliminary work on a publish/subscribe system for QoI-aware data collection in opportunistic mobile sensing networks. We first present related work on QoI and wireless mobile networks in Section II. Then, we describe the scenario of our mobile sensing application in Section III. Section IV discusses the major QoI metrics for mobile sensor networks and compares them in different kind of WSNs. We present QoI-aware network configuration and data dissemination in Section V. Section VI illustrates our ongoing work on ubiquitous publish/subscribe system for mobile sensor networks.

II. Related Work

The concept of "Quality-of-information (QoI)" was introduced by Bisdikian et al. to measure attributes like timeliness, accuracy, reliability, completeness, and relevance for sensing information [6], [7]. QoI is also used to give the users' perspectives for databases as elaborated on in [8]. Information fusion methodology has been proposed [9] for maximizing overall QoI, subject to constraints on energy. Kho et al. [10] have proposed a decentralized algorithm to minimize

978-1-4244-9529-0/12/$31.00 ©2012 IEEE

the uncertainty of sensing data, subject to the constraint of a limited number of samples taken per node.

Mobile sinks and *data mules* are applied for improving the performance of data collection in wireless sensor networks. Shah et al. introduces mules to collect sensing data in [3]. Bisnik et al. [11] were among the first to study the problem of providing coverage using mobile sensors. In particular they analyzed the effect of controlled mobility on the fraction of events captured. Gu et al. [12] proposed an algorithm for scheduling the movement of mobile nodes for best coverage of events while minimizing speed and overflow. In a recent paper, Xu et al. [13] studied delay tolerant event collection in sensor networks with mobile sinks which considers the spatial-temporal correlation of events.

The above works focus on controlling the movement of mobile sinks for data collection, which is different from a mobile phone scenario with independent users and uncontrollable mobility. Moreover, they do not consider the information utility obtained by mobile phone users through data dissemination in a sensing field.

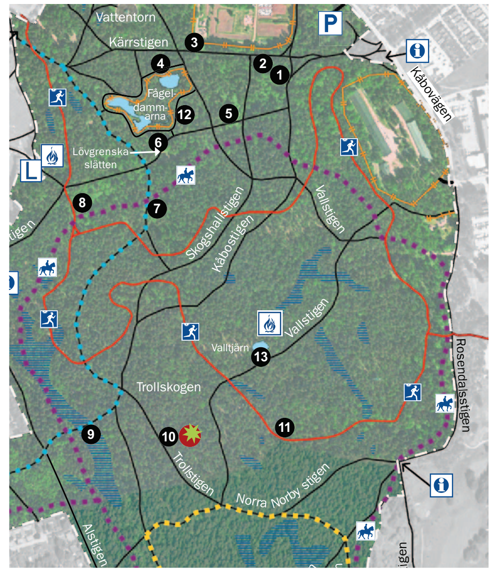

Fig. 1. Hikers can collect sensing data such as temperature, humidity, their locations and hiking speeds in a mobile sensing application.

III. Application Scenario

Figure 1 shows a forest map with hiking trails. Stationary sensors are deployed along the trails to collect sensing data such as temperature, humidity and water quality and pollen level. Their deployment locations (indicated with numbers on the map) are suggested by the nature reserve rangers according to the needs for environmental monitoring or protection. The sensed data are also beneficial to users performing different kind of activities in the reserve such as hiking, camping, exercising, and picnicking, etc. In our scenario, sensors 1-8 and 12 are within wireless communication range with each other and can communicate via multihop routing to a sink. Assume that node 1 is a sink and it is the only node that has a 3G connection on which it can send data to monitor station of the reserve.

Apart from the stationary sensors, smart phones of ordinary visitors to the reserve could also be utilized as sensors for taking pictures, recording sound, reading accelerometers and collecting GPS locations. Users could add tags, location information and other meta data to the sensed data of the phones to increase the quality of the data.

Most users are likely to follow the trails rather than wandering randomly within the reserve. Still, the mobile phones complement the stationary sensors and we will get a better sensing coverage of the area. In our scenario user mobility and how many users that participate are unpredictable. In a more controlled scenario it is of course possible schedule users to follow a systematic route to get a predictable coverage. The sensing data are uploaded to the server on the Internet by the mobile phones with 3G or WiFi connectivity.

For the remotely deployed sensors 9, 10, 11 and 13, mobile phones can be utilized as mobile mules to collect data from the sensors through short-range communications, such as Bluetooth, Wifi or NFC. When an authorized phone passes these sensors it will pick up the data and if the user of that phone later passes one of the sensors 1-8 or 12 the data will be downloaded to the sensor and forwarded to the sink, i.e. sensor 1 in this scenario, which will use the 3G connection. This data relaying function by a mule is especially important for sparsely deployed sensors in remote areas without direct Internet connectivity.

Wireless sensors are usually deployed for detecting and reporting events of interest in a sensing field. In our scenario, users specify their interests on particular kind of events by a sending a query to the system on the sensing type with QoI parameters such as precision in location, coverage of an area, time period, freshness of data, etc.

IV. QoI for Mobile Sensor Networks

Quality-of-information in mobile sensor networks measures the quality of sensing data collected by both stationary sensors and mobile devices. Common QoI metrics such as *accuracy, timeliness, completeness, usefulness and security* from traditional WSNs are also applicable for mobile sensor networks. However, the mobility itself will have profound effect on these metrics and pose a challenge on the design of the system both to compensate for and take advantage of spatial and temporal effects.

The QoI metrics also have different importances depending on the sensing context and application requirements. For instance, timeliness of data would be very important for reporting traffic accidents in vehicular networks, while security would be more important for health monitoring in body area networks. The requirements of QoI may also change with the user interests, sensing context and environments at different times and locations.

We compare how these QoI metrics are affected when we introduce mobility in WSNs. Table I summarizes the effect of mobility on the QoI parameters. In our comparison we

TABLE I

COMPARISONS OF QOI METRICS WITH RESPECT TO MOBILITY IN WIRELESS SENSOR NETWORKS

QoI Metrics	**(i) Stationary Sensors**	**(ii) Mobile Sensors**	**(iii) Mobile Sinks**	**(iv) Mobile Mules**
Accuracy	Sensor precision, sampling rate, and coverage.	Mobility pattern and accuracy in sensor localization. Sampling rate depends on speed.	Depends on controlled and scheduled movement.	Depends on stochastic movements of mules.
Timeliness	Sampling rate for detection. Communication distance to sink for reporting.	Time-varying distance to sink.	Inter-arrival time of sinks to disconnected sensors.	Unpredictable waiting time of mobile mules to sensors.
Completeness	Geographical coverage, number of sensors and their locations.	Increases coverage but becomes time-dependent.	Increases coverage by visiting disconnected sensors.	Increases coverage but becomes stochastic.
Usefulness	User interests and context. Data fusion and refinement of data.	Mobile sensors can be directed areas of user interests.	Mobile sink can act as a local fusion unit.	Mules can do opportunistic data processing.
Security	Data integrity, authorization and user access rules.	Location privacy.	Authentication of sinks.	Authentication of mules.

include a conventional network with **(i) Stationary sensors** for reference. In such a network, data propagates to a sink over one or several hops and all nodes are stationary. **(ii) Mobile sensors** networks have both stationary and mobile sensors, and a **(iii) Mobile sinks** network have one or more mobile sinks, and lastly a **(iv) Mobile mules** network has devices (e.g smart phones) that are used opportunistically to read sensor data and carry it towards the sink.

We distinguish between controlled and uncontrolled mobility. With controlled we mean that a node, a sensor, a sink or a mule, will follow a predetermined schedule and path within the sensing area. This is like a garbage collector truck in a residential area which follows the same route on a specific day in a week. With uncontrolled mobility we mean that a node is moving more or less randomly within the area. It is not predictable where and when a node will be in a sensing area. For controlled mobile sensor nodes we can predict when a certain area will get sensing coverage while with uncontrolled sensors we can only stochastically predict coverage depending on mobility pattern, number of sensors and their speed.

For our discussion we assume that the Mobile sink has controlled mobility, i.e. a sink will follow a pre-determined path through the area in such a way that all sensors will eventually be reached. For the Mobile mule case we assume uncontrolled mobility, i.e. the number of mules, their paths in the area, and when and how often they enter the area are unknown. For simplicity we assume that sensors are stationary in both the Mobile sink and Mobile mule cases. Given that stationary sensor networks have already been widely investigated, we focus on the mobility cases.

A. QoI metrics and mobility

In this section we refer to the summary in Table I. It should be noted that the table does not contain an exhaustive list of metrics or give precise definitions of them. The purpose of the table is to be able to discuss the mobility impact on the main metrics. The columns (ii) - (iv) summarizes the impact on the main metrics and how it differs from the metrics of stationary sensors in the reference column, (i) Stationary Sensors.

1) Accuracy: The accuracy of sensing data collected by a sensor networks concerns how accurate the data can represent the physical world. It depends on the precision of sensing data, the sampling rate and the (physical) coverage of the sensors. Sensors with high precision provides measurements closer to the physical world. The range of a sensor, together with the location, defines the coverage of a sensor (often modeled as a circular disc) where sensing data with enough precision for the user/application can be obtained. Sensors usually obtain data with higher precision if the monitored event is closer to the sensor than at the border of the range. The sampling rate defines the accuracy in the time domain. It has to be high enough to capture discrete events or time varying and continuous physical parameters, such as temperature. With a too slow sampling rate the accuracy will decrease while a too high rate will not increase the accuracy further and just create redundant data and consume resources.

When a mobile sensor is introduced the accuracy will also depend on the mobility and thus it will be time dependent.

The location of the actual samples will vary with the speed and direction of the sensors. On one hand, the total coverage of a sensor will increase with the movement, but on the other hand the sensing of a specific region will depend how often a mobile sensor will visit that region (actually how often a region is within sensing range). The sampling rate will now also depend on the speed of the sensor. Two samples will have different locations and hence different coverage. This also means that higher sampling rates may be needed to avoid a coverage gap between two consecutive samples due to the movement. Another challenge is that the accuracy now also depends on the localization precision of a sensor which is not trivial to measure and calculate.

When a mobile sink with controlled movement is introduced it is necessary to ensure that all sensors will be able to upload data to the sink within specified time otherwise the accuracy will decrease. The same applies for mobile mules, but here the random movement does not guarantee that all sensors will be able to upload data and hence the accuracy will depend on the stochastic movements of the mules.

2) Timeliness: The timeliness of sensing data measures the time taken to detect and report events of interest from the monitored area. The event detection time depends on the sampling rates and the locations of sensors. Sensors that have higher sampling rates and shorter distances to the event are likely to detect events more quickly.

The report time depends on the time to forward the data in the sensor network to the sink and then further on, on regular networks to the destination. Within wireless sensor networks, data are forwarded hop-by-hop from one sensor to another until it reaches a sink which is assumed to have a faster communication link to the destination. In general, WSN communication is relative slow due to constrained technologies and conservative scheduling of communication resources in order to save energy. Still, for stationary sensor nodes the forwarding time between nodes is predictable and for most protocols it can be bounded. For mobile nodes however, the forwarding time also depends on the connectivity graph to other sensors, route selection or discovery time and the distance to a sink. It will vary with location but can be bounded by the diameter of the network provided that the mobile nodes always have connectivity.

When a mobile sink is introduced (e.g. a smart phone with 3G connectivity), the forwarding time from stationary sensors to the sink will vary with the current location of the sink. If the sensor network is not fully connected, a sensor may have to wait to forward a message until the sink is within direct or multi-hop communication range of the sensor. Then the forwarding time will also depend on the mobility pattern and/or schedule of the mobile sink. The waiting time for the mobile sink to come into wireless reach may result in high data delivery delays.

A mobile mule device could to some extent mitigate the long delays that occur when a mobile sink must physically visit sensor nodes. When mobile mules are used to carry data closer to a sink the delay depends both on the number of available mules that want to carry data as well as their mobility pattern which normally is unpredictable. The delay could be shortened by using broadcasting techniques, like Epidemic forwarding, at the cost of more communication and buffer space. A challenge is that there is no guarantee that a mule will pass a sensor when their mobility pattern is not controlled.

3) Completeness: The Completeness of sensing data measures the amount of data obtained that are relevant to the ground truth. The metric is related to the number of sensors, their geographical coverage and their locations in the sensing field. More sensors can usually provide better sensing coverage and hence the system will be less likely to miss sensing events. The Completeness may also depend on the sampling rates of the sensors. For instance, sensors with high sampling rates can obtain more fine-grained measurements for scientific analysis in continuous monitoring applications.

Mobile sensors actually increases the Completeness with respect to coverage. It is possible to control the movement of sensors such that they can “fill in the holes” between stationary sensors. On the other hand, the Completeness will now be time dependent which may not be acceptable for some applications. A mobile sink and a mobile mule also can increase the Completeness by visiting regions of sensor nodes that are otherwise not interconnected. The increased Completeness is paid for by varying delays with consequences for the Timeliness.

4) Usefulness: Providing useful information to the users is indeed one of the major goals in QoI-aware networking. The usefulness of data from sensor networks depends heavily on the interest of users, sensing context and applications. The usefulness can be increased by processing data from several sensors, i.e. by data fusion and refining. Such processing can be done in the sensor nodes, the sink or/and at servers close to the destination. From communication point of view it is preferable to do fusion in the WSN if the amount of information is reduced. This means that users should be able to specify to a query on what kind of sensing types, locations and sensing ranges that they are interested in, so that the sensor networks could be deployed, configured and data forwarded to processing units to meet the user expectations. In the next section we describe a publish/subscribe system in mobile sensor networks for matching user queries.

Mobility can potentially increase the Usefulness. If mobile sensor movement is controlled it is potentially possible to direct mobile sensors to areas and hot-spots that users are interested in or in a participatory sensing situation, only configure the smart phones that are at the right place at the right time. Furthermore, Mobile sinks could be relocated to hot-spots and act as local data fusion units and Mobile mules could opportunistically be used for fusion when passing sensors.

5) Security: Security concerns the integrity of sensing information and authorization access to sensing data. Depending on the sensitivity of the data and the need of applications, the provider of the data should be able to control what data should be disclosed to different users. Likewise users want to ensure the authenticity of data including sensor location. Conventional methods for wired networks are applicable for stationary sensor networks, although the limited capabilities of sensor nodes and communication constraints complicates the security architecture.

When mobile sensors, sinks and mules are introduced, location privacy becomes an additional issue. Also stationary sensors need authenticate a mobile sink, that it is authorized to consume their sensor data and that mobile mules actually will forward data in the system. Providing an authentication system in a wireless systems with partial connectivity is a still a research issue.

V. QoI-Aware Data Collection for Sensor Networks with Mobile Mules

We focus on QoI-aware data collection for sensor networks with mobile mules in this section. Network configuration and data dissemination mechanisms are discussed to illustrate how to improve the QoI and reduce the system cost.

A. QoI-Aware Network Configuration

Based on the interests of users, the mobile and stationary sensors can collect sensing data from the environment adaptively. The stationary sensors and mobile sensors can collaborate with each other to improve the overall sensing quality and data availability. Since stationary sensors have fixed locations, they can provide more stable sensing quality and coverage. On the other hand, mobile sensors such as smart phones can move around and cover in a larger area potentially, though they may not be able to provide constant sensing quality and coverage. It is possible for us to minimize the deployment cost of stationary sensors by considering the availability of mobile sensors and the interests of users [14]. For instance, the area with high number of mobile sensors may require less stationary sensors to be deployed.

Apart from the deployment of stationary sensors, we can enable the sensing capability of the mobile sensors and stationary sensors adaptively to their availability and the QoI requirements. For example, stationary sensors can be turned off to save energy if there are enough mobile sensors in the surrounding to collect sensing data. Mobile sensors can also coordinate with each other to share their sensing duties according to their sensing capabilities and locations. The system can target for minimizing the energy consumption or prolonging the network lifetime, while providing satisfactory QoI as specified by the users.

B. QoI-Aware Data Dissemination

Sensing data from applications such as fire detection or object tracking are time-sensitive, which have to be reported within short delivery time. According to the information quality and the application requirements, the sensors can adjust their sampling rates and data transmission rates. The reduced sampling rates and data transmission rates can reduce the network traffic and energy consumption of the nodes. For example, the sensing data with low QoI can be dropped to preserve more network capability for transmitting data with high QoI. Quality-of-Service (QoS) routing can also be applied to achieve short packet delay for time-sensitive sensing information.

Since multihop routing may not be available for sparsely deployed wireless sensors, mobile phones could be utilized as mobile mules to relay sensing data to the sink. The wireless sensors can cache the sensing data in their buffers and wait for the mobile nodes to collect them. However, the mobile mules only approach the stationary sensors opportunistically, which may lead to long and unpredictable data delivery delay. Opportunistic caching can be employed to store data at multiple sensors to increase data availability and reduce data delivery delay. Sensing context such as sensing type, locality and time-to-live of data can be considered to further enhance the QoI and reduce the communication overhead in data dissemination [15], [16]. It is important to consider the network infrastructure and the radio quality when designing the data dissemination mechanisms. Depending on the network connectivity, advanced data forwarding and filtering techniques can be applied to reduce the data delivery time [17], [18].

VI. A Ubiquitous Publish/Subscribe System for Mobile Sensor Networks

We suggest that publish/subscribe system as an ideal architecture for ubiquitous data access in wireless sensor networks with mobility. Unlike the client/server model, the publish/subscribe model decouples time, space, and flow between publishers and subscribers, which is especially suitable for data collection in mobile wireless networks with intermittent network connectivity.

A subscriber in our system could be a user connected through the Internet to the WSN, but it could also be a user using direct communication (e.g. with a smart phone) with sensors in the WSN. For example, in our scenario in Figure 1, a user may establish a direct communication with sensor 10 subscribing to the event "is the trail passing sensor 9 open or closed". Sensor 10 should then be able to collect such published information from sensor 9 about the event even if they only have contact through a mobile mule.

An ideal ubiquitous publish/subscribe system should be able to operate out of any WSN node independent of the nodes are fixed or mobile, or act as mobile sinks or mules, as well as out of stationary servers on the Internet. The mobility of nodes puts some special requirements on the system, in particular when mobile mules are used as publish/subscribe servers. Such a mule based system has similarities with publish/subscribe systems suggested for content-oriented opportunistic networks [19]. Assume a publish/subscribe system is located on each mule in order to give the best service to the subscribers. The mules will pick up the published data and meta information from the sensors that they are passing as well as the subscriptions from the users that they meet. When meeting another mule, they will exchange their publish/subscribe information and thereby each mule will gradually build a distributed publish/subscribe system. The idea is that the user subscriptions as well as the published sensor data and services will be propagated through the network with the mules' movements and meetings.

A. Design Study of a Publish/Subscribe System

We have designed a first instance of a publish/subscribe system in order to understand how it will work with mobile and stationary sensors [20]. There are two basic functions in our publish/subscribe system. One is to forward subscriptions from the Internet and mobile users to both the stationary and mobile sensors. Another is to collect sensing data from the sensors back to the subscribers. There are three major entities in our system (see Figure 2). Consumers are the Internet or mobile users who subscribe for sensing data through our publish/subscribe platform. The sensing modules on the stationary or mobile sensors are the publishers who collect and report sensing data. The platform server provides services for relaying subscriptions and sensing data between the subscribers and the sensors.

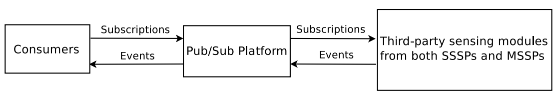

Fig. 2. Three major entities in our publish/subscribe system for mobile sensor networks.

A context-based data representation scheme can be designed to express the interest of users with metadata such as time, location, and sensing context associated with the sensing data. Internet or mobile users can subscribe to the sensing data of interests using a subscription message. The subscription message should indicate the location of the target area, the sensing types, the data range, and the time period of interest. Other kind of application requirements and constraints can also be included such as the freshness and accuracy of the data, etc.

VII. Conclusions and Future Work

In this paper, we provided a comprehensive study on major QoI metrics in sensor networks with different kind of mobility. We focused on QoI-aware data collection for mobile sensor networks that involve both stationary sensors and mobile phones. Parameters such as mobility of sensing devices, location of stationary sensors, user interests and sensing context that give significant influences on QoI have been highlighted. Network configuration and data dissemination mechanisms have been discussed for optimizing the QoI. Our ongoing research on context-aware and opportunistic information sharing have been illustrated. We also suggested publish/subscribe as an ideal architecture to implement ubiquitous data collection for mobile sensor networks.

Future work may include implementation and experimentation with the proposed publish/subscribe architecture in real-world applications such as hiking trail monitoring and emergency rescues. We would also like to investigate context- and social-aware data sharing mechanisms, and study the tradeoff between QoI and user privacy in mobile sensor networks.

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