A sensing coverage analysis of a route control method for vehicular crowd sensing

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Abstract—General vehicles have much potential to contribute to city surveillance in a context of Smart City. Vehicular crowd sensing is essential for reasonable and sustainable city surveillance. We propose route control method to enhance sensing coverage of crowd sensing system. The method is composed of sensing demand-aware cost assignment and a cooperative path reservation. We performed a traffic simulation to evaluate the route control method. The result shows sensing coverage of vehicular crowd sensing can be significantly enhanced without much additional travel of sensing vehicle. Therefore total sensing ability can be increased without enhancing sensor ability or enhancing the number of sensing vehicles.

Keywords—Vehicular sensor networks; Route guidance;

I. INTRODUCTION

A crowd sensing approach in various Smart City applications is promising. A crowd of cheap sensors possessed by citizens has huge potential for a city wide sensing. Typically these private sensors are implemented in a smart phone, a wearable device, a home appliance, or a smart house. A vehicle is also considered as an important source of sensing information. To deploy a number of sensors in a city environment is not realistic in most scenario. So a number of Smart City applications employ crowd sensing approach [1].

Recently a vehicle tends to have powerful sensors for an intelligent autonomous driving. A radar, a camera mounted on a front part of vehicle can collect information about succeeding vehicle, pedestrians, and road environment [11][12][13]. These sensors are primary used to detect threats for the driver, however, the sensing information have also potential to contribute to city surveillance. For example, a position of an obstacle on the road can be utilized to other driving vehicles or road management authorities. A distribution of pedestrians in a city might be useful for traffic management, area marketing or crime prevention.

One of key performance indices (KPIs) of a crowd sensing system is a sensing coverage. The number of sensors is a prime factor for sensing coverage. Secondary, trajectory (or path of a vehicle) of sensors becomes also an important factor of a coverage when the sensors have mobility. The path of a vehicle are normally controlled by a shortest time path to a destination, an efficient delivery route for a logistics vehicle or routes of a public transportation. None of them treats sensing coverage for a city surveillance. We propose a path control which take sensing coverage into account.

In our previous work, we proposed a route control method for vehicle bourn crowd sensing system to expand sensing coverage with mutual route information sharing [19]. Each car shares route information as a reservation on each road link. Each car also can find better route to avoid occupied road link with a proactive route guidance algorithm. This route control algorithm can disperse vehicle trails therefore leads higher coverage. To evaluate a coverage, we employed area coverage which assumes uniform sensing importance of each position in the previous work. We also confirmed a travel time of the vehicles is also reduced rather than being extended.

Most of real-world sensing applications assume a particular sensing target, for example, hot-spots on traffic intensity, pedestrian population or crime rate in a city. In this paper we evaluate target coverage which has non-uniform sensing importance rather than area coverage. We define a term, a sensing demand represents a sensing target or a sensing importance. We propose a route control method for non-uniform and dynamic sensing demand and evaluate them with a traffic simulation.

In second chapter, we overview related works from Smart City, intelligent transportation system, and mobile sensor networks. In third chapter, we define sensing demand distribution and target coverage. In chapter 4 we evaluate route guidance method for static sensing demand. In chapter 5, we extend sensing demand to compatible with dynamic sensing demand. We confirmed applicability of our route control methods to enhance target coverage in various sensing demands. We also revealed suitable situation of applicability of the methods.

II. RELATED WORKS

Crowd sensing for Smart City has been explored as an effective way of collecting information about a city. The advantage of crowd sensing are considered as, sharing and reusing data, reduction of data acquisition cost, collecting data previously unavailable [1]. Some previous Smart City projects practically tried to apply crowd sensing on urban air pollution [5], traffic surveillance [3], natural disaster [4], crime prevention [2], and health activity [6].
Floating car data (FCD) is a major technique in ITS (Intelligent Transportation System) to collect spatial and real-time sensor data from general cars in a city. At present, FCD is widely used in many cities as a part of real-time traffic information system. A conventional FCD system mainly used to collect traffic condition in a city [8] [10]. Some other applications such as a road state sensing [11], weather sensing [9], are also explored [7].

In ITS, traffic information system, car navigation system is important for Smart City in a different context. These systems can potential to reduce environmental impact by reducing usage of oil. Real-time traffic information is a key to provide a shortest time route. However traffic is highly dynamic so current shortest route won’t sometimes be the best route in a future. There are many kinds of traffic prediction techniques [17] [18], however they sometimes has large error. Some researchers took up cooperative navigation systems, which share destinations, to refine route quality [10]. We previously evaluated this method in which drivers proactively share their destination and route information with others [19]. We confirm not only enhancement of traffic efficiency and an effect of expand sensing area coverage.

We also investigate sensing coverage by this crowd sensing system. Various kinds of researches have already tackled this problem in vehicular mobile sensor networks [20] [21]. Most of these efforts are made for a communication establishment and a (packet) routing or a network topology management. Researchers for mobile sensor networks or multi robot surveillance already investigated sensing coverage in certain environments [23]. These kinds of researchs mainly targeted to free space in which conflicts of routes between agents don’t become a large issue. Wireless sensor networks are also applied to traffic surveillance [24]. Static sensor network provide easy to install and low cost solution for a traffic surveillance. However we’d like to focus on more volatile mobility for sensors because city changes faster than update interval of the static sensors. We assume the sensor can only follow road network. We also assume the user of each mobile sensor has their own destination and wouldn’t like to care about a city surveillance proactively. It relies on user’s cooperation to a city surveillance as same as other participatory sensing architecture.

III. SENSING COVERAGE AND ROUTE GUIDANCE

In this chapter we define a sensing coverage which represents bias of sensing importance in a city. We also instruct a conventional route guidance method which control general vehicles which in a city. We also introduce how to modify the route guidance with various factors of road link preference.

A. Sensing Demand

A sensing target which distribute in a city can have continuous ratio of importance. We define a sensing demand as sensing requirement by a crowd sensing system operator in a certain scenario. A sensing demand distributes over space and time. For example, a facility checking task targets some facilities (ex. bridges, buildings, road side facilities). Such demands are distributed static over a city. On the other hand, many sensing tasks deal with dynamic phenomena in a city (ex. weather, pollution or human activity) (Figure 1). We have already confirmed an effect of (area) sensing coverage and some route guidance methods in a uniformly (and statically) distributed sensing demand setting in the previous work. In this work we extend our method to more general case include statically or dynamically distributed sensing demand.

B. Sensing Coverage

A sensing coverage index should reflect a sensing demand distribution. We used area coverage in our previous work therefore we assumed only uniform sensing demand over space and time. Sensing coverage is measured link by link as explained in a latter section. We defined this coverage as Area coverage (AC):

\[
AC = \frac{\sum_{t} \sum_{l} v_{l,t}}{NT}, \quad v_{l,t} = \begin{cases} 1, & \text{any car visit link}_t \text{ at } t \\ 0, & \text{otherwise} \end{cases}
\]

where N is the number of links, T is the number of observation periods. We also define dynamic sensing demand \( D_{l,t} \) on each link, each time. We define target coverage on the sensing demand as demand satisfaction (DS). \( D_{l,t} \) can have an arbitral value, however we assume a range [0,1] for a simplicity in this work. Total DS is defined as follows:

\[
DS = \frac{\sum_{t} \sum_{l} v_{l,t} D_{l,t}}{\sum_{t} \sum_{l} D_{l,t}}, \quad v_{l,t} = \begin{cases} 1, & \text{any car visit link}_t \text{ at } t \\ 0, & \text{otherwise} \end{cases}
\]

A sensing demand is assumed to be fully satisfied by supply of a sensing from a vehicle. The DS involves apparently both uniform and static demand distribution cases. DS also can be read as weighted area coverage. Because of this involvement of special cases we expect a route guidance for a dynamic sensing demand can cover all cases above.

C. Route guidance

Unlike typical mobile sensor networks such as robots or UAV, a general vehicle in a city can only exist on road networks. Therefore the decision making of transportation is performed link by link manner. Road link here is a fragment of a road that typically connects two crossings and have no branch road internally. A route guidance in car navigation systems uses these links to find shortest route to destination. To find shortest route, some path finding methods such as
Dijkstra or A* algorithms are used [15] [16]. Basically a distance of a link used as a link cost. To deal with dynamically changing traffic situation, a link travel time is used as a link cost. Some other preference information can be integrated into a link cost such as, road width, road condition, slope, curve and even a scenery of view. To attract vehicles to a link cost would be decremented. We employ this simple mechanism to attract vehicles to visit sensing demands.

With telematics based traffic information, the system can provide a shortest time route to the destination. The traffic information system can provide current or predicted link travel time which can be collected by a road side traffic observation facility or a floating car system. For these kinds of route search we can formulate distant, current travel time, predicted travel time costs of links respectively as follows:

\[ C^\text{dist}_{link_i} = \text{len}(link_i) \]
\[ C^\text{CT}_{link_i} = \text{travel time}(link_i) \]
\[ C^\text{PT}_{link_i} = \text{travel time}_i(link_i) \]

We employ these basic route guidance methods as baseline.

D. Route guidance with reservation

We proposed a reservation based proactive route search in our previous work [19]. Each car shares its route with other car as a route reservation (Figure 2). A route reservation cost is combined with a distance cost. If there are many reservations on a link, other cars avoid to choose the link. Therefore the routes of vehicles would be dispersed. This mechanism has some desirable effects. One is coverage expansion, the other is reduction of a traffic congestion. With this effect the vehicular crowd sensing system can expand coverage and reduced travel time simultaneously. We defined reservation based cost as follows:

\[ C^\text{reservation}_i = \text{len}(link_i) + \alpha \cdot \text{reservation}(link_i) \]

![Figure 2 Route reservation](image)

Because we assumed uniform sensing demand, the dispersion of route directly yielded higher coverage. To apply this method to more typical city surveillance scenario, we extend sensing demand non-uniform and dynamic.

We define sending demand in a certain link as \( D_i \). We employ a cost function with a current sensing demand and a predictive sensing demand respectively as follows:

\[ C^\text{SD}_{link_i} = \text{len}(link_i) + \alpha \cdot D_i \]
\[ C^\text{STD}_{link_i} = \text{len}(link_i) + \alpha \cdot D_{link} \]

The bias \( q \) should be a negative value in order to attract a vehicle route to certain link. These costs apparently lead traffic concentration. So we also tried combined cost with a route reservation which has an effect of traffic dispersion. We define this Current Reservation (CR) cost function as follows:

\[ C^\text{SDCR}_{link_i} = \text{len}(link_i) + \alpha \cdot D_i + \beta \cdot \text{reservation}(link_i) \]
\[ C^\text{STD}_{link_i} = \text{len}(link_i) + \alpha \cdot D_{link,2} + \beta \cdot \text{reservation}(link_i) \]

We also extend reservation technique to predictive. We divide reservation slots into time slot. We call this cost function Predictive Reservation (PR). A reservation should be performed according to predicted arrival time for each link.

\[ C^\text{SDPR}_{link_i} = \text{len}(link_i) + \alpha \cdot D_i + \beta \cdot \text{reservation}_t(link_i) \]
\[ C^\text{STD}_{link_i} = \text{len}(link_i) + \alpha \cdot D_{link,2} + \beta \cdot \text{reservation}_t(link_i) \]

We expect a sensing demand cost would bring better tracking of sensing demand. We also expect reservation cost would bring route dispersion effect to expand coverage.

IV. EVALUATION I STATIC SENSING DEMAND

We examine these route guidance methods in several sensing demand types. We performed traffic simulation to examine relationship route guidance and sensing coverage. We build grid map and simple traffic. We employ simple 10*10 grid city and left to right uniform traffic (Table 1). We employ traffic demand with 50 cars per hour from one origin-destination pair. We perform simulation 10 times for each setting and take average of evaluation values.

<table>
<thead>
<tr>
<th>Map size</th>
<th>10 * 10 grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total OD pattern</td>
<td>100 (10 west origins to 10 east destinations)</td>
</tr>
<tr>
<td>Total time step</td>
<td>20000 sec</td>
</tr>
<tr>
<td>Sensing interval</td>
<td>Once in 30 sec</td>
</tr>
</tbody>
</table>

Table 1. Traffic simulation setting with our traffic simulator
Route update frequency: Once in 1 minute

A. Static Sensing Demand

First we examine non-uniform static sensing demand distribution. We employ current SD cost $C^{SD}_i$. We perform sensitivity analysis with some range of SD densities of random distribution. The distribution is created with random selection of links that has fixed SD. The result shows coverage of current SD cost outperforms conventional ones in the range from 0.02 to 0.1 of demand density (Figure 3). The result implies, if a sensing demand distribution has more density, knowledge of SD position cannot contribute coverage.

![Figure 3 Coverage on demand density](image)

We also evaluated travel time to destination to find trade-off between detouring and coverage. Because detouring leads deterioration of quality of service for participant driver with longer travel time to its own destination, a detouring should be eliminated. As shown in Figure 4, travel time is increased substantially in higher density. However, the ratio of detouring is limited in lower density which also yield higher coverage. Totally this result encourage applicability of the method to enhance coverage without much extension of travel time as long as demand density is lower than 10%.

![Figure 4 Travel time on demand density](image)

B. Enhancement with path dispersion factor

We also examined situation with higher traffic demand. The simple current SD route search leads traffic concentration and cause duplication of sensing in same route. This leads low coverage and traffic congestion. We propose two methods to disperse traffic. The one is current excess sensing demand cost which introduce demand satisfaction mechanism (Figure 7). Each link has default (max) demand value and the demand value decreased or satisfied when car arrived on the link. Satisfied demand recover its value to max value over time. This mechanism is expected to reduce duplicating path on same link therefore we expect paths are dispersed. The other method is the reservation we introduced in the previous work.

![Figure 5 Two types of SD costs](image)

The result shows advantage of reservation method over excess sensing demand and conventional one (Figure 6). This doesn’t lead travel time extension in any traffic demand (Figure 7).

![Figure 6 Coverage on traffic demand](image)

![Figure 7 Travel time on traffic demand](image)
C. Enhancement with predictive reservation

We employed simple reservation method which have one reservation slot on each link. This will work in a short range path however in longer range path the latter part of path will tend to have unnecessary reservation. This leads exceed reservation in further part of maps. This will be corrected by predictive reservation table. With the predictive reservation table the reservation is performed according to a passing time on each link (Figure 8).

![Figure 8 Predictive reservation table](image)

To evaluate this effect, we examined this method in various map sizes. Deterioration of coverage performance is observed in current reservation cost (Figure 9). The predictive reservation can suppress this effect. And this doesn’t lead extension of much travel time (Figure 10).

![Figure 9 Coverage on map size](image)

![Figure 10 Travel time on map size](image)

V. Evaluation 2 Dynamic Sensing Demand

We extend sensing demand to change dynamic over time. We examined with random distribution of sensing demands and we change the distribution each time interval (same with sensing interval 30 seconds). We compared three kind of route search methods distance, current sensing demand, and predictive sensing demand. We assumed system can use correct prediction of sensing demand distribution without error.

A. Dynamic sensing demand with uneven situation

We examined with biased situation whose demand distribution exist only northern and southern arterial (Figure 11). We switch demand value between 0 and 1 for northern and southern demand area respectively. In this situation distance cost will fail because their paths tends to concentrate to center area in a map.

![Figure 11 Biased sensing demand distribution](image)

As shown in a result (Figure 13) in extreme case (outside 1), predictive cost outperform other conventional ones. Predictive information of sensing demand can help when the sensing demand drastically changes. We consider most of practical cases are in between unbiased and biased situations.

B. Dynamic sensing demand with reservation

We also examined combination of predictive sensing demand and path reservation in dynamic scenario. Under most of conditions of demand density the predictive SD with predictive reservation outperforms other methods. (Figure 13)
We introduced a variety of route control methods for sensing vehicles which enhance sensing coverage. We confirmed applicability of a sensing demand based cost route search outperforms conventional methods in terms of coverage in static and dynamic sensing demand distribution. We also confirmed the coverage is increased by path reservation cost in most cases. We also enhanced reservation method with predictive reservation table in order to apply for longer path.

We will examine these methods in real maps and real traffic to find more practical issues in a future work. And we would like to apply optimization technique such as VRP (Vehicle Routing Problem [25]) over these sensing demand and compare our methods with exact solution.

VI. CONCLUSION AND FUTURE WORK

We proposed a vehicular crowd sensing system with route control of participant sensing vehicle. We defined a sensing demand which corresponds sensing target in a city and examined sensing coverage which represents how the system efficiently cover a city. We introduced a variety of route control methods for sensing vehicles which enhance sensing coverage.

We confirmed applicability of a sensing demand based cost route search outperforms conventional methods in terms of coverage in static and dynamic sensing demand distribution. We also confirmed the coverage is increased by path reservation cost in most cases. We also enhanced reservation method with predictive reservation table in order to apply for longer path.

We will examine these methods in real maps and real traffic to find more practical issues in a future work. And we would like to apply optimization technique such as VRP (Vehicle Routing Problem [25]) over these sensing demand and compare our methods with exact solution.

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