# Localization In Mobile Ad Hoc Networks Using Cumulative Route Information

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## ABSTRACT

Discovering the location of the mobile nodes carried by people is important issue for many sensor applications. Several localization techniques have been proposed, but human mobility patterns and collaboration between mobile nodes have been seldom considered. In this paper, we propose a mobile node localization system based on collaboration and route information that characterizes human mobility. To validate the feasibility of our approach, the proposed system is implemented and experiments are conducted on real routes and to evaluate various scenarios, simulation experiment was also conducted.

## ACM Classification Keywords

C.2.1 [Computer System Organization]: Network Architecture and Design - Distributed networks, Wireless communications

## General Terms

Algorithms, Design, Experimentation

## Author Keywords

Mobile node localization, Collaboration, Wireless Sensor Networks

## INTRODUCTION

Wireless sensor networks, which are one of the practical areas of mobile ad hoc networks, have started establishing connections between human-made networks and physical world, and our life-style has been changing along with the recent advances in networking technology. As the mobile computing technologies are improved, various styles of sensor nodes are introduced for wireless sensor networks. For example, some sensor nodes are built in mobile devices such as PDA and cellular phones while others are built in things closer to our body such as clothes and shoes. Furthermore, some of them even stick to the human skin in health care applications. These kinds of human-centric sensor nodes move along with people and the number of nodes is rapidly increasing. Now, the physical information around people is being sensed, gathered, and processed to increase the quality of our lives [1, 2, 3, 4].

The localization of such mobile nodes is required for mapping of collected data [5] and enabling location-aware services. A GPS-enabled mobile node can easily figure out its location [6]. However, due to their cost and size, most sensor nodes with limited resources can not be incorporated with such devices. Therefore, they infer their location based on the information they receive from other nodes. In this manner, several localization techniques have been studied [10-18].

We propose a localization system focusing on human-centric mobile nodes. Here are three major considerations of our research: (1) Human-centric mobile nodes are carried by people. Therefore, the location is affected by people's moving patterns, which are constrained by public facilities such as a paved walkway. Such a constrained movement appears more intensely in urban life. In this research, we focus on the problem of locating pedestrians walking along streets in a city. Now, it is reasonable to use information on routes of public facilities in a localization system. Here, we use the term "route" to describe a path that a mobile node moves along. In order to increase efficiency of the localization system, route information should be automatically gathered by mobile nodes without intentional movements and be continuously updated. (2) There exist a great number of mobile nodes, so the probability of encountering other nodes is very high. The estimated locations of nearby nodes can be a clue for determining how accurately a mobile node estimates its location. Collaborations between mobile nodes sharing their estimations improve an accuracy of a localization system. The effect of unexpected movements is also mitigated by collaboration between mobile nodes. (3) There is still one big chance to be considered in a localization system. It is that the number of GPS-enabled mobile devices is also highly increasing. However, it is not enough to share one point of GPS location solely. A GPS-enabled mobile node

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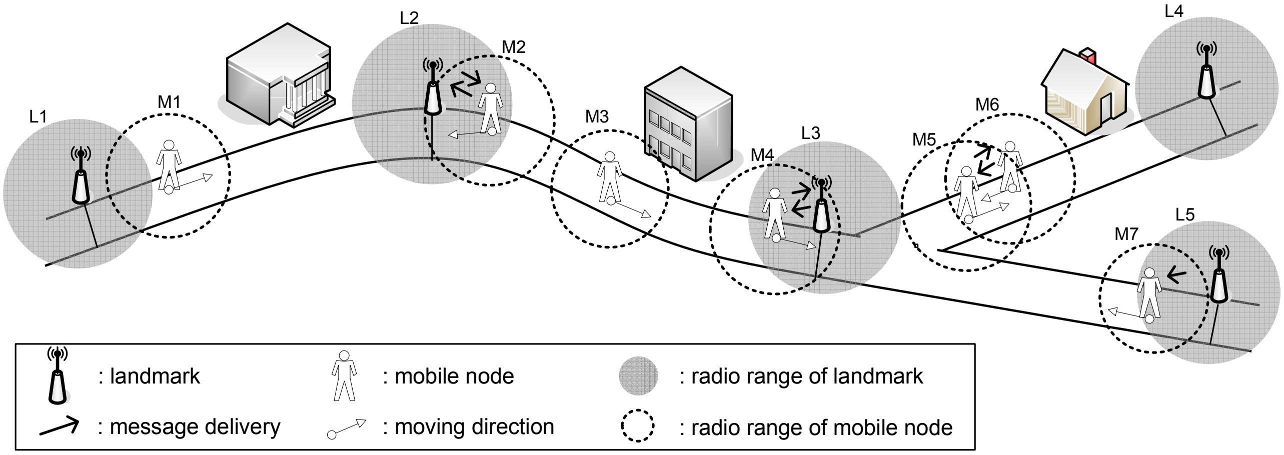


Figure 1: Human-Centric Mobile Node Localization System Overview.

detects route's shape from its moving trajectory, and then the route information is used in a localization system.

We have implemented our localization system on real sensor motes and validated the feasibility through real experiments. To evaluate various scenarios, simulation experiment was also conducted in the same route condition of real experiment. The experimental results show that the system using accumulated route information is appropriate for localization in a real environment. We have also verified that the collaboration between mobile nodes improves the localization performance dramatically.

## A HUMAN-CENTRIC MOBILE NODE LOCALIZATION SYSTEM

### *System Overview*

The proposed system consists of two components: *a landmark* and *a mobile node*. A landmark has a location-aware device such as a GPS, and is statically deployed along a pedestrian way. A Landmark initially knows its own location, but it does not have any information about nearby landmarks. Landmarks can communicate with others in a direct or multi-hopping manner. However, if no node is found within radio range, a landmark has no way to communicate with other landmark. To reduce costs, we deploy landmarks sparsely, only at corners or intersections. In our approach, a mobile node takes a role of a data deliverer between landmarks. Through mobile nodes, landmarks collect route information and various kinds of data, and the accumulated data is used for a localization of a mobile node afterwards.

Route is modeled as a sequence of straight lines, and each straight line refers a section of successive two landmarks. Each landmark constructs *route information*. Route information is composed of locations of neighbor landmarks and its own location. Other useful information also can be included, i.e., average moving speed in the section, which is inferred from elapsed time for mobile node coming from previous landmark.

Figure 1 illustrates the overall localization system, where five landmarks (L1~L5) are statically deployed and seven mobile nodes (M1~M7) are carried by people who walk on the road. The dotted circle represents a radio range of a mobile node and the gray circle shows a radio range of a landmark. Within a radio range, landmarks and mobile nodes can communicate with each other. Radio link between nodes is not always symmetry. M2 deliver message to L2 and receive message from L2. However, L5 cannot receive a message from M7 even though M7 receives a message from L5. Since each node has a different radio range, this problem happens.

Every landmark has its neighbors. In case of L2, there are two neighbor landmarks, which are L1 and L3. In case of L3, there are three neighbor landmarks, which are L2, L4 and L5. The neighbor information is acquired by mobile nodes. For instance, M1 moves from L1 to L2. M1 received information of L1 when it was in the radio range of L1. M1 is going to delivers information of L1 to L2, when it enters into the radio range of L2. In case of M2, it delivers information of L3 to L2. Now, L2 obtained the locations of L1 and L3. The same process occurs to every landmark.

Once landmarks obtain information of neighbor landmarks, a mobile node uses the information for its localization. For instance, M3 moves from L2 to L3. Since M3 receives information of the next landmark from L2, it recognizes that it is on the route from L2 to L3. By using this knowledge, M3 localize itself in real-time. In case of M5, route information is ambiguous. M5 comes from L2, passes by L3, and finally moves to L4. However, M5 receives information of two landmarks, which are L4 and L5, as the next route from L3. At the time of encountering M6 which comes from L4, M5 can verify its real route. To enhance localization accuracy, a mobile node shares its own information with other mobile node which it encounters.

### *Route Information Construction*

Route information is constructed by mobile nodes in runtime. A landmark knows its own location and periodically broadcast it. When a mobile node passes through a radio range of a landmark, a mobile node receives the location. When a mobile node enters into a radio range of another landmark, it receives a new location. At that time, the mobile node sends the location of previous landmark to the new landmark. Again, the mobile node delivers the location of the new landmark to another new landmark. In this process, locations of neighbors are accumulated in a landmark. This scheme is highly efficient since route information is autonomously constructed by mobile nodes without any intentional movements. A landmark includes several parameters as its information: identification, location, average speed of mobile nodes, and average node numbers per minute.

When a landmark is newly inserted or deleted, route information is automatically updated by a mobile node that passes by. No explicit effort is needed. An actual route can be divided into several directions. Considering crossroads, neighbor information is stored up to four instances. With a single pass of a mobile node from each directions of a route, route information is completely constructed. Once route information is constructed, a mobile node uses the information to estimate its location.

### *Localization Mechanism*

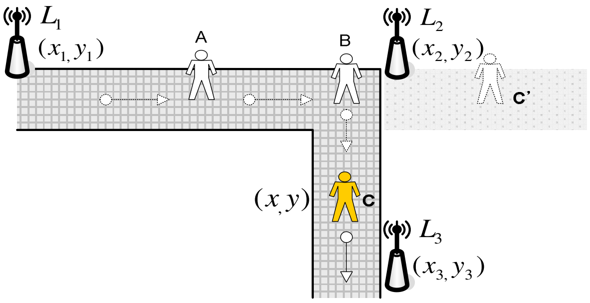
In intermittently connected environment, a mobile node estimate its location based on the information that it obtains when it is connected to other nodes. Here are three types of methods:

(Method 1) No prediction.

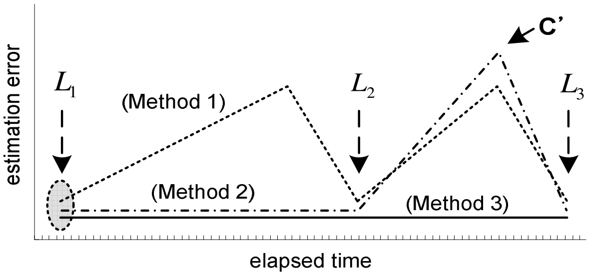
(Method 2) Prediction based on history.

(Method 3) Prediction based on route information.

In method 1, a mobile node does not perform any algorithm to estimate a location. It only adopts the location of latest landmark. This is the simplest method, but estimation error is very high when landmarks are sparsely deployed and connection rate between nodes is low. In method 2, a mobile node predicts its location based on previous movement. A well known algorithm for this approach is Dead-Reckoning [18]. The speed and heading of a mobile node are decided from the positions of previous two landmarks, and the elapsed time. The speed and direction is used to predict its next location. However, when a moving direction changes sharply, estimation error can be even bigger than Method 1. In Figure 2 (a), a mobile node moves from L1, through L2, and toward L3. But the route direction changes in 90 degrees at L2. After a mobile node arrives at location C, the estimation result is location C' by using method 2. To solve this problem, we propose Method 3. This method uses route information to estimate a location. From L2, a mobile node receives a location of the next landmark, L3. Therefore, the changed direction is accommodated in estimation process. Figure 2 (b) shows the performance of three methods in the scenario of (a). The y-axis represents a Euclidean-distance between an actual location and estimation. At the start point, L1, the errors of the three methods are the same but the graphs for the other two methods are shifted up a little bit so they can be easily distinguished from each other.



(a) Mobile node movement on a road (L1->L2->L3)



(b) Performance comparison of localization methods

Figure 2: Mobile node localization.

In the real environment, there are some considerations in using route information. For example, a route can be divided into several paths. Such case, next destination cannot be decided. To alleviate this problem, we can densely deploy landmarks in such areas. A careful deployment of landmarks improves overall system performance. This approach, however, is not cost-effective. Instead, we adopt a collaboration mechanism because it is highly probable that a mobile node is intermittently connected to other mobile nodes.

### *Collaboration between mobile nodes*

People's movements are not always predictable. Sometimes people suddenly stop and then continue to walk again. On a downhill road, people walk fast, and on a crowded road, people's walking speed reduces. Without any surplus information, localization performance will be limited. To overcome this, we considered a collaboration scheme of mobile nodes to create additional information.

When a mobile node encounters another mobile node, they exchange their estimations. If the two estimations are similar, they conclude that the estimations are right. In case a mobile node receives several estimations and the estimations are similar except its own estimation, the mobile node may adopt the average of other estimations. However, the estimations are error prone. So, we introduce an estimation reliability factor ( $r$ ) that shows how accurately a mobile node estimates its location. $r$ reflects the effects of time, route condition, and collaboration results. Equation 1 represents our definition of the estimation reliability factor.

$$r(t) = r_{init} - \beta(t) + \alpha \cdot NoC \qquad (1)$$

*where,*

$0 < r(t) < 1$

$r_{init}$ : initial reliability value

$\beta(t)$ : penalty factor as time elapses

$\alpha$ : weighting factor about collaboration

$NoC$ : number of collaboration

An initial value ( $r_{init}$ ) includes an effect of a route condition. In such a place where a route is divided into several paths, $r_{init}$ sets as a relatively low value due to the high probability of an incorrect estimation. The penalty factor ( $\beta(t)$ ) is an increasing function on time *t*. It is reasonable to assume that estimation error increases as time goes. Equation 2 describes it. Here, $T_{predicted}$ is the expected time to reach to a next landmark. This value is induced from a previous speed and a length of a next route. By using a larger value to $\beta_{outTime}$ than $\beta_{inTime}$, we give a big penalty when the expected time is exceeded.

$$\beta(t) = \begin{cases} \beta_{inTime} \cdot \dfrac{t}{T_{predicted}} & ,where\ 0 < t \le T_{predicted} \\ \beta_{outTime} \cdot \dfrac{t}{T_{predicted}} & ,where\ t > T_{predicted} \end{cases} \qquad (2)$$

A mobile node decides that the estimation is reliable if it receives a similar estimation value from another mobile node. Estimation reliability factor increases in proportion to the number of mobile nodes with similar estimation results. $NoC$ is the number of nodes whose Euclidean distance is below a certain threshold. $\alpha$ is the weighting factor of $NoC$.

For collaboration, mobile nodes exchange several data such as a location of previous landmark, elapsed time, current estimation, and an estimation reliability factor. A mobile node re-estimates its location based on this data. New estimation can be represented as a weighted sum of the current estimation and the received value.

The collaboration scheme successfully handles the multi-path problem that we mentioned previously. When the node encounters a node coming from the opposite direction, they exchange messages. Since the messages include locations of previous landmarks, a real route is discovered. The mobile node re-estimates its location with the correct route information. The accuracy increases proportional to the number of encountering mobile nodes.

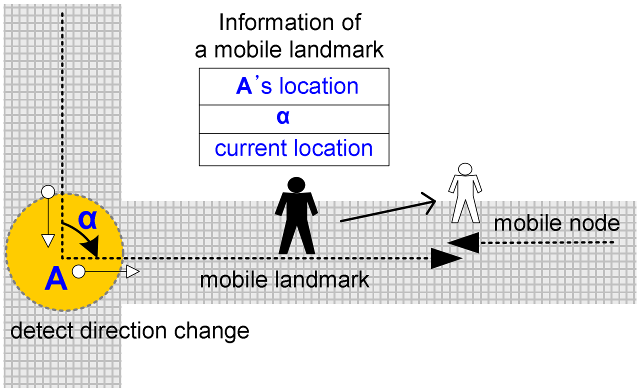


Figure 3: A Behavior of Mobile Landmark

### *Mobile Landmark*

A *mobile landmark* is a GPS-enabled mobile device carried by people. However, to imitate a static landmark with route information, it detects a route shape from a moving trajectory. At a corner or an intersection, a moving direction of a mobile landmark may change. The moving direction can be induced from at least two locations of a mobile landmark at a certain time difference. In case that an angle of a changed direction is larger than a certain threshold, a mobile landmark regards the position as a location of a detected landmark. In this research, $\pi/6$ is used as a threshold. When a mobile landmark detects a direction change, it saves the location and the angle of the direction change, $\alpha$. Through this process, a mobile landmark accumulates route information and it delivers the route information as well as its current location. Figure 3 shows the behavior of a mobile landmark.

A mobile node estimates its location according to route information from a mobile landmark. A mobile node sets its location as a location of a mobile landmark, and regards a detected landmark as a possible destination. But it does not start a prediction process since the possible destination could be a wrong destination. When the mobile node encounters another mobile landmark, it analyzes the current situation. If it concludes that new mobile landmark is on the same route from the previous mobile landmark, it takes the previous possible destination as a real destination and starts to predict its location. To avoid an overestimation, it finishes its prediction when it arrives at the destination.

In the previous sections, we simplified that human walks in straight lines and constant speed between landmarks. Even though these assumptions look very limiting, a lot of mobile landmarks make routes between landmarks shorten. Therefore, the restriction can be relieved in reality.

## PRACTICAL CONSIDERATIONS

The radio range of sensor node varies from several to several tens of meters depending on environmental elements, hardware characteristics, body effects, and so on. Signal strength fluctuates and a radiation pattern is not isotropic. These may affect a performance of localization. In practice, various factors should be considered in a real environment. Here, we address some of these issues.

**Radio Effect:** A mobile node receives same messages several times while passing through one landmark area due to a relatively wide range of radio. So, estimation accuracy is affected by a selection of a reference time when a mobile node starts a localization of a new section. Here, we use an arithmetic mean of a first and a last received time of message as a reference time.

The radio range is in practice not uniform. Its shape is distorted due to various environmental factors. Even though a mobile node is able to receive a message from a landmark at the boundary of its communication range, it happens to fail to receive a message at a closer position to a landmark. A change of Received Signal Strength (RSS) value is used to determine the exit point from a landmark.

**Estimation Period:** Moving speed of a mobile node may not be the same as before. In case of moving fast, a mobile node receives a landmark message earlier than expected. In the reverse case, a mobile node does not receive a message even after the expected time has elapsed. Therefore, a mobile node has to decide when to stop a current localization and start a new localization for a next section. A mobile node continues to estimate its location up to an expected landmark location when it moves slowly. In case that landmark message is received early, a mobile node keeps on estimating location before it leaves a landmark area. After leaving landmark area, a mobile node starts to re-estimate its location based on newly received information.

**Deployment:** In order to achieve an appropriate localization performance, static landmarks should be deployed at every turning point of a road. However, newly developing mobile phones are equipped with GPS module. These location-aware mobile nodes are regarded as mobile landmarks. Therefore, even though static landmarks are not densely deployed, localization accuracy increases according to the number of a mobile landmark.

**Energy and Performance:** Initially, we assumed that a mobile node is carried by people and this node can be recharged [9]. However, the minimization of energy consumption is still needed. A static landmark broadcasts its message periodically. To reduce the time of using RF transmitter, a mobile node has two strategies as follows: First, a mobile node works in a reactive fashion. A mobile node broadcast its message only when it receives a message from a landmark. If landmarks are 10 seconds apart from each other, a mobile node uses its RF transmitter only one time per 10 seconds. Second, a message broadcast for collaboration is allowed when it is required. In case a reliability factor drops below a certain level, a mobile node broadcasts a collaboration request message to other mobile nodes and a mobile node to hear that broadcasts its message back to the node.

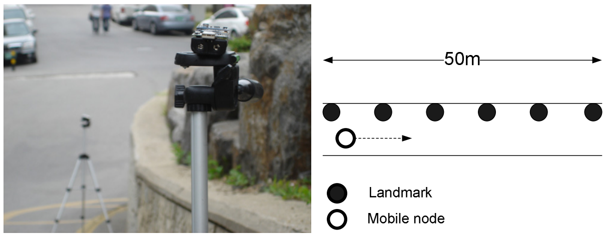


Figure 4: Simplified System Deployment

## EVALUATION

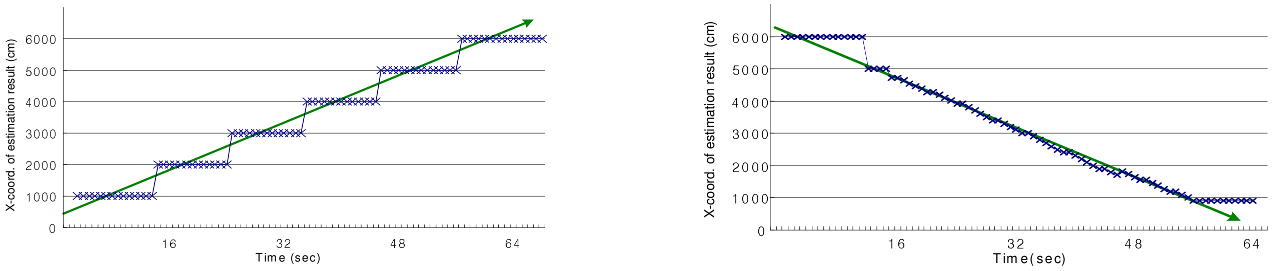
In this section, we present the experimental results of the proposed localization system. We have implemented the algorithm in real hardware and validated the feasibility through real experiments in various situations. We used Tmote Sky and RETOS [19] for implementation. To evaluate various scenarios, simulation experiment was also conducted in the same route condition of real experiment.

### *Basic Experiments*

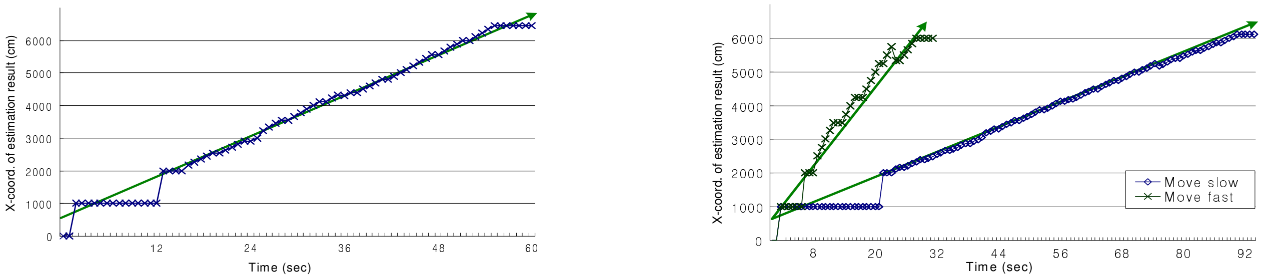
Before examining the fully installed system, we devised simple test scenarios and observed the system operation. The experiments were conducted on campus roads. Figure 4 shows the actual deployment of the system deployed in linear topology. Landmarks are deployed straight along a road side. In the system, landmarks broadcast beacon messages which contain the information of neighbor landmarks and the landmark itself. Mobile nodes also broadcast when they receive beacon from landmarks. The mobile messages include previous landmark information, estimated location, elapsed time and an estimation reliability factor. Landmarks construct neighbor landmark information with previous landmark information of mobile nodes, and mobile nodes calculate their position with next landmark information from a landmark.

To observe the operation of the system, we deployed six landmarks on a straight road ten meters apart as shown in Figure 4. Each landmark has a position on a 2D plane as (1000, 0), (2000, 0), (3000, 0), (4000, 0), (5000, 0) and (6000, 0). We reduced the radio transmission power of the sensor nodes to prevent direct communication between landmarks. During the experiments the radio transmission range was about 3 meters.

Figure 5 shows the localization result of mobile nodes with the straight landmark topology. In the graphs, the X-axis represents the time and the Y-axis represents the X-coordination of the estimation results. We use arrows to show the actual trajectory of mobile nodes in each experiment. Figure 5 (a) shows the localization result when landmarks do not have any neighbor landmarks' information. Since the mobile node fails to receive the next landmark information, the mobile node cannot predict the position. The mobile node sets up the location as the location of the previous landmark; hence the graph is shown as a step function. However, during this process, the mobile node carries the previous landmark information onto the



(a) Localization result before Landmark initialization (b) A mobile node localization moving in the opposite direction



(c) Localization result after Landmark initialization (d) Two mobile nodes with different speeds

Figure 5: Localization results of mobile nodes with uniform motion.

next one. Figure 5(b) shows the result when a mobile node passes the road going opposite direction. Since the landmarks have received the neighbor node information by the experiment in Figure 5(a), they send the next landmark information to the mobile node. When the mobile node passes the first landmark, it is impossible to estimate the right location because of the lack of average speed. After the node passes by the second landmark, however, the mobile node predicts its current position smoothly.

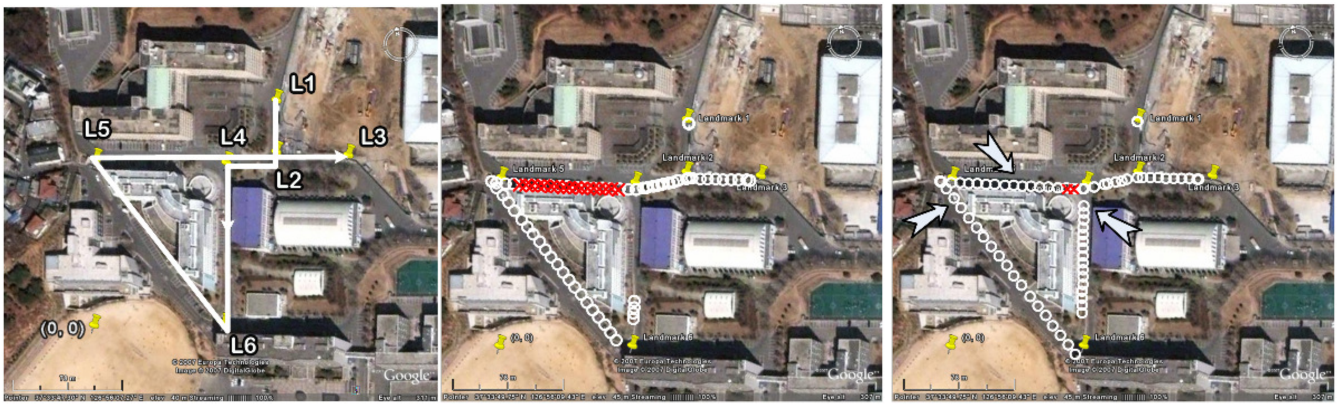
Through the experiment shown in Figure 5 (a) and (b), the landmarks constructed the route information of both directions with the two mobile nodes. After the landmarks initialize the neighbor landmark information, all mobile nodes from any direction successfully estimate its locations as in Figure 5(c). We used two mobile nodes to observe the result when the nodes move at different speeds. Figure 5(d) shows the result. The faster node passed by the 6 landmarks within 30 seconds while the slower one took about 90 seconds. The location prediction is considerably close to the actual trajectory. A few of missed predictions occurred with the faster mobile node because of the difficulty of maintaining fast and uniform velocity in practice.

### *Outdoor Experiment*

Since our system is designed for a network of roads, we examined the system in a relatively large field. The field is about 200m x 200m and contains slopes and crossroads. Satellite images, by Google earth, in Figure 6 show the deployment and results of the system. We deployed six landmarks on cross points of the roads. The locations of landmarks are set on the basis of an origin (0, 0) which is pointed out in the satellite images and manually stored in each sensor node. We also assumed that all information of neighbor landmarks is initialized before the experiments. During the experiment, the radius of transmission range was approximately 10m which covers the width of general roads but does not produce any radio range intersection of landmarks.

Figure 6 (a) shows the trajectory of a mobile node. During the experiment, the mobile node passed by eight landmarks in the order of L1, L2, L4, L6, L5, L4, L2 and L3. For the further explanation, we declare [L*n*, …, L*m*] as a route section which is expressed by a sequence of landmarks. The whole path of the experiments is expressed as [L1, L2, L4, L6, L5, L4, L2, L3]. Note that section [L4, L6] is downhill and [L6, L5] is uphill. The landmark L2 and L4 have three neighbors' information. Hence, a mobile node needs to decide which way to predict its location when it passes through the landmarks. In this experiment, the mobile object manually decides the route in the situation. During the scenario in Figure 6 (a), the mobile node would decide L5 as the next landmark when it passes L4 in section [L2, L4, L6] instead of L6.

Figure 6 (b) shows the estimation result when a mobile node explores the planed route. White circles represent the estimation result with correct landmark information. Marked Xs between L4 and L5 represent the wrong estimation while a mobile node moves through section [L4, L6]. Even when the mobile node is moving toward L6, the node chooses L5 as its next landmark. Hence the estimated positions are on the way toward L5 instead of L6. When the mobile node gets in to the region of L6, it realizes the next landmark decision was incorrect and recovers the present position with a new next landmark, L6. Since the system relies on the average speed and next landmark information,



(a) Trajectory of target mobile node (b) Result with 6 landmarks (c) Result with 6 landmarks and 3 mobile nodes

Figure 6: Location estimation results in large scale experiments

the estimation error is large when the mobile node decides on the wrong next landmark. Besides, compared to the scale of the experiment field, the number of landmarks is relatively small. Hence, the mobile node has a hard time retrieving the correct estimation and the estimation error is getting larger until the node arrives at range of the other landmark.

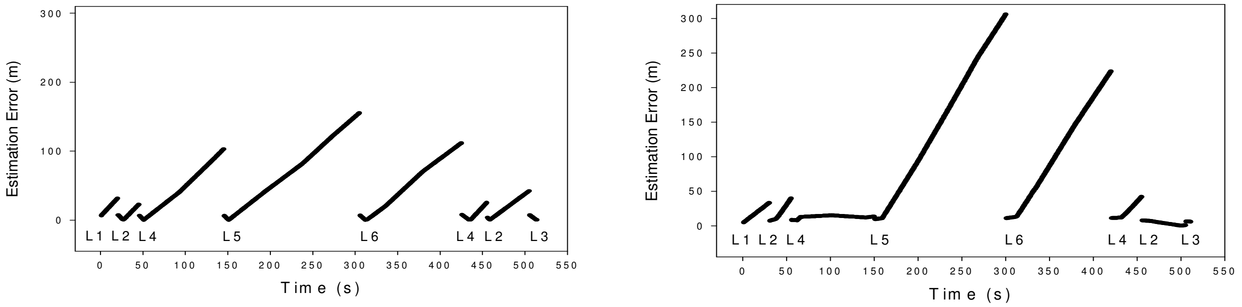
The estimation error caused by wrong decision of the next landmark can be recovered rapidly with many landmarks. As the distance between two landmarks is short, the mobile node would retrieve its position sooner. On the other hand, the existence of other mobile node can also reduce the error. Figure 6 (c) shows the result when three other mobile nodes are roaming from place to place. Three arrows on the figure represent the position where the target mobile node encounters the other mobile nodes. When the target mobile node passes by L4 of route [L2, L4, L6], the node chooses L5 as the next landmark, as in the previous experiment. However, as soon as the target mobile node encounters another mobile node on [L4, L6], the target mobile node perceives that it has wrong next landmark information and changes the information for correct position estimation. The mobile node meets two more mobile nodes until the end of the experiment. The result does not show drastic changes any more since the location prediction was correctly operated at the times. This result shows the effect of mobile node cooperation, and well estimated mobile nodes can play the role of landmarks. This fact makes the system work within sparsely deployed landmarks in a large scale road environment.

Some interesting characteristics of the system are shown in the results. The estimation results, expressed as circles, do not form a smooth line around L6 both in Figure 6 (b) and (c). This feature occurs because of the topographical characteristics of the environment. As we mentioned before, the road from L4 to L6 is a downhill. Without any restriction, the mobile node moves faster on the downhill. Hence, the mobile node passes L6 faster than its position prediction. Topographical characteristics of the environment considerably affect the estimation results of our system. Designing a system tolerant of topographical changes is one of the considerations for our further work.

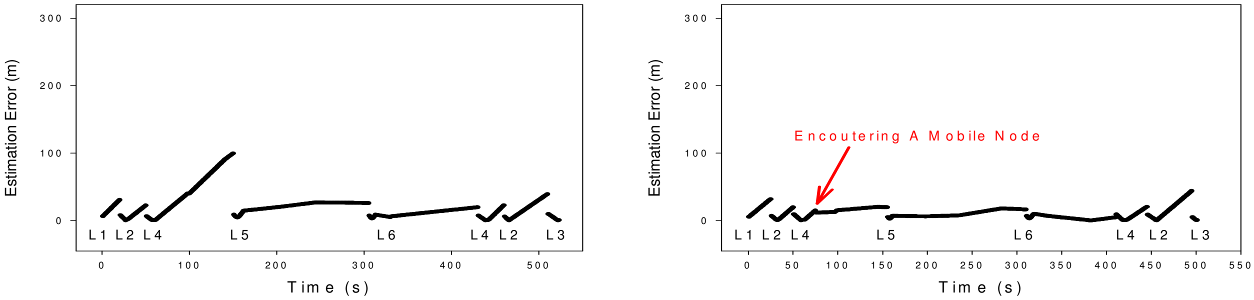
### *Simulation Analysis*

To evaluate our localization system performance, we simulated several scenarios of the proposed system in the same route condition of previous large-scale outdoor experiment in Figure 6. The field is about 200m x 200m and every node in the experiment is restricted to move only on a predefined route. We assume a fixed transmission range, r, of 10m for both mobile nodes and landmarks. Average moving speed of a mobile node is 4km/h, and an actual speed is randomly chosen between 80% and 120% of the average moving speed. A speed change occurs one or two times in every route section. In all experiments, we gather estimation results from one mobile node which moves a route in the order of L1, L2, L4, L5, L6, L4, L2 and L3. The total length of this trajectory is about 540m.

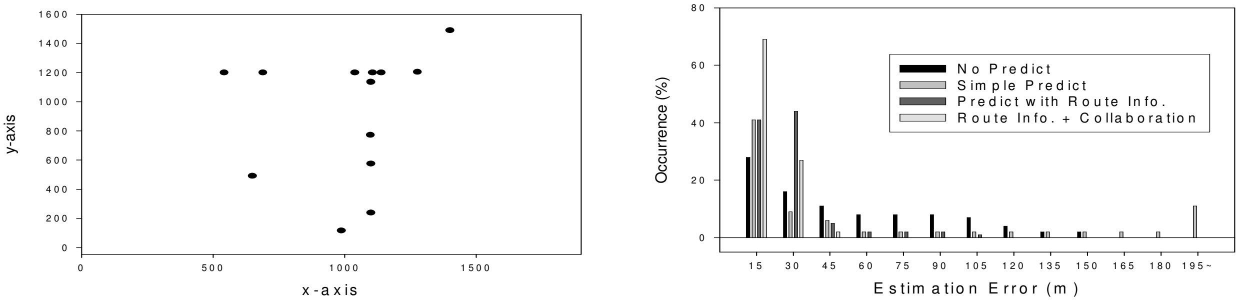
We deployed one static landmark at each position of L1, L2, L3, L4, L5, and L6, and experimented four methods; (1) no prediction, (2) simple linear prediction, (3) prediction with route information, and (4) prediction with route information and mobile node collaboration. In case of no prediction, a mobile node simply takes a location of static landmark as its own location. So, the estimation error increases linearly according to the distance from a static landmark. When it reaches at a new static landmark, its estimation is updated. Figure 7 (a) shows the result of no prediction case. In the graph, x-axis represents a time in second, and y-axis represents a Euclidean-distance error between a real location and an estimated location. Estimated locations are obtained every second. Since the distance between L5 and L6 is the largest one in this experiment, the estimation error is the highest just before L6.



(a) No Prediction (b) Simple Linear Prediction



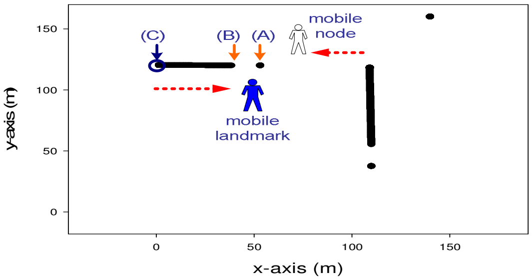
(c) Prediction with Route Information (d) Route Information + Collaboration (10 mobiles)



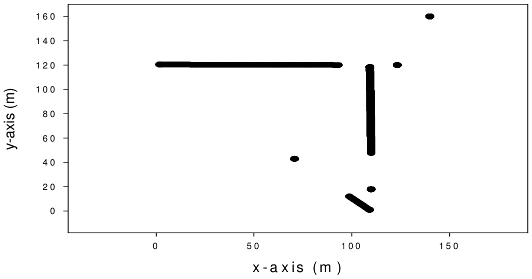
(e) Encountered Positions of Mobile Nodes (f) Error Occurrence with different methods

Figure 7: Evaluation of Localization Performances

When a mobile node predicts its location based on locations of current and previous landmarks, the localization performance is highly affected by a route condition. In Figure 7 (b), since L2, L4, and L5 are on the same linear line, the estimation error between L4 and L5 is reduced compared to Figure 7 (a). However, the estimation error between L5 and L6 is highly increased. The highest error is about 300m, which is almost double value of 150m in Figure 7(a). It is because the route direction is severely changed at L5. Consequently, the prediction was quite a different from the real route. This kind of incorrect prediction can be avoided by using route information. With route information, a mobile node catches the fact that the route direction is being changed at L5. Based on this fact, a mobile node predicts its location toward the right destination, L6. Figure 7 (c) shows the result of prediction with route information. Between L4 and L5, a mobile node did not predict its location because it knew that the route is split into several paths, L5 and L6, at L4. A mobile node may go into L5 and L6. Localization System does not have any information about where a mobile node goes. Here, the worst estimation error is about 120m. We added 10 mobile nodes in this experiment. Consequently, collaborations between mobile nodes helped to solve the previous multi-path problem. In Figure 7 (d), collaboration occurred at red arrow point between L4 and L5. The ambiguity of multi-paths disappeared due to encountering a mobile node coming from L5. The worst error reduced to about 50m. Figure 7 (e) shows one example of places where a mobile node encountered other mobile nodes. X-axis and y-axis represents x-y coordination in meter. In the graph, there were total 13 times of encountering. Figure 7 (f) shows the histogram of estimation errors. X-axis represents an estimation error in meter, and y-axis represents the



(a) 6 Mobile Landmarks



(b) 10 Mobile Landmarks

Figure 8: Localization with Mobile Landmarks

| Localization Method | | Average Error (m) | Standard Deviation (m) |
|---|---|---|---|
| No Prediction | | 47.94 | 40.67 |
| Simple Linear Prediction | | 76.01 | 82.03 |
| Prediction with Route Info. | | 21.34 | 19.28 |
| Route Info. + Collaboration | | 10.68 | 7.85 |
| Mobile Landmarks | 6 | 51.99 | 42.63 |
| | 10 | 21.36 | 21.20 |
| | 14 | 15.01 | 16.26 |

Table 1: Summary of Localization Results

percentage of occurrence in a given error range. In our proposed methods, we see the tendency that the occurrences are concentrated on the lower errors.

In addition, a simulation experiment was also conducted on the proposed mobile landmark system. In this experiment, no static landmark is deployed and only mobile landmarks and one mobile node are used. We varied the number of mobile landmarks, 6, 10, and 14. Figure 8 (a) shows the estimation result in case 6 mobile landmarks move. In the graph, x-axis and y-axis represents x-y coordination in meter, and black dots represent estimated locations. A mobile node moves along the same trajectory as the earlier experiments. A mobile node encounters a mobile landmark at position (A) and sets its location as one of the mobile landmark. From the mobile landmark, the next landmark position (C) was also obtained. At position (B), the mobile node encounters another mobile landmark coming from (C). Now, the mobile node starts to predict its location between (B) and (C). Figure 8 (b) shows 10 mobile landmarks case. Predicted sections are increased compared to Figure 8 (a). Increased chances to encounter mobile landmarks enhanced the overall performances.

Table 1 summarizes the results of simulation experiments. Compared to 'No Prediction', accumulated route information reduces the estimation error in half. Moreover, collaboration mechanism again reduces the error in half from 47.94m to 21.34m. In our proposed system, there was no explicit route information construction process. Just by its own movement of a small mobile node, route information is autonomously constructed and collaboration takes place. Since nodes communicate in a manner of request and response, power consumption is also small. The case of 10 mobile landmarks has similar performance to the case of 'prediction with Route Info.' with 6 static landmarks. In our experiment, transmission range, *r*, is 10m and the total length of the route is 540m. In case of 'Route Info. + Collaboration', the density of landmarks is about 0.2, and the localization error is only around 1**r*. Even in a very sparse network, our system achieves high performance.

## RELATED WORK

The changing environment of wireless sensor networks requires active research on a mobile sensor node [7, 8, 9]. The Princeton ZebraNet project [7] is an interesting pioneer study on a mobile sensor node. The project focuses on how successfully a biological data on animal can be delivered to researchers through mobile nodes that are carried by animal. To achieve this goal, energy-efficient and location-aware routing algorithms were explored from the viewpoint of a mobile node Cartel is a good recent project for mobile sensor networks. In this project, several issues on an intermittently-connected environment were studied [8].

Several localization techniques for wireless sensor networks have been proposed. These techniques are generally classified as range-based or range free. Range-based techniques require distance information. To measure distance, Received Signal Strength [12], time difference of arrival of two different signals [13], and angle of arrival [14] are commonly used. However, these techniques need special hardware, and measurements are not accurate in many practical environments.

Range-free techniques use connectivity-based information. DV-Hop [11] is one of the well-known range-free techniques. In this algorithm, landmarks flood their location to a whole network, and nodes estimate their location based on hop-counts and hop-distances. However, it is not appropriate to apply these algorithms to mobile sensor nodes. Since locations of mobile nodes continuously change, flooding should be periodically executed to obtain hop-distance and hop-count [16].

MCL [15] is specifically developed for mobile sensor nodes. In this algorithm, sensor nodes randomly predict their positions based on their previous positions, and filter the prediction by using the transmission range of the seed nodes. When the sensor nodes obtain a sufficient number of position samples, the locations are estimated by calculating the center of the sample positions. In [17], a movement of a mobile node is detected from an accelerometer. Once a movement is detected, localization is newly executed.

PlaceLab is a well-known beacon based localization system [10], and works well under various situation. The system uses various kinds of beacons, but requires database on locations of beacon nodes. Moreover, no algorithm to use route information or collaboration scheme was proposed.

## CONCLUSION AND FURTHER WORK

In this paper, we proposed a system framework for mobile node localization suitable for large-scale wireless sensor networks. We focused on using the route information which characterizes the mobility of mobile nodes. Route information can be automatically built up and collaborations between mobile nodes increase the accuracy of localization. To validate the feasibility of our approach, a real system is implemented and experiments are conducted on campus route. Simulation results show that our collaboration scheme enhances the overall localization performance.

Our system requires a large number of mobile devices that are willing to collaborate and share their location information. However, collaboration is not free and incurs overhead in message exchange and computation. As our further efforts, we plan to build up a mechanism to join mobile nodes into collaboration while minimizing resource usage.

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