PAPER Special Section on Internet Architectures, Protocols, and Management Methods that Enable Sustainable Development

Wide-Area Publish/Subscribe Mobile Resource Discovery Based on IPv6 GeoNetworking

Satoru NOGUCHI[†a)], **Satoshi MATSUURA**[†], *Nonmembers*, **Atsuo INOMATA**[†], **Kazutoshi FUJIKAWA**[†], *and* **Hideki SUNAHARA**[††], *Members*

SUMMARY Resource discovery is an essential function for distributed mobile applications integrated in vehicular communication systems. Key requirements of the mobile resource discovery are *wide-area geographic-based discovery* and *scalable resource discovery* not only inside a vehicular ad-hoc network but also through the Internet. While a number of resource discovery solutions have been proposed, most of them have focused on specific scale of network. Furthermore, managing a large number of mobile resources in the Internet raises a scalability issue due to the mobility of vehicles. In this paper, we design a solution to wide area geographical mobile resource discovery in heterogeneous networks composed of numerous mobile networks possibly connected to the Internet. The proposed system relies on a hierarchical publish-subscribe architecture and geographic routing so that users can locate resources according to geographical coordinates without scalability issue. Furthermore we propose a location management mechanism for mobile resources, which enables to reduce periodic updates of geographical location. Numerical analysis and simulation results show that our system can discover mobile resources without overloading both mobile network and the Internet.

key words: *resource discovery, publish/subscribe, IPv6 GeoNetworking*

1. Introduction

Distributed mobile applications for emerging vehicular communication systems (VCS) consume a wide variety of *resources* provided by applications and possibly network services. Mobile applications dynamically orchestrate the resources, for instance, an in-vehicle driving assistance application may try to obtain road traffic information from surrounding road users (e.g., vehicle, pedestrian, roadside) inside a specific intersection along its driving route, and then find out a parking slot along a street without traffic jam. In this case, the application needs to consume two types of resources provided by a kind of *road traffic information service* and *parking slot navigation service*. Recent years, such applications have been studied as a part of Intelligent Transport System (ITS) applications [1]–[3].

A key function for mobile applications in VCS is Resource Discovery. Before communicating with resource providers, applications need to locate them in dynamic mobile environments. From the point of view of networking, the resource discovery locates communication endpoint (e.g., socket address) of application and network resources using arbitrary descriptions of resources, such as resource identifier and resource specific attributes.

The main challenge of resource discovery for VCS is to discover resources according to their geographical position in heterogeneous environments. Since VCS applications are highly dependent on physical location, resources must be discovered according to their geographical position. An important issue regarding the geographical resource discovery is the diversity of underlying network topology and protocol, which prevent integrating Geographical routing protocols designed for a specific type of network. Applications and requested resources might be connected with each other through several different types of networks; for instance, they are connected (i) within single wireless mobile ad-hoc network using a specific multi-hop routing protocols, (ii) through a WLAN access point using conventional IP routing protocols, or (iii) with single-hop broadcasting. Furthermore, they communicate with each other via multiple networks. Even though there are a number of geographic routing protocols, inter-domain Geocasting relying on a specific protocol is not a feasible solution. In addition to the geographical discovery, scalability must also be taken into account due to a huge number of mobile nodes.

In this paper, we propose a mobile resource discovery system that supports not only local scope but also global scope discovery according to geographical position. The system is built on a hierarchically-distributed publish-subscribe architecture, which enables scalable resource discovery, in combination of a geographic routing protocol. The loose coupling nature of publish-subscribe [4] scheme, which enables applications to communicate with potential resource providers asynchronously and anonymously, is suited to resource discovery for VCS. To handle a huge number of mobile resources in VCS, our system relies on the distributed publish-subscribe architecture; the publish-subscribe server (namely *broker* in this paper) is distributed to several nodes in static (core) and mobile networks. The intra-domain geographical messaging is supported by IPv6 GeoNetworking, a sub-network-layer geographic routing protocol, while the distributed brokers support the inter-domain scenario.

We focus on two main issues in the distributed publish-subscribe resource discovery for VCS. The first is a scalability issue due to frequent location updates by resource providers. In the case of geographic-based mobile resource

Manuscript received November 8, 2012.
Manuscript revised February 18, 2013.
[†]The authors are with the Graduate School of Information Science, Nara Institute of Science and Technology, Ikoma-shi, 630-0192 Japan.
[††]The author is with the Graduate School of Media Design, Keio University, Yokohama-shi, 223-8526 Japan.
a) E-mail: satoru-n@is.naist.jp
DOI: 10.1587/transcom.E96.B.1706

discovery, resource providers need to publish available resources with their current geographical positions. Since this information must be frequently updated depending on publishers' mobility in order to keep the consistency of registered information, the huge number of location updates from publishers may cause a scalability issue.

The second issue is how to select an appropriate scope for discovery: the smallest scope is a single hop inside one single mobile ad-hoc network, whereas a larger scope may be from a mobile network to another mobile networks via several networks through the Internet. The appropriate scope is not known a priori, since applications issue discovery queries only containing requested resource identifier, geographical position, and additional attributes, which do not help to determine the topological scope. Larger scope is preferable to discover resources certainly, however, large-scope discovery may cause a scalability issue. On the other hand, a smaller scope is desirable to discover resources rapidly, but it may fail to discover potential publishers. The main contributions of this paper are therefore as follows:

- **A geographically-distributed publish/subscribe system:** to reduce control messages, dedicated servers compose a group of publish/subscribe brokers on top of a geographically-distributed overlay network (namely, *core brokers*), while mobile nodes supporting a GeoNetworking protocol, act as *mobile brokers*, connect to the core brokers. These two types of brokers localize communications between publishers and subscribers according to their geographical and topological locations by utilizing the information of boundary of GeoNetworking-enabled network. It contributes to discover resources without incurring bandwidth usage.
- **Adaptive scope selection according to topological and geographical location:** to reduce unnecessary queries from subscribers to brokers, mobile brokers adaptively select an appropriate scope of discovery according to the geographical destination of subscription taking into consideration of the boundary of geographical routing-enabled domains.
- **Mobility aware, event driven location update:** to reduce the number of location update from publishers, a location update is issued only when a publisher changes its mobility pattern, i.e., speed and/or heading. It contributes to reduce bandwidth usage due to large amount of periodic location updates.
- **Integration of the standardized IPv6 GeoNetworking:** the proposed system exploits the standardized IPv6 GeoNetworking mechanism [6]–[8], a geographical routing protocol designed for emerging VCS. We evaluate extensibility of IPv6 GeoNetworking for resource discovery.

The reminder of this paper is organized as follows. Section 2 explores existing relevant solutions for the geographical publish-subscribe mobile resource discovery. Section 3 defines assumptions, the considered network model and then describes the protocol operation of our system. We then present comparative performance evaluations in Sect. 4 and Sect. 5. Section 6 finally concludes the paper.

2. Related Work

Resource discovery protocols: one of popular categories of resource discovery techniques is service discovery. It enables to discover communication endpoints of software and/or hardware services [21]. There have been a number of standardized service discovery protocols. Service Location Protocol version 2 (SLPv2) is an IP multicast-based service discovery protocol standardized by IETF [11], [12], composed of User Agent (UA), Service Agent (SA), and optional Directory Agent (DA). UAs request location of services to SPs or DAs using a type and attributes of necessary service. If a service description managed by a SP and/or DA satisfies the request, the SP/DA returns a list of URL representation of available services in the considered network. UAs and SAs directory communicate with each other via IP multicast, only when DAs are not detected. If DAs are available in the network, UAs communicate with DAs via unicast. SAs always deliver messages to UAs via unicast. The benefit of this protocol is to send messages to a specific subset of nodes that manages a particular service using the IPv6 multicast. However, it is designed for relatively-stable and small-scale network; it does not fit the wide-area mobile resource discovery depending on geographical position.

Multicast DNS (mDNS) with DNS-based service discovery (DNS-SD) is a service discovery protocol also relying on IP multicast [16], [17], which discovers services using the standard DNS message via IP multicast using a dedicated DNS domain '.local.'. DNS servers are not necessarily used since mDNS/DNS-SD nodes work as distributed DNS servers. Both SLPv2 and mDNS/DNS-SD can efficiently discover services in stable and/or local networks, however, regarding the resource discovery in VCS, they may consume significant bandwidth due to the traditional IP multicast without geographical position support.

IP mobility support protocols: our focus, discovering mobile resources, is conceptually similar to the network-layer mobility support protocols [13], [15]. The difference between these protocols and our approach is the complexity of resource: these protocols are dedicated to IP routing (IP address discovery), which enables to discover *Care of Address* (transient, actually-routable topological location) according to *Home Address* (permanent topological location), thus the discovery manner in these protocols is exact matching: which node need to be discovered is explicitly determined a priori. On the other hand, we focus on discovering communication endpoints and descriptions of resources according to complex predicates (i.e., current geographical position, resource type, supplemental attributes). It is not the exact matching of IP address discovery but content-based lookup; clients do not know which nodes are discovered until they receive results of discovery. After receiving the results, clients choose one of (or a number of) nodes from discovered *candidates*. It raises different requirements, in particular, multi-attribute, geographical position-based lookup, and extension of data elements.

Geographic routing protocol: to deliver packets according to geographical position, the European Telecommunications Standards Institute (ETSI) has specified a GeoNetworking protocol and its adaptation mechanism to IPv6 (*GN6ASL: GeoNetworking to IPv6 Adaptation Sub-Layer*) [9], which enables IPv6 be operated over the network-layer GeoNetworking protocol [8]. The GeoNetworking protocol is a full set of sub-IP geographical messaging technologies, including a geographical addressing, geographical routing, and geographical location resolution mechanism (namely Location Service). The GeoNetworking protocol is located between the network layer and the link layer, and GN6ASL provides interfaces to IPv6 so that upper layer entities can use GeoNetworking through conventional IPv6. Several types of geographical routing have been specified, such as GeoUnicast, GeoBroadcast, and GeoAnycast. In particular, GeoBroadcast delivers packets to all nodes inside an certain geographical area, described as a circle, rectangle, or ellipse.

Publish/subscribe systems: the publish-subscribe is a mature paradigm; there have been a wide variety of publish-subscribe systems, such as [20], [23]. A mobility support mechanism for distributed publish-subscribe systems has been proposed, which can handle mobile clients by means of service proxies, which act as an interface for clients to the publish-subscribe system [10]. Subscriptions and publications are managed by proxies on behalf of clients. Thanks to the buffering and synchronization of subscriptions/publications, clients can move from an access point to others so that it minimizes the inconsistency of information.

3. Geographically Distributed Mobile Publish/Subscribe Resource Discovery

3.1 Assumption and System Model

We assume a set of networks composed of two types of mobile nodes, the one supports IPv6 with mobility support protocols and IPv6 GeoNetworking, while the other dose not support GeoNetworking. A subset of former type of nodes composes a wireless ad-hoc network using GeoNetworking (namely *GeoNetworking domain*). On the other hand, the latter type is not capable of ad-hoc multi-hop communication according to geographical position. Since each node supports IPv6 mobility support protocols, at least one permanent IPv6 address is assigned to each node regardless of the point of attachment and underlying communication stack. These mobile nodes may be temporally disconnected from the Internet, even in this case mobile nodes can communicate with other ones inside their nearby area using temporally-assigned IPv6 address. Each mobile node can obtain geographical position from GPS devices, static configuration file, etc. In this paper, we assume the obtained geographical position is accurate.

Our system consists of four components: *publisher*, *subscriber*, *core broker* and *mobile broker*, as depicted in Fig. 1. Publishers act as resource providers, while applications are subscribers. Core brokers are connected to each other, while mobile brokers are attached to one of them. Publishers and subscribers only communicate with topologically neighboring core or mobile brokers, for instance, an in-vehicle publisher/subscriber is attached to a mobile broker installed in an in-vehicle mobile node. Regardless of the type of broker, publishers and subscribers just send publication (information of available resources) and subscription (resource discovery request) to the connected broker. Note that the distinction between the four system components is conceptual; some components may be installed in an identical node (e.g., a smartphone may be a publisher, subscriber, and mobile broker at the same time).

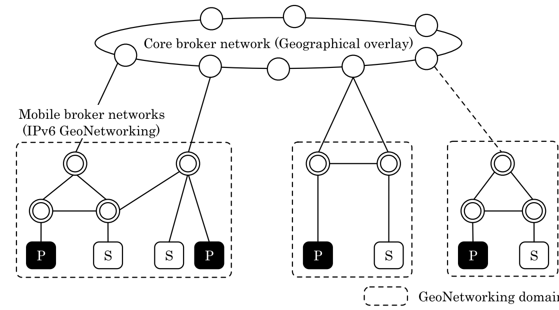

Fig. 1 System model. S and P represents subscriber and publisher, respectively.

To manage a large number of publications and subscriptions, core brokers act as a distributed database on an overlay network, where each core broker is assigned an identifier in the overlay generated using e.g., the Z-order curve [22]. Thanks to the space-filling curve, which maps multi-dimensional space (in this paper, 2D surface in the earth) to one dimension with keeping its locality, each core broker manages publications according to geographical area using geographical coordinates. In other words, publications in a neighboring area are likely to be stored to the same core broker.

The main requirements for the overlay network as a foundation of the core broker network are therefore as follows: *geographic search*, *range search*, and *scalable search*. As described previously, a geographic search is a key requirement for the proposed system. A range search is needed to search resources by *area* instead of *point*, the capability of range-based lookup is necessary instead of exact-matching-based lookup for better performance. Regarding the scalable search, it is necessary to finish a lookup in reasonable cost even the number of nodes are large, for instance, broadcast-based approach, sequential lookup to all nodes, is not applicable.

While our proposed mechanism itself is independent of the overlay networking mechanism as long as it supports the above requirements, we assume [26] as a foundation of the core broker network, which is a structured overlay network using the Z-order curve-based IDs that can search stored value by $O(\log N)$ according to geographical position and supports range search.

In the proposed system, resource discovery is performed with three main functions: *publish*, *subscribe*, and *notify*, as in typical publish/subscribe systems [20]. Resource providers publish descriptions of resources to one of brokers, while applications subscribe to a certain resource to brokers. Brokers match the publications and subscriptions, and then notify subscribers if publications satisfy the subscriptions. For instance, in the case of the route guidance application outlined in Sect. 1, the driving assistance application at first subscribes to a *road traffic information* service with geographical addresses of intersections along its driving route to one of brokers. The broker then notifies descriptions of the service if there are publications of the *road traffic information* service in the requested area.

3.2 Data Model

In the proposed system, a resource is described as a *Resource Description*, a set of data elements containing geographical position, socket address, resource identifier, and resource-specific attributes (e.g., organization, type of vehicle, priority, etc.). To reduce bandwidth usage, we separate the resource description in two types of data sets: *static profile* and *dynamic profile*. The static profile is delivered only once from mobile to core brokers, while the dynamic profile is generated when the static profile needs to be updated. The static profile is composed of tuples of the form $(HP, SA, rd_1, ..., rd_i)$, where HP points to the *Home Position*, the primary geographical position of resource provider: the position when a resource provider is activated. SA, stands for *Socket Address*, shows the communication endpoint of resource provider. rd_i comprises ith *Resource Description*. A Resource Description is represented as a tuple $(RI, A, at_1, ..., at_j)$, where RI is *Resource Identifier*, a unique identifier for the resource, and A is *Availability*, a binary integer that represents whether the resource is active or not. at_i is the ith *Attribute*.

The dynamic profile basically represents the mobility of resource providers. To describe the current status of mobile nodes while protecting location privacy, the mobility of resource providers is described as a sequence of differences of coordinates compared to HP. The dynamic profile is composed of tuples of the form $(DP, rdm_1, ..., rdm_k)$, where DP is *Difference of Position* that describes the difference of coordinates from last update, and rdm_i is ith *Resource Description Modifier*, comprises corresponding resource identifier and optional updates, which enable to modify the availability and attributes of corresponding resource registered with the static profile.

While a publication message is composed of a static profile or a dynamic profile, a subscription message is composed of tuples of the form (SA, TA, rd) where SA is the socket address of a resource consumer. TA is a target area where requested resources must be inside. On the other hand, a notification message is composed of a list of data elements (SA, rd) which contains the socket address of a discovered resource provider.

3.3 Geographical Locality-Aware Discovery Scope Selection

The key issue to wide-area resource discovery is the selection of scope of discovery. The topological scope of subscription should be small enough as long as it covers the geographical destination, however, it is difficult to specify an appropriate topological scope corresponding to the requested geographical destination. Although GeoNetworking can perform such a routing, as of now basically it is only applicable to a single GeoNetworking domain.

The proposed system thus exploits the concept of *Geographical Virtual Link (GVL) area* of GN6ASL. A *GVL* is a logical link covering multiple physical links, separated by geographical boundaries [9]. GVL is used by associating to a corresponding geographical area (*GVL area*). Since each GVL is associated with a certain geographical area, geocast packets delivered on a certain GVL is propagated only within its associated geographical area. This feature can be used by mobile brokers to know whether the destination area is reachable with the geographical routing. In other words, nodes in a place covered by a GVL area can be reachable using the geographical routing through their associated GVL.

By exploring the above feature of GVL, the proposed discovery scope selection is performed as follows: When a mobile broker receives a subscription message containing a description of a requested resource and a destination area, the mobile broker checks if it has a network interface supporting GeoNetworking. If there is a GeoNetworking-enabled interface, the mobile broker calculates the *intersection area* of the destination area for subscription and the GVL area of the network interface. If the size of intersection area is larger than a certain threshold, the mobile broker directly delivers the subscription as a GeoBroadcast packet to all mobile brokers inside the destination area.

On the other hand, if the size of the intersection area is smaller than the threshold, or the mobile broker does not have a GeoNetworking-enabled interface, the subscription is delivered as a unicast packet to a core broker instead. For instance, in Fig. 2, the subscriber S knows the size of ge-

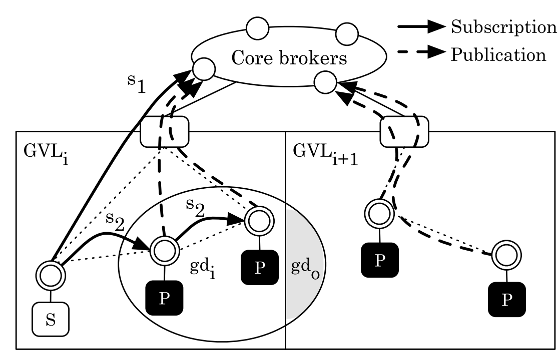

Fig. 2 Discovery scope selection. Geocast-based local area discovery (path s_2) is performed only when gd_i is larger than a certain threshold.

```
s ← received SUBSCRIPTION{rd, gd}
for all interface i_k ∈ I do
    if i_k supports GeoNetworking then
        g ← GVL area of i_k
        if s.gd ∪ g ≠ φ ∧ |s.gd∪g| / |s.gd| ≥ r_gd then
            geocast s to all nodes inside the area s.gd
        end if
    end if
end for
if s is not delivered yet then
    unicast s to a core broker
end if
```

Fig. 3 Pseudo-code of the scope selection.

ographical area GVL_i. Since the area gd_i, an intersection area of $gd = gd_i + gd_o$ and GVL_i is large enough, the mobile broker connected to S delivers a subscription message to gd_i (path s_2) instead of the core brokers (path S_1). The algorithm for the scope selection invoked in mobile brokers is therefore described in Fig. 3. In this figure, rd is the resource description, gd is the geographical destination of corresponding subscription, I is a list of active network interfaces, and $r_{gd}(0 < r_{gd} \leq 1)$ is the minimum ratio of the size of the intersection area for gd, used as the threshold.

Some of the existing solutions also support multiple discovery scope, such as [11], [12], however they need static configuration. The proposed mechanism, on the other hand, can dynamically select the scope according to descriptions of subscriptions and underlying network topologies.

3.4 Mobility Aware Event-Driven Location Update

In the proposed system, geographical locations of publishers are stored in core brokers in a distributed manner. Mobile brokers update their locations by sending their current locations to one of core brokers, then the core broker propagates these locations to the other core brokers. These brokers manage locations using two mechanisms: *Home Position Registration*, and *Event driven location update*, performed as a part of publication. The description of each mechanism is described as follows:

Home Position Registration is performed only on boot of mobile brokers: when a mobile broker is connected to one of core brokers, it registers the home position P_{home}, composed of its current latitude and longitude (obtained by e.g., in-vehicle GPS) as one of data elements in the *static profile* described in Sect. 3.2, to the core broker. Note that it is assumed each publisher registers its resources to a mobile broker a priori.

Event driven location update is performed as a part of publication when mobile brokers change speed, heading, and/or position over certain thresholds. Subsequent to *Home Position Registration*, each mobile broker sends a difference in position Δp between its P_{home} and current position. In the next update, it also sends Δp which contains a difference in position from the last update. Using P_{home} and the sequence of Δp, core brokers calculate geographical position of publishers at a certain time t: a geographical position at a certain time P_t is calculated as $P_{t+1} = P_t + \sum_{i=1}^{t} \Delta p_i$, where Δp_i is the Δp at the ith location update. P_0 corresponds to P_{home}.

In addition to these location update mechanisms, to recover from location update failures due to e.g., packet loss, we introduce a set of error correction mechanism performed in core and mobile brokers: at a certain interval, both brokers exchange the difference of position between P_{home} and current up-to-date position. If the difference contains a certain amount of error, each mobile broker sends error correction information to a core broker: how much the difference needs to be adjusted. These three mechanisms are sequentially invoked so that the above mentioned two location updates and the error correction does not conflict with each other.

The main advantage of the proposed mechanism is, compared to the periodic update, it can reduce the number of updates. Furthermore, it can avoid propagating the complete geographical position; the geographical coordinates are delivered to core brokers only once. Malicious nodes cannot get the complete geographical position unless they obtain P_{home} and all sequence of Δp. It thus contributes to the location privacy protection.

4. Accuracy Evaluation

To evaluate the effectiveness of the proposed mechanism, in this section we study the accuracy of location update of the proposed system using the ns-3 network simulator. In this evaluation, we focus on the impact of frequency of location update and failure in the accuracy of updated location on core brokers. The accuracy of location update from mobile to core brokers depends on the mobility of mobile nodes, frequency of location update, and ratio of location update failure due to e.g., packet loss. We thus evaluate the accuracy of location update of a pair of mobile and core broker under different mobility patterns and the reliability ratio of successful location update r_p, using the ns-3 network simulator. We use two mobility patterns: regular and high mobility. Under each mobility pattern, the mobile broker moves to randomly-selected direction. Its behavior is based on the random walk model, but it constantly accelerates/decelerates after/before corners. We implemented this model by extending the random walk model in ns-3. Table 1 shows the settings in each mobility pattern. In each mobility pattern, we used three settings for $r_p = \{0.1, 0.3, 0.5\}$. It means location updates from mobile to core brokers are failed with probability 10%, 30% and 50%. The other settings are shown in Table 2.

In the medium mobility scenario, the average size of error is 9, 15, and 24 meters in the r_p 0.1, 0.3, and 0.5, respectively. In these cases, the numbers of successful location updates are 846, 662, and 464 while the numbers of error corrections are 51, 57, and 76, respectively. In the high mobility setting, the average error sizes are 10, 15, and 23 meters in each r_p settings respectively. The numbers of successful location updates are 974, 762, and 541 while the numbers of error corrections are 82, 78, and 84, respectively.

Table 1 Mobility setting for accuracy evaluation.

Parameters	Medium mobility	High mobility
Maximum speed	60 km/h	80 km/h
Turning speed	10 km/h	20 km/h
Acceleration	1.5 m/s^2	2.5 m/s^2
Deceleration	1.5 m/s^2	2.5 m/s^2

Table 2 System setting for accuracy evaluation.

Parameters	Value
Simulation duration	1 hour
Speed threshold (ΔS)	5 km/h
Heading threshold (ΔH)	5 deg.
Distance threshold (ΔD)	0.5 km
Error correction threshold (th_{error})	25 m
Error check interval	60 second
Error check time after turning	5 second

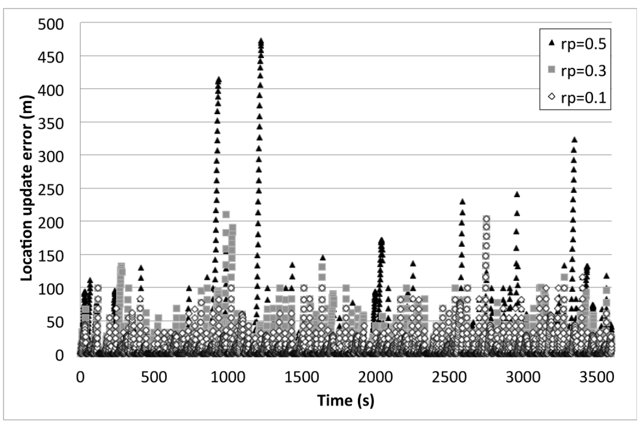

Fig. 4 Accuracy of location update (Medium mobility).

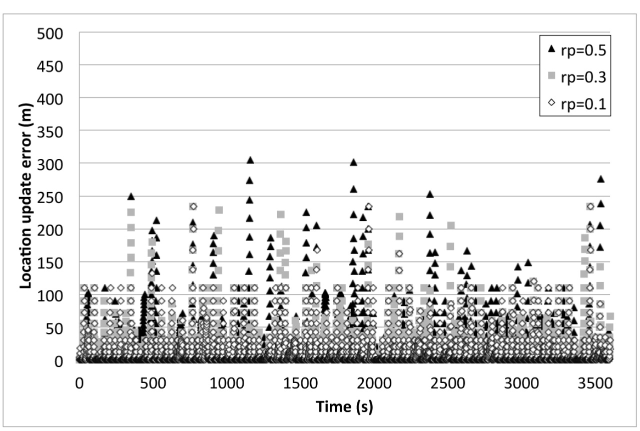

Fig. 5 Accuracy of location update (High mobility).

The distribution of the location update error for each mobility is shown in Figs. 4 and 5. These results show that the size of the location update error is 25 meters in the worst case, which corresponds to (i) the size of an edge of a small intersection (double lane with sidewalk on each side), (ii) around the length of 5 passenger vehicles without inter-vehicular distance, or (iii) around a typical inter-vehicle distance in a suburban area. Consequently, the proposed system has enough capability of locating resources inside an intersection, and also within an inter-vehicle distance.

Compared to the periodic update mechanism relying on GPS, in which a location update is invoked every time nodes obtain a new position from GPS (typically, every second), the proposed mechanism can reduce the number of packet. For instance, in the medium mobility scenario, it reduced the number of update about by 80%; $662 + 57$ updates in the proposed mechanism ($r_p = 0.3$) compared to 3600 updates in the periodic update mechanism.

5. Control Cost Analysis

In this section, we evaluate the control overhead of the proposed system by presenting a simple analytical model for each process. We focus on the impact of the size of network (e.g., the number of mobile nodes, size of GVL area, etc.) to the amount of control messages generated by core and mobile brokers; The analytical model is designed to study the total amount of control messages generated by the proposed system, including publication, subscription and notification messages for each discovery scope. We model the amount of control messages for (i) one mobile network, and (ii) the core broker network. All notations and settings used in the analysis are found in Tables 3 and 4.

The system is composed of N_{cb} core brokers, N_p publishers, and N_s subscribers, and an arbitrary number of mobile brokers. The number of mobile brokers is not specified in this analysis since the control overhead depends only on the number of publishers and subscribers in our proposed system. Mobile brokers are connected or directly installed to mobile routers which support both ad-hoc multi hop routing by GeoNetworking and conventional IP routing protocols (possibly using multiple access interfaces for each routing, e.g., WLAN and Cellular). Publishers and subscribers are connected to one of mobile brokers. For simplicity, each publisher has one resource in this analysis. Mobile brokers compose GeoNetworking-enabled mobile networks bounded to GVL area. We assume the entire geographical area in this evaluation are separated to 2D-grid shaped GVL areas and each area is assigned to one of mobile networks. The size of each GVL area is assumed to be same. Each node is uniformly distributed to the networks.

The scope for each discovery, (i) in-network Geocast-based discovery or (ii) unicast-based discovery to core brokers, depends on the location and size of destination area for discovery, the number of mobile network, and the size of each mobile network (corresponds to the size of a GVL area). For simplicity, we assume the destination area has a circular shape with a fixed l_r meter radius, and the location of destination area is randomly selected among entire mobile networks. We also fix r_{gd} at 0.5. In this scenario, the probability that a subscriber specifies a destination area inside its own mobile network (local network) is p_l. Inside the local network, the subscriber randomly specifies a certain destination area. The probability that the ratio of the inter-

Table 3 Notation of model variables.

Symbol	Definition
N_{cb}	Number of core brokers in the system
N_p	Number of publishers in the system
N_s	Number of subscribers in the system
$N_p^{(m)}$	Number of publishers in one mobile network
$N_s^{(m)}$	Number of subscribers in one mobile network
$N_p^{(gd)}$	Number of mobile brokers inside geographical destination
p_{gd}	Probability that the ratio of the intersection area of destination area and the local network is larger than r_{gd}
r_{local}	Local area discovery invokation ratio
C_{mobile}	Total control overhead for one mobile network
C_{core}	Total control overhead for the entire core broker networks

Table 4 Notation of model parameters and settings.

Symbol	Definition	Value
p_l	Probability that a subscriber specify a destination inside its own mobile network	0.5
λ_s	Ratio of subscription per unit time	1
λ_n	Ratio of notification per unit time	1
λ_p	Ratio of publication (location update)	0.26
λ_{pe}	Ratio of location update error correction	0.01
h_{mm}	Hop count between mobile nodes	5
h_{mg}	Hop count (mobile node/access router)	1
l_e	Length of edges of a mobile network	500 m
l_r	Radius of the destination area	50 m
l_s	Packet length of subscription message	256
l_n	Packet length of notification message	512
l_{sp}	Packet length of publication (static profile)	640
l_{dp}	Packet length of publication (dynamic profile)	128
l_{lu}	Packet length of overlay lookup message	64

section area of the destination area and the local network is larger than $r_{gd} = 0.5$, in other words, the probability that a subscription message is delivered as Geocast packets inside a mobile network, p_{gd} is thus given by

$$p_{gd} = \frac{{l_e}^2 - 2{l_r}^2}{{l_e}^2},$$

where l_e is the length of edge of a mobile network. Consequently, the ratio that a subscriber performs a local area discovery r_{local} is $r_{local} = p_l p_{gd}$. In other words, $(1 - r_{local})$ means the ratio of wide area discovery.

We assume the average hop counts among mobile brokers is 5 hops, according to the default hop limit of 5 specified in [8]. The settings of the length of each packet includes underlying layers' protocol headers, such as LLC, MAC, GeoNetworking (GeoBroadcast), IPv6 and UDP. The ratio of publication and *location update error correction* are derived from Sect. 4, which showed the amount of location update (publication) and error correction.

5.1 Cost for Mobile Network

The control overhead for a mobile network is described as the sum of messages for subscription and notification between mobile brokers in the local and wide area discovery, and publication from mobile to core brokers. The number of mobile brokers which reply to the subscriber is derived according to the density of mobile brokers and the size of geographical destination for subscription. The control overhead for each mobile network per unit time C_{mobile} is expressed by

$$\begin{aligned} C_{mobile} = {} & N_s^{(m)}\{r_{local}h_{mm}(\lambda_s l_s + N_p^{(gd)}\lambda_n l_n) \\ & +(1 - r_{local})h_{mg}(\lambda_s l_s + N_p^{(gd)}\lambda_n l_n)\} \\ & +N_p^{(m)}\{h_{mg}(l_{sp} + \lambda_p l_{dp} + \lambda_{pe} l_{dp})\}, \end{aligned}$$

where $N_s^{(m)}$ and $N_p^{(m)}$ are the numbers of subscribers and publishers in a single mobile network. λ_s and λ_n are ratio of subscription and notification per unit time, while λ_p and λ_{pe} are ratio of publication and location update error correction per unit time, respectively. h_{mm} is the average hop count between mobile nodes, and h_{mg} is the hop count between mobile nodes and gateway of mobile network (e.g., access router). l_s and l_n are packet length of subscription and notification, whereas l_{sp} and l_{dp} are the length of packet containing the static and dynamic profile, respectively. $N_p^{(gd)}$ is the number of mobile brokers inside the geographical destination, thus $N_p^{(gd)} = \pi {l_r}^2 \cdot N_p^{(m)} / {l_e}^2$.

5.2 Cost for Core Broker Network

Regarding the cost for core brokers, we analyze the control overhead to the *entire* core broker network, and the overhead to *each* core broker. The control overhead for the entire core broker network is the sum of subscription/notification messages from/to mobile brokers in the wide area discovery, publication messages from mobile brokers, and lookup messages within the core broker network. The cost for the core broker network per unit time C_{core} thus yields

$$\begin{aligned} C_{core} = {} & N_s\{\lambda_s(1 - r_{local}) \cdot (l_s + l_{lu}(\log N_{cb} + 1)) + N_p^{(gd)}\lambda_n l_n\} \\ & +N_p\{l_{sp} + \lambda_p(l_{dp} + l_{lu}(\log N_{cb} + 1)) \\ & + \lambda_{pe}(l_{dp} + l_{lu}(\log N_{cb} + 1))\}, \end{aligned}$$

where l_{lu} is the length of packet used to lookup a core broker managing the requested geographical area by the subscription message. The control overhead for each core broker $C_{core}^{(i)}$ is therefore obtained as $C_{core}^{(i)} = C_{core}/N_{cb}$.

5.3 Numerical Results

Cost for mobile network: Fig. 6 shows the impact of the number of publishers in a mobile network on the control overhead (C_{mobile}) under different numbers of subscribers. The total amount of messages in one mobile network is about 35 MBytes/s at a maximum number of publishers and subscribers. Accordingly, as the number of subscriber increases, the amount of messages rapidly increased since the number of publishers in a particular area represents the density of nodes replying to subscription messages.

In this analysis we assume the maximum number of vehicles (i.e., publishers and subscribers) in one mobile network is 1000, which corresponds to a typical scenario in a

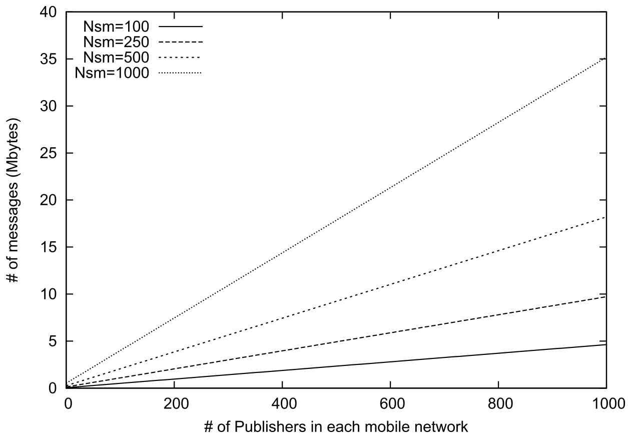

Fig. 6 Impact of the number of publishers on the control overhead in one mobile network.

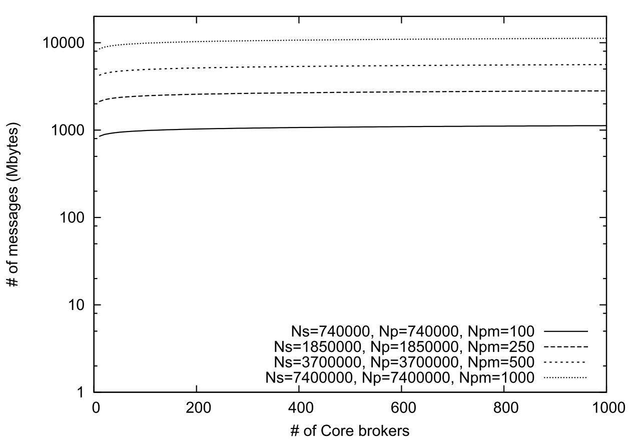

Fig. 7 Impact of the number of core brokers on the control overhead to the entire core broker network.

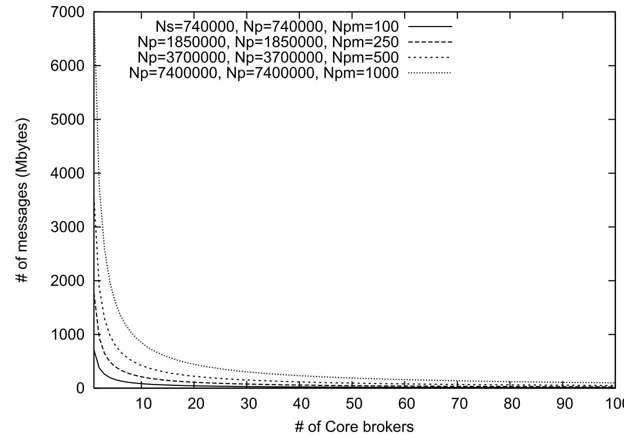

Fig. 8 Impact of the number of core brokers on the control overhead to each core broker.

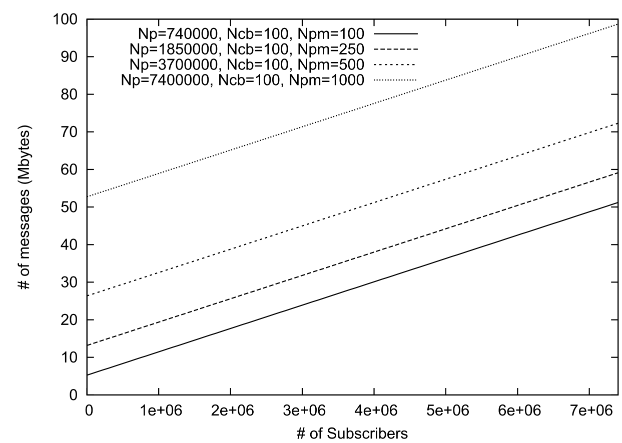

Fig. 9 Impact of the number of subscribers on the control overhead to each core broker.

congested urban area with 100% penetration (all vehicles support the proposed system): suppose that there are 1000 vehicles in one mobile network consisting of a 500 m^2 rectangular area, in which there are 20 grid-shaped, double-lane streets at 50 m interval. It is assumed that the length of a vehicle is 5 m and an inter-vehicle distance is 15 m, therefore there are 25 vehicles in a lane.

This result shows that the impact of the penetration of the proposed system on vehicles (how many vehicles support the proposed system); it shows that the control overhead in one mobile network with penetration ratios of 10%, 25%, 50%, and 100% in a congested urban area: even if all vehicles support the system, the amount of control message for each node is 35 KBytes/s. The proposed system therefore needs fairly low amount of control messages.

Cost for core brokers: Fig. 7 shows the impact of the number of core brokers for the control overhead in the entire core broker network under several different numbers of publishers and subscribers. In the following analysis, we assume the maximum number of vehicles (i.e., publishers and subscribers) in the system is 7.4 million, which corresponds to the number of vehicles in use in Japan as of 2012 [25]. These results therefore show the control overhead in the entire core broker network with the penetration ratio of 10%, 25%, 50%, and 100%. They show that the total control overhead to the entire core broker network does not depend on the number of core core brokers so much but the number of publishers and subscribers. It implies that system administrators can add an arbitrary number of core brokers to reduce the load of each broker according to the population of users.

Figure 8 shows the impact of the number of core brokers on the control overhead for each core broker. By installing 20 core brokers, even in the high penetration scenarios, the overhead on each core broker can be reduced to less than 500 MBytes/s. On the other hand, Fig. 9 shows the impact of the number subscribers on the control overhead for each core broker. These results show that if the overhead for each core broker must be reduced to100 MBytes/s, it is necessary to install 100 core brokers in the 100% penetration scenario.

Evaluation results in this section show the control overhead on brokers in basic scenarios, in which all nodes are uniformly distributed in the system and the load for each broker is flat. It is obviously possible that there are some hotspots: a large number of nodes connected to a particular broker and other brokers do not have much users. This kind of scenario must be evaluated in the future, nonetheless, the results in this Section also help to study costs in such a highly-loaded scenario, since the settings of these evaluations include a totally congested scenario.

6. Conclusion

In this paper, we presented a wide-area geographical publish/subscribe resource discovery scheme for vehicular communication systems to design a common data infrastructure for emerging ITS. The proposed scheme relies on a hierarchical publish-subscribe architecture by combining the geographically-distributed overlay network and IPv6 GeoNetworking, which supports not only conventional routing technologies but also the geographic routing so that users can locate resources according to geographical coordinates either inside a local mobile network or in other networks. Such a resource discovery mechanism is essential for future mobile environments, in which each mobile application is distributed to any node and dynamically consumes a wide variety of resources provided by other nodes. Since there have been various location-based services, a common, universal infrastructure of geographical resource discovery that supports all potential mobile users is therefore necessary.

A number of evaluations have been conducted, in which two important performance metrics have been studied. At first we have evaluated the accuracy of the location update mechanism using the ns-3 network simulator, then the control overhead in (i) each mobile network and (ii) core brokers by simple numerical models. Evaluation results showed that our system can provide the capability of geographical resource discovery to a large number of vehicles (i.e., resource provider as publisher and resource consumer as subscriber) without losing scalability: the proposed location update mechanism contributes to reduce control messages for publication, while the characteristics of structured overlay network contributes to reduce messages for subscription. Consequently, even in the highly-populated scenario, in which all vehicles in Japan support the proposed system, the control overhead in the core and mobile networks can be limited to be fairly small. As a next step we are preparing to conduct to implement an actual system and field experiments.

References

[1] P. Papadimitratos, A. La Fortelle, K. Evenssen, R. Brignolo, and S. Cosenza, "Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation," IEEE Commun. Mag., vol.47, no.11, pp.84–95, Nov. 2009.
[2] ETSI TR 102 638, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions," V1.1.1, June 2009.
[3] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, and T. Weil, "Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions," IEEE Communications Surveys & Tutorials, vol.13, no.4, pp.584–616, 2011.
[4] P.T. Eugster, P.A. Felber, R. Guerraoui, and A.-M. Kermarrec, "The many faces of publish/subscribe," ACM Comput. Surv., vol.35, no.2, pp.114–131, June 2003.
[5] GeoNet Project, "D1.2 final GeoNet architecture design," June 2010.
[6] GeoNet Project, "D2.2 Final GeoNet specification," Jan. 2010.
[7] ETSI TS 102 636-2, "Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 2: Scenarios," V1.1.1, March 2010.
[8] ETSI TS 102 636-4-1, "Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 1: Media-Independent Functionality," V1.1.1, June 2011.
[9] ETSI TS 102 636-6-1, "Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 6: Internet Integration; Sub-part 1: Transmission of IPv6 Packets over GeoNetworking Protocols," V1.1.1, March 2011.
[10] M. Caporuscio and Carzaniga, "Design and evaluation of a support service for mobile, wireless publish/subscribe applications," IEEE Trans. Softw. Eng., vol.29, no.12, pp.1059–1071, 2003.
[11] E. Guttman, C. Perkins, J. Veizades, and M. Day, "Service location protocol, version 2," RFC 2608, Internet Engineering Task Force, June 1999.
[12] E. Guttman, "Service location protocol modifications for IPv6," RFC 3111, Internet Engineering Task Force, May 2001.
[13] V. Devarapalli, R. Wakikawa, A. Petrescu, and P. Thubert, "Network Mobility (NEMO) basic support protocol," RFC 3963, Internet Engineering Task Force, Jan. 2005.
[14] T. Narten, E. Nordmark, W. Simpson, and H. Soliman, "Neighbor discovery for IP version 6 (IPv6)," RFC 4861, Internet Engineering Task Force, Sept. 2007.
[15] C. Perkins, D. Johnson, and J. Arkko, "Mobility support in IPv6," RFC 6275, Internet Engineering Task Force, July 2011.
[16] S. Cheshire and M. Krochmal, "Multicast DNS," Internet-Draft draft-cheshire-dnsext-multicastdns-15, Internet Engineering Task Force, 2011. (Work in progress).
[17] S. Cheshire and M. Krochmal, "DNS-based service discovery," Internet-Draft draft-cheshire-dnsext-dns-sd-11, Internet Engineering Task Force, 2011. (Work in progress).
[18] A. Fei, G. Pei, R. Liu, and L. Zhang, "Measurements on delay and hop-count of the Internet," IEEE GLOBECOM'98 — Internet Mini-Conference, 1998.
[19] F. Begtasevic and P.V. Mieghen, "Measurements of the hopcount in Internet," Proc. Passive and Active Measurement, 2001.
[20] A. Carzaniga, D.S. Rosenblum, and A.L. Wolf, "Design and evaluation of a wide-area event notification service," Trans. Computer Systems (TOCS), vol.19, no.3, Aug. 2001.
[21] A.N. Mian, R. Baldoni, and R. Beraldi, "A survey of service discovery protocols in multihop mobile ad hoc networks," IEEE Pervasive Computing, vol.8, no.1, pp.66–74, Jan.-March 2009.
[22] J.K. Lawder and P.J.H. King, "Using space-filling curves for multidimensional indexing," Proc. 17th British National Conferenc on Databases: Advances in Databases, pp.20–35, London, UK, UK, 2000.
[23] D. Tam, R. Azimi, and H.-A. Jacobsen, "Building content-based publish/subscribe systems with distributed Hash tables," presented at the In International Workshop On Databases, Information Systems and Peer-to-Peer Computing, pp.138–152, 2003.
[24] X. Zhang, J.G. Castellanos, and A.T. Campbell, "P-MIP: Paging extensions for mobile IP," Mob. Netw. Appl., vol.7, pp.127–141, April 2002.
[25] Japan Automobile Manufacturers Association INC., "The motor industry in Japan," http://www.jama-english.jp/publications/MIJ2012.pdf, 2012.
[26] S. Matsuura, K. Fujikawa, and H. Sunahara, "Mill: A geographi-

cal location oriented overlay network managing data of ubiquitous sensors," IEICE Trans. Commun., vol.E90-B, no.10, pp.2720–2728, Oct. 2007.

Satoru Noguchi received M.E. degree from Nara Institute of Science and Technology in 2009 and is currently a Ph.D. candidate in Graduate school of Information Science at Nara Institute of Science and Technology. His research interest is resource discovery, mobile networking, IPv6 GeoNetworking.

Satoshi Matsuura received M.E. and Ph.D. degrees in Information Systems from Nara Institute Science and Technology in 2005 and 2008. Currently, he is an associate professor in Graduate School of Information Science, Nara Institute Science and Technology. His research interest includes overlay networks and large scale sensor networks.

Atsuo Inomata received M.E. degree in information science from 1997 and 1999 and a Ph.D. in information science from Japan Advanced Institute of Science and Technology in 2002. Currently, he is an associate professor in Graduate School of Information science, Nara Institute of Science and Technology. His research focuses on cryptography, information security. He is a member of IPSJ and JSISE.

Kazutoshi Fujikawa received M.E. and Ph.D. degrees in information and computer sciences from Osaka University in 1990 and 1993, respectively. Currently, he is a professor of Information Initiative Center, Nara Institute of Science and Technology. His research focuses on multimedia communication systems, digital libraries, ubiquitous computing, and mobile networks. He is a member of ACM, IEEE, and IPSJ.

Hideki Sunahara received B.S. and M.S. degrees in electrical engineering from Keio University in 1983 and 1985 and a Ph.D. in computer science from Keio University in 1989. Currently, he is a professor in the Graduate School of Media Design, Keio University. His research focuses on multimedia communication systems, digital libraries, computer architecture, parallel processing, distributed systems, operating systems, and computer networks. He is a member of ACM, IEEE, Internet Society, JSSST, and IPSJ. He is also a board member of the WIDE project.