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A Routing-Based Mobility Management Scheme for IoT Devices in Wireless Mobile Networks

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SUMMARY Internet of Things (IoT) devices, which have different characteristics in mobility and communication patterns from traditional mobile devices such as cellular phones, have come into existence as a new type of mobile devices. A strict mobility management scheme for providing highly mobile devices with seamless access is over-engineered for IoT devices' mobility management. We revisit current mobility management schemes for wireless mobile networks based on identifier/locator separation. In this paper, we focus on IoT communication patterns, and propose a new routing-based mobility scheme for them. Our scheme adopts routing information aggregation scheme using the Bloom Filter as a data structure to store routing information. We clarify the effectiveness of our scheme in IoT environments with a large number of IoT devices, and discuss its deployment issues.

key words: *Internet of Things (IoT), mobility management, routing architecture, Bloom Filter*

1. Introduction

Internet of Things (IoT) [1] devices, which have different characteristics in mobility and communication patterns from traditional mobile devices such as cellular phones, have come into existence as a new type of mobile devices [2]. IoT devices do not require a strict mobility management scheme, which the traditional mobile devices require, for providing seamless access. This is because IoT devices have following communication patterns [3]: low mobility, intermittent transmissions of small data, infrequent transmission, etc. The communication patterns eliminate the need for expensive handover functions, which are the key of the strict mobility management scheme. The strict mobility management scheme is over-engineered for IoT devices' mobility management.

Most traditional mobility architectures, which strictly manage devices' mobility, embrace a common concept of identifier/locator separation so that the device is identified by its identifier and that packets are routed according to its locator [4]. Even if a mobile device changes its location, we are able to access it by updating a mapping between its identifier and its new locator. In these architectures, the mapping is managed for each device, since the devices' movements are independent of each other. The seamless access pays the serious cost of the fatal defect that mapping cannot be aggregated. This results in the large size of routing information.

We revisit current mobility management schemes for wireless mobile networks based on identifier/locator separation. We break with the separation, and aggressively aggregate identifiers themselves leveraging IoT communication patterns. For example, since IoT devices deployed densely to sense a target area upload similar data packets repeatedly, all of them need not to be delivered. This loose requirement enables routers to advertise imprecise routing information.

We propose a new routing-based mobility management scheme for IoT devices. As the first step to design the scheme, we focus on wireless mobile networks which are well managed by mobile network operators. We address the following research question: how to reduce the size of routing information associated with IoT devices.

The research question is raised because a huge number of identifiers assigned independently of devices' locations is a main obstacle to reduce the routing information size. We adopt a Bloom Filter [5] as a data structure to store routing information at routers inspired by the fact that studies on efficient IPv4 and IPv6 longest prefix matching [6] do so. The Bloom Filter enables to reduce the routing information size at the cost of its impreciseness, i.e., their false positive probability.

The contributions of this paper are summarized as follows: (1) This paper is one of the first studies of adopting the Bloom Filter to a mobility management scheme to reduce the routing information size as far as we know. (2) The proposed routing-based mobility management scheme eliminates strict mobility management by shedding light of IoT communication patterns. The fact that their communications do not need accuracy in, i.e., a high delivery rate, enables to do so. (3) Feasibility of the proposed scheme is validated through simulations for a regional-scale wireless mobile network. (4) Finally, this paper shows a migration path by discussing key deployment issues. We believe that the discussion supports our proposal of replacing current mobility architecture with a routing-based one.

The remainder of this paper is organized as follows. In Sect. 2, we review related work. In Sect. 3, we present our scheme using Bloom Filters. In Sect. 4, we present the preliminary simulation results. Then, we discuss deployment issues in Sect. 5. Finally, Sect. 6 contains our conclusions.

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2. Related Work

2.1 Mobility Architectures for Mobile Networks

Many mobility architectures for wireless mobile networks have been proposed, and they use the common concept that they separate identifiers and locators of devices [4]. The concept requires mapping between identifiers and current locators, and a couple of approaches are proposed in the literature: *using anchor nodes* and *using global name-to-address (location) resolution services* [7].

The approaches using anchor nodes always track devices' physical locations, and maintain and update mappings between identifiers and locators of the mobile devices to provide tunnels to them. For example, in the Mobile IP [8], [9] architecture, a router called "Home Agent" maintains a mapping between a home address as an identifier and a care-of address as a locator for each mobile device. As another example, in an long term evolution (LTE) network, a home subscriber server maintains a fixed international mobile subscriber identity as an identifier and a list of tracking areas (TAs) as a locator to manage tunnels between a packet data network gateway and the mobile device [10].

The approaches using global name-to-address resolution services maintain and update mappings between identifiers, whose namespace is flat, to locators of *all* mobile devices. Devices and routers can use the name-to-address resolution service to resolve names of destination devices to the addresses depending on their locations. For example, MobilityFirst architecture [11] provides global name resolution service to resolve device names to network addresses of networks which the devices belong to.

These two approaches suffer from large memory for maintaining *all* mobile devices' states and communication overheads for updating mappings every time when the devices move. For instance, when a Mobile IP network accommodates N mobile devices, its home agent has to store N mappings and handle N devices' movement using control messages, that is, when the N devices move, the home agent has to handle N messages to update their mappings. In contrast, our scheme can eliminate the need for the large memory for maintaining *all* devices' states by aggregating them using Bloom Filters. It can also reduce the number of control messages to update the states by periodically exchanging the aggregated states as the Bloom Filters.

2.2 Applications of Bloom Filters in Networking

A Bloom Filter has been widely used in the research area of networking [5], [12]. Tarkoma et al. [12] summarized the basic Bloom Filter and its variants, and then classified applications of the Bloom Filters into some categories (e.g., caching, peer-to-peer (P2P), packet routing and forwarding, and security applications). This paper is classified as a packet routing and forwarding application.

Among them, Yu et al. [13] propose a Bloom filter-based forwarding architecture for large-scale enterprise and data center networks. They mainly focus on the large size of forwarding information base (FIB) in a router and reduce its size by using a Bloom Filter. In contrast, this paper focuses on reducing the size of route update information exchanged among routers as well as that of a FIB. This paper enables to aggregate Bloom Filters including route update information pieces by the bitwise OR operation of them. This reduces both the sizes of FIBs and route update information.

Blanni et al. [14] propose a similar aggregating mechanism for avoiding denial-of-service (DOS) attacks. Each host declares a constraint which specifies a legitimate path to it and Bloom Filters which contain the constraints are created by edge routers. They are aggregated by core routers using the bitwise OR operation like this paper. The basic idea of our and their papers are similar, but our paper applies an aggregating mechanism to a FIB, which is a key data structure for forwarding, whereas their paper applies to an access control list (ACL), which is a supplement one.

In our previous study [15], we proposed a key mechanism of our routing-based mobility management scheme using Bloom Filters. In this paper, we extend our previous study by considering deployment issues. The key difference of this study from the above previous studies is that this paper seamlessly integrates Bloom Filters into a routing protocol as route update information whereas the previous studies only focus on reduction of the size of data structures which have many entries for individual networking applications. Representing the route update information as Bloom Filters simultaneously solves the both scalability issues about the size of mapping/route update information and the size/number of control messages for advertising them. In addition, this paper quantitatively evaluates packet delivery rate degradations due to Bloom Filters' false-positives when devices move.

3. Routing-Based Mobility Management Scheme

3.1 Design Principles

Departing from identifier/locator separation, we propose a new routing-based mobility management scheme wherein routing information about non-aggregated IoT devices' identifiers is advertised in an intra-domain network. We consider that such a scheme is feasible from the observations on IoT communications.

First, target IoT applications do not require that a packet delivery rate is nearly one since it can be expected that slight dropping data packets of the IoT applications such as an environment monitoring is not critical. We adopt an aggregation scheme such that the number of device states maintained at routes is reduced by allowing a slight decrease of the packet delivery rates.

Next, we assume that the networks have hierarchical topologies like Internet Service Provider (ISP) networks. Thus, our scheme takes care of aggregating routing infor-

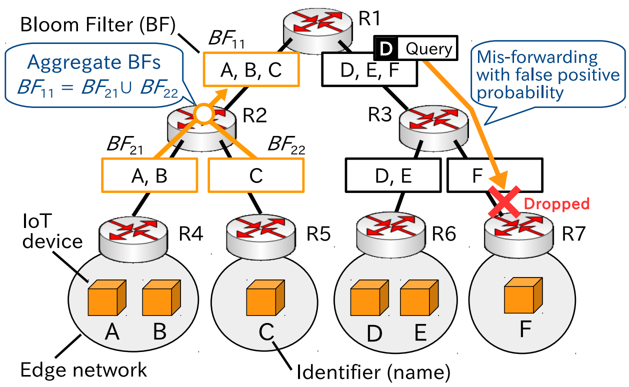

Fig. 1 An overview of our routing-based mobility management scheme: routers store routing information using the Bloom Filter data structure.

mation toward upstream routers from downstream ones.

Finally, we assume that IoT devices have unique identifiers (e.g., IP addresses or names) to distinguish devices from each other. Management of IoT devices' mobility based on routing convergence times could not be a critical issue since IoT devices for sensing or monitoring applications need not change their locations frequently.

3.2 Bloom Filter Based Routing

We show an overview of our Bloom Filter based routing architecture in Fig. 1.

In our scheme, a router has Bloom Filters on a per-port basis to store routing information associated with the IoT devices that may exist in the direction toward the port. The Bloom Filter employs an array of m bits, which are initialized to all 0, and a fixed number k of hash functions $h_1(), h_2(), \ldots h_k()$ which return integer values in the range from 1 to m [5]. All routers use the same filter size m and same k hash functions. The edge routers (i.e., R4 through R7 in Fig. 1) initially obtain routing information of the IoT devices in each edge networks.

Assuming that the router knows which ports upstream/downstream are, the router aggregates the routing information toward upstream routers periodically by the bitwise OR operation of its Bloom Filters and send the aggregated filter to the upstream router. For example, in Fig. 1, the router R2 aggregates its filters F_{21} and F_{22}, then sends the aggregated filter as F_{11} to the router R1. When a data packet, which an identifier of a destination device is X, arrives a router, the router tests a membership of the identifier X in each their filters to decide the next hop. In the case when the router cannot find the next hop, it drops the data packet.

4. Performance Evaluation

In this section, we evaluate the performance of our mobility management scheme through simulations. We investigate the effectiveness of size reduction of Bloom Filters.

Table 1 Parameters for truncated Lévy walk model.

Parameter	Value
flight scale	10
flight alpha	0.5
flight limit [m]	10000
pausing scale	0.1
pausing alpha	1.5
pausing limit [sec]	100
speed coefficient	18.72
speed power	0.79

4.1 Setup

In the simulations, we assume an IoT environment wherein 500,000 IoT devices move in a square field independently. A mobility model of the IoT devices is truncated Lévy walk [16] describing human mobility because we assume that many devices are wearable devices. The parameters of the mobility model are shown in Table 1. The square field size is 512×512 [km^2], which is similar to the area of the main island of Japan or the United Kingdom. It is divided into 16,384 small square blocks, each size of which is 4×4 [km^2]. This size is similar to the area of a TA in cellular networks. A network topology consisting of routers is a complete quadtree of which height is seven. Edge routers, which locate at the leaves of the quadtree, manage the information of IoT devices in each small 4×4 [km^2] square block.

We simulate IoT device movements and route updates for 3,600 [sec]. The routers update routing information every 600 [sec]. We generate queries, which should be routed to a randomly selected IoT device from the root router, to deliver data packets every 50 [sec], and calculate the packet delivery rate.

4.2 Initial Results

Figure 2 shows the relation between the size of Bloom Filters m and the packet delivery rate. From Fig. 2, we observe that the packet delivery rate takes around 0.9 when the size of Bloom Filters m is more than 0.6×10^6 [bit] ($\approx$ 73 [kbyte]). In contrast, when the size of Bloom Filters m is less than 0.6×10^6 [bit], the packet delivery rate takes less than 0.9. This is due to the false positive probability increase of the Bloom Filter when the size is small.

This result suggests that our scheme has the significant effectiveness of size reduction of Bloom Filters. For instance, if we assume to use traditional routing tables requiring a routing entry per destination, which the size of the routing entry is 24 [byte], the size of routing table amounts about 11.4 [Mbyte] to store routing information of 500,000 IoT devices at a router. Since we expect that the effectiveness of size reduction depends on the number of IoT devices or the mobility of IoT devices, it is important to more minutely evaluate our scheme in order to set the parameter associated with real IoT environments accurately.

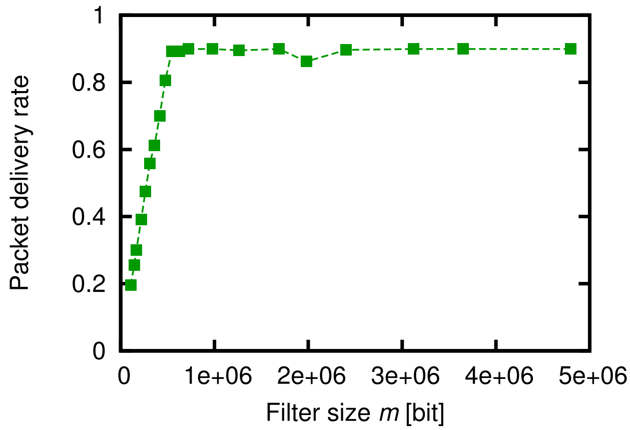

Fig. 2 The relation between the size of Bloom Filters *m* [bit] and the packet delivery rate (simulation time [sec]: 3,600, number of devices: 500,000, mobility model: truncated Lévy walk, route update interval [sec]: 600)

5. Deployment Issues

Finally, we present deployment issues to show a migration path.

5.1 Handling Micro Mobility

This subsection addresses how the proposed routing-based scheme handles micro mobility. By the word "micro mobility", we mean either that an IoT device moves within an area managed by an attachment point or that it moves to another area managed by a neighboring attachment point. For example, in the case of LTE, an eNodeB is an attachment point and it accommodates multiple cells as its areas [10].

The scheme hides the two cases of micro mobility in the following way: First, micro mobility in the same attachment point is inherently solved by placing a router at all attachment points, e.g., eNobeBs. Second, when an IoT device moves to another attachment point as discussed in Sect. 4, a packet to it is dropped. Thus our routing-based scheme cannot inherently achieve 100% packet delivery ratio. However, 100% packet delivery is feasible just adding any of established micro mobility techniques to our scheme. For instance, an LTE network handles such attachment point changes as follows: When downlink packets arrive at a source eNodeB during the handover procedures to a target eNodeB, the source eNodeB forwards these packets to the target eNodeB [10]. This forwarding mechanism can be easily adapted and built into an edge router of our scheme.

5.2 Naming Scheme

Since our scheme uses only IoT devices' identifiers, i.e., their names, for their mobility management, the choice of naming schemes is a crucial issue. Our scheme can support both flat and hierarchical names since our scheme does not have any constraint on identifiers. However, the difference of the naming schemes has an impact on macro mobility. By the word "macro mobility", we mean that a packet is routed to a gateway between a mobile wireless network which is controlled by our scheme and external networks. Thus, we address following research question: Which naming scheme is better suited for our scheme?

When the flat name is used, IoT devices have unique identifiers such as GUIDs [11]. In this case, all names of IoT devices should be advertised to routers in the mobile wireless network as well as to those in external networks. This means that our scheme or another mobility management scheme provide scalability at the Internet scale, but that this achievement is still an open research question.

On the contrary, when the hierarchical name is used, some upper components of the name is used as a prefix as in NDN/CCN [17]. In this case, only such prefixes need be advertised to external networks and apparently, there is no scalability problem. Thus our scheme prefers hierarchical names to flat ones.

5.3 Applicability to Large-Scale Networks

Our scheme can be built into existing large-scale wireless mobile networks such as LTE-based cellular networks. The scheme uses all the mechanisms except for forwarding/routing without any modification. For example, tracking and paging mechanisms of cellular networks are used as they are. Besides, co-existence with traditional mobility strict mobility mechanisms for seamless access is feasible by using router virtualization techniques.

This paper uses a distance vector routing protocol on tree-like topologies because traditional sink-client communications wherein information pieces are uploaded from devices to a single sink are popular. However, our Bloom Filter-based forwarding/routing mechanism is easily built into a link-state routing protocol, e.g., open shortest path first (OSPF). This adoption enables it for our mechanism to support multiple sinks in large-scale non-tree topology networks. In the case of OSPF, router link state advertisements (LSAs) are represented as Bloom Filters of all devices' identifiers which a router accommodates. The router LSAs are flooded to all routers in a network and each router calculates the shortest path to the set of identifiers included in each router LSA. This enables it for each router and device to send a packet to anyone and thus multiple sinks are supported in arbitrary topologies. In addition, since the link-state routing protocol regards both root/sink nodes and IoT devices as devices attached to a network, the adoption of it makes it possible for our mechanism to handle movements of the both sinks and IoT devices. This can achieve similar performances for communications from/to sinks in movement as shown in Sect. 4.

The adoption of the link-state routing protocol naturally resolves a scalability issue as well. The network is divided into multiple OSPF stub areas, and a summary LSA, which is obtained by the bitwise OR operation of all router LSAs in a stub area, is advertised by an area border router to the others. Thus, each area border router has the Bloom Filters corresponding to summary LSAs, of which the number is the same as that of all stub areas. We consider that this protocol is enough scalable to a large number of devices as described below. We assume that a cellular network accommodates 10,000,000 IoT devices and that the network is divided into 20 stub areas. In this case, each stub area accommodates 500,000 IoT devices and it is similar to the network in Sect. 4. Thus each area border router has only to have 20 Bloom Filters of 73 [kbyte] to support movement of the IoT devices as described in Sect. 4.

5.4 Application Issues

The proposed routing-based scheme differs from most traditional schemes, e.g., in particular tunnel-based schemes, in that other communication patterns are supported. Our scheme provides routing/forwarding to and from IoT devices in the both download and upload direction whereas most traditional schemes provide that from them in the upload direction. Typical scenarios of the download direction are updating firmwares of IoT devices or enabling/disabling their sensing/actuating functions remotely. Besides IoT devices communicate with each other directly, which is often called M2M communication, without using anchor nodes and this reduces latency between them. By adopting link-state routing protocols as described in Sect. 5.3, our scheme also supports the M2M communications between mobile IoT devices. We believe that these communication patterns help create new applications, e.g., ones of fog computing on IoT architectures [18], which could not be achieved by using traditional upload communication patterns.

5.5 Remaining Issues

Most issues about scalability and migration are resolved as explained above. However, the following issues need be addressed for our scheme as well as traditional strict mobility management schemes: First, we should address how to implement security functionalities such as access control and data certification at IoT devices of which computing power is small. Second, congestion control of simultaneous uploads from a huge number of IoT devices is a cold, but important issue.

6. Conclusion

In this paper, we have proposed the routing-based mobility management scheme using Bloom Filters for the IoT devices, and then have clarified the effectiveness of our scheme. Consequently, we have shown that our scheme can reduce the size of routing information, which are stored in Bloom Filters at routers, to approximately 73 [kbyte] when required packet delivery rate is around 0.9.

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