IoT Middleware over Information-Centric Network

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***Abstract*—To build a unified IoT platform in which physical and digital objects can be accessible by application across different organization and domain, many state of art approaches are based on IP-overlay architecture. These solutions inherit the constrain of the current internet, especially in terms of naming, heterogeneity, mobility and security. Thus, we propose a new Information-Centric Network (ICN) based IoT middleware to address these challenges. In this paper, we introduce detailed protocol design for the functions in the middleware and evaluate the efficiency of service discovery.**

I. Introduction

Many standalone Internet of Things (IoT) platforms have been developed and deployed in different domains in the past. The recent trend, however, is to evolve towards a globally unified IoT platform, in which billions of objects connect to the Internet, available for interactions among themselves, as well as interactions with many different applications across boundaries of administration and domains.

Building a unified IoT platform, however, poses a set of unique challenges and requirements on the underlying network and systems.

- **Identity**: To realize a unified IoT platform, the first step is the capability to assign names (or IDs) that are unique within the scope and lifetime of each device, data items generated by these devices, or a group of devices towards a common objective. Currently, IoT systems have multiple vertical stacks with their own identity mechanisms that do not inter-operate with one another.
- **Heterogeneity**: IoT devices will have heterogeneous means of connecting to its application environment, and often have severe resource constraints, e.g., constrained resources in power, computing, storage, bandwidth.
- **Mobility**: In some scenarios, the data producer is mobile and unable to provide reliable connection with data consumers. Thus, in presence of mobility, a unified IoT platform requires the system to deliver IoT data within delays that are acceptable to applications.
- **Security**: The heterogeneity and openness of the IoT environment imposes great attack surface towards IoT devices and services. Without carefully considering security concerns such as identity authentication, data integrity and privacy, any IoT platform is hard to be adopted by either end-users or enterprises.

A. ICN-IoT Middleware

Current approaches towards a unified IoT platform are mostly based upon Internet overlays, whose inherent inefficiencies hinders the platform from satisfying the challenges outlined earlier. In recent years, in order to address the inefficiencies of today's Internet, Information-Centric Network (ICN) has been proposed. ICN identifies a network object (including a mobile device, content, or service) by an application-centric name instead of its IP address, and adopts a name-based routing, lending itself to supporting the unified IoT platform. In this paper, we propose a unified IoT middleware, referred to as *ICN-IoT* middleware, which can support several specific ICN architectures. Shown in Figure 1, the ICN-IoT middleware mainly consists of the following modules: publish/subscribe management, device/service discovery, context processing, naming service and discovery service. Among these modules, the publish/subcribe management is a centralized service while others are implemented in a distributed manner (discussed in Section III-A). Finally, the security component is implemented across all services.

It is worth noting that functions in the proposed middleware are required to comply with the IoT deployment requirements and protocol agnostic, and therefore the instantiation of the ICN-IoT middleware may differ depending on the underlying ICN protocol. To be specific, in this paper we will discuss there IoT functions with respect to the hierarchical name-based NDN and flat name-based MobilityFirst.

B. Name Data Networking (NDN)

NDN [16] provides a receiver-driven architecture by transmitting two types of packets : Interest and Data. Consumer issues Interest of the hierarchical content name and forwards it to Data Producer. When the interest arrives at some node (either intermediate router or Data producer) that owns the requested content, the node will reply the requested content(in the form of Data Packet) along the reverse path to the Data Consumer. NDN provides three types of key components to support such functionality. Forwarding Information Base (FIB) maintains the forwarding information at each NDN node. The content prefix and out-face mapping is recorded in the FIB. Once a certain face receives Data packet for a Pending Interest Table , it could be added into the FIB to indicate a healthy data retrieving path.Pending Interest Table (PIT) is a data structure that maintain the set of pending Interest routed by the node that expecting Data packet in return. PIT entry is created by receiving Interest, and filters the redundant Interest that carried the same content name. Due to the limitation of PIT size, every

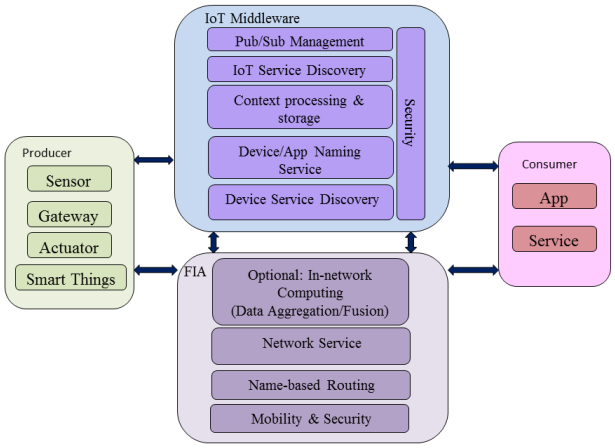

Fig. 1: ICN-IoT middleware functionality break down.

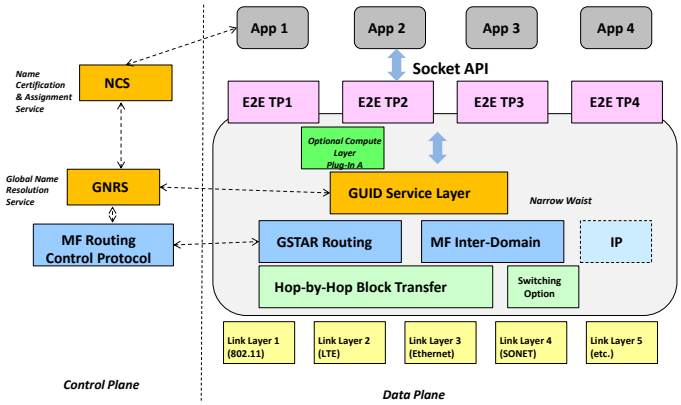

Fig. 2: Mobilityfirst architecture.

PIT entry comes with a timeout which is consumer defined or estimated based on a round trip time. Once a matching Data packet being received by the node, it is forwarded via the face recorded in the PIT before this entry being removed. Content Store(CS) is a data cache for storing Data packet for matching Interest along the reverse path. Also, due to the constraint of local CS size, Data Producer can define the freshness of the Data packet in order to timeout it in the cache. With such transmission mechanism, NDN eliminates the notion of source and destination as it is in IP network, and handle routing only for Interest Packet.

C. MobilityFirst (MF)

MF [13] utilizes GUID to name every network object, while separating this GUID from its actual network address. This identifier(GUID)/locator(network address) split design allows MF supporting dynamic address binding, multiple addressing binding and late binding. Shown as Figure 2, MF core network architecture includes the following network component.

Global Name Resolution Service(GNRS): GNRS is a centralized service that maintains mappings between GUID and network address. MF routers create the entries by performing an insert for the GUIDs of attached network devices and the associated network address, and query GNRS for a translation from GUID to the latest binding network address. Recent work shows that this translation performance is much better (50-100 ms delay) than DNS resolution [15].

Hybrid GUID/NA address routing: Each of the router in MF can make routing decision based on NA or GUID in the header of data packet, since routing decision are made on a hop-by-hop manner [9].

Delay-Tolerant Network(DTN): The storage in each MF router provides the capability of caching the data packe. Hence, data can be stored or forwarded based on different routing policies, such as quality of the link, which is very useful over wireless interface.

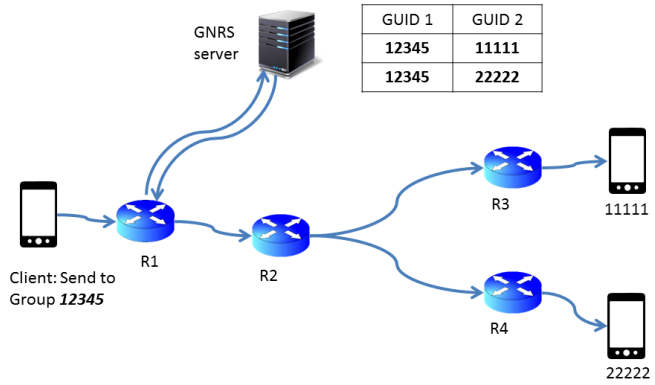

Fig. 3: MF multicast example: A client sends a message to Group 12345

MF multicast: MF multicast is based on the idea of group GUID that gathers multiple network objects into one entity. Group GUID to object GUID mapping is a one-to-many mapping that being maintained at GNRS server. Network object can claim to join the multicast group, and either edge router or a centralized management service will perform insertion of the object GUID to group GUID mapping to into GNRS server. When the first router queries GNRS server for a group GUID mapping, GNRS server returns a list of member GUIDs. The router assembles these GUIDs into the header and performs "Longest Common Path(LCP)" algorithm to determine the next hop address.Shown as Figure 3, routers look up the routing table for these GUIDs, and check if there are multiple next hops. When the number of the results is more than one, the router reassembles the header and forwards the copied packet to corresponding interfaces. If the number of multicast group members becomes significant, another approach can be adopted to resolve this issue–instead of assembling all GUIDs into the header after one query, each router on the path queries GNRS server for the group members and performs LCP to decide next hop.

II. Related Work

ICN is a clean-slate architecture for the future Internet, including the Internet of Things. Previous studies by Zhang Y. et al [17] and Li S. et al [8] summarize the benefits that the ICN network is able to bring to IoT, including efficient data retrieval, good support of mobility, naming, scalability and security.

Driven by the same vision, a few earlier studies have demonstrated the feasibility of ICN on supporting specific IoT applications. For example, the study by Amadeo et al. in [3] provides a solution to efficient multi-source data retrieval. It proposes to use a single Interest packet to retrieve multiple data with different suffixes from different locations by adjusting the traditional NDN protocol to support "prefix-based" interests. For example, let us suppose a subscriber is interested in the resource named "/office/temperature", which includes information from multiple sensors deployed in his office. At the same time, temperature sensors should advertise their resource with this prefix and their own suffix (e.g sensor in the conference room should be named "/office/temperature/conferenceroom"). Hence, the subscriber can issue a single interest to retrieve multiple resources simultaneously.

George et al. [11] proposes a Publish-Subscribe Internetworking ICN architecture where identifiers can be used to represent a thing, an application, a group of similar things, or any contextual specific entity in the network. A Rendezvous Node functions as a middle box where advertisements from publishers and subscription requests from subscribers can meet to form a membership.

There are also studies that take one step further to implement IoT systems over the ICN architecture. In the study by Shang et al. in [14], a practical use case that integrates NDN with a Building Management System (BMS) is represented. It shows that human-readable hierarchical naming scheme brings convenience in configuring and managing a large number of BACnet devices. Baccelli et al. [4] reports a CCN experiment over a deployed IoT system, in which they ported light-weight CCN-lite code over RIOT operating system. Based on this platform, the authors measured the performance of various routing protocols and the impact of different caching schemes.

III. ICN-IoT Middleware Design

In this section, we present the overall ICN-IoT middleware design. It consists of three system components, as shown in Figure 4– an Aggregator, Local Service Gateway, and IoT server, which offer four principle functionalities, including device discovery, device naming service, IoT service discovery and Pub/Sub management. In contrast to centralized or overlay-based implementation in the legacy IP-based IoT platform, our ICN-IoT architecture pushes these middelware functionalities down to the distributed components to enable self-configuring subsystem to provide not only local services but can also scale to large service enablement. ***YZ: I don't get what this sentence is trying to say. ***

A. System Architecture

The proposed architecture has the following three main system components:

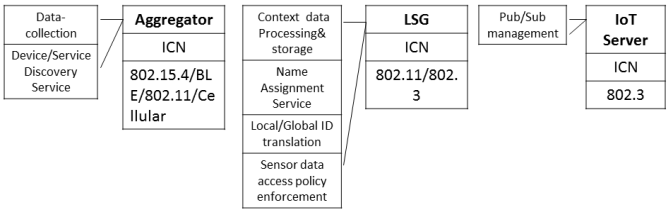

Fig. 4: Physical components of ICN-IoT middleware

- *Aggregator*, which interconnects various IoT services in a local network. An Aggregator usually plays two roles: one is to act as the gateway to bridge the communication between resource-constrained wireless sensors and the rest of the nodes in the local network, and the other one is to integrate sensing/actuating services in the local network.
- *Local Service Gateway (LSG)*, which connects the local IoT system to the rest of the global IoT system, and handles local name assignment and enforces data access policies for local IoT devices. In addition, it can run context processing services to publish only the contextual information (instead of raw data) to the IoT server.
- *IoT Server*, which is a centralized server that maintains subscription memberships and provides the lookup service for subscribers. Unlike legacy IoT servers that are involved in the data path from publishers to subscribers – raising the concern of its interfaces being a bottleneck – the IoT server in our architecture is only involved in the control path where publishers and subscribers exchange their names and certificates.

In the following subsections, we will discuss the breakdown functionality for each system component and present detailed protocol design.

B. Device Discovery

The objective of device discovery is to contextually establish relationship for nodes in proximity. Device discovery is a key component of any IoT system, and can be considerably simplified by the ICN network. In today's IoT systems, the IP overlay device discovery module does not only focus on the reach-ability of a device, but also the device physical properties [2], [1]. Moreover, a translation service is required to maintain the mapping from network addresses to physical attributes, which often involves manual configuration. In ICN-IoT, however, device discovery does not involve any manual configuration or name translation because ICN directly uses names to discover new devices. In what follows, we explain the ICN-IoT device discovery in detail, including both devices that are able to run full-stack protocols (referred to as *resource-rich sensors*) and devices that are unable to do so (referred to as *resource-constrained sensors*).

Resource-rich sensors: Many a resource-rich sensor comes with a manufacture secure ID and model name, which needs to be exposed to both the aggregator and LSG to facilitate device

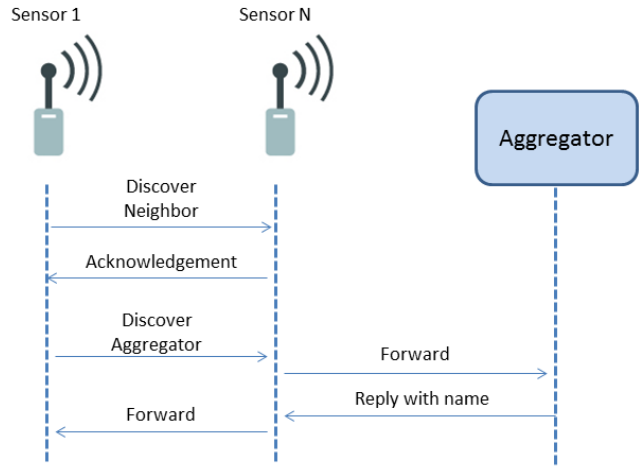

Fig. 5: Device discovery for resource-constrained sensor

discovery. This aim can be achieved by different means with respect to NDN and MF. In NDN, this process is initiated by the configuration service running on LSG, which periodically broadcasts discovery Interests (using the name $/iot/model$). The new sensor replies to the discovery interest with its information, and the configuration service then registers the sensor and generates a local ICN name for the sensor. In MF, we can set the model number, $group\text{-}GUID$ as the destination address, and the configuration service issues a request via multicasting. When receiving such request, the new device replies with the manufacture secure ID, and the configuration service registers the device and generates a local ICN name for it.

Resource-constrained sensors: Many resource-constrained sensors connect to the Internet using the IEEE 802.15.4 technology via a border router [7]. These sensors voluntarily discover each other in proximity and establish forwarding paths to the border router by self-organizing into a mesh network. Similarly, for our ICN-IoT middleware, Aggregator acts as a border router, and neighbor discovery among sensors can be achieved differently with respect to NDN and MF as follows. In NDN, when a new sensor arrives, it broadcasts a neighbor discovery message to connect with neighbors. After establishing connectivity with neighboring sensors, it broadcasts an Interest named $/ndn/aggregatorservice$ to discover the Aggregator. In MF, neighbor discovery is naturally supported, and the new sensor simply needs to send a discovery request to a well-known broadcast GUID to discover the Aggregator. The above process is shown as Figure 5

C. IoT Service Discovery

IoT services can be generally categorized into two classes: sensing and actuating. In today's IoT platforms, sensors are connected via a server, which requires considerable development effort such as maintaining a local name to IP mapping. In ICN-IoT, IoT service discovery and configuration becomes much simpler. Specifically, we consider two service discovery modes: $peer\text{-}to\text{-}peer$ and $master\text{-}slave$.

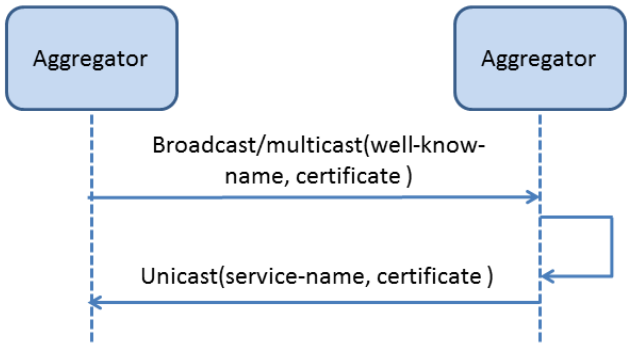

Fig. 6: Peer-to-peer service discovery

Peer-to-peer Service Discovery: In this mode, we consider the scenario in which an aggregator (referred to as the source aggregator) tries to discover an IoT service provided by another peer aggregator (referred to as destination aggregator). In NDN, the source aggregator broadcasts an interest using the well-known name $/area/servicename/certificate$, which will eventually reach the destination aggregator. NDN's Interest/Data mechanisms allows only one response for each Interest send while discovery requires to learn multiple entities, hence efficient discovery is realized by using exclusion via Selector in the protocol or as an overlay protocol [12]. In MF, this is handled by multicast (discussed in Section I-C) instead of flooding the entire local network. All sensors that provide relevant services can join the multicast group identified by a $Group\text{-}GUID$. After establishing the multicast group, the source aggregator sends a request containing the service name and certificate to the multicast group.The destination aggregator that hosts the service checks the certificate and registers the source Aggregator if there is a matched service. It replies with an acknowledgement containing its certificate to the source aggregator. The message flow is shown as Figure 6 In an example of NDN smart home, a thermostat expresses a request to discover a air conditioning (AC) service using well-known name $/home/ac/certificate$ via broadcast channel. In MF case, a multicast group GUID 1234 can be assigned to all home appliance IoT service. The thermostat sends request containing the service name and certificate to 1234. In both cases, the AC hosting this services replies with acknowledgement if all conditions match.

Master-slave Service Discovery: In some IoT applications, there are more than one sensing service or actuating service connecting to one control service. A source aggregator hosting control service expresses a request with service name and its certificate to discover a service from all available aggregators. The destination aggregators verify the certificate. If valid, the destination aggregators register the source aggregator and answer with acknowledgement containing their certificates if there is a matched service.

In the AC control NDN example, the number of AC

service provider increases to three, which can be named as $/office/ac/1$, $/office/ac/2$ and $/office/ac/3$. The thermostat expresses a partial name $/office/ac/certificate$ via a broadcast channel periodically. In the MF case, a multicast group GUID 1234 can be assigned to identify AC service. The thermostat sends request with service name and certificate to 1234. The destination ACs reply with their certificate if the request meets all criteria.

D. Secure Device Discovery, Naming Service and Service Discovery

Security guarantee is always treated as an essential function for the IoT middleware. Generally speaking, the security objective is to assure that the device that connects to the network should be authenticated, the provided services are authenticated and the data generated (through sensing or actuating) by both devices and services can be authenticated and kept private (if needed). To be specific, we consider the approach to secure device discovery, naming service and service discovery, because other services, such as pub/sub management and context processing & storage, can be properly secured according to application-specific demands.

Recall that our goal is to assure that either device or service itself is authenticated, attempting to prevent sybil (or spoofing) attack [10] and the assigned name closely binds to the device (or service). In what follows, let us consider how to secure device discovery and name assignment. Suppose that the device (i.e., sensor) can be either programmable so that before deployment the owner can preload some identity information (such as secure ID, a pair of public/private key and a certificate) , or has some manufacture ID and a pair of public/private key (which is certified by the manufacturer). That is, the device is associated with information including device identity, public/private keys (PK_{device}, SK_{device}) and a certificate either from the owner or the manufacturer which certifies the device identity and public/private keys. For the ICN-IoT middleware on top of NDN, when discovering a device, the aggregator will first verify the device identity (e.g., the device can generate a signature with the private key SK_{device} and present the signature and the certificate to the aggregator so that the aggregator can verify it), and then assign a name to the device as follows: the aggregator will issue a request to LSG together with its device identity and PK_{device}, so that LSG can assign an NDN name and generate a certificate (certifying the binding of NDN name, PK_{device}). To this end, the NDN name and the certificate will be sent back to the aggregator and will be stored locally if the device is resource-restricted. Otherwise, the NDN name and the certificate will be passed to the device. For the MF-IoT, assigning a GUID for a device is rather straightforward: after verifying the device identity, the Aggregator inserts the public key PK_{device} and device information to the upper layer component to verify if there is a conflict in the corresponding scope. Specifically, LSG is in charge of local scope and IoT server guarantees the global uniqueness. Finally, the unique public key is used a GUID for the new device. Analogously, service discovery can be secured in a similar way.

Before a service being discovered, a secured name needs to assigned to the service host. Especially in MF IoT, secured group GUID is utilized to realize service request multicast, which may be owned by multiple hosts, hence conventional public/private key scheme may not be suitable for this case. As a alternative, group key management protocol (GKMP) [6] can be adopted to resolved the issue above – A naming service residing at LSG or IoT server (depending on application scope) generates a group public key that used as group GUID for a service, then assignment this group public/private keys pair to each Aggregator that host this service. The service host Aggregator in the group then listen on this group GUID, and use the group private key to decrypt the incoming discovery message.

Note that the above discussion assumes that there exists key infrastructure (a centralized and hierarchical system) , which greatly simplify the system trust model. In some ad hoc network this assumption may not hold and some other trust mechanisms may need to be employed, such as PGP [**?**].**LS: do you mean Pretty Good Privacy? ** Moreover, in order to comply with the capability of resourced-restricted devices, light-weight cryptographic primitive (such as symmetric cryptography) may be used instead of public key cryptography.

E. Publish/Subscribe Management

Data Publish/Subscribe (Pub/Sub) is an important function for ICN-IoT, and is responsible for resource sharing and management. In conventional IP network, most of the IoT platforms provide a centralized server to aggregate all IoT service and data. While this centralized architecture ensures high availability, it scales poorly and has high bandwidth consumption due to high volume of control/data exchange by a central server. Thus, we consider a decentralized pub/sub model in ICN-IoT middleware. Specifically, we will discuss rendezvous mode and a data-control separation mode.

Rendezvous Mode: Rendezvous mode is a classic pub/sub scheme in which data and requests meet at an intermediate node. While NDN is a Pull-based architecture without supporting the Pub/Sub mode naturally, COPSS [5] proposes a solution to fix this problem. It integrates a Push-based multicast feature with the pull based NDN architecture at the network layer by introducing Rendezvous Node (RN). RN is a logical entity that resides in NDN forwarder. The publisher first forwards a Content Descriptor (CD) as a snapshot to the RN. RN maintains a subscription table, and receives the Subscription message from subscribers. The data publisher just sends the content using Publish packet by looking up FIB instead of PIT. If the same content prefix is requested by multiple subscribers, RN will deliver one copy of content downstream, which reduces the bandwidth consumption substantially.

Data-control separation Mode: Compared with the Rendezvous mode in which data plane and control plane both reside on the same ICN network layer, we consider an architecture where the control message is handled by the centralized server while data is handled by ICN network layer. Following the naming process mentioned above, the LSG has the ICN name for the local resource which is available for publishing on

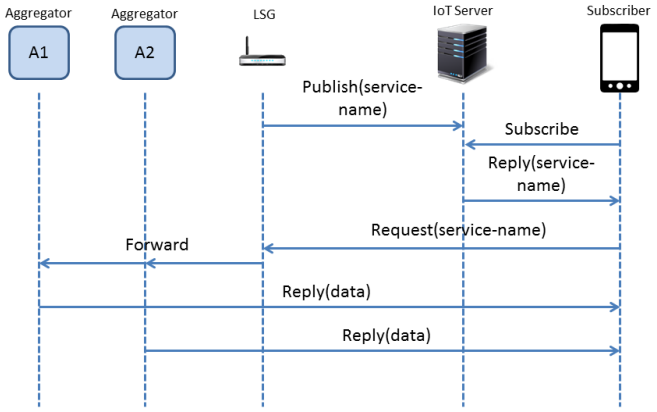

Fig. 7: Publish/subscriber management message flow

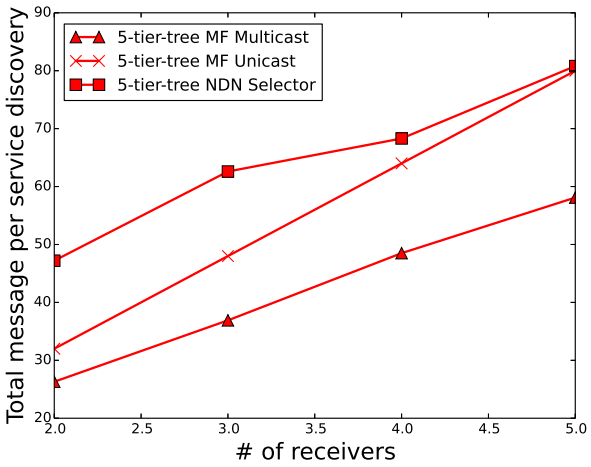

Fig. 8: Overhead of service discovery in 5-tier tree

IoT server. IoT server maintains the subscription membership, and receives subscription requests from subscribers. Since the subscribers has non knowlege about the number of resource providers and their identities in a dynamic scenario, IoT server has to take responsibility of grouping and assigning group name for the resource. The generic message flow for publish/subscribe function is shown in Figure 7, and we will illustrate the detail in each individual architecture. In NDN, the grouping resource is intuitive: all resources have the same schematic prefix will be grouped together, and the prefix can be used to identify the service. The traditional NDN supports using a common partial name to retrieve multiple resources via Selector, but M. Amadeo et al. [3] provides a more efficient solution to improve this mechanism by introducing long-life multi-source Interest in PIT. MF takes advantage of $Group\text{-}GUID$ to identify a service provided by multiple resources. This $Group\text{-}GUID$ will be distributed to the subscriber as well as the publisher. In an example of NDN, it uses the common prefix$/home/monitoring/$ to identify a group of resource that provides multiple monitoring services such as $/home/monitoring/temperature$ and $/home/monitoring/light$. The subscriber retrieves the prefix from the IoT server, and sends Interest toward the resource. In a MF example, $GUID\text{-}x$ identifies the "home monitoring" service that combines with "light status" and "temperature". The resource producers, i.e. the host of "temperature" and the host of "light status" are notified that their services belong to $GUID\text{-}x$, then listen on $GUID\text{-}x$. The subscriber sends the request containing $GUID\text{-}x$ through multicasting which ultimately reaches the producers at last common node. Once receiving the request, the resource producer unicasts the data to the subscriber. In addition, if multiple resource consumers subscribe to the same resource, the idea of $Group\text{-}GUID$ can be reused here to group the consumers to further save bandwidth using multicast.

IV. Evaluation

In this section, we investigate the efficiency of service discovery based on MF multicast, MF unicast and NDN interest selector. We have conducted a detailed experiment in NS3-based MF simulator and ndnSIM. MF network protocol is implemented over standard NS3 P2P module and the experiments are running in a tree-based topology. In MF multicast case, $GroupGUID$ is used to identify a service at unknown location, i.e., service host (SH) can be at any leaves of the tree while service requester (SR) attaches to the root of the tree. SR issues a request and the first router then performs GNRS lookup for the $GroupGUID$. On receiving of the service request message, the matched receivers will reply with a acknowledgement to the service requester via unicast. While in MF unicast case, we configures the SR to issue request periodically and each matched SH will reply the request sequentially.In NDN selector experiment, SR expresses Interest with name "/service", and corresponding full name is "/service/
1,2,..., n}". On receiving of the response from one of the SHs, the SR appends the response's name to the exclusion list of a Interest and re-express a Interest with the same name. This operation will repeat until no response comes back. Figure 8 shows the overhead in terms of total message per service discovery in a 5-tier tree. We observe that MF multicast introduces the least overhead among three schemes, as it triggers only one GNRS lookup per request, and the routers only forwards request duplicates based on the next common hop(s). When the number of SH increases to 5, NDN interest selector and MF unicast achieve similar performance. This is due to selector prevents both routers and SHs forwarding the discovered responses, which decreases the total response message. In MF unicast, total message number grows linearly as the number of SH increases. Figure 9 demonstrates the result of the same experiment in a 6-tier tree. NDN selector scheme encounters the highest overhead due to the impact of network scale increment on Interest broadcast.

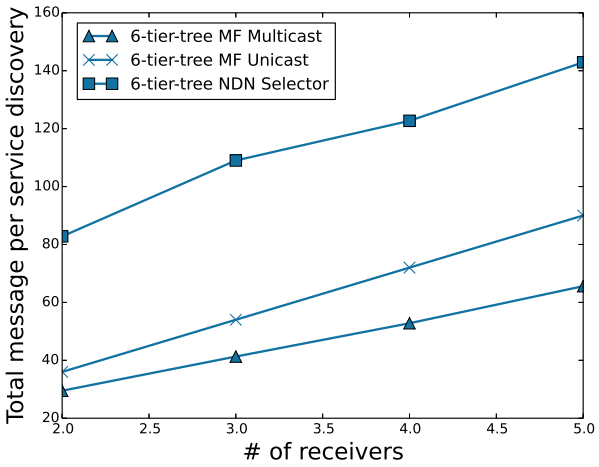

Fig. 9: Overhead of service discovery in 6-tier tree

V. Conclusion

In this paper, we present the feasibility of a ICN-based middleware to support various IoT application, and define detailed protocol design for the funtionalities of the middleware including device discovery, naming, service discovery and pub/sub management. Through detailed simulation, we find that service discovery over MF multicast introduce less overhead than MF unicast and NDN Selector if multiple service hosts belong to the same service group. To realized a full-fledged ICN-IoT middleware, our next step will involve prototyping the platform in a real enviroment and develop a naming service for both hierarchical and flat naming scheme.

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