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A Hierarchical Distributed Energy Management Agent Framework for Smart Homes, Grids, and Cities

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Abstract

The installation of smart grids by utilities is driving the growth of the energy industry, allowing energy management systems (EMSs) to improve operational efficiency. Increasing consumers' interest in efficient energy consumption and distributed energy resources requires an EMS that can manage large numbers of powered devices within homes, buildings, and residential areas. An energy management agent (EMA) is a technology standard under development by ISO/IEC JTC 1/SC 25/WG 1. The EMA standard offers convenient and intelligent energy management services while supporting interoperability for demand response signals to smart grids. As wireless providers transition toward 5G and optical networks, EMAs are evolving into powerful frameworks of interconnected EMAs associated with cloud and edge computing. This article proposes a hierarchical distributed architecture that combines the advantages of both hierarchical and distributed architectures. A hierarchical architecture provides large-scale information acquisition, communications, processing, and control for cooperative energy management in homes and grids through cloud computing, while a distributed architecture provides autonomous decision making capability with agent-based intelligence through edge computing. The experimental results demonstrate the substantial achievements of the proposed hierarchical distributed EMA framework based on an actual protocol and system implementation. Finally, this article introduces various opportunities for using this framework with selected emerging technologies in smart city environments.

Introduction

An energy management system (EMS) aims to balance power consumption with power generation to create a holistic infrastructure that is sustainable without blackouts [1]. EMSs are often integrated with home automation systems and play an important role in the control of home energy consumption to meet the needs of today's evolving energy markets [2].

The emergence of home energy management systems (HEMSs) [3] has opened a new consumer energy management market for a home electronic system (HES) [4]. HEMSs encompass HES products, including smart appliances, heating, ventilation, air conditioning, and distributed energy resources (DERs) in homes, buildings, and apartment complexes. These products are interconnected with other systems through an HES gateway within the home as well as outside the home. An HEMS drives energy management interactions according to the demand from the utility and the necessity of the operational efficiency of an HES.

The International Standards Organization (ISO)/International Electrotechnical Commission (IEC) Joint Technical Committee (JTC) 1 Subcommittee (SC) 25 is considering revising ISO/IEC 15067-3, which provides a model of an energy management agent (EMA) for the design and evaluation of energy efficiency in HEMSs for their deployment. ISO/IEC 15067-3-3 builds upon ISO/IEC 15067-3 by extending the EMA model to allow more complex interactions in energy management installations. These extensions include a high-level architecture and a set of models for an EMS with interacting EMAs in a home or community housing facility (e.g., on-campus housing or apartment buildings) or with supplemental EMAs in the cloud.

As communication networks transition toward 5G and optical networks [5], EMAs are evolving into an energy management framework (EMF) that supports information acquisition, communications, processing, and control for energy management. A centralized architecture is suitable for systems that require strong cooperation between multiple EMAs to meet the operator's needs for the highest efficiency. However, as the number of EMAs increases, the centralized architecture framework has posed a major challenge [1]. The centralized architecture reaches its physical limit when managing the energy consumption of multiple EMAs, causing service congestion, serious latency, and reliability problems [3]. In the current architecture, a large-scale demand response (DR) service must be processed at a centralized server, resulting in substantial processing burdens to minimize the total electricity cost while supporting user demands.

To solve this problem, Jang and Qian [6] proposed a distributed communication architecture to support advanced metering infrastructure (AMI) in smart grids. Cheng *et al.* [7] proposed

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From an energy management infrastructure viewpoint, the EMAs are interconnected over the smart home and grid infrastructure in an HD architecture. Therefore, an EMA is capable of information acquisition and dissemination and of making decisions that concern energy consumption and generation within different levels of the hierarchy by using agent-based intelligence.

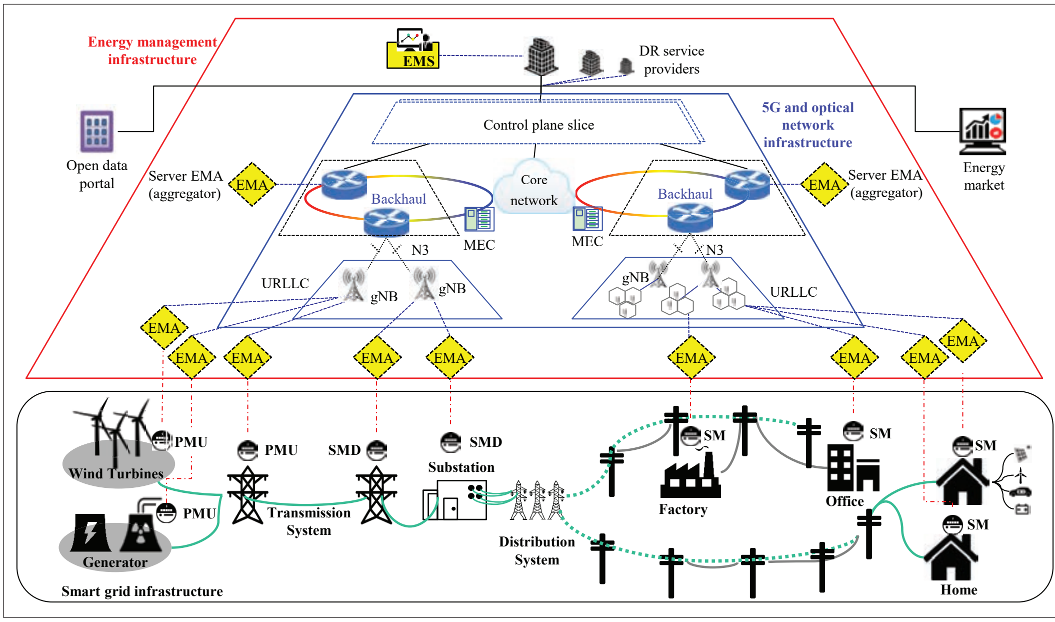

Figure 1. A hierarchical distributed energy management agent framework for homes and the grid consisting of three infrastructures: a smart grid infrastructure, an energy management infrastructure, and a 5G and optical network infrastructure.

a number of distributed microgrid solutions to achieve multiple operational goals, such as reliability improvement, cost reduction, and market participation. Barbato *et al.* [8] proposed a fully distributed demand-side management system for smart grid infrastructures to reduce the peak demand of residential users at the network edge. Celik *et al.* [3] studied the energy management coordination among multiple households. Cosovic *et al.* [5] presented distributed state estimation based on the evolution of massive machine-type communications and the concept of mobile edge computing (MEC) in smart grids.

Even though a hierarchical distributed (HD) architecture was evaluated in a multiagent system framework [9], this work did not discuss how distributed agents can obtain an adequate environment to provide local decision making at the network edge. Moreover, this architecture still faces a significant challenge: providing coordinated control and energy management for the large-scale deployment of energy management entities while supporting interoperability, controllability, and confidentiality based on growth in a number of smart homes and smart city industries. In addition, selecting the optimal architecture between the hierarchical and distributed approaches is difficult; in fact, this problem is still under study by many industries, international standards organizations, and academic institutions [9].

This article proposes an HD energy management agent (HD-EMA) framework that combines the advantages of both the hierarchical and distributed architectures, allowing massive EMA deployments while ensuring distributed energy management from the home to the grid. The experimental results validate that the HD-EMA allows coordinated control and management through cloud computing and provides distributed energy management using the concepts of MEC.

The rest of this article is organized as follows. The following section introduces the HD-EMA framework, which is based on an EMA. Next, I present some experimental results when using the HD-EMA framework. Then the emerging challenges that HD-EMA faces in smart cities are introduced. Finally, the last section summarizes the conclusions.

The Hierarchical Distributed Energy Management Agent Framework in Homes and the Grid

Hierarchical Distributed Energy Management Agent Framework Architecture

Figure 1 shows the HD-EMA framework architecture, which consists of three infrastructures. The smart home and grid infrastructures are broken down into segments that include generation, transmission, distribution, and consumption. Each segment is equipped with a large number of smart-grid measurement devices, such as supervisory control and data acquisition measurement devices (SMDs), phasor measurement units (PMUs), and massive-scale SMs. These devices acquire voltage amplitude, current phasor, active/reactive power, and quality of supply information at high sampling rates.

From an energy management infrastructure viewpoint, the EMAs are interconnected over the smart home and grid infrastructure in an HD architecture. Therefore, an EMA is capable of information acquisition and dissemination and of making decisions that concern energy consumption and generation within different levels of the hierarchy by using agent-based intelligence. At the infrastructure edge, the bottom-level client EMA (cEMA) is associated with the measurement devices or actuators to enable distributed information acquisition and autonomous appliance decision making within homes and buildings. The cEMAs are connected to the EMS via server EMAs (sEMAs). The intermediate sEMAs allocate a limited energy budget at the metro-edge level aggregation points (the metro-edge). The top-level EMS enables dynamic cooperation among different EMAs to allocate the limited energy resources and calculates customers' energy bills, allowing the data to be processed in a coordinated and controlled fashion. The EMS provides coordination control and cost optimization in the cloud to offload computation and store data from the EMAs. The DR provider accepts energy management tasks assigned from the EMS and facilitates the deployment of a number of novel energy management applications.

This HD architecture [9] allows EMAs to offload computation of novel energy management applications, store data in remote cloud servers, and facilitate autonomous decision making at the grid edge. The hierarchical architecture allows the EMS to provide an adequate environment for coordinated control and energy management for a large-scale deployment of energy management entities while supporting interoperability, controllability, and confidentiality and allowing the growth of smart homes and smart city industries. An HD architecture has become crucial for the success of smart home and grid systems because the applications require the dynamic cooperation of different appliances to allocate limited energy (or meet the constraints of a limited energy budget) and support autonomous decision making concerning energy sources under the concept of edge computing [11].

This fifth generation (5G) and optical network infrastructure will provide a hierarchical service network with distributed information processing that is ideally suited for energy management services [5]. The network interconnects EMS, the DR service providers, the open data portal, and the energy market requiring low latency and massive machine-type communication through network slices. A network slice is implemented with network functions virtualization (NFVs) and its corresponding network resources for energy management services. NFV allows massive machine-type communication using New Radio base stations (gNBs) that enable ultra-reliable and low-latency communications (URLLC). Distributed MEC allows localized communication, storage, processing, and management among EMAs in an HD architecture.

Hierarchical Distributed Information Acquisition and Dissemination

The top-level EMS collects required energy data (e.g., metering, renewable energy, energy storage, consumer, and control information) from the EMAs in a hierarchical way while considering data security and privacy concerns. The EMS consolidates the aggregated information, including DR capacity and market bid metrics, to achieve maximum energy savings based on all the energy resources. While collecting data readings more frequently could allow the EMS to provide more accurate control and help prevent missed power outages, a centralized EMS will cause data congestion, serious latency, or even overflow losses. These effects can significantly impair energy management services.

To solve this problem, the HD architecture introduced in this article allows the EMAs to refine their local metering and event data into a smaller volume by abstracting the valuable and manageable data. Different from the hierarchical architecture described earlier, in this architecture, the EMS also disseminates the summary data back to the EMAs. These summary data are used for local decision making such as metering data analyses, energy cost calculations, DR operations, and energy provisioning, and for reacting to various abnormal situations with agent-based intelligence. Notably, the HD architecture includes bidirectional information exchange between layers.

This HD information acquisition and dissemination allows each EMA to communicate with only its predecessor and successor in the hierarchy and avoids flooding the network. The hierarchical approach supports a high level of scalability for a large number of heterogeneous energy management entities, including homes, buildings, and utilities. Moreover, HD information acquisition and dissemination also achieves information confidentiality because the EMS and the EMAs can collect and maintain abstracted state information in a hierarchical way while still preserving confidential information. Thus, the proposed framework improves scalability while preserving confidential information.

Hierarchical Distributed State Estimation and Decision Making

An energy management service includes a wide range of reactive or preventative actions and incorporates HES appliances, DERs, and utility with a full range of energy management programs from home to grid. The utility wants to encourage consumers to use less energy during peak hours or to shift their energy using activities to off-peak hours, such as nights and weekends. Moreover, the utility also encourages consumers to detect and counteract power grid disturbances in real time when the DERs augment the power load of the grid.

To support these requirements, the HD architecture facilitates the construction of energy management services based on EMAs as well as the EMS. In the hierarchical architecture, the top-level EMS improves operational efficiency by providing cooperative control for power consumption and power generation. For that purpose, the DR service providers automatically send DR signals to the EMAs to shed load depending on system conditions. The EMAs can reduce electricity use by flattening or shifting demand to help with the integration of various renewable energy sources, and they can use energy storage units to store energy during off-peak hours or to discharge stored energy during peak hours at the customer side. This type of data analysis, which discerns energy usage patterns and uses collected data to predict demands, has arisen in cloud computing and is associated with deep learning, a technique that is ideally suited to scalable services as a way to maintain the power balance across multiple smart homes and grids.

In contrast to a hierarchical architecture, an HD architecture features refined local state estimates and autonomous decision making. Local state estimation is desirable because it can support cost optimization, quality assurance, mission-critical supervisory control, and data acquisition to

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prevent power instabilities and blackouts in smart homes and grids. Autonomous decision making is desirable for making energy-related decisions regarding stringent requirements in terms of data rates, latency, and reliability for smart city industries. Thus, local state estimates and autonomous decision making are dramatically decreasing service response latency, reducing the traffic load on the centralized EMS, and improving context awareness in EMAs through the concept of edge computing [11].

Furthermore, unlike the distributed architecture, an HD architecture allows EMAs to not only accept management tasks assigned by the EMS but also make local decisions autonomously for energy provisioning. Local decisions involve very precise demand tuning by adopting agent-based intelligence at the grid edge. Agent-based intelligence in conjunction with aggregated loads and historical data ensures that EMAs can allocate the limited available energy among houses and schedule electricity consumption by HES appliances while simultaneously exchanging surplus power among houses. The EMAs autonomously match the supply at all times in such a way that customers minimize electricity costs, thereby reducing the peak-to-average power ratio of the load demand for the utility [12].

The HD architecture reduces the utility processing burden by leveraging the local EMAs' autonomous decision making abilities. Moreover, this architecture is capable of not only overcoming the challenge of a centralized EMS but also improving robustness against failures. Therefore, the HD-EMA will eventually lead consumers to more efficient energy consumption and a power infrastructure that is sustainable without blackouts. This architecture meets the needs of today's smart grid interaction models (e.g., DR, feed-in tariffs, renewable energy) as well as those of tomorrow (e.g., smart appliances and retail energy market transactions) to support the growth of emerging smart cities.

Other Key Technologies of the Hierarchical Distributed Energy Management Agent Framework

With the deployment of open data portals, AMI, and energy markets, the framework can further adjust customers' electricity costs by shifting demand from peak time to off-peak times or trading of surplus or limited energy (or adapt to a limited energy budget) among houses [2]. From open data portals, the framework retrieves information concerning the weather, temperature, and ambient patterns, and uses this and other information to predict consumers' electricity usage levels, which can vary dramatically even over short timeframes. The framework obtains the current market prices from the energy market in response to power reductions, allowing it to obtain maximum profit [3]. From the PMUs, SMDs, and SMs, the framework supports accurate measurements of time-based information and frequent collection of energy consumption data. Based on these data, the framework attempts to satisfy the electricity demand without compromising user comfort and to provide electricity and end-user benefits by reducing demands below the level of power generation.

Compromising the distributed framework could lead to disruptive cyberattacks on distributed applications, resulting in economic loss, loss of power flow, and even loss of cooperative control [7]. The HD solution not only delivers system-level reliability through the supervisory detection technique but also provides resilient control by embedding the security mechanism into the distributed EMAs as an alternative to classical centralized schemes.

Experimental Results

An Experimental Testbed

Figure 2 shows an HD-EMA testbed. Figure 2a shows a screenshot of the testbed on the EMS; Fig. 2b shows the corresponding snapshot of the deployed testbed; and Fig. 2c depicts a protocol architecture with recommended protocols, but other protocols are also applicable. The testbed consists of one EMS (i.e., DR service provider), two sEMAs (i.e., aggregators), 20 cEMAs (i.e., 10 cEMAs per sEMA), and 100 appliances (i.e., 5 appliances per cEMA). The EMS is implemented with an Open Automated Demand Response (OpenADR) virtual top node (VTN) server running on Ubuntu 16.04 and equipped with an Intel Xeon E5-2620. The sEMAs are implemented as an OpenADR virtual end node (VEN) client running on Ubuntu 16.04 and equipped with an Intel Core i-7-7600. The cEMAs are implemented with a lightweight OpenADR client running on openWRT 15.05. Finally, the appliances are implemented with a control and automation protocol running on a Raspberry Pi 3 based on Linux Mate.

The vertical architecture in Fig. 2c shows the top-down protocol layering based on the DR application profile, application layer protocol, transport/network layer protocols, and link layer protocols to support energy management applications in a home-to-grid or building-to-grid environment. These layered models foster interoperability among products from competing or complementary manufacturers.

The horizontal architecture in Fig. 2c shows the protocol interactions, where the application profile supports the DR service between the EMS and appliances. The OpenADR protocol is a standard protocol between EMS and sEMA to provide automated DR. It is implemented based on OpenADR2.0b and uses HTTP/XML. The EMA Protocol (EMAP) is a relay protocol between an sEMA and cEMAs. It is a lightweight version of the OpenADR protocol based on the Constrained Application Protocol (CoAP) and JavaScript Object Notation (JSON). The automation and control protocol between a cEMA and appliances is implemented based on the Message Queue Telemetry Transport (MQTT) protocol with EMAP.

Test Procedures and Results

This section describes some experimental results of information dissemination, DR provisioning, and event processing procedures using the testbed. Figure 3a shows the message flows of the DR provisioning procedure. The message flows depict the push-based provisioning procedure and relay functions for DR service from the grid to the home. As shown in Fig. 3a, the top-level EMS generates a DR provisioning request to the sEMAs

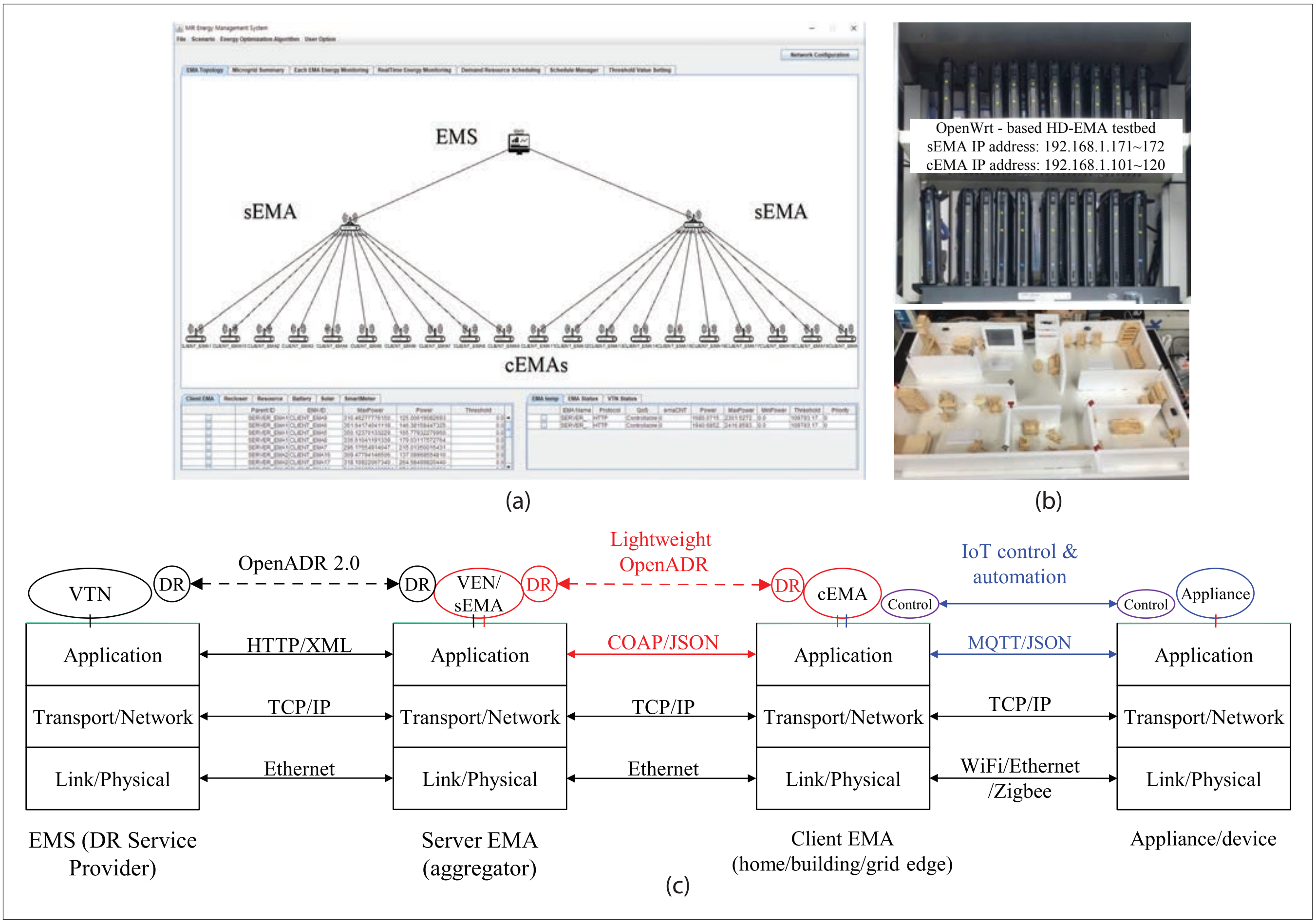

Figure 2. Experimental testbed and results: a) a screen shot of the EMS; b) a corresponding snapshot of the deployed EMAs and appliances; c) a protocol architecture.

using a long polling technique. The sEMAs receive these DR provisioning requests from the EMS and deliver them to the cEMAs through CoAP messages. When a cEMA receives a DR provisioning request, it executes its own energy scheduling algorithm and sends control signals directly to the appliances to reduce power consumption below the threshold. The DR provisioning profile is crucial for the success of a smart home/smart grid system because it enables different appliances to dynamically cooperate under limited energy allocations (or to adapt to a limited energy budget) or energy source switching.

The implementation of the DR provisioning profile demonstrates the coordinated control of different EMAs at different levels of the hierarchy, where multiple energy management entities cooperatively work well to control appliances. These interactions enable the dynamic cooperation of different EMAs to allocate limited energy and collect metering data to calculate the energy bills and customer statuses in the hierarchical architecture. The intermediate sEMAs relay limited energy budget information at the aggregation point of the metro-edge level. The bottom-level cEMAs enable distributed information acquisition and autonomous appliance decision making or energy source switches in a unified way. A full evaluation of the resource availability of the provisioning procedure remains as future work.

Figure 3b shows the message flows of the event processing services and offloading mechanisms of the services from the home to the grid. Three use case scenarios for distributed event handling and autonomous decision making are considered based on the different hierarchy levels. The first is autonomous decision making with the cEMA as an edge computing device. The second is HD coordinated control at the aggregation point of the metro edge level. The third use case is HD coordinated control in the cloud. These results experimentally validate the effectiveness of the framework, where the client EMA enables autonomous decision making by agent-based intelligence to make cost optimizations and provide quality assurance. The event handling and autonomous decision making aspects of the framework are crucial for the success of any smart home/smart grid system because its underlying control paradigm requires very low latency (i.e., on the order of 50 ms) and high carrier-grade reliability (i.e., 99.999 percent availability).

Figure 4a shows the traffic burden on the EMS and sEMAs over 60 s as the number of EMAs increases from 20 to 180 in the centralized architecture (CA) and the HD-EMA architecture. In the experimental scenario, each cEMA periodically sends EiReport/Response messages every 9 s. I performed 30 experiments for 60 s each. The results are shown as averages with a 95 percent confidence interval. The results validate that the

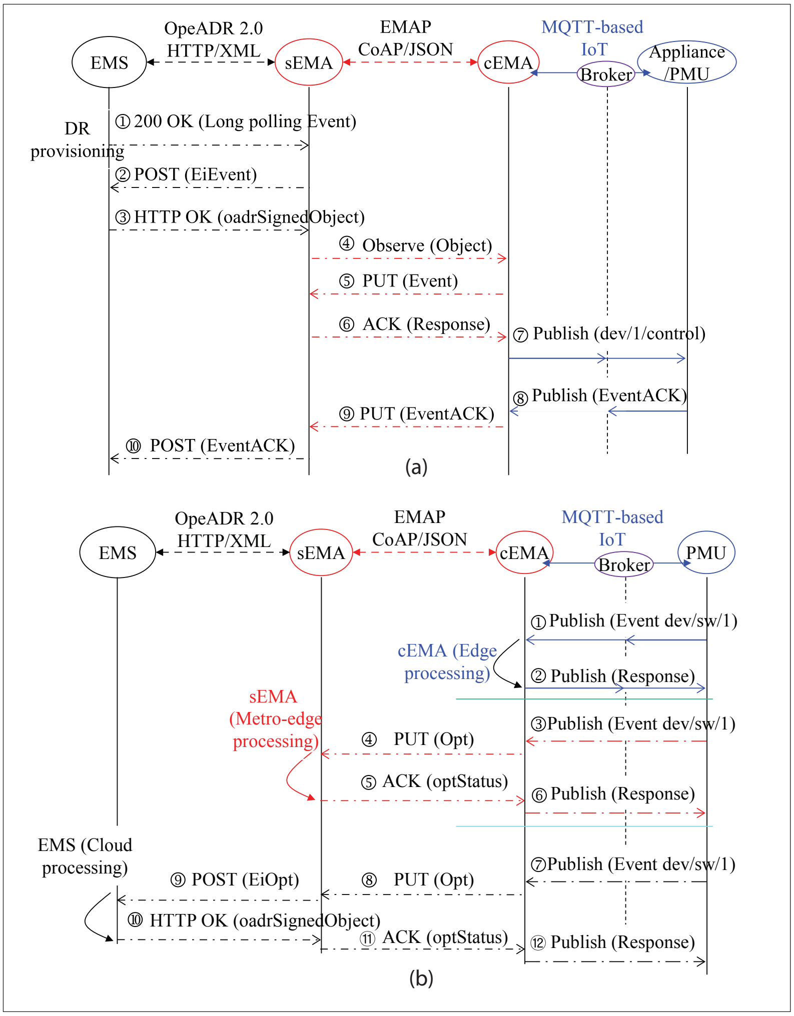

Figure 3. Experimental procedures: a) push-based DR provisioning; b) event processing.

proposed approach reduces the traffic to the EMS because the EMAs disseminate information only between adjacent layers, which avoids flooding the network. Moreover, the proposed approach reduces the burden by distributing it evenly among all the EMAs while performing abstraction. This distributed load balancing effect helps to improve the performance as the number of EMAs increases. Although the summary data are still sent to the EMAs, the traffic overhead is marginal compared to that of the hierarchical architecture (HA). Consequently, HD information dissemination improves scalability but significantly reduces management costs and complexity.

Figure 4b shows the delay performance as a function of the number of events with different offloading mechanisms. This figure shows the event processing delay as the event arrival rate increases from 10 to 1500 Erlangs. For the convenience of the analysis, the event processing time is assumed to be 1 hour on average. The event processing delay is observed to be higher in the cloud than in the edge. For example, under 20 Erlangs, the EMS and sEMA processing delays are below 69.99 ms and 26.81 ms, respectively. However, when the event load increases above 150 Erlangs, the EMS processing delay is severely affected, and its delay performance degrades. A similar trend can be seen in the case of an sEMA processing delay of approximately 1000 Erlangs. When edge processing is applied to a cEMA, the event processing delay remains below 53 ms even when the event load increases to 2500 Erlangs.

The delay performance is affected not only by the processing delay but also by the propagation delay. Because the propagation delay is determined by the geographical distance, the processing delay will be dominant as the number of cEMAs increases. Importantly, Fig. 4b provides insight that many delay-sensitive and mission-critical applications requiring low latency and massive machine-type communications can be offloaded onto the EMA rather than onto the conventional EMS. In contrast, it is often better to offload delay-tolerant applications on the EMS when the application requires dynamic cooperation among different appliances.

Emerging Challenges and Opportunities in Smart Cities

In recent years, significant advances have been made in emerging technologies, including smart appliances, artificial intelligence (AI), big data, the Internet of Things (IoT), and NFV [5, 12, 13]. Imbuing appliances with intelligence could automate the decision making and control of smart appliances in response to forecasted energy prices and customers' preference (utility vs. customer). Energy big data provide new opportunities in data governance strategies and service organizations. IoT allows accurate electricity consumption patterns to be detected. NFV offers opportunities for service-oriented frameworks for distributed monitoring and control tasks in a virtualized computing environment.

The HD-EMA framework supports interoperability among EMAs across disparate networks for energy management as part of the smart grid infrastructure. The framework accommodates the progressive deployment of these emerging challenges and can accelerate market acceptance. The framework can be extended to homes and buildings at neighborhood or larger scales through different service providers, fostering cooperative home security management, better surveillance, healthcare, transportation, and environmental monitoring [14, 15]. These extensions may also integrate information about gas and water consumption along with electricity consumption in a seamless manner and create multiple business opportunities in the context of smart cities. At large scales, the HD-EMA approach to energy management (e.g., supply and demand) provides opportunities in which new applications can easily be combined with previously existing capabilities to achieve the vision of the smart city.

Conclusions

This article presents an energy management framework focusing on the HD architecture for a massive deployment of EMAs. Through experiments using an experimental implementation, the effectiveness of the proposed HD-EMA architecture was demonstrated. The studied advantages are as follows. The HD architecture provides cooperative information acquisition and dissem-

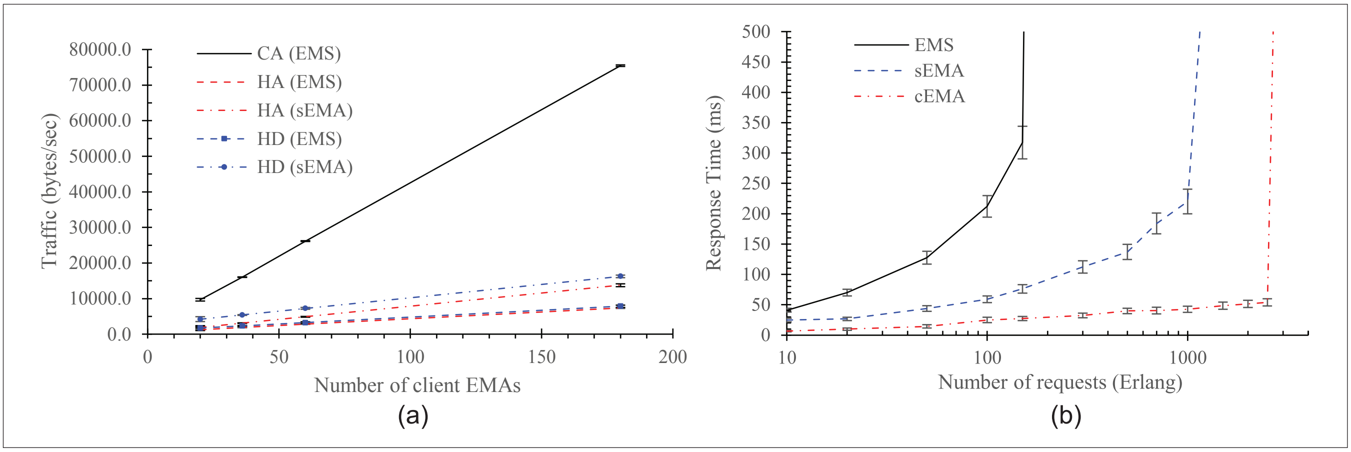

Figure 4. Experimental results: a) a traffic comparison of a centralized framework vs. a hierarchical distributed framework; b) event processing delay with different offloading mechanisms.

ination across a large number of heterogeneous energy management entities, including homes, buildings, and utilities, through cloud computing. The HD architecture also provides autonomous decision making through agent-based intelligence associated with edge computing. Therefore, the HD architecture is capable of overcoming scalability challenges for information acquisition and dissemination, improving the confidentiality and robustness of the centralized EMS, leveraging the distributed EMAs to allow autonomous decision making, and reducing the processing latency to prevent power instabilities and blackouts.

The proposed framework provides not only interfaces and protocols but also a service infrastructure that supports third parties interested in developing energy management applications. The framework can be further improved as the emerging technologies of AI and big data improve, and 5G and IoT communication infrastructures associated with edge computing, cloud computing, and security become ubiquitous. Moreover, the proposed framework is also applicable to other domains in smart cities, such as water/gas management, surveillance management, sustainability management, and survivability management, at large scales. Although these application models and interfaces may not be fully realized in the HD-EMA, such extensions are attractive and deserve further investigation in future work as aspects of the smart city concept. In addition, an optimal design and performance analysis of the framework can be investigated in future work.

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Biographies

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