DISTRIBUTED ACCESS CONTROL FRAMEWORK FOR IPv6-BASED HIERARCHICAL INTERNET OF THINGS

YUN LI, KOK KEONG CHAI, YUE CHEN, AND JONATHAN LOO

ABSTRACT

IPv6 is considered as the most promising approach to enable the interoperability of the future Internet of Things due to its ability to provide sufficient public addresses. At the same time, hierarchical machine-to-machine communications have been identified as the key driver to integrate various IoT applications. This article focuses on wrapping up these technologies to provide seamless and interoperable IoT communications. We first introduce the background and standard supports for IPv6-based hierarchical M2M communications. Then the challenges and existing solutions are investigated for the massive access of IPv6-based hierarchical M2M networks with heterogeneous IoT applications. To this end, a systematic distributed access control framework is proposed with the aim of improving the overall network performance, achieving fairness, and dealing with dynamic network conditions. In addition, the optimal control and potential algorithms for the proposed control framework are developed. The performance evaluation shows significant performance gains in terms of utility maximization, network fairness, and application differentiation.

INTRODUCTION

A machine-to-machine (M2M) network is a communication network with massive interconnected devices. M2M networks have been identified as one of the key drivers to enable the integration of the heterogeneous Internet of Things (IoT) applications and services, such as smart cities, health care, transport systems, public safety, and industrial and agricultural automation [1]. Besides the heterogeneous IoT applications integrated in M2M networks, it has been expected that by 2020, the number of connected M2M devices will be more than 50 million, and M2M traffic flows will constitute up to 45 percentage of all Internet traffic [2]. Therefore, providing sufficient device address spacing, managing massive access of devices, and satisfying heterogeneous application requirements become critical to enable seamlessness and interoperability for IoT communications.

IPv6 is emerging as the de facto solution to scale up the massive devices due to its ability to provide wide spacing of globally reachable unique addresses [3, 4]. The European Telecommunication Standards Institute (ETSI) M2M Technical Committee has proposed a hierarchical architecture to offer heterogeneous services and seamless devices access for various M2M applications [5]. Recently, a large number of academic projects, such as IoT-A, IoT6, and Expanding LTE for Devices (EXALTED), have proposed similar IPv6-based hierarchical M2M communication solutions. In addition, some industry projects led by Cisco, Alcatel-Lucent, AnyBridge, and others have also taken place to perform initial exploration of the hierarchical architecture with commercialized products and solutions [1].

The main advantages of the IPv6-based hierarchical M2M communication approach are:

- It is able to provide wide spacing of globally reachable unique addresses.
- The stateless auto-configuration of IPv6 allows devices to automatically acquire IP addresses without human intervention or the need for Dynamic Host Configuration Protocol (DHCP) servers.
- Direct cellular connection is not required by its low-cost and low-energy-consumption M2M devices.
- It is able to aggregate, offload, and shape M2M traffic to cellular networks or the Internet.

Our concentration is on effective access management of massive energy constrained devices for IPv6-based hierarchical M2M networks with heterogeneous IoT applications. We first introduce the existing challenges, current research foci, and standardization efforts on enabling IPv6-based IoT communications. Then the massive access problem of energy constrained devices with heterogeneous IoT applications is investigated for IPv6-based hierarchical M2M networks. To this end, we propose a systematic distributed control framework with the aim of improving the overall network performance, achieving fairness, and dealing with dynamic network conditions.

IPv6-BASED HIERARCHICAL M2M NETWORKS

The wireless communications standard stack for IoT has been under discussion for decades. Since 2003, different standard organizations, including

Yun Li is with the Information Science Academy of China Electronics Technology Group Corporation.

Kok Keong Chai and Yue Chen are with Queen Mary University of London.

Jonathan Loo is with Middlesex University.

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The wireless communications standard stack for IoT has been under discussion for decades. Since 2003, different standard organizations, including the IETF, the IEEE, and the ETSI have been making efforts to enable the seamless and reliable IPv6-based IoT communications.

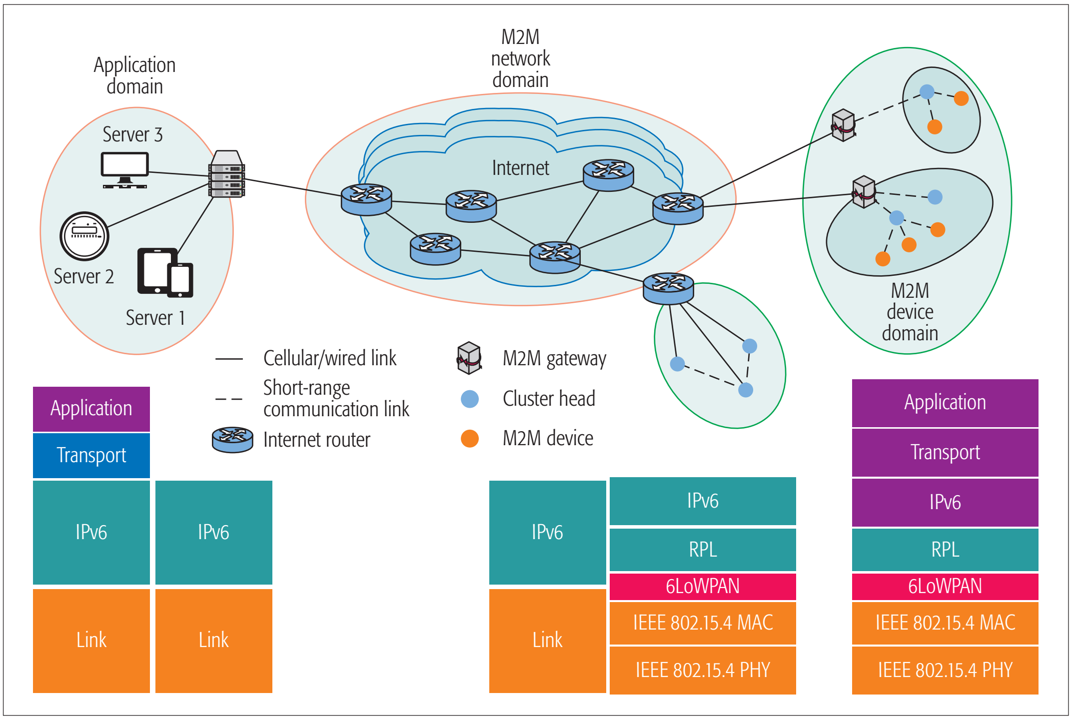

Figure 1. IPv6 based Hierarchical M2M networks.

the Internet Engineering Task Force (IETF), IEEE, and ETSI, have been making efforts to enable seamless and reliable IPv6-based IoT communications.

To address the IPv6 integration problem, the IETF 6LoWPAN and RoLL RPL Working Groups have made some efforts to enable seamless and reliable IPv6 datagram exchange over IEEE 802.15.4 for low-power and lossy networks (LLNs). The IETF 6LoWPAN introduces the adaptation layer between the IPv6 layer and IEEE 802.15.4 medium access control (MAC) layer to enable IPv6 packet transmission over the IEEE 802.15.4 MAC layer. 6LoWPAN specifies the mechanisms of stateless header compression, IPv6 address compression, node discovery using compressed IPv6 addresses, and so on. The IETF RoLL Working Group developed the RPL standard to quickly build up network routes, distribute routing knowledge among nodes, and adapt the topology for IPv6-based LLNs.

The benefits of implementing IEEE 802.15.4 are:

- It provides ultra low complexity, ultra low cost, and ultra low power consumption.
- It provides a duty-cycle-based power management mechanism.
- It supports an optional retransmission scheme based on acknowledgments, which contributes to the reliable transmission.
- It is compatible with ready-to-use standards such as 6LowPAN and RoLL RPL.
- It is supported by well commercialized M2M devices and various applications.

Figure 1 shows an IPv6-based M2M network based on the ETSI M2M Technical Committee proposed hierarchical architecture. The network consists of an IPv6-based application domain (AD), an M2M network domain (ND), and an M2M device domain (DD). The AD manages the various IoT applications that run the service logic and deliver the services to end users. The M2M ND is the access and transport network that provides the interconnection of an M2M device or gateway to application servers. In the M2M DD, also referred to as capillary networks, M2M devices are connected via short-range network access technologies, such as IEEE 802.15.4 and IEEE 802.11x [6].

According to [6], the applications in AD can be categorized into four classes:

1. Elastic applications: These applications are rather tolerant of delays (e.g., environment monitoring).
2. Hard real-time applications: These applications need their data to be served within a given delay constraint. Vehicle and asset tracking are typical applications of this class.
3. Delay adaptive applications: These applications are delay-sensitive but can be made rather tolerant of occasional delay bound violation and dropped packets. An example is remote monitoring in e-Health services.
4. Rate adaptive applications: These applications adjust their transmission rates according to available radio resources while maintaing moderate delays. Video transmission is one example application.

The M2M ND is mainly composed of the core network (CN) and the access network (AN). The CN provides IP connectivity, interconnection with other networks, roaming with other CNs, and service and network control functions. The AN represents the link, such as radio access networks, to allow an M2M device or an M2M gateway to access CN services.

With the aid of gateways in M2M DD, each M2M device attaches to the existing cellular infrastructure or Internet by which higher-layer connections to the application server are provided. M2M DD consists of the following devices:

M2M gateways: provide the interconnection between the CN and the capillary networks. It provides protocol translation, resource management, device management, and data aggregation, and acts as an M2M local service provider in the capillary network.

M2M devices: support one or more M2M applications. They are categorized into two classes:

1. Devices have LTE-A interface and can connect to the ND directly.
2. Devices do not have LTE-A interface and connect to the ND through an M2M gateway and run M2M applications locally.

Cluster heads (CHs): are part of capillary networks. The communication from a regular M2M device may be directed through and managed by a CH. The functionalities of CHs may include data aggregation, device management, and so on. CHs will not perform protocol translation.

CHALLENGES OF IPV6-BASED HIERARCHICAL M2M NETWORKS

Subsequent challenges lie in the access management of capillary M2M networks [7], as it offers the traffic aggregation and protocol translation services for the network. These challenges include the following.

Capacity limited devices: Most of the devices involved in M2M networks have limited capacities in terms of computation and memory. Thus, the access control for M2M communications need to be designed with low computation and storage complexities.

IPv6 Integration: The integration of IPv6 on top of a low-power wireless technique is not straightforward due to the protocol differences in terms of packet size, address assignment, transmission rate, power saving mechanism, and so on.

Massive access: Concurrent and massive access of devices can cause efficiency and performance degradation, such as energy waste, intolerable delay, packet loss, and unfairness.

Heterogeneous applications: Due to the diverse IoT applications, how to effectively multiplex the massive access with enormously diverse application requirements turns out to be another challenging task.

Energy efficiency: Energy efficiency (EE) is one of the most important resource allocation objectives due to the fact that most M2M devices are power constrained. EE is also highly related to the operational costs and profit margins of network operators.

Network throughput: Maximizing the network throughput is another big challenge, due to the massive devices, limited spectrum resources, duty-cycled operation, and low data rate of low-power wireless radios.

Flexibility: Flexible adaptation is required in practical scenarios where channel conditions and traffic change over time. In addition, less control information exchange will also increase the transmission efficiency.

Feasibility: In practice, it is hard or impossible for devices to have reliable statistical network information such as traffic or instant channel conditions. Thus, access control needs to work effectively with little or no a priori network information.

Recently, the IP Smart Object Alliance (IPSO) actively promotes IPv6-embedded devices for M2M applications; also, there is some research focusing on the implementation of the IPv6 protocol stack on system platforms, such as TinyOS and Contiki [8]

On the other hand, some works have been especially designed for hierarchical M2M networks. A data compression strategy is proposed in [9] to reduce traffic congestion in cellular networks. A topology control is proposed in [10] to take hierarchical advantage of the network for M2M networks with two different types of devices. A novel MAC back-off time decision rule is proposed in [11] that fits hierarchical M2M networks. The theoretical success probability for channel access is derived and compared by simulations. In [12], a scalable hybrid MAC protocol is designed to maximize the channel utility for M2M networks.

Besides the aforementioned efforts to enable IPv6 or hierarchical M2M communications, a systematic framework to optimize the overall network performance for IPv6-based hierarchical M2M communication with heterogeneous applications is still lacking.

DISTRIBUTED ACCESS CONTROL FRAMEWORK

Based on the nature of the ETSI proposed architecture, we propose a cluster-based control framework for IPv6-based hierarchical M2M networks with heterogeneous applications. Implementing novel access controls at M2M gateways and cluster heads in capillary networks will ensure overall network performance in terms of throughput, delay, and EE, as they manage massive access of M2M devices. Compared to centralized access control, distributed access control has the advantages of supporting future network virtualization by integrating software defined networking (SDN) and network functions virtualization (NFV) technologies.

Taking advantage of well defined standby standards and commercialized devices, the proposed distributed access control framework is designed for M2M networks, the PHY and MAC of which are based on IEEE 802.15.4, the network layer on IETF 6LoWPAN and RoLL, and the transport layer on TCP/IP.

CONTROL PROCESS

The control of hierarchical M2M networks are modeled as a Markov decision process (MDP) that takes various network dynamics into consideration. Then a distributed optimal control framework is proposed, as shown in Fig. 2.

Gateway control: The gateway control is implemented at each gateway to schedule the traffic from its child cluster heads. The aim of the gateway control is to maximize the aggregated network utility with consideration of different cluster applications, fairness, and the bid price offered by each cluster head.

Cluster head control: The cluster head control is distributed and implemented at each clus-

Implementing novel access controls at M2M gateways and cluster heads in capillary networks will ensure the overall network performance in terms of throughput, delay and energy efficiency, as they manage the massive access of M2M devices.

Due to the diversity of applications in M2M networks, the utility of the network is more informative than the simple QoS indicator. Thus the optimal solution of the proposed control framework can be achieved distributively by solving the designed utility optimization problem of each control, separately.

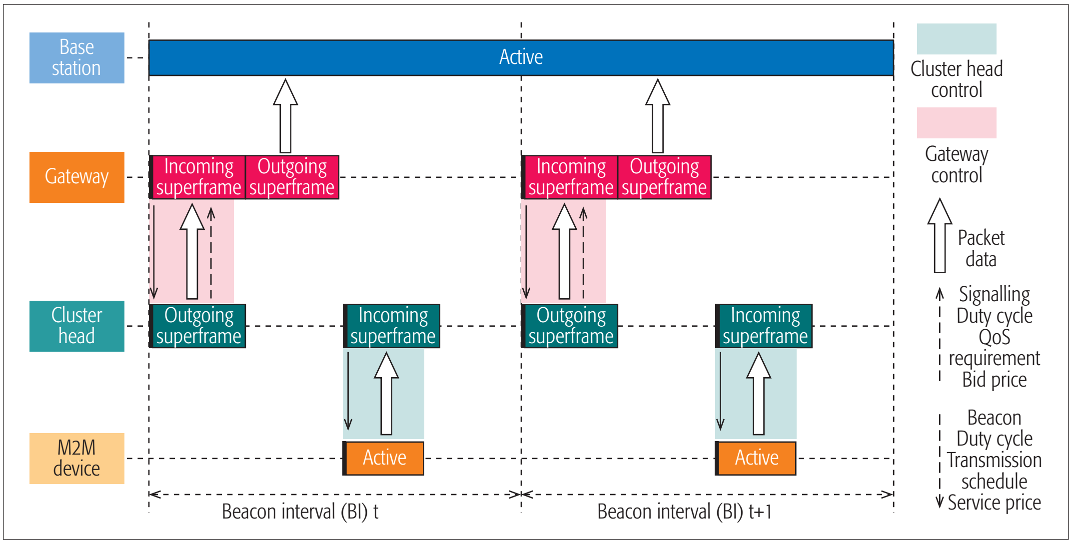

Figure 2. Transmission process.

ter head to decide its local transmission schedule and duty cycle setting, and operate the bid price offer to the gateway. The cluster head control aims at maximizing the single cluster utility taking both empirical networks performance and cluster economic benefits into consideration.

Duty cycle control: Cluster heads and M2M gateways decide their own duty cycle based on local traffic conditions. The duty cycle control aims at balancing the tradeoffs between energy efficiency and utility. The duty cycle control decision is delivered to the child devices via beacon transmission.

Beacon transmission: For beacon-enabled IEEE 802.15.4, a device needs to listen to the beacon from its parent to synchronize the superframe structure. The control decisions will provide duty cycle, transmission schedule and service charge for each child device. The control information exchange is inclosed in current IEEE 802.15.4 beacon frame, no extra control overhead is introduced.

Signaling transmission: At the end of the packet transmission duration between a cluster head and its parent gateway, the cluster head will send a signaling to its parent gateway. The information included is its current duty cycle, the application requirements, and the bid price for next time period.

It is worth mentioning that TCP provides traffic control and congestion control through automatic repeat request (ARQ) techniques to ensure end-to-end reliability over IP-based networks. However, to do so, the amount of transmitted packets and end-to-end packet confirmation will directly lead to expensive energy consumption. To reduce the control information exchange, we utilize the go-back-*N* ARQ scheme at the MAC layer by enabling the optional acknowledgment in the proposed control framework.

OPTIMAL CONTROLS

The utility function is a mathematical measurement to reflect the identified network performance. Due to the diversity of applications in M2M networks, the utility of the network is more informative than the simple quality of service (QoS) indicator [6]. Thus, the optimal solution of the proposed control framework can be achieved distributively by solving the designed utility optimization problem of each control separately.

Gateway Control: The gateway control is based on the network aggregated utility maximization problem[13].

The aggregated utilities $\Sigma_{i\in\mathcal{I}_n}\mathcal{U}_{n,i}$ at the gateway depends on the application class of its child cluster heads i, where $\mathcal{I}_n$ is the set of child cluster heads of gateway n. The widely used utility function design approach uses a logarithmic function for the elastic source (elastic applications) and a sigmoid function for the inelastic source (hard-real-time applications, delay-adaptive applications, and rate-adaptive applications) [6, 14]. One illustration of the utility function $\mathcal{U}_{n,i}$ of each application class is shown in Fig. 3.

The general network utility optimization problem over T time periods at gateways is formulated as $\mathcal{P}1$,

$$\begin{aligned} &\mathcal{P}1:\max\& \sum_{t=0}^{T}\sum_{i\in\mathcal{I}_n}\mathcal{U}_{n,i}(f_i^t) \\ &s.t.\quad (a)\quad \sum_{i\in\mathcal{I}_n} f_i^t \le C_n^t, \\ &\qquad\quad (b)\quad 0\le f_i^t \le C_{i,n}^t. \end{aligned} \tag{1}$$

where f_i^t is the number of packets the child cluster head i sent to the gateway, $C_{i,n}^t$ is the link capacity between cluster head i and gateway n, and C_n^t is the link capacity of gateway n to the cellular base station.

One possible control algorithm for the gateway control is the classic utility proportional fairness (UPF) algorithm, which is able to maximize throughput and achieve proportional fairness among clusters running the same class applications. The P-UPF algorithm proposed in [13] addressed the mixed applications network scenarios while addressing the trade-off between utility maximization and utility fairness. Based on P-UPF, the mixed integer programming (MIP) control is proposed to ensure the adjacent allocation of resource slots, as the IEEE 802.15.4 utilizes the slotted CSMA/CA during the active periods to avoid the frequent wake up and sleep problem.

Cluster Head Control: The cluster head control is based on the single cluster utility optimization problem [1].

The single cluster utility contains both an empirical network performance component and an economical component. The empirical network performance take throughput, energy efficiency, end-to-end delay, and packet drop ratio into consideration. And the economical component is the economical return on revenue of a cluster head, which includes charges of receiving packets and costs for forwarding packets. As an example, for each cluster head i, a *quasi-linear* form utility optimization problem is formulated as

$$\mathcal{P}2: \max \sum_{t=0}^{T} \sum_{i \in \mathcal{I}_n} \left\{ \log\left(1 + V_i^t(r_i^t)\right) + R_i^t(r_i^t) \right\}$$

$$s.t. \qquad r_i^t \le \min(C_i^t, q_i^{\max}),$$

where r_i^t is the number of packets cluster head i received from its child M2M devices, V_i^t is the empirical network performance component, and R_i^t is the economical component. The C_i^t and $q_i^{\max}$ are the link capacity and maximum buffer size of device i, respectively. The quasi-linear form is chosen because any equilibrium solution to the utility maximization problem is independent of the initial economical setting of each cluster head.

The possible control algorithms for cluster heads include a dynamic programming (DP) algorithm, which is able to provide the optimal control. Complexity-reduced approximate dynamic programming algorithms, such as a rollout algorithm, are chosen for devices with limited computational capacity. In addition, a reinforcement learning algorithm such as Q-learning is applied for scenarios where the cluster heads have no a priori network information and need to gradually learn the optimal control by interacting with the networks.

Duty Cycle Control: In the end, the duty cycle control is derived based on the amount of traffic the device needs to transmit at each active period r_i^t. More specifically, r_i^t could be the optimal solution of cluster head control and gateway control. According to the duty cycle definition in the IEEE 802.15.4 standard, the duty cycle control is expressed as

$$\text{Duty cycle} = \frac{\text{Superframe Duration (SD)}}{\text{Beacon Interval (BI)}} = \frac{D_{packet} + D_{bcn}}{aBaseSuperframeDuration \times 2^{BO}},$$

where D_{packet} is the total packet transmission duration for r_i^t packets, D_{bcn} is the beacon transmission duration, BO stands for the MAC attribute *macBeaconOrder*, and *aBaseSuperframeDuration* = 15.36 ms as defined in the standard.

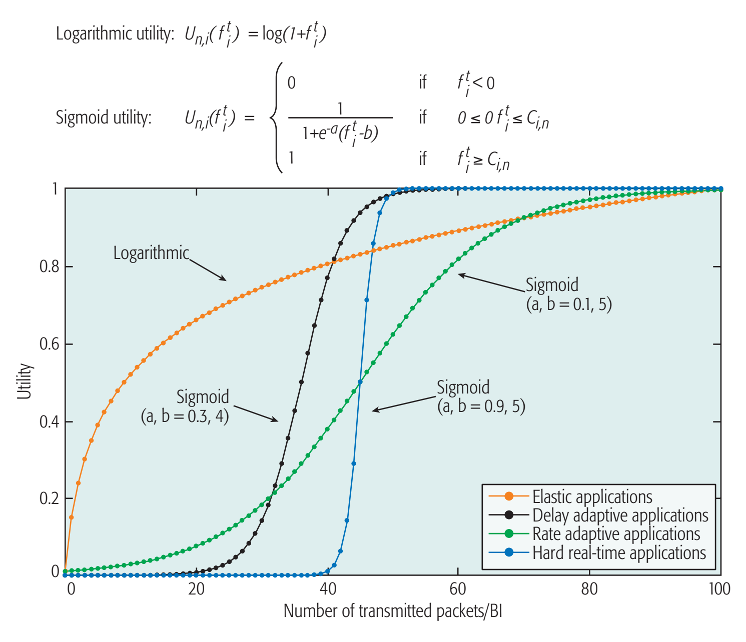

Figure 3. Utility function illustration for different applications.

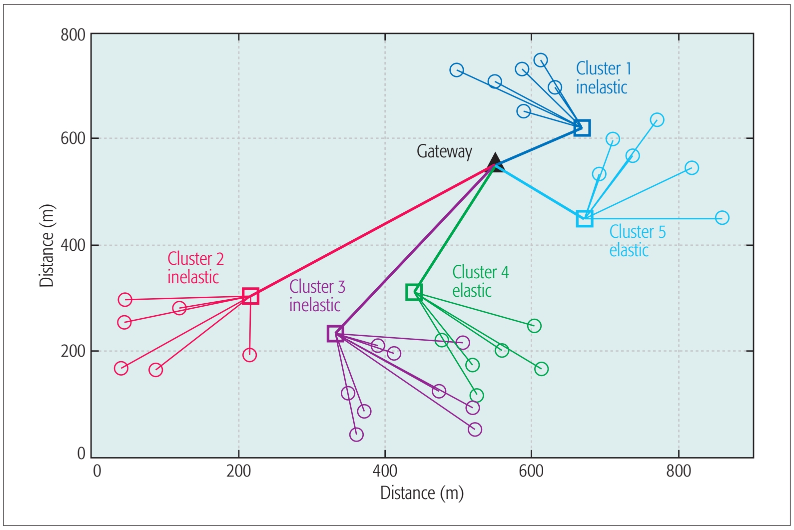

Figure 4. Simulated network. The M2M gateway, cluster heads, and M2M devices are presented by triangle, squares, and circles, respectively.

NETWORK PERFORMANCE

In this section, we show the evaluation of the proposed control framework for a two hop hierarchical M2M capillary network. Each cluster head is connected with M2M devices and clusters may run different applications.

Similar to [13], we adopt the empirical dual-slope propagation model of path loss with distance, Nakagami frequency-flat small-scale fading, and lognormal shadowing. The device energy consumption parameters are based on the XBee/RF data sheet. XBee 802.15.4 is used for M2M devices, and XBee-PRO 802.15.4 is used for cluster heads in the capillary networks. For the purpose of illustration, the device parameters and simulation results of one realization of the hierarchical M2M capillary network are shown in Fig. 4.

The simulated network consists of one M2M

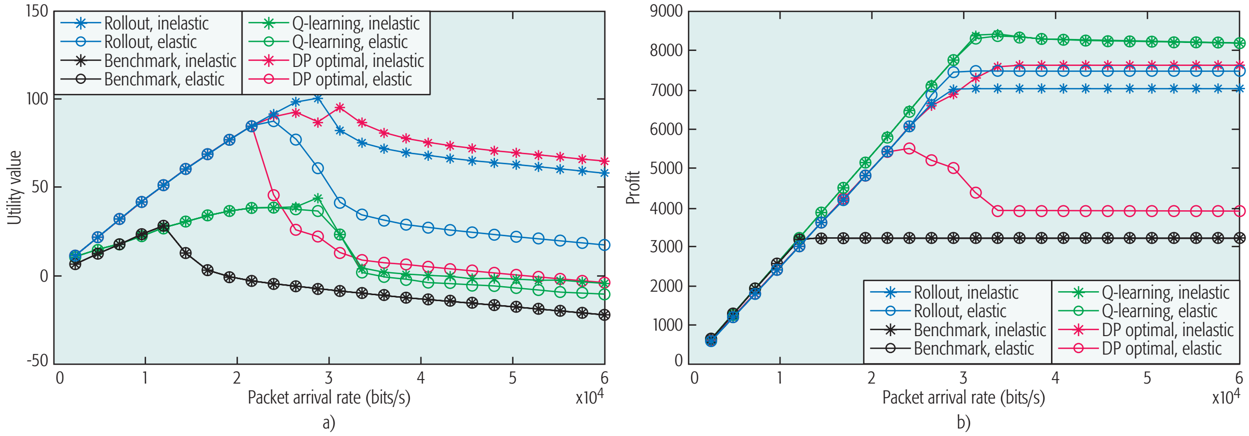

Figure 5. Network performance of cluster head controls: a) cluster utility; b) cluster return on revenue

gateway and five clusters, where clusters 1 and 2 run an inelastic application (rate adaptive application) with low cluster traffic load (0–120 kb/s), cluster 3 runs the same rate adaptive application with higher cluster traffic load (0–180 kb/s), and 4 and 5 run an elastic application with low cluster traffic load (0–120 kb/s). The traffic load of each cluster is related to the number of M2M devices within each cluster. The simulation results of the other traffic and applications combinations are omitted due to space limitation.

The simulation results of the proposed control framework are presented with the control algorithms discussed in the previous section. Figure 5 shows the results of cluster head control, where the DP optimal, rollout, and Q-learning cluster head controls are compared to benchmark control, which is random cluster head control. Figure 6 shows the results of gateway control, where the UPF, P-UPF, and MIP gateway controls are compared to a No PF random gateway control.

The averaged utility curves in Fig. 5a have a concave shape, where the peak of the curve shows the maximum utility the cluster head achieved. The Q-learning control needs to approach the optimal solution over time gradually; thus, the utility curve of Q-learning cluster head control is lower than that of DP optimal control and rollout cluster head control. Figure 5b shows the cluster return on revenue with different cluster head control algorithms. The profit is calculated as the amount of unit return on revenue the cluster head received during the whole transmission. The cluster head with Q-learning control has the highest return on revenue regardless of the application classes.

The cluster heads achieve both similar utility and similar return on revenue with the proposed Q-learning cluster head control, while that of rollout cluster head control and DP optimal control differs for clusters with different applications. This shows that the proposed Q-learning cluster head control is able to achieve fairness among clusters with different applications. This also illustrated the trade-off between utility maximization and fairness.

Figure 6 shows a snapshot of the averaged throughput and averaged utility of different gateway controls where the Q-learning cluster head control is implemented. From Fig. 6a, it can be seen that the throughput is similar among different clusters with UPF and no PF gateway controls. The clusters run inelastic application (1, 2 and 3) with P-UPF gateway control than the other clusters. Clusters run elastic application (4 and 5) with MIP gateway control have higher throughput than the other clusters. In Fig. 6b, the utilities varies a lot among five clusters with P-UPF and MIP gateway controls, while those of the UPF and no PF random gateway controls are almost same. It is clear that the P-UPF and MIP gateway controls are able to provide application differentiation in terms of both throughput and utility.

Based on the above discussion, we conclude that the proposed P-UPF and MIP gateway controls have different application preferences for networks with mixed applications. The P-UPF gateway control tries to maximize the throughput and utility of clusters run inelastic applications, while MIP control tries to maximize that of the clusters run elastic applications.

CONCLUSION

This article discusses the challenges of integrating IPv6 with hierarchical M2M networks to achieve seamless and reliable IoT communications. The challenges of massive access of capacity limited devices with heterogeneous applications are addressed by the proposed distributed access control framework for an IPv6-based hierarchical M2M network. More specifically, three distributed control components, gateway control, cluster head control, and duty cycle control, are proposed. Each control aims to solve the local optimization problem with foci on EE, throughput, and network utility maximization. In addition, the optimal control problem and potential algorithms for each control component are developed taking the device capacity limitation, and flexibility and feasibility of control algorithms into consideration.

Simulation results illustrate that the proposed distributed control framework is capable of achieving network utility maximization, application differentiation, and utility fairness among clusters.

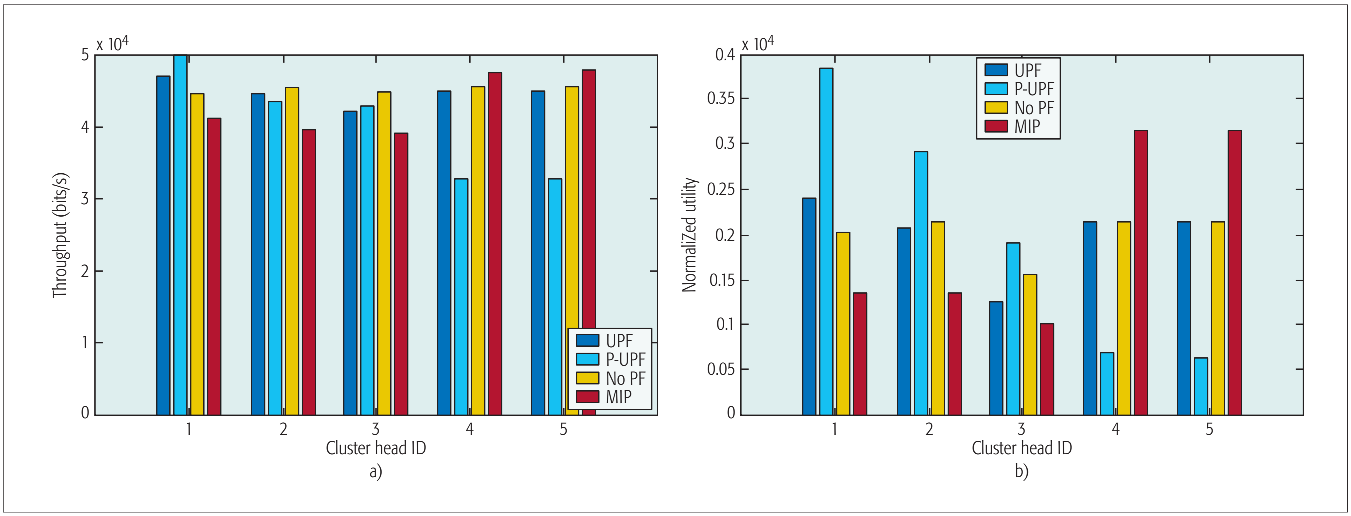

Figure 6. Network performance of gateway controls: a) averaged throughput; b) averaged utility.

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BIOGRAPHIES

Yun Li Yun Li (liyun_cetcisa@163.com) received her B.Sc. degree in engineering (Hons.) from Queen Mary University of London (QMUL), United Kindom, and her B.Sc degree in management from Beijing University of Posts and Telecommunications (BUPT), China, both in 2011. She got her Ph.D degree in electronic engineering from QMUL in 2016. Currently, she works at the Information Science Academy of China Electronics Technology Group Corporation. Her research interests include Internet of Things architecture and networks, and smart cities systems.

Kok Keong Chai (michael.chai@qmul.ac.uk) received his B.Eng. (Hons.), M.Sc., and Ph.D. degrees in 1998, 1999, and 2007, respectively. He is an associate professor and Internet of Things programme lead at Queen Mary University of London. His current research interests are medium access control for massive wireless sensor networks, dynamic resource management in wireless communications, cooperative multiple-input-single-output transmission schemes, and sensing and prediction in distributed smart grid networks.

Yue Chen [S'02, M'03, SM'15] (yue.chen@qmul.ac.uk) received her Ph.D. degree from Queen Mary University of London in 2003. Currently, she is an associate professor at the School of Electronic Engineering and Computer Science, Queen Mary University of London. Her current research interests include intelligent radio resource management (RRM) for wireless networks, MAC and network layer protocol design, cognitive and cooperative wireless networking, HetNets, smart energy systems, and the Internet of Things.

Jonathan Loo (J.Loo@mdx.ac.uk) received his M.Sc. in electronics (with distinction) and Ph.D. degrees in electronics and communications from the University of Hertfordshire, United Kingdom, in 1998 and 2003, respectively. Currently, he is an associate professor in communication networks at the School of Science and Technology, Middlesex University, United Kingdom. His current research interests include network architecture, communication protocols, network security, wireless communications, embedded systems, video coding and transmission, digital signal processing, and optical networks.