Modeling and Analysis for Admission Control of M2M Communications Using Network Calculus

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***Abstract*—Machine-to-machine (M2M) communications and applications are expected to be a significant part of the next generation 5G networks. While there have been a large amount of research studies with respect to radio resource management, load balancing, and devices grouping for M2M communications, few of them has addressed the issue of admission control. In this paper, we propose a new admission control model for M2M communications, which classifies all M2M requests into delay-sensitive and delay-tolerant first, and then aggregates all delay-tolerant requests, aiming to reduce the number of requests from devices to base stations. An admission control algorithm based on this model is devised to prevent congestion and to improve the quality of services, and a network calculus based performance-analyzing technique is developed for this model. Both theoretical analyses and simulation results show that the proposed model is feasible and valid.**

I. Introduction

The development of the Internet of Things (IoT) together with the emerging 5G wireless technology bring us not only new opportunities but new challenges as well. As part of the IoT, machine-to-machine (M2M) communications refer to either the entire communications among man, machine, and system, or the communications between machines (devices) only, and can be understood as an automated process which requires minimum human interventions [1]. Tasks such as remote surveillance, smart grids, environment monitoring, and intelligent transportation are well-known instances of M2M communications. Personal navigation, e-pay, and industry automation are also expected to be benefited from M2M communications. As such, the study on M2M communications has drawn a substantial amount of interests in both academia and industry. Note that recent activities of 3GPP, ETSI and IEEE standardization bodies aim to provide protocols and standards for M2M applications [2]. Due to the fact that most existing 4G base stations are designed to provide broadband services to regular Human-to-Human (H2H) subscribers, but M2M communications typically transmit small-sized packets in a frequent manner by using sporadic uplinks, so M2M communications are unable to effectively take advantage of the communication channels. Although the idea of random accesses from machine type communication devices (MTCDs) to channels may mitigate this problem for M2M communications, the huge number of MTCDs jammed on channels will lead to a significant rise of collisions, a higher packet loss rate, and a performance degradation for both M2M and H2H services [3]. Incidentally, the co-existence of M2M and H2H communications is essential for both service providers and users, which leads to the need of simultaneously maximizing the spectrum usage efficiency and minimizing the M2M random access in order to ensure the quality of network services.

While there are various studies on M2M communications, the present and primary challenge lies in how to deal with the frequent requests for accessing base stations sent from the exponentially increasing number of M2M devices, which has not been addressed adequately in the literature yet. Given the huge amount of access requests initiated by MTCDs, traditional network gateway is no longer able to handle these requests satisfactorily. An effective admission control mechanism for M2M communications can not only reduce the number of collisions caused by MTCDs' random accesses, but also ensure the effective exploitation of the wireless resources, and therefore is exigently needed.

Emerged as an important and effective mathematical tool for the quantitative study of network system performances, *network calculus* has been widely used in the modeling and analysis of quality of service (QoS) of networks. Network calculus primarily consists of two parts: deterministic network calculus (DNC) and stochastic network calculus (SNC). DNC calculates the delay bound, backlog bound, and other service quality parameters by using the arrival and service curves. Compared with the traditional statistics theory, DNC has the edge of being able to provide a determined boundary analysis for the performance of systems, and offer a strict service guarantee by computing the worst-case scenarios. We, in this paper, propose a new admission control model for M2M communications and analyze its performance by using network calculus within the framework of the IoT. Specifically, the main contributions of this paper are as follows.

- We present a new IoT architecture, through which the network control and data transmission are separated. This architecture follows the same design philosophy of SDN, and thus enhances the manageability and the controllability of the entire network. Under this architecture, we propose an admission control model, which can effectively reduce the number of needed connections from MTCDs to base stations, and mitigate the possibility of collisions on channels generated by MTCDs' random requests.
- We present an admission control algorithm for massive M2M requests. The algorithm can effectively prevent access request congestions, thereby improving the quality of M2M access connections. We also apply the network calculus to analyzing the performance of the proposed algorithm. Performance bounds, which provide design

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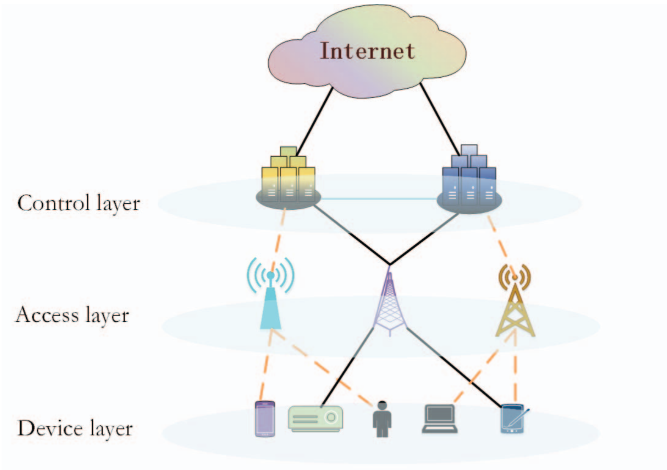


Fig. 1. The architecture of the M2M-supporting IoT system.

guidelines for building large-scale IoT, are derived.

- We evaluate the proposed model and examine the theoretical results by conducting extensive experiments. The validness and effectiveness of the developed theory are further confirmed. The idea of aggregating access flows of a massive number of devices/machines can effectively enhance the system efficiency.

The reminder of this paper is structured as follows. Section II reviews related work. Section III introduces the M2M system model, the admission control model via flow aggregation, and some network calculus basics. Section IV describes the admission control algorithm and the performance analysis of the system. Experimental results are presented in Section V, and Section VI concludes the paper.

II. Related Work

Standardization of M2M communications, together with related requirements and architecture, have already been proposed by 3GPP. Chen et al. [4] presented a survey of recent developments in home M2M networks, summarizing the architecture M2M communications and positing some related challenges. These challenges are about the large-scale maintenance of devices and remote management, and these issues are addressed in [5]. Zheng et al. [6] explicated the M2M communication architecture and performance in LTE-advanced networks. Solutions for M2M support and LTE resource management as well as various MAC protocols for M2M communications were discussed in [7]. The existing M2M solutions can be split into two classes: (i) radio resource optimization and (ii) co-operation among devices. Viewed from the networking perspective, radio resource management is of the utmost importance in terms of maintaining a certain level of QoS, and reliable resource pooling schemes [8] are proposed to ensure the QoS and the reliability of M2M operations. In [9], Liu et al. proposed a scalable hybrid MAC protocol for machine type communications within heterogeneous networks. A batch data model was suggested by [10] and [11] to reduce the updating frequency of M2M core networks, where a self-adaptive access barring parameter was used to optimize the system performance by changing resource blocks. IEEE 802.11 ah MAC for M2M communications was enhanced in [12] with the mechanism of self-adaptive Restricted Access Windows. To support more machine accesses, MTCDs, just like the base stations, can be grouped together to collaborate one another toward load balancing or resource sharing. A cooperative access class barring protocol to balance the number of MTC requests in overlapping macro- and micro-cell coverage area was proposed in [13]. In [14], Wang et al. described a clustered M2M network and focused on spatial reuse of random access resources in LTE-advanced environment to support a larger number of MTCDs and to reserve more random access resources for H2H communications. The use of capillary network and gateway was studied by many researchers to reduce the network congestions [15], and recent development of M2M communications in the area of wireless senor security networks can be found in [16], [17], [18], [19].

In summary, most M2M studies in the literature, up to this point, focus either on radio resource management or on load balancing or on M2M devices grouping, few of them have aimed at the optimization of networks through the admission control of M2M requests. This motivates us to explore a new and more efficient admission control model for M2M communications in order to reduce the chance of collisions caused by MTCDs' random access and to effectively exploit the wireless resources.

III. System Model

A. System Overview

The successful design and implementation of M2M communications are supposed to be supported by an existing architectural framework. Under such an architectural framework support, ubiquitous MTCDs can be effectively allowed to access base stations. Therefore, there is an urgent need for the IoT to become an open, complete, standardized, and universal architecture which will allow various newly developed techniques including M2M communications to be included into it in a consistent and effective manner.

Unfortunately, such an expectation has not been met by the current IoT. Much like its concept, the current IoT lacks a widely-agreed, uniformed, and normalized architecture to support most conceivable functions in the world. We thus in this section sketch a new IoT management and control architecture that intends to support various M2M communications. As shown in Fig. 1, the proposed architecture comprises three layers: a device layer, an access layer, and a control layer. The device layer is located at the bottom of the system and consists of a variety of wireless terminals, i.e., machines. The access layer is at the middle of the system, which allows the bottom-layer devices to access networks through cellular and/or WIFI technologies. The top layer is the control layer which provides administration and control over the access requests and data transfer activities at the lower layers, and is connected to the Internet for real time analyses and feedbacks. Essentially, this architecture follows the same philosophy of SDN, which is able to enhance the manageability and control of the massive M2M requests in IoT.

B. M2M Admission Control Model

We now introduce an admission control model for M2M communications, which is depicted in Fig. 2. In the context

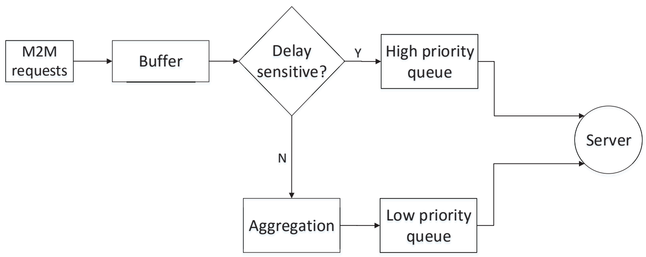


Fig. 2. The M2M admission control model.

of the IoT, all M2M access requests can be classified either as delay-sensitive or as delay-tolerant. As indicated in Fig. 2, delay-sensitive requests will be directly placed into a high-priority queue, and *all* delay-tolerant requests will be placed into a low-priority queue waiting to be processed.

Note that compared with the random access of MTC, this this priority-based access control model reduces the collision probability of the MTC requests by organizing the massive MTC requests in order. Moreover, the above model is able to guarantee the delay performance of the requests. For example, consider a public safety scenario in a smart city where a severe flood warning is being issued. In this case, the data update on water levels of surrounding bayous, rivers, ditches, and culverts in various areas of the city is of critical importance, and forms a delay-sensitive request flow. Other requests, such as air pollution monitoring, vehicle parking, transportation management, etc. are aggregated as the delay-tolerant flow. Evidently, the random access mechanism cannot guarantee the delay performance in the above example. Also, the resource allocation/scheduling is independent of this admission control as it is a subsequent step of this procedure. Thus, this model is applicable to both downlink and uplink cases.

Note also that we assume that all access requests flows are regulated by the common technique of token bucket, so that the request flows can be processed smoothly. The basic algorithm of token bucket is as follows. Let r be the rate of adding tokens to the bucket, i.e., one token will be added to the bucket per $1/r$ second, and b_0 be the maximum number of tokens the bucket can hold. If a token arrives when the bucket is full, then that token will be discarded. When a request in length n arrives, n tokens will be removed from the bucket and the packet will be sent to the network if the bucket has more than n tokens available; otherwise, the packet has to wait until the bucket has sufficient number of tokens to be removed. As such, the input function of a flow, after being shaped by the token bucket, is $f(t) = rt + b$, where r is the rate and b is the initial burst traffic.

C. Network Calculus Basics

Network calculus will be subsequently used to analyze the performance of this setting in Fig. 2. Network calculus is a theory of queuing systems, which offers a deep insight into data flow problems found in computer networks. It was initiated by Chang and Cruz, and further developed by A-grawal, Le Boudel, and others. At present, network calculus has successfully found applications in many areas such as QoS control, software defined networks, traffic scheduling, and controls of queue lengths and delays. The basic notions and notations of network calculus that are used in this paper are presented below.

Definition 1 (Arrival Curve): Given a wide-sense increasing function α defined for $t \geq 0$, we say that a flow with (accumulative) input function R is constrained by α if and only if for all $s \leq t$, we have $R(t) - R(s) \leq \alpha(t - s)$ and in this case we say that R has α as an arrival curve, or also that R is α-smooth.

Definition 2 (Service Curve): Consider a system S and a flow going through S with R and R^* as its (accumulative) input and output functions. We say that β is the service curve offered by the system S if and only if β is wide-sense increasing, $\beta(0) = 0$, and $R^* \geq R \otimes \beta$. Typically, β is expressed as $\beta(t) = r(t - T)^+$, where r is the service rate and T is the time delay.

Theorem 1 (Backlog Bound): Suppose a data flow is constrained by α and goes through a system whose service curve is β. Then at any time t, the backlog $R(t) - R^*(t)$ satisfies $R(t) - R^*(t) \leq v(\alpha, \beta) = \sup_{s \geq 0}\{\alpha(s) - \beta(s)\}$ where $v(\alpha, \beta)$ is the vertical deviation between α and β.

Theorem 2 (Delay Bound): Suppose a data flow is constrained by α and goes through a system whose service curve is β. Then at any time t, the virtual delay $d(t)$ satisfies $d(t) \leq h(\alpha, \beta) = \sup_{s \geq 0}\{\inf\{T \geq 0 : \alpha(s) \leq \beta(s + T)\}\}$ where $h(\alpha, \beta)$ is the horizontal deviation between α and β.

IV. Admission Control Algorithm and Performance Analysis

A. Admission Control Algorithm

Due to the enormous amount of access requests to a network, which is typical in M2M communications, an acceptance and/or rejection algorithm with regard to these requests must be in place to avoid traffic congestion in the network. We thus devise such an algorithm to handle the large-scale M2M access requests on the basis the arrival rate and the service ability of the service node.

One of the critical conditions to ensure a regular trouble-free running of a network is that the arrival rate of the request flow cannot be larger than the service rate (or ability) of the network. Otherwise, the flow will tend to encounter an infinite delay, causing a malfunction of the network. If the current service ability of the network is able to handle the incoming access request, then the request will be accepted; otherwise, it will be rejected. The notations used in the algorithm and the algorithm itself are given in Table 1 and Algorithm 1, respectively.

TABLE I. Notations used in Algorithm 1

Notation	Meaning
r	The total service rate (capability) of the system
r_i	The packet rate of the i-th M2M device
r_h	The packet rate of the unfinished high-priority flow
r_l	The packet rate of the unfinished low-priority flow
I	The total number of M2M devices

B. Performance Analysis

In this section, we use network calculus to analyze the performance of the model depicted in Fig. 2, where all

Algorithm 1 Admission Control Algorithm

Input:
$r_i, r_h, r_l, r; \quad \forall i \in \{1, 2, ..., I\}$
Output:
reject/accept request $i \quad \forall i \in \{1, 2, ..., I\}$

For each current request i
if $r_i \leq r - r_h - r_l$ **then**
accept request i;
else
reject request i;
end if
update r_h, r_l;
Repeat the process for the next due request

M2M communication requests will be routed into a delay-sensitive high-priority flow or a delay-tolerant low-priority flow. Throughout this section, we use f_h and f_l to denote the high-priority flow and low-priority flow, respectively; R_h and R_h^* to denote the input and output functions of f_h , and R_l and R_l^* to denote the input and output functions of f_l.

We assume that the order of arrivals of f_h and f_l is completely arbitrary without any timing constraints, that the service curve β offered by the system can be expressed as $\beta_{r,T}(t) = r(t-0)^+$ where if $t > 0$, $\beta_{r,T}(t) = r(t-0)$; otherwise, $\beta_{r,T}(t) = 0$, and that f_l and f_h have $\alpha_l(t) = r_l(t) + b_l$ and $\alpha_h(t) = r_h(t) + b_h$ as their arrival curves, respectively. (Note that the reason of having these linear arrival curves was explained at the end of Section III.B.) In the sequel, we analyze the performance of the system by the order of arrivals of f_l and f_h and by considering cases of preemptive scheduling and non-preemptive scheduling.

1) f_h Arrives Earlier than or Simultaneously with f_l: In this case, preemptive scheduling or non-preemptive scheduling will make no differences. So the system will process those unfinished requests at hand first, and then continue to process requests from f_h and f_l in order. Let $l_{\max}$ be the amount of unfinished requests in the system, r be the total service rate of the system. Then in the time interval $(s, t]$, the amount of packets transmitted by f_h is

$$R_h^*(t) - R_h^*(s) \geq r(t-s) - l_{\max} \tag{1}$$

with

$$\beta_{r_h,T} = r(t - \frac{l_{\max}}{r}). \tag{2}$$

By Theorems 1 and 2, the delay bound and backlog bound can be obtained as follows:

$$d_h \leq \frac{b_h + l_{\max}}{r}, \tag{3}$$

$$q_h \leq b_h + r_h \frac{l_{\max}}{r}. \tag{4}$$

Similarly, the amount of packets transmitted by f_l is

$$R_l^*(t) - R_l^*(s) \geq r(t-s) - [R_h^*(t) - R_h^*(s)] - l_{\max} \tag{5}$$

with

$$\beta_{r_l,T} = (r - r_h)(t - \frac{b_h + l_{\max}}{r - r_h}), \tag{6}$$

and its delay bound and backlog bound would be

$$d_l \leq \frac{b_l + b_h + l_{\max}}{r - r_h} \tag{7}$$

and

$$q_l \leq b_l + r_l \frac{b_h + l_{\max}}{r - r_h}, \tag{8}$$

respectively.

2) f_h Arrives Later than f_l: In this case, preemptive scheduling or non-preemptive scheduling will yield different results, and needs to be considered separately.

Non-Preemptive Scheduling. By the nature of the non-preemptive scheduling algorithm, the system will process its unfinished requests first, and then continue to process requests from f_l and f_h in order. As such, the amount of packets transmitted by f_l in the time interval $(s, t]$ is

$$R_l^*(t) - R_l^*(s) \geq r(t-s) - l_{\max} \tag{9}$$

with

$$\beta_{r_l,T} = r(t - \frac{l_{\max}}{r}). \tag{10}$$

The delay bound and backlog bound can be obtained as follows:

$$d_l \leq \frac{b_l + l_{\max}}{r}, \tag{11}$$

$$q_l \leq b_l + r_l \frac{l_{\max}}{r}. \tag{12}$$

In a similar fashion, the amount of packets transmitted by f_h in the time interval $(s, t]$ is

$$R_h^*(t) - R_h^*(s) \geq r(t-s) - [R_l^*(t) - R_l^*(s)] - l_{\max} \tag{13}$$

with

$$\beta_{r_h,T} = (r - r_l)(t - \frac{b_l + l_{\max}}{r - r_l}), \tag{14}$$

and f_h's delay bound and backlog bound are

$$d_h \leq \frac{b_l + b_h + l_{\max}}{r - r_l} \tag{15}$$

and

$$q_h \leq b_h + r_h \frac{b_l + l_{\max}}{r - r_l}, \tag{16}$$

respectively.

Preemptive Scheduling. In this case, the system will serve requests from f_l until the request from f_h arrives. At that time, the system will stop processing requests from f_l and start processing requests from f_h until all requests from f_h have been processed, and then resume the processing of requests from f_l. As such, the amount of packets transmitted by f_h in the time interval $(s, t]$ is

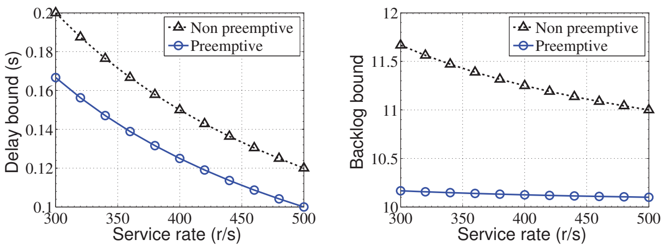
$$R_h^*(t) - R_h^*(s) \geq r(t-s) \tag{17}$$

with

$$\beta_{r_h,T} = r(t-0)^+. \tag{18}$$

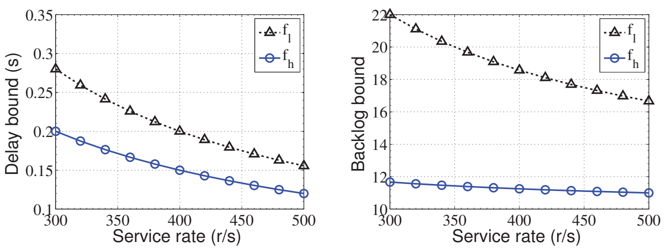
We can find its delay bound and backlog bound as follows:

$$d_h \leq \frac{b_h}{r}, \tag{19}$$



(a) Delay bound (b) Backlog bound

Fig. 3. Delay bound and backlog bound of f_h with preemptive scheduling and non-preemptive scheduling.



(a) Delay bound (b) Backlog bound

Fig. 4. Delay bounds and backlog bounds of f_h and f_l, with non-preemptive scheduling, when f_h arrives earlier than or simultaneously with f_l.

$$q_h \leq b_h + \frac{r_h}{r}. \tag{20}$$

Similarly, the amount of packets transmitted by f_l in the time interval $(s, t]$ is

$$R_l^*(t) - R_l^*(s) \geq r(t-s) - [R_h^*(t) - R_h^*(s)] \tag{21}$$

with

$$\beta_{r_l,T} = (r - r_h)(t - \frac{b_h}{r - r_h}), \tag{22}$$

and f_l's delay bound and backlog bound are

$$d_l \leq \frac{b_l + b_h}{r - r_h} \tag{23}$$

and

$$q_l \leq b_l + r_l \frac{b_h}{r - r_h}, \tag{24}$$

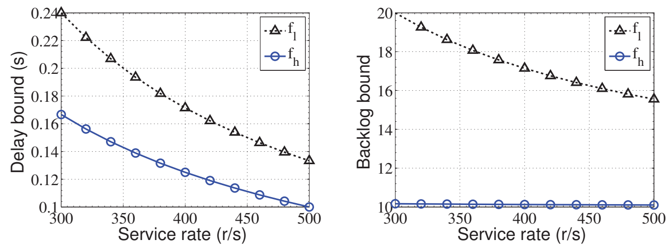
respectively.

V. Experimental Results

A. Numerical Experiments

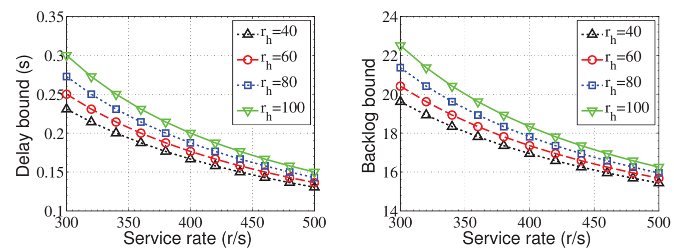
We in this section further validate the theoretical performance analysis carried out in the previous section by numerical investigations. For all figures in this section, except Fig. 6, the parameters are set as follows: $r \in [300, 500]$ requests/second (r/s), $r_l = r_h = 50$ r/s, $b_l = b_h = 10$, and $l_{\max} = 10$.

Fig. 3 shows the delay bound and backlog bound of f_h with respect to preemptive scheduling and non-preemptive scheduling. It can be seen clearly that preemptive scheduling delivers a superior performance than non-preemptive scheduling. Fig. 4 depicts the delay bounds and backlog bounds of f_l and f_h when f_h arrives earlier than or simultaneously with f_l, and the non-preemptive scheduling scheme is used. We can see that



(a) Delay bound (b) Backlog bound

Fig. 5. Delay bounds and backlog bounds of f_h and f_l, with preemptive scheduling, when f_h arrives earlier than or simultaneously with f_l.



(a) Delay bound (b) Backlog bound

Fig. 6. With preemptive scheduling, the changes of delay bound and backlog bound of f_l with respect to the variations of arrival rate r_h of f_h.

f_h has lower backlog bound and delay bound than f_l. Fig. 5 exhibits the situation of Fig. 4 with non-preemptive scheduling being replaced by preemptive scheduling, and similar results to that of Fig. 4 can be observed. Fig. 6 shows the comparisons of the delay bound and the backlog bound of f_l with the arrival rate r_h of f_h being set to 40, 60, 80, and 100 when the preemptive scheduling scheme is used. Clearly, both bounds increase as r_h increases, as expected.

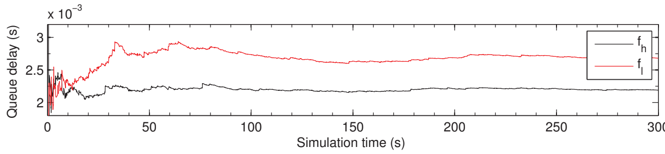
B. Simulation Results

We now demonstrate the result of simulating our proposed model by using the simulation software OMNET++ [20]. As in the numerical experiments, two queues f_h and f_l are set up, where f_h is the delay-sensitive high-priority queue and f_l is the delay-tolerant low-priority queue.

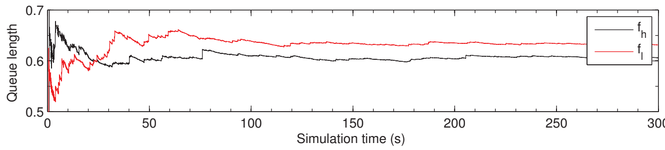
Fig. 7 shows the average queue delay and length of f_h and f_l when the systems service rate $r = 500$ r/s and the arrival rates of f_h and f_l are $r_h = r_l = 50$ r/s, and the preemptive scheduling scheme is utilized. We can see that f_h excels f_l in terms of both delay and length. This is not surprising and actually matches the theoretical result as expected, due to the nature of the preemptive scheduling. Fig. 8 depicts the changes of the average queue delay and length of f_l with respect to $r_h = 40, 60, 80, 100$ r/s when the service rate $r = 500$ r/s and arrival rate of f_l is $r_l = 50$ r/s. Again, we are able to see that both delay and length of f_l grow as the arrival rate of f_h grows, and this is also consistent with the previous numerical experiments and the theoretical results in Section IV.

VI. Conclusion

How to effectively deal with the enormous amount M2M access requests and the ensuing delay performance is the

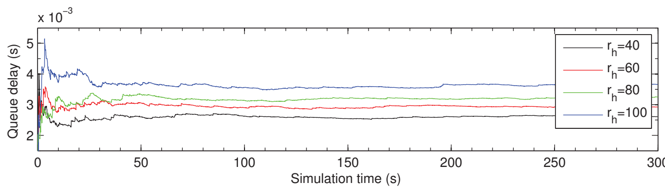


(a) Average queue delay

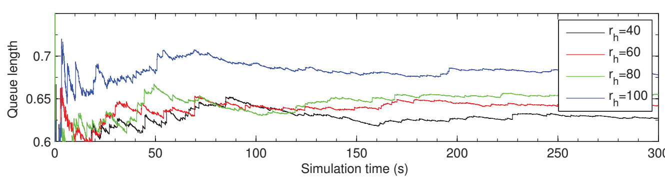


(b) Average queue length

Fig. 7. Average delay and length of queues f_h and f_l with preemptive scheduling.



(a) Average queue delay



(b) Average queue length

Fig. 8. Variations of the average delay and length of queue f_l with respect to different r_h.

bottleneck hindering the further development of the IoT. Considering that most M2M messages are delay-tolerant, we have proposed an admission control model for M2M communications, which reduces the number of M2M access requests to base stations and the collision possibility caused by the random M2M accesses on channels. The performance of this model is subsequently analyzed. The consistency of results in theoretic analyses, numerical experiments, and simulations validates the effectiveness and correctness of the proposed model.

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