Dynamic QoS-aware Queuing for Heterogeneous Traffic in Smart Home

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***Abstract*—Smart home gateways have to forward multi-sourced network traffic generated with different distributions and with different Quality of Service (QoS) requirements. Most of the current QoS-aware scheduling methods consider only the conventional priority metrics based on the IP Type of Service (ToS) field to make decision for bandwidth allocation. Such priority-based scheduling methods are not optimal to provide both QoS and QoE (quality of experience) since higher-priority traffic do not necessary require higher stringent delay than lower-priority traffic. To solve the gaps between QoS and QoE, we propose a new queuing model for QoS-level Pair traffic with mixed arrival distributions in Smart Home network (QP-SH) to make a dynamic QoS-aware scheduling decision which meets delay requirements of all traffic while preserves their degrees of criticality. A new metric which combines, the ToS field and the maximum number of packets that can be processed by the system's service during the maximum required delay, is defined. Our experiments show the proposed solution provides an improvement regarding the number of packets that meet their priorities and their maximum delays as well as the mean number of packets in the system.**

***Index Terms*—Smart home, quality of service, traffic scheduling optimization**

I. Introduction

Smart home network is a network that connects sensors, home appliances, and intelligent devices that react with each other with user instructions or system provider [1]. Smart home networks are evolving rapidly to include a large number of smart devices that generate different types of traffic with different distributions. Also, a variety of applications with different requirements is putting more constraints in smart home traffic scheduling such as congestion and delay. This requires automated management of traffic loads within the home gateway by offering more than one priority class. From the perspective of Internet Service Providers (ISP), this priority is decided based on bandwidth requirements for critical applications using IP ToS field [2], however, from the perspective of the home user, the priority is decided based on delay requirement especially for video streaming applications. For example, regarding criticality, packets generated from a fire detector or medical sensors get higher service priority than packets generated from streaming devices, and regarding the delay, streaming devices require a lower maximum delay compared to periodic sensing objects as medical sensors. The most challenging issue faced by smart home gateway is to provide both ISP and home users satisfactions in terms of QoS (quality of service) and Quality of Experience (QoE) especially to delay-sensitive applications [3], [4], [5], [6] through finding an automatic way to schedule multi-sourced packets while considering their degree of criticality and meeting their maximum required delay. Most of the previous work that target scheduling with QoS problems [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18] cannot be efficiently applied in a smart home network since they do not consider the impact that prioritizing specific traffic based only on static metrics like TOS field or user-defined preferences may have on other network traffic. In this paper, we propose a dynamic model for optimizing packet scheduling in the smart home network with mixed arrival distributions while considering both the critical nature of the application and the maximum allowed delay. The contribution of this paper includes a new dynamic queuing model for smart home network traffic generated by heterogeneous sources, which increases the number of packets that meet their deadline while preserves their degree of criticality. The rest of the paper is organized as follows. We will discuss related studies on QoS based scheduling in Section II. In Section III, we will describe the smart home traffic scheduling with QoS constraints. QoS scheduling problem is presented in Section IV. Section V describes the proposed queuing model for QoS-level Pair Heterogeneous-sourced traffic in the smart home network (QP-SH). Performance results of our solution are provided in Section VI. Finally, we draw conclusions and present future work.

II. Related Work

Many scheduling algorithms have been proposed in previous work to manage different type of network traffic and provide ISP and/or user satisfaction based on different network or user parameters. Yang et al. [10] proposed a cloud-based scheduling solution to prioritize home applications based on packet inspection. The authors evaluate their solution using video streaming applications. Their architecture risk to let queues of the low-high priorities starve since it's considers only the static nature of priority assignments.

A number of approaches which considered some parameters besides QoS criteria to enhance network traffic scheduling are presented in [11], [12], [13], [14], [17]. These approaches have considered the bandwidth criterion [11], [17], the traffic load

[12], [13] and the delay between source and destination nodes [17] as additional criteria to prioritize their traffic. Chaabnia et al. [11] contributed a new distributed model for home network traffic prioritization using SDN technology. Works in [12], [13] proposed dynamic scheduling algorithm using Weighted round-robin algorithm (WRR) a generated form of Fair Queuing (FQ), which allows, at each scheduling round, en/de-queuing a certain number of packets (weights) from each queue. Gueguen et al. [14] proposed a cross-layer scheduler approach to extend wireless coverage by inciting potential network nodes to cooperate without deteriorating their QoS in terms of delay and throughput. A distributed traffic adaptation approach for wireless mesh networks (WMN) is proposed in [17] to control congestion and optimize network performance. This approach allows to regulate traffic by dropping best-effort traffic and adapting QoS-sensitive traffic rate based on two parameters; the delay between source and destination nodes and buffer occupancy of intermediate nodes. However, the slow network adaptation caused by the end-to-end based traffic regulation decision, make the system inappropriate for real-time applications. Recent scheduling approaches considered other scheduling criteria like the priority order of inserting packets [7] using a fixed priority algorithm based on Priority Queuing (PQ), user-defined profile priorities [8], user-defined context priorities (which includes the person's profiles, sensed data, e-Health services priorities and user preferences) [16], the currently active applications and devices [9], the number of their direct neighboring nodes, the average link quality with these nodes, and the number of hops between the gateway and the SC [15] and the location of the congestion [18].

In general, most of the existing scheduling solutions rely on static metrics in the priority assignment task. They are either based on user-defined profiles, current active applications or class of service. Even though there are solutions that assign priorities dynamically (based on traffic loads, real-time bandwidth allocation, network traffic statistics or source-destination distance), they consider a specific type of home application (multimedia and video streaming applications) or only a particular optimization goal. They either focus on improving QoS from the perspective of ISP (optimize bandwidth utilization based on traffic loads to meet ToS priorities) or improving QoE from the perspective of the home user (optimize delay based on the distance between the source and destination nodes).

Specific queuing metrics, which need to be determined in the smart home network, like traffic application criticality (or type of service) and the maximum required delay along with heterogeneous distributions queuing adaptability, has never been taken into account. These factors are very important in the context of the home network to fill the gap between QoS and QoE for any home application in an automated way. Our approach mitigates these limitations by considering these important key factors to deploy a new scheduling scheme specific to the smart-home network context. More specifically:

- Proposing a new deterministic queuing model for multi-sourced traffic generated with different distributions using a new composite QoS-level metric based on both criticality-based priority and delay-based priority to avoid local network congestion by optimizing the number of packets that meet their allowed delay while preserving their degree of criticality.

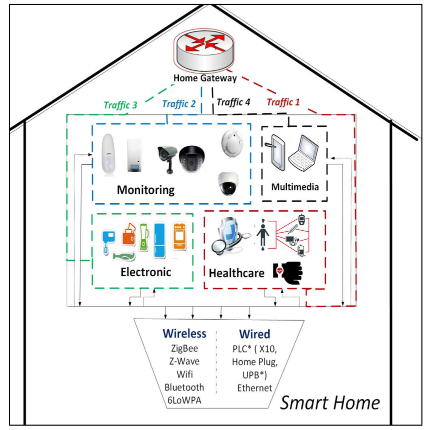


Fig. 1: Smart Home Network

III. System Description

Fig. 1 depicts a typical smart home network. Each home network includes many different multimedia devices (i.e., tablets, smart-phones, connected TVs, etc.) and objects (i.e., sensors, electronics, appliances, etc.). Sensors are devices used to detect the location of people and objects or to collect data or states (i.e., temperature, energy consumption, open windows/doors, movement, broken glass). Electronic devices include phones, televisions, and laptops. Electrical devices refer to toasters, kettles, light bulbs, etc. Appliances refer to washing machines, refrigerators, etc. Such a network offers services to a wide range of application like monitoring, health assistance, safety, and energy efficiency, producing traffic with different Quality of Service (QoS) levels [19], [20], [21](marked by different colors in Fig. 1) and managed by the smart home gateway. Fig. 2 illustrates an example of the smart home gateway. Home gateway contains three modules[22]; Classifier, Scheduler, and Service. in this paper, we use two-level classifier which classifies the network packets firstly according to their criticality-based priority and then, according to their maximum allowed delay-based priority. Scheduler contains the queue in which classified packets will be scheduled according to their arrived time and their two-level priorities.

In our proposed architecture, a simple modification on the TCP protocol will be made by encapsulating a new field in the TCP frame that reflects the maximum allowed delay for each packet. We assume that the main queue of the system has an unlimited size (storage area). The problem we address in this paper is to provide optimal scheduling for packets generated from different sources and with varying distributions with respect to their delay budget and their degree of criticality.

IV. QoS-aware Scheduling Problem

Our problem is optimizing QoS scheduling for smart home network traffic. It consists of finding a way to schedule multi-

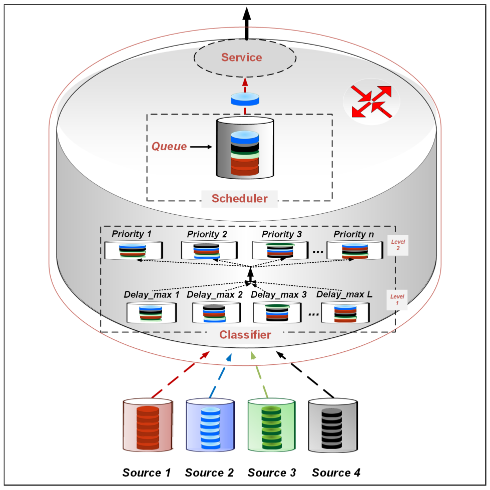


Fig. 2: System Description

sourced packets, that ensures their maximum tolerated delay and preserves their degree of criticality. The contribution of this paper is improving previous work by introducing a dynamic QoS level pair for multi-sourced traffic with different arrival rate, that considers the criticality of the application all along the maximum number of packets that can be processed before processing the packet based on its maximum tolerated delay.

A. Modeling and characterizing the input traffic and the service

Incoming traffic can follow different distributions depending on their data type as well as the type of their generation process (or source Si):

a) Periodic sensing objects (S_1) : These objects periodically detect and send to a central server (usually on the cloud) the states of monitored devices for each period T (i.e., connected thermostats, network sensors, medical sensors, etc.). This type of source generates discrete traffic, with each period T (synchronous) and with a constant, determined distribution (D). A packet should be sent out by the gateway before 2T (the time when the following packet arrives).

b) Event-triggered sensing objects (S_2) : These objects generate traffic by triggering some events (for example, door/window sensors, motion detectors, etc.) to indicate the status of the monitored object or person. We define $D^{q_i}_{max}$ the maximum tolerated delay for QoS-level q_i traffic. The generation of this traffic is generally rare and does not depend on any other traffic (decorrelated). The arrival of this type of traffic (average arrival number λ_2)) can, therefore, be modeled according to a distribution of the Poisson process with an exponential inter-arrival rate (M).

c) Streaming objects (S_3) : These objects generate a continuous data stream (by tablets, connected televisions, surveillance cameras, etc.). These data do not always require QoS, however, for delay-sensitive applications like VOIP and video streaming (security camera or films), data should not be delayed to provide QoE or security to the end user. The maximum tolerated delay for QoS-level q_i traffic generated from these type of objects is $D^{q_i}_{max}$. The generating data may reach peaks during periods of heavy use or may be negligible (like traffic from surveillance cameras or during the rest of the day). We have modeled this type of traffic with a binary Markov-Modulated Poisson Process (MMPP):

- State 0: incoming traffic follows a Poisson process with a very high average number of arrivals ($\lambda_2 \ll \lambda_3$). This traffic corresponds to the flows generated during peak periods of use.
- State 1: incoming traffic follows a Poisson process with a low average number of arrivals ($\lambda_3 \gg \lambda_{31}$). This traffic corresponds to the negligible flows generated during the rest of the day or by surveillance cameras.

The packet rate generated by the source S_2 and the packet rate of the state 1 of the source S_3 are generally similar, and they can, therefore, be modeled by the same distribution with the same arrival rate. We can, therefore, consider that the average arrival rate $\lambda_2 = \lambda_{31}$ is fixed according to the utilization rate (the behavior of the inhabitants). The arrival flow of our system therefore follows two different distributions; a predetermined distribution with an arrival rate λ_1 and a binary Markov distribution with an arrival rate ($\overline{\lambda_2}$). If we consider $Pr(s = i)$ the probability that an arrival packet is in state i (with $i \in \{0, 1\}$) then we have:

$$\overline{\lambda_2} = Pr(s = 0)\lambda_2 + Pr(s = 1)\lambda_3 \tag{1}$$

$$Pr(s = 0) = \frac{(r_1)}{(r_0 + r_1)} \tag{2}$$

$$Pr(s = 1) = \frac{(r_0)}{(r_0 + r_1)} \tag{3}$$

with r_0 and r_1 are respectively the average lengths of stay in the state 0 and state 1 and therefore the arrival rate will be:

$$\overline{\lambda_2} = \frac{\lambda_2 * r_1 + \lambda_3 * r_0}{(r_0 + r_1)} \tag{4}$$

We have a single domestic gateway with c servers. A server can process any packet with a size up to the Maximum Transmission Unit (MTU). We assume that all packets are MTU-sized packets and the service follows a deterministic distribution with a rate $\frac{1}{s}$.

B. Modeling QoS requirements for smart home network devices

For each smart home network application, we define a QoS level based on two main QoS parameters; a priority level and a maximum required delay. Priority level depends on the degree of the application criticality. Exceeding delay for critical applications is fatal, however, for non-critical applications, it is better to meet the deadline, but it is no crucial. For example, the processing time of packets generated from a fire detector must not exceed their maximum required delay otherwise the fire will rapidly turn fatal, however, a high processing time of a packet from video streaming applications, that exceeds its required maximum delay, will deteriorate the service without causing a real disaster. In our proposed architecture, three primary sources of traffic are considered (as described in section IV-A); type 1 sensor S_1, type 2 sensors S_2 and multimedia devices S_3, along with only one home gateway. Each source can generate different QoS-levels of network traffic at different time slots, and a maximum of k packets can be processed at each service time using c servers. Our system is modeled as $D/G/c$ for traffic generated from source of type $S_1$and $MMPP{-}2/G/c$ for traffic from sources of type S_2 and S_3. The service can serve:

- Up to c packets in s time slots,
- Up to $\frac{c}{s}$ packets in one time slot,
- Up to$\frac{c * D_{max}(P_i)}{s}$ packets during the maximum required delay $D_{max}(P_i)$ of a packet P_i.

Thus, for each packet P_i we define a maximum window size $w_{max}^{P_i}$ as the maximum number of packets that can be processed by the system's service during its required delay $D_{max}(P_i)$ as follows:

$$w_{max}^{P_i} = \frac{c * D_{max}(P_i)}{s} \tag{5}$$

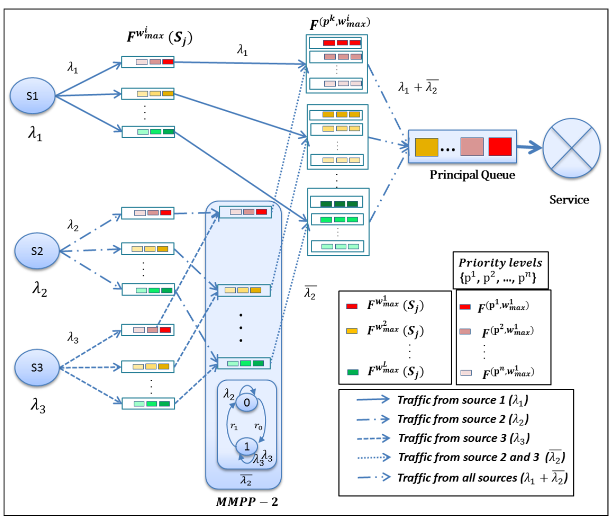


Fig. 3: QP scheduling model

We define the QoS-level pair q^{P_i}, for each network packet P_i as follows:

$$q^{P_i} = (p^{P_i}, w_{max}^{P_i}) \tag{6}$$

With p^{P_i} is the priority level of the P_i's application type.

We set a queue F^{q^i} for each QoS-level pair q^i and a scheduling discipline $D_F(F^{q^i})$ for composite QoS level packets from different F^{q^i} queues that we will determine later. We define a delay function for each packet $P^{(q,g)}$ generated from source S_i and having the QoS-level pair q as follow:

$$D_T(P^{(q,S_i)}) = \alpha_T(P^{(q,S_i)}) + s \tag{7}$$

With $\alpha_T(P^{(q,S_i)})$ is the waiting time of the packet $P^{(q,S_i)}$ before being served and s is the service time.

The smart home network is a heterogeneous infrastructure made of multiple electronic and electrical network devices like sensors, detectors, and laptops. These data sources generate a wide range of traffic with different distributions and various QoS and QoE requirements. A key challenge of this problem is to find a reasonable way to schedule multi-sourced packets from a composite class of service with respect to their QoS and QoE requirements. Thus, to meet the delay constraint, the delay of a packet $P_{ij}^{(q,S)}$ must be lower than the delay budget D_{max}^q required by the pair of class of service q:

$$D_T(P_{ij}^{(q,S)}) \leq D_{max}^q \tag{8}$$

The QoS-aware scheduling problem consists of finding an optimal way to schedule packets from multi-sourced traffic with dynamic QoS-level pair that ensures the maximum tolerated delay and preserves their degree of criticality. We formulate the QoS-aware scheduling problem by the following objective function:

$$D_F(F^{q^i})^* = argmin_{D_T(P_{ij}^{(q,g)})} \begin{cases} P_{ij}^{(q,g)} \in P \\ D_T(P_{ij}^{(q,g)}) \leq D_{max}^q \end{cases} \tag{9}$$

V. QP-SH: Queuing model for QoS-level Pair traffic in smart home network

To solve the queuing problem of smart home traffic that have a composite class of service $q^i = (p^i, w_{max}^i)$ and generated with different distributions, we propose a QP scheduling model as described in Fig. 3. The QP model dedicates a QoS-level pair $q^i = (p^i, w_{max}^i)$ for each packet generated from the different source of traffic. All packets with the same w_{max} will be merged to a single queue with the same w_{max} until reaching the main queue of the system. Then, packets in the same w_{max} queue will be scheduled according to their priority level p to ensure that each packet is processed according to its QoS-level pair whatever its source. In our proposed architecture, three main traffic sources are considered, as described in section IV-A; type 1 sensors (S_1), type 2 sensors (S_2) and multimedia devices (S_3). Each source S_i has a set $F^W(S_j)$ of L queues for each w_{max}^i traffic generated from it with the rate $\lambda_j, F^W(S_j) = F^{(w_{max})}(S_j), w_{max} \in W \subset F$ with W is the set of w_{max}. Traffic from S_2 and S_3 are then modeled by a binary MMPP while keeping their priorities queues. All same w_{max} queues are merged to a single queue with the arrival rate ($\overline{\lambda_2}$). Then, all the same w_{max} queues from MMPP and S_1 are merged again to a single queue and sending to the principal queue with the arrival rate $\lambda_1 + \overline{\lambda_2}$ and $F^q = F^{(p,w)}, w \in W, p \in Q \in F^W \subset F$. In the QP-SH algorithm, each arriving packet $P_{ij}^{((p^k,w_{max}^i),S_k)}$ generating from source S_k, is mapped to the queue $F^{w_{max}^i}(S_k)$. Then, all $F^{w_{max}^i}(S_k)$ queues from different sources of traffic will be merged to a single $F^{w_{max}^i}$ queue. All $F^{w_{max}^i}$ queues form a set $F = F^{w_{max}^i}, i \in L$ of queues. Then, all packets in each $F^{w_max^i}$ queue are grouped by priority into n sub-queues $F^{(p^k,w_{max}^i)}$. The system processes all $F^{w_{max}^i}$ queuing in an ascending order beginning from the group of queue with the lowest w_{max}^i. Packets within the samew_{max}^i group are scheduling according to their priorities; packets highest priority are served first. After each service round, the value of w^i_{max} for all $i \in L$ is decremented by the number of served packets (up to c packets since we have c servers), as the number of packets that can be processed by the system's service before processing each packet $P_{ij}^{((p^k, w^i_{max}), S_k)}$ is decremented by the number of served packets.

VI. Performance Evaluation

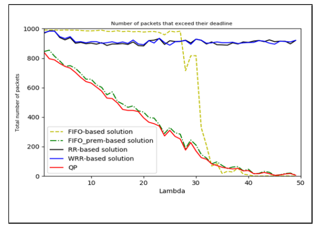
To evaluate the performance of the proposed QP-SH algorithm, we build a simulation with up to 1000 network packets generating with different distributions and one server. Traffic from periodic sensing objects are generating each 5ms with a rate of 1/5 packet/ms. Incoming traffic from event-triggered sensing objects follow exponential distribution with a rate λ_2 = (0.5 * λ_3) since it is much lower than λ_3 (as described in section IV-A). This negligible traffic is generated during r_0 = 40% of the day.

TABLE I: Experimental Setup

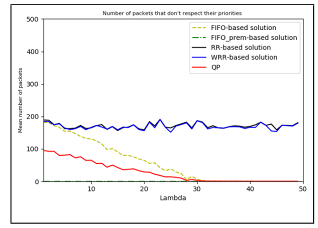
Parameter	Value
Number of packets	1000
D_{max}	uniform(200,250) (ms)
Priority	randint(0,10)
λ_1	1/5 (packet/ms)
λ_2	0.5 * λ_3 (packet/ms)
λ_3	1-50 (packet/ms)
Service time	30 ms (in scenario 1), 10-60 ms (in scenario 2)
r_0	40 (%)
r_1	20 (%)

Incoming traffics from streaming objects follow an exponential distribution with a rate λ_3 set from 1 to 50 packet/ms. This traffic is generated during periods of heavy use, during r_1 = 20% of the day. We calculate $\overline{\lambda_2}$ as defined in Eq.(1). We randomly set the packet priority and the maximum delay. Regarding the service time, we consider two scenarios; in the first scenario, the service can serve a packet in 30 ms with a rate of 2 packet/s, and, in the second scenario, the service time varies from 10 ms to 60 ms. In both scenarios, we compare our QP-SH algorithm with recent scheduling approaches which are based on the classical Round-Robin(RR) [12], Weighted RR (WRR) [13], First in First out (FIFO) and FIFO preemptive (FIFO-prem) [7] algorithms. All approaches are implemented in Python 3.7. Table.I describes our experimental setup.

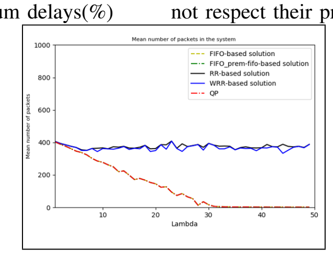
Fig. 4 shows the performances of the proposed QP-SH algorithm in function of the arrival rate $lambda$ calculated as defined in Eq.(1); $lambda = \overline{\lambda_2} + \lambda_1$. The different values of $lambda$ are obtained by varying λ_3 from 1 to 50 and λ_2 in function of λ_3 (λ_2= (0.5 * λ_3)). In Fig. 4, we consider the first scenario where the service time is fixed, and we plot the curves of the number of packets whose delays exceed their maximum allowed delays (Fig.4(a)), the mean number of packets which are processed by the system regardless of their priorities (Fig.4(b)), and the mean number of packets in the system (Fig.4(c)) in function of the arrival rate $lambda$. We note that the curves obtained with QP-SH algorithm are under the curves obtained with the RR, WRR, FIFO and FIFO



(a) Percentage of packets that exceed their maximum delays(%)



(b) Percentage of packets that do not respect their priorities(%)



(c) Mean number of packets in the system

Fig. 4: QP-SH performances in function of the arrival rate $lambda$ (the service time is fixed to 30 ms)

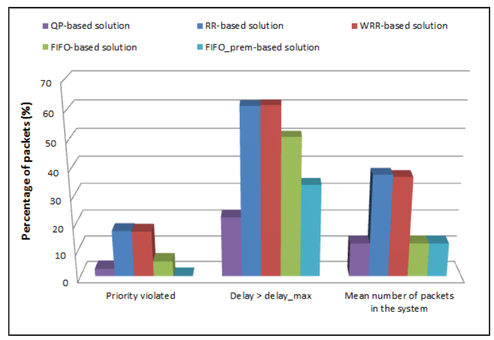
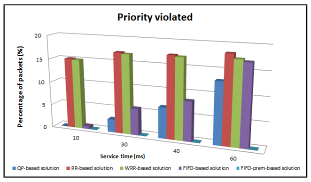
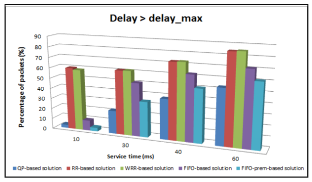


Fig. 5: QP-SH performances compared to existing solutions (the service time is fixed to 30 ms)

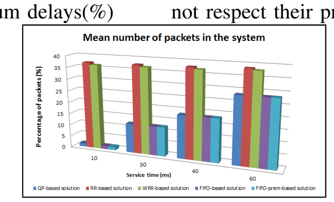
preemptive based-solutions based solutions for the majority of criteria. We also note that the number of QP-SH based packets that exceed their maximum delay (Fig.4(a)) and do not respect priority criterion (Fig.4(c)) decreases when we increase the arrival rate up to zero packets for arrival rates more than 40 packets/ms. Therefore, our approach performs better in heavy traffic networks which is the case of smart home network. However, varying the arrival rate has no impact on the performance of RR and WRR based solutions since they mainly focus on providing certain fairness between packets from different QoS levels. In Fig. 5 we consider the first scenario where the service time is fixed, and we compare the performance of our algorithm QP-SH and the existing RR, WRR, FIFO, and FIFO-prem based solutions. The comparison is made regarding a) the percentage of packets that exceed their maximum deadline, the percentage of packets that do not respect their priorities, and the mean number of packets in the system for different values of arrival rates. We note that the proposed QP-SH algorithm outperforms the existing solutions for the majority of criteria, with 15% higher for priority, 40% higher for the delay and 25% higher for the mean number of packets in the system. On the other hand, FIFO-prem based solution remains the optimal solution that guarantees priority criterion while increasing the delay since it is based only on priority. WRR and RR based solutions provide certain fairness between different QoS based packets while introducing the highest delay and the highest mean number of packets in the system. We also study the performance of



(a) Percentage of packets that exceed their maximum delays(%)



(b) Percentage of packets that do not respect their priorities(%)



(c) Mean number of packets in the system

Fig. 6: QP-SH performances for different values of service time compared to existing solutions

the proposed QP-SH and the existing based solutions (Fig. 6) regarding the impact of varying the service time on a) priority violation (Fig.5(a)), b) deadline violation (Fig.5(b)), and c) mean number of packets in the system (Fig.5(c)). We note that when we increase the service time per packet, the performance of all solutions decreases and QP-SH maintains the lowest values except for FIFO-prem in priority criterion.

VII. Conclusion

In this paper, we proposed a new dynamic queuing model for smart home network traffic generated by heterogeneous sources, to increase the number of packets that meet their deadline while preserving their degree of criticality. We tested our solution with 1000 network packets generating with different distributions. Then, we compared it to the existing based scheduling solutions for each criterion. Our experimental results demonstrated that the proposed algorithm outperforms the current solutions in almost the totality of criterion.

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