A New Traffic Model for Core-stateless Scheduling

Gang Cheng, Li Zhu, and Nirwan Ansari
Advanced Networking Laboratory
Department of Electrical and Computer Engineering
New Jersey Institute of Technology
University Heights, Newark, NJ 07102, USA

***Abstract*—Core-stateless scheduling algorithms can provide a similar level of guaranteed services as the stateful approach, while they do not need per-flow management. They hence possess both the properties of Quality-of-Service (QoS) provisioning and high scalability. In this paper, by showing the current existing traffic models are not applicable to core-stateless networks, a new and efficient traffic model for characterizing traffic in a core-stateless network is proposed, and its properties are presented.**

***Index Terms*— Core-stateless network, traffic scheduling, QoS**

I. Introduction

Many integrated service architectures were proposed [1]-[6] aiming to provide guaranteed services in packet-switched networks. These architectures possess properties of high flexibility and high degree of service assurance. Since they need to maintain per-flow state and per-packet classification, it is difficult to implement such solutions in a scalable fashion.

In contrast to the integrated service model, the differentiated service network architecture incorporates classification and conditioning functions only at network boundaries, and all flows belonging to a same class only share a single FIFO in core nodes, thus achieving a higher level of scalability than the integrated service architecture. However, it was shown [7] that the worst-case delay bound, which is a function of the hop count for a general network configuration (single FIFO), explodes at a certain utilization level, i.e., the worst-case delay at each router is bounded only when the network utilization level is limited to a factor smaller than $1/(H^*-1)$, where H^*, referred to as the network diameter, is the maximum number of hops a path is allowed. Thus, the overall network utilization must be limited to a small fraction of its link capacities in order to provide guaranteed delay services for all flows using FIFO. Aiming to overcome the above drawback of the differentiated services, Z. Zhang *et al.* [8] proposed two new classes of aggregated packet scheduling algorithms: the static earliest time first (SETF) and dynamic earliest time first (DETF). It was shown that the maximum allowable network utilization level can be greatly increased while the worst-case delay bound is decreased if additional time stamp information is encoded in the packet header. In [9], a core-stateless version of Jitter Virtual Clock (CJVC), which achieves the same worst-case delay bound as Jitter Virtual Clock, has been proposed. Like Jitter Virtual Clock, CJVC is non-work conserving, i.e., the server may be free even if there are packets in the buffer. The network resource may thus be under-utilized. In [10], a methodology to transform any stateful Guaranteed Rate (GR) per-flow scheduling algorithm into a core-stateless version was proposed. At the network edge, each packet is encoded with a time stamp which is a function of the packet's arrival time, and the amount of arrived traffic and the flow to which the packet belongs; this time stamp is updated at each core node. Packets are served according to the order of their time stamps. The proposed mechanism is proven to provide the same delay bound as the corresponding stateful GR server.

In literature, many traffic models have been proposed to characterize network traffic. Among them, the (σ,ρ) traffic model proposed in [11] owing to its simplicity and efficiency has been widely adopted for the network performance analysis; here, the network performance analysis is referred to as the analysis of the worst-case delay, worst-case jitter, packet loss ratio, and so forth. In this paper, it is shown that the (σ,ρ) traffic model is not appropriate for characterizing traffic in a core-stateless network. Instead, we introduce a new traffic model, the (β,α) traffic model, which can better describe flows in a core-stateless network. Based on this model, three important issues are addressed: time stamp encoding at the network edge, traffic pattern distortion in a core network, and the worst-case delay analysis. We also show that the time stamp encoding scheme proposed in this paper is optimal in terms of minimizing the worst-case delay bound of a flow.

Assumptions

1. We only consider an arbitrary network topology with links and switches where each link is associated with a delay bound (propagation delay), and each switch is non-blocking.
2. A packet is considered "arrived" only after its last bit has arrived.
3. Since a packet will only be delayed at a node if there is a packet being served, or there are packets waiting in the buffer with earlier time stamps, we assume the start time

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of each busy period is initialized at 0. The delivery time of a packet at a node is the time when the last bit of the packet leaves the node.

We assume that the time stamp of each packet lags behind its arrival time at any given node. This assumption may not hold for some core-stateless scheduling algorithms. However, note that packets are served by the order of their time stamps; the delivery order of packets will not change (thus, the delay for each packet to traverse the network remains the same) if the time stamps of all packets are increased by a constant D at the network boundary. Therefore, if D is large enough (for example, let D be the worst-case delay of any packet through a given network, if such a bound exists), our assumption can be satisfied. We assume that, if the burst of each flow is bounded and the capacity of any link is no less than the average rate of the flows traversing the link, there exists a worst-case delay bound in the network, i.e., the worst-case delay of a flow to traverse any pair of nodes in the network with a limited number of hops is bounded. The framework proposed in this paper is only applicable to a work-conserving core-stateless network with bounded-delay..

II. THE (β,α) TRAFFIC MODEL

We first introduce the core-stateless network model we used in this paper.

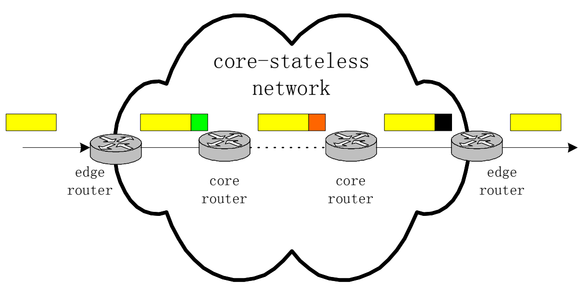

Figure 1. Core-stateless network model.

As shown in Fig. 1, routers are classified into edge routers, located at network boundaries, and core routers, located inside the network. When a packet arrives at the network boundary, the edge router will attach a label to the packet. The label includes some per-flow information such as the reserved bandwidth of the flow, and a time stamp, which could be a function of the arrival time of the packet, the packet length, and the reserved bandwidth. The time stamp may be updated at each core router. The label will be removed from each packet after it traverses the network. At all routers, packets are served by the increasing order of their time stamps.

In literature, the (σ,ρ) traffic model proposed in [11] has been widely adopted for characterizing traffic in a network, i.e., if the total traffic of a flow $F(t_1,t_2)$ arrived in the time interval $(t_1,t_2]$ is bounded by

$$F(t_1,t_2) \le \sigma + \rho(t_2 - t_1), \qquad (1)$$

this flow is referred to as conforming to the traffic parameter (σ,ρ). Packets are served by the order of their arrival times in the network where a single FCFS (First Come, First Served) queue is deployed in each node, and thus no per-flow information is maintained. In a stateful network, packets are served by the order of their time stamps, which are a function of the performance parameters, the amount of the previously arrived traffic of the corresponding flows, and the arrival times of the corresponding packets. Note that per-flow information is maintained at core nodes in the stateful network, and the performance parameters of each flow are static. Therefore, only one time parameter (arrival time) associated with each packet is enough for performance analysis in the stateful network and the "FCFS" network (where a single FCFS queue is used in each node), i.e., given the arrival times and sizes of all packets, the delivery time of each packet can be derived, and thus the worst-case delay and jitter of each flow can be computed. However, in a core-stateless network, per-flow information is not maintained in core nodes, and packets in the buffer are served by the order of their time stamps, not their arrival times. There is also no distinct relation between the time stamp of a packet and its arrival time. Consider the following example.

Given two CBR flows 1 and 2 that are contending for the bandwidth of a link with a capacity of $2L/c$. The reserved bandwidths of the two flows are both L/c, and all packets are of size L. However, the inter arrival times of two consecutive packets of flows 1 and 2 are c and $c/2$, respectively. Assume the first packets of both flows arrive at time 0, and the arrival time of the kth packet of flow i, $i=1,2$, is A_i^k, where $A_i^k=(k-1)c$ if $i=1$, and $A_i^k=(k-1)c/2$ if $i=2$. The time stamp attached to the kth packet of flow i is, however, kc, which is independent of i and will make each flow attain its reserved bandwidth. Therefore, it can be observed that the worst-case delay of flow 1 is c and it is infinity for flow 2. However, if the time stamp of the kth packet of flow i, $i=1,2$, is set to A_i^k+L/c, the worst-case delays of both flows become infinity. Assume the difference between the arrival time of a packet and its time stamp is known. The worst-case delay of each packet can be computed, which is the difference between its delivery time and its arrival time plus the worst-case delay of packets with respect to their time stamps. With (σ,ρ), the worst-case delay of packets is infinity. However, we cannot tell which flow will experience such delay. Therefore, instead of using the (σ,ρ) traffic model, we will develop another traffic model to characterize traffic in a core-stateless network, that could enable us to easily compute the worst-case delay of all packets with respect to their time stamps. Moreover, from the point of view of a node, packets are served only by the order of their time stamps, and their arrival times seem irrelevant. Thus, a packet with an earlier time stamp than another packet, though arrives later, may be served first. So, it is more reasonable to evaluate a packet's delay with reference to its time stamp, which is referred to as the ***virtual delay*** of a packet, rather than merely its arrival time. Therefore, a new mechanism to characterize traffic in the core-stateless network is necessary.

Since we evaluate the delay of a packet with reference to its time stamp, an intuitive idea to characterize a flow in the core-stateless network is to define a parameter (β,α) such that the total traffic of the flow of packets, whose time stamps are in the range of $(t_1,t_2]$, is no larger than $\beta+\alpha(t_2-t_1)$, similar to the (σ,ρ) traffic model. Assume packets are ordered by their time stamps as $P_1,P_2,...,P_k,...$ ($R_i \ge R_j$, if $i>j$; where R_i is the time stamp of packet P_i). Equivalently, for any two packets P_m and P_k ($k\ge m$), $\beta+\alpha(R_k-R_m)\ge\sum_{i=m}^{k}L_i$, where, L_i is the size of P_i. In this case, the parameter for the aggregated traffic of flow 1 and 2 in the above example is (L,c). However, note that the virtual delay of each packet is 0, and the intuitive implication of the virtual traffic parameter (L,c) is that the worst-case virtual delay of a packet (i.e., the worst-case delay with reference to its time stamp) is L/c. A packet may receive service as long as there is no packet in the buffer when it arrives. Thus, it is necessary to take into account of the arrival time of a packet to characterize traffic in the core-stateless network. Therefore, we define the ***virtual traffic parameter*** (β,α) $(\alpha>0,\beta\ge 0)$ ***of a flow as follows: for any two packets*** P_k ***and*** P_m ***of this flow (*** $k\ge m\ge 1$ ***),*** $\beta+\alpha(R_k-\max\{R_{m-1},\min\{A_m,A_{m+1},...,A_k\}\})\ge\sum_{i=m}^{k}L_i$, ***where*** A_i ***is the arrival time of packet*** P_i, $i=1,2,...$, we refer to $F(t_1,t_2)=\beta+\alpha(t_2-t_1)$ in the time interval $(t_1,t_2]$ as the ***virtual traffic function*** of this flow with the virtual traffic parameter (β,α), and the traffic model for characterizing traffic in the core-stateless network with the virtual traffic parameter is referred to as the (β,α) traffic model.

Our proposed traffic model, the (β,α) traffic model, is different from those proposed in the literature. A virtual reference system that has the virtual space property: $R_{k+1}-R_k\ge L_{k+1}/\alpha$, is introduced in [12]. It can be observed that, only when $\beta=0$, the (β,α) traffic model possesses the virtual space property. A scheduler is said to possess the Coordinated Multihop Scheduling (CMS) property [13] if

- $R_k=A_k+\delta_k$ at the entrance node,
- $R_k=R_{k-1}+\delta_{k-1}$ at a core node,

where $\delta_k\in[\delta-\eta,\delta+\eta]$, δ and η are two constants that may vary with different nodes and flows. Since we do not place any constraint on the difference of the time stamps of two consecutive packets ($|R_k-R_{k-1}|$ and $|R_k-A_k|$ could be infinity in our traffic model), the (β,α) traffic model does not possess the CMS property. Note that the time stamp is referred to as the priority index in [13].

III. PROPERTIES OF THE (β,α) TRAFFIC MODEL

Since packets are served by the order of their time stamps, and no per-flow information is maintained at core nodes, all packets are treated as if they belong to a single flow. Therefore, the performance analysis of an individual flow at a node can be achieved by analyzing the performance of the aggregated flow at this node, which can be facilitated with the knowledge of the aggregated flow's traffic parameter. It is well known that the aggregated traffic of two flows with traffic parameters of (σ_1,ρ_1) and (σ_2,ρ_2) in the (σ,ρ) traffic model, respectively, has the traffic parameter $(\sigma_1+\sigma_2,\rho_1+\rho_2)$. Here, we show that the aggregated traffic in a core-stateless network also possesses the same additive property by Theorem 1 with respect to the virtual traffic parameter.

[Theorem 1] Given two flows with virtual traffic parameters (β_1,α_1) and (β_2,α_2), the virtual traffic parameter of the aggregated traffic of the two flows is $(\beta_1+\beta_2,\alpha_1+\alpha_2)$.

Proof: Assume packets are ordered by their time stamps. Given any two packets P_k and P_m ($k\ge m$) of the aggregated flow, assume packets P_{i_1}, $P_{i_2},\ldots,P_{i_n}$, ($i_1<i_2<...<i_n$ and $n\le(k-m+1)$) belong to flow 1, and the rest of packets $P_{j_1},P_{j_2},...,P_{j_p}$, ($j_1<j_2<...<j_p$ and $p\le k-m+1$) belong to the other flow. Thus, by definition of the virtual traffic parameter,

$$\beta_1+\alpha_1(R_{i_n}-\max\{R_{i_1-1},\min\{A_{i_1},A_{i_2},...,A_{i_n}\}\})\ge\sum_{s=i_1}^{i_n}L_s, \qquad (1)$$

and

$$\beta_2+\alpha_2(R_{j_p}-\max\{R_{j_1-1},\min\{A_{j_1},A_{j_2},...,A_{j_p}\}\})\ge\sum_{s=j_1}^{j_p}L_s. \qquad (2)$$

Since $\max\{R_{i_n},R_{j_p}\}=R_k$, $\min\{\min\{A_{i_1},A_{i_2},...,A_{i_n}\},\min\{A_{j_1},A_{j_2},...,A_{j_p}\}\}=\min\{A_m,A_{m+1},...,A_k\}$ and $\min\{R_{i_1-1},R_{j_1-1}\}=R_{m-1}$,

$$\begin{aligned}&(\beta_1+\beta_2)+(\alpha_1+\alpha_2)(R_k-\max\{R_{m-1},\min\{A_m,A_{m+1},...,A_k\}\})\\ &\ge[\beta_1+\alpha_1(R_{i_n}-\max\{R_{i_1-1},\min\{A_{i_1},A_{i_2},...,A_{i_n}\}\})]+\\ &\quad[\beta_2+\alpha_2(R_{j_p}-\max\{R_{j_1-1},\min\{A_{j_1},A_{j_2},...,A_{j_p}\}\})]\\ &\ge\sum_{s=m}^{k}L_s. \qquad (3)\blacksquare\end{aligned}$$

By Theorem 1, the virtual traffic function of an aggregated traffic can be derived provided that all the virtual traffic functions of individual flows are known.

In Theorem 1, in order to derive the virtual traffic parameter of the aggregated flow, we assume the traffic parameters of all individual flows are known. A connection's traffic can be characterized at the entrance to the network, but the traffic pattern may be distorted inside the network, and thus the source characterization is not applicable at a core node traversed by the connection. Moreover, as one of the major components for some core-stateless scheduling algorithms, such as DETF and GR, packets' time stamps are updated at core nodes, that may also contribute to the traffic pattern distortion. From the viewpoint of the virtual traffic function, we provide Theorem 2 to analyze the variation of the traffic parameter of a flow in a core-stateless network.

[Theorem 2] Assume the traffic parameter of the input traffic of a flow at a node is (β,α), and the worst-case virtual delay to traverse this node is D. The virtual traffic parameter of the output traffic of this flow is (β',α) if all of its packets are updated by an increment d at this node, where $\beta' = \max\{0, \alpha(D-d)+L_{\max}\}+\beta$.

Proof: Assume packets are ordered by their delivery times, i.e., for packets P_k and P_m, $(k \ge m)$, $T_k \ge T_m$, where T_i, the delivery time of packet P_i, $i=1,2,...$, is also the arrival time of P_i of the output traffic. Since the worst-case virtual delay is D, for any packet P_i, $i=1,2,...$

$$T_i \le R_i + D. \quad (4)$$

Furthermore, since the time stamp of each packet that has been delivered by node j is updated by d, and $\beta' = \max\{0, \alpha(D-d)+L_{\max}\}+\beta$, for any two packets k and m $(k \ge m \ge 1)$,

$$\begin{aligned}&\beta' + \alpha[R_k + d - \max\{R_{m-1}+d, T_m\}]\\ &\ge \beta' + \alpha[R_k + d - \max\{R_{m-1}+d, R_m + D\}]\\ &\ge \min\{\beta+\alpha(R_k - R_{m-1}), \beta + L_{\max} + \alpha(R_k - R_m)\}. \quad (5)\end{aligned}$$

By the definition of the virtual traffic function,

$$\begin{aligned}&\beta + \alpha[R_k - \max\{R_{m-1}, \min[A_m, A_{m+1},...,A_k]\}].\\ &\ge \sum_{i=m}^{k} L_i \Rightarrow \alpha(R_k - R_{m-1}) \ge \sum_{i=m}^{k} L_i. \quad (6)\end{aligned}$$

Thus, define $R_i' = R_i + D + \frac{L_{\max}}{\alpha}$ as the time stamp of packet P_i in the output traffic, $i=1,2,...$; by Equations (5) and (6),

$$\begin{aligned}&\beta + \alpha[R_k' - \max\{R_{m-1}', \min[T_m, T_{m+1},...,T_k]\}]\\ &\ge \min\{\beta + \alpha(R_k - R_{m-1}), \beta + L_{\max} + \alpha(R_k - R_m)\}\\ &\ge \min\{\sum_{i=m}^{k} L_i, \sum_{i=m+1}^{k} L_i + L_{\max}\} \ge \sum_{i=m}^{k} L_i. \quad (7)\end{aligned}$$

Therefore, the virtual traffic parameter of the output traffic of this flow is (β',α). ■

[Lemma 1] Assume the traffic parameter of the input traffic of a flow at a node is (β,α), and the worst-case virtual delay to traverse this node is D. Assume the propagation delay for a packet of this flow to transmit from node j to its next node is δ. The virtual traffic parameter of the input traffic of this flow at the next node is (β',α) if all its packets are updated by an increment d at this node, where $\beta' = \max\{0, \alpha(D+\delta-d)+L_{\max}\}+\beta$.

Proof: From the viewpoint of the input port of a node, the worst-case virtual delay of a flow is $D+\delta$ if there is no time stamp update at the previous node of this flow, where D is the worst-case virtual delay of this flow at that node, and δ is the propagation delay between the two nodes. Thus, by Theorem 2, the virtual traffic parameter of the input traffic of this flow at this node is (β',α) if all of its packets are updated by an increment d at the previous node, where $\beta' = \max\{0, \alpha(D+\delta-d)+L_{\max}\}+\beta$. ■

Based on the concept of the virtual traffic function and parameter, and their properties, we shall next analyze and derive the worst-case delay of a flow to traverse a node in a work-conserving core-stateless network, with the assumption that the virtual traffic function of the aggregated flow or all individual flows is known.

[Theorem 3] Assume the input traffic of a node consists of flows $1,2,...,v$, whose virtual traffic parameters are (β_i,α_i), respectively, and the capacity of the output link of this node is c, $(c \ge \sum_{i=1}^{v}\alpha_i)$. Let packets of each flow be ordered by their delivery times, and P_k^i represents the k_{th} packet of flow i. Define $\theta_i = \max\{\min_{k \ge m > 1}\{R_{m-1}^i - \min\{A_m^i, A_{m+1}^i,...,A_k^i\}\}, 0\}$, where R_m^i and A_m^i are the time stamp and arrival time of P_m^i. Thus, the worst-case virtual delay at this node is bounded by

$$\frac{\sum_{i=1}^{v}(\beta_i - \alpha_i\theta_i) + L_{\max}}{c}, \quad (8)$$

where $L_{\max}$ is the maximum size of a packet.

Proof: Let P_k $(k=1,2,...)$ represent the k_{th} packet of an aggregated flow in which packets are ordered by their time stamps. For any packet P_k, assume m be the largest integer $k > m > 0$ such that $R_k < R_m$ and $T_k > T_m$, where R_i and T_i are the time stamp and delivery time of P_i. Thus,

$$R_m > R_k \ge R_i \text{ for all } m < i < k, \quad (9)$$

and

$$T_k > T_i > T_m \text{ for all } m < i < k. \quad (10)$$

That is, packet P_m is transmitted before packets $P_{m+1},...\ ,P_k$; however, its time stamp is larger than that of packets $P_{m+1},...,P_k$. So,

$$\min\{A_{m+1},...,A_k\} > T_m - \frac{L_m}{c}. \quad (11)$$

Since $P_{m+1},...,P_k$ arrive after $T_m - \frac{L_m}{c}$, and depart before P_k,

$$T_k = T_m + \frac{\sum_{i=m+1}^{k} L_i}{c}. \quad (12)$$

Note that $R_i \ge A_i$ (Assumption 4) for all $i=1,2,...$, and thus $R_k \ge R_i \ge A_i \ge T_m - \frac{L_m}{c}$ for $i = m+1,...,k-1$. Furthermore, according to the definition of the virtual traffic function,

$$\begin{aligned}&\theta_i = \max\{\min_{k \ge m > 1}\{R_{m-1}^i - \min\{A_m^i, A_{m+1}^i,...,A_k^i\}\}, 0\}\\ &\Rightarrow \min\{A_m^i, A_{m+1}^i,...,A_k^i\} + \theta \le \max\{R_{m-1}^i, \min\{A_m^i, A_{m+1}^i,...,A_k^i\}\}\\ &\Rightarrow \beta_i + \alpha_i[R_k^i - (\min\{A_m^i, A_{m+1}^i,...,A_k^i\} + \theta_i)] \ge \sum_{j=1}^{k} L_j^i. \quad (13)\end{aligned}$$

Since packets $P_{m+1},...,P_k$ comprise the packets of flows $1,2,...,v$,

$$\begin{aligned}&\sum_{i=m+1}^{k} L_i \le \sum_{i=1}^{v}\{\beta_i + \alpha_i[R_k - (\min\{A_m, A_{m+1},...,A_k\} + \theta_i)]\}.\\ &\le \sum_{i=1}^{v}(\beta_i - \alpha_i\theta_i) + (\sum_{i=1}^{v}\alpha_i)[R_k - (T_m - \frac{L_m}{c})]. \quad (14)\end{aligned}$$

From Equations (12) and (14),

$$T_k = T_m + \frac{\sum_{i=m+1}^{k} L_m}{c}$$

$$\leq T_m + \frac{(\sum_{i=1}^{v}\alpha_i)[R_k - (T_m - \frac{L_m}{c})] + \sum_{i=1}^{v}(\beta_i - \alpha_i\theta_i)}{c}$$

$$\leq R_k + \frac{L_{\max}}{c} + \frac{\sum_{i=1}^{v}(\beta_i - \alpha_i\theta_i)}{c}$$

$$\Rightarrow T_k - R_k \leq \frac{L_{\max}}{c} + \frac{\sum_{i=1}^{v}(\beta_i - \alpha_i\theta_i)}{c}. \quad (15)$$

If there does not exist such m, then $P_1,...P_{k-1}$ all leave the node before P_k; thus

$$T_k = \frac{\sum_{i=1}^{k}L_i}{c} \leq \frac{(\sum_{i=1}^{v}\alpha_i)R_k + \sum_{i=1}^{v}(\beta_i - \alpha_i\theta_i)}{c}$$

$$\Rightarrow T_k - R_k \leq \frac{\sum_{i=1}^{v}(\beta_i - \alpha_i\theta_i)}{c}. \quad (16)$$

So, for any packet, its virtual delay is bounded by $\frac{\sum_{i=1}^{v}(\beta_i - \alpha_i\theta_i) + L_{\max}}{c}$. ■

It should be noted that, by deploying our proposed (β,α) traffic model, the design and performance analysis of core-stateless algorithms such as the one proposed in [10] can be easily achieved. For example, in order to make the virtual traffic parameter of each flow at the input port of any node $(0,\alpha)$, where α is the requested rate of this flow, by Lemma 1, all its packets' time stamp of this flow should be updated by an increment $d = D + \delta + \frac{L_{\max}}{\alpha}$ at a node, where D is its worst-case virtual delay to traverse this node, and the δ is the propagation delay from its previous node to this node. Moreover, by Theorem 3, it can be derived that $D = \frac{L_{\max}}{c}$, because the virtual traffic parameters of all flows are in the form of $(0,\alpha)$. Therefore, the time stamp increment of a flow at a node is $d = \frac{L_{\max}}{c} + \delta + \frac{L_{\max}}{\alpha}$, which is the same the one in [10].

IV. CONCLUSIONS

In this paper, by showing that the current existing traffic models are not applicable to core-stateless networks, a new traffic model, the (β,α) traffic model, for core-stateless networks is proposed, and its properties are presented. It has been shown that it is simple and efficient.

However, as the first step for a core-stateless network to deliver packets, time stamps are encoded in packets at network boundaries. Since we propose the (β,α) traffic model to describe the traffic in a core-stateless network, it is necessary to investigate how to encode time stamps of packets of a flow that conforms to a given virtual traffic parameter. We will address this issue by proposing a time stamp encoding mechanism in our next paper, and show that it is optimal in terms of minimizing the end-to-end worst-case delay of a flow to traverse a core-stateless network. Moreover, we will also provide the worst-case delay of any flow in a core-stateless network with our proposed (β,α) traffic model.

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