A Markov Model of CCN Pending Interest Table Occupancy with Interest Timeout and Retries

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***Abstract*—The occupancy of the pending interest table (PIT) in content-centric networks (CCN) and other information-centric networking (ICN) architectures has an undeniable effect on the congestion level and the performance of the network. Each interest packet forwarded upstream by a node results in at most one data packet arriving back at the node and being possibly forwarded to many interfaces downstream. Clearly, to regulate the rate of arrival of new data chunks at a node, one can regulate the arrival rate of interest packets. To be able to design effective mechanisms to control the traffic in CCN, a systematic study and analysis of the PIT occupancy is thus imperative. In this paper, we derive an analytical model to estimate the PIT occupancy distribution via an approximate continuous time Markov (CTMC) model and validate the model via simulation experiments with different system parameters. Our proposed model is not only useful in the design of traffic controllers for managing the PIT occupancy but also offers an effective method for dimensioning the PIT.**

I. Introduction

The emergence of content-centric networking (CCN) [1] and named-data networking (NDN) [2] brought a change in the future Internet communication model from a host-centric to a content-centric approach. With this new networking paradigm, network resource efficiency is put forward and is enforced via a bundle of features such as universal in-network caching where each data chunk that traverses a node is cached in the node for future reuse if possible, and interest aggregation to avoid repeated forwarding upstream of content requests that are already pending in the PIT. These two techniques already prune out a great deal of redundant traffic from the network. Nevertheless, due to various reasons, such as the preponderance of non-reusable (one-timer) content in the network, the popularity distribution of traffic and the huge ratio of the universal content available to the cahce sizes in the nodes, congestion can still take place in such networks, which warrants the design of new clean-slate congestion control mechanisms that stem from the characteristics of CCN/ICN.

Every interest packet forwarded upstream by a CCN node returns at most one data packet which in turn is forwarded downstream at most one per interface. To regulate the rate of arrival of new data chunk one can regulate the rate of arrival of interests. Therefore, the first step towards developing effective and efficient congestion control mechanisms for CCN and other ICN proposals, is to analyse and characterize the occupancy of the Pending Interest Table (PIT), a data structure that keeps track of all interests forwarded upstream, as it influences directly the occupancy of the data packet transmission buffer.

In this perspective, one needs to take into account several aspects of the characteristics of the PIT, such as interest blocking, interest timeout, interest retries, interest filtering due to cache hit in the node and interest filtering due to aggregation. We have studied this problem recently in [3] and modelled the CCN PIT occupancy analytically using the system model shown in Fig. 1. In this model, the PIT P is instantiated by a multi-server loss queueing model where each server represents one entry in the PIT. The service time of each PIT entry represents its lifetime derived directly from the average round trip time distribution in a network. The round-trip time in this case is the time from when an interest is forwarded upstream and occupies an entry in the PIT at a given CCN node until the time this interest is consumed (purged) by the corresponding data chunk that arrives back at the node.

Each PIT entry that is created occupies a server in P until a data packet returns and consumes it or it times out. Interests that arrive at the PIT and for which there is already a copy pending are aggregated and therefore the rate of arrival of interests is scaled down by a factor of h_p which represents the hit rate in the PIT. Blocked interests (i.e., interests that cannot be aggregated and that arrive to a full PIT) as well as timed out PIT entries generate a possible retry after a constant time out interval. The number of such interest packets pending retry is tracked by queue D that has an infinite capacity. To study this system, we proposed a two-dimensional continuous time Markov chain (CTMC) in [3] and resorted to truncation on the size of queue D to solve the model numerically. To reduce the complexity of such model, we propose a more accurate and less complex approach in this paper where we resort to state aggregation and approximation instead of truncation.

In this paper, we present this simpler analytical model of the CCN PIT occupancy using an approximate two-dimensional CTMC to estimate the interest packet blocking probability at a given node in the network. The effect of the detailed description of the new and retransmitted interest arrival process on the complexity of the model solution is alleviated. The blocking probability is defined as the probability that an arriving interest finds the PIT full and is dropped eventually given the size of a CCN PIT and traffic load at a node. We then validate the model via simulation experiments including numerical results

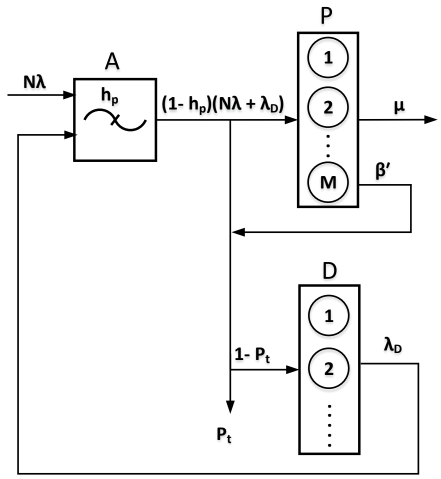

Fig. 1: System model

showing the impact of the PIT size, network load and PIT entry timeout on the performance. In addition we compare the results of the present model to those obtained from the truncated CTMC model in [3].

The remainder of this paper is organized as follows. Section II describes our analytical model of the CCN PIT while our network model is described in Section III-A including numerical results that show our model validation and analysis. Related works on the performance study and analysis of the PIT are given in Section IV. We conclude this paper in Section V.

II. Analytical Model of the PIT Occupancy

This section presents an analytical model of the PIT using approximate CTMC. We focus on the estimation of the interest packet blocking probability while taking into account caching, aggregation, blocking, timeout and retries.

The system model is shown in Fig. 1 and described in the following section.

A. Model description and assumptions

A PIT of size M entries is considered, in which interest packets from N consumers are received. We assume the arrival process of new interests at the CCN node after filtering by the content store (CS) follows a Poisson process with rate λ for each consumer such that the total rate of new interest arrival at the node after filtering at the CS is $N\lambda$. This assumption has been validated in [3] via a simulation study of the in-network content filtering effects in CCN. Indeed, it is well know that due to the skewed content popularity distribution and the caching that takes place in CCN, heavy interest filtering takes place at access nodes, and only those interests that are not cached in the access nodes would reach the network. We have verified in [3] via simulation that the deeper we go in the network towards a content origin server the closer the interest inter-arrival times get to an exponential distribution.

This simple system can be modelled by a M-server queueing system with no waiting room with an arrival process that follows Poisson with rate $N\lambda$ as shown in Fig. 1. We denote the PIT hit rate as h_p. Arriving interests with the same name as an existing PIT entry are further filtered. Only new interest arrival at the PIT triggers the creation of a new entry in the PIT; therefore the creation of new entries in the PIT follows a Poisson process with a rate of $\lambda' = (1-h_p)N\lambda$. In our system model shown in Fig. 1, this is represented by the action of aggregator element A.

Depending on the status of caching nodes, the content popularity and the rate of arrival of requests for the same data chunk, the same interest can fetch content from different nodes in the network at different times. As such, we assume the time from when an interest is forwarded upstream to the time the requested data chunk is received to be exponentially distributed with rate μ

New interests that arrive at the PIT and find the PIT full are blocked and pending interests that timeout and expire may retry transmission. In this case, they enter an infinite queue D with probability $1 - P_t$ to wait for their timer for retransmission. In particular, a consumer decides not to retransmit an interest with probability P_t, and retransmitted interests arrive at P with rate $\alpha = (1 - h_p)\lambda_D$.

Pending interests (entries) in the PIT may timeout when the forwarded interests take relatively too long time to return data or fail to return data. Such pending entries whose timers expire leave queue P at a conditional rate $\beta' = 1/T$ where T is the PIT entry timeout. Therefore, we assume the times t between the creation and deletion of PIT entries to follow a truncated exponential distributed instead. We define the rate of requests that timeout as: $\eta = 1 - e^{-\mu T}$ which holds for any waiting time $t > T$.

B. Approximate Continuous Time Markov Chain model of Pending Interest Table

Similar to [3], we assume that downstream and upstream nodes do not change the arrival process of interests at a given node. Therefore, we can approximate the system performance by analysing the PIT of a single node in isolation. In [3] we model the PIT at a single node by a 2-dimensional Markov process. We model the PIT as a queueing system with M servers (PIT entries) with no waiting queue, denoted by P. See Fig. 1. We represent each state in the model by the 2-tuple (i, j) where $i = 0, \ldots, M$ is the number of pending interests in the PIT and $j = 0, \ldots$ is the number of interests in the system waiting for retry.

To solve the Markov chain in [3], we reduce the state space by truncation, an approach that is associated with several shortcomings described in Sections I and IV. To overcome these shortcomings, we propose to use an approximate CTMC, an approach that was proposed by Marsan *et al.* in [4] for estimating call blocking probability in cellular networks with customer retrials. In this paper, we represent each state in our model by the 2-tuple (i, d) where i is the same as defined earlier (i.e., represents the number of PIT entries containing pending interests) while d is a Boolean variable representing the presence of blocked interests in queue D awaiting retry or not: $d = 1$ if the retry queue D is non-empty, otherwise, $d = 0$. In this case, the state space is simply $2(M + 1)$ states

In the approximate CTMC, d indicates only the existence of a blocked/timeout interest in the queue D while hiding the detailed information about the number of blocked/timeout interests. Denoting $\overline{N}_D$ as the average number of blocked/timeout interests in the system, the rate at which blocked/timeout interests are retransmitted is $\overline{N}_D\lambda_D$. Similar to [4] we define a probability P as the probability that a blocked or timeout interest finds queue D non-empty. P is used to estimate $\overline{N}_D$. We follow the approach used in [4] to estimate $\overline{N}_D$ and P. However, we modify the approach to cater for interests whose timeout have expired and therefore enter queue D

Fig. 2 shows the state transition rate diagram of our approximate CTMC model with M entries and $d \in \{0, 1\}$. We define $\mu' = (1 - \eta)\mu + \eta\beta' P_t$ and $\beta = (1 - P_t)\eta\beta'$. We also define two rates of retry from queue D, ω (that leaves queue D empty, i.e. $\omega = (1 - P)\overline{N}_D\lambda_D$) and γ (that leaves queue D non-empty, i.e. $\gamma = P\overline{N}_D\lambda_D$). We define ω as the average conditional rate of retry from queue D given that queue D is empty while γ as the average conditional rate of retry from queue D given that queue D is non-empty. The rates and the events that trigger the transitions in Fig. 2 are as follows:

- A new interest arrives and queue D is empty: Corresponds to $(i, 0) \rightarrow (i + 1, 0), 0 \leq i < M$ and happens at a rate of λ'
- An interest arrives and queue D is non-empty: Corresponds to $(i, 1) \rightarrow (i + 1, 1), 0 \leq i < M$ and happens at a rate of $\lambda' + \gamma$
- A pending interest is consumed by a returned data packet before the corresponding PIT entry's timeout expires and queue D is empty: Corresponds to $(i, 0) \rightarrow (i-1, 0), 0 < i \leq M$ and happens at a rate of $i\mu'$
- A pending interest is consumed either by a returned data packet or the PIT entry's timeout expires and queue D is non-empty.: Corresponds to $(i, 1) \rightarrow (i - 1, 1), 0 < i \leq M$ and happens at a rate of $i(\mu' + \beta)$
- A PIT entry's timeout has expired while no blocked/timeout interest in queue D. The timeout interest is queued in the retry queue D: Corresponds to $(i, 0) \rightarrow (i - 1, 1), 0 < i \leq M$ and happens at a rate of $i\beta$
- A new interest arrives when the PIT is full and queue D is empty: Corresponds to $(M, 0) \rightarrow (M, 1)$ and happens at a rate of $(1 - P_t)\lambda'$
- The last interest in queue D is retransmitted causing queue D to become empty: Corresponds to $(i, 1) \rightarrow (i + 1, 0), 0 \leq i < M$ and happens at a rate of ω
- The last interest in queue D is retransmitted when the PIT is full and the blocked/timeout interest decides not to enter retry queue D. The timeout or blocked interest is retransmitted from the retry queue D: Corresponds to $(M, 1) \rightarrow (M, 0)$ and happens at a rate of $P_t\omega$

Let $\Pi_{i,d}$ denote the probability that the system is in state (i, d). To obtain the model solution, we express P and $\overline{N}_D$ as

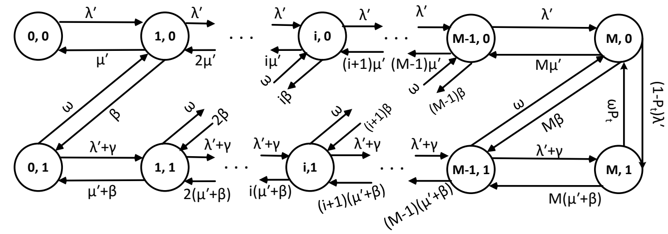

Fig. 2: Transition diagram of CTMC model for the existence of a blocked/timeout interest

Equation 1:

$$\overline{N}_D = \frac{P}{1 - P} \tag{1}$$

where P is given as Equation 3

$$P = \frac{\lambda' \sum_{i=0}^{M} \Pi(i, 1)}{\lambda' (\sum_{i=1}^{M} \Pi(i, 0) + \sum_{i=0}^{M} \Pi(i, 1))} \tag{2}$$

$$= \frac{\sum_{i=0}^{M} \Pi(i, 1)}{\sum_{i=1}^{M} \Pi(i, 0) + \sum_{i=0}^{M} \Pi(i, 1)} \tag{3}$$

We use a similar iterative method used in [4] to compute the values of P and $\overline{N}_D$. The method stops when a level of relative accuracy of 10^{-6} is reached.

We apply the normalization condition, $\sum_i \sum_d \Pi_{i,d} = 1$ and solve the system of equation numerically for the equilibrium state probabilities, from which we can calculate the interest blocking probability P_B defined as Equation 4:

$$P_B = \sum_{d \in 0,1} \Pi_{M,d} \tag{4}$$

III. Numerical Results

In this section we validate our approximate model via simulation using a realistic network with realistic traffic. We also compare the accuracy of our model to the truncation method in [3]. Table I describes the notations used in the simulation model. We consider an access router and assume the arrival process of users to the router follows a Poisson process with rate λ_u. Every user that arrives requests a particular content drawn from the content popularity distribution. Each content consists of a number of data chunks that are requested at a constant rate λ_c until all the data chunks belonging to this content are received. The superposition of all user requests results in a process that consists of primary events that follow a Poisson distribution, and where each of them triggers a number of secondary events that are deterministic with respect to their primary event. Such queueing system has been studied in [5] and is known to be non-Markovian. We assume the content

TABLE I: Notations and their definitions

Symbols	Meaning
L	Number of access routers
κ	Average size of a content (in chunks)
τ_n	Average RTT from node n to the content producer
λ_u	Average arrival rate of users per access router
λ_c	Average chunk request rate per user
t_u	Average time spent by a user before departure

popularity follows a Zipf distribution. We denote by κ the average content size in number of chunks. Every user also has a timer for each chunk request forwarded upstream. Upon expiration, the user retransmits the request with the same rate λ_c.

Note that there are no publicly available real CCN traffic traces at the time this work was carried out. As such we adopt in this paper the traffic characteristics described earlier in this section.

In [3] we derive an equation for the average number of entries in the PIT for a given node n, Γ_n as Equation 5

$$\Gamma_n = L\lambda_u t_u \lambda_c \tau_n (1-h_c)(1-h_p) \quad (5)$$

where $L, \lambda_u, t_u, \lambda_c$ and τ_n are defined in Table I. To avoid setting the size of the PIT too small or too large in the case of finite PIT size, we use the worst case (when $h_c = 0$ and $h_p = 0$) average PIT size to guide the setting of the size of the PIT used in our simulation experiments.

A. Simulation description and set-up

First we use a network topology, obtained from Rocketfuel network topology traces for ISP Exodus [6]. The topology consists of 157 routers and 341 links. To avoid over-burdening our simulator, we remove nodes and links carrying traffic that is of little or no impact on our simulation results. The resulting topology is shown in Fig. 3. Interested readers are referred to [3] for details on how we obtain the network topology shown in Fig. 3.

Our interest is to analyse the performance impact of traffic load on the PIT occupancy. Therefore, we set the link capacities and delays as follows. The capacities and delays of backbone to backbone links are set as 1Gb/s and 20ms, respectively; gateway to access router links are set as 0.1Gb/s and 5ms, respectively and backbone to gateway (including gateway to gateway) links are set as 0.5Gb/s and 10ms, respectively. The size of each data chunk is 1500 bytes. We use proWGen [7] to generate workloads for our simulation experiments with content popularity following Zipf distribution with parameter α. All content requests at each access router share the same content popularity. Table II gives other simulation parameters. Using the ndn/ccn ns-3 modules [8], the network model described earlier in this section was simulated in ns-3. We use our custom application module in [3] that can use our workload generated by ProwGen and match our network model well in ns-3.

We consider two scenarios in our simulation experiments:

- **Scenario 1:** Users send requests for contents through an access router. The router forwards the requests to upstream routers. Each request is satisfied by an upstream router with a uniform probability. Interest packets arrive at the access router at a rate of 3000 interests per second and we set the interest life time to 1s. The link capacities are set such that they do not contribute to the PIT occupancy. This scenario is used to verify and validate the accuracy of our model. We obtain the model solutions numerically via an iterative method that stops when a level of relative accuracy of 10^{-6} is reached.
- **Scenario 2:** The network topology considered in this scenario is shown in Fig. 3. Traffic and user characteristics are as described in Section III-A. All nodes in the network, except node br-2, has an infinite PIT size. Each node has a cache of size 1% of the content universe. Node br-2 has a finite PIT size. We also use this scenario to validate our approximate model.

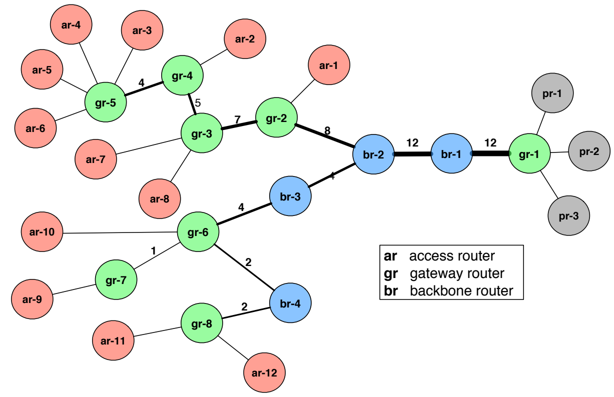

Fig. 3: Network topology: gray nodes are content servers, red nodes are access routers (requesters), green nodes are gateway routers and blue nodes are backbone routers. Edge labels indicate the number of paths from red nodes to gray nodes that share the edges.

TABLE II: Values of simulation parameters

Parameter	Values
#requests per access router	10,000
Zipf skewness, α	0.75
#distinct content	4,200
Mean κ (and standard deviation) of content size, in chunks	193 (160)
Size of PIT (entries: one entry denotes one distinct interest)	infinite, finite (1000)
Cache size (chunks)	1% of universe content
Arrival rate of users (users/sec/node)	10
Chunk request sending rate (chunks/user/sec)	10

B. Model validation using Scenario 1

For the simulation results, we report the 95% confidence intervals of the average interest blocking probability over several simulation runs. We collected the interest blocking probabilities at the access router for different values of the PIT size and network load. We consider different values of the PIT size in the simulation from 100 to 500 for heavily

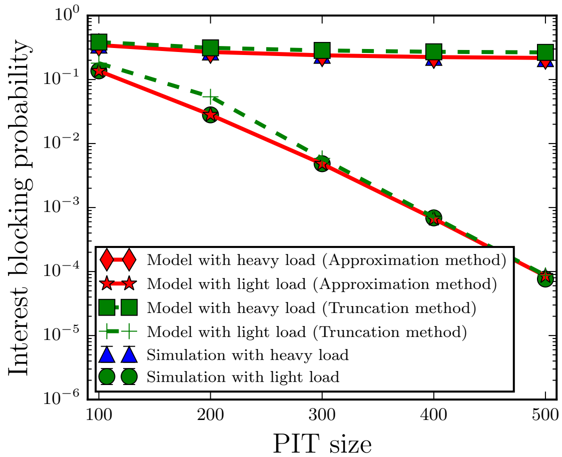

Fig. 4: Scenario 1: Interest blocking probability versus PIT size in heavily and lightly loaded networks

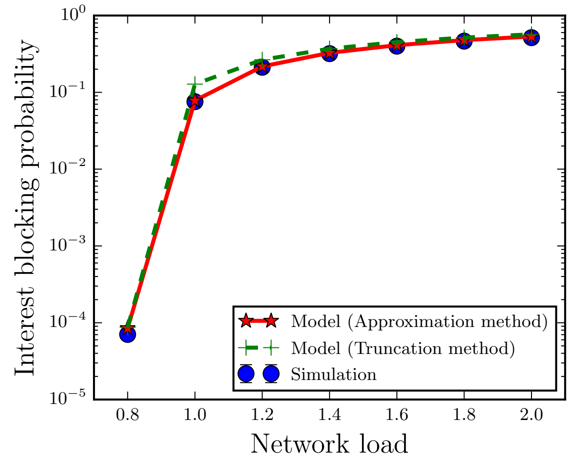

Fig. 5: Scenario 1: Interest blocking probability versus network load ρ

and lightly loaded networks. Fig. 4 shows how the interest blocking probability varies with increasing size of the PIT in both heavy load and light load networks. As we expect, the blocking probability decreases with increasing PIT size for both simulation and model. For Scenario 1 that we consider, we achieve over 90% accuracy in heavily and lightly loaded networks while comparing the results from simulation to our model.

In addition, we analyse the impact of the network load on the interest blocking probability by considering different values of the network load ρ in the range [0.8, 2.0] for a fixed value of the PIT size, 500 in this case. As shown in Fig. 5, we observe that increasing the load in the network leads to a higher probability of blocking an arriving interest packet at a router. Interestingly, the results from our model match the simulation with over 90% accuracy. On the comparative performance of our CTMC models with approximation and truncation methods, the approximate CTMC model is slightly more accurate than the truncated CTMC model in addition to being computationally less costly in terms of memory space and CPU time.

Note that in our model, we assume that the service times (the time from when an entry in the PIT is created to the time the entry is consumed by the arrival of the requested data chunk) are exponentially distributed. In the simulation, the distribution of the service times for Scenario 1 is not exponential but uniform. The results given in Fig. 4 and Fig. 5 show that our model is independent of the service times distribution but on the average value.

C. Model validation using Scenario 2

To see how well the results from our model match simulation results in a more complex network topology than the one used in Scenario 1, we simulate Scenario 2. We consider a single node br-2 in Fig. 3 and collected the interest blocking probabilities for different sizes of the PIT in heavily and lightly loaded networks. We vary the PIT size in the range $[1000, 1400]$ and the rate at which users arrive the network (10 and 20 users per second). In this Scenario, we also report the 95% confidence intervals of the average interest blocking probability over several simulation runs. Clearly, Fig. 6 shows that increasing the size of the PIT decreases the interest blocking probability for the results from our model and simulation for both user arrival rates. The figure further shows the accuracy of our model including its independence on the service times distribution as contents can be fetched from any nodes beyond br-2 up to the content producer. On the comparative performance of our CMTC models, similar behaviour to Fig. 4 and Fig. 5 is observed.

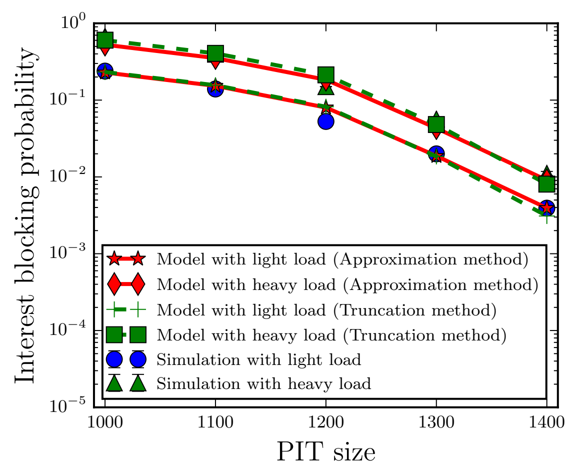

Fig. 6: Scenario 2: Interest blocking probability versus PIT size under heavily and lightly loaded networks

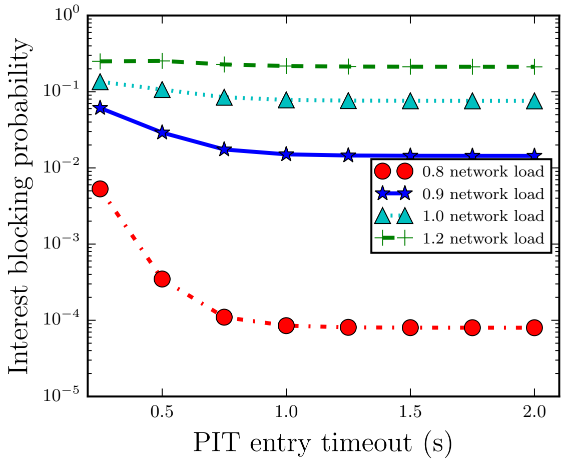

Fig. 7: Interest blocking probability versus PIT entry timeout under different loads in the network

D. Impact of PIT entry timeout

Retransmitted interests can lead to more interest packets that are blocked especially if the requester(s) does(do) not slow down the interest sending rate(s). We use our proposed approximate model to show the impact of the PIT entry timeout on the interest blocking probability in Fig. 7 under different loads in the network. In all the network loads consider, the interest blocking probability decreases with increasing timeout value. The decrease factor depends on the traffic load in the network.

As shown in Fig. 7 high network loads result in little or no impact of the PIT entry timeout on the interest blocking probability while low network loads accentuate the effect of increasing the timeout on the blocking probability. In the case of high network loads, most of the interests that are blocked are due to the PIT being saturated making the impact of timeout insignificant. On the other hand, most of the blocked interests are due to interests that timeout and later retransmitted in the case of low network loads. In Fig. 7, our model results suggest that setting the timeout too small in low network loads can lead to a significant number of interests that are blocked. Setting the timeout too high may not be desirable as the PIT may become full when interests take too long time to return data or never return data [9].

E. Complexity of the approximate model

The solution complexity of our approximate model is significantly lower than the complexity of obtaining the solution of the model in [3]. On the average over all the points on the curves presented in this paper, the number of iterations until convergence with the approximate CTMC model is 4 times better than the truncated CTMC model.

In addition, the CPU time taken by the approximate CTMC model on the average is $\frac{1}{100}$ times the CPU time taken by the truncated CTMC. This is because of the smaller state space of the approximate CTMC model including a faster convergence.

IV. Related Work

Research on the performance study and analysis of a CCN/NDN PIT has witnessed a great deal of effort over the past few years. This is largely due to the role the PIT plays in controlling traffic in CCN/NDN. Several works aim at studying, analysing and managing the occupancy of the PIT under different traffic and network conditions [10], [11], [9], [12], [13], [3].

In the literature, two different approaches are used to manage the PIT entry lifetime: Fixed [14], [10] and dynamic [11], [9] PIT entry lifetime. The fixed value approach is oblivious of the network conditions such as delay and packet loss. Kazi and Badr propose a novel method for dynamically estimating the PIT entry lifetime at routers and the interest packet timeout at receivers [11]. However, this method assumes both interests and data chunks travell the full diameter of the network. This assumption is indeed unrealistic as in-network caching which enables interest packets to be satisfied by intermediate routers in the network is one of the selling points of CCN. Our work in [9] uses the maximum data chunk response delay observed within an interval of time. Simulation results reveal the efficiency of this method as compared to using a fixed-value PIT entry lifetime.

There are other works that have analysed the performance of CCN PIT by estimating the PIT size from the interests arrival rate, the data chunk response time and so on, [12] [13]. Our recent work [3] proposes an analytical model of the PIT to estimate the interest packet blocking probability using two-dimensional CTMC given the network load and the cache and PIT hit rates. However, the model solution was obtained by reducing the state space via truncation. In fact, this makes the model solution to be sensitive to the maximum number of blocked interests. To minimize the state space and the CPU time for computing the model solution while being insensitive to the maximum number of blocked and timed out interests, we present in this paper a more efficient method, inspired by the work of Marsan *et al.* in [4], for estimating the PIT blocking probability.

V. Discussion and Conclusion

This paper presented an analytical model of the Pending Interest Table that efficiently estimate the interest blocking probability at a given node in a content centric network using an approximate 2-dimensional continuous-time Markov chain. We use results from simulation using ndnSIM module in ns-3 to validate the model. In addition we have shown that the PIT can represent a bottleneck in the presence of high traffic load in a content centric network even in the absence of bottlenecked links. As a result, the interest packet blocking probability estimated by the model can be used in managing the PIT occupancy, which can be used in turn to design effective and efficient congestion control mechanisms for CCN and other ICN proposals.

Given the values of the following parameters: traffic load, PIT hit rate, cache hit rate and PIT size, we can estimate the probability that an arriving interest finds the PIT saturated and is eventually dropped. Alternatively, given an interest blocking probability we can determine the cache hit rate or PIT hit rate at a node that will achieve the blocking probability. This also applies to the traffic load at a given node in the network. A CCN network designer can use our model to dimension the PIT for a given loss rates and traffic load. In addition as argued earlier, since there is a direct relationship between the number of interests forwarded upstream and the number of packets received by the CCN router, controlling the interest rate would have a direct impact on the data rate, therefore our model could be invoked to design an effective and efficient traffic control mechanism for CCN. We shall explore this and other approaches of using our model in real network in the future.

Additional works are needed in modelling the content popularity and in addressing the interaction between the cache dynamics and the PIT occupancy as the content store and PIT have a joint impact on the performance of content centric networking. We also leave these for future work.

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