MM3C: Multi-Source Mobile Streaming in Cache-enabled Content-Centric Networks

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***Abstract*—Along with an ever-growing demand for rich video applications by a rapidly increasing population of mobile users, it is becoming difficult for the Internet backbone to cope with a constantly increasing mobile traffic. Though multi-source mobile streaming (MS^2) was proposed to solve the bottleneck issue of the Internet backbone considering simultaneous multiple low streaming rate transmissions to mobile users, it does not consider redundant transmissions of popular contents. Recently, Content Centric Networking (CCN) is proposed as a content name-oriented approach to disseminate content to edge gateways/routers. In CCN, if the content is popular, the previously queried content can be reused for multiple times to save bandwidth capacity, reduce overall energy consumption, and improve users' Quality of Experience (QoE). Inheriting all advantages of CCN, a novel architecture "MM3C", which integrates CCN with MS^2, is proposed as a better solution to the problem. Using OPNET, the performance of MM3C is evaluated. Compared to MS^2 under the same network configuration, the simulation results show that MM3C exhibits less bottleneck links, shorter round trip times, and better performance in terms of traffic offloading.**

I. INTRODUCTION

Recent forecasts about mobile traffic growth indicate two important trends: namely the exponential growth of mobile data traffic and the dominance of mobile video traffic [1]. Due to the current bottleneck of Internet backbone, a single-source single-path (SSSP) streaming approach may be inefficient in satisfying the requirements of video streaming applications, particularly ensuring acceptable Quality of Service (QoS) for an ever-growing population of mobile users. A single-source multi-path (SSMP) streaming approach has been thus proposed, aiming for a better utilization of the overall possible routes between end users and servers [2]. Obviously, the requirement for high streaming rates can be satisfied using multiple and simultaneous low-rate streaming connections. Indeed, by an appropriate split of data packets among uncorrelated routing paths, the probability of packet losses on each path, and consequently the average packet drop rate, becomes smaller, even at congestion times.

In [3], a multi-source mobile streaming (MS^2) architecture is proposed to further alleviate the impact of network congestion on mobile streaming services, by efficiently utilizing the available network resources through an effective rate allocation scheme among multiple sources that collaborate to stream the same content in a complementary manner. Whilst the MS^2 architecture is proven efficient to increase the overall system capacity, the total bits transferred between the involved servers and end users, and the power required by network nodes to process them along the different routes, remain noticeable. To achieve energy efficiency and therefore build a "green" MS^2 architecture, servers selected for the delivery of a particular stream shall be placed closer to the user receiving the service. Alternatively, caches of the desired content could be made closer to the user. The Content Centric Networking (CCN) concept can largely help with this regard [4].

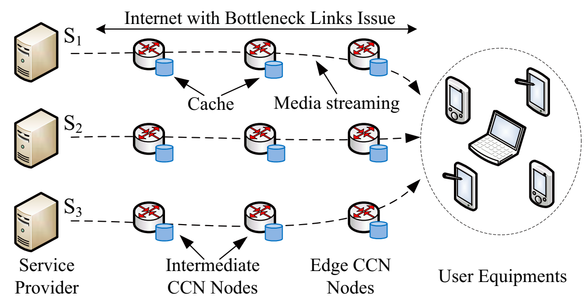


Fig. 1. Example for multi-source transport of media and in-network caching.

Indeed, CCN can be used for caching popular content at different caches (i.e., routers and gateways); some of which can be selected, by the MS^2 framework, for the stream of a particular content to a given user. Such integration of CCN with MS^2 shall maximize the probability of content sharing while minimizing upstream bandwidth demand and lowering downstream latency. Furthermore, reducing traffic load by in-network caching shall contribute to the energy efficiency of mobile networks. In order to interwork with CCN, MS^2 adds a new function to service management which is carried out by a Domain Manager or a Decision Marker (DM) [3]. In CCN, information exchange is based on named data instead of IP addresses. When DM receives from a mobile subscriber a request for a service identified by content name, DM has to include a name-based routing to deliver the requested content to appropriate CCN routers/gateways. DM can be seen as a special CCN node which only comprises Forward Information Base (FIB) for routing function. Fig. 1 illustrates the caching of popular contents along the routing path from server to user equipment (UE). For instance, five UEs request the same content from the Service Provider (SP). Without in-network caching, SP must send five copies redundantly via the Internet network. With CCN integration, the traffic from SP to edge CCN nodes is reduced. As shown in Fig. 1, the UE often encounters with the issue of bandwidth bottleneck, and it may take a long duration to complete transmit content through

TABLE I. USED NOTATIONS.

Symbol	Definition
n_{UE}	Number of User Equipment (UE)
R_p	UE play rate
n_S	Number of servers
R_i	Streaming rate along each path
BW_i	Available bandwidth (BW) on each path
R_{VBR}	Traffic generated by Variable Bit Rate (VBR)
$R_{Offloading[i]}$	Traffic offloading on each path
H_i	Hitting rate on each path
$U_{Link[i]}$	Link utilization on each path

the Internet. By caching content, the bandwidth bottleneck is reduced, end-to-end delay is also decreased, and server traffic is offloaded.

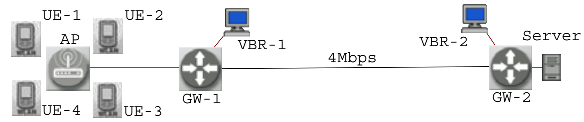
In this paper, our main contributions are two folds: (1) we first evaluate the MS^2 architecture using OPNET, ensuring its proper working [5] [6]; (2) CCN is then integrated in the validated MS^2 architecture, yielding our proposed MM3C architecture. The MM3C performance is evaluated and compared against that of MS^2. The simulation results prove that MM3C outperforms MS^2, achieving shorter round trip times and lower overall network utilization.

For the sake of better readability, Table I lists up the notation used in this paper. The remainder of this paper is structured as follows. Section II highlights some recent research work pertaining to multi-path and multi-source streaming techniques. Section III presents the basic MS^2 network architecture and validates its performance using computer simulations. Section IV describes our new MM3C architecture and evaluates its performance. Finally, the paper concludes in Section V.

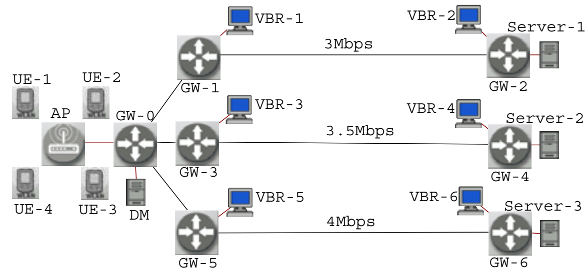
II. RELATED WORK

Streaming services from nearby nodes or routers goes back to a decade or longer [7]. Content Centric Networking came to organize such an efficient streaming based on smart caching of popular content nearby the requesting users. A typical CCN framework is described in detail in [4]. It presents a simple and effective communication model. For the actual delivery of streaming services, a wide library of research work has been conducted. Many research work have considered the delivery of multimedia on multiple routing paths. In [8], original packets are fractured into sub-packets that are delivered on multiple paths. Their arrivals are scheduled in a way that reduces the end-to-end delay. A D/M/1 queuing model is used to obtain the expression of dynamic packet splitting ratio for each involved communication path. In [9], a multi-path Scalable Video Coding (SVC) video streaming approach is proven to achieve better performance than the single-path counterpart, and that is in terms of packet loss rate, video playback peak-signal-to-noise-ratio (PSNR), and delay jitter, ultimately yielding an efficient utilization of the network resources.

The concept of multi-path routing has been also investigated in the context of CCN. In [10], the CCN best-face routing (BFR) mechanism selects the path with the best performance to complete the Interest packet (IntPk) routing and the Data packet (DataPk) download. Others possible faces are ignored. So the capacity of these faces is wasted, and the load of



(a) Typical single-source single-path (SSSP) model.



(b) Basic MS^2 model.

Fig. 2. Mobile multimedia streaming via a single access point: single-source single-path streaming vs. MS^2.

the best face and the repository become heavy. To cope with this limitation, the adoption of multi-path routing scheme is proposed, whereby different chunks of one content can be simultaneously retrieved from different repositories. Similarly, in [11], the traffic splitting strategy follows a Round Robin distribution mechanism, considering the skewness popularity of content and adopting replacement policies such as Least Recently Used (LRU), First In First Out (FIFO), and random replacement.

III. A BASIC MS^2 ARCHITECTURE AND ITS VALIDATION

The basic MS^2 architecture, along with its supporting mechanisms, is described in details in [3]. In this section, we provide a brief description of MS^2 and validate its performance using a newly developed OPNET model and compare it against that of a single-source single-path (SSSP) streaming model. Fig. 2(a) depicts a typical topology for single-source single-path streaming. In the envisioned topology, there are four User Equipment (UEs) requesting different streaming content from a single multimedia server via a single path. Videos are streamed at a constant rate, 800Kbps, and each for a duration of 100s. UEs request videos randomly, 50s after the start of the simulation. To simulate a realistic environment, variable bit rate (VBR) background traffic, with two different shapes (e.g. Uniform distribution and Poisson distribution for inter-arrival time transmission packets), is also considered between GW-1 and GW-2. Congestions at these nodes result sometimes in the dropping of packets, that are requested for retransmission by UEs within a predefined time window. The packet size (PKSize) is fixed at 1KB. All VBRs are initiated 10s after the start of the simulation. Table II lists six envisioned VBR scenarios, representing heavy and dynamic background traffic to light background traffic.

Fig. 2(b) depicts the considered MS^2 model simulation topology, which involves three media servers servicing a number of UEs via a single access point (AP). Whilst in the envisioned topology, we consider the case of video streaming via a single access point, it shall be stressed out that multimedia streaming via different paths and different access points shall

TABLE II. SIMULATION PARAMETERS.

Packet types	Information	32 B
	Interest (IntPk)	32 B
	Data (DataPk)	1 KB
UE	Buffer size	100 Pks
	Play rate	100 Pk/s
	Wireless interface	802.11g @54 Mbps
	DataPk time-out	0.6 s
DM/Server	Monitoring time interval	0.3 s
Bottleneck links	SSSP	4 Mbps
	MS^2	3; 3.5; 4 Mbps
Other links	GW-GW	OC-24
	other links	1000BaseX
VBR scenarios	1	Uniform(0.002;0.02)s + Poisson(0.02)s
	2	Uniform(0.002;0.02)s + Poisson(0.03)s
	3	Uniform(0.002;0.02)s + Poisson(0.04)s
	4	Uniform(0.002;0.02)s + Poisson(0.08)s
	5	Uniform(0.002;0.02)s + Poisson(0.12)s
	6	Uniform(0.002;0.02)s + Poisson(0.2)s

be also possible [12]. The topology consists of three uncorrelated paths from the servers to the gateway traversing a number of routers and gateways. The bandwidth and delay of each of these links are also shown in Fig. 2(b). VBR background traffic are also set up similarly to the SSSP approach. The MS^2 architecture comprises also a Domain Manager or a Decision Maker (DM) that carries out the overall service management [3]. As MS^2 involves multiple servers and multiple paths for the delivery of the same content, link utilization, jitter and completed download time are used as metrics to compare network performance when the two schemes are adopted. Table II lists other parameters considered in the simulations.

As detailed in [3], MS^2 operates following a number of steps. Effectively, DM sends a request information packet to $Server[i]$ with $i = 1,2,3$; and receives some reply information packets from $Server[i]$. The path delay (D_i) from $Server[i]$ to DM is calculated referring to the inter-arrival times of two adjacent arriving packets from $Server[i]$. The available bandwidth (BW_i) of the bottleneck link between DM and $Server[i]$ is then estimated from the ratio of the information packet size to the path delay. Using all links to the servers, DM calculates the values of the following parameters for each $Server[i]$ [3]: streaming rate (R_i), number of packets (P_v^i) to be sent during the monitoring period (δ), data packet inter-transmission times (Δ_i), and the time to commence the transmission (τ_i). Finally, the two parameters R_i and τ_i are communicated to $Server[i]$, as elaborated in details in [3].

When a UE desires to view a content video, it sends an Interest packet (IntPk) to DM. DM selects, following a certain logic, the servers to be involved in the delivery of the content and communicates to them the parameters R_i and τ_i. Based on the path delay from each of these servers to DM, and subsequently on the computed values of τ_i, Δ_i and P_v^i, the servers schedule the delivery of DataPks packets to the UE in a way that the packets of the same content are arriving in order at UE, without high jitter, and most importantly without duplicate packets that could drain up the battery lifetime of the UE [3]. Based on the assumption that all UEs have on average the same play rate (R_p), a total content traffic for all UEs is $n_{UE}.R_p$. While in case of SSSP, the available BW of a single bottleneck link should be higher than the sum of $n_{UE}.R_p$ and the background traffic to avoid network congestion, in case of MS^2 this condition has to be verified with multi-path bottleneck links achieved using Eq. (1).

$$BW_i > n_{UE}.R_i + R_{VBR}, \forall i = 1,2,..,n_S \quad (1)$$

where n_S denotes the total number of involved serves. From the relation of the streaming rate of the selected servers to the bandwidths of their respective paths [3], link utilization on each path is calculated by Eq. (2).

$$U_{Link[i]} = \frac{n_{UE}.R_i + R_{VBR}}{BW_i} = \frac{n_{UE}.(\frac{BW_i}{\sum_{i=1}^{n_S} BW_i}.R_p) + R_{VBR}}{BW_i} \quad (2)$$

Fig. 3(a) compares the link utilization under the VBR scenario-6, representing a light background traffic scenario. In case of the SSSP scheme, the single-path utilization often reaches its maximum resulting in congestion. In case of the MS^2 scheme, the content delivery is distributed among three servers with uncorrelated routing paths to UE. This helps in maintaining moderate link utilizations and ultimately avoiding network congestion. In the following, we compare the link utilization obtained from the mathematical model and the one achieved in the simulations. Considering VBR scenario-6, we first calculate the average background traffic generated by two shape distributions, e.g. $Uniform(a,b)$ and $Poisson(x,\lambda)$.

$$E[R_{VBR}] = E[R_{Uniform} + R_{Poisson}] = PkSize.(\frac{2}{a+b} + \frac{1}{\lambda}) \quad (3)$$

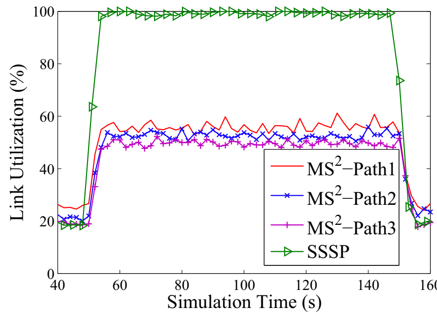
$$= 1^{KB}.(\frac{2}{0.002^s + 0.02^s} + \frac{1}{0.2^s}) \simeq 0.75Mbps \quad (4)$$

We then compute the average bottleneck link utilization based on Eq. (2): $U_{Link} \simeq 96.9\%$ in the SSSP scheme, and $U_{Link[i]} \simeq 54.8$, 51.2, and 48.5% in the MS^2 scheme. Comparing among the obtained values and the OPNET simulation results in Fig. 3(a), we observe that they are approximate values, demonstrating the accuracy of our mathematical model and validating our simulation setup.

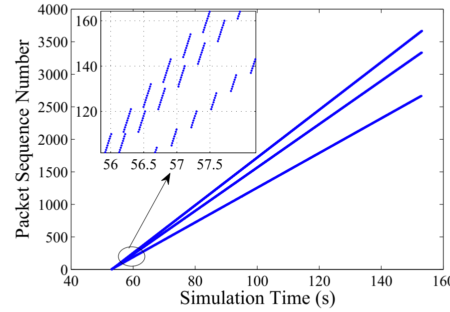
Fig. 3(b) plots the sequence number of data packets received by UE from the three servers. The figure demonstrates that despite the fact that the data packets are sent from three servers with no self-organization features, they reach the UE in order and with almost no duplicate packets, demonstrating that the design goals of MS^2 are successfully achieved.

Fig. 3(c) plots the inter-arrival times of data packets at UE considering VBR scenario-1 that involves heavy and highly dynamic background traffic. In case of the SSSP scheme, at congestion events, some dropped data packets get retransmitted and reach UE after an unacceptable timeout, resulting in their discarding at the UE's application layer. Packet drops followed by retransmissions result in high jitter, which may impact the Quality of Experience perceived about the video. In case of MS^2, it is observed that the experienced jitter remains stable in the vicinity of 0.01s. This demonstrates that even under heavy traffic scenarios, MS^2 still ensures seamless and smooth playback of video at UE.

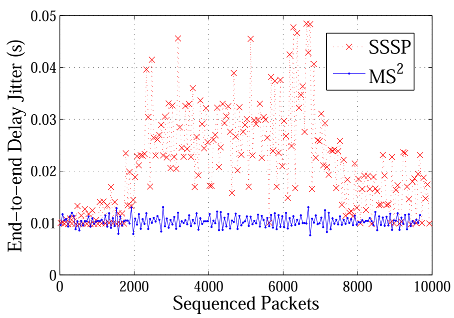
Fig. 3(d) further compares the performance of SSSP against that of MS^2 considering different VBR scenarios, and that is in terms of the total time required for completing the download of videos (of a duration of 100s). From the figure, it becomes noticeable that in case of SSSP, the actual download



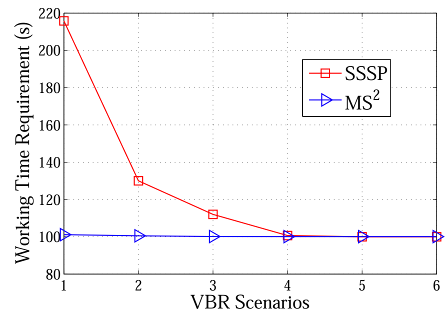
(a) Bottleneck links utilization in the VBR scenario-6.



(b) Sequence of DataPks at the UE in the MS^2 model.



(c) Inter-arrival times of DataPks at the UE in the VBR scenario-1.



(d) Time required to complete watching 100s video content.

Fig. 3. Validating MS^2 and comparing its performance against that of SSSP.

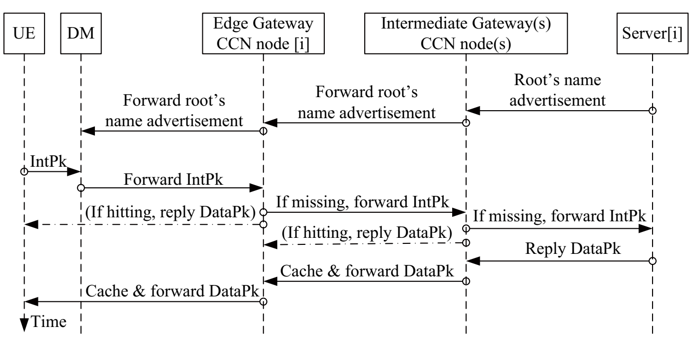


Fig. 4. MM3C flowchart with $i = 1, 2, .., n_S$.

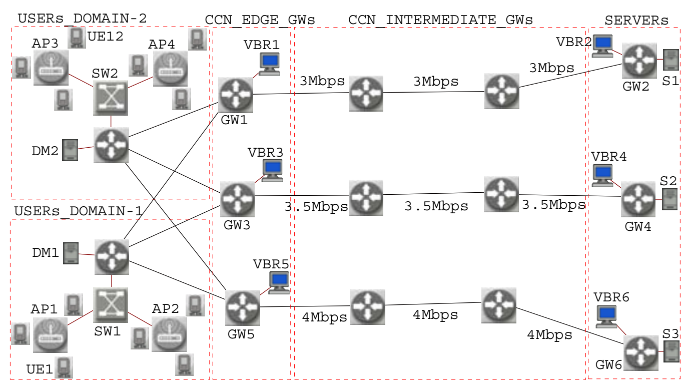


Fig. 5. MM3C model with edge GWs caching (GW-1, GW-3 and GW-5).

time exceeds 100s. This is mainly attributable to dropped and retransmitted packets. Indeed, from the figure, the heavier the background traffic is, the longer the total video download time becomes. In case of MS^2, the video download time remains stable at 100s and that is for the different VBR scenarios.

IV. Integrating CCN with MS^2

Having described MS^2 and having validated its performance, we now focus on how CCN can be integrated with MS^2 to further improve its performance achieving a further efficient utilization of network resources. Fig. 4 illustrates the interworking of MS^2 with CCN caching. In CCN, root's name element is referred to a globally-routable name, broadcasted by servers [4]. When CCN nodes receive a root's name, they add it to their Forwarding Information Base (FIB) and forward the root's name to their neighbors. Servers keep updating CCN nodes with up-to-date root's names by broadcasting them periodically. DM in the proposed MM3C architecture is slightly modified to interwork with CCN mechanisms. Similar to CCN nodes, DM also maintains FIB, without including Pending Interest Table (PIT) and Content Store (CS). When a DM receives an IntPk from a UE, DM refers to its FIB and forwards the IntPk to the nearest CCN node.

In the OPNET simulations, CCN is overlayed over the IP layer. Indeed, we integrated the CCN processing modules into routers/gateways and modified other network elements, such as UE, DM, and server. In MM3C, popular content are cached at edge gateways (e.g., GW-1; GW-3 and GW-5 in Fig. 5). It shall be noted that caching is performed at the data object level, e.g. DataPk. Caches are then considered in the server selection algorithm carried out by DM when responding to a request from a user for a popular video content. In general, all CCN routers located along the reverse path from servers to DM can cache data objects. However, a lot of research papers have shown that the highest benefits of CCN is achieved at the edge routers/gateways [13] [14]. Intelligent caching at edge routers and gateways is of vital importance for the efficiency of CCN. For this reason, we focus only on edge CCN gateways. However, global CCN caching, supported with Self-Organized Networking (SON) functions among caches can offer benefits well beyond only edge caching in sub-networks [15].

In MM3C, when caches are selected for the stream of a particular content, they are instructed, in the same fashion of MS^2, on how to deliver data packets of the content in a way that they reach the requesting UE in order and with no duplicate transmissions. To demonstrate the positive impact of CCN on MS^2, we expand the simulation network of Fig. 2(b) to two wireless domains as shown in Fig. 5. All UEs within the radio ranges of AP-1 and AP-2 are managed by DM-1. Similarly, UEs, connected to AP-3 and AP-4, are handled by DM-2. Videos are streamed at a constant rate, 800Kbps, and each for a duration of 2s. It shall be noted that the duration of video are easy set longer than 2s. We choose very short duration because of speed-up simulation time. UEs request videos randomly, 50s after the start of the simulation. The considered background traffic is similar to that of VBR scenario-6 described in Table II. In the envisioned network, popular contents are accessed from nearby caches, bypassing bottleneck links. For this reason, the average data packet delays become reduced. In the simulations, content popularity is assumed to follow a Pareto distribution function, e.g., Pareto (10^4,10^2) [16].

The Fine-Grained Popularity-based Caching (FGPC) and Dynamic-FGPC (D-FGPC) replacement policies are used as they outperform LRU and ensure highly effective caching [17]. A variety of cache sizes and popularity skewness are often considered to evaluate the performance of different replacement policies. Since this is not the main focus of this paper, we set the cache size to a fixed value, 5000 packets; worth of storing 25 videos. Let H_i denote the hitting rate obtained on each path from servers to UE, $R_{Offloading[i]}$ denotes amount of traffic offloaded on $Path[i]$, the network non-congestion condition and bottleneck link utilization on each path will be:

$$R_{Offloading[i]} = H_i.(n_{UE}.R_i), \forall i = 1,2,..,n_S \tag{5}$$

$$BW_i > (1-H_i).n_{UE}.R_i + R_{VBR} \tag{6}$$

$$U_{Link[i]} = \frac{(1-H_i).n_{UE}.(\frac{BW_i}{\sum_{i=1}^{n_S} BW_i}.R_p) + R_{VBR}}{BW_i} \tag{7}$$

In order to demonstrate the positive impact of CCN on MS^2, we consider the network congestion happening in the original MS^2 architecture but being avoided in the MM3C model. By contrasting Eq. (1), we have:

$$n_{UE}.R_p + n_S.R_{VBR} \geq \sum_{i=1}^{n_S} BW_i \tag{8}$$

Assuming that:

$$n_{UE}.R_p + n_S.R_{VBR} = 1.1 \sum_{i=1}^{n_S} BW_i \tag{9}$$

$$\Rightarrow n_{UE} = \lceil \frac{1.1 \sum_{i=1}^{n_S} BW_i - n_S.R_{VBR}}{R_p} \rceil = 12. \tag{10}$$

In other words, from Eqs. (1) and (6), the great advantage of CCN becomes noticeable when Eq. (11) is satisfied.

$$n_{UE}.R_i + R_{VBR} \geq BW_i > (1-H_i).n_{UE}.R_i + R_{VBR} \tag{11}$$

Fig. 6 compares among the utilization of the bottleneck links and that is under VBR scenario-6. In MS^2, in spite of content delivery being distributed over multiple servers, the bottleneck link utilization still reaches 100 percent as the number of UEs requesting videos increases. This limitation can be alleviated involving more servers and further paths in the content delivery. In MM3C, by leveraging the concept of CCN, popular content are cached at edge gateways, enabling their delivery to UEs without traversing longer paths over the network. For this reason, MM3C demands less bandwidth and helps in avoiding network congestion.

Fig. 7(a) illustrates the different hitting rates at Paths 1-3. Over the data path with the highest available BW, e.g. Path 3, the highest number of data packets is transmitted, resulting in frequent replacements of data packets at caches. For this reason, the number of times to reuse cached content decreases, resulting in lower hitting rate. In this vain, it should be reiterated that the content caching/replacement policies for different cache sizes may strongly affect the overall system performance. The impact of caching policies on the system performance is outside the scope of this paper; the simple LRU, FGPC and D-FGPC replacement policies are applied and compared for our simulations as seen in Fig. 7(b) [17]. We further check consistency between results from the derived mathematical model and the simulations. In case of the VBR scenario-6, R_{VBR} is approximately $0.75Mbps$. From Fig. 7(a), the final state hitting rate (H_i) of the D-FGPC policy reaches 0.43, 0.37, and 0.33, respectively. Based on Eq. (7), we have $U_{Link[i]} \simeq$ 75.9, 77.7, and 78.6%. Obviously, we can notice the similarity between these average utilization link values and the simulation results shown in Fig. 6.

Fig. 7(c) and 7(d) plot the total time elapsed since a UE issues an IntPk requesting a video title till it receives the first DataPk of the video. As shown in Fig. 7(c), in case of MS^2, all DataPks are fetched from the servers, passing through bottleneck links. At congestion events, the delivery delay of DataPks increases and some packet losses occur. This results in long and fluctuating delays in responses from servers, and that is during the entire simulation time. In case of MM3C, in Fig. 7(d), when the desired content is cached at edge gateways, it can be intuitively accessed immediately from nearby nodes with negligible delays.

V. Conclusion

In this paper, we integrated Content Centric Networking in our recently proposed MS^2 architecture for mobile multimedia streaming. The resultant architecture, dubbed MM3C, improves further the performance of MS^2 as it makes popular

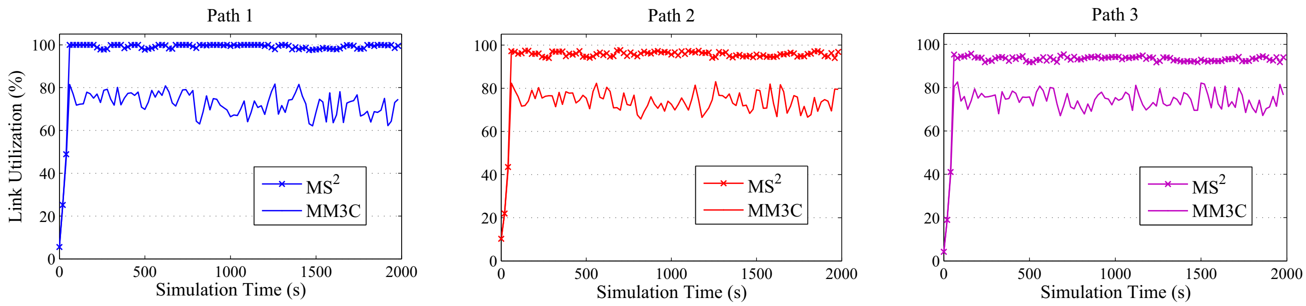
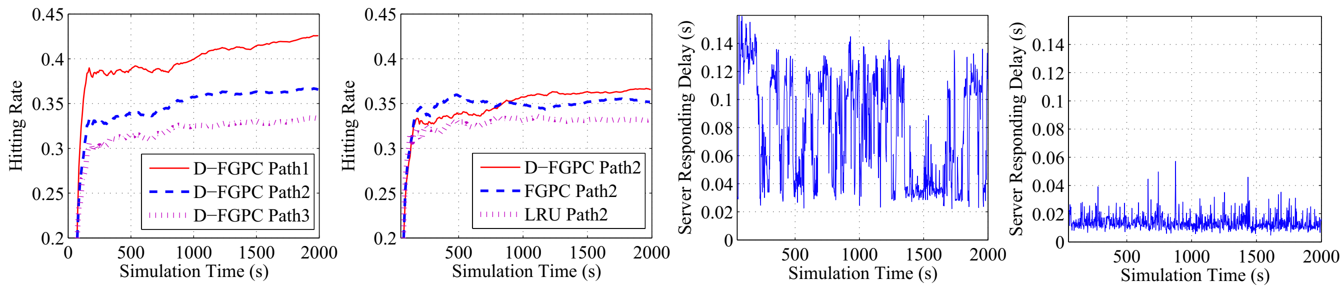


Fig. 6. Bottleneck links' utilization.



(a) Hitting rate at GW−1,3,5 respectively. (b) Multiple replacement policies comparision. (c) MS^2 scheme. (d) MM3C scheme.

Fig. 7. Comparing the performance of MS^2 and MM3C.

content available to mobile users at caches placed nearby Radio Access Networks. This helps in avoiding the access to popular content from far away servers along paths that could otherwise get congested. The performance of MM3C was evaluated through computer simulations and compared against that of MS^2. The obtained results demonstrated the effectiveness of MS^2 as well as MM3C in achieving their design goals. Additional simulation results on video playback quality such as delay and jitter stability also demonstrated that MM3C could outperform MS^2 in utilizing overall network resources more efficiently. Investigating the impact of smart and cooperative caching on MM3C, supported by accurate assessment of available network resources along the movement path of users, form one of our future research directions in this particular research area.

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