Supporting Consumer Mobility Using Proactive Caching in Named Data Networks

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***Abstract*—Mobility management in Named Data Networks (NDNs) is one of the main challenges of seamless operation in the future Internet. Techniques used in existing proposals for Consumer mobility are either reactive or semi-proactive, which try to reduce data access time, but yet retransmissions are required. We propose a fully proactive optimal scheme (*OpCCMob*) that adopts location and data patterns forecasts to proactively support Consumers movements in the network. In essence, the scheme will optimally cache the predicted content close to the Consumer such that it will be satisfied before handover and avoid Interests retransmissions. A mathematical formulation of the problem is provided such that it bounds the overhead on the network and minimizes the delay of fetching the data. *OpCCMob* is implemented in ndnSIM and used as a benchmark to evaluate mainstream NDN mobility schemes under various practical scenarios. The results of different experiments show that the delay can be maintained during Consumers movements using control messages as an overhead. Moreover, a sensitivity analysis is conducted to measure the robustness of proactive schemes during imperfect predictions.**

I. INTRODUCTION

Named Data Network (NDN) [1] is one of the cutting-edge designs of the future Internet, Information-centric Network (ICN). The promising NDN architecture is designed to tackle the current and future challenges of the Internet [2]. In particular, the evolution of content, devices and applications have caused a shift in the way the Internet operates. With the increasing use of the Internet, CISCO's Virtual Networking Index (VNI) [3] predicts that the global traffic will reach 164 Exabytes per month by 2019, nearly a threefold increase over 2014 statistics. However, the Internet was built on a host-to-host model, thus patching it up would be a suitable practical solution to maintain scalable operations. Overlays such as Content Distribution Network (CDN) and Peer-to-peer (P2P) are examples of such patching protocols, which are suboptimal under the projected future traffic [1]. On the contrary, NDN is built for data where the current and future content-based applications can run smoothly and natively.

A core feature of the future Internet's design is supporting mobility as a network primitive. This is a requirement to cope with the projected growth in mobile nodes and content, where wireless and mobile devices are predicted to account for 79% of IP traffic by 2020 [4]. In particular, supporting seamless operations is essential in NDN, as users are then able to move in the network without impacting applications performance. However, the implicit assumption, in NDN's design, that mobility is supported intrinsically by Interests retransmissions is found to be suboptimal. This increases the data access time and degrades the network's total throughput. Therefore, a design of a mobility management scheme for both Consumers and Producers is inevitable to successful NDN. Several efforts have addressed the mobility challenge in NDN by handling both Consumer and Producer movements [1]. The proposed existing schemes use reactive or semi-proactive techniques to recover after a mobile event, whereas in this paper, we consider a fully proactive approach to support seamless Consumer mobility before handover.

This paper designs a proactive mobility support scheme, *OpCCMob*, that exploits Consumers' location predictions and data request patterns to find the optimal data placement in network caches and avoid data drops and retransmissions. The contributions of this paper are summarized as follows:

1) We formulate the problem of the content placement based on the forecasted Consumers' locations. The formulation minimizes the total Consumer's delay while considering network overheads associated with data placement.
2) An optimal benchmark solution is then obtained using Gurobi optimization solver [6], which is essential to evaluate existing and future NDN mobility schemes.
3) In the light of the NDN compliant assessment framework in [7], we define the performance gains due to using location predictions in mobility supporting schemes.

The remainder of this paper is organized as follows. In Section II, an overview of the mainstream NDN Consumer mobility management schemes is introduced. The formulation of the optimal caching scheme is presented in Section III. The simulation framework is explained in detail in Section IV. Our simulation experiments and results are discussed in Section V. We conclude our findings in Section VI and present insights into future directions in NDN mobility support.

II. RELATED WORK

The goal of NDN is to make data the core entity in the network. This is coupled with a receiver-driven communication

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[1] While Producer mobility has been studied in our previous work [5], Consumer mobility is the focus of this paper.

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model [1], where Consumers (i.e., data receivers) initiate connections by sending requests to Producers (i.e., data owners). Then the latter sends the data back to the former. Since there are no IP addresses in NDN, data is requested by sending Interest packets with its hierarchical and unique name. Moreover, every node in NDN has two structures to forward both Interests and Data packets. The Forwarding Information Base (FIB) is used to forward Interests to Producers, which has a similar functionality to the routing table in the IP network. The second structure is the Pending Interest Table (PIT), which keeps track of unsatisfied Interests and routes the data back to Consumers. Furthermore, to support in-network caching in NDN, a structure called Content Store (CS) is available in every NDN node. Similar structures are used in different networks such as [8], [9].

Given that mobility events are inevitable, seamless mobility support is a requirement in the future Internet. However, the current proposed design of NDN does not consider a special scheme for mobility. It simply depends on Interest retransmissions to recover from such mobility events. Specifically, in the case of a mobile Consumer, the requester will retransmit unsatisfied Interests again after connecting to the new Point of Attachment (PoA) to get the data. However, the delay caused by this process may not be acceptable for real-time applications. Therefore, schemes to handle Consumer mobility are needed to support seamless operations.

Multiple mobility management schemes have been proposed in the literature to support Consumer mobility and can be classified into two categories: Reactive and Semi-Proactive. The schemes in the first category [10]–[12] take action after the handover event when the Consumer connects to the new PoA. For example, in [11] the old PoA will not drop the data of a mobile Consumer once it receives a handover notification (e.g., disassociation message). Instead, the data will be cached until the Consumer connects to the new PoA and retrieves it. The difference between this approach and NDN's is that it asks for the data from the old PoA not from the Producer. However, this is only beneficial if the delay to access the Producer is longer than the old PoA.

The second category is the semi-proactive based schemes, that depend on predicting handover events, thus mobility supporting actions can be taken in advance. The schemes proposed in [11], [13]–[15] use the prediction information to cache the content near the new location to reduce the data access time. For example, in [15] the Consumer will predict the movements and notify its PoA with the Interests that most probably be missed due to handover. The old PoA in cooperation with the predicted new PoA will cache the data in the latter such that it will be ready once the handover is done and the retransmission is issued. The advantage of this semi-proactive approach is that the delay is lower than the reactive and NDN, however, retransmissions are still needed to request the content from the new PoA.

Our proposal of the optimal scheme is fully proactive since it caches the data near the old PoA and hence no retransmissions are required. Additionally, the optimal scheme considers caching in any router in the network not only the PoA (1-hop neighbor), therefore more resources are available to support mobile Consumers in case of high load scenarios.

III. OPTIMAL CONSUMER MOBILITY SUPPORT *OpCCMob*

A. *Scheme Overview*

A moving Consumer will not be able receive the data requested just before the handover event, since it will be disconnected from its old PoA. Hence, the Consumer will retransmit the Interests after connecting to the new PoA. However, if the data is cached near the Consumer such that it can be retrieved before the handover, then the data will not be dropped. This is the core idea of *OpCCMob*. In particular, *OpCCMob* will proactively choose the optimal routers to cache the required data such that no retransmissions are needed and with bounded overhead. To proactively identify the interests that may not be satisfied due to handover, two pieces of information are needed in advance, first we need to predict the time of handover of mobile users and the Interests that will be requested in the near future.

Handover events can be foreseen using the network's topology and the location of the Consumer. The location information can be predicted using position estimators such as [16], [17]. The location predictor will estimate the new position of the node at a specific time. If a change in location leads to switching PoAs (e.g., node is closer to another AP), a handover event is detected as well.

The second required piece of information is the knowledge of data which will be requested by the mobile Consumers before handover. Requests patterns predictors such as [18], [19] can be used to find the time and name of future requests. We can then find the potential Interests to be dropped after a Consumer mobile event, and take the necessary action in advance to cache the data. We assume such information to be available and correct (i.e., perfect knowledge of the future), to find the optimal data placement.

Assume that the handover of a mobile Consumer occurs at t_{HO}. The Interests requested by this user between $t_{HO} - RTT$ and t_{HO}, where RTT is the average time to retrieve the data from the Producer, are predicted to be dropped and will be retransmitted. Additionally, the time horizon is divided into small time slots where the data placement at each time slot is considered as a separate optimization problem. Given the set of predicted requests of all mobile Consumers in one time slot, we can define the problem as finding the optimal placement of data in network caches such that no retransmissions of Interests are required by mobile Consumers and with bounded overhead on the network.

The overhead can be of two types: 1) Path updates: Caching on a router that is not on the path from a Consumer to a Producer will require a route to be created temporarily from the Consumer to the router chosen. Hence, an overhead to update the FIBs of the new path is needed. 2) Cache cost: Adding data to a full cache will replace other items, based on the replacement policy. Both the total number and value of removed data should be bounded.

B. System Model

Let U be the set of users in the network. Each user $u \in U$ can be either a Consumer or a Producer for data $d \in D$, where D is the list of all data items. The role of user u for data d is defined by two indicator variables i_u^d, o_u^d. Specifically, i_u^d is 1 if user u requests data d or 0 otherwise, while o_u^d is 1 if user u produces data d or 0 otherwise.

Let R be the set of routers in the topology, where every $r \in R$ has a maximum cache capacity of c_r^{max} and current capacity identified by c_r. The network topology is represented by a graph $G = (V, E)$, where nodes in V are either users, APs or routers. The path taken by a packet (Interest or Data) from node x to node y is denoted by a sequence of nodes $P_{x \to y}$. Accordingly, the cardinality $|P_{x \to y}|$ represents the number of hops traversed to reach the destination y from the source x.

Each Data d has a value ϵ_d which can represent content's popularity, Producer's quality or user's priority. In this work, ϵ_d is assumed to be the popularity of an item d.

C. Problem Formulation

Finding the best possible placement of data with bounded overhead can be formulated as an optimization problem with two decision variables that will determine where to place the data and which data to remove. The first decision variable δ_r^d is 1 if the solution decides to cache data d in router r. The second decision variable is ρ_r^m, which decides on how many items should be removed from the cache to provide a space for the new data. In particular, ρ_r^m is 1, then m items will be removed from router r. The formulation is as follows:

$$\min_{\delta_r^d, \rho_r^m} \sum_{d \in D} \sum_{u \in U} \sum_{r \in R} i_u^d |P_{u \to r}| \delta_r^d \tag{1}$$

S.t.

$$\sum_{r \in R} \delta_r^d = 1 \quad \forall d \in D \tag{C1}$$

$$\sum_{r \in R} \mathbb{P}_{u,u'}^r \delta_r^d i_u^d o_{u'}^d < \sigma \quad \forall d \in D, \forall u, u' \in U \tag{C2}$$

$$\sum_{m=0}^{c_r} \rho_r^m = 1 \quad \forall r \in R \tag{C3}$$

$$c_r + \sum_{d \in D} \delta_r^d - \sum_{m=0}^{c_r} m \rho_r^m \leq c_r^{max} \quad \forall r \in R \tag{C4}$$

$$\sum_{d \in D} \delta_r^d - \sum_{m=0}^{c_r} m \rho_r^m \geq 0 \quad \forall r \in R \tag{C5}$$

$$\sum_{m=0}^{c_r} m \rho_r^m < \alpha \quad \forall r \in R \tag{C6}$$

$$(\sum_{m=0}^{c_r} \rho_r^m k_r^m - \sum_{d \in D} \epsilon_d . \delta_r^d) / K_r < \beta \quad \forall r \in R \tag{C7}$$

The objective function 1 is to minimize the delay of data retrieval from the chosen router. The delay calculated as the total number of hops to reach the router ($|P_{u \to r}|$). Constraint (C1) ensures that each data will be cached only once in any of the routers. The overhead of updating the path is bounded by Constraint (C2) whose left-hand side represents the number of path updates for each data d. $\mathbb{P}_{u,u'}^r = (|P_{u \to r}| - |P_{u \to u'} \cap P_{u \to r}|)$ is the number of non-common edges between $P_{u \to u'}$ (path from the Consumer u to Producer u') and $P_{u \to r}$ (new path from the Consumer u to the chosen router r).

Constraints (C3) to (C7) are related to caching and data replacement. In particular, (C4) is used to ensure that the number of items in the cache does not exceed the maximum cache capacity. Constraint (C5) minimizes the replacement by only allowing data removal from the cache if it is full. α is a threshold to bound the total number of replacements per router using (C6) and thus minimizes the cache cost overhead. Since some content will be replaced, the total content value of the router will change. The reduction of this value is bounded by a threshold β in Constraint (C7). The value of variable k_r^m is the total content value of m items to be removed from router r, and K_r is the total content value of all the items in r.

The objective function and all the constraints are linear and all the decision variables are binary. Therefore, the problem is a 0-1 Integer Linear Program (0-1 ILP) whose optimal solution can be obtained using branch and bound methods implemented in commercial solvers.

IV. SIMULATION MODEL

In this section, we discuss the benchmark tool that will be used to evaluate the introduced optimal proactive Consumer mobility scheme. Moreover, we detail the necessary extension to the tool and the implementation of the optimal scheme.

A. Benchmarking Tool

The assessment framework proposed in [7] was designed to evaluate different mobility management schemes which handle Producer movements specifically. The benchmarking tool tests schemes under different scenarios using various performance metrics. It consists of four main blocks; Mobility, Topology and User planes and the NDN simulator. Users' movements in the network is the output of the mobility plane which we choose to be generated by Simulation of Urban MObility (SUMO) to mimic real scenarios. The Topology plane creates hierarchical networks such as Tran-Stub topologies. Additionally, the user plane generates users' profiles and requests' patterns.

The output of the previous blocks is the scenario that will be imported by the NDN complaint network simulator (ndnSIM) [20]. Moreover, an abstract MobilityManagement Module was added to ndnSIM which is the basis for Producer mobility schemes implementations. The tool can be customized to be used for Consumer mobility by installing the *MobilityManagement* module on the Consumer nodes, instead of Producers.

B. Implementation of OpCCMob

The optimal Consumer mobility management scheme is implemented by using the aforementioned *MobilityManagement* module as a base class. The module's functionalities are:

TABLE I
SIMULATION PARAMETERS

	Parameter	**Value**
General	Simulation Duration	1000s
	Transit Period	80s
	Map size	$1400m \times 1400m$
	Number of Blocks	7×7
	Number of Users	100
	Producers	50
	Consumers	50
Application	Interest Rate	50-80 *I*/s
	Zipf s	0.2
	Content per Producer	$1000 \times 1KB$
Topology	APs	49
	AP Range	200m
	Number of Routers	40
	Core router's links	10Mbps
	Access router's links	5Mbps
	Propagation delay	10ms
Mobility	Model	Manhattan
	Handover delay	0.5s
	Speed	70 km/h
NDN	Forwarding Scheme	BestRoute
	Cache replacement	LRU
	Cache Size	1000 objects
OpCCMob	Optimization Window	2s
	α	10%
	β	10%

1) Predict the Interests that will be dropped due to mobility events. Since perfect knowledge is assumed for finding the optimal solution, the new module will use the information provided from the Mobility and User planes to find these Interests.
2) Create a Gurobi model of the formulation proposed in Section III. The current state of the network is used to find the thresholds and constraints' boundaries.
3) The model is solved periodically for every time slot (optimization Window) considering the suspected Interests to be dropped in the next slot.
4) The solution that Gurobi finds is then applied to the network. For every $\sigma_r^d = 1$, data d will be cached in router r, using special cache space mentioned earlier. If r is not on the path from the Consumer to the Producer (i.e., $r \notin P_{u \to u'}$), FIB entries are added to every non-common router in $P_{u \to r}$.

Following these steps ensure that all Interests issued just before a handover event will be directed to a stored data in the special caching space chosen by the optimizer. Hence, no retransmission is required.

V. RESULTS AND DISCUSSION

A. Experiment Setup

The configuration of the assessment framework is summarized in Table I. Specifically, there are 100 users (split into 50 Consumers and 50 Producers) moving in 7x7 street grid plan. The Consumers send requests with a rate of 50 to 80 Interests per second following a popularity distribution Zipf with $s = 0.2$. A hierarchal topology is used with 40 core routers distributed in 5 domains. The content store of each router has a capacity of 1000 data items, and uses Least Recently Used (LRU) replacement policy. Moreover, there is an AP on every intersection (i.e., 49 APs).

For every experiment, one factor is varied to test its impact on the scheme's performance. Moreover, each experiment was executed for 20 runs with different random seeds, to test the statistical significance of the result. We found that with 95% confidence, all results have a maximum deviation of 5% from the reported average values.

B. Schemes and Evaluation Metrics

We study *OpCCMob* and compare it with three other schemes under different scenarios. First, NDN with no Consumer mobility scheme while Interests retransmissions are solely used (it will be referenced as Pure-NDN). The second scheme is proposed in [11] which will be used to represent the Reactive schemes. Lastly, the third scheme is Semi-proactive which will be simulated according to the work in [15]. Proactive schemes usually predict more than one future location to adapt with uncertainty. However, in the following experiments (except the last one), we assume the best case scenario where the future PoA is correctly predicted.

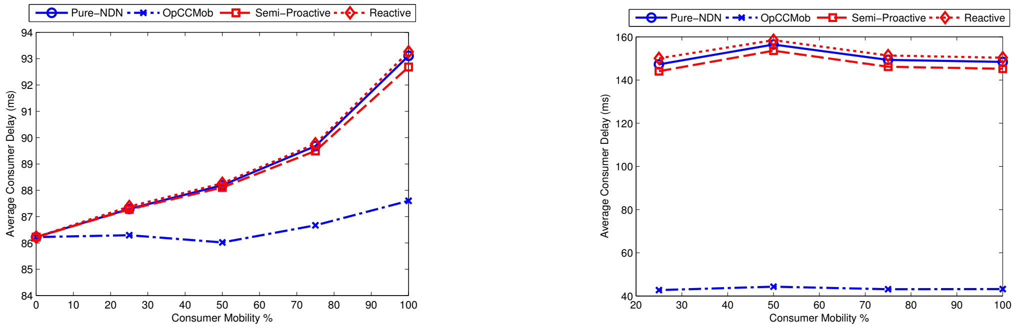
Furthermore, the following metrics are considered in the evaluation since they reflect the satisfaction of the Consumer and the network:

1) Consumer Delay: is the total data access time, which is calculated as the time difference between the first attempt of sending the Interest and successfully receiving the Data. It includes the total timeout period and the delay of both the retransmitted Interests and Data packets.
2) Delivery Ratio: is the percentage of successful Data packets received by the Consumer to the total number of sent Interests. Higher delivery ratios reduce the load on the network since no Interests retransmission are sent.
3) Overhead: calculated as the percentage of the total number of control packets generated by the scheme to the total number of Interests.

C. Consumer Mobility

In the first experiment, we evaluate the effectiveness of the aforementioned mobility schemes under various percentages of Consumer mobile nodes in the network. Fig. 1a shows the ability of the optimal scheme *OpCCMob* to relatively mitigate the effect of mobility on the average Consumer delay and provide stable performance. In particular, proactively caching the required data near the Consumer has avoided retransmission, hence the delay is not increased (stays at 86-87 ms) and the delivery ratio is close to 100%.

Comparatively, Pure-NDN suffers from longer delays which have increased by 8%. This is the result of the simple approach of NDN which relies on Interests retransmissions. Moreover, the performance of the two schemes representing the main approaches proposed in the literature are close to pure-NDN. For further comparison, Fig. 1b and Table II show the metrics for the Interests sent during handover (i.e., Interests sent in $[t_{HO} - RTT, t_{HO}]$). The delay of the Reactive technique is relatively longer than Pure-NDN by 2 ms. This is due to the approach taken by the Reactive scheme where the retransmitted Interests are directed to the old PoA (instead of the Producer as in Pure-NDN), assuming it can be closer to the new PoA which is not always true, especially in case of moving to a new domain. On the other hand, the Semi-proactive scheme has successfully reduced the delay by 2%



(a) Average Consumer Delay for all Interests

(b) Average Consumer Delay for Interests issued in $t_{HO} - RTT \longrightarrow t_{HO}$

Fig. 1. Comparing the performance of *OpCCMob* with Pure-NDN, Semi-Proactive and Reactive schemes by varying the percentage of Consumer mobility

TABLE II
AVERAGE DELIVERY RATIO AND SCHEME OVERHEAD IN ALL SCHEMES

Scheme	Delivery Ratio for Mobile Interests	Overhead message per Interest
Pure-NDN	89%	0
OpCCMob	95%	1.06
Semi-Proactive	89%	1
Reactive	89%	1

TABLE III
OUTCOMES OF MOBILITY PREDICTION ERRORS ON *OpCCMob* AND SEMI-PROACTIVE SCHEMES

		Prediction		
		HO		No HO
		Correct PoA	Wrong PoA	
Actual	HO	Case 1	Case 2	Case 3
	No HO	Case 4		Case 5

Case 1 & 5	Perfect prediction, No problem
Case 2	Semi-proactive will fail
Case 3	Both schemes will fail
Case 4	Extra overhead

compared to Pure-NDN. The limited improvement is the result of relying on Interests retransmissions, and under utilizing caching resources while storing the data. This can be shown as well in the delivery ratio (Table II) where it is very similar to Pure-NDN. On the contrary, *OpCCMob* has a higher delivery ratio (95%) since no retransmissions are needed.

While *OpCCMob* provides lower and upper bounds for the Consumer's delay and delivery ratio, respectively, the gap between the former and each of the other schemes provides room for enhancing their performance. For instance, the semi-proactive scheme can consider other caching resources besides the PoA of the Consumer. However, the optimality of *OpCCMob* requires extra overhead to deliver the data near the Consumer and to update the path to the chosen router. Table II compares the overhead of all schemes. *OpCCMob* has an extra 6% overhead over other schemes. This is the result of the path update messages needed to support off-path caching.

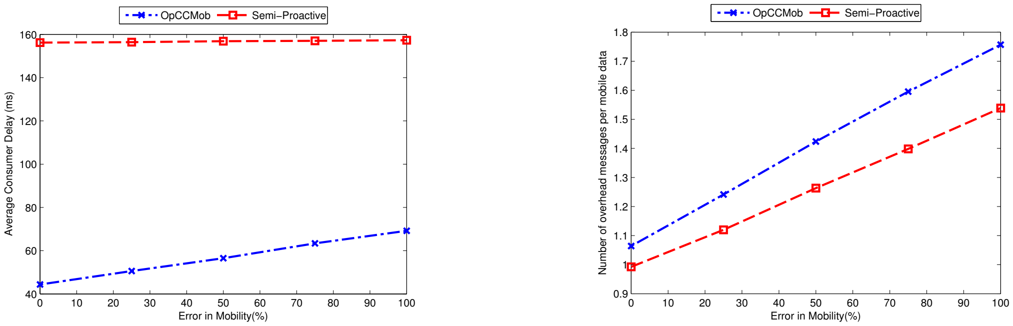
D. Sensitivity Analysis

In the previous experiments, we assume that the Semi-proactive schemes and *OpCCMob* adopt error-free predictions. To measure the impact of imperfect prediction in mobility and requests, we conduct the following two experiments.

1) Imperfect Mobility Prediction: Error in predicting the future location of a node may lead to incorrect PoA. To simulate such errors, we add a uniformly distributed random number to anticipated Consumer's positions such that the PoA of nodes on the edge of an AP is altered to one of the neighboring PoA. This can lead to 5 outcomes summarized in Table III. When the prediction is correct (i.e., Case 1 and 5), the schemes will work as explained above with full knowledge of future handover events. For Case 4, when false positive occurs, the schemes will try to optimize unnecessary requests, hence excess overhead will be created on the network. The worst scenario is in Case 3 where a handover event is missed, since the schemes will not handle those Interests and retransmissions are required as in Pure-NDN. Finally, the case when the handover event is predicted but with wrong new PoA (Case 2), only the performance of the Semi-Proactive scheme is affected. This is because *OpCCMob* is handles the handover before it occurs, therefore the exact information of the new PoA is not needed to optimally cache the data.

Fig. 2a and Fig. 2b depict the delay and overhead of Semi-Proactive and *OpCCMob* schemes with error in mobility prediction. The average Consumer delay in Semi-Proactive scheme increases by a small percentage to reach the upper bound (i.e., pure-NDN), whereas the delay in *OpCCMob* is increased by 75% when all location prediction are wrong. The extra delay is due to the scenarios of Case 3 mentioned above when handover events are missed. Nevertheless, there is still a performance gap for other schemes to improve. The overhead of both schemes is increased by 59%, due to Case 4 scenarios. The performance of the schemes can be improved by considering multiple future PoAs to avoid the uncertainty, which requires optimizing the overhead and caching resources.

2) Imperfect Requests Prediction: *OpCCMob* uses requests predictors to identify the data that should be prefetched before handover. If wrong requests are predicted, the delay of these requests will be optimized whereas the mobile requests will not. In this experiment, a uniform random error is added to the predicted Interests such that the name of the request is changed. Fig. 3 demonstrates the average delay at 50% mobile Consumers for the Semi-proactive scheme and *OpCCMob* with 0%, 50% and 100% percentages of error in prediction. Furthermore, 3 different cache sizes are tested. The delay increased on average by 100 % during 50% wrong predictions. Additionally, the performance is close to Semi-Proactive scheme when the predictor provides with erroneous information.



(a) Average Consumer Delay with 50% mobility (b) Overhead of *OpCCMob* with 50% mobility

Fig. 2. Comparing the performance of *OpCCMob* with Semi-Proactive scheme by varying the percentage of mobility prediction error

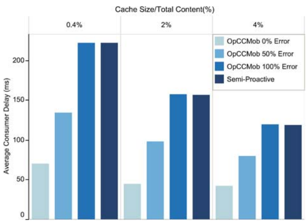


Fig. 3. Impact of errors in requests' patterns

VI. CONCLUSIONS AND FUTURE WORK

A big share of the current and predicted future use of the Internet is related to mobile devices, therefore supporting Consumer mobility in NDN is fundamental. We propose an optimal proactive Consumer mobility management scheme that uses in-network caching and location prediction to support seamless operations in NDN. The evaluation of *OpCCMob* shows the advantage of proactively caching the data before handover. In particular, the average delay is not changed with the increase of mobile events, however overhead packets are required. The results contribute as a benchmark for other schemes proposed currently or in future literature.

The performance of *OpCCMob* compared to the two main approaches of Consumer mobility (Reactive and Semi-proactive) provides a gap that can be filled by utilizing more cache resources. That is in addition to the use of mobility predictions to provide fully proactive solutions. On the other hand, the overhead associated with *OpCCMob* is an upper-bound to other schemes. With the provided bounds of performance, a trade-off between an acceptable delay and overhead cost can be introduced. The sensitivity of *OpCCMob* to errors in location predictions and requests forecast was analyzed. The results have shown that the proposed scheme is robust to imperfect location predictions and provides sub-optimal results to data requests' errors. Our future work will consider studying the complexity and scalability of the *OpCCMob* and provide real-time nea-optimal solution the

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