Increasing Network Resiliency via Data-Centric Offloading

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***Abstract*—Mobile traffic volume is increasing rapidly, pressuring the underlying infrastructure to quickly increase its capacity. New applications are further exacerbating this problem. Device-to-Device communication has been long recognized as a means to offload traffic from the infrastructure; however, the host-oriented model of the TCP/IP-based Internet poses challenges to this communication pattern. This paper addresses these issues by proposing a scheme that uses a data-centric model to fetch contents from nearby peers while increasing the resiliency of the network in cases of outages and disasters. We collected real data from social media to create a content request pattern and evaluate our approach through the simulation of realistic urban scenarios. Additionally, we analyze the scenario of large crowds in sports venues. Our simulation results show that we can offload traffic from the backhaul network by up to 51.7%, suggesting an advantageous path to support the surge in traffic while keeping complexity and cost for the network operator at manageable levels.**

***Index Terms*—Information-Centric Networking, Cellular Networks, Device-to-Device Communication, Crowdsourcing**

I. Introduction

The ever increasing popularity of smartphones and other mobile devices allows users to access a variety of services such as video on demand, online banking, and social media virtually anywhere in the world. Smartphone technology and wireless networks also play a key role in emergency and disaster scenarios, where first responders need to communicate among themselves, command posts, and the public to perform emergency management tasks (e.g., to perform triage in the case of many significant injuries). With the current infrastructure reaching its capacity limits in dense urban scenarios, it is fundamental that communication in the case of an emergency can be performed in a timely and reliable manner.

The evolution of Radio Access Networks (RAN) is mostly focused on increasing capacity and reducing cost for network operators. For instance, the Third Generation Partnership Project (3GPP), the body responsible for cellular network standards, adopted carrier aggregation and multiple input multiple output (MIMO) technologies in the LTE standard [1] that specifies data rates on the order of 300 Mbps. This increase in capacity has the goal to cope with the rapid increase in demand from users. This demand is predicted to increase 7-fold by 2021 on top of an 18-fold increase from 2011 to 2016 [2]. Consequently, mobile network operators (MNO) have been deploying more base stations and femtocells to accommodate this increase in traffic, an approach that increases complexity, cost, and management for the MNO. To alleviate the infrastructure, the 3GPP formalized in releases 13 and 14 the LTE Licensed Assisted Access (LTE-U/LAA/eLAA), that allows the coexistence of LTE in unlicensed 5 GHz ISM-bands to expand the capacity of current networks. While these solutions increase network capacity in response to the rising user demand, their increasing complexity makes them more vulnerable in the face of disasters. The recent events in the aftermath of Hurricane Maria [3] on the island of Puerto Rico have demonstrated this in a shocking manner.

We believe that Device-to-Device (D2D) communication has the potential to address the challenge in providing extra capacity to the edge of the network, while reducing capacity requirements at the core. Moreover, it increases reliability in disaster scenarios, where low-capacity networks are usually deployed to maintain a minimum level of connectivity with emergency services. For instance, the authors in [4] analyzed network data during the 2014/2015 floods in Malaysia and Indonesia, finding that the signal quality from the available base stations deteriorates while users tend to use more WiFi networks when available. However, a reliable D2D communication is challenging as nodes can enter and exit the communication range at any time, breaking end-to-end paths and altering routing state. Additionally, in larger ad hoc networks, nodes are subject to hidden terminal problems.

We present a scheme that combines Information-Centric Networking (ICN) [5], [6] with D2D communication to offload traffic from cellular networks, allowing users to communicate even without the aid of wireless infrastructure. In ICN, data is immutable and decoupled from its location, enabling a node to fetch content from any other node in the network that has a cached copy of the requested data. In-network caching is supported as part of the architecture. Furthermore, ICN supports multipath communication and prevents loops. These characteristics make ICN more tolerant to delay and disruptions than host-centric architectures. The work presented in this paper is based on Named-Data Networking (NDN) [7], one of the many flavors of ICN. We provide a brief explanation of NDN in Section II-A.

In this paper, we assume that mobile nodes have two wireless interfaces (e.g. Wi-Fi and cellular) which is the case for modern smartphones. Therefore, when a node sends out a request to fetch data, it first queries nearby devices for a cached copy. If the request times out, the request is retransmitted to the cellular network. We evaluate our approach through simulations using NS-3 and ndnSIM [8].

Our contributions are the following. First, we propose a scheme that utilizes D2D communication and ICN to offload increasingly congested base stations, facilitating the communication between peers when the infrastructure is impaired. Additionally, our scheme considers energy saving measures and reduces content flooding in the MANET by suppressing the propagation of requests when the energy on the node falls below a certain threshold. Our solution successfully offloads traffic from the base station, consequently reducing cost and complexity for the cellular network.

The remainder of this paper is organized as follows: In Section II, we discuss related work. In Sections III and IV, we present our model and simulation results, respectively. Sections V and VI conclude the paper and discuss future research directions.

II. Background and Related Work

A. Named-Data Networking (NDN)

NDN is a consumer driven architecture, i.e., the consumer application initiates the communication by sending *Interest* packets upstream to retrieve *Data* packets. Interest packets are generally small packets (approximately 40 bytes) that are used by the consumer to express interest in retrieving certain data. It does so by using a hierarchical naming scheme, also called namespace (a set of named contents that begins with a certain prefix, e.g., */edu/umass/*home/version). Data packets contain the actual payload, with all packets being signed by the originator. NDN also has a Negative-Acknowledgment (NACK) packet type, used by the network nodes to express that a certain content is not present or that it received a duplicate Interest request. Similar to IP networks, packets are forwarded by intermediate nodes towards the destination. In NDN however, these nodes are augmented by the following data structures:

- A *Content Store (CS)* that caches incoming Data packets. Upon receiving an Interest request, the node verifies whether the requested data is cached, returning it if positive. Besides reducing the amount of traffic that is sent upstream, this feature increases the tolerance to disruption (in the case of a disconnection, the content will be stored closer to the client).
- A *Pending Interest Table (PIT)* keeps a record of Interest requests, incoming and outgoing interfaces, aggregating similar requests, resulting in a stateful data plane. Data packets follow the reverse Interest path. As a result from Interest aggregation, the PIT prevents loops from happening in the network, which is an important feature in ad hoc networks.
- The *Forwarding Information Base (FIB)* holds the information on which interface to forward a specific Interest packet. Another important part of the NDN architecture is the strategy layer, that determines the behavior of a node when multiple paths exist. Moreover, a node can apply different strategies to different namespaces. We describe our forwarding strategy in Section III.

B. D2D Communication and VANET

There have been a number of studies focused on using D2D communication to offload cellular base stations in the TCP/IP domain. In fact, the authors in [9] survey the literature to classify existing offloading approaches into two main categories: AP-based (where traffic is offloaded via IEEE 802.11 networks) and Terminal-to-Terminal (or simply D2D communication). In the latter, we can further segment the techniques into timer-based (where nodes delay forwarding to reduce collision) [10], [11], geographical-based (where farther nodes re-broadcast first) [12], [13], randomized broadcasting (again to reduce collisions by making nodes re-broadcast at random times) [11], contact-based (based on the number of neighbors (degree of a node) or number of visited nodes) [14], and a combination of two or more approaches [15]. On the contrary, there have been few studies to use *ICN over LTE* to take advantage of in-network caching to decrease traffic in the backhaul network.

In [16], Lopes et al. developed an application whereby messages are stored in a *Content Manager* module, much like a cache. In the case that the destination is not in the vicinity of the sending node, the *Routing* module consults the *Social Proximity* of the neighbors to decide which node to forward the packet to. This decision is based on the frequency that each node meets the destination node (thus, social proximity). Therefore, the sending node creates a socket-like connection via WiFi-Direct and transfers the message to the node that will most likely meet the destination node in the future. Every node can also carry other nodes' messages (data muling). Although this scheme implements concepts of ICN, it uses MAC addresses to route messages instead of content names. Moreover, it does not support multicast, as only the node that has seen the destination more often carries the request.

The authors in [17] expand an LTE-based architecture to include NDN routers, which are co-located with eNBs to implement caches at the backhaul network, then address the problem of content allocation optimization. In particular, the problem of content allocation optimization is addressed by determining where, when, and how content should be migrated. Their approach enhances the network response to user mobility via a set of parameters derived from the LTE network. Among the results, Gomes et al. found that latency can be reduced by using NDN default caching strategies (e.g. LRU). In addition, considering the amount of free space at the destination cache when placing content yields the most benefits. The authors, however, do not consider D2D communication as part of their design. In our work, we leave content migration to the LTE handover process (which was not considered in [17]).

In the vehicular network domain, Navigo [13] proposes a location-based packet forwarding mechanism to reduce disruption and path changes. The main idea is to forward requests to geographical regions where the content might be located. The location of contents is computed using a broadcast strategy,

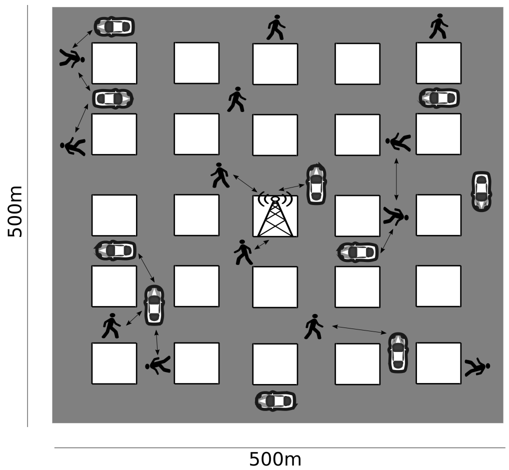

Fig. 1. Manhattan-Grid mobility model. Nodes (cars and pedestrians) can only move along the gray roads.

called exploration phase. Navigo is purely ad hoc as it does not consider base stations in their topology. Our approach is comprised of an ad hoc and infrastructure components. In [18], Vigneri et al. propose an augmented architecture where public service vehicles serve as relay points to offload traffic from the backhaul network. In this architecture, MNOs can place content on these vehicles that can later be retrieved by end-users. This approach showed improvements of up to 50% in the traffic offloaded from the backhaul network. The authors in [19] use an ICN approach to disseminate road emergency information (e.g. flooding and crashes) to other vehicles in an ad-hoc fashion. They do so by translating the 2-D coordinates of the emergency area into one value using a mapping function (more specifically, the Cantor pairing function used by the authors in [20]) and appending this information directly to NDN packet names. Then, the NDN forwarding strategy is modified to consider the geographical coordinates and velocity of the nodes to delay the re-broadcasting of packets with a timer-approach.

In contrast, our approach differs from previous works in the sense that we modify the NDN protocol stack to develop a custom forwarding strategy to better take advantage of D2D communication that improves the reliability of cellular networks, making it more resilient to failures.

III. Model and implementation

Our application scenario is focused on data dissemination in urban environments, including pedestrian and vehicular nodes. We assume that all nodes have at least two wireless interfaces, one WiFi and one LTE, and that they are willing to join the MANET, and share storage space for collaborative caching.

In our first scenario, nodes move along a Manhattan grid (shown in Figure 1) generated using BonnMotion [21], a widely used mobility generation tool. We implement two other scenarios: the vehicular cloud proposed in [18] and a pedestrian crowd (e.g., concerts or sports events). For evaluation, we use the ndnSIM simulator [8], a NS-3 based NDN simulator.

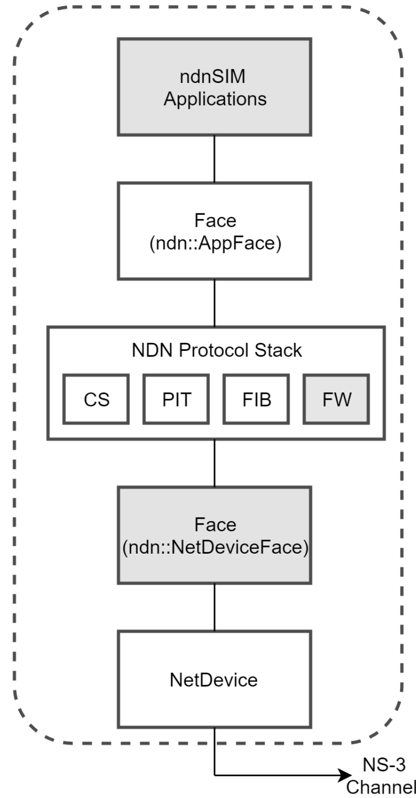

Fig. 2. NDN-Node block diagram with the modified blocks in gray.

We customized the NDN forwarder to meet our application scenarios as follows (a complete view of the node structure and modified blocks is shown in Figure 2). First, when a node sends out an Interest request to the network, it attaches a retransmission tag (*Retx tag*) to the outgoing packet. The Retx tag informs the forwarder whether the packet is a retransmission or not. I.e., if the desired content was not found in the MANET within one timeout period, it sets the Retx tag. All retransmitted Interest packets are forwarded directly to the cellular network. We use the hop count tag (*HopCount*) to identify if a node is the originator or a forwarder. If a node is a forwarder, it may drop packets based on its energy level, which we will described next. This approach is motivated by the fact that energy might be scarce in disaster scenarios due to power outages. In such a case, users might not be willing to deplete there battery below a certain threshold.

Considering the energy consumption of the nodes, we create two thresholds where nodes change their forwarding behavior based on the current energy level. The first threshold, E_{th_1}, is at 35% battery level and the second threshold, E_{th_2}, is at 25%. These thresholds were chosen based on a common Li-Ion battery discharge curve [22]. At the beginning of each simulation, each node is randomly assigned an initial energy level ranging from 5% to 100%. When the energy at a certain node falls under E_{th_1}, it stops forwarding packets with hop count greater than three. In our initial tests, we found that more than 90% of the packets retrieved from the MANET come from a range of 3 hops or less. Therefore, this threshold aims at saving energy by reducing a packet's reachability while still being able to serve the majority of contents. Furthermore, when the energy level falls below E_{th_2}, the node leaves the MANET by forwarding all Interest packets directly to the cellular network. The described behavior is formalized in Algorithm 1.

Algorithm 1: Modified behavior of NDN forwarder

Input : Interest packet
Output: Interface to forward

if $HopCount = 0$ **then**
    if $E_n \leq E_{th_2}$ **then**
        return LTE;
    else
        return WiFi;
    end
else
    if *(* $E_n \leq E_{th_1}$ *and* $HopCount \leq 3$ *) or*
    ($E_n > E_{th_1}$ *and* $HopCount \leq 6$ *)* **then**
        return WiFi;
    else
        return Drop;
    end
end

For the consumer application, we gathered real data from Twitter's trending topics in the United States to create our content request pattern.[1] Through maximum likelihood estimation, we found that the popularity in our dataset follows a Zipfian distribution with $\alpha = 0.7$ and $q = 0.7$, described by Equations 1 and 2. Other works have characterized Internet content to follow the Zipfian distribution as well, among them [23], [24]. The main assumption is that some tweets will reach more users than others, which is the case with popular accounts from public figures (usually millions of followers) and regular accounts (a couple dozen to hundreds of followers).

$$f(k; N, q, \alpha) = \frac{1/(k+q)^{\alpha}}{H_{N,q,\alpha}} \tag{1}$$

$$H_{N,q,\alpha} = \sum_{i=1}^{N} \frac{1}{(i+q)^{\alpha}} \tag{2}$$

Our content catalog (N) is composed of a total of 1,000 contents. Each node requests an Interest every 20 ms, and can cache contents varying from 0.1% to 10% of the content catalog. We simulate three scenarios where the infrastructure is being challenged by the rapid increase in traffic and it would benefit from D2D communication in the case of a crisis.

[1]https://developer.twitter.com/en/docs/trends/locations-with-trending-topics/api-reference

TABLE I
SUMMARY OF SIMULATION PARAMETERS FOR SCENARIO I

Parameter	Value
Node count	25, 50, 100, 150
Area	500 x 500 m^2
Access technology	IEEE 802.11g and LTE
Communication range	Wi-Fi: 100 m, LTE: To base station
Node cache (CS)	1, 5, 50, 100 kB
Cache Policy	LRU
Data payload	1 kB
Total contents	1,000

A. Urban Scenario

This scenario resembles an urban environment where nodes can only move along the grid (streets). Due to the large number of users, MNOs turned to small cell densification to cope with the increase in network traffic. For our simulations, half of the nodes are pedestrians (moving at 1 m/s) and half are vehicles (moving at 13 m/s). Node count and simulation area were calculated using the framework in [25]. There is one base station located at the center of the grid that is used only when end-users cannot fetch the requested content from neighboring nodes. Table I summarizes the simulation parameters.

B. Vehicular cloud

Following the findings in [18], we implemented the concept of a vehicular cloud where utility or emergency vehicles serve as data mules to assist end-users in fetching content. In our implementation, nodes move according to the Manhattan-Grid model. First, the vehicular nodes randomly request contents from the backhaul network to fill up their caches (i.e., a node will sequentially request as many contents as it can store in its cache, with the first requested content being randomly selected), then consumer nodes request contents from the vehicular cloud. If that request times out, pedestrians retransmit to the cellular network. In this scenario, the only communication allowed is device-to-vehicle and device-to-infrastructure. We vary the number of vehicles from 25 to 100 nodes in increments of 25, while the number of pedestrians remains static at 25 nodes. Moreover, we evaluate the effects that different cache sizes on the vehicular node has on the network. The expectation is that as the number of vehicular nodes increase, pedestrians will be able to fetch more contents from them. Similarly, as vehicle cache size increases, the pool of contents available to pedestrians will be greater.

C. Large crowds

Another possible application for our model is large crowds, where often the influx of people exceeds the capacity of the infrastructure. In [26], the authors reported that terabytes of data were transfered via cellular networks (AT&T, Verizon, and Sprint) by in-stadium fans during the 2015 Superbowl. We develop a scenario where spectators at an arena are able to watch on-demand replays, reducing the load on the infrastructure. Our scenario comprises of 200 users in one section of a stadium. Users can communicate with the LTE base station (in this case a femtocell) as well as other users in the same stands to fetch contents. The replay videos have a total duration of 20 seconds each, segmented into 2-second chunks (following the MPEG-DASH standard [27]). The chunk size is 100 kB. We leave the question of fetching different quality levels for future work. In total, five replay videos are requested by all users, with the video segments being requested in order. However, each user will start requesting the videos at a random time within a short interval (10 seconds). The reason for this interval is two-fold: in reality, not all spectators request videos at the same time; second, by using slightly different times, nodes can take advantage of caching.

IV. Simulation Results and Evaluation

We first analyze the Manhattan-Grid scenario (Section III-A). Figure 3 shows the average percentage of traffic that was successfully offloaded from the cellular network with different node densities and different cache sizes (CS). The remaining requests that could not be satisfied from the MANET were served by the cellular network. The error bars are the standard deviation of ten runs. According to Figure 3, our model can offload up to 51.7% of traffic from the infrastructure. We attribute this result to the combination of inherent in-network caching in NDN (enabled by named-content) and the Zipfian request pattern described earlier. We can also observe a higher variation in lower density scenarios. This is due to the social proximity of the nodes, i.e., in low densities, nodes are more susceptible to the presence of neighbors, as for higher densities the pool of content from neighbor caches is greater. Additionally, we see an increase in the traffic being offloaded as the density increases. This can also be attributed to the higher social proximity in higher densities (more neighbors translate to a greater set of contents to choose from). Figure 3 confirms our expectation that the network performance increases as cache size increases.

In applications that are more tolerant to a higher latency (e.g., where the infrastructure is partly unavailable), the fraction of offloaded traffic can be improved by increasing the number of retries injected in the MANET. Figure 4 shows the percentage of traffic that is offloaded when the consumer application rebroadcasts the Interest request to the MANET, instead of sending it directly to the cellular network. Our experiments show improvements of up to 16.61% (68.31% offload in total) when resending up to four requests to neighboring nodes before sending it to the cellular network.

Figure 5 depicts the PDF of data packets' hop count in all node densities when the cache size per node is 0.5% of the total content catalog. We can see that in all cases, less than 5% of contents come from the nodes' own cache, while the majority of contents comes from nodes that are three hops away. It is important to note that as MANET grows, the PDF becomes wider. We do not limit the propagation of data packets (as we do with Interest packets); therefore, in some occasions, the data packets travel multiple hops back to the consumer node before the Interest timeout expires. Figure 6 shows the CDF for latency for different node densities. We compute latency as the elapsed time from the first Interest requested by a node until the data packet returns, either via the MANET or via the cellular network. We also distinguish between vehicular and pedestrian nodes to study the effects of mobility on latency; however, the graphs do not show a significant difference in latency between pedestrian and vehicular nodes with both curves overlapping in most cases. Figure 6 also shows that in approximately 80% of the cases the latency is below 50 ms. The retransmission timeout in NDN varies according to the number of satisfied (timeout decreases) and lost requests (timeout increases); thus, the tail in the CDF in the MANET cases. The LTE CDF shows the sum of the first timed-out request plus the retransmitted request to the cellular network. Moreover, the shallower slope in the LTE case reflects the variation of the Interest timeout in the MANET.

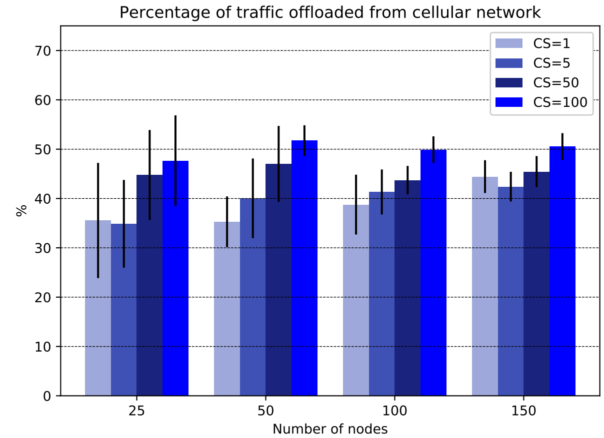

Fig. 3. Percentage of traffic offloaded via the MANET, illustrating the effect of varying cache size and node density.

We also evaluated the energy consumption on the nodes. Our simulation results showed that nodes below the first (25% $< E_n \leqslant$ 35%) and second ($E_n \leqslant$ 25%) threshold consume 5.8% and 2.9% less energy than other nodes, respectively. Nodes that are in the low power range have a steeper drop in the energy levels due to the battery discharge curve. This energy saving approach provides a longer battery life for mobile user equipment, which is specially important when the infrastructure is impaired (e.g. power outages).

The vehicular cloud case (Section III-B) is presented in Figure 7. The *x-axis* represent the number of utility vehicles, while the bars show the average percentage of traffic that was offloaded from the cellular network for different cache sizes used in the simulation. The error-bars represent the standard deviation of ten runs. Figure 7 shows the effect of increasing the number of vehicles, increasing the cache size, and a combination of both. As expected, increasing the number of vehicular nodes that cache content for the MNO has a positive impact on the amount of traffic that can be offloaded from the LTE network as more cache space becomes available. Similarly, increasing the cache size on the available nodes also has a positive impact on the offloaded traffic. It is important to

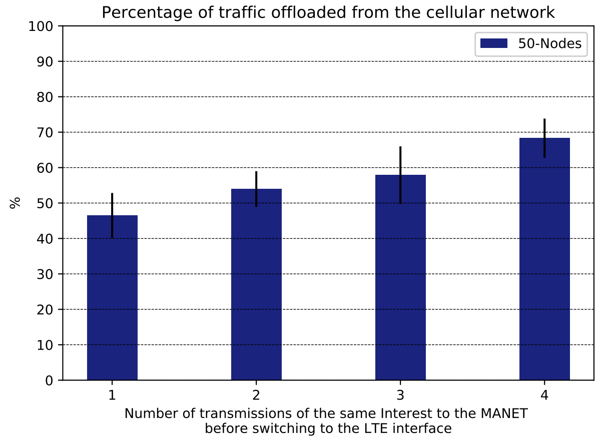

Fig. 4. Percentage of traffic offloaded from the cellular network when the consumer application retries to send Interest requests to the MANET. The figure shows up to 4 transmissions of the same Interest to the MANET for the 50-Node case.

note that increasing the number of vehicles is more effective than increasing the cache size on the vehicles, suggesting that the network benefits from more nodes joining the MANET, but without the necessity of having large caches. This result can be explained because increasing the number of vehicles increases cache diversity in the network, since end-users benefit from the short contact time (when communication between vehicles and consumers happens) with the utility vehicles. Furthermore, our simulation results are aligned with the findings in [18], where the authors experienced an offload ratio of approximately 50% in their vehicular cloud.

The third scenario (Section III-C) focuses on large crowds, where spectators at a sports event have the capability to watch instant replays at their mobile devices. Figure 8 (a) shows the percentage of traffic offloaded by the MANET, as well as the percentage of the video that was downloaded for different request rates. Figure 8 (b) shows the average and standard deviation of latency to fetch one segment. According to Figure 8 (a), 10.3% and 16.59% of traffic was offloaded by the MANET for request rates of 1 and 5 Interest/s, respectively, showing that we can alleviate traffic from the backhaul network. It is important to note that as we increase the request rate, the network saturates and we are no longer able to download the entire video, leading to re-buffering. Moreover, we see a lower offload traffic compared to the two urban scenarios, which reflects the sequential request pattern used in this case (as opposed to the Zipfian pattern used previously). Figure 8 (b) shows the average and standard deviation of latency for each 2-second video segment. In all cases the latency remained under 1.2 seconds and decreases as the request rate increases, suggesting a smooth playback for lower request rates. This decrease in latency reflects the variation in the retransmission timeout (RTO), that reduces as more packets that are in flight are served by the producer or neighbor caches.

All of the above results are available at the project website.[2]

V. Conclusion

This work proposes and evaluates a custom ICN design tailored to environments where the infrastructure is being pressured by the surge in traffic, while increasing reliability in disaster scenarios. Our forwarding strategy seeks to empower D2D communication so users can download contents directly from the MANET, easing the burden on the wireless access network as well as the core. We assessed our model in two urban scenarios using real data from social media to create our request pattern, and one indoor in-stadium scenario where users can view on-demand replays directly on their devices. Our simulation results showed an improvement of up to 51.7% in traffic being offloaded from the cellular network in the urban scenario. Moreover, our energy saving approach reduces the average consumption by up to 5.8% compared to the normal operation, despite the steeper decrease in the battery discharge curve towards the end of its cycle. In the in-stadium scenario, our approach successfully downloads 20-second replay videos where 10.3% of the contents are fetched from nearby devices. We believe that offloading traffic from next-generation cellular networks (5G and onwards) is a promising solution to accommodate the traffic generated from new applications without increasing the complexity and capacity for the MNO. Additionally, an ICN D2D communication has the potential to play a key role in disaster scenarios where the infrastructure is impaired.

VI. Future Work

During the development of this work, we have identified limitations and improvements in our model that we plan to address in the near future. For instance, since the MNO has more information about the overall contents that are being requested in the network, it can have control of what content gets cached in the nodes to maximize cache hits. Optimizing the wireless channel to reduce the probability of collisions is another improvement that we will address in the near future, an approach that was has shown to be efficient in similar ad hoc scenarios [10], [11]. Moreover, [28] developed a scheme based on named-data correlation to more accurately calculate the retransmission timeout of NDN packets, which greatly benefit vehicular and ad hoc networks. Additionally, in lieu of the high potential that ICN has to offer to D2D communication (in-network retransmissions for example), we plan to develop our model in real smartphones to collect more realistic data.

Acknowledgement

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[2]http://people.umass.edu/tteixeira/icn-adhoc.html

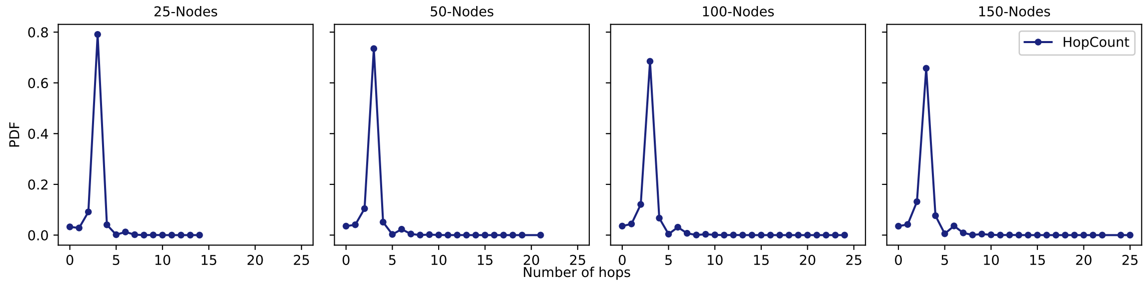

Fig. 5. Number of hops from successfully retrieved data packets.

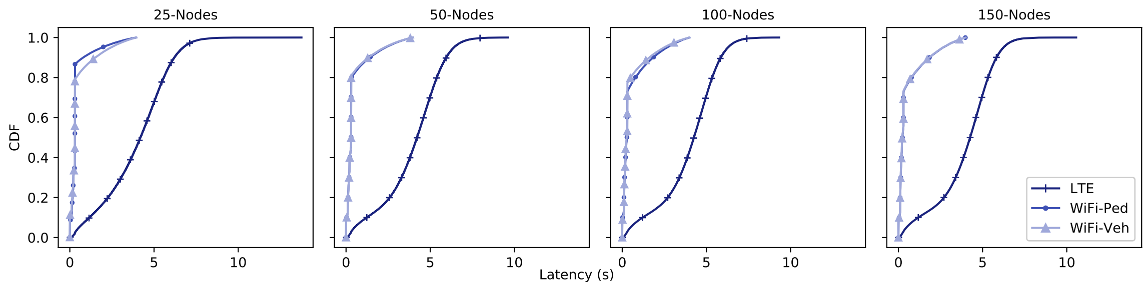

Fig. 6. Cumulative distribution function of latency for different node densities.

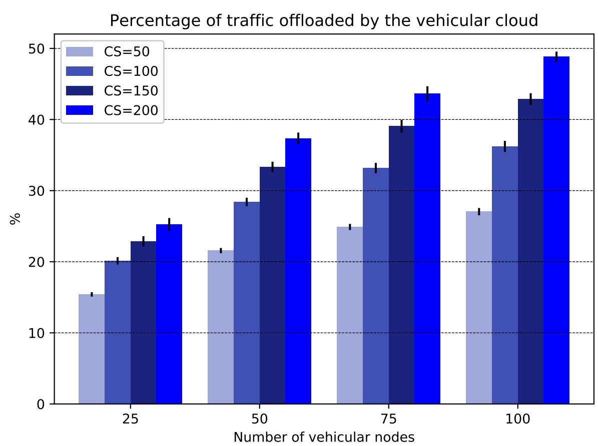

Fig. 7. Percentage of traffic offloaded by the vehicular cloud for different node densities and cache sizes.

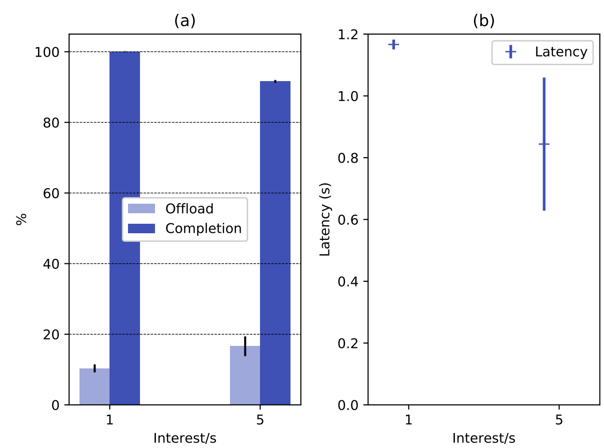

Fig. 8. Percentage of traffic offloaded, video download completion (a), and latency (b) for 200 nodes in sports events.

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