Social-aware Forwarding in Opportunistic Wireless Networks: Content Awareness or Obliviousness?

Waldir Moreira, and Paulo Mendes
SITI, University Lusófona, Lisbon, Portugal
{waldir.junior, paulo.mendes}@ulusofona.pt

***Abstract*—Information-Centric Networking (ICN) has been gaining increasing attention from the research community as it is able to improve content dissemination by releasing the dependency on content location. With the current host-based Internet architecture, networking faces limitations in dynamic scenarios, due mostly to host mobility. The ICN paradigm mitigates such problems by releasing the need to have an end-to-end transport session established during the life time of the data transfer. Moreover, the ICN concept solves the mismatch between the Internet architecture and the way users would like to use it: currently a user needs to know the topological location of the hosts involved in the communication when he/she just wants to get the data, independently of its location. Most of the research efforts aim to come up with a stable ICN architecture in fixed networks, with few examples in ad-hoc and vehicular networks. However, the Internet is becoming more pervasive with powerful personal mobile devices that allow users to form dynamic networks in which content may be exchanged at all times and with low cost. Such pervasive wireless networks suffer with different levels of disruption given user mobility, physical obstacles, lack of cooperation, intermittent connectivity, among others. This paper discusses the combination of content knowledge (e.g., type and interested parties) and social awareness within opportunistic networking as to drive the deployment of ICN solutions in disruptive networking scenarios. With this goal in mind, we go over few examples of social-aware content-based opportunistic networking proposals that consider social awareness to allow content dissemination independently of the level of network disruption. To show how much content knowledge can improve social-based solutions, we illustrate by means of simulation some content-oblivious/oriented proposals in scenarios based on synthetic mobility patterns and real human traces.**

***Index Terms*—information-centric networking; opportunistic routing; dynamic networks; social awareness; content knowledge**

I. INTRODUCTION

Information-Centric Networking (ICN) as its own name suggests is driven by information. That is, data traverses the network according to the match between its name and the interests that users have in such content, independently of its location, resulting in an efficient, scalable, and robust content delivery.

Given its potential, ICN has become of great interest to the research community [1]. Currently, there are different approaches for defining an ICN architecture, such as Data-Oriented Network Architecture (DONA), Named Data Networking (NDN), and Network of Information (NetInf). Each of these proposals has its own particularities (e.g., employ their own naming scheme) and look into different ICN aspects (e.g., naming, security, routing, ...) emphasizing few of these aspects according to the application to which they are being devised.

Yet, these different ICN flavors have some principles in common [2]: i) the publish/subscribe paradigm, where users announce the content that they want to disseminate, and register to receive content made available by others; ii) the notion of universal caching, upon which any network node with persistent storage can keep copies of data that passed through them, or that they requested from other nodes to answer future requests; iii) security models, which are totally shaped around the content itself. All these architecture proposals aim at improving content dissemination in fixed networks (i.e., Internet at large) with few examples related to ad-hoc and vehicular networking [3], [4], [5].

However, wireless devices have become more portable and with increased capabilities (e.g., processing, storage), which is creating the foundations for the deployment of pervasive wireless networks, and encompassing personal devices (e.g. smartphones and tablets). Additionally, wireless technology has been extended to allow direct communication: vehicle-to-vehicle - for safety information exchange; device-to-device - aiming at 3G offloading; Wi-Fi direct - overcome the need for infrastructure entities (i.e., access points). In such a dynamic scenario, users are prosumers (i.e., producers and consumers) of information with a high demand to share/retrieve content anytime and anywhere, independently of the intermittency level of connectivity, their dynamic behavior, physical obstacles between them, among others.

In these dynamic networks, opportunistic contacts among mobile devices may improve content dissemination, mitigating the effects of network disruption. This gave rise to the investigation of Opportunistic Networks (OppNets), of which Delay-Tolerant Networks are an example, encompassing different forwarding proposals to quickly send data from one point to another even in the absence of an end-to-end path between them. Such proposals range from flooding content in the network up to solutions that take into account the social interactions among users. The latest set of research findings show that by exploiting social network structures, social-aware opportunistic networking can indeed improve data forwarding between two intermittently connect hosts with less cost and latency than solutions based only on the users' mobility patterns. This is due to social structures being more stable than connectivity links created based on the number and frequency of wireless contacts due to mobility.

By looking at the nature and properties of OppNets and ICN, one can see the potential of applying content knowledge for driving networking in OppNets: ICN abstracts the need for establishing an end-to-end communication session in an environment where end-to-end paths have little probability of being available. Thus, with ICN, content could reach the interested parties as they subscribe their interests in such type of content, releasing the assumption about the existence of an end-to-end path between any pair of nodes.

Thus, in this paper we show the advantages of combining social-aware opportunistic networking with the ICN paradigm, more specifically the knowledge about the content type and users' interests in such content. Since we refer ICN and OppNets principles, it is important to note that the words *information*, *data*, *messages*, and *content*, as well as *users* and *nodes* are used interchangeably throughout this paper.

The remainder of the paper is structured as follows. Section II goes over the social-aware and/or content-based proposals. In Section III we present our experiments that support our claims, and Section IV concludes our work.

II. Social-aware Forwarding in Opportunistic Wireless Networks

Different ICN architecture proposals have emerged considering the availability, security, and location-independence features of the new paradigm identified in the Internet such as DONA, NDN, and NetInf. It is not our intent to list all the efforts to devise an ICN architecture nor to analyze them as this was already done [2], [1]. Yet, our goal is to show that, besides most of the current ICN approaches targeting communication over fixed networks, the ICN paradigm has great potential in more dynamic networking scenarios.

As ICN suitably copes with mobility of hosts (and consequently disruptive/intermittent communications), initial works have investigated its potential when applied to ad-hoc [3], [4] and vehicular [5] networks. However, these dynamic networks still assume the existence of at least one end-to-end path between any pair of nodes. In this case, the challenge posed by such networks is to find the needed end-to-end path as fast as possible.

Efforts to devise ICN solutions should target more dynamic scenarios, in which we cannot assume the existence of end-to-end paths. The ICN principle has the potential to operate in such disruptive networking scenarios, since the concept of in-network caching is perfectly aligned with the concept of persistent storage present in OppNets. Hence, it would be possible to apply content knowledge (e.g., type and interested parties) in OppNets by revisiting the breadcrumb approach (data is forwarded over an interface where previously an interest was received) to operate based on contact opportunities and not on stable network interfaces.

However, if we look at available opportunistic networking solutions, all of them aim to forward data from point A to point B considering single-copy forwarding or content replication at different levels based on node encounter, resource usage, or social similarity. That is, opportunistic networking operates based on the identification of the hosts (source, destination) and is not based on the transported content, despite the fact that it has been shown how dynamic scenarios can benefit (performance improvements and wise resource usage) from considering the content properties while performing forwarding [6], [7].

From the opportunistic networking solutions, the social-aware family of replication-based proposals gained attention given its ability to avoid the volatile property of mobility. That is, instead of considering the number and frequency of contacts due to the mobility of hosts, such approaches take into account more stable social aspects (e.g., common social groups and communities, node popularity, levels of centrality, shared interests, and future social interactions), aiming to reduce the cost of opportunistic forwarding.

By looking at this social-aware family, one can distinguish between proposals that are completely unaware of content information (i.e., content-oblivious) and those that consider different levels of content knowledge (i.e., content-oriented) while taking forwarding decisions. For the sake of simplicity, we only list the most relevant and latest proposals.

Among the social-aware content-oblivious proposals, we analyzed *Bubble Rap* [8], *CiPRO* [9], and *dLife* [10].

Bubble Rap combines the node centrality with the notion of community to make forwarding decisions. The centrality metric identifies hub nodes inside (i.e. local) or outside (i.e., global) communities. Messages are replicated based on global centrality until they reach the community of the destination host (i.e., a node belonging to the same community). Then, it uses the local centrality to reach the destination inside the community.

CiPRO considers the time and place nodes meet throughout their routines. *CiPRO* holds knowledge of nodes (e.g., carrier's name, address, nationality, ...) expressed by means of profiles that are used to compute the encounter probability among nodes in specific time periods. Nodes that meet occasionally get a copy of the message only if they have higher encounter probability towards its destination. If nodes meet frequently, history of encounters is used to predict encounter probabilities for efficient broadcasting of control packets and messages.

dLife takes into account the dynamism of users' behavior found in their daily life routines to aid forwarding. The goal is to keep track of the different levels of social interactions (in terms of contact duration) nodes have throughout their daily activities in order to infer how well socially connected they are in different periods of the day.

Regarding social-aware content-oriented proposals, we analyzed *SocialCast* [11], *ContentPlace* [12], and *SCORP* [13].

SocialCast considers the interest shared among nodes. It devises a utility function that captures the future co-location of the node (with others sharing the same interest) and the change in its connectivity degree. Thus, the utility function measures how good message carrier a node can be regarding a given interest. *SocialCast* functions are based on the publish-subscribe paradigm, where users broadcast their interests, and content is disseminated to interested parties and/or to new carriers with high utility.

ContentPlace considers information about the users' social relationships to improve content availability. It computes a utility function for each data object considering: i) the access probability to each object and the involved cost in accessing it; ii) the social strength of the user towards the different communities which he/she belongs to and/or has interacted with. The idea is having the users to fetch data objects that maximize the utility function with respect to local cache limitations, and choosing those objects that are of interest to users and can be further disseminated in the communities they have strong social ties.

SCORP considers the type of content and the social relationship between the parties interested in such content type. *SCORP* nodes are expected to receive and store messages considering their own interests as well as interests of other nodes with whom they have interacted before. Data forwarding takes place by considering the social weight of the encountered node towards nodes interested in the message that is about to be replicated.

Generally speaking, although OppNets can provide communication support when facing disruptive networks, ICN has the potential to cope with disruptive/intermittent communications since it does not require the establishment of associations between the source and destination of content. Both paradigms mainly differ in what concerns forwarding: ICN forwarding considers data names and OppNets forwarding focuses on hosts. Thus, by combining content knowledge with social-aware forwarding may increase the performance of data exchange in OppNets, since: i) nodes sharing interests have higher probability to meet each other; and ii) social-awareness results in fast dissemination given the contact opportunities among nodes.

III. Content Awareness or Obliviousness: Which way to go?

Based on experiments, we analyze what is the impact of combining content and social awareness to forward data in opportunistic networks. We consider two social-aware content-oblivious opportunistic routing solutions (i.e., *dLife* and *Bubble Rap*) and one social-aware content-oriented opportunistic routing solution (i.e., *SCORP*). It is worth mentioning that our goal is not to show which proposal is the best; instead, we want to show the gains of combining content knowledge and social awareness, and for that we chose the benchmark proposals that are readily available for the Opportunistic Network Environment (ONE) simulator [14].

Two scenarios are considered: human traces to observe the impact of network load; and synthetic mobility to study how proposals cope with different mobility levels, from high mobile to near static nodes. This section starts by presenting the evaluation methodology and experiment settings, then followed by the results in the considered scenarios.

A. Methodology and Experimental Settings

Results are presented with a 95% confidence interval and in terms of averaged delivery probability (i.e., ratio between the number of delivered messages and the number of messages that should have been delivered), cost (i.e., number of replicas per delivered message), and latency (i.e., time elapsed between message creation and delivery).

The used CRAWDAD traces [15] corresponds to contacts of 36 students during their daily activities.

The synthetic mobility scenario simulates a 4-day interaction between 3 groups (A, M, and B) of 50 people each, who carry nodes equipped with 250-Kbps Bluetooth interfaces, and follow the *Shortest Path Map Based Movement* model (i.e., nodes choose destinations and reach them by using the shortest path) with speed up to 1.4 m/s. By varying the node pause times between 100 and 100000 seconds, we have different levels of mobility (varying from 3456 to 3.4 movements in the simulation).

Proposals experience the same load and number of messages that must reach the destinations. In the trace scenario, the *Bubble Rap*/*dLife* source sends 1, 5, 10, 20 and 35 different messages to each of the 35 destinations, while the *SCORP* source creates 35 messages with unique content types, and the receivers are configured with 1, 5, 10, 20, and 35 randomly assigned interests. Thus, we have a total of 35, 175, 350, 700, and 1225 generated messages. The *msg/int* notation represents the number of messages sent by *Bubble Rap* and *dLife* sources, or the number of interests of each of the *SCORP* receivers.

In the synthetic mobility scenario, 200 messages are generated. With *Bubble Rap* and *dLife*, node 0 (group A) generates 100 messages to nodes in groups B and M, and node 100 (group B) generates 100 messages to nodes in groups A and M. For *SCORP*, each group has different interests: group A (*reading*), group B (*games*), and group M (*reading* and *games*). The source nodes, 0 and 100, generate only one message for each content type, *game* and *reading*. This guarantees the same number of messages expected to be received, i.e., 200.

Concerning TTL, data-centric networking is expected to allow content to reach interested nodes independently of how long it takes, due to the assumption about persistent storage. So, in these experiments, TTL is set to avoid messages being discarded due to expiration (i.e., the length of the experiment: 3 weeks and 4 days for for trace-based and synthetic mobility scenarios, respectively). Message size ranges from 1 to 100 kB. Despite nodes may have plenty of storage, we consider nodes having different capabilities (i.e., smartphones). Thus, nodes have buffers limited to 2 MB as we consider that nodes may not be willing to share all their storage space. These settings follow the specification of the Universal Evaluation Framework [16] to guarantee fairness throughout the evaluation process.

Since *Bubble Rap*/*dLife* sources generate more messages, in the trace-based scenario node 0 has no buffer restriction and message generation varies with the load: 35 messages/day rate (load of 1, 5, and 10 messages), and 70 and 140 messages/day rates (load of 20 and 35 messages, respectively). In the synthetic mobility scenario, all source nodes have restricted buffer, but rate is of 25 messages every 12 hours. This is done so that *Bubble Rap*/*dLife* do not discard messages prior to even trying exchange/deliver them given the buffer constraint.

As for proposals, *Bubble Rap* uses the K-Clique and cumulative window algorithms for community formation and centrality computation as in [8]. As for *dLife* and *SCORP*, both consider 24 daily samples (i.e., each of one hour) as mentioned in [13].

B. Impact of Network Load

This section presents the impact that different levels of network load have on the performance of the content-oblivious and -oriented forwarding proposals. Fig. 1 presents the average delivery probability with different messages/interests being generated.

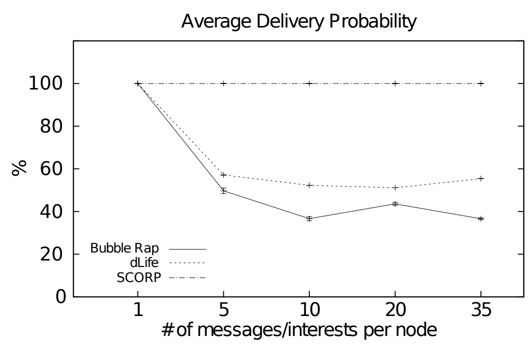

Figure 1. Delivery under different network loads

In the 1 msg/int configuration, formed communities comprise almost all nodes. This means that each node has high probability to meet any other node, which is advantageous for *Bubble Rap* since most of its deliveries happen to nodes sharing communities. Due to the dense properties of the network, *dLife* and *SCORP* take advantage of direct delivery: 57% and 51% of messages, respectively, are delivered directly to destinations.

As load increases, *Bubble Rap* has an 50% decrease in delivery performance. This occurs since it relies on communities to perform forwardings, and consequently buffer space becomes an issue. To support this claim, we estimate buffer usage for the 5 msg/int configuration: there is an average of 80340.7 forwardings, and if this number is divided by the number of days (12[1]) and by the number of nodes (35, source not included), we get an average of 191.28 replications per node. Multiplied by the average message size (52kB), the buffer occupancy is roughly 9.94 MB in each node, which exceeds the 2MB allowed (cf. Sec. 4.1). This estimation is for a worst case scenario where *Bubble Rap* spreads copies to every encountered node. Since this cannot happen, as *Bubble Rap* also relies on local centrality to reduce replication, buffer exhaustion is really an issue given that messages are replicated to fewer nodes and not to all as in our estimation. As more messages are generated, replication increases: this causes the spread of messages that potentially take over forwarding opportunities from other messages, reducing *Bubble Rap*'s delivery capability.

dLife has a 43% performance decrease when network load increases, as it takes time to have an accurate view of the social weights. This leads to forwardings that never reach destinations given the contact sporadicity. For the 10 msg/int configuration, *dLife* also experiences buffer exhaustion: estimated consumption is 2.17 MB per node. Still, by considering social weights or node importance allows *dLife* a more stable behavior than *Bubble Rap*.

Since content is only replicated to nodes that are interested in it or that have a strong social interaction with other nodes interested in such content, the delivery capability of *SCORP* raises as the ability of nodes to become a good carrier increases (i.e., the more interests a node has, the better it is to deliver content to others, since they potentially share interests). The maximum estimated buffer consumption of *SCORP* is of 0.16 MB (35 msg/int).

Fig. 2 presents the average cost behavior. In the 1 msg/int configuration, all proposals create very few replicas to perform a successful delivery, 7.95 (*Bubble Rap*), 14.32 (*dLife*), and 23.46 (*SCORP*), as they rely mostly on shared communities and/or direct deliveries. We also observe that *SCORP* produces more replicas than *dLife*, since *SCORP* nodes with interest in a specific content of a message not only process it, but also replicate it to other interested nodes, thus creating extra replicas.

For the 5, 10, 20 and 35 msg/int configurations, replication is directly proportional to the load. Thus, cost is expected to increase as load increases, as seen with *Bubble Rap* and *dLife*. Despite their efforts, these replications do not improve their delivery probabilities, contributing only to the associated cost for performing successful deliveries.

The cost peaks relate to the message creation time and contact sporadicity: when a message is created in a period of high number of contacts, resulting in much more replications. This is more evident with *Bubble Rap* as it relies on shared communities to forward: as mentioned earlier, most of the communities comprise almost all nodes, which increases its replication rate.

With more interests, a *SCORP* node can serve as a carrier for a larger number of nodes. Consequently, the observed extra replicas make the proposal rather efficient: *SCORP* creates an average of 6.39 replicas across all msg/int configurations, while *Bubble Rap* and *dLife* produce an average 452.41 and 96 replicas, respectively.

[1] In simulation it is worth ~12 days of communications.

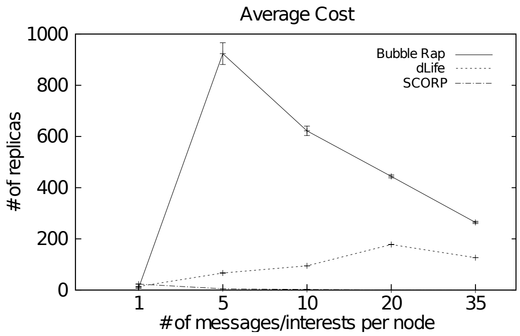

Figure 2. Cost under different network loads

Fig. 3 shows the average latency that messages experience. The latency peak in the 1 msg/int configuration refers to the message generation time: some messages are created during periods where very few contacts (and sometimes none) take place followed by long periods (12 to 23 hours) with almost no contact. Consequently, messages are stored longer, contributing to the increase of the overall latency. This effect is mitigated as the load increases with messages being created almost immediately before a high number of contacts take place.

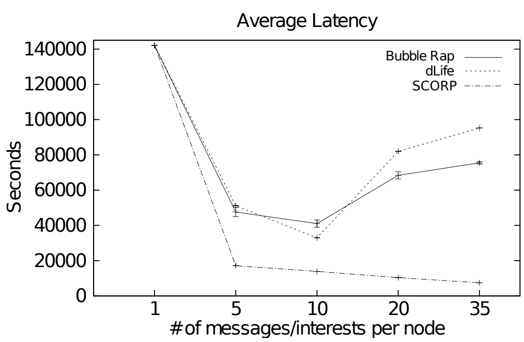

Figure 3. Latency under different network loads

Since latency is in function of the delivered messages, the decrease and variable behavior of *Bubble Rap* and *dLife* is due to their delivery rates decrease and increase, and also to their choices of next forwarders that may take longer to deliver content to destinations. *SCORP* experiences latencies up to approx. 90.2% and 92.2% less than *Bubble Rap* and *dLife*, respectively. The ability of a node to deliver content increases with the number of its interests. Thus, a node can receive more messages when it is interested in their contents, and consequently becomes a better forwarder since the probability of coming into contact with other nodes sharing similar interests is very high, thus reducing latency.

C. *Impact of Mobility Rates*

This section presents the impact that node mobility has on the proposals. As ICN approaches are devised to rather stationary scenarios (e.g., Internet), we observe the performance of the analyzed proposals under a variety of node mobility, including a near-static scenario.

Fig. 4 presents the average delivery probability. Given the community formation characteristic of this scenario, *Bubble Rap* relies mostly on the global centrality to deliver content. By looking at centrality [8], we observe very few nodes (out of the 150) with global centrality that can actually aid in forwarding, i.e., 19.33% (29 nodes), 10.67% (16 nodes), 21.33% (32 nodes), and 2% (3 nodes) for 100, 1000, 10000, and 100000 pause time configurations, respectively. So, these nodes become hubs and given buffer constraint and long TTL (i.e., messages created earlier take the opportunity of newly created ones), message drop is certain, directly impacting *Bubble Rap*.

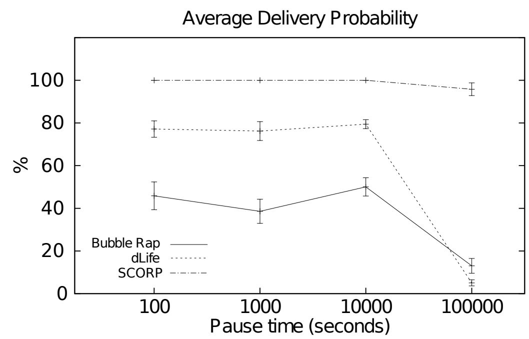

Figure 4. Delivery under varied mobility rates

Given the high number of contacts, the computation of social weight and node importance done by *dLife* takes longer to reflect reality: thus, *dLife* replicates more and experiences buffer exhaustion. Indeed, social awareness is advantageous, but still not enough to reach optimal delivery rate in such conditions.

Independent of the number of contacts among nodes, *SCORP* can still identify nodes that are better related to others sharing similar interests, reaching optimal delivery rate for 100, 1000, and 10000 pause time configurations. By considering nodes' interest in content and their social weights, *SCORP* does not suffer as much with node mobility as *dLife* and *Bubble Rap*.

With 100000 seconds of pause time, the little interaction happening in a sporadic manner (with intervals between 20 and 26 hours) affects *Bubble Rap*, *dLife* and *SCORP* as they depend on such interactions to compute centrality, node importance, and social weights, as well as to exchange/deliver content.

Fig. 5 presents the average cost behavior. As pause time increases, the number of contacts among nodes decreases, providing all solutions with the opportunity to have a stable view of the network in terms of their social metrics with 100, 1000, and 10000 seconds of pause time. This explains the cost reduction experienced by *Bubble Rap* and *dLife*: both are able to identify the best next forwarders, which results in the creation of less replicas to perform a successful delivery.

SCORP has a very low replication rate (average of 0.5 replicas) given its choice to replicate based on the interest that nodes have on content and on their social weight towards other

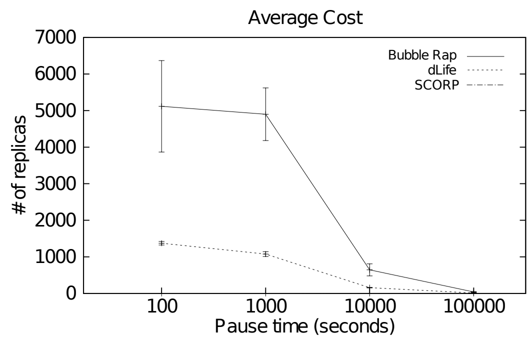

Figure 5. Cost under varied mobility rates

nodes interested in such content. When the intermediate node has an increased number of interests (i.e., by having different interests, the node can potentially deliver more content) as observed in Sec. III-B, replication costs are even lower. Furthermore, *SCORP* suitably uses buffer space with an estimated average occupancy of 0.03 MB per node per day.

With 100000 seconds of pause time, as cost is in function of delivered messages (and deliveries are very low, due to contact sporadicity), proposals have a low cost.

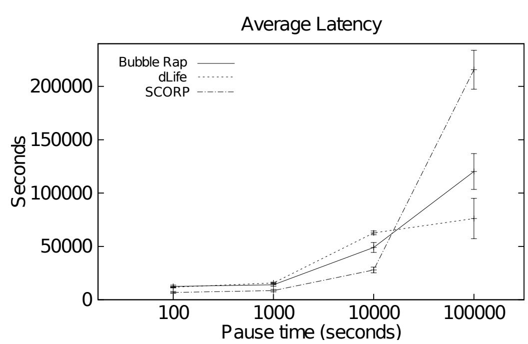

Figure 6. Latency under varied mobility rates

As expected (cf. Fig. 6), latency increases as node mobility decreases: encounters are less frequent, and so content must be stored for longer times. Also, the time that the social metrics take to converge (i.e., a more stable view of the network in terms of centrality, social weight, and node importance) contributes for the increase in the experienced latency. The highest increase in latency with 100000 seconds of pause time is due to contacts happening in a sporadic fashion with intervals between them of up to 26 hours, thus proposals take much longer to perform a delivery.

IV. Conclusions

Information-Centric Networking has become of great interest to the research community and we have witnessed a number of efforts towards the definition of what the ICN architecture should be. Yet, most of the ICN application scenarios encompass fixed networks (i.e., Internet at large) with few ad-hoc and vehicular networking examples [3], [4], [5].

Concerning more dynamic networks, opportunistic networking is being investigated to support forwarding between any two points even in the absence of end-to-end paths. Within all opportunistic networking solutions, one trend for dealing with network disruption is considering the social interactions among users. Social-aware approaches have indeed shown great potential considering different types of social metrics.

By looking at the nature of OppNets and the properties of ICN, one can see the potential of applying content knowledge (i.e., type and interested parties) for driving networking in opportunistic networks: the ICN paradigm abstracts the need for establishing an end-to-end communication session in an environment where end-to-end paths have little probability of being available. Nevertheless, one open question is related to the impact that content awareness may bring to forwarding in opportunistic networks.

Therefore, this paper discusses on the advantages of building social- and content-aware forwarding schemes for networking in disruptive scenarios. Our experiments show that by building a content-oriented social-aware opportunistic forwarding scheme, delivery in disruptive networks can be improved by 60% while latency and cost can be reduced by 75% and 90% respectively, when compared to content-oblivious forwarding schemes.

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