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# On the Impact of Disorder on Dynamic Network Navigation

Anh-Dung Nguyen<sup>\*†</sup>, Patrick Senac<sup>\*†</sup>, Michel Diaz<sup>†</sup>  
anh-dung.nguyen@isae.fr, patrick.senac@isae.fr, michel.diaz@laas.fr  
<sup>\*</sup>ISAE-University of Toulouse, Toulouse, France  
<sup>†</sup>LAAS-CNRS, Toulouse, France

Dynamic networks like Online Social Networks or Disruption Tolerant Networks (DTNs), when considering their spatial, temporal and size complexity, even if partly wired, are exposed to nodes and links churns and failures which can be modeled with dynamic graphs with time varying edges and vertices. Recently, it has been shown that dynamic networks exhibit some regularity in their temporal contact patterns [1], [2]. The impact of this regularity on network performances has not been well studied and analyzed.

One of the most interesting problem in research on dynamic networks is the issue of efficient navigation techniques in such networks. For dynamic networks, because there is still no widely developed theoretical background to understand deeply the problems, research traditionally tends to propose heuristic solutions [3]. In the context of DTNs, these solutions tend to answer to some specific questions about navigating in a dynamic network (e.g., how to reduce energy consumption of routing, how to maximize the delivery probability) while usually ignoring and not leveraging on the profound structural properties of the dynamic network. In this work, we aim to contribute to understanding the impact of this dynamic structure on information routing and show how to exploit this structure for efficient navigation in such networks.

First, we highlight the temporal structure that can be found in dynamic networks. If we focus only on the temporal aspect of dynamic network by making abstraction of node's movement, the network can be seen as a temporal graph  $G(E(t), V(t))$  where  $E(t)$  and  $V(t)$  are respectively the set of edges and vertices of the network at time  $t$ . The notion of dynamic path length in dynamic network was formalized in [4]. Basically, a dynamic path from node  $i$  to node  $j$  at time  $t$  is a time ordered sequence of temporal links which allows a message to go from  $i$  to  $j$  according to the store-move-and-forward communication mechanism. The shortest dynamic path from node  $i$  to node  $j$  at time  $t$  can be based on two simple metrics: delay and hops. The delay of node  $i$  with respect to node  $j$  at time  $t$  is the elapsed time from the last moment when there was a dynamic path from  $j$  to  $i$ . The number of hops is the number of nodes on the path.

From this elementary bricks, if each node in a dynamic network keeps track of its metrics with respect to the others, the metric values in the network build a temporal structure which maintains a order relation between all the nodes. Indeed, this order relation represents how "close" in time and space nodes are from each other in term of delay and hops. Consequently, this order relation forms a gradient field from a node towards the others. In practice, building and maintaining such structure

is analog to maintaining routing tables in static networks, except that in this case, the routing tables are updated via opportunistic contacts between nodes.

This rises the question of how a dynamic network is structured. A dynamic network may be very regular, for example, a network with a periodic contact pattern in which a node is always connected to the same node after the same time interval. In such network, the temporal structure maintains a constant or periodic metric values between nodes. On the contrary, the network regularity may be random such that a node can be connected to any node at any time. In this case, the temporal network structure is disordered. We propose a simple parametric model able to capture the disorder degree of the temporal structure. This model is able to cover the full scope between a totally regular network and a totally random network by gradually increasing the disorder of contact pattern into a network. Starting from a totally regular network, we inject gradually the disorder by randomly rewiring its contacts with a probability  $p$ . This rewiring process results in: when  $p = 0$ , the network is totally regular and expresses a periodic pattern; when  $p = 1$ , the network is totally random i.e. any contact can happen at any time; by varying  $p$  between 0 and 1, we gradually inject disorder into the network. Therefore the parameter  $p$  plays the role of disorder degree of the dynamic network. We illustrate this rewiring process in Figure 1. In the second step, we investigate various real dynamic networks traces to estimate their disorder degree. We provide an algorithm to detect the repeated contact patterns and estimate the probability  $p_{\text{real}}$  of the traces. The results show that real dynamic networks exhibit a disorder degree ranging from medium (about 50%) to quite high (about 70%), as shown in Table I.

Navigation or routing aims to find an efficient path from a node to another which minimizes some costs. Finding an efficient temporal path is made difficult by the lack of a-priori knowledge of the evolution of the dynamic network topology. In other words, nodes can base their information routing decisions on their local knowledge only. Viral diffusion or flooding solutions, while guaranteeing the best delay, induces buffering and network capacity overheads which make them impracticable in reality. In static networks, classic approaches leverage on spatial or structural properties, such as nodes relative or absolute positions [5], social structure [6], etc, that nodes can use to enforce the navigation decision. This approach can be extended to dynamic networks by inferring the spatio-temporal nodes relationships from their peer to peer interactions [7]. In this work, we adopt another point of view that consists in studying the impact on navigation efficiency of

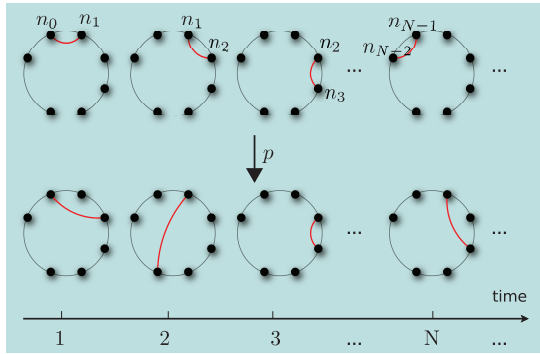


Fig. 1. *Disordered network model: Let a dynamic network of  $N$  nodes  $n_0, \dots, n_{N-1}$  evolve over time with a periodic communication pattern as follows. At time 0,  $n_0$  is connected to  $n_1$ ; at time 1,  $n_1$  is connected to  $n_2$ ; at time 2,  $n_2$  is connected to  $n_3$  and so on. This communication pattern repeats until time  $T_{max}$  beyond which we no longer observe the network. Note that we consider that contact arrivals are atomic and so can be serialized. We introduce disorder into this network by rewiring its links as follows. For each contact, with a probability  $p$  we replace it with a contact between another pair of nodes. With probability  $1-p$  we let the contact unchanged. We process the rewiring by advancing in time until time  $T_{max}$  (i.e., rewire the first contact, rewire the second one and so on until the contact at  $T_{max}$ ).*

Dataset	Number of nodes	Duration (days)	Environment	$p_{real}$ (%)
MIT	104	246	campus,city	57.13
St-Andrews	25	79	city	58.63
Cambridge06	36	54	city	71.14
Cambridge05	12	6	laboratory	76.24
Intel	9	6	laboratory	70.51
Infocom06	98	4	conference	74.75
Infocom05	41	4	conference	78.3

TABLE I. *Estimated disorder degree of real dynamic networks*

an global, instead of local, intrinsic property of the network. More precisely this work focuses on the generic study of the impact of the degree of disorder, expressed from the periodicity and regularity on inter-contact patterns, on routing performances. We propose a simple and efficient solution leveraging on the order relation between nodes created by the temporal structure. Such order relation can be the cue allowing a node to find the efficient path. Indeed, when two nodes are in contact, they know which one is closer to the destination based on the routing metrics they maintain. Therefore the decision of forwarding the message to the destination can be made based on this order relation.

We introduce a class of navigating or routing algorithms that uses only one message copy to find efficient paths to a destination. We focus on this worst case solution in term of the number of allowed copies. We propose two greedy algorithms that exploit the temporal structure. In these algorithms, the messages follow the gradient slope of the temporal structure of the dynamic network to reach the destination. In the first algorithm, named GRAD-DOWN, a node forwards the message if the encountered node has a lower delay or an equal delay with a lower hop number. Conversely, the second algorithm GRAD-UP consists in forwarding the message as soon as the encountered node has a higher delay or an equal delay with a higher hop number. We then study the performance of these algorithms in function of the disorder degree of the network. We also compare them with the classical approaches for DTNs such as Direct Delivery, First Contact and PROPHET. Direct

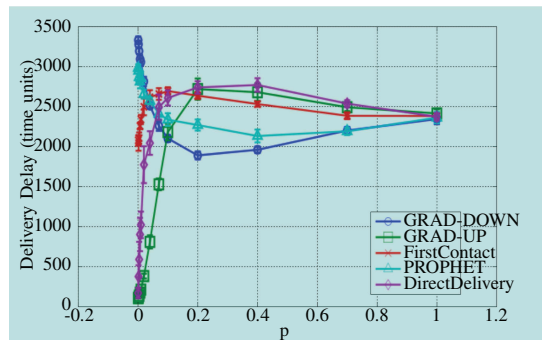


Fig. 2. *Routing algorithm performance as a function of network disorder*

Delivery is the most radical solution in which a node wait until being in contact with the destination to deliver the message. FIRST-CONTACT consists in forwarding systematically the message at the first contact. The more elaborated PROPHET routing protocol [8] is based on the contact history to infer the probability that a node will encounter the destination.

These results illustrated by Figure 2 show that routing performances in dynamic networks greatly depends on the degree of disorder. Specifically when we introduce a small disorder into the network (about 20% rewired links), the network becomes highly navigable. But the more disorder increases, the less we can leverage on time structure. Intuitively, the optimal point corresponds to a network structure in which the contact order is still conserved but the number of injected shortcuts created by the disorder is just enough to reduce the delay until being in contact with a node with smaller gradient value. Our analytical analysis confirms this observation. Besides, GRAD-DOWN in overall outperforms the other algorithms. This illustrates that navigation based on the temporal structure is a good performance/resources trade-off technique. Moreover, the analysis of network traces suggests that this technique is the most adapted in real context.

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