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Navigating temporal networks

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HIGHLIGHTS

- Introducing the problem of navigation on temporal networks.
- Exploring different ways to operationalize the incomplete information.
- Proposing different navigation strategies that are only using ex ante information.
- Found that both static and temporal network structure determine the navigability.
- Shows that in real networks there are structures that could be exploited in navigation.

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ABSTRACT

Navigation on graphs is the problem how an agent walking on the graph can get from a source to a target with limited information about the graph. The information and the way to exploit it can vary. In this paper, we study navigation on temporal networks—networks where we have explicit information about the time of the interaction, not only who interacts with whom. We contrast a type of greedy navigation – where agents follow paths that would have worked well in the past – with two strategies that do not exploit the additional information. We test these on empirical temporal network data sets. The greedy navigation finds the targets faster and more reliably than the reference strategies, meaning that there are correlations in the real temporal networks that can be exploited. We find that both topological and temporal structures affect the navigation.

1. Introduction

Temporal networks can be seen as an extension of the static network paradigm to include information about when interactions happen, not only between whom [1–3]. Just as for static networks, it is interesting to study dynamic phenomena happening on temporal networks, and how the structure of the interaction affects these. In the literature, there has been a great focus on disease spreading [4]. Somewhat less commonly, researchers have studied random walks [5–14] and threshold models of social spreading phenomena [15–17]. Another fundamental dynamic problem on networks is navigation [18,19]. This concerns agents traveling on the network with given starting points and destinations, but with incomplete knowledge of the network, such as the sense of direction in spatially embedded networks [19]. The problem of navigation on temporal networks has so far not been explored in the literature. The goal of this paper is to establish this research question and investigate solutions in form of an extension of spatially navigating agents.

The basic setting is a stream of contacts – triples (i, j, t) of two nodes i and j and a time t – representing an interaction event between the two nodes. Then we assume an agent, as a walker in a random walk, can move to another node at the

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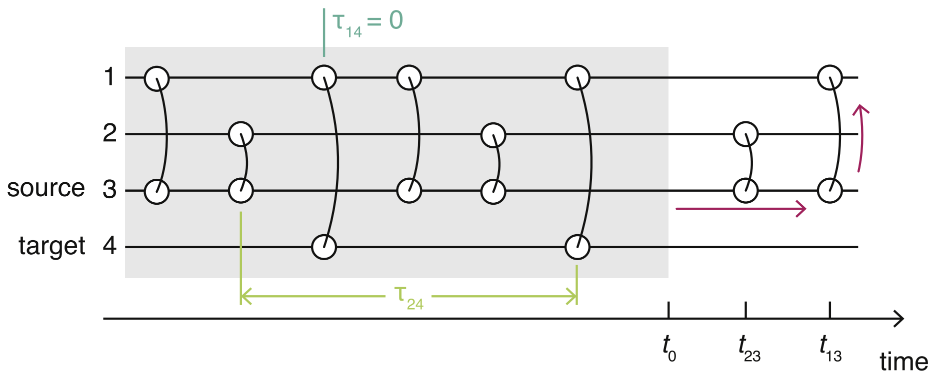

Fig. 1. Schematic diagram of greedy navigation in temporal networks. Each horizontal line component corresponds to a node, horizontal axis represents time, and vertically connected nodes represent contacts at that time [1–3]. At time $t = t_0$, node 3 (the source) wants to send a unit of package to node 4 (the target).

time of a contact. When a contact happens, we assume that the agent can make the decision whether or not to take a step, based on the history of the temporal network. In line with the assumption of incomplete information, we assume that future contacts are not known to a node. For simplicity, however, we assume the last observed time from destination to target is obtainable for all nodes. In this setting, we test three strategies. One is called *greedy navigation* (GN) where agents jump from *i* to *j* at a contact (i, j, t) if the previously observed time to reach the target is the shortest from *j* among all of the nodes. The other two strategies are for reference and not using any available information. The second strategy is the *greedy walk* (GW) of Ref. [20] where agents move at every contact. The third strategy is to simply wait at the origin until there is a contact with the target, we call it the *wait-for-target* (WFT) strategy.

We explore the strategies on six empirical temporal networks. The reason why we use empirical contact data rather than temporal-network models as the basis of our work is twofold. First, there is a very large number of possible structures and correlations in temporal networks compared with static networks, so that one cannot simply scan through them in models [2]. It is also very challenging to identify the most important structures for the dynamic process in question [2]. Second, studying empirical networks contributes to the understanding of the original system itself. Such an analysis enables us to see how different data sets differ with respects to navigating agents.

In the remainder of this paper, we will present and motivate the model of navigation, present the empirical data sets, our analysis procedure, and our simulation results.

2. Preliminaries

2.1. Temporal network representations

There are different ways to incorporate information about the timing of contacts into network modeling. In this work, we will use the so-called *contact list* framework [1]. In that setting, the basic unit of interaction is a *contact* (or *event*)—a triple (i, j, t) showing that nodes *i* and *j* are in contact at discrete time step *t*. The time from the first to last time in a data set is the *duration* T. Other descriptive quantities are the time resolution (minimal time between two contacts) δt, the number of contacts C, and the number of nodes N.

2.2. Greedy navigation (GNH and GNT)

Our model for temporal network navigation is inspired by our work on network navigation with spatial information [19]. The idea for our *greedy navigators* is that the agents know the direction of their target, and then takes steps as close as possible (angularly) to its direction at every step. In that case of spatial (and static) networks, therefore, the available information is embedded in the location of the nodes. In the case of temporal networks, illustrated in Fig. 1, we consider the entire past or history as available information, and, for simplicity, assume that it is accessible to every node. During the run, we keep updating the information of the shortest path from a certain node to another. For instance, in Fig. 1, node 3 at $t = t_0$ estimates, based on its experience, that it takes one step from node 1 to node 4 and three steps (via node 3 and 1) from node 2 to node 4 in terms of the shortest hopping distance (the number of vertical jumps in the diagram), while τ_{14} from node 1 to node 4 and τ_{24} from node 1 to node 4 in terms of the shortest time duration (the horizontal time duration in such a diagram, assuming that all of the interactions are instantaneous), based on the history up to $t = t_0$.

The way our agents exploit the information – i.e. the way they are greedy – is realized by the following rule: if a walker at node 3 tries to move to node 4 at time $t = t_0$, as the node "closest" (the closest node is chosen uniformly at random in case of ties) to the target (node 4) is node 1, node 3 indefinitely waits for an interaction with node 1 ($t = t_{13}$), even if the