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Rendezvous of heterogeneous mobile agents in edge-weighted networks ☆

Dariusz Dereniowski [a], Ralf Klasing [b], Adrian Kosowski [c], Łukasz Kuszner [a,*]

[a] Faculty of Electronics, Telecommunications and Informatics, Gdansk University of Technology, Narutowicza 11/12, 80-233 Gdańsk, Poland
[b] LaBRI, CNRS and University of Bordeaux, 351, cours de la Libération, 33405 Talence cedex, France
[c] GANG Project, Inria Paris and LIAFA, CNRS and Paris Diderot University, Case 7014, 75205 Paris Cedex 13, France

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ABSTRACT

We introduce a variant of the deterministic rendezvous problem for a pair of heterogeneous agents operating in an undirected graph, which differ in the time they require to traverse particular edges of the graph. Each agent knows the complete topology of the graph and the initial positions of both agents. The agent also knows its own traversal times for all of the edges of the graph, but is unaware of the corresponding traversal times for the other agent. The goal of the agents is to meet on an edge or a node of the graph. In this scenario, we study the time required by the agents to meet, compared to the meeting time T_{OPT} in the offline scenario in which the agents have complete knowledge about each others' speed characteristics. When no additional assumptions are made, we show that rendezvous in our model can be achieved after time $O(nT_{OPT})$ in an n-node graph, and that such time is essentially in some cases the best possible. However, we prove that the rendezvous time can be reduced to $\Theta(T_{OPT})$ when the agents are allowed to exchange $\Theta(n)$ bits of information at the start of the rendezvous process. We then show that under some natural assumption about the traversal times of edges, the hardness of the heterogeneous rendezvous problem can be substantially decreased, both in terms of time required for rendezvous without communication, and the communication complexity of achieving rendezvous in time $\Theta(T_{OPT})$.

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1. Introduction

Solving computational tasks using teams of agents deployed in a network gives rise to many problems of coordinating actions of multiple agents. Frequently, the communication capabilities of agents are extremely limited, and the exchange of large amounts of information between agents is only possible while they are located at the same network node. In the rendezvous problem, two identical mobile agents, initially located in two nodes of a network, move along links from node

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* Corresponding author.
E-mail addresses: deren@eti.pg.gda.pl (D. Dereniowski), ralf.klasing@labri.fr (R. Klasing), adrian.kosowski@inria.fr (A. Kosowski), kuszner@eti.pg.gda.pl (Ł. Kuszner).

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to node, with the goal of occupying the same node at the same time. Such a question has been studied in various models, contexts and applications [1].

In this paper we focus our attention on heterogeneous agents in networks, where the time required by an agent to traverse an edge of the network depends on the properties of the traversing agent. In the most general case we consider, the traversal time associated with every edge and every agent operating in the graph may be different. Scenarios in which traversal times depend on the agent are easy to imagine in different contexts. In a geometric setting, one can consider a road connection network, with agents corresponding to different types of vehicles moving in an environment. One agent may represent a typical road vehicle which performs very well on paved roads, but is unable to traverse other types of terrain. By contrast, the other agent may be a specialized mobile unit, such as a vehicle on caterpillars or an amphibious vehicle, which is able to traverse different types of terrain with equal ease, but without being capable of developing a high speed. In a computer network setting, agents may correspond to software agents with different structure, and the transmission times of agents along links may depend on several parameters of the link being traversed (transmission speed, transmission latency, ability to handle data compression, etc.).

In general, it may be the case that one agent traverses some links faster than the other agent, but that it traverses other links more slowly. We will also analyze more restricted cases, where we are given some a priori knowledge about the structure of the problem. Specially, we will be interested in the case of *ordered agents*, i.e., where we assume that one agent is always faster than the other one, and the case of *ordered edges*, where we assume that if in a fixed pair of links, one agent takes more time to traverse the first link, the same will also be true for the other agent.

We study the rendezvous problem under the assumption that each agent knows the complete topology of the graph and its traversal times for all edges, but knows nothing about the traversal times or the initial location of the other agent. In all of the considered cases, we will ask about the best possible time required to reach rendezvous, compared to that in the "offline scenario", in which each of the agents also has complete knowledge of the parameters of the other agent. We will also study how this time can be reduced by allowing the agents to communicate (exchange a certain number' of bits at a distance) at the start of the rendezvous process.

1.1. The model and the problem

Let us consider a simple graph $G = (V, E)$ and its weight functions $w_A : E \mapsto \mathbb{N}_+$ and $w_B : E \mapsto \mathbb{N}_+$, where $\mathbb{N}_+$ is the set of positive integers. Let $s_A, s_B \in V$, $s_A \neq s_B$, be two distinguished nodes of G – the agents' A and B starting nodes. We assume that initially an agent $K \in \{A, B\}$ knows the graph G, s_A, s_B and w_K. Thus, A knows w_A but it does not know w_B, and B knows w_B but it does not now w_A. We assume that the nodes of G have unique identifiers and that G is given to each agent together with the identifiers. The latter in particular implies that the agents have unique identifiers – they can 'inherit' the identifiers of the nodes s_A and s_B. Also, the agents do not see each other unless they meet. Both agents are non-oblivious, i.e., equipped with memories which persist over successive time steps.

The weight functions indicate the time required for A and B to move along edges. That is, given an edge $e = \{u, v\}$, an agent $K \in \{A, B\}$ needs $w_K(e)$ units of time to move along e (in any direction). We assume that both agents start their computation at time 0 by exchanging messages. The time required to send and to receive a message is negligible.

Once an agent $K \in \{A, B\}$ is located at a node v, it can do one of the following *actions*:

- the agent can wait $t \in \mathbb{N}_+$ units of time at v; after time t the agent will decide on performing another action,
- the agent can start a movement from v to one of its neighbors u; in such case the agent moves with the uniform speed from v to u along the edge $\{u, v\}$ and after $w_K(\{v, u\})$ units of time K arrives at u and then performs its next action.

While an agent is performing its local computations preceding an action, it has access to all messages sent by the other agent at time 0. We assume that the time of agent's computations preceding an action is negligible.

We say that A and B *rendezvous at time t* (or simply *meet*) if they share the same location at time t,

- they both are located at the same node at time t, or
- $K \in \{A, B\}$ started a movement from u_K to v_K at time $t_K < t$, $u_A = v_B$, $v_A = u_B$, $e = \{u_A, v_A\}$, $t_K + w_K(e) < t$ and $\frac{t-t_A}{w_A(e)} = 1 - \frac{t-t_B}{w_B(e)}$ (informally speaking, the agents 'pass' each other on e as they start from opposite endpoints of e), or
- $K \in \{A, B\}$ started a movement from u to v at time $t_K < t$, $e = \{u, v\}$, $t_K + w_K(e) < t$ and $\frac{t-t_A}{w_A(e)} = \frac{t-t_B}{w_B(e)}$ (informally speaking, both agents start at the same endpoint but the one of them 'catches up' the other: $t_A < t_B$ and $w_A(e) > w_B(e)$, or $t_A > t_B$ and $w_A(e) < w_B(e)$).

Observe that the last case is not possible in an optimum offline solution, as the agents could rendezvous earlier in the vertex u.

We are interested in the following problem:

> Given two integers b and t, does there exist a deterministic algorithm whose execution by A and B guarantees that the agents send to each other at time 0 messages consisting of at most b bits in total, and A and B meet after time at most t?

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