Replanning in Advance for Instant Delay Recovery in Multi-Agent Applications: Rerouting Trains in a Railway Hub

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When executing a multi-agent train-routing plan and an agent is delayed, the agent must reroute to minimize the effect on other agents. In many real-world settings, minor delays happen frequently and can compound into larger holdups propagating through the network. Thus, replanning must be solved as soon as possible, which is challenging because the search space grows exponentially in the number of agents. We aim to swiftly handle holdups that can be resolved by rerouting only the delayed agent. Such a setting represents a set of problems that we name Multi-Agent Execution Delay Replanning (MAEDeR) problems. These are single-agent problems that occur during the execution of a multi-agent plan. By quickly reacting without violating the pre-existing plans of other agents, we are more likely to avoid a cascade of delays. Moreover, if the delay can be recovered by replanning only the delayed agent, this can be done faster than replanning all agents and requires no communication with the other agents or modifications of their plans.

Previous approaches to multi-agent delay recovery usually replan all agents, which can be improved upon by using prediction [3], robust planning [1], or post-processing to avoid delay propagation [2]. However, all these approaches handle delays reactively.

We propose a method for solving MAEDeR problems by replanning in advance using any-start-time safe interval path planning (@SIPP) [5], allowing instant delay recovery. A Safe Interval Path Planning (SIPP) problem [4] is a single-agent state-space search problem where each state is a configuration (e.g., a location) and a time interval in which this configuration is safe, and these states are connected by edges which also have an interval in which the transition between those states is safe. To solve SIPP, we can perform an A^* search using the scalar earliest arrival time at a SIPP state as the cost function $g(s)$. Any-start-time SIPP [5] builds on this by using arrival time functions instead of scalar and searching for a family of related paths instead of a single plan.

So, our search procedure for solving MAEDER computes an any-start-time plan for each agent, which is the set of optimal plans for all possible starting times, ahead of execution. As this search is based on a SIPP search, which is a single-agent algorithm, we treat the other agents executing their plans as moving

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obstacles and thus produce a plan for every agent, for every starting time (within the given horizon). These any-start-time plans are computed in advance, so a delayed agent can instantly recover a safe plan once its delay is known and execute it without affecting other agents.

Previously, any-start-time planning was used for single-agent problems in grid-based settings. We show how it can be useful in a multi-agent context, with experiments on the example of railway hub delay replanning. A railway hub is an area with a train station and surrounding shunting yards, where trains can be parked and serviced. This context is chosen because railway hub delay replanning has several characteristics that are emblematic of real-world applications. First, the agents have a spatial extent and, thus, a temporal extent and can occupy several locations simultaneously. Because real-world problems rarely have one type of agent, we allow for heterogeneity in size and speed. In a railway hub, switches further constrain a train's possible moves. We create a reduction from railway hub delay replanning to a graph used in the SIPP search that inherently encodes the direction of an agent. Finally, we include context-dependent safety measures that agents must respect, like a variable headway (the time between two consecutive trains) that depends on the relative travel directions. While we show the example of dense infrastructure hubs, which are the most difficult to plan, the same problem representation applies to larger railway networks.

We performed experiments on realistic-size railway hubs. These showed competitive runtimes for both the precomputation of any-start-time plans, up to a second for 50 trains, as our method scales quadratically with the number of agents. Since we compute plans for each agent, for each starting time, and every other agent is an obstacle that can result in at most one possible interval. Moreover, we showed that querying the any-start-time plan to retrieve the new plan for an agent is instantaneous and done in nanoseconds. This means that our approach lets agents recover a safe plan and immediately execute it without any extra waiting time.

In conclusion, we solve delay response in railway hub delay replanning by applying any-start-time planning to Multi-Agent Execution Delay Replanning problems. We instantly recover a safe plan to reroute the delayed train without affecting other trains' plans. The precomputation of safe plans allows us to rapidly recover the ability to handle a new delay, showing promising results for handling delays in real-world problems. Our method is also extendable to other multi-agent settings that can be modeled as a MAEDeR problem, for example, routing automated guided vehicles in container terminals. Moreover, our method can be used for on-demand planning, such as planning new trains in an existing schedule, which is common in freight traffic.

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