Autonomous Control by Means of Distributed Routing

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Introduction

In current logistic practices, routing and assignment of transport orders to vehicles are done centrally by a dispatching system and/or a human dispatcher. Here, the dispatching problem is generally of static nature and is solved either by the use of heuristics, e.g. evolutionary algorithms or Tabu search, or by applying "rules" that are gained from experience, when done by a human dispatcher.

The modern logistic systems permit incorporation of dynamic features into the dispatching problem. Here, dynamic means that not all orders are known a-priori, and an order can change its attributes with time. In most solution methods, the dynamic problem is broken into a sequence of static problems, so that the same or similar heuristic approaches can be used sequentially. The problem is thus repeatedly solved at the central planning instance whenever some change occurs in the order situation. Such algorithms are known as online algorithms (Fiat and Woeginger 1998, Gutenschwager et al. 2004).

In the subproject B1 "Reactive Planning and Control", a completely different approach for dealing with dynamic problems is introduced and investigated: Vehicles and packages are considered to be intelligent and autonomous. They can decide about routes and loads by themselves based on local knowledge. This requires replacement of the centralised decision-

making approach by a decentralised, distributed autonomous control approach. For this approach, methods and algorithms from other domains of science and technology are evaluated for their suitability for application in transport logistics. One promising technology domain is the wide range of routing algorithms used in communication networks.

Routing algorithms in communication networks

Distributed routing as such has already been successful in communication networks for several decades. Therefore, routing methods used in communication networks are identified to be interesting for use in transport networks.

As far as use of routing algorithms is concerned, communication networks can be classified into infrastructure-based networks and ad-hoc networks. These two different types have specific properties that lead to a significant difference in the way routing is done.

Infrastructure-based networks

Currently, most communication networks are infrastructure-based. In this type of networks, there is a hierarchy present where routing is usually done by dedicated nodes, called routers, within the network. Their responsibility is to keep track of the network status and enable attached nodes to communicate with others. Usually, the topology of infrastructure-based networks is not very dynamic, as the routing information there can be valid for a long time.

Large-scale networks often consist of several subnetworks which are interconnected through router to router connections. There can also be several levels of hierarchy there, like for example in Internet - local provider - company level network - department level network and so on. At different levels of the hierarchy, different routing methods may be used.

Basically, routing protocols in infrastructure-based networks are divided into Interior Gateway Protocols (IGP) and Exterior Gateway Protocols (EGP), depending on whether they route within one network or between networks. The most prominent IGPs are Routing Information Protocol (RIP) (Malkin 1998) and Open Shortest Path First (OSPF) (Moy 1998). As EGP, the Border Gateway Protocol (BGP) (Rekhter et al. 2006) is most

widely used and can be considered as the "quasi-standard" routing protocol in the Internet.

Ad-hoc networks[1]

In ad-hoc networks, there is no fixed infrastructure and hierarchy. Mostly, the term ad-hoc networks is used for mobile/wireless ad-hoc networks where wireless devices „spontaneously" form a network. In such networks, there are no nodes that are specifically dedicated for routing, but each node may act as a router. Further, due to the node mobility, the network topology is not necessarily fixed once the network is established, and may change very frequently as nodes move or even leave the network. This means that routing in ad-hoc networks has to cope with the dynamic changes in network topology. Several different approaches to solve this problem have led to a vast amount of routing algorithms which can be classified into three categories: Proactive routing, reactive routing and hybrid routing (Perkins 2001).

Proactive routing

When proactive routing is used, each node in the network maintains a routing table for all other nodes in the network. The nodes exchange their route information either on a regular basis or as soon as they detect a change. The advantage of proactive routing is that up-to-date information about the routes and thus the network status is always available. The drawback is that it needs a high signalling overhead to maintain the routing tables, especially in highly dynamic networks.

The most common examples of proactive routing protocols are Destination Sequenced Distance Vector (DSDV) (Perkins and Bhagwat 1994) and Optimized Link State Routing (OLSR) (Clausen and Jacquet 2003).

Reactive or on-demand routing

In contrast to proactive routing, reactive routing, often referred to as on-demand routing, does not constantly maintain routing tables on all nodes. Here, routes are reactively detected when they are needed, i.e. the node that wants to send something starts the route discovery process by sending a route request to its neighbours. This request propagates through the network until a route to the destination is found, then a route reply is sent

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[1] See also chapter 2.3 on "Historical Development of the Idea of Self-Organization in Information and Communication Technology".

back to the originator, which then leads to the establishment of the data link.

The obvious advantage is that there is less signalling overhead related to the maintenance of route tables. A drawback is that route discovery takes some time, which results in an initial delay for the sender before it can transmit its data. Further, in large scale ad-hoc networks, frequent route request floods can also produce a high signalling overhead.

Examples for on-demand routing protocols are Dynamic Source Routing (DSR) (Johnson and Maltz 1996), Ad-Hoc On-Demand Distance Vector (AODV) (Perkins et al. 2003) and Dynamic MANET On-Demand Routing (DYMO).

Hybrid routing

Hybrid routing tries to combine the advantages of proactive and reactive protocols. One example is Zone Routing Protocol (ZRP) (Haas 1997), where routing is done proactively for routes to nodes inside a limited zone and on-demand for routes to nodes outside the zone.

Context aware routing

A special class of ad-hoc protocols that is currently emerging covers more than just link quality or hop counts: Context aware routing protocols are designed to include information about the context of a node. This context information can be information about the node's location, energy resources, importance of the transmission and so on. In most cases they consider one context only, e.g. energy of the individual nodes. The context aware routing protocols extend the existing proactive and reactive protocols.

Comparison of logistic and communication networks

For a transfer of routing methods from communication networks to logistic networks, it is necessary to identify where these networks are similar and where they have differences. Obvious similarity between both networks is that in both, payloads have to be transported from a source to a destination. Generally, there are different routes available for such a transport, so that the best route has to be chosen based on some selection criteria. However,

the criteria that influence the decision between two or more route options can be very different and specific to the network type.

Another similarity is the possibility for resource reservation in both networks. In both cases, it is related to a Quality of Service (QoS), in case of logistics, this means fulfilling certain transport conditions, in case of communication networks, it means guaranteeing the fulfilment of bandwidth requirements, loss probability limits etc.

Size and dynamics of both network types are also comparable. The autonomous-control approaches for transport logistics are specifically targeted for efficient operation of dynamic large-scale networks, which is achieved in communication networks by using decentralized control.

There are also significant differences between communication and logistic networks. One difference is that there are entities such as vehicles, containers and pallets in a logistic network that are physically existent and limited in their number, whereas there is nothing comparable in communication networks, especially concerning the persistence, but also concerning the hierarchy. This hierarchy of movable objects leads to the possibility of conflicting interests concerning the route choice. If, for example, the load's goal is a fast or just-in-time transport, and the vehicle's goal is maximum utilisation of its cargo space, they might prefer different routes to reach their individual goals.

Furthermore, there is a difference in how to handle losses. In communication networks, a packet loss is not unusual, and the packet can be retransmitted. This is not the same in logistics, as a piece of good can not be duplicated easily, making a retransmission either very expensive or even impossible.

A very significant difference between both networks is the scale of time. In communication networks, both the route formation and the actual data transmission work on time periods in the range of seconds or milliseconds. The time that is required for route selection is generally not negligible in comparison to the transmission time. In logistics, on the other hand, the transport of the payload takes much longer (hours, days). This implies that the time needed to determine a route is far less compared to the transport duration and therefore, it is permissible to do more communication and calculations in order to get the best route for the current conditions.

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This leads to the conclusion that routing methods from communication networks cannot be transferred directly into logistics. Nevertheless, routing approaches in communication networks can inspire in devising routing approaches for logistic networks. In doing this, it is desirable to address the special requirements of transport networks while keeping the advantages of the proven communication network methods such as robustness and automatic failure recovery to the maximum possible extent.

For distributed routing of autonomous components, it is necessary that they collect information that influences the routing decisions. This can be information about the current status of edges[2], such as traffic jams and information about other components' plans if they have influence on the route. This information retrieval is a point where aspects from communication networks can be used. Assuming the information is available at the vertices[3], it can be collected similar to a route discovery process in ad-hoc routing algorithms: Route request messages are sent from the entity that needs the information. These requests are propagated through the network from vertex to vertex until they reach their destination, then a route reply message is sent back.

A distributed routing concept

In the following, a concept for distributed routing in a logistic network is presented. In this concept, vehicles as well as packages are considered as autonomous. They have sufficient intelligence and communication capabilities to get their information and to decide on the next steps to be undertaken.

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[2] Edges are connections between locations (vertices) in a logistic network, e.g. roads. For details about the definition of logistic network components see chapter 4.2: Dynamic Transport Reference Scenarios.

[3] Vertices are locations in the logistic network where edges meet, e.g. depots. See also footnote 2.
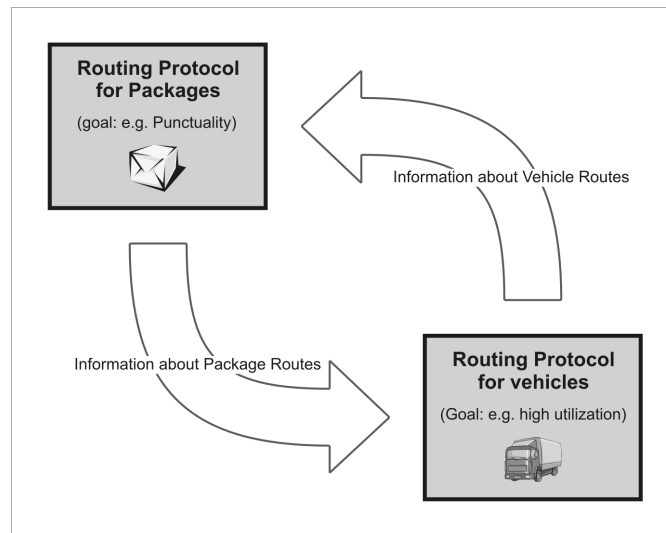
Figure 1. Interdependence of routes

In this concept, next steps mean calculating a route or deciding about being loaded into a vehicle (from the package's view) or picking up a package (from the vehicle's view). If both the vehicles and the packages determine routes based on their individual goals, the dilemma arises that the routes are most probably different. To make it worse, the decisions are interdependent: The package needs knowledge about vehicle routes to find candidate vehicles and the vehicle needs knowledge about the package routes to be able to find an efficient route where its capacity is best utilized. Figure 1 illustrates this interdependence.

The interdependence implicitly gives rise to another issue: The knowledge of each other's existence, i.e. how does the package know which vehicles are there, and further: How does the vehicle know about the packages? If there is no way to get to know about each other, they cannot communicate and thus cannot exchange their information.

There are two possibilities to solve this problem:

- Direct communication: An entity, say a package that enters the system, broadcasts some information about itself and collects responses from all other present entities. This is very inefficient and would lead to a high load of communication signalling, and the entities which are currently out of communication range might not get the information.

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- Indirect communication: This assumes the presence of some kind of knowledge brokers or repositories in the network. In this way, both the vehicles and the packages know entities to whom they can send their information and where they retrieve other information.

Distributed Logistic Routing Protocol (DLRP)

Due to the drawbacks of the other solution, the indirect communication was chosen as the way to solve the interdependence problem. As it is not intended to introduce an additional central repository, which would in fact foil the idea of a distributed system, the vertices that are present in the logistic network are chosen as the "relays" for indirect communication and therefore as the knowledge brokers. This fits perfectly into the distributed nature of the concept, as each vertex has only a part of the global knowledge, rather than the complete knowledge about all routes and all packages in the system.

In detail, the concept, named "Distributed Logistic Routing Protocol" (DLRP), operates as follows (Scholz-Reiter et al. 2006):

The vertex is a knowledge broker for the vehicles and packages. Before deciding about a route, a vehicle/package requests current information from the current or next vertex. Each vertex includes relevant information available from its current knowledge-base and forwards the request to neighbour vertices. The neighbour vertices do the same and forward it further. This way, the request is propagated through the network until the destination or a predefined hop limit is reached. Then the last vertex creates a reply message that is sent back directly to the originator of the request. This reply contains all the information that has been collected during the propagation of the request message through the network, including the last vertex. In general, an entity can receive more than one route reply as there are multiple paths possible. As it is not known how many replies would get back, a timeout and an upper limit for the number of replies are specified in order to trigger the decision process without long waiting periods.

After receiving the reply messages, the entity is ready to make its route decision based on its individual preferences and the data received. After making the decision, it withdraws its old route if any, and announces its new route to all relevant vertices. This way, the vertices get an information update, which will be used in processing the future requests. Figure 2 shows the information flow in DLRP.
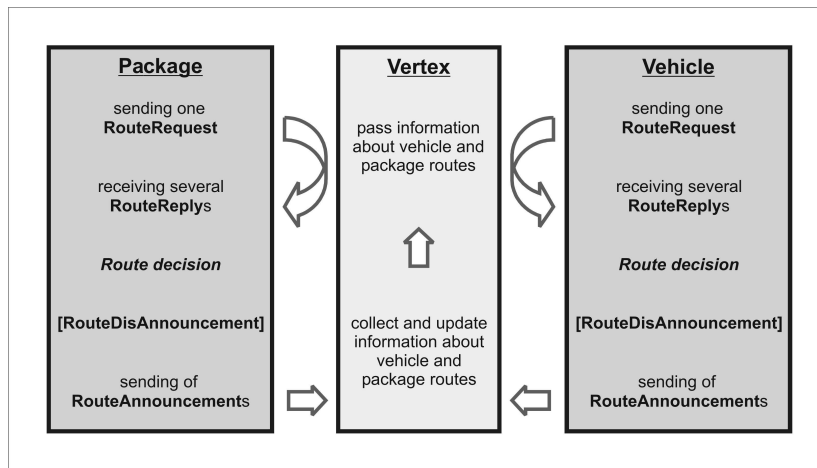
Figure 2. DLRP information flow

This approach also leads to uncertain knowledge: As a package does not know in advance whether a specific vehicle picks it up or not, it looks for a set of alternative routes to increase the probability to reach its destination in time. All these alternative routes are announced to the vertices, so that the announced package routes are just valid with a certain probability. If a package is picked up by a vehicle, unused routes have to be cancelled again. Vehicles on the other hand do not necessarily stick to a single route, so the vehicle routes also are uncertain. The vehicles check the current state of their options whenever they reach a vertex. If they find a route that is better than the original one, they can either change their decision depending on their individual settings, or stick to the old one.

The DLRP itself does not specify the functions that are used by the packages and vehicles to decide about their routes, it just specifies the interaction. Therefore, it should be regarded as an interaction framework which provides a basis for distributed information management and decision making in logistic scenarios. The logistic performance that can be achieved with this framework strongly depends on how the logistic entities utilise the information they can obtain. There are several possibilities for decision making, for example fixed rule sets (e.g. always take the shortest route), heuristic, probabilistic or fuzzy logic approaches etc. Some of these options are under investigation for their use in the DLRP framework.

Currently, the DLRP functionality has been successfully implemented in a logistic simulation environment. Now, suitable decision making ap-

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proaches are being developed and evaluated by simulation in that simulation environment.

In the first decision-making approaches, the vertices calculate a metric based on the route announcements of vehicles and packages at this vertex, excluding those from the vehicle/package that initiated the current routing process and those from vehicles/packages that are expected to be later than it. This metric m is calculated according to the following formula:

$$m = \sum m_{package} - \sum m_{vehicle} \tag{X.1}$$

Here, $m_{package}$ is the individual metric related to a package route announcement, and $m_{vehicle}$ is the one related to a vehicle route announcement. The package metric is determined as follows:

$$m_{package} = \frac{0.25^{d_1}}{d_2} \tag{X.2}$$

Here, d_1 is the distance between the package's current location and metric-calculating vertex and d_2 is the distance from this vertex to the package's destination. In this way, the closer the package is to the vertex, the more relevant it is for routing. The vehicle-related metric is calculated similarly:

$$m_{vehicle} = C * 0.5^{d_1} \tag{X.3}$$

The distance d_1 is again the distance between the vehicle's location and the vertex, and C is the vehicle's capacity.

The package's goal is now to find a route with a low metric, as a low metric means it is more likely to find free vehicle capacity there. Vehicles on the other hand try to find high metrics in order to maximize the utilisation of their capacity.

From the simulations, additional constraints were derived that have to be taken into account for the route decision process:
- Vehicles should prefer continuing a route they have started. Therefore, in each re-routing step, routes that continue the current one get a bonus.
- Package routes should not lead the package back to where it came from when a package is recalculating its routes.

- If there are several alternative routes from one package registered at a vertex, only one of them (preferably the one with earliest arrival time) is considered for metric calculation.

These constraints have shown to be crucial for the approach to operate as intended.

The decision-making approach presented here is currently being investigated in detail to evaluate its performance, and in-depth results will be shown in publications in the near future.

Summary and Outlook

This chapter presents the DLRP, a fully distributed routing concept for dynamic logistics. The concept has been implemented into a logistic simulation environment to prove its feasibility. For performance evaluation, different decision functions are being investigated using simulations within this concept in order to obtain an efficient solution for routing in dynamic logistic environments.

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