

Multi-Agent Control for the Transportation Networks of the Future

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When going from Delft to Rotterdam by train, or when driving over the highway, or biking through the Dutch landscape, did you ever look up and wonder about the network of power lines that span our country? The electricity network, globally one of the largest structures created by mankind, is a complex system consisting of thousands of power transmission lines, power generation stations, transformer substations, and consumption points. Day-in day-out electricity is transmitted from one point to another to enable our modern life. Can you imagine living a whole day with no electricity at all?

To ensure efficient and secure operation of power networks, network operators adjust controls in the network to meet certain control objectives. These controls consist of adjusting power generation, changing transformer taps, switching off consumption, etc. Control objectives typically consist of maintaining values of network variables like voltages and frequency at or close to pre-specified values. The values of these network variables can be manipulated by changing the flows of power over the network. Network operators change the flow of power over the network by using the controls available. Although controlling the flows has always been a challenging task, the ever growing increase of energy consumption, the changes in the power market, and the increasing appearance of small scale, so-called *embedded* generation, make the control of power networks in the future become even more challenging.

Generic Transportation Networks Power networks are just one particular type of network from a much larger group of transportation networks. To give you an idea of this, think about what type of transportation network the illustration in Figure 1 could represent. Indeed, the schematic illustration

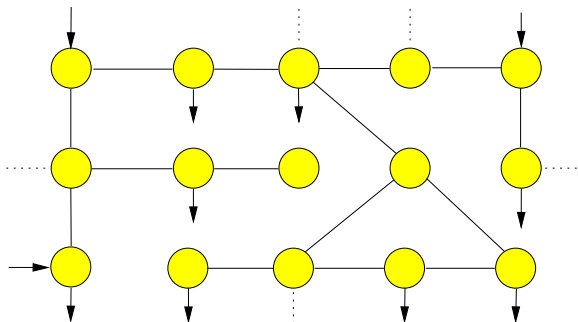


Figure 1: A generic transportation network: commodity enters the network at sources, flows over the network through links, and leaves the network at sinks.

could represent a variety of transportation networks, like for example a road traffic network, a water distribution network, a sewer network, or a rail network. Common to each of these networks is that at a generic level they can be viewed as having some commodity that is brought into the network at sources, flows over links to sinks, and is influenced in its way of flowing by elements inside the

network. Of course, for a particular domain the particular form of the commodity, sources, links, etc. takes on different shapes. Nonetheless, it is worth to consider modeling and control approaches for transportation networks in a generic setting. On one hand, methods developed for the generic setting can be applied to a wide range of specific domains, perhaps with additional fine-tuning to improve performance. On the other hand, approaches specifically developed for a particular domain can be applied to other domains after having transferred them to the generic framework.

Network control As pointed out above, network operators can adjust controls inside the network to change the flow of commodity over the network. The operators have to choose the adjustments of the controls such that control objectives are met as closely as possible. For example, in power networks power generation may be increased or consumption may be cut off in order to prevent black-outs. Although nobody likes power black-outs, sometimes it may be necessary to cut off certain parts of the network from electricity consumption in a controlled way in order to prevent larger black-outs.

To find the actions that reach the objectives as well as possible, the network operators have to make a trade-off between the different options for choosing actions. All relevant information about the consequences of choosing certain actions should be taken into account in this to encourage finding the best actions. For power networks, typical information that is available consists of forecasts on power consumption and exchanges, capacity limits on transmission lines, and dynamics of components like generators, capacitor banks, transformers, and loads. Besides this, wide-area measurements of voltages across the network are included to provide an up-to-date status of the current situation of the network at the time of optimization.

Model predictive control A particularly useful form of control for transportation network that uses all available information is *model predictive control*. This type of control involves solving an explicit optimization problem over a time horizon of N steps in the future. Based on predictions made of the evolution of the power network over this horizon, given the predicted consumption, dynamics, and so on, the actions that give the best performance are determined. In this way, undesirable situations in the future can be anticipated at an early stage and all available information can be taken into account. In model predictive control, at each discrete time step k actions are chosen by solving an optimization problem of the following form:

$$\text{minimize} \quad \text{the objective function in terms of actions over the horizon from } k \text{ to } k + N, \quad (1)$$

$$\text{subject to} \quad \text{dynamics of the whole network over the horizon from } k, \quad (2)$$

$$\text{constraints on, e.g., ranges of actuator inputs and link capacities,} \quad (3)$$

$$\text{initial measurement of the situation of the whole network at time } k, \quad (4)$$

where the dynamics of the network are a combination of dynamics of sources, dynamics of sinks, capacity constraints on links, etc. Once the actions have been determined, the actions for time step k are implemented on the network, after which the control system moves on to time step $k + 1$ and solves the next optimization problem.

Single versus multi-agent control In the situation where (1)–(4) is solved from one central point we have a so-called centralized, or *single-agent* control system, see Figure 2. This single agent has to collect information from measurements of the whole network to determine which actions to take throughout the whole network. Large transportation networks, however, are hard to control by a single agent for several reasons. Some of these reasons are of technical nature, e.g., coming from

communication delays and computational requirements; other reasons are more of practical nature, e.g., unavailability of information from one part of the network to another and restricted control access. In addition for power systems, the increase in embedded generation coming from wind mills, solar panels, and other small scale power generators, increases the degrees of freedom of the optimization problem and therefore makes it more complex to solve. Also, the deregulation of the power market makes that a centralized control simply becomes practically infeasible.

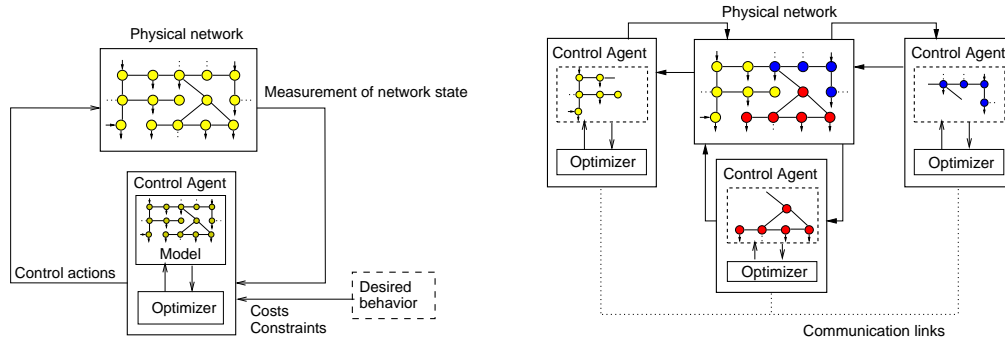


Figure 2: Single-agent (left) versus multi-agent control (right).

Therefore, instead of using a single-agent approach, a *multi-agent* (or distributed) control approach has to be employed. In such an approach several control agents, each with only limited information gathering and processing skills and moreover limited action capabilities, control the sub-networks that together make up the overall network, see Figure 2. Thus, the optimization problem (1)–(4) is split into multiple smaller optimization problems, each of which is solved by such a local agent. For an agent i controlling subnetwork i the optimization problem at time step k becomes:

- minimize the objective function of agent i in terms of actions that agent i can perform over the horizon from k to $k + N$,
- subject to dynamics of the subnetwork of agent i over the horizon, constraints on, e.g., ranges of actuator inputs and link capacities for subnetwork i , initial measurement of the situation of subnetwork i at time k .

Challenges The challenges in implementing such a multi-agent model predictive control scheme come from ensuring that the combined solution of the optimization problems of the individual agents is as good as the solution of a hypothetical centralized overall problem in which all information is available to a hypothetical single agent. The actions that an agent in a multi-agent setting takes influence both the evolution of its own subnetwork, and the evolution of the subnetworks connected to its subnetwork. Since the agents in a multi-agent setting usually have no global overview and can only access a relatively small number of sensors and actuators, predicting the evolution of a subnetwork over a horizon involves even more uncertainty than when a single agent is employed. Communication can reduce this uncertainty, since it allows agents to inform one another about their plans. The agents can then take into account these plans and anticipate on any undesirable situation. Moreover, through communication agents can obtain agreement on taking actions that give both locally and overall good performance. What information they communicate and how they incorporate this information in their optimization problems is crucial for the overall network performance.

Concluding remarks The growing requirements on safety and security of the operation of our ever more intensely used power networks, road traffic networks, water networks, and other transportation networks motivate our research on multi-agent control approaches for these networks. Our current research for transportation networks in general, and power networks in particular, focuses on schemes that encourage the agents controlling networks to come to agreement on how flows of commodity should go between subnetworks.

Limitations on space prohibit further exposition of the approaches that we are developing, but for further information, publications, and references, feel free to visit the author's website at <http://www.dcsc.tudelft.nl/~rnegenborn/> or contact him through e-mail at r.r.negenborn@tudelft.nl.