

## Invited Tutorial

### INTRODUCTION TO NETWORK CALCULUS

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#### KEYWORDS

Deterministic queueing, QoS guarantees, min-plus algebra, traffic policing, traffic scheduling

#### ABSTRACT

Network Calculus (NC) is a novel system theory for deterministic queueing systems. It is an approach of developments which main focus is to provide insights into flow problems encountered in networking. The mathematical theory of dioids, and here in particular, the Min-Plus algebra, is the foundation of NC.

To this day it is a big challenge to give assured information about performance-guarantees of telecommunication systems by mathematical methods. This refers to both the design of future systems and analysis on the one hand and evaluation of existing systems on the other hand. For systems constrained to hard real-time conditions or for QoS-capable networking systems special timed quality requests may be an inherent aspect of system functionality, e.g. like timeliness of especial events, messages etc. Therefore the classical performance evaluation based on stochastic methods and resulting in (stochastic) expectation values - i.e. mean values - has to be extended by a mathematical tool producing guaranteed boundings for worst case scenarios. The aim for example is to get lower and upper bounds for end-to-end delays of nodes or collections of nodes within a network, for traffic backlog and for output limitations. By means of these performance-analytic bounding values – characterizing worst-case behaviour of traffic flows – it is possible e.g. to dimension the corresponding buffer(s), to make sure not exceeding a special burst etc.

In this tutorial we will introduce into the main deterministic framework of NC like *arrival curves* (as an abstraction of traffic policing) and *service curves* (as an abstraction of scheduling mechanisms) from which deterministic bounds of *backlog*, *delay* and *output* of data (-streams) are derivable. Then we will demonstrate concatenation results – important for deterministic bounding of groups of network elements, we explain the concept of traffic shapers based on NC and give practical examples of using the results of NC such as in the case of Internet Integrated Services or Internet Differentiated Services.

We in our department want to use the Network Calculus for estimation and optimization concerning QoS guarantees in packet switched communication systems.

