2016 INFORMS Telecommunications Conference

Boca Raton, FL

March 20-22, 2016

PROGRAM

Sunday March 20

9:15-9:30		Opening
9:30-10:30	SA-01	Plenary Raghavan
10:30-11:00		Coffee break
11:00-12:30	SB-01	Network optimization
12:30-14:00		Lunch
14:00-16:00	SC-01	Handling uncertainty
16:00-16:30		Coffee break
16:30-17:30	SD-01	Wireless Networks I
18:30		Welcome reception

Monday March 21

9:00-10:30	MA-01	Wireless Networks II
10:30-11:00		Coffee break
11:00-12:30	MB-01	Trees
12:30-14:00		Lunch
14:00-15:00	MC-01	Plenary Ben Ameur
15:00-15:30		Coffee break
15:30-17:30	MD-01	Best paper award
17:30-18:30		Section business meeting
19:00		Conference dinner

Tuesday March 22

9:30-10:30	TA-01	Energy efficient networks
10:30-11:00		Coffee break
11:00-12:00	TB-01	Plenary Schneur
12:00-12:15		Closing

Sunday, 9:30-10:30

■ SA-01

Sunday, 9:30-10:30 -

Plenary Raghavan

Stream: Plenary sessions
Chair: *Dimitri Papadimitriou*

1 - Mathematical Programming Approaches to Influence Maximization Problems on Social Networks
S. Raghavan

The study of viral marketing strategies on social networks has become an area of significant research interest. Roughly, these problems seek to identify which individuals in a social network to target so that a given proportion of the target population is influenced at minimum cost. Motivated by the desire to develop a better understanding of fundamental problems in social network analytics, we study two problems in this domain and seek to develop mathematical programming approaches to solve them exactly. We first consider the weighted target set selection (WTSS) problem. Here the weights (on the nodes) have a natural interpretation as the cost or effort associated with influencing the node (or individual). Next, we consider the least cost influence problem (LCIP). The difference between the LCIP and the WTSS problem lies in the fact that nodes selected for targeting in the LCIP may be provided partial incentives (i.e., payments) in the viral marketing context; while in the WTSS problem no partial payments are permitted. Both problems are NP-hard on general graphs. Motivated by the desire to develop mathematical programming approaches to solve these two problems, we focus on developing strong formulations for these problems on trees. In particular, we are interested in formulations whose linear programming relaxations are integral. In radically different ways we develop tight and compact formulations for the WTSS and LCIP problem on trees. Based on the observation that the influence propagation network is a directed acyclic graph, these integral formulations can be embedded into a larger exponential sized integer programming formulation for these two problems on general graphs. Using this idea we design and implement a branch-and-cut approach to solve the WTSS and LCIP problems on general graphs and share our computational experience on networks with up to 10,000 nodes. Extensions of this work to related problems and variants will be discussed.

Sunday, 11:00-12:30

■ SB-01

Sunday, 11:00-12:30 -

Network optimization

Stream: Contributed abstracts
Chair: *Luís Gouveia*

1 - On the Convex Piecewise Linear Unsplittable Multicommodity Flow Problem
Bernard Fortz, *Luís Gouveia*, *Martim Joyce-Moniz*

We consider the problem of finding the cheapest routing for a set of commodities over a directed graph, such that: i) each commodity flows through a single path, ii) the routing cost of each arc is given by a convex piecewise linear function of the load i.e. the total flow) traversing it. We propose a new mixed-integer programming formulation for this problem. This formulation gives a complete description of the associated polyhedron for the single commodity case, and produces very tight linear programming bounds for the multi-commodity case.

2 - Finding maximum subgraphs with relatively large vertex connectivity
Vladimir Boginski, *Alexander Veremyev*, *Oleg Prokopyev*, *Eduardo Pasiliao*

We consider a clique relaxation model based on the concept of relative vertex connectivity. It extends the classical definition of a k-vertex-connected subgraph by requiring that the minimum number of vertices whose removal results in a disconnected (or a trivial) graph is proportional to the size of this subgraph, rather than fixed at k. Consequently, we further generalize the proposed approach to require vertex connectivity of a subgraph to be some function f of its size. We discuss connections of the proposed models with other clique relaxation ideas from the literature and demonstrate that our generalized framework, referred to as f-vertex-connectivity, encompasses other known vertex-connectivity-based models, such as s-bundle and k-block. We study related computational complexity issues and show that finding maximum subgraphs with relatively large vertex connectivity is NP-hard. An interesting special case that extends the R-robust 2-club model recently introduced in the literature, is also considered. In terms of solution techniques, we first develop general linear mixed integer programming (MIP) formulations. Then we describe an effective exact algorithm that iteratively solves a series of simpler MIPs, along with some enhancements, in order to obtain an optimal solution for the original problem. Finally, we perform computational experiments on several classes of random and real-life networks to demonstrate performance of the developed solution approaches and illustrate some properties of the proposed clique relaxation models.

3 - Optimal Traffic Routing and VNF deployment for Service Function Chaining in SDN
Nancy Perrot, *Zaid Allybokus*, *Eric Gourdin*

This paper deals with the instantiation of service function chains in a software-defined network. The software-defined networking (SDN) paradigm allows separating the control plane and the data plane of a network. It hence brings flexibility to the network management and it is a powerful enabler to reduce the energy consumption of the networks. Furthermore, with the rise of Network Function Virtualization (NFV) technics, advanced service functions such as Firewall, Deep Packet Inspection (DPI), load-balancer etc. that used to be part of dedicated equipment within a service chain could now be processed as a virtual machine on generic hardware. Thus, SDN coupled with NFV would allow packets to be routed in a network while deploying the network functions only when needed along the traffic paths. This work is a contribution to the key challenge of operators and service providers to build efficiently such service function chains. We propose a mixed integer linear programming formulation that provides the best feasible paths for flow services and jointly finds the best function placement on the network nodes while taking into account several additional constraints, such as, capacitated flow routing constraints, bounded capacity of the hardware (memory), bounded capacities of the network functions, ordering of functions within each path depending on the service type. Using a Mixed-Integer Linear Programming solver, this formulation provides optimal solutions in terms of active network resources for small instances. To tackle realistic instances of a wide area network, we also propose a heuristic algorithm based on a decomposition of our formulation. Experimentations show that our heuristic often provides close to optimum solutions in a few seconds.

Sunday, 14:00-16:00

■ SC-01

Sunday, 14:00-16:00 -

Handling uncertainty

Stream: Contributed abstracts
Chair: *Walid Ben-Ameur*

1 - Learning Uncertainty Sets for Robust Network Optimization Problems

Dimitri Papadimitriou

As solution to optimization problems can exhibit high sensitivity to perturbations in the problem parameters and in turn render infeasible or suboptimal solution, we consider modeling the optimization problem by means of the set induced robust optimization method to immunize solutions against bounded uncertainty in the parameters of the problem. This technique intrinsically depends on the features characterizing uncertainty sets. When considering data-driven statistical methods, the key question becomes how to perform inference tasks (density estimation and hypothesis test) from samples and when considering model-driven methods how to produce and select an hypothesis which best explains the data. In both cases, the goal is to minimize the difference between the solution obtained using the true distribution vs. estimated/ modeled distribution.

In this paper, we propose a machine learning algorithm to automate construction of uncertainty and perturbation sets for mixed-integer network optimization problems showing uncertainty in demands and associated traffic parameters. To this end, considering traffic is driven by a general stochastic process, we estimate the Hurst parameter and then perform a Normality or Pareto distribution test depending on the estimated value of this parameter. We then perform either a non-linear least squares curve fitting or a Pareto distribution data fitting to extract the model that best explains the traffic. One can then derive the perturbation sets delimiting traffic uncertainty in a less conservative form than worst-case safety margin models commonly applied in strict robustness. We apply this data-driven uncertainty set construction technique to the robust variant of the combined routing-facility location problem; present related computational challenges and methods; finally, we compare results with those obtained when using bounded linear perturbation and safety margin models.

2 - Handling uncertain behavior of clients during FTTH splitter allocation

Mateusz Żotkiewicz

We consider a problem of optimal selection of splitters in FTTH deployment. The problem appears mainly while maintaining an FTTH network. However, it can also be encountered during FTTH design and optimization phases, especially, when the uncertainty of demands is taken into account. In this research, we assume that a network plan is given and cannot be modified. The only decisions to be made are dealing with more efficient execution of the given plan. We understand the term network plan to mean physical locations of all equipment needed to connect expected clients. The network plan consists of, among others, a set of access points. For each access point the input data are independent and consist of the following entries: set of splitters, number of outputs of each splitter, cost of each splitter, probability that a client will appear at a given time providing that the previous client has appeared at another given time. In addition, we assume the following: network plan has to be followed, i.e., only available splitters can be used; uncertain number of clients will appear at random moments in time; splitter has to be installed only if there is an unserved client willing to connect to the access network and there is no vacant outputs among already installed splitters; once a client is connected to the access network and is assigned to a splitter the assignment cannot be changed. The considered optimization problem is to select and install an unused splitter, whenever a client that cannot be connected to already installed splitters appears. The selection should be done in the way minimizing the expected total cost of splitters. Notice here, that usually not all splitters from the network plan have to be installed. We present a dynamic programming method solving the considered problem. Although the method is not polynomial, is solves practical cases in reasonable time. This research was supported by National Science Centre under grant 2014/15/D/ST7/05320

3 - Spectrum Allocation in Flexgrid Optical Networks under Demand Uncertainty: Complexity and Computations

Arie Koster, *Christina Büsing*, *Martin Tieves*

Classical wavelength Assignment in optical networks asks for the allocation of the minimum number of wavelengths to a set of so-called lightpaths. Each lightpath is operated on a fixed bitrate along a routing path from origin to destination. With the introduction of flexgrid (or elastic) optical networks, the fixed wavelength grid in optical communications is replaced by a flexible allocation of finer granularity spectrum slots. This technology allows the operation of optical channels of different sizes and at different bitrates. By this, demands of different sizes and/or of dynamic nature can be facilitated more efficiently. Given a fixed (single path) routing and static demands, the remaining spectrum allocation problem can be modelled as a generalized vertex coloring problem.

In this talk, we model the dynamic nature of the demands by a robust optimization approach. We develop a model where the network planner prepares a spectrum allocation that can evolve to an allocation for any of a discrete set of demand scenarios: the allocations of slots to the same demand in different scenarios should have at least one slot in common. This problem is trivial if the network resembles to a single link and a single demand scenario, but becomes already hard to solve if a single link and two demand scenarios are considered. Moreover, if the robust allocation scheme is restricted further by requiring that the first or the last slot is common between the scenarios, the resulting problem on a single link corresponds to a maximum weighted matching problem. For general networks, we develop an integer

linear programming formulation and present preliminary computational results for improvements by strengthening model inequalities and deriving valid inequalities.

This work was partly supported by the Federal Ministry of Education and Research (BMBF grant 05M13PAA, joint project 05M2013 - VINO: Virtual Network Optimization).

4 - Impact of perceived risk on consumer e-shopping behavior across device types.
Stanko Dimitrov, *Brian Cozzarin*

We present work characterizing the role of consumer perceived risk, the personal concern with using their credit card on the Internet, on consumers' propensity to engage in e-commerce using different device types, PC or mobile device. Using a two-step hurdle model we characterize consumer e-commerce purchase decisions. In the first step we determine the likelihood of engaging in e-commerce, and in the second step the number of orders is estimated. With data from the Canadian Internet Use Survey, administered by Statistics Canada, we are able to derive sufficiently large sub-samples, according to access device type, to draw statistically significant conclusions. From our analysis we conclude that perceived risk has a significantly larger impact on the purchase decisions of mobile users than PC users.

Sunday, 16:30-17:30

■ SD-01

Sunday, 16:30-17:30 -

Wireless Networks I

Stream: Contributed abstracts
Chair: *Arie Koster*

1 - On Accurate Optimization Models for Interference-Constrained Resource Allocation in Cellular Networks
Di Yuan, *Grit Claßen*, *Arie Koster*, *Anke Schmeink*

A common approach to model interference in cellular networks is the condition that the signal-to-interference-and-noise ratios (SINRs) have to meet a given threshold. However, constraints modeling such a requirement are numerically difficult. The SINR values are typically embedded, directly or indirectly, in other constraints such as those for coverage and capacity, and simply adding the SINR constraints to an interference-free formulation turns out to be insufficient for obtaining an accurate model. We present two novel approaches to overcome these disadvantages without violating the SINR requirements or capacity constraints. The first approach is a set-wise formulation from a user's point of view, while the second exploits discrete channel quality indicators. We compare these formulations with three known approximate approaches numerically, revealing the superior performance of our approaches in terms of exactness. Moreover, since the exact models comprise an exponential number of either variables or constraints, we discuss their pros and cons in a further computational study and develop a more efficient algorithm dealing implicitly with the constraints.

2 - Radio Frequency and Time-slot assignment in Mobile Adhoc Networks: An Exact Mathematical solution
David Foroudi

Consider a centrally managed network of multi-band/multi-mode radios, required to broadcast/ unicast messages with their neighboring nodes at distinct frequencies/time-slots and under several bottleneck constraints. We developed mathematical models in MPL/CPLEX for assigning distinct frequencies to radios at each timeslot, formulated as a bottleneck generalization of the famous Map Coloring problem in Combinatorial Optimization. We were able to solve this problem quickly even though computational complexity is NP-Complete.

Monday, 9:00-10:30

■ MA-01

Monday, 9:00-10:30 -

Wireless Networks II

Stream: Contributed abstracts
Chair: *Di Yuan*

1 - Airborne Recovery of the Emergency Communication Network during Disaster Response
Recep Berk Ozgur, *Burak Sever*, *Sezgin Kaplan*

Cellular communication networks can be partly or completely cut off due to many types of disruption in the technological infrastructure as a result of natural disasters. However, maintenance of the communication systems has a vital importance, especially in the first 72 hours, to avoid interruptions in the response operations of emergency teams and data backhaul to the command-control center. In this study, the role of unmanned aerial vehicles (UAVs) as an alternative to the damaged base stations has been examined in the airborne recovery of the cellular communication network. A mixed integer linear programming model has been formulated to determine the loitering locations of a certain number of relay UAVS to maximize the coverage of emergency response teams subject to be continuously connected with each other and also to the center. Finally, the results obtained by the proposed model have been demonstrated for various randomly generated disaster damage scenarios.

2 - Mathematical optimization tool for real-time practical solutions to dynamic network routing, connectivity and reliability
David Foroudi

Given a network of communication satellites and ground stations, this tool stochastically fails some satellites and some additional cross-links in order to evaluate and validate connectivity and reliability of the network under various failure scenarios. We have developed and implemented efficient network optimization models and algorithms for flow throughput and routing across the network constellation nodes. We present faster than real-time exact solution, mathematical programming approach with dynamic graphical representation of solutions. One-to-one antenna steering requirements of such problems are modeled as Binary Integer Programs, which computationally are a member of the NP-Complete class of combinatorial optimization problems. The computing platform is PC and we demonstrate that even computationally non-polynomial time algorithms such as these are tractable, if modeled prudently.

3 - Hybrid Accuracy-Time Trade-off Solution for Spectrum Sensing in Cognitive Radio Networks
Albena Mihovska, *Antoni Ivanov*, *Vladimir Poulkov*, *Ramjee Prasad*

The rise of the cognitive radio systems as a concept for future networks has seen a great amount of scientific effort in the recent years. Appropriately, much attention is given to how the vital function of spectrum sensing should be executed. It is evident that the cognitive radio device is required to be able to evaluate the spectral environment properly so that it may not create an additional interference to the primary users. The complexity of the task is further increased by the need for the optimization of the speed of the process so that the spectrum holes can be utilized fully. Because the sensing accuracy and sensing time are conflicting parameters, a suitable trade-off is necessary for an optimal efficiency. This paper proposes a solution that combines two approaches to the problem. The decision about the presence or absence of primary users is made using the measured signal to noise ratio and noise levels as inputs in a fuzzy logic algorithm. The result is then used as a measure of the environment in a mathematical model, which takes into account the probability of miss-detection and the expected distribution of the primary user traffic. Finally, an optimal balance between the sensing and transmission times is obtained for the current environmental conditions using the derived closed form expression. Starting with the simulation results, a comparison in terms of sensing time and accuracy will be made between the proposed algorithm and other existing methods.

Monday, 11:00-12:30

■ MB-01

Monday, 11:00-12:30 -

Trees

Stream: Contributed abstracts
Chair: *S. Raghavan*

1 - Spanning Trees with a contraint on the number of leaves. A new formulation

Luís Gouveia, *Luidi Simonetti*

In this paper we present a new extended model for the problem of finding a minimum cost spanning tree such that the number of leaves is equal to (greater than, less than) L. We show that with these variables we are able to derive stronger linking constraints in a flow based model permitting us, by using projection techniques, to derive a model with enhanced cut constraints. The new variables also permit us to strengthen, in an extended space, strong inequalities that are well known from the literature. We show that the strengthened inequalities imply an exponential sized set of inequalities presented previously by Fujie (2004). A new exponential sized set of inequalities that are also implied by the new model will also be proposed. We also discuss the new model in the context of a related problem, the max-leaves problem where one wants to find a spanning tree with a maximum number of leaves. Computational results taken from several sets of instances known from the literature indicate that the new model improves previously known gaps for the three constrained versions and that despite the extra number of variables, it leads to best solution time sin almost all cases. For the max-leaves problem the new model proves to be competitive with the existent approaches.

2 - Solving Minimum-Cost Shared Arborescence Problems

Ivana Ljubic, *Eduardo Álvarez-Miranda*, *Martin Luipersbeck*, *Markus Sinnl*

In this work the minimum-cost shared network problem (MCSN) is introduced, where the objective is to find a minimum-cost subgraph, which is shared among multiple entities such that each entity is able to fulfil its own set of topological constraints. The topological constraints may induce structures like Steiner trees, minimum spanning trees, shortest paths, etc. The cost function to be minimized is a combination of the costs for the shared network and the costs incurred by each entity.

The minimum cost shared Steiner arborescence problem (SAS) is a special case of the MCSN, in which the underlying structures take the form of Steiner trees. The SAS has been used in the literature to establish shared functional modules in protein interaction networks. A cut formulation for the SAS and Benders decomposition thereof are proposed in this article and computationally evaluated and compared with a previously proposed flow-based formulation. The effectiveness of the algorithms is illustrated on two types of instances derived from protein-interaction networks (available from the previous literature) and from telecommunication access networks.

3 - A biased random-key genetic algorithm for the capacitated minimum spanning tree problem

Mauricio Resende, *Efrain Ruiz*, *Maria Albareda Sambola*, *Elena Fernandez*

We focus on the capacitated minimum spanning tree (CMST) problem. Given a central processor and a set of remote terminals with specified demands for traffic that must flow between the central processor and terminals, the goal is to design a minimum cost network to carry this demand. Potential links exist between any pair of terminals and between the central processor and the terminals. Each potential link can be included in the design at a given cost. The CMST problem is to design a minimum-cost network connecting the terminals with the central processor so that the flow on any arc of the network is at most Q. A biased random-key genetic algorithm (BRKGA) is a metaheuristic for combinatorial optimization which evolves a population of random vectors that encode solutions to the combinatorial optimization problem. This paper explores several solution encodings as well as different strategies for some steps of the algorithm and finally proposes a BRKGA heuristic for the CMST problem. Computational experiments are presented showing the effectiveness of the approach: Seven new best-known solutions are presented for the set of benchmark instances used in the experiments.

This research was published in Computers & Operations Research, vol. 57, pp. 95-108, 2015.

Monday, 14:00-15:00

■ MC-01

Monday, 14:00-15:00 -

Plenary Ben-Ameur

Stream: Plenary sessions
Chair: *Bernard Fortz*

1 - Robust routing in communication networks
Walid Ben-Ameur

We review some recent developments related to robust routing in communication networks. Starting from static routing, we present fully dynamic routing, affine routing, and multi-static routing. We will then describe a multipolar robust optimization framework encompassing the previous approaches and allowing a compromise between complexity and quality.

Monday, 15:30-17:30

■ MD-01

Monday, 15:30-17:30 -

Best Paper Award

Stream: Best Paper Award
Chair: *Eli Olinick*
Chair: *Young Myoung Ko*

1 - Improved structures for data collection in static and mobile wireless sensor networks

Michael Segal, *Jon Crowcroft*, *Liron Levin*

In this talk we consider the problem of efficient data gathering in sensor networks for arbitrary sensor node deployments. The efficiency of the solution is measured by a number of criteria: total energy consumption, total transport capacity, latency and quality of the transmissions.

We will show two novel approaches to achieve different tradeoffs between several criteria: balance nodes and clever shortcuts in trees. The first approach aims to build data collection routes based on centrally located nodes in topologies which are already efficient in terms of some of the metrics while the second approach adds the shortcut links (in the size of certain arithmetic progression) to the currently constructed topology in order to allow the required tradeoff between studied criteria. The first approach also leads to the new construction of balanced tree partition which is of independent interest for the operation research community. For both novel approaches we present proven analytic approximation bounds and simulative results showing superiority of our algorithms over all previously proposed solutions.

We will describe the output-sensitive behavior of power assignment in dynamic environments where the sensors have no information about each other, just its current location and next trajectory step — this is done by choosing a proper spanning graph and an observation that the worst cases can be observed either in the start or end point. By observing an elegant connection between spanning trees and Hamiltonian cycles we will explain how the proposed schemes can deal with fault-tolerance and interference-awareness issues.

2 - The Generalized Regenerator Location Problem

Ivana Ljubic, *Si Chen*, *S. Raghavan*

In an optical network a signal can only travel a maximum distance dmax before its quality deteriorates to the point that it must be regenerated by installing regenerators at nodes of the network. As the cost of a regenerator is high, we wish to deploy as few regenerators as possible in the network, while ensuring all nodes can communicate with each other. In this paper we introduce the Generalized Regenerator Location Problem (GRLP) in which we are given a set S of nodes that corresponds to candidate locations for regenerators, and a set T of nodes that must communicate with each other. If S = T = N, we obtain the regenerator location problem (RLP) which we have studied previously and shown to be NP-complete. Our solution procedure to the RLP is based on its equivalence to the maximum leaf spanning tree problem (MLSTP). Unfortunately, this equivalence does not apply to the GRLP; nor do the procedures developed previously for the RLP. To solve the GRLP, we propose reduction procedures, two construction heuristics, and a local search procedure; that we collectively refer to as a heuristic framework. We also establish a correspondence between the (node-weighted) directed Steiner forest problem and the GRLP. Using this fact, we provide several ways to derive natural and extended integer programming (IP) and mixed-integer programming (MIP) models for the GRLP and compare the strength of these models. Using the strongest model derived on the natural node selection variables we develop a branch-and-cut approach to solve the problem to optimality. The results indicate that the exact approach can easily solve instances with up to 200 nodes to optimality, while the heuristic framework is a high-quality approach for solving large-scale instances.

3 - Nonstationary loss queues via cumulant moment approximations

Jamol Pender

In this paper, we provide a new technique for analyzing the nonstationary Erlang loss queueing model with abandonment. Our method uniquely combines the use of the functional Kolmogorov forward equations with the well-known Gram-Charlier series expansion from the statistics literature. Using the Gram-Charlier series expansion, we show that we can estimate salient performance measures of the loss queue such as the mean, variance, skewness, kurtosis, and blocking probability. Lastly, we provide numerical examples to illustrate the effectiveness of our approximations in the telecommunications literature.

4 - Efficient Algorithms for the Maximum Concurrent Flow Problem

Pierre-Olivier Bauguion, *Walid Ben-Ameur*, *Eric Gourdin*

In this paper, we propose a generic decomposition scheme for the maximum concurrent flow problem. This decomposition scheme encompasses many models, including, among many others, the classical path formulation and the less studied tree formulation, where the flows of commodities sharing a same source vertex are routed on a set of trees. The pricing problem for this generic model is based on shortest-path computations. We show that the tree-based linear programming formulation can be solved much more quickly than the path or the aggregated arc-flow formulation. Some other decomposition schemes can lead to even faster resolution times. Finally, an efficient strongly polynomial-time combinatorial algorithm is proposed for the single-source case.

Tuesday, 9:30-10:30

■ TA-01

Tuesday, 9:30-10:30 -

Energy efficient networks

Stream: Contributed abstracts
Chair: *Ivana Ljubic*

1 - An MIP for Energy-efficient Data Center: Reformulation for Distributed Computing and Server Clustering
Yongkyu Cho, *Young Myoung Ko*

In the era of growing information communication technology driven by mobile devices, large-scale data centers are necessary for processing and storing huge amount of incoming data. Large-scale data centers, however, consume tremendous amount of energy up to 3% of all global electricity production while producing 200 million metric tons of CO2. Achieving energy-efficiency is one of the key problems in data center operations. So far, many research studies developed mathematical models and algorithms exploiting various methodologies such as mixed integer programming (MIP), nonlinear programming (NLP), queueing theory, and control theory. For example, one of the research studies developed an MIP successfully incorporated well-known energy-saving techniquesvirtualization, speed scaling, and powering on/off serversin a single formulation. However, NP-hardness of MIP problems restricts scalability for solving problems with realistic size. To address this issue, we decompose the MIP problem into smaller ones so that we can utilize distributed computing technologies. We apply Benders' decomposition method to exploit the bordered block-diagonal structure of the formulation. The problem is divided into a part with complicating integer variables and the other part with real variables. The virtualization plan is determined by solving the master problem whereas the subproblems check the feasibility of the determined virtualization plan. In addition, we incorporate new constraints constituting clusters of servers to see the effectiveness of server clustering frequently used for convenience in data centers. The numerical experiments are conducted to see the effect of server clustering on energy consumption and propose a clustering strategy achieving energy efficiency.

2 - The Virtual Network Embedding Problem: Complexity and Dynamic Programming
Martin Tieves, *Edoardo Amaldi*, *Stefano Coniglio*, *Arie Koster*

We consider the Virtual Network Embedding problem (VNE). Such problem consists of a substrate (or physical) network with node and edge capacities and a set of virtual networks with node capacity demands and node-to-node traffic demands. The virtual networks are endowed with profits which the substrate owner obtains, if the corresponding virtual networks are embedded onto the substrate. This way, VNE asks for an embedding of (a subset of) the virtual networks onto the substrate network which maximizes the total profit while respecting the physical node and edge capacities.

In the first part of this work, we investigate the computational complexity of VNE. In particular, we present a polynomial-time reduction from the maximum stable set problem which implies strong NP-hardness for VNE even for very special sub classes of graphs and yields a strong inapproximability result for general graphs. We also consider the special cases obtained when fixing one of the dimensions of the problem to one. We show that VNE is still strongly NP-hard when a single virtual network request is present or when each virtual network request consists of a single virtual node and that it is weakly NP-hard for the case with a single physical node.

In the second part of this work, we investigate settings where dynamic programming approaches can be employed to tackle VNE. We present a general recursive formula and show under which conditions it can effectively be evaluated. In particular, we focus on the case where the virtual networks are given as stars. We revise results from the literature and show a dynamic program for embedding non uniform stars on a single link. We conclude with a proof that embedding general stars on a general graph is NP-hard.

Tuesday, 11:00-12:00

■ TB-01

Tuesday, 11:00-12:00 -

Plenary Schneur

Stream: Plenary sessions
Chair: *Mauricio Resende*

1 - The Ingredients to Make Analytics Work
Rina Schneur

Analytics has become commonly used in different contexts and at various levels. Yet, it remains challenging to realize the tremendous impact analytics, and especially advanced analytics, can bring to organizations. What are the key elements needed to make analytics successful? Will discuss the challenges to expect and ideas to overcome them, drawing from personal experience in telecom and other domains.