Application

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Information about application

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Keywords: wireless communication networks, dynamic traffic routing, multicommodity flow networks, optimization and integer programming, discrete event simulation

Funds applied for

Year:	2016	2017	2018	2019
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Descriptive data

Project info

Project title (Swedish)*

Flow Thinning - en vägvalsstrategi för kommunikationsnätverk med varierande länkkapaciteter

Project title (English)*

Flow Thinning - a traffic routing strategy for communication networks with variable link capacity

Abstract (English)*

The project deals with Flow Thinning (FT) – an original traffic routing strategy controlling logical end-to-end tunnels in communication networks with variable (fluctuating) link capacity. The phenomenon of fluctuating link capacity, especially profound in wireless networks, should be controlled in the process of routing end-to-end traffic flows in order to avoid link overload and at the same time keep instantaneous traffic admitted to the network at maximum. FT is expected to effectively address this control issue and offer a solution that could be applied in practice.
This 4-year project will be divided into several research tasks, starting from mathematical modelling of FT and developing optimization algorithms for tunnel capacity control, through numerical experiments revealing its traffic efficiency, to an FT implementation specification, realized in a network simulator.
The main aim of the project is to develop centralized and distributed algorithms for optimizing the tunnel flow control parameters, as well as an FT implementation solution that will be based on the use the MPLS virtual tunnel technology and on enhancements of the RSVP and OSPF-TE protocols from the TPC/IP stack. As the result, the project will produce a consistent proposal of FT that could then be implemented in a field experiment.
Significance of the project stems from importance of wireless communications as such, and from the fact that FT does take into account fluctuations in the available capacity of links – a distinctive feature of wireless networks where the link transmission rate and range can (and should) be adapted to changing channel propagation conditions. This feature has not been considered to a satisfactory extent in the current and past proposals of wireless network traffic routing control. The area of applications of FT includes wireless mesh networks that provide broadband Internet access for fixed and mobile users.

Popular scientific description (Swedish)*

Trådlösa meshnätverk består av IP routrar hopkopplade av trådlösa länkar baserat på radio, mikrovågs eller optisk teknologi. Meshnätverk ar visat sig bli en viktig komponent för att förse användare med bredbandsaccess till Internet. Anledningen till detta är att meshnätvekr möjliggör konnektivirtet som är billigare och enklare att installera och managera än fasta teknologier i många utrullningsscenarios. Ett exempel på detta är områden där fasta kommunikationssystem inte är utbyggda där täckning kan erhållas med ett fåtal noder direktanslutna till Internet. Ett annat exempel är installationer av optiska nätverk i en meshkonfiguration för att koppla ihop byggnader med optisk kommunikation.
En av de mest framträdande egenskaperna hos mesh nätverk är stor varians i kapacitet över länkarna, beroende på faktorer som väder betingelser. Därför, eftersom maximal kapacitet generellt sett inte är tillgängligt över alla länkar, varians i kapacitet borde vara en av de fundamentala parametrar som tas i beaktning medan den totala kapaciteten maximeras. Denna mekanism som kallas flow-thinning (FT) är den centrala mekanismen i detta projekt. FT är mycket lovande för att lösa de ovanstående problemen medan mekanismerna kan implementeras i realiteten.
FT som är en ny metod för att managera IP trafik använder tunnlar mellan ändpunkterna med kontrollerbar lokalkapacitet vilka kontrolleras av on-line av tunnel noderna på så sätt att variansen i länkkapacitet kan följas. I detta projekt kommer vi att utveckla en modell för FT tillämpat på meshnätverk som bär IP trafik i logiska tunnlar med hjälp av MPLS över trådlösa länkar. Två viktiga exempel på sådana nätverk nämndes ovan.
Huvudmålet i projektet är att centraliserade och distribuerade algoritmer som optimerar tunnelflödesparametrar tillsammans med implementerbara FT lösningar baserat på MPLS virtuell tunnel teknik och utvecklingar av RSVP och OSPF-TE protokollen inom TCP/IP stacken.
Detta 4 åriga projekt är indelat i 7 delar med början i matematisk modellering av FT och utvecklandet av optimeringsalgoritmer för att kontrollera kapaciteten i tunnlarna, samt genom numeriska studier undersöka effektiviteten av FT till att ta fram en specifikation och slutligen implementera en simuleringsstudie.
Signifikansen kommer sig av den vikt modern kommunikation fäster vid trådlös kommunikation samt att FT är en metod som både kan realiseras och även ta varians i beaktning då resurser skall kontrolleras i trådlösa nätverk, något som inte studerats i detalj tidigare. Specifikt har inte tidigare forskning undersökt on-line routning av data där tunnellagret tar länklager varians i beaktning. Faktum är att FT inte på något sätt är begränsat till mesh nätverk. Till exempel kan FT tillämpas på användandet av oprioriterad trafik i optiska nätverk.
Den nya kunskapen genererad består i helt nya icke triviala optimeringsmetoder och algoritmer för FT. Kunskapen kommer att bidra till heltalsprogrammering som fält, en fundamental optimeringsmetod för att tackla många viktiga reella problem inom teknikområdet. Simulerinsstudierna kommer även att avslöja hur pass effektivt FT är i jämförelse med andra mindre sofistikerade metoder för att tackla dessa problem.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Classifications

Select a minimum of one and a maximum of three SCB-codes in order of priority.

Select the SCB-code in three levels and then click the lower plus-button to save your selection.

SCB-codes*	1. Naturvetenskap > 102. Data- och informationsvetenskap (Datateknik) > 10202. Systemvetenskap, informationssystem och informatik (samhällsvetenskaplig inriktning under 50804)

Enter a minimum of three, and up to five, short keywords that describe your project.

Keyword 1*

wireless communication networks

Keyword 2*

dynamic traffic routing

Keyword 3*

multicommodity flow networks

Keyword 4

optimization and integer programming

Keyword 5

discrete event simulation

Ethical considerations

Specify any ethical issues that the project (or equivalent) raises, and describe how they will be addressed in your research. Also indicate the specific considerations that might be relevant to your application.

Reporting of ethical considerations*

The research foreseen in this project application does not raise any ethical issues.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

1. Purpose and aims

Roughly, wireless meshed networks (WMN) are composed of fixed IP routers and Internet gateways, interconnected by wireless links based on the radio, microwave, or free space optical (FSO) technologies. WMNs are becoming an important solution for providing broadband Internet access for fixed and mobile users connected to the routers. The reason is that in many circumstances WMNs are cheaper, faster and simpler to deploy, maintain and operate than their wired counterparts [1]. This is for example the case in areas lacking network infrastructure where WiFi radio based WMNs can provide Internet access to entire communities despite the fact that only few nodes (gateways) have direct access to the Internet. Such WiFi networks employing fixed mesh routers are also considered for the smart city applications. Another example is a corporate WMN deployed in a large city using FSO links, connecting pairs of transceivers in the line-of-sight installed on the roofs of buildings.

A major distinctive feature of WMNs (and, for that matter, wireless communications in general) is variable link capacity: the link range and its transmission rate can (and should) be adapted to changing, for example weather-dependent, channel propagation conditions. This is achieved through automatic adjustment of modulation and coding schemes making wireless transmissions fit the current channel state. Such a mechanism is in particular applied in the WiFi radio (IEEE 802.11 family of standards), microwave, and FSO communications which are basic technologies in today's wireless networking. Since the maximum installed capacity is in general not simultaneously available on all the links (as the usable capacity of each link varies between zero and its maximal value), the process of routing (controlling) the end-to-end WMN traffic streams should directly consider the fluctuations in link availability in order to avoid link overload and at the same time keep instantaneous traffic admitted to the network at maximum. Such a control mechanism, called Flow Thinning (FT in short), is dealt with in this project. Thus, FT addresses a real world problem, i.e., the traffic routing control issue in question, and is expected to offer an effective, feasible solution that is simple to implement in practice.

FT is a traffic routing strategy that makes use of logical tunnels (as MPLS virtual tunnels called LSP – label switched paths) with a separate set of end-to-end tunnels dedicated to carry the packets of each end-to-end packet traffic demand. The (logical) capacity of the tunnels is controlled through thinning their nominal capacity in order to follow links' capacity fluctuations. Since FT works at the MPLS tunnel level, the actual way the end-to-end packet traffic is handled using the total logical capacity currently accessible in the set of its dedicated tunnels is irrelevant to FT – it is only assumed that the packet traffic routing mechanism can be effectively implemented when the current tunnel capacity is made known to the packet traffic originating nodes. This makes FT generic in the sense that packet traffic flow control (that in general depends on the networking technology) does not have to be directly considered. The concept of FT is described in more detail in Section 5.

The main purpose and aim of the project is two-fold. First, we will work out a complete mathematical model of the FT strategy including centralized and distributed algorithms for optimizing parameters that control instantaneous tunnel capacity to make it fit the current link availability state (this is crucial for proper tunnel control in FT). Second, we will develop an implementable FT solution based on the use of the MPLS/LSP virtual tunnel technology and on enhancements of the RSVP and OSPF-TE protocols from the TPC/IP stack. In effect, the project will produce a consistent proposal of FT that could then be (but not within this project) implemented in a field experiment.

In more detail, we are aiming at:

- Working out a multicommodity flow network model and algorithms for optimizing logical tunnel thinning factors that determine the tunnel capacity as a function of link availability states, both in a centralized (for benchmark solutions) and a distributed (for practical implementations) way – see Tasks 1-5 in Section 3.

- Developing a functional model specifying the tunnel thinning mechanism and protocol extensions necessary for implementation of FT in contemporary wireless mesh networks carrying IP traffic (Task 6).
- Implementing a proof-of-concept simulation model on a network simulator (like NS-3) level that will demonstrate feasibility of the proposed FT solution, as well as its traffic efficiency in WMN/ MPLS network with the FSO (free space optics) transmission technology (Task 7).

Generic character of the notion of logical tunnel and of link availability state, as well as the modest signaling requirements, make FT a general purpose strategy, applicable not only to WMNs, but also to other networks that, for some reason, experience link capacity fluctuations and are capable of establishing virtual, or, as a matter of fact, physical end-to-end tunnels.

2. Survey of the field

As already mentioned, the main goal of the proposed project is to develop a novel traffic routing strategy, taking both its theoretical and implementation aspects into consideration. Below we will survey the research field related to our project mainly from the optimization aspects of the FT viewpoint. In fact, the implementation aspects cannot be discussed here as they are specific to FT, and no implementation of a similar proposal of a logical tunnel-based routing strategy reactive to link availability states is known to us.

Certainly, an indirect mechanism of reacting to link capacity fluctuations is intrinsic to TCP, a basic IP network protocol that controls end-to-end packet flows. In the considered case of variable wireless link capacity, however, the TPC reaction time and efficiency in packet traffic handling is unclear. That said, examining this complex issue is not the goal of our project. Instead, we address a complementary mechanism – a traffic routing strategy that controls capacity of end-to-end logical tunnels (used to carry aggregated flows of packets) and is capable to instantaneously adapt the tunnels to the current state of the available links' capacity. Somewhat surprisingly, such potentially simple strategies for increasing traffic efficiency in networks with variable link capacity have not yet attracted due attention of the communications research community, at least to our best knowledge. This gap in research is the main motivation of our project.

In the project we will work out a multicommodity flow network optimization model that addresses an important and virtually not investigated subarea in survivable network design that concerns networks with partial multiple resource failures (that can be also interpreted as limited availability of the resources capacity). Thus, our research belongs to a field in multicommodity flow network theory that deals with modeling communication networks robust to partial link (and node) failures under an assumed flow routing and protection/restoration strategy. One of the main approaches, besides stochastic programming, to such modeling is to use a multi-state description to account for the link availability and traffic states – the approach that will be followed in this project.

Although the advances in multi-state multicommodity flow network optimization are substantial (see for example [2], [3], [4] and the references therein), for at least two reasons most of the research in this area is not well fit to a number of contemporary communication networks. First, the notion of the state has typically been limited to total failures of single links, i.e., where all the network links can fail but only one at a time, and when a link fails then its entire capacity is lost. Actually, this assumption is valid but mainly for the fixed (wired) transport networks, such as optical networks, where single optical cable cuts are the most common failures. In fact, when we consider higher layers of fixed communication networks, then multiple link failures become profound. This case has also been studied but again assuming totally failing links. In the literature, a set of simultaneously and totally failing links is sometimes referred to as *shared-risk link group* – SRLG [5]. Although the theoretical work done for the SRLG scenarios is valuable (see [6] and the references therein), that work is, unfortunately, of limited relevance for practice since multiple failures in communication networks are typically partial (unless the links are subdivided – an approach hardly effective). For example, consider an optical cable cut in the transport layer. This failure will be seen in an upper network layer, such as the IP layer, as partial failures of several IP links since such links will lose only a part of capacity as typically they are realized in the transport layer over diverse transmission paths.

In the project we consider network survivability from a different angle. We treat partial availability of network links as typical, and, consequently, we use the notion of link availability state. This viewpoint is adequate for dealing with various communication networks, as illustrated in the two following examples:

- IP/MPLS over wireless (the already described basic case for this project). In wireless mesh networks a typical link availability state is characterized by a subset of those links that lose a fraction of their maximum capacity (achieved under perfect signal propagation) because of the current weather state that directly affects the radio channel condition. The links adapt to the detected channel condition by switching to an adequate modulation and coding scheme (see [7]) and the current capacity is determined by the scheme used.
- Optical networks, as for example DWDM networks with λ-switching. If we consider two priority classes of λ-connections [8], then the low-priority connections can be considered as using the network composed of links with the available capacity equal to the capacity not occupied by the (semi-permanent) high-priority connections. This capacity is variable. Note that in this case the FT logical tunnels would in fact be physical (in the sense of tunnel capacity) rather than virtual as in the MPLS case, since each such tunnel is established as a collection of end-to-end λ-paths, out of which some are not available in a given link availability state.

From the optimization viewpoint, the FT model dealt with in this project is directly applicable to the wireless mesh broadband networks applying microwave communication [9], [10], or free space optical communication [11], [12], the cases that will be studied in the FT implementation context in Task 7. The model is directly applicable for the second case as well. It can be also extended to WMNs based on the WIFi IEEE 802.11 standard family by taking link interference into consideration through adding signal-to-interference-plus-noise-ratio constraints – this, however, leads to severe modeling difficulties and is outside the scope of this project. We also note that virtually all the failure scenarios considered in the literature are special cases of our state characterization so in this sense our theoretical investigations are of a general nature.

The second reason of limited practicability of the research in survivable network design under multiple total link failure scenarios is that it has been mostly focused on traffic flow rerouting strategies (see [2], [4], [13]) that are not applicable to multiple partial failures. To the best of our knowledge, only the so called *global rerouting* (GR) has been studied in the partial multiple failure context, see [4] and the references therein. GR restores the demand's traffic by establishing their flows from scratch in the surviving capacity without any restrictions (contrary to FT where given nominal flows can only be thinned). Because of that, GR is the most effective traffic rerouting strategy we can think of, but at the same time it is quite impractical in the context assumed in our project, due to excessive end-to-end flow rerouting.

The flow thinning strategy proposed in this paper is an extension of *demand-wise shared protection* (DWSP) developed in [14], [15] that makes use of the concept of diversification introduced in [13]. DWSP was further studied in [4], [6], [16] under the name *path diversity protection*. Recall that DWSP assumes total link failures, i.e., failure scenarios which admit only binary state of link capacity (fully available or totally failed). DWSP is a protection strategy where in a failure state the tunnels using the failing links are simply disconnected. The surviving tunnels maintain their nominal capacity that must be sufficient to realize the demand's traffic volumes, possibly decreased with respect to the nominal demand volumes. In fact, under the total link failure assumption FT becomes identical to DWSP.

FT is also related to *elastic rerouting* (ER) [17]. The ER strategy allows for decreasing the flows of unaffected demands, as well as for increasing (to a limited extent) path-flows of affected demands.

Affine flow thinning, an important version of FT that will be developed in this project, is based on a general framework of affine decision rules [18], and on its application to traffic routing introduced in [19] and further investigated in [20].

A network dimensioning problem for microwave networks involving partial multiple link failures was studied in [21]. It uses a different approach (chance constrained programming) to cope with link availability states. Yet, it assumes static flows and full realization of traffic demand in all possible states, thus considerably simplifying the problem.

3. Project description

Below we describe the duration, contents, and the theories and methods of the consecutive tasks planned for the project.

Task 1: FT optimization model **M1–M4 (duration: Month 1 – Month 4)**

In Task 1 we will work out a detailed multicommodity flow network model of FT. We will study two FT optimization problems: FTOP1 (joint optimization of the tunnel (flow) thinning factors and link capacities – appropriate for FT network planning), and FTOP2 (optimization of the tunnel thinning factors for given link capacities – appropriate for FT operation). Both variants are *NP*-hard and will be approached using mixed-integer programming (MIP) formulations along with appropriate pricing problems for path generation to be used in the overall branch-and-price optimization algorithm. We will consider the two problems for the general form of thinning factors and, what is more important from the implementation viewpoint, for AFT (affine flow thinning) with its specific form of thinning factors that permits to effectively cover general sets of link availability states and opens a way to practical, distributed implementations of FT. It should be noted that both versions of FTOP are challenging in terms of effective solution algorithms and require deep optimization knowledge to be appropriately dealt with.

Task 2: Centralized algorithms for FT optimization **M4–M9**

Next, we will elaborate a set of centralized algorithms for FTOP1 and FTOP2 that will be able to optimize link capacity (FTOP1), nominal tunnel capacity (FTOP1 and FTOP2), and thinning factors (FTOP1 and FTOP2) as a function of (applied in response to) the link availability states. The basic approach will use a state-of-the-art MIP solver (such as Gurobi) for linear and MIP formulations developed in Task 1, enhanced with the cutting plane method. We will study the related path generation issues and present a set of theoretical results that can help to efficiently solve the pricing problem in several important special cases. We will also provide compact (and thus efficiently solvable) lower bound formulations that will be used in Task 3 to study traffic efficiency of FT. Finally, we will consider heuristic algorithms that will be necessary to deal with large networks as well as to speed-up the branch-and-bound algorithms used in the MIP solvers. The optimal FTOP solutions obtained in a centralized way will serve as benchmarks for evaluating the solutions obtained in a decentralized way with the distributed algorithms elaborated in Task 4.

Task 3: Numerical studies of centralized FT optimization **M8–M12**

An extensive numerical study of Task 3 will be based on a set of selected network examples from the SNDlib library. Using the centralized algorithms developed and implemented in Task 2, we will first of all exhibit how efficient in terms of carrying traffic are the FT and AFT strategies in comparison with other potential (but hardly practical) strategies such as GR (global rerouting), and to strategies where link capacity fluctuations are not considered at all. The study will also illustrate computational efficiency of the developed algorithms. The optimal FTOP solutions obtained in a centralized way will serve as benchmarks for evaluating the solutions obtained in a decentralized way with the distributed algorithms elaborated in Task 4.

Task 4: Distributed algorithms for FT optimization **M13–M24**

For practical implementations of FT, decentralized flow thinning optimization algorithms for FTOP2 are necessary. We will identify basic pieces of information required in the network nodes, together with the way they are interchanged between the nodes, in order to be able to distribute the otherwise centralized optimization process (dealt with in Task 2) among the nodes. As we expect that the developed distributed approaches may not lead to optimal solutions, one of the issues will be to make them as accurate as possible maintaining a reasonable node processing time and the overall convergence time of the algorithm. These times must be short enough, especially for AFT, to make the FT implementations work in practice.

Task 5: Numerical studies of distributed FT optimization **M20–M30**

We will repeat the FTOP2 numerical study of Task 3, this time using the distributed algorithms developed and implemented in Task 4. As a result we will be able to assess the capability of the algorithms in achieving near optimal solutions, as well as to examine their computational efficiency and convergence rate from the perspective of the node computational burden.

Task 6: FT network implementation issues **M31–M40**

A selected AFT version of FT will be considered for a feasible implementation in metropolitan IP/MPLS wireless meshed networks based on FSO. The choice of the free space optical communication technology is motivated by the relative simplicity of the FT optimization model for FSO due to lack of interference of link transmissions in optical wireless communications (such interference is present in radio networks). The study will also be valid for microwave link-based wireless networks.
There are two main processes to be specified.

(i) The first process, performed periodically in long cycles (once a day, say), consists in off-line optimization of the affine flow thinning functions (i.e., solving FTOP2 for AFT). The process requires specification of a selected distributed optimization algorithm prepared in Task 4, and a way the input data is gathered and interchanged between the nodes.
(ii) The second process is an on-line flow thinning process activated after any non-negligible change in the link availability state. When the capacity of a link is changed, this fact is signaled back to the originating nodes of all the tunnels incident to the link's originating node so that the tunnel originating nodes can apply the proper flow thinning factors optimized by the first process.

These two processes will be specified in terms of information exchange and storage, as well as in terms of extending the existing protocols (OSPF-TE and RSVP) to make their control messages usable for the AFT purposes. In this task we will also select a proper network simulator (as NS-3 or OMNET++, both open-source simulators) to be used in Task 7.

Task 7: Simulation model of a FT network implementation **M38–M48**

Finally, we will implement the selected AFT version of FT for FSO metropolitan networks in a network simulator. A series of runs for networks of different size and various link state availability scenarios (with changing weather conditions modeled as a random process) will be performed and in this way a proof-of-concept for the proposed FT solution will be presented.

This 4-year project will be carried out at the Department of Electrical and Information Technology (EIT) of Lund University by prof. Michal Pioro (30% of his full working time will be devoted to the project for its entire duration) and a PhD student (90%, to be recruited). The employed PhD student will complete his PhD thesis under supervision of the applicant.

4. Significance

Importance of the proposed project stems from importance of wireless communications in general and wireless mesh networks in particular, and from the novel control mechanism of FT that directly takes into account fluctuations in the available link capacity – an important intrinsic feature of wireless networks that has not been considered to a satisfactory extent in the current and past proposals for wireless traffic control. Additionally, FT provides a generic solution applicable to networks other than WMNs, wherever link capacity fluctuations become important and logical tunnels are implementable.

Wireless communications is a key element in voice, video and data transfer today. In 2013, the global number of mobile-cellular subscriptions almost reached the World's population (Fig.1), generating an unprecedented growth in communication traffic volume that mounted to almost 3 Exabytes (3 million terabytes) in 2014, and, according to predictions, will continue to grow exponentially in the coming years (Fig.2). Certainly, this growth concerns, to a great extent, wireless mesh networks as well.

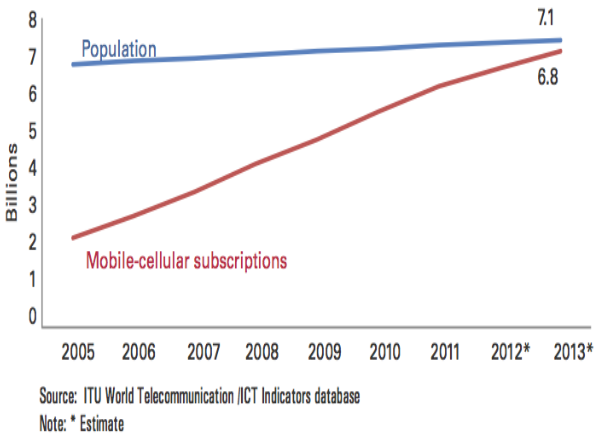

Figure 1. World's mobile subscriptions.

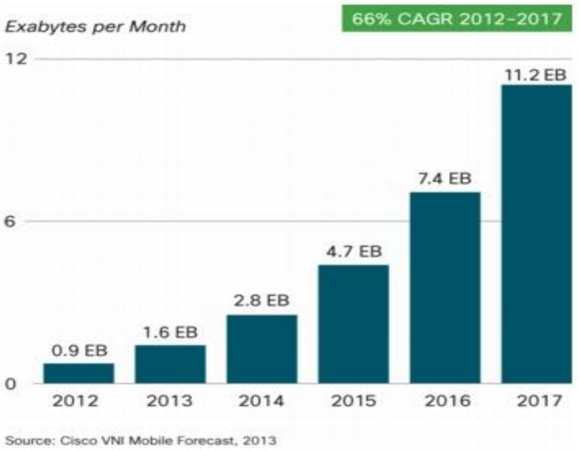

Figure 2. Communication traffic.

Significance of the project stems from its novelty and originality, theoretical value, potential practicability, and importance of its applications. Effective traffic routing strategies in wireless meshed networks are of interest because of the scale of the wireless traffic volume. As will be demonstrated by the results of the project investigations, without considering the phenomenon of link capacity fluctuations in traffic routing, significantly less traffic can be carried in a wireless mesh network at a given quality of service level. Our proposal, FT, takes the fluctuations in question directly into account in a direct, simple, yet reasonable, way.

The concept of FT is novel, as so far there are seemingly no practical, implementable proposals of traffic routing strategies based on logical tunnels, capable of reacting to fluctuations of links' capacity while assuring the assumed levels of traffic carried. Practicability of FT is implied by the following features of its AFT version that will be elaborated within the project for the wireless IP network applications:

- feasibility of implementation
- simplicity of operation
- effectiveness in carrying traffic
- robustness to unpredicted link availability states.

All these features will be verified through a proof-of-concept simulation model.

The results specifying an implementable version of FT and the simulation model will constitute the first group of the significant results of the project. The second group will consist of theoretical results that will include novel non-trivial optimization models and algorithms, both centralized and distributed, related to FT (and similar concepts). This will constitute a non-negligible contribution to Integer Programming – a fundamental optimization approach to real world engineering problems.

5. Preliminary results

Preliminary results presenting a concept of FT and a centralized optimization approach to FTOP1 have been reported in a series of papers [22-24]. The results presented there, extended in paper [25] (under revision for the Operations Research journal), are summarized below.

The concept of FT is as follows.

- At any time instant of time the network is in some *link availability state* (state in short) characterrized, for each link, by the given fraction (called the *link availability coefficient*) of its maximum capacity (called *nominal capacity*) that is currently available. Value 0 of such a coefficient means total link unavailability, value 1 means its full availability, while the value between 0 and 1 is the fraction of the nominal capacity available on a given link. The (possibly only hypothetical) link availability state with all links fully available is called the *reference state*.

- Traffic of each end-to-end demand is carried over a set of dedicated logical tunnels such as MPLS virtual tunnels (i.e., LSPs). Each tunnel is realized along a selected routing path connecting the demand's origin and destination. The maximum (logical) capacity reserved on a tunnel is called its *nominal capacity* or, equivalently, its *nominal flow*. It is assumed that the nominal flows can be simultaneously realized on the tunnels without exceeding the nominal link capacities so that the nominal flows are realizable in the reference state.

- Since in a given link availability state the capacity available on the affected links is reduced with respect to their nominal capacity, the flows assigned to the affected tunnels must in general be also reduced (thinned) with respect to their nominal flow, so that the links do not get overloaded when the capacity currently assigned to the tunnels is fully utilized by the packet traffic. In effect, the flow of each tunnel is state-dependent – it is adjustable according to the current link availability state (characterized by the set of the current set of link availability coefficients) and controlled by its originating node. The state-dependent *thinning factors* used at a node for thinning the nominal flows of its originating tunnels are stored in the node *tunnel thinning table*. Note that in general not all possible link availability states must be reflected in the thinning table. For a state not reflected in the table, its thinning factors can be approximated using the factors of the neighboring states that are taken into account in the table.

- The maximum volume of the packet traffic carried for a given demand is also state-dependent, as it is limited by the total flow currently assigned to its dedicated tunnels. In FT the originating node of a traffic demand is aware of the current capacity assigned to its outgoing tunnels (this information is stored in the thinning table) so that it can apply appropriate mechanisms to ensure effective tunnels' utilization without exceeding their current capacity. Hence, an important element underlying proper FT operation is an admission mechanism applied at an originating node that locally controls the amount of packet traffic admitted to enter each of its outgoing tunnels – this amount must not exceed the flow assigned to the tunnel. Such a control can be achieved through the QoS traffic access/policing/shaping control mechanisms including leaky bucket.

- In order to satisfy traffic demands, the tunnels, and consequently the links, should be properly dimensioned so that the state-dependent total capacity of the dedicated tunnels is always sufficient to carry the traffic volume assumed for each demand. For example, if for a certain demand a fixed given volume of traffic must be carried regardless of the link availability state, the total nominal capacity of its tunnels must be redundant so that after any state-dependent capacity reduction it will still be sufficient to carry the assumed traffic volume. In fact, to avoid substantial network over-dimensioning, and hence excessive network cost, the demands should in general accept reduction of their desirable carried traffic volumes, at least in the states with significant link capacity reduction. Clearly, the degree to which the preferable traffic volume is decreased should reflect the fractions of the nominal link capacity available in a given state.
- A practical way to optimize the thinning tables' contents is to apply the so called *affine flow thinning* (AFT). With AFT, the capacity of each tunnel is specified as an affine function of the availability coefficient values of a subset of links (for example the subset of links incident to the nodes along the tunnel). In an implementable version of AFT, the current availability coefficient values of the links incident to the nodes along a tunnel are delivered on-line to the tunnel's originating node. This can be achieved by means of appropriately extended messages of a standard protocol from the TCP/IP stack, for example using path-error messages in Resource Reservation Protocol (RSVP). Also, an algorithm for off-line optimization of the tunnel flow-defining affine functions should preferably be distributed and performed locally by the network nodes. This can be realized using a feasible information exchange mechanism, for example the OSPF-TE protocol.

For the above described concept of FT we have already achieved a number of results. These are:

Task 1: We have identified and proved that FTOP1 is *NP*-hard and formulated a basic linear programming formulation for the general (not affine) version of FTOP1. Because of *NP*-hardness, this formulation is necessarily non-compact and requires path generation (paths represent the FT tunnels). The problem related to path generation is also *NP*-hard. It turns out to be interesting from the theoretical point of view, and consists in finding a shortest path with the length defined in a non-standard way. We have managed to find effective polynomial algorithms for solving the resulting shortest-path problem for some special cases of link availability states scenarios, for example where pairs of links lose a part of their capacity, or where all links incident to a node lose a part of their capacity. For these cases we have also found compact (and thus effectively solvable) linear formulations of FTOP1. Besides, we have found and proved some other theoretical properties of FT, for example on the lower bounds of the minimal network cost.

Task 1: We have formulated a linear programming FTOP1 formulation for several affine versions of FT (i.e., for AFT) but without path generation. We have introduced a new kind of uncertainty sets derived from the budgeted uncertainty set notion of [26] that allow to partially relax some of the problem constraints when the uncertainty (in regard to the link capacity in our case) is profound.

Task 2: We have implemented an exact solution algorithm for the general version of FTOP1 based on path generation and for the affine version of FTOP1 (in this case without path generation).

Task 3: We have performed a numerical study of the FT traffic effectiveness and computational efficiency of the centralized solution algorithms. As far as traffic effectiveness is concerned, the results are encouraging, still computational efficiency of the optimization algorithms has to be improved. For example, we have shown that for a certain set of test network topologies, the general version of FT is only 6-14% inferior (in terms of the cost of installed link capacity) to GR (global rerouting, the strategy achieving the lower bound of the link cost). Moreover, the simplest version of AFT (with thinning factors depending on the availability coefficients of the links along the tunnel) increases the cost difference to 16-30%. This is figure is entirely acceptable, as GR is not practical.

Besides, we have substantial experience in network modeling and optimization [27] (knowledge required in Tasks 1-5), including wireless mesh networks [28-30], and FSO networks in particular [31-32] (knowledge required in Tasks 6-7). Finally, we wish to note that the following important issues have not been considered yet: (i) path generation for the affine versions of FTOP (path generation for affine versions of FT is different from path generation for the general version of FTOP), (ii) distributed versions of the FTOP solution algorithms, and (iii) FT network implementtation issues (an important part of the project).

6. International collaboration

Tasks 1, 2, and 4 will be executed in collaboration with prof. Dritan Nace from Université de Technologie de Compiègne (France) who contributed to the concept of FT when the applicant (Michał Pióro) was a visiting professor in Compiègne in 2013. Task 6, in turn, will be executed in collaboration with prof. Antonio Capone from Politecnico di Milano who has vast experience in wireless networking protocol technologies (Michał Pióro spent three months with the group of A. Capone in Milan in 2014 within the Marie Curie project MESHWISE).

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17. I.Shinko, D.Nace, Y.Fouquet, A study on a distributed rerouting scheme, *Proc. AINA 2013, Workshop NetMM*, pp.1461-1466, 2013.
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22. M.Pióro, D.Nace, Y.Fouquet, An optimization model for communication networks with partial multiple link failures, *Proc. RNDM 2013, 5th International Workshop on Reliable Networks Design and Modeling, co-located with ICUMT 2013 Congress,* 2013.
23. M.Pióro, D.Nace, M.Poss: Traffic Performance of Affine Flow Thinning, *Proc. 2nd European Teletraffic Seminar (ETS 2013),* 2013.
24. M.Pióro, Y.Fouquet, D.Nace, M.Poss, M.Żotkiewicz : An optimization model for communication networks resilient to partial multiple link failures, *INFORMS Telecommunications Conference*, 2014.
25. M.Pióro, Y.Fouqet, D.Nace, M.Poss: Optimizing flow thinning protection in multicommodity networks with variable link capacity, *Operations Research* (submitted 2014).
26. D.Bertsimas, M.Sim, The Price of Robustness, *Operations Research* 52(1), pp.35-53, 2004.
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30. Y.Li, M.Pióro, D.Yuan, J.Su: Optimizing Link Rate Assignment and Transmission Scheduling in WMN through Compatible Set Generation, *Telecommunications Systems* (accepted 2014, in press).
31. Y.Li, N.Pappas, V.Angelakis, M.Pióro, D.Yuan: Optimization of free space optical wireless network for cellular backhauling, *IEEE Journal on Selected Areas in Communications* (submitted 2014, under minor revision).
32. Y.Li, M.Pióro: Design of cellular backhaul topology using the FSO technology, *Proc. 2nd International Workshop on Optical Wireless Communications (IWOW 2013),* 2013.

Interdisciplinarity

My application is interdisciplinary

☐

An interdisciplinary research project is defined in this call for proposals as a project that can not be completed without knowledge, methods, terminology, data and researchers from more than one of the Swedish Research Councils subject areas; Medicine and health, Natural and engineering sciences, Humanities and social sciences and Educational sciences. If your research project is interdisciplinary according to this definition, you indicate and explain this here.

Click here for more information

Scientific report

Scientific report/Account for scientific activities of previous project

Budget and research resources

Project staff

Describe the staff that will be working in the project and the salary that is applied for in the project budget. Enter the full amount, not in thousands SEK.

Participating researchers that accept an invitation to participate in the application will be displayed automatically under Dedicated time for this project. Note that it will take a few minutes before the information is updated, and that it might be necessary for the project leader to close and reopen the form.

Dedicated time for this project

	Role in the project	Name	Percent of full time
1	Applicant	Michal Pioro	30

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	PhD Student	Nya aställning	90	471,172	485,307	499,866	514,862	1,971,207
2	Applicant	Prof Michal Pioro	30	353,380	363,982	374,901	386,148	1,478,411
	Total			824,552	849,289	874,767	901,010	3,449,618

Other costs

Describe the other project costs for which you apply from the Swedish Research Council. Enter the full amount, not in thousands SEK.

Premises

	Type of premises	2016	2017	2018	2019	Total
1	Office and general facilities	108,126	108,582	111,693	114,897	443,298
	Total	108,126	108,582	111,693	114,897	443,298

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Computers		20,000				20,000
2	Travelcosts	conferences, tickets, conference fee etc	30,000	40,000	40,000	40,000	150,000
3	Software	AMPLE	11,000				11,000
	Total		61,000	40,000	40,000	40,000	181,000

Depreciation costs

Depreciation cost	Description	2016	2017	2018	2019

Total project cost

Below you can see a summary of the costs in your budget, which are the costs that you apply for from the Swedish Research Council. Indirect costs are entered separately into the table.

Under Other costs you can enter which costs, aside from the ones you apply for from the Swedish Research Council, that the project includes. Add the full amounts, not in thousands of SEK.

The subtotal plus indirect costs are the total per year that you apply for.

Total budget

Specified costs	2016	2017	2018	2019	Total, applied	Other costs	Total cost
Salaries including social fees	824,552	849,289	874,767	901,010	3,449,618		3,449,618
Running costs	61,000	40,000	40,000	40,000	181,000		181,000
Depreciation costs					0		0
Premises	108,126	108,582	111,693	114,897	443,298		443,298
Subtotal	993,678	997,871	1,026,460	1,055,907	4,073,916	0	4,073,916
Indirect costs	299,228	300,491	309,100	317,967	1,226,786		1,226,786
Total project cost	1,292,906	1,298,362	1,335,560	1,373,874	5,300,702	0	5,300,702

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

Wages: Professor Michal Pioro will spend 30% of full his time in the project research during its whole duration. Besides direct research, his activities within the project will include tutoring the PhD student who will be recruited for 4 years. The PhD student will spent 90% of her/his time in the project research, and 10% in teaching and other department's duties, also during the whole project's duration.

Computers: The PhD student will need a powerful computer for running optimizations and simulations.

Travel costs: Professor Pioro and the PhD student will present their work at selected conferences and workshops when accepted. The conference travel budget will cover 1-2 travels per year.

Software: An AMPL software licence will be needed to faciltate using the Gurobi optimization package which we, as academic stafff, will be able to use for free.

Facilities: Michal Pioro and the PhD student will be charging the project cost for office space and general facilities. The indirect cost is currenly 33,79% of the direct cost (excl. facilities). This figure will vary with the years, and will be charged to the project accoding to the principle of the full coverage of costs.

Other funding

Describe your other project funding for the project period (applied for or granted) aside from that which you apply for from the Swedish Research Council. Write the whole sum, not thousands of SEK.

Other funding for this project

Funder	Applicant/project leader	Type of grant	Reg no or equiv.	2016	2017	2018	2019

CV

Michał Pióro – curriculum vitae

1. **Higher education qualifications:** 1973, MSc in applied mathematics and automatic control, Warsaw University of Technology (WUT), Poland.

2. **Doctoral degree:** 1979, telecommunications, WUT, Poland, *Combinatorial Foundations of the Design of Optimal Gradings*, supervisor Prof. Marian Dabrowski.

3. **Postdoctoral positions (selected):** Visiting Professor: Politecnico di Milano (Italy, September-November 2014), Université de Technologie de Compiègne (France, May-June 2013), Université Libre de Bruxelles (Belgium, October-November 2012), Gwangju Institute of Science and Technology (South Korea, February 2011), Universita degli Studi (Milan, Italy, October 2005), Technical University of Montevideo (Uruguay, March 2005) University of Missouri–Kansas City (USA, August-December 2003), Danmarks Tekniske Universitet (Lyngby, Denmark, 1995, 1996, 1999, 2000, 1 month each time).

4. **Qualifications required for appointment as a docent:**
   Doctor of Science (habilitation) in telecommunications, monograph: *Design Methods for Non-hierarchical Circuit Switched Networks with Advanced Routing*, Warsaw University of Technology, 1990.
   Polish State Professorship in Technical Sciences (the highest scientific title in Poland, awarded by the President of Republic of Poland), 2002.

5. **Current positions:**
   Professor (in telecommunications), Department of Electrical and Information Technology, Lund University, since January 2001 (90% in research).
   Professor (in telecommunications), Institute of Telecommunications, Faculty of Electronics and Information Technology, Warsaw University of Technology, since September 1996 (50% in research).

6. **Previous positions and periods of appointment:**
   Advisor of the President of Tel-Energo SA (a Polish telecom operator), 2001-2003.
   Senior Expert, International Telecommunication Union (Geneva), 1986, 2000, 2002.
   Research position in networking, 1997 (one year), Department of Communication Systems, Lund University of Technology, Sweden (leader of two projects: one for Ericsson Telecom AB in node placement, one for NUTEK in ATM network design–SWAP).
   Professor, National Institute of Telecommunications (a Research Centre of the Polish Ministry of Post and Telecommunications), 1996.
   Expert in telecommunication network planning, Price Waterhouse BIT, 1994-95.
   Professor, Franco-Polish School of New Information and Communication Technologies (Poznan, Poland), 1994-1996.
   Senior Network Specialist, Alcatel SESA (Madrid, Spain), 1990-91 (1 year).
   Research Assistant (Forskningsassistent), 1984-87 (3 years), Department of Communi-cation Systems, Lund Institute of Technology (leader of the project "Intelligent Routing" for LM Ericsson).
   Programmer (1974-75), Teaching Assistant (1976-78), Assistant Professor (1979-90), Associate Professor (1991-95), Professor (1996, until now), Institute of Telecommuni-cations, Warsaw University of Technology.

7. **Interruptions in research:** no interruptions.

8. **Supervision of doctoral students:** Ulf Ahlfors, Lund University (LU) 1999; Stanislaw Kozdrowski, Warsaw University of Technology (WUT) 2000; Piotr Gajowniczek (WUT) 2005; Piotr Karas (WUT) 2005; Pål Nilson (LU) 2006; Eligijus Kubilinskas (LU) 2008; Grzegorz Wojtenko (WUT) 2008; Igor Margasinski (WUT) 2008; Michal Zagozdzon (WUT) 2009; Mateusz Dzida (WUT) 2009; Sebastian Orlowski, Technische Universität Berlin, 2009; Mateusz Zotkiewicz (WUT and Telecom SudParis) 2011; Mariusz Mycek (WUT) 2014; Yuan Li (LU) 2015.

9. **Other merits of relevance to the application**

Current/former member of journal editorial boards: IEEE Communications Magazine, International Journal on Advances in Internet Technology, International Journal on Advances in Software, Digital Telecommunications, Journal of Telecommunications and Information Technology, Infocommunications Journal.

TPC member of the following (selected) international conferences: International Telecommunications Network Strategy and Planning Symposium NETWORKS (general chair in 2008-2010 2008), IEEE GLOBECOM, IEEE International Conference on Communications ICC, International Teletraffic Congress ITC, IEEE Symposium on Computers and Communications ISCC, International Network Optimization Conference (chairman), Design of Reliable Communication Networks DRCN, International Workshop on IP Operations and Management IPOM (co-chairman in 2008), International Working Conference on Heterogeneous Networks HET-NET, European Conference on Universal Multiservice Networks ECUMN, Next Generation Internet Networks Traffic Engineering EURO-NGI, Polish-German Teletraffic Symposium PGTS (co-chairman), European Teletraffic Seminar ETS (co-chairman).

Reviewer of around 50 PhD theses (Finland, France, Germany, Italy, Hungary, Poland, RSA, Spain, Sweden), 7 habilitation applications (France, Poland), 5 professorship appli-cations (Poland, Sweden, USA). Evaluator of FP6 and FP7 projects. Reviewer of books for Morgan-Kaufmann Publishers (Elsevier) and J. Wiley. Numerous reviews for leading journals on communications and operations research.

Leadership of projects (selected): Leader of more than 30 Polish, Swedish, French, and European research and scientific projects in communication network modeling, performance analysis and design. Among them projects for: Ericsson AB, Alcatel SESA, TP (Polish dominant telecom), ERA GSM (Polish mobile operator), France Telecom R&D, EU projects (Copernicus, IDEALIST, 6^{th} and 7^{th} Framework NoEs: Euro-NGI, Euro-FGI Euro-NF, COST 293, COST OPTICWISE, Celtic Eureka, IDEALIST).

Invited seminars (selected): Teletraffic Research Centre at University of Adelaide (Australia), Ericsson Telecom AB (Stockholm), AT&T Bell Labs (USA), Bellcore (USA), Univeriste de Quebec (Canada), INRS Montreal (Canada), University of Bremen (Germany), Telecom SudParis (Evry, France), France Telecom R&D (Paris), KTH (Stockholm), Ericsson Teletraffic Laboratories (Budapest), University of British Columbia (Vancouver).

Direct cooperation with researchers (selected): W.Ben-Ameur (Telecom ParisSud), A.Capone (Politecnico di Milano), T.Cinkler (Budapest University of Technology and Economics), Z.Dziong (Universite de Quebec), G.Fodor (Ericsson Research, Stockholm), B.Fortz (Université Libre de Bruxelles), E.Gourdin (France Telecom R&D), K.Holmberg and D.Yuan (LiTH), A.Jüttner (Ericsson Traffic Lab, Budapest), D.Kofman (Telecom ParisTech), D.Medhi (University of Missouri), D.Nace (Université de Technologie de Compiègne), W.Ogryczak and A.Tomaszewski (Warsaw University of Technology), P.Pavon (University of Cartagena), M.Ruiz (University Polytechnic of Catalonia, Spain), A.de Sousa (University of Aveiro), B.Staehle and D.Staehle (Wuerzburg University), R.Wessäly (Zuse Institut Berlin).

Key scientific/research/teaching qualifications: Communication and computer network modeling, planning, design and performance analysis (DWDM, SDH, ISDN, ATM, IP, GSM, UMTS, WMN), including traffic routing and resource protection. Specialist in operations research including optimization theory and integer programming, queueing theory, teletraffic engineering, reliability, graph theory.

Publication list

List of publications of Michał Pióro since 2007

Number of citations according to Google Scholar as for March 09, 2015

1. Peer-reviewed original journal articles

1. Y.Li, M.Pióro, D.Yuan, J.Su: Optimizing Link Rate Assignment and Transmission Scheduling in WMN through Compatible Set Generation, *Telecommunications Systems Journal* (accepted 2014) [Number of citations: 0].
2. Y.Li, M.Pióro, B.Landfeldt: Fair flow rate optimization by effective placement of directional antennas in wireless mesh networks, *Performance Evaluation* (2014) (published online) DOI: 0.1016/j [Number of citations: 0].
3. M.Żotkiewicz, M.Ruiz, M.Klinkowski, M.Pióro, L.Velasco: Reoptimization of Dynamic Flexgrid Optical Networks After Link Failure Repairs, *Journal of Optical Communications and Networking* 7(1) (2014) 49-61. [Number of citations: 0].
4. W.Ogryczak, H.Luss, M.Pióro, D.Nace, A.Tomaszewski: Fair optimization and networks: a survey", Journal of Applied Mathematics (2014) 1-25 (DOI: http://dx.doi.org/10.1155/2014/612018) [Number of citations: 2].
5. W.Ogryczak, H.Luss, D.Nace, M. Pióro: Fair optimization and networks: models, algorithms and applications, Journal of Applied Mathematics (2014) 1-3 (DOI: http://dx.doi.org/10.1155/2014/340913) [Number of citations: 0].
6. I.Fajjari, N.Aitsaadi, M.Pióro, G.Pujolle: A New Virtual Network Static Embedding Strategy within the Cloud Private Backbone Network, *Computer Networks* 62 (2014) 69-88 [Number of citations: 1].
7. M.Ruiz, L.Velasco, A.Lord, D.Fonseca, M.Pióro, R.Wessäly, J.P.Fernandez-Palacios: Planning Fixed to Flexgrid Gradual Migration: Drivers and Open Issues, *IEEE Communications Magazine* 52(1) (2014) 70-76 [Number of citations: 9].
8. W.Ben-Ameur, M.Pióro, M.Żotkiewicz, Fractional Routing Using Pairs of Failure-disjoint Paths, *Discrete Applied Mathematics* 164 (2014) 47-60 [Number of citations: 2].
9. Y.Li, M.Pióro: Integer programming models for maximizing parallel transmissions in wireless networks*, Electronic Notes in Discrete Mathematics* 41 (2014), 197-204 [Number of citations: 0].
10. *M.Pióro, M.Żotkiewicz, B.Staehle, D.Staehle, D.Yuan: On Max-min Fair Flow Optimization in Wireless Mesh Networks, *Ad-hoc Networks* 13 (2014) 134-152 [Number of citations: 22].
11. M.Pióro, J.Rak, K.Szczypiorski: Networks for the e-Society, *Telecommunication Systems Journal* 52(2) (2013) 931-933 [Number of citations: 1].
12. M.Ruiz, M.Pióro, M.Żotkiewicz, M.Klinkowski, L.Velasco: Column Generation Algorithm for RSA Problems in Flexgrid Optical Networks, *Photonic Network Communications* 26 (2013) 53-64 [Number of citations: 10].
13. Y.Li, M.Pióro, D.Yuan, J.Su: Optimizing Compatible Sets in Wireless Networks through Integer Programming, *Euro Journal on Computational Optimization* (published online 2013), DOI 10.1007/s13675-013-0015-y [Number of citations: 0].
14. F.Solano, M.Pióro: WDM Network Re-optimization Avoiding Costly Traffic Disruptions, *Telecommunication Systems Journal* 52 (2013) 907–918 [Number of citations: 0].
15. D.Nace, M.Pióro, A.Tomaszewski, M.Żotkiewicz: Complexity of a Classical Flow Restoration Problem, *Networks: an International Journal* 62(2) (2013) 149-160 [Number of citations: 2].
16. M.Żotkiewicz, M.Pióro: Exact Approach to Reliability of Wireless Mesh Networks with Directional Antennas, *Telecommunications Systems Journal* (published online 2013) DOI: 10.1007/s11235-013-9829-4 [Number of citations: 1].
17. D.Santos, A.Sousa, F.Alvelos, M.Pióro: Optimizing Network Load Balancing: an Hybridization Approach of Metaheuristics with Column Generation, *Telecommunication Systems Journal* 52(2) (2013) 959-968 [Number of citations: 2].

18. *D.Hock, M.Hartmann, M.Menth, M.Pióro, A.Tomaszewski, C.Żukowski: Comparison of IP-Based and Explicit Paths for One-to-One Fast Reroute in MPLS Networks, *Telecommunication Systems Journal* 52(2) (2013) 947-958 [Number of citations: 6].
19. F.Matera, M.Mayer, M.Listanti, M.Pióro, J.Rak: Networks 2012 Conference in Rome, Italy, *IEEE Communications Magazine*, 51(11) (2012) [Number of citations: 0].
20. S.Orlowski, M.Pióro: Complexity of Column Generation in Network Design with Path-based Survivability Mechanisms, *Networks: an International Journal*, 59(1) (2012) 132–147 [Number of citations: 37].
21. D.Santos, A.Sousa, F.Alvelos, M.Dzida, M.Pióro: Optimization of Link Load Balancing in Multiple Spanning Tree Routing Networks, *Telecommunication Systems Journal* 48(1-2) (2011) 109-124 [Number of citations: 15].
22. U.Körner, A.Hamidian, M.Pióro, C.Nyberg: A Distributed MAC-scheme to Achieve QoS in Ad-hoc Networks, *Annals of Telecommunications*, 66 (2011) 491-500 [Number of citations: 2].
23. M.Klinkowski, P.Pedroso, D.Careglio, M.Pióro, J.Solé-Pareta: Joint Routing and Wavelength Allocation subject to Absolute QoS Constraints in OBS Networks, *OSA/IEEE Journal of Lightwave Technology* 29(22) (2011) 3433-3444 [Number of citations: 5].
24. P.Pavon, M.Pióro: On Total Traffic Domination in Non-complete Graphs, *Operations Research Letters* 39(1) (2011) 40-43 [Number of citations: 3].
25. C.Żukowski, A.Tomaszewski, M.Pióro, D.Hock, M.Hartmann, M.Menth: Compact Node-Link Formulations for the Optimal Single-Path MPLS Fact Reroute Layout, *Advances in Electronics and Telecommunications* 2(1) (2011) 55-60 [Number of citations: 0].
26. W.Ben-Ameur, P.Pavon, M.Pióro: On traffic domination in communication networks, *Lecture Notes in Computer Science* 6821 (2011) 191-202 [Number of citations: 2].
27. M.Pióro, J.Rak, K.Szczypiorski: Networks 2010 Conference in Warsaw, Poland, *IEEE Communications Magazine*, 49(5) (2011) [Number of citations: 0].
28. F.Solano, M.Pióro: Lightpath Reconfiguration in WDM Networks, *IEEE Journal of Optical Communications and Networking* 2(12) (2010) 1010–1021 [Number of citations: 18].
29. M.Zotkiewicz, W.Ben-Ameur, M.Pióro: Finding Failure-disjoint Paths for Path Diversity Protection in Communication Networks, *IEEE Communication Letters* 14(8) (2010) 776-778 [Number of citations: 15].
30. M.Zotkiewicz, W.Ben-Ameur, M.Pióro: Failure Disjoint Paths, *Electronic Notes in Discrete Mathematics* 36 (2010) 1105-1112 [Number of citations: 1].
31. *S.Orlowski, M.Pióro, A.Tomaszewski, R.Wessäly: SNDlib 1.0 - Survivable Network Design Library, *Networks: an International Journal* 55(3) (2010) 276-285 [Number of citations: 255].
32. A.Tomaszewski, M.Pióro, M.Zotkiewicz: On the Complexity of Resilient Network Design, *Networks: an International Journal* 55(2) (2010) 108-118 [Number of citations: 17].
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4. Books and book chapters

1. M.Pióro: Network Optimization Techniques, chapter in the book *Mathematical Foundations for Signal Processing, Communications, and Networking* (E.Serpedin, T.Chen, D.Rajan, eds.), ISBN 978-1-4398-5513-3, pp.627-684, CRC Press, Boca Raton, USA, 2012 [Number of citations: 7].
2. A.Bley, B.Fortz, E.Gourdin, K.Holmberg, O.Klopfenstein, M.Pióro, A.Tomaszewski, H.Ümit: Optimization of OSPF Routing in IP Networks, chapter in the book *Graphs and Algorithms in Communication Networks–Studies in Broadband, Optical, Wireless, and Ad Hoc Networks* (A.Koster, X.Muñoz, eds.), ISBN 978-3-642-02249-4, pp.199-240, Springer-Verlag Berlin Heidelberg, 2010 [Number of citations: 14].
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5. A.Feldman, P.J.Kuehn, M.Pióro, A.Wolisz (eds.): *Proceedings of the 5th Polish-German Tele-traffic Symposium (PGTS)*, ISBN 978-8325-2047-2, Logos Verlag Berlin GMBH, 2008 [Number of citations: 0].
6. N.Akar, M.Pióro, C.Skanis (eds.): *Proceedings of the 8th IEEE international workshop IPOM 2008*, LNCS 5275 (2008) ISBN 978-3-540-87356-3 [Number of citations: 0].
7. M.Dzida, M. Zagozdzon, M.Pióro, T.Śliwiński, W.Ogryczak: A Column Generation Technique in the Design of Resilient Networks, chapter in the book *Control and Automation: Current Problems and Their Solutions*, ISBN 978-83-60434-42-0, pp.285-294, Academic Publishing Company EXIT, Poland, 2008 [Number of citations: 2].

5. Patents

1. G.Fodor, L.G.Malicskó, M.Pióro: *Method and apparatus for optimizing elastic flows in a multi-path network for a traffic demand*, (Ericsson AB), US Patent 7,317,684, January 8, 2008 [Number of citations: 2].

List of 5 publications with the highest citation:

1. M.Pióro, D.Medhi: *Routing, Flow, and Capacity Design in Communications and Computer Networks*, Morgan-Kaufmann Publishers (Elsevier), USA, 775 pages, ISBN 0-12-557189-5, 2004 [Number of citations: 967].
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3. M.Pióro, A.Szentesi, J.Harmatos, A.Jüttner, P.Gajowniczek, S.Kozdrowski: On OSPF Related Network Optimization Problems, *Performance Evaluation* 49 (2002) 201-213 [Number of citations: 117].
4. D.Nace, M.Pióro: Max-Min Fairness and Its Applications to Routing and Load-Balancing in Communication Networks–a Tutorial, *IEEE Communications Surveys and Tutorials* 10(4) (2008) 5-17 [Number of citations: 70].
5. W.Ogryczak, M.Pióro, A.Tomaszewski: Telecommunications Network Design and Max-Min Optimization Problem, *Journal of Telecommunications and Information Technology*, 4 (2005) 43-53 [Number of citations: 59].

Total number of citations of my publications: 2491
Total number of my publications: 265
Total number of my publications with 4 or more citations: 78

CV

Name: Michal Pioro	**Doctorial degree:** 1979-02-20
Birthdate: 19510409	**Academic title:** Professor
Gender: Male	**Employer:** No current employer

Research education

Dissertation title (swe)
Combinatorial foundations of the design of optimal gradings

Dissertation title (en)
Combinatorial foundations of the design of optimal gradings

Organisation	Unit	Supervisor
Warsaw University of Technology, Poland Not Sweden - Higher Education institutes	Faculty of Electronics and Information Technology	Marian Dabrowski

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
10201. Datavetenskap (datalogi)		1979-02-20

Publications

Name: Michal Pioro	**Doctorial degree:** 1979-02-20
Birthdate: 19510409	**Academic title:** Professor
Gender: Male	**Employer:** No current employer

Pioro, Michal has not added any publications to the application.

Register

Terms and conditions

The application must be signed by the applicant as well as the authorised representative of the administrating organisation. The representative is normally the department head of the institution where the research is to be conducted, but may in some instances be e.g. the vice-chancellor. This is specified in the call for proposals.

The signature*from the applicant*confirms that:

- the information in the application is correct and according to the instructions form the Swedish Research Council
- any additional professional activities or commercial ties have been reported to the administrating organisation, and that no conflicts have arisen that would conflict with good research practice
- that the necessary permits and approvals are in place at the start of the project e.g. regarding ethical review.

The signature *from the administrating organisation* confirms that:

- the research, employment and equipment indicated will be accommodated in the institution during the time, and to the extent, described in the application
- the institution approves the cost-estimate in the application
- the research is conducted according to Swedish legislation.

The above-mentioned points must have been discussed between the parties before the representative of the administrating organisation approves and signs the application.

Project out lines are not signed by the administrating organisation. The administrating organisation only sign the application if the project outline is accepted for step two.

Applications with an organisation as applicant is automatically signed when the application is registered.