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# PARSIMONIOUS ESTIMATES OF SOME QUALITY OF SERVICE MEASURES IN TELECOMMUNICATION NETWORKS

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Summary of the Ph.D. Dissertation

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# 1 Introduction

In the era of info-communications, one of the major driving forces of evolution is the construction of high bandwidth connectivity between any two points of the world in any way possible. Wired or wireless, fix or mobile, uni- multi- or broadcast are all typical issues on the way towards creating the global information society. Surprisingly enough, the more the bandwidth of transmission networks increase the more is the need for additional bandwidth. Killer applications, that are responsible for the overloading of a network, appear in very short periods of time. Although, currently in network backbones the technology – most likely only temporarily – took the lead, on the field of access networks – wired or wireless –, however, requirements are far beyond availability.

One way to ease the grasp of the capacity insufficiency is to increase the utilization of existing communication networks. A major branch of such researches investigate the effects of statistical multiplexing, that is the condition of many loosely dependent transmission flows with varying rate are multiplexed on a common link. Such approach can be successful when the fluctuation of individual flows is high, i.e. the ratio of the mean and peak data rate is small. On an infinite time scale the utilization of such a link is equal to the sum of the individual mean rates of the flows which using it, divided by the capacity of the link. Moving away from dedicated channels, however, has a significant side-effect which is the main scope of research in this area, that is the traffic and network management functions become considerably harder to realize, as well as the engineering part. On this matter, constructing quality of service (QoS) policies also turn out to be a highly nontrivial task.

The worldwide Internet typically uses the best-effort policy, that provides high utilization in the network, making it at same time, however, unreliable for real-time or quasi real-time (typically multimedia) applications. Such a policy is also an obstacle to create refined pricing mechanisms by network operators or service/application providers.

The first step towards turning the Internet into a QoS aware network is to design appropriate QoS policies. Quality parameters should be defined that are to be guarantied from the network part, and acceptable traffic flow descriptors that are to be required from the network user along with the appropriate treatment policies used when the negotiated conditions are not fulfilled (e.g. the way to handle excess traffic). The invented QoS parameters and traffic description techniques should not only be capable of determining traffic conditions at certain time intervals, but also have to capable of using for other management tasks most importantly for pricing and accounting or in a larger time scale for network planning.

A further step in QoS network design is to establish traffic management algorithms and appropriate protocols. One of the most important of them are resource reservation algorithms, which are used to build QoS guaranteed point-to-point transmission paths between communicating endpoints. Evidently to make the algorithms work appropriate protocols should be designed. In construction of the new network architecture, it is of utmost importance to make sophisticated plans for the conversion from the best effort policy to the QoS aware one.

My dissertation focuses on the development of resource description techniques that can be used to meter the quality of data transmission services together with a good assessment of the amount of resources that the fulfillment of the service requires. One of the most important features of the developed techniques is that they require very few information (i.e. parsimonious) about the state of the network making it easy to implement in real systems. Naturally, using only restricted amount of information also limits the description capabilities of the resulting algorithms. Extensive real measurements and simulations prove, however, that the presented characterization techniques can be good compromise between practicability and exactness.

# 2 Research Objectives

The objective of the dissertation is threefold. In the first part new parsimonious moment-generating function estimation techniques are introduced. Such investigations turned out to be helpful in the development of QoS descriptors in the case of many loosely dependent/independent traffic sources. As a part of the first thesis group conditions are also shown when the presented formulae give optimal results (i.e. no better one can be given). The results in this part are quite general and have much deeper consequences than it is exploited in later parts of the dissertation.

The second part of the dissertation deals with conservative upper-bounds – based on the results of the first thesis group – for saturation probability ($P_{\text{sat}}$) and workload loss ratio (WLR). These formulae used as service level descriptors have significant role in the provision of quality in future QoS networks specifically in bufferless traffic management. A special feature of the algorithms shown is that the exploited amount of information for the computation is rather restricted – they are also called parsimonious –, only first order statistics of the state of the network are used. The motivation behind the developed suboptimal formulae in this section is the need for much faster (or real time computation) of the otherwise quite complicated algorithms.

The purpose of the third thesis group is to shed some light on the relation of the $P_{\text{sat}}$ or WLR and the corresponding capacity estimation techniques. More efficient computation – again – is among the reasons in the first place to develop formulae that give equivalent capacity type results explicitly instead of saturation/packet-loss probability. Typical traffic management algorithms are aware of the link-capacity values in advance and also have the information about the required degree of quality to be guarantied on the managed links (e.g. packet loss probability). When a newcomer flow provides its peak transmission rate, as a first guess it can be summed up with the computed equivalent capacity value and the – e.g. admission – rule is that the sum should not exceed the total capacity of the link. In such a case the equivalent capacity can be computed off-line, and in the critical moment only a summation need to be carried out. Although in some cases appropriate closed form formulae for equivalent capacity cannot be derived without causing unreasonable inaccuracy in the computation, fast numeric algorithms can be proposed that are applicable also in real-time environment. For such purpose suitable fixed-point algorithms are presented, the performance of which are carefully investigated.

Another important reason that makes the results of the third thesis group relevant is that connected research works in this field prefer to investigate the capacity explicit type of formulae. The results of the third thesis group makes the analytical comparison of previous and new contributions easier.

# 3 Methodology

In the modeling framework of the research, communication sources were characterized by their data-rate time-function. This function were considered as a stationary stochastic process, resulting in representing one flow merely by one random variable as the instantaneous data-rate distribution. The random variables are mostly assumed to be independent. In research work, under the bufferless fluid flow multiplexing concept, traffic is considered arbitrarily divisible. Resulting transmission quality measures under this concept are easily adaptable to that of packet-based networks. The investigation were related to one-link abstraction, in which parts or the whole network between a source and destination are modeled by one logical link.

The formulae in the dissertation were obtained mostly through analytical methods. Since the derivation of some of the formulae contains simplifying assumptions and approximations, the effect of which analytically are hardly tractable, extensive numerical and simulative investigations have been carried out to validate the exactness of such results. The numerical analysis are made by using the numeric and symbolic computational engine of the Mathematica software, while the simulations are done with the aid of the NS2 (Network Simulator) discrete event simulator.

# 4 New Results

## 4.1 Parsimonious Models for Moment-generating Functions of Sums of Non-negative Valued Random Variables

Parsimonious modeling is an essential tool in describing and managing service classes in modern QoS networks. The construction of such models require only very restricted amount of information, yet provide good approximation of real operations. In the first thesis group, under the concept of the bufferless traffic management, the basic objects of research are simple non-negative valued random variables representing transmission rates in the network. Parsimonious estimation (ie. estimation that requires few *a priori* parameters) techniques aiming to approximate different statistical properties of random events, typically rely on the knowledge of the mean and the peak (maximum) values of these random variables. In current research further restrictions come from the fact that real applications in communication networks are not even aware of the individual mean rates of groups of monitored traffic flows, at most only their aggregate mean can be measured. A concentrated investigation on the conservative estimation of the moment generating function of a sum of the random variables is proved to be a useful idea before establishing further results for resource assessment in bufferless traffic management.

In the first thesis group conservative approximations and important properties of moment-generating function (MGF) estimations of sums of bounded random variables are presented. The variables are assumed to be independent, however, need not to be identical. In related publications beginning with Hoeffding's celebrated paper [13] concerning conservative bounds for the sum of random variables, the majority of the results assumes the knowledge of the mean and the variance. Some of the bounds are proved to be optimal, generally the ones concerning independent and identically distributed variables. Many of the results are improved by Talagrand [24], where the results are yielded by combining the Hoeffding formulae with large deviation results [27]. The so called "missing factor", in his work, refers to a parameter depending also on the variation of the random variables. Later on remaining on the same track, quite a few new results are achieved (see e.g. [19], [12]), mostly by mathematicians examining tail distributions under different conditions. Researchers of communication networks started explicitly studying the field in the 1990's with especially the popularization and standardization of the ATM technology. In many of these research works [4] [9] parsimonious characterization of traffic sources deliberately eliminates the knowledge of the variance parameter, however, most of the results refers to sources with identical peak rates, deriving estimations for the inhomogeneous case only indirectly, yielding quite poor performance. Turanyi et al, in their research work

[25] provide a family of admission control algorithms based on the the equivalent capacity concept that assumes traffic sources with different peak rates directly.

The MGF bounds presented in the following section applies to the (finite) sum of heterogenous random variables. The variables are assumed to be independent, positive valued and bounded. The most important characteristic of the derived conservative estimations is that the exploited information are only the aggregate mean value, the individual maximum value and the number of the random variables. The contributions presented in the thesis group are published in several conference and journal papers, most importantly [J6] and [C17].

Let $X_1, X_2, \ldots, X_n$ be $n$ pieces of independent random variables, where $0 \leq X_i \leq p_i$, and denote $X \doteq \sum_{i=1}^{n} X_i$, $M \doteq E[X]$ (that is $p_i$ are the peak values of the variables and $M$ is the aggregate mean). Furthermore let $G_X(s) = E[e^{sX}]$ be the MGF of random variable $X$, $s > 0$.

**Theses 1.** ***[J6] [C17]****I have developed two upper estimation techniques for the moment generating function of a (finite) sum of general non-negative valued bounded independent random variables, and investigated their most important properties giving necessary and sufficient conditions for their optimality as well. I have pointed out their usefulness in developing resource estimation techniques for bufferless traffic management.*

### 4.1.1 Upper approximation techniques of MGF for the sum of random variables

**Thesis 1.1.** ***[J6] [C17]****I have established the following inequalities for bounding the generating function of sums of non-negative and independent random variables:*

$$G_{X(s)} \leq G_{X,ih}(s) = \prod_{i=1}^{n} \frac{e^{sp_i} - 1}{p_i} \left( M + \sum_{k=1}^{n} \frac{p_k}{e^{sp_k} - 1} \right)^{n} \tag{1}$$

*and*

$$G_{X(s)} \leq G_{X,so}(s) = \left( 1 - \frac{M}{n_y p} + \frac{M}{n_y p} e^{sp} \right)^{n_y}, \tag{2}$$

*where* $p = max_i\{p_i\}$ *and* $n_y = \lceil \frac{\sum_{i=1}^{n} p_i}{p} \rceil$.

The significance of inequalities (1) and (2) lies in the fact that the used information about the random variables are only their individual maximum values and the aggregate mean value. The applicability of different maximum values in the formulae also proves to be a useful feature. Concerning optimality, Thesis 1.3 gives the corresponding results. Results can also be applied for the more general case where $a_i \leq X_i \leq b_i$ and $p_i = b_i - a_i$.

### 4.1.2 Important properties of MGF bounds

Moment generating functions of random variables have some properties that prove to be essential to be inherited to their approximations as well, without which the estimation – in most practical cases – loses its rationality. Under current investigation these properties come from the behaviour of the MGF around zero, namely that:

$$G_X(s)|_{s=0} = 1 \tag{3}$$

and

$$\frac{d}{ds}G_X(s)|_{s=0} = M. \tag{4}$$

**Thesis 1.2.** ***[J6] [C17]*** *I have proven the following important properties of MGF approximations (1) and (2):*

$$\lim_{s\to 0} G_{X,ih}(s)|_{s=0} = 1 \tag{5}$$

$$\lim_{s\to 0} G_{X,so}(s)|_{s=0} = 1 \tag{6}$$

$$\lim_{s\to 0} \frac{d}{ds}G_{X,ih}(s)|_{s=0} = M \tag{7}$$

$$\lim_{s\to 0} \frac{d}{ds}G_{X,so}(s)|_{s=0} = M \tag{8}$$

*I also proved that for formula (2):*

$$G_{X,so(s)} = E[e^{sY^{\mathrm{ON/OFF}}}], \tag{9}$$

*where* $Y^{\mathrm{ON/OFF}} = \sum_{i=1}^{n_y} Y_{i,\mathrm{ON/OFF}}$*,* $Y_{i,\mathrm{ON/OFF}}$ *are homogenous random variables defined as* $P(Y_{i,\mathrm{ON/OFF}} = 0) = 1 - \frac{M}{n_y p}$ *and* $P(Y_{i,\mathrm{ON/OFF}} = p) = \frac{M}{n_y p}$ *and so* $E[Y_{i,\mathrm{ON/OFF}}] = \frac{M}{n_y}$*.*

Formula (9) also gives the basis for the investigations carried out in connection with Thesis 1.3 about the optimality of formula (2).

Second order behaviour of the estimations are not considered, as the given formulae are only based on first order moments of the random variables under investigation.

### 4.1.3 Analytical investigation of MGF bounds

Results in recent publications building around an approximation of the distribution of sums of random variables often supported by showing that comparing them to some other well known formulae they perform better in some special cases (e.g. to some representative parameter sets of a simulation work). General optimality of them even under some restricted conditions, however, can rarely be proven. Contrary to this practice both to $G_{X,\mathrm{ih}}(s)$ and $G_{X,so}(s)$ can be given such criterion .

**Thesis 1.3.** ***[J6] [C17]*** *$G_{X,ih}(s)$, the MGF approximation of a sum of positive real valued bounded random variables is optimal on a set $S$ of $s$ if the following conditions are met:*

1. *All the information known are $n$ the number of the random variables, the aggregate mean $M$ and the individual maximum values $p_1, p_2, \ldots, p_n$ of the random variables.*

2. *The following inequality holds*

$$0 \leq \frac{M - \sum_{k=1}^{n} \left( \frac{p_i}{e^{sp_i}-1} - \frac{p_k}{e^{sp_k}-1} \right)}{n} \leq p_i, \ \forall i, \ s \in S. \tag{10}$$

*$G_{X,so}(s)$ is optimal provided that—likewise at the case of $G_{X,ih}(s)$—only the number of random variables $n$, the aggregate mean $M$ and the individual maximum values of the random variables are known and all the maximum values are equal.*

*I also shown that even if condition (10) is not fulfilled or the maximum values are not equal $G_{X,ih}(s)$ and $G_{X,so}(s)$ can give better results than $G_{X,hoe}(s)$ for several distribution and for many $s$, where*

$$G_{X,hoe}(s) = e^{sM} e^{\frac{s^2 \sum_{i=1}^{n} {p_i}^2}{8}}. \tag{11}$$

In short, condition (10) tells us that the maximum values $p_i$ should not diverge substantially, only between bounds set by the average of the individual mean values (e.g. the inequality becomes apparent when the maximum values are equal). On the other hand the result is also the function of $s$ the often called *space* parameter. As it will be seen in the next thesis group, for the purpose of traffic characterisation, the resulted formulae (that will use the MGF approximations) will be the subject of optimization over parameter $s$, which sets the typical operation interval of it. In practice, set $S$ established by condition (10), according to extensive numerical investigation, turns out to contain the operation point (in several extreme cases, other simplification steps can also be carried out to achieve acceptable results).

Note that $G_{X,\mathrm{hoe}}(s)$ appears as a middle step approximation in the derivation of the famous Hoeffding formula [13], that gives the bases of many recent contributions that concerns statistical properties of sums of independent random variables.

## 4.2 Conservative Upper-bounds for Saturation Probability and Workload-loss Ratio

In telecommunications applications under the bufferless fluid flow multiplexing (bffm) scheme (which applied when buffering is minimal during the transfer of a data flow, e.g. due to delay constraints), aggregate (instantaneous) transmission rate of the traffic on a link can be computed as the sum of the instantaneous transmission rates of the individual sources. The individual rates, in stationary systems, can be modeled by non-negative valued (in current research independent) random variables. Many practical research works in telecommunications put extremely strict assumptions on the available information on the network states or traffic flows traversing the network. Many works [23], [1] even discuss the effect of non-stationarity of the ever growing traffic. When studying traffic characterization, stochastic modeling assumptions rarely consider more than the mean and the variance of the applied distributions. The several contributions only assumes mean rates of traffic flows to be known. Several papers e.g. on measurement-based traffic engineering [21] even goes further and assumes only aggregate mean arrival rates. Under these circumstances, the application of Hoeffding's results arise naturally. F.P. Kelly in many of his works [16] [17] use these results for charging issues in communication networks. Among many others S. Floyd, Jamin et al, Brichet et al., Gibbens et al. apply the Hoeffding formulae to establish Measurement-based Admission Control algorithms [8] [15] [2] [4] [10] mainly for bufferless multiplexing and using simple traffic characterization. In these works the admission control algorithm relies on a quality of service characterization parameter referred to as the saturation probability, although some considers loss performance as well [18].

In the following thesis group I will present conservative bounds and approximations on the saturation probability ($P_{\text{sat}}$) and workload loss ratio ($WLR$) under the *bffm* framework. The basis of the derived results is the Chernoff bounding method [5]. The results presented in the thesis group are published in journal and also conference papers, most importantly in [J5], [C9] and [C10].

In the derivation of the results the following two important formulae have been used extensively:

$$P_{\text{sat}} \le e^{\inf_{s>0} \Lambda_X(s) - sC} \tag{12}$$

and

$$WLR \le \frac{1}{s^* M} e^{\inf_{s>0} \Lambda_X(s^*) - s^* C},$$

where $s^* = \text{arginf}_s \, \Lambda_X(s) - sC$.

In the first thesis of this group, I have used the MGF estimation formulae of Thesis group 1 directly, and so the performance of the results inherits their conditionally optimal behaviour. In Thesis 2.2 and 2.3, on the other hand, due to the simplifying steps carried out in the derivations, only numerical or simulative validation is feasible. The purpose of the comparative evaluation of the results of Thesis 2.2 and 2.3 is to investigate their relation to the widely and almost exclusively used original Hoeffding formulae.

**Theses 2.** ***[J5] [C9] [C10]*** *I have derived novel upper-bounds and approximation techniques for two important traffic management QoS parameters, the saturation probability, and the workload loss ratio. To reduce computational complexity I have also derived practical closed form solutions for the most important formulae. [J5] [C9] [C10]*

### 4.2.1 Conservative Upper-bounds for $P_{\mathbf{sat}}$ and WLR

**Thesis 2.1.** ***[J5] [C9]*** *I have derived novel upper-bounds for the saturation probability ($P_{sat}$):*

$$P(X > C) \leq e^{-s^*C} \left( \frac{M + \sum_{j=1}^{n} \frac{p_j}{e^{s^* p_j} - 1}}{n} \right)^n \prod_{k=1}^{n} \frac{e^{s^* p_k} - 1}{p_k}, \tag{13}$$

*where $s^*$ is the solution of the following equation:*

$$\sum_{k=1}^{n} \frac{e^{sp_k} p_k}{e^{sp_k} - 1} - \frac{n \sum_{j=1}^{n} \frac{e^{sp_j} p_j^2}{(e^{sp_j}-1)^2}}{M + \sum_{j=1}^{n} \frac{p_j}{e^{sp_j}-1}} - C = 0, \tag{14}$$

*and*

$$P(X > C) \leq \left( \frac{M - n_Y p}{C - n_Y p} \right)^{n_Y - \frac{C}{p}} \left( \frac{M}{C} \right)^{\frac{C}{p}}, \tag{15}$$

*where $p = \max(p_i, i = 1, \ldots, n)$, $n_Y = \lceil \sum_{i=1}^{n} p_i / p \rceil$.*
*I have also provided novel upper bounds for the workload loss ratio (WLR):*

$$WLR \leq \frac{1}{s^* M} e^{\widehat{\Lambda}_{X,ih}(s^*) - s^* C}, \tag{16}$$

*where $s^* = arginf_s\ \Lambda_{X,ih}(s) - sC$ and $\widehat{\Lambda}_{X,ih}(s) = \log G_{X,ih}(s)$,*

$$WLR \leq \frac{1}{s^* M} e^{\widehat{\Lambda}_{X,so}(s^*) - s^* C}, \tag{17}$$

*where $s^* = arginf_s\ \Lambda_{X,so}(s) - sC$ and $\widehat{\Lambda}_{X,so}(s) = \log G_{X,so}(s)$,*

$$WLR \leq \frac{1}{s^*_{hoe} M} e^{\widehat{\Lambda}_{X,hoe}(s^*_{hoe}) - s^*_{hoe} C}, \tag{18}$$

*where* $s^* = arginf_s\ \Lambda_{X,hoe}(s) - sC$ *and* $\widehat{\Lambda}_{X,hoe}(s) = \log G_{X,hoe}(s)$.

*I have shown that the saturation probability formulae presented above inherit the optimal characteristics of the MGF approximations used in their derivation. This means that the (Chernoff-type) approximating formulae are the best available ones under the conditions of the corresponding MGF approximations.*

As it is easy to see, the $P_{\text{sat}}$ and corresponding WLR bounds (13) and (16) define the optimal $s$ by implicit equations, which involve $s$ in an essentially non-algebraic way. This deficiency is rather significant as according to analytical and numerical investigations (13) proved to be a considerable improvement on previous results (that assumes identical peak rates), when heterogeneity of traffic sources is high. In Thesis 2.2 I propose modified (thus suboptimal, yet still quite accurate) formulae for the above cases, that offer means for closed form computation.

### 4.2.2 Computationally feasible $P_{\text{sat}}$ and WLR bounds

Important results (13) and (16) in Thesis 2.1 are non-closed formulae, the evaluation of which should be performed by the adoption of numerical optimization techniques. Real applications, on the other hand, for the most part require efficient computational methods instead of time consuming numerical evaluations. The following theorem aims to answer to this problem:

**Thesis 2.2.** ***[J5] [C9]*** *I have derived closed form upper bounds for the saturation probability:*

$$P(X > C) \leq \left(\frac{1}{n}\left(M + \sum_{j=1}^{n} \frac{p_j}{e^{\frac{C-M}{K}p_j} - 1}\right)\right)^n e^{-\frac{(C-M)C}{K}} \prod_{k=1}^{n} \frac{e^{\frac{C-M}{K}p_k} - 1}{p_k}, \tag{19}$$

*where*

$$K = \frac{1}{4}\sum_{k=1}^{n} p_k^2 - \frac{1}{n}\left(M - \frac{1}{2}\sum_{k=1}^{n} p_k\right)^2$$

*and*

$$P(X > C) \leq e^{-C\sqrt{\frac{n}{P_2}}\log\frac{C(P-M)}{M(P-C)}} \left(\frac{M + \sum_{j=1}^{n}\frac{1}{L_j}}{n}\right)^n \prod_{k=1}^{n} L_k, \tag{20}$$

*where*

$$L_j = \frac{1}{p_k}\left(\left(\frac{C(M-P)}{M(C-P)}\right)^{p_k\sqrt{\frac{n}{P_2}}} - 1\right),\quad P = \sum_{k=1}^{n} p_k,\ \text{ and } P_2 = \sum_{k=1}^{n} {p_k}^2$$

*and for workload loss ratio (WLR):*

$$WLR \leq \frac{1}{\widetilde{s}^* M} e^{\widehat{\Lambda}_{X,ih}(\widetilde{s}^*) - \widetilde{s}^* C}, \tag{21}$$

*where* $\widetilde{s}^*$ *is one of the following two possibilities:*

$$\widetilde{s}_1^* = \frac{C - M}{\frac{1}{4}\sum_{k=1}^n p_k^2 - \frac{1}{n}\left(M - \frac{1}{2}\sum_{k=1}^n p_k\right)^2}$$

$$\widetilde{s}_2^* = \sqrt{\frac{n}{\sum_{k=1}^n p_k^2}} \log \frac{C\left(\sum_{k=1}^n p_k - M\right)}{M\left(\sum_{k=1}^n p_k - C\right)}$$

*I have shown that in the case of heavy mix of stream traffic consisting of (MPEG2 and MPEG4 compressed) video and voice traffic sources, applying the above formulae, the achievable gain can be up to 40% in the resource estimation process with respect to previous results (applying* $G_{X,hoe}(s)$ *as the essential approximation step).*

Note that both $P_{\text{sat}}$ bounds in the above thesis are derived using the original approximation (13). Also note that bound (20) has the important feature of inheriting the optimality of (13), when traffic sources have identical peak rates. This later property is very useful, as even in a quite homogenous traffic situation, the approximation keeps its dominance above previous results, that aims to estimate resources for the homogenous traffic mixes.

### 4.2.3 Refined Approximations for Saturation Probability and Workload-loss Ratio

In guaranteeing a predefined quality of service, the application of appropriate upper-bounds are in most cases unavoidable. This kind of approach is justified when the measures are used to provide firm guarantees for a certain value. This is the case for example when a virtual circuit-switched connection is to be established. In several cases, however, (e.g. quasi-realtime applications) general approximations are also acceptable. In such situations, the general approximations are much more favorable as the estimation error is significantly less, yielding improved resource utilization. In the following thesis I have derived such approximations using the Bahadur-Rao improvement.

**Thesis 2.3.** ***[C10]*** *I have derived an efficient approximation for the saturation probability:*

$$P_{sat} \approx e^{-I-\frac{1}{2}\log 4\pi I}, \tag{22}$$

*where*

$$I = -\inf_s \Lambda_X(s) - sC \tag{23}$$

*and for the workload loss ratio*

$$WLR \approx e^{-I-\frac{1}{2}\log 4\pi I - \log s^* M}, \tag{24}$$

*where*

$$s^* = arginf_s \Lambda_X(s) - sC. \tag{25}$$

As numerical investigations and also simulations show, many times even these approximations are turn out to be conservative upper bounds, this property in general, however, is not guaranteed.

## 4.3 Connection and transformation between saturation probability/workload loss ratio and equivalent capacity

A common feature of the contributions applying simple characterization in traffic engineering is the adoption of the equivalent capacity concept, referring to the amount of bandwidth necessary to achieve a target QoS requirement. In this sense, there exists equivalent capacity belonging to e.g. saturation probability ($C_{\text{equ,sat}}$) or workload-loss ratio ($C_{\text{equ,wlr}}$). Developing $C_{\text{equ,sat}}$ and $C_{\text{equ,wlr}}$ formulae under different assumptions is a popular topic in recent publications aiming to design QoS traffic management techniques. Turanyi et al [25] provides a family of such type of admission control algorithms for the saturation probability. In his well-received paper [16] F. P. Kelly gives a thorough analysis of a special form of equivalent capacity coined as the effective bandwidth.

There are many advantages of dealing with equivalent capacity formulae directly. In many telecommunications applications it is vital to bring traffic management decisions in real-time, even at the price of suboptimal resource usage due to the inaccuracy of the formulae used. In such cases, considerable time can be saved by computing equivalent capacity values explicitly, instead of saturation probability/workload loss ratio explicit formulation, even so that in many cases the latter ones can be computed efficiently in closed forms, however the former method almost always gives approximations needed to be numerically optimized. The application of such process results in considerable inaccuracy, on the other hand as it is pointed out in [22], it displaces the computational-time to non-critical time intervals. To better understand the concept, consider for a simple example, a measurement based admission control algorithm, where decision on the admittance of a newcomer flow is based on, as to weather or not the sum of the measured equivalent capacity of the already accepted flows and the peak rate of the newcomer flow is exceeds the link capacity. It is easy to see that admittance can be decided in the time of only one *addition* operation and a comparison, if the equivalent capacity of aggregate traffic is already established, while the time consuming operations (e.g. numerical optimization) can be done in "off-line" time periods between two arrivals. On the other hand, if the rule refers explicitly to e.g. the saturation probability, these tasks should be done in real time, when the peak rate of the newcomer flow is already available.

In the following thesis group I have presented efficient equivalent capacity formulae, and investigated their relation to the $P_{\text{sat}}$ and WLR bounds and approximations provided in the previous thesis group. In a few cases of the derived formulae further improvements can be achieved by numerically performed algorithms, of which purpose recursive fixed-point equations are proposed. The results of this these group are published in several research papers, more importantly in [J2],[J5] and [C13].

The analyzed equivalent capacity measures are based on the following two definitions:

$$C_{\text{equ,sat}} \stackrel{\text{def}}{=} \inf\{C : P_{\text{sat}} \leq e^{-\gamma}\} \ , \tag{26}$$

$$C_{\text{equ,wlr}} \stackrel{\text{def}}{=} \inf\{C : WLR \leq e^{-\gamma}\}. \tag{27}$$

**Theses 3.** ***[J2] [J5] [C13]*** *I have shown*

- *important connections between saturation probability and equivalent capacity approximation techniques*
- *several equivalent capacity formulae in different approximation scenarios discussed in Thesis group 2*
- *fixed-point equations for the efficient computation of the equivalent capacity and saturation probability formulae. [J2] [J5] [C13]*

### 4.3.1 Connection between equivalent capacity and saturation probability approximation formulae

Let

$$C^{CH}_{\text{equ,sat}} \stackrel{\text{def}}{=} \inf\{C : \inf_{s>0} \exp(\Lambda_X(s) - sC) \leq e^{-\gamma}\}, \tag{28}$$

$$C^{CH}_{\text{equ,wlr}} \stackrel{\text{def}}{=} \inf\{C : \inf_{s>0} \exp(\Lambda_X(s) - sC - \log sM) \leq e^{-\gamma}\}, \tag{29}$$

where $\Lambda_X(s)$ is the CGF of $X$, be the definitions of computing equivalent capacity for a given fixed saturation probability or WLR (for the notation see Thesis group 2). In accordance with the above notations let $\widehat{C}^{\text{CH}}_{\text{equ,sat}}$ and $\widehat{C}^{\text{CH}}_{\text{equ,wlr}}$ denote conservative bounds of $C^{\text{CH}}_{\text{equ,sat}}$ and $C^{\text{CH}}_{\text{equ,wlr}}$ computed as follows:

$$\widehat{C}^{\text{CH}}_{\text{equ,sat}} \stackrel{\text{def}}{=} \inf\{C : \inf_{s>0} \exp(\widehat{\Lambda}_X(s) - sC) \leq e^{-\gamma}\}, \tag{30}$$

$$\widehat{C}^{\text{CH}}_{\text{equ,wlr}} \stackrel{\text{def}}{=} \inf\{C : \inf_{s>0} \exp(\widehat{\Lambda}_X(s) - sC - \log sM) \leq e^{-\gamma}\}, \tag{31}$$

where $\widehat{\Lambda}_X(s)$ can be any conservative bound on the CGF of $X$.

**Thesis 3.1.** ***[J5] [C13]*** *I have proved the following equivalence statements*

$$\inf_s \Lambda_X(s) - sC < -\gamma_{sat} \Leftrightarrow \inf \frac{\Lambda_X(s) + \gamma_{sat}}{s} < C, \tag{32}$$

$$\inf_s \Lambda_X(s) - sC = -\gamma_{sat} \Leftrightarrow \inf \frac{\Lambda_X(s) + \gamma_{sat}}{s} = C, \tag{33}$$

$$\inf_s \Lambda_X(s) - sC - \log sM < -\gamma_{loss} \Leftrightarrow \inf \frac{\Lambda_X(s) + \gamma_{loss} - \log sM}{s} < C, \tag{34}$$

$$\inf_s \Lambda_X(s) - sC - \log sM = -\gamma_{loss} \Leftrightarrow \inf \frac{\Lambda_X(s) + \gamma_{loss} - \log sM}{s} = C, \tag{35}$$

*where $\Lambda_X(s)$ is any CGF of $X$ or any conservative bound on it, which is monotone in $s$!*

*Corollary:*

$$\widehat{C}^{CH}_{equ,sat} = \inf_s \frac{\tilde{\Lambda}_{X(s)} + \gamma_{sat}}{s} \tag{36}$$

*and*

$$\widehat{C}^{CH}_{equ,wlr} = \inf \frac{\Lambda_X(s) + \gamma_{loss} - \log sM}{s} \tag{37}$$

The immediate consequence of the thesis is that the decision rules e.g. in a CAC mechanism described in the introduction of the current section based upon a target $P_{\mathrm{sat}}$ or WLR constraint or the corresponding target $C_{\mathrm{equ,sat}}$ or $C_{\mathrm{equ,wlr}}$ are equivalent regardless of the underlying different optimization tasks. However, it should be emphasized, that the statements hold for the optimal parameters $s$ only. On the other hand, in practice, often suboptimal solutions are used like the closed forms described in the second thesis of the second thesis group, in which case e.g. the admission control algorithms based on the two approaches could provide quite different results.

It is also important to note, that the results of above thesis do not depend on the bounding technique used at $\Lambda_X(s)$. The only necessary condition we need is the monotone decreasing relation between the equivalent capacity and the saturation probability. Note that after performing certain approximations on the resulting Chernoff-like upper bound [C27], [7] (e.g. for the sake of simplicity) this relation may disappear.

### 4.3.2 Efficient equivalent capacity explicit formulae for targeted saturation probability or workload loss ratio

According to the results of Thesis 3.1, it is possible to compute equivalent capacity explicitly in the following form:

$$\widehat{C}^{\text{CH}}_{\text{equ,sat}} = \inf_{s} \frac{\widehat{\Lambda}_X(s) + \gamma_{\text{sat}}}{s} \tag{38}$$

and

$$\widehat{C}^{\text{CH}}_{\text{equ,wlr}} = \inf \frac{\widehat{\Lambda}_X(s) + \gamma_{\text{loss}} - \log sM}{s}. \tag{39}$$

Applying the above equations I have derived conservative bounds and approximations for the equivalent capacity, described in the following thesis:

**Thesis 3.2.** *[J2] [C13] I derived two upper bounds for the equivalent capacity:*

- *for a targeted saturation probability:*

$$\widehat{C}_{equ,sat} = \inf_{s>0} \frac{\widehat{\Lambda}_X(s) + \gamma_{sat}}{s} . \tag{40}$$

- *for a targeted workload loss ratio:*

$$\widehat{C}_{equ,wlr} = \inf_{s>0} \frac{\widehat{\Lambda}_X(s) + \gamma_{loss} - \log sM}{s} , \tag{41}$$

*where* $\widehat{\Lambda}_X(s)$ *in both cases is either* $\widehat{\Lambda}_{X,ih}(s) = \log G_{X,ih}(s)$ *or* $\widehat{\Lambda}_{X,so}(s) = \log G_{X,so}(s)$,

*and two approximations:*

- *for a targeted saturation probability:*

$$\widetilde{C}_{equ,sat} \approx \inf_{s>0} \left\{ \frac{\widehat{\Lambda}_X(s)}{s} + \frac{\gamma}{s} - \frac{\gamma \log 4\pi\gamma}{s(1+2\gamma)} \right\} \stackrel{\text{def}}{=} \widetilde{C}^{\text{B-R}}_{equ,sat} , \tag{42}$$

- *for a targeted workload loss ratio:*

$$\widetilde{C}_{equ,wlr} \approx \inf_{s>0} \left\{ \frac{\widehat{\Lambda}_X(s) + \gamma - 1 + \log M + \frac{2\gamma}{1+2\gamma} \log \frac{1+2\gamma}{4M\sqrt{\pi}\gamma^{\frac{3}{2}}}}{-\frac{1}{M} + s} \right\} \stackrel{\text{def}}{=} \widetilde{C}^{\text{B-R}}_{equ,wlr} , \tag{43}$$

*where* $\widehat{\Lambda}_X(s)$ *is any kind of suitable upper bound on* $\Lambda_X(s)$, *eg.* $\widehat{\Lambda}_{X,ih}(s)$ *or* $\widehat{\Lambda}_{X,so}(s)$.

It is important to note that the results of the thesis provide formulae that (aside from slight restrictions) are not bound to the applied MGF (or CFG) approximations used above, possibly better ones adopted could be equally applicable.

### 4.3.3 Efficient fixed-point algorithms for fast equivalent capacity calculation

The techniques proposed in the previous theses, provide solutions of calculating the saturation probability, the workload loss ratio and respective equivalent capacity values in both closed form and implicit formulae, using parsimonious traffic characterisation techniques. The results are all based on the Chernoff-bounding method leaving an optimization task in the formulation to be performed. In a few cases, this task can be simplified by solving an explicit equation, in others, it is done through suitable reformulation and approximation, however, in many cases none of these actions can be performed in a reasonable way. In the previous thesis, a number of formulae have been derived for the computation of equivalent capacity values, nevertheless, the attempt to yield upper bounds in closed forms, or even to make appropriate approximations to get one have met several difficulties. In these cases, to reach acceptable results, numerical approximation techniques are inevitable to use, yielding drastically increased processing time, which may be inadmissable in real-time traffic management.

I have chosen the fixed-point type algorithm for several reasons. Most importantly this type of method in general provides very fast convergence, which is, as discussed previously, a fundamental requirement in real-time decision making processes. Also an important fact is that due to the approximating nature of the bounds to be optimized, more than one derivation on the objective function would yield unreasonable loss of exactness, for which reason the fixed-point type optimum search algorithm is also suitable.

**Thesis 3.3.** *I have derived recursive fixed-point equations for the efficient computation of equivalent capacity formulae given in Thesis 3.2:*

$$s_{n+1} = \sqrt{\frac{\gamma s_n^2}{-\Lambda(s_n) + s_n \frac{\partial_s \Lambda(s)}{\partial s} |_{s=s_n}}} \tag{44}$$

$$s_{n+1} = \sqrt{\frac{\gamma}{\frac{\partial_s \alpha(s)}{\partial s} |_{s=s_n}}}, \tag{45}$$

*and for saturation probability ($P_{sat} = e^{-\gamma}$) given in the form of (12):*

$$s_{n+1} = \frac{{s_n}^2 (C + \frac{\partial_s \Lambda(s)}{\partial s} |_{s=s_n}) - 2 s_n \Lambda(s_n)}{2 s_n \frac{\partial_s \Lambda(s)}{\partial s} |_{s=s_n} - 2\Lambda(s)} \tag{46}$$

*and*

$$s_{n+1} = \frac{C - \alpha(s_n) + s \frac{\partial_s \alpha(s)}{\partial s} |_{s=s_n}}{2 \frac{\partial_s \alpha(s)}{\partial s} |_{s=s_n}} \tag{47}$$

*I have shown that the above algorithms in typical traffic situations find the optimum of the formulae presented in Thesis 3.2 in 3–6 steps with a relative error of* $10^{-6}$.

Note that the provided equation contains $\Lambda(s)$ as the CGF of $X$ or $\alpha(s)$ as the effective bandwidth, that can be a directly measurable characteristic of the traffic.

# 5 Applicability of the Results

The moment-generating function estimation techniques proposed in the first group go far beyond telecommunications applications and is of important consequences in statistical engineering. Along with the optimality criteria the presented methods can be effectively used to investigate statistical properties of random events when the available *a priori* information is very few. The proposed two conservative estimation of moment generating functions are the basis of the proposed formulae expressing saturation probability and workload loss ratio based bounds and approximations shown in Thesis group 2 and 3.

The formulae presented in the second thesis group can be directly applied to construct traffic management functions of QoS-aware networks, where the target service quality parameter is either the link-saturation probability or the workload (eg. packet) loss ratio. The derivation of such functions is the main concern of many telecommunications related publications as in [14], [3] and [8]. Investigating the tail distribution of sums of independent random variables, however, have applications in reliability theory and insurance mathematics in risk analysis but in several other fields as well [6]. The proposed computationally efficient simplified formulae in the thesis group have the advantage that they can be applied in real-time systems with tight time constrains.

The purpose of the closed form capacity estimating formulae proposed in Thesis group 3 is twofold. First, in many traffic management functions where the central resource to be handled is the link capacity, such formulae are more comfortable to use and can be computed more efficiently making the algorithms considerably faster. Secondly, the exactness of these formulae are more easily comparable to that of former contributions (see eg. [11], [26], [20], which for the most part belong to this category. For the efficient computation of the formulae that can only be evaluated numerically, efficient fast converging fixed-point algorithms are proposed, the application of which is apparent for traffic management algorithms in real-time environments.

The presented results of the dissertation have been applied in several mostly Hungarian research and applied research projects, most importantly IKTA, NKFP and Jedlik Ányos Programme. As of this date 12 (foreign) references have been discovered to the published papers containing the results of the theses, 5 of them in prominent international journals, and 7 in scientific conferences. Moreover, 2 of the publications won best paper award.

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