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Towards the Sound Understanding of the Nature of Network Traffic and Its Efficient Transport

Collection of Habilitation Theses

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1 Introduction

The accurate **characterization of network traffic** is vital for efficient network engineering, design and management. That is the reason why in order to understand the characteristics of network traffic an enormous amount of work has begun from that day when long and high-precision traffic recordings was possible. This research yielded the building of numerous useful traffic models that can play a significant role in network engineering mechanisms. However, the fast growing and new applications generate different types of traffic that make the ever-changing characteristics of network traffic difficult to capture thus, the models can very soon become obsolete. Related research results often contradict each other (e.g. fractal characteristics and their interpretation), which leads to vivid discussions in the research community.

Transmission Control Protocol (TCP) has played an important role in the success of Internet. However, TCP cannot perform well in recent networks. For example, standard TCP (Reno version) cannot provide acceptable performance in wireless or mobile environments. Over the years the upcoming new challenges have always caused changes in the original protocol resulting in a number of new TCP versions. A major challenge is to cope with high bandwidth networks hence, the research community has proposed several new transport protocols referred to as **high speed transport protocols**. The performance of these TCPs is of high importance in recent research. Moreover, the comparative performance analysis of these proposals is crucial so as to choose the best solution for a given purpose.

The modifications of TCP versions have resulted in rather overtuned and unfriendly transport protocols from an engineering point of view. These protocols have several problems: they are difficult to analyze, it is demanding to set their parameters and implement them correctly. Concerning the limitations of these protocols there is a significant justification to rethink the concept of this transport protocol and to redesign it from scratch omitting the main TCP-related features most interestingly, its congestion control mechanism. Possible future transport protocols working **without congestion control** can have more efficient performance properties than recent TCP versions working with the limitations of congestion control.

2 Research Goals

My research goals were to contribute with new research results to the three research areas mentioned above thus helping the efficient design and development of future networks.

First, I realized there was confusion regarding fractal traffic in the research community so, my aim was to get a deeper understanding of the real scaling nature of network traffic. I pointed out a number of reasons that create confusion and unveiled several fallacies regarding the definition, testing, interpretation, modeling and implications of fractal traffic.

Second, I noticed that in spite of the fact that a number of traffic analysis results have been published most of them have a very limited generality and focus on special and non-realistic environments. I aimed at carrying out a number of traffic analysis studies on different networks all over the world in various environments to get a deeper understanding of the nature of network traffic. I also realized that results from commercial networks are often confidential consequently, the research community has a limited understanding of the most important networks so, my goal was also to get measurements from such networks for the analysis.

Third, I faced the lack of complete understanding of the behavior of new TCP versions especially that of high speed TCPs. My goal was to understand a number of unknown properties of such TCPs. Moreover, I became conscious of the fundamental drawbacks of TCPs due to their inherent congestion control mechanism on which grounds I set the objective of designing and developing a new architecture with a new protocol for future networks.

3 Research Methodology

One of the main targets of my research was to comprehend the nature of actual network traffic. For this reason, geting **real measurements** for the analysis became extremely important. I had the privilege to use several measurement data from different locations of the world recorded in both mobile and fixed commercial networks.

I used **statistical analysis** to evaluate measured data. In addition, **analytical work and simulation study** have been performed when needed for modeling and performance evaluation purposes.

I also considered the implementation of my proposed new transport protocol as a crucial methodological proof of the concept since simulation and tractable but also simplified analytical evaluations often neglect many real-world factors. Since proof of the pudding is in the eating, the protocol was not only evaluated by analytical and simulation studies but was also **tested in different testbeds as an implemented prototype**.

4 New Scientific Results

I summarize my research results categorized in three Thesis Groups. In the first Thesis Group all the results related to the fractal traffic characterization of network traffic are collected.

The second Thesis Group considers results regarding the real nature of network traffic.

The third Thesis Group covers my research results related to the evaluation of TCP versions and also to the development of a new network architecture with a new transport protocol.

4.1 On the Fractal Nature of Network Traffic

A revolution took place in the field of traffic modeling two decades ago. Starting with the research of Leland et al. [1] a lot of traffic measurements and analysis work reported that **fractal characteristics** had been found in network traffic. The research community had been convinced that the traditional Markovian-type models were not adequate any more for accurate traffic modeling since they were unable to capture such fractal properties like **self-similarity** and **long-range dependence (LRD)** found in those traffic analysis results [2].

However, due to the non-rigorous analysis of actual network traffic a great number of myths have been established regarding the fractal nature of network traffic and its impact on traffic engineering. These misunderstandings include the **definition, testing, modeling, interpretation and the origin of fractal nature of network traffic**.

I report claims in this Thesis Group that may help to reveal these myths and to get a better understanding of the fractal nature of network traffic. Furthermore, I also contribute with results to identify and model the real nature of network traffic.

Thesis Group 1 ***The Myths about Fractal Network Traffic***

Traffic modeling is usually built on traffic characteristics based on the assumption of stationarity of the traffic under investigation. However, this assumption is frequently far from reality and this observation requires a thorough analysis of the measured data e.g., the application of stationarity analysis. In the previous two decades a huge number of research papers have been published claiming that network traffic has fractal properties but it has been difficult to find papers that would take stationarity into consideration.

This mistake is especially dangerous when identifying fractal traffic for it is rather difficult to make a conclusion about the traffic nature based on finite data set if we want to distinguish a stationer self-similar traffic from a non-stationer traffic having nothing to do with self-similarity but rather misleading our statistical tests: resulting in the same results.

Moreover, additional nevertheless important factors can even further disturb the reliability of test results like sample size or the statistical properties of the investigated test method. These parameters are often neglected in the research studies accepted by the research community.

Thesis 1.1 ***The forgotten factors of fractal traffic analysis***

I have shown that the widely used and popular self-similar and LRD tests (VT, R/S, Periodogram, Wavelet) can easily result in ***misleading conclusions regarding the fractal nature of measured network traffic and the estimated Hurst parameter****. I have also shown that the major origin of such errors is due to the inherent non-stationarity of actual network traffic. More precisely, I have concluded the following reasons being able to cause misleading results in self-similar and LRD tests: lack of stationarity, limited data size, different sensitivity of test methods and the blind belief in test results. I have presented the relationships among different kinds of fractal properties. [B12, J2],****[J6]****,[J7, C4, C8, C11, C14]*

The fractal revolution had tempted researches to use fractal models with their appealing parsimonious properties. For example, Fractional Brownian Motion (FBM) based models offered that advantage [3]. However, other research results showed that simple monofractal scaling cannot capture the whole scale of network traffic therefore, more sophisticated multifractal models were needed especially, for modeling at low time-scales [3].

As a result, the real nature of network traffic has a rather complex characteristic. In addition, how these characteristics change as packets go via the network became also of high interest.

Thesis 1.2 ***The complexity of scaling characteristics***

I have proven that the aggregated network traffic has ***complex scaling and correlation characteristics and can seldom be described by only monofractal or even by only complex multifractal models****. I have shown that the scaling properties of the aggregated network traffic is influenced by several characteristics of many traffic components at different layers and is also impacted by numerous networking mechanisms. I have presented the scaling properties of different applications and their influence on the scaling properties of the aggregation. I have shown the scaling properties of transport protocols. I have given examples for both monofractal and multifractal models to capture scaling properties with their applications. [B2, B3, B5, B7, B6, B8, B11, B12],****[J1]****,[J8],****[J10]****,[C1, C3, C5, C6, C9, C12, C75].*

The general belief about the nature of fractal properties of network traffic is that it is originated by the superposition of ON/OFF type traffic sources having heavy-tailed distributions, first proved by Taqqu [5]. However, this discovery cannot explain the general presence of fractal properties where there is no aggregation or heavy-tails involved. A more careful look at the issue is needed to explain the appearance of fractal properties in different networking environments.

Thesis 1.3 ***The origin of fractal properties***

I have shown that the origin of fractal properties in network traffic can have three major reasons: being ***created, transferred or imitated****. The* ***creation*** *of fractal properties has been demonstrated for VoIP applications where the underlying reason is the heavy-tailed ON/OFF periods. The* ***transfer*** *of fractal properties has been illustrated for TCP traffic where the underlying reason is that TCP can transfer fractal properties to other TCPs. Finally, the case of* ***imitation*** *has been pointed out for non-stationer traffic where the underlying reason is the misleading results of fractal tests. [J7],****[J11]****,[J3, C1, C4, C8, C13, C14].*

The impacts of fractal properties on performance metrics is also of great importance [3]. Different types of scaling behavior have different effects depending on several (mostly undiscovered) factors. The relevance for fractal properties for practical QoS metrics is also an unsolved research issue.

Thesis 1.4 ***The performance implications of fractal properties***

*I have shown the **queueing performance** of both monofractal and multifractal properties of network traffic based on appropriate fractal models. I have presented practical examples based on measured traffic.* ***[B9]****,[B12, J4, J5, C2, C3, C7, C9].*

4.2 Understanding Traffic Characteristics

In order to properly design, control and manage our networks we must know the properties of traffic they carry. The high-precision measurement tools made it possible for us to have opportunities to carry out extensive measurements on a broad range of time scales over operational networks. Based on these measurements we can build useful models for our engineering purposes.

This descriptive approach leads to the so called black-box modeling, which describes the observation without explaining the mechanisms generating these observations. This process is useful and widely applied but also has the possibility of leading to wrong conclusions due to the limitations and non-realistic assumptions of such models (e.g, stationarity, generality, robustness, etc.).

Moreover, it is possible that obtained results may prove to be outdated before being published due to the the fast evolution of the Internet and the nature of its traffic. As a consequence, finding robust characteristics is a must [4].

Thesis Group 2 ***Squeezing the Most out of Network Traffic***

In order to avoid incorrect conclusions about the nature of network traffic and to cease using non-useful models (as it happened frequently in the history of traffic modeling research in the previous decades!) we need to use our statistical tools carefully and to interpret their results with keeping their limitations in mind.

We also need to obtain information about the characteristics of traffic from a different point of view, which is also general at the same time. It requires a **multi-dimensional traffic characterization framework**, which I intended to build.

Furthermore, understanding the performance metrics requires similar considerations if we do not want to misunderstand the dynamics of our networks.

Thesis 2.1 ***Discovering the nature of network traffic***

I have carried out a number of comprehensive traffic analysis studies by the application of a broad set of traffic analysis tools on measured traffic recorded in several different networks all over the world (e.g., Sweden, Spain, the USA, Hungary) including both commercial and university campus networks and also fixed and mobile networks in order to get a ***sound understanding of the nature of network traffic****. I have concluded the main characteristics of actual network traffic for the investigated broad range of cases based on the results including basic statistical analyses, stationarity analyses, correlation analyses, burstiness analyses, leaky bucket analyses, peakedness analyses and fractal analyses. [B1, B13, J2, J12, J13, J20, J22, F1, F2, F3, F6, C15, C17, C18],*___[C19]___*,[C23, C24, C27, C28, C29, C36, C37, C38, C45]*

Beyond understanding the fundamental characteristics of network traffic in general it is vital to go deeper and to find the dominant applications that generate traffic, which can significantly determine the nature of the aggregation. In addition, it is also of high importance to identify and to capture the main features of traffic from popular and intensively growing applications.

Thesis 2.2 ***The nature of traffic sources***

I have ***classified, characterized and modeled network traffic generated by a broad range of applications*** *that have significant role in forming the traffic nature of recent network traffic on different time scales (connection level, session level, flow level, packet level) from several networking environments including peer-to-peer (P2P aggregation, BitTorrent), VoIP (Skype), video, gaming, social networking (Facebook), video sharing (YouTube), etc. traffic. [B1, J12, J13, J14, J15],*___[J16, J17]___*,[J18, J19, F5, F6, C16, C25, C26, C30, C31, C32, C33, C34, C35, C38, C39, C40, C41]*

Traffic characteristics are not unmodified inside the network but can be changed as traffic streams are traveling via network elements, interacting other streams and affected by several control mechanisms. Moreover, performance metrics can also be changed due to such traffic changes. These considerations have led to the relevance of the following thesis.

Thesis 2.3 ***Impacts of network elements on traffic characteristics and performance metrics***

I have shown the ***impacts of network elements*** *(multiplexers, shapers, etc.) on a wide range of* ***traffic characteristics*** *in a number of network scenarios based on measurements taken from real networks. I have also shown the* ***impacts of network elements*** *(multiplexers, shapers, etc.) on several* ***QoS metrics*** *(loss, delay, delay variation). The results are concluded from actual measured traffic. [F2, C7, C9],**[C19]**,[C56].*

4.3 Architectures and protocols of future networks

During the previous decade a huge growth can be observed both in the number of systems connected to the Internet and also in the required bandwidth they use. Furthermore, upcoming applications become more sophisticated and demand various QoS metrics. These tendencies revealed several limitations of network architectures and of the operation of current protocols. There is an urgent need to cope with this challenge.

Thesis Group 3 ***Towards Efficient Future Networks***

TCP congestion control has poor performance in high-speed networks because of its slow response with large congestion windows in wide-area networks. This problem has resulted in the development of a number of new TCP versions to solve this issue. However, there is a lack of clear understanding and comparative results of the dynamics of these protocols, which is a must for the applications of these TCPs [J24].

Thesis 3.1 ***High Speed TCP Performance***

I have carried out a comprehensive performance evaluation of high-speed TCPs (HSTCP, FAST TCP, Scalable TCP, TCP BIC, TCP CUBIC) and also of some other TCPs (TCP New Reno SACK, TCP Limit) by analytical-, simulation- and measurement-based approaches and concluded their ***performance behavior in several metrics*** *(throughput, fairness, stability, etc.). The results are based on an overall analysis including flow-level, packet-level, queueing and spectral analyses in different topologies and parameter settings covering both in short-term and long-term behavior. I have also shown the* ***performance of some Adaptive Queue Management (AQM) and scheduling methods***

(RED, AAR, wireless fair scheduling). *[B4, B10, J21, J23, J24, J25, J26, J27],****[J28]****,[J29, J30, J31, J32, J33, J34, F4, F7, F8, C46, C47, C48, C49, C50, C51, C52, C53, C54, C55, C57, C58, C59, C60, C61, C62, C63, C67, C68, C69, C70, C71, C72, C73, C74, C20, C21, C22, C42, C43, C44, P1, P2]*

One of the fundamental questions for future networks is how to efficiently transfer data traffic generated by versatile applications in heterogeneous and fast changing environments. The lesson learned from the history of the Internet is that congestion control performed by TCP can be a solution. However, due to the limitations of TCP versions it is necessary to look for alternative networking paradigms.

Thesis 3.2 ***Network architecture for future networks***

I have designed a ***network architecture*** *as a clean state research proposal for future networks. This architecture omits congestion control (TCP) with all its disadvantages and uses a fountain code-based transport protocol and fair schedulers. I have proposed the Raptor code as an efficient erasure code and Deficit Round Robin (DRR) as a simple scalable scheduler for the architecture.* ***[B15]****,[C65, C64, C66]*

The new transport protocol of the architecture described above must be correctly designed, tested, implemented and finally applied in real networking environment. These research results are given in the following thesis.

Thesis 3.3 ***Digital Fountain based Communication Protocol***

I have designed a ***new transport protocol*** *called* ***Digital Fountain based Communication Protocol*** *(DFCP). DFCP has been implemented as a prototype and been investigated intensively. I have validated the operation of DFCP with analytical, simulation and measurement tools. I have analyzed DFCP using various network topologies and settings, and on three different testing platforms including our laboratory testbed, the Emulab network emulation environment and the ns-2 network simulator. I have carried out the* ***comparative performance evaluation study of DFCP*** *with recent TCP versions (TCP CUBIC and TCP New Reno SACK).* ***[B15]****,[C65, C64, C66].*

5 Applications and Impacts of Results

I reported several results in the first Thesis Group that might help the research community to get a sound understanding about the fractal nature of network traffic. I presented a number of results unveiling several misconceptions regarding the definition, testing, interpretation, modeling and implications of fractal traffic. The application of these results appears in the engineering design and dimensioning tasks of the involved models reported.

I presented results in the second Thesis Group that provide proper traffic models and tools for efficient traffic engineering. Some of these results are directly applicable for traffic dimensioning, design and control tasks since they are focusing on QoS metrics relevant from an engineering point of view. The results derived from commercial networks are also special since these are often confidential as a result of which, the research community has a rather limited information on such data.

I gave comprehensive comparative performance results about recent TCPs, especially high-speed TCPs. I also proposed a new network architecture with a new transport protocol that is based on a completely different paradigm than that of TCP's. My research has resulted in an implemented prototype of the protocol which is my current main research work.

During my research I have participated in several national and EU research projects. Some of these results have also been utilized and have received international recognition. For example, I was the project leader from BME of the TRAMMS (Traffic Measurements and Models in Multi-Service Networks) CELTIC EU project (2007-2009) where I was leading the traffic analysis and modeling research. TRAMMS has been selected as **Celtic Gold Award winner 2009** and nominated for the **Celtic Innovation Award 2012**.

My results have been supported by more than **150 international book chapter, journal and conference publications** and received over **1000 citations** according to Google Scholar: `http://scholar.google.hu/citations?user=xMOmHOoAAAAJ&hl=hu&oi=ao`. Moreover, **two patent applications** utilized by Ericsson also demonstrate the practical applications of the results.

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