Budapest University of Technology and Economics

Modeling TCP Dynamics and Engineering Service Differentiation in TCP/IP Networks

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Summary of the Ph. D. Dissertation

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1 Introduction

In recent years, the Internet and its protocol suite the TCP/IP have had unprecedented success and impact on the way we interact and communicate. The Internet has become the single global and most successful network used by millions of computers around the world.

Currently, because of the lack of precise analytic methods, network engineers have to rely on heuristics and overprovisioning when they want to design or manage TCP/IP networks. These methods are not cost efficient, especially not in wired and wireless access networks.

Precise analytic models are needed, but state of the art traffic and performance models are based on too many simplifying assumptions rendering these models not suitable in practice. Dimensioning methods, for example, are usually based on deterministic bounds, or the traffic sources have to possess very strict statistical properties. The most important such properties are: identically distributed, short-range dependent, fit parametric distributions, etc. Real network measurements proves that traffic sources cannot be easily described with simple parameters, and the previously mentioned properties do not hold generally [LTWW93, CrBe96, CTB96, PaFl95].

Current traffic models also suffer from a simplifying assumption stating that traffic sources are independent, thus the usual step when modeling a network is to decompose it as a mash of individual traffic flows and a network queues. This conventional method, unfortunately, also proved to be not applicable when modeling the Internet. There are complex feedback algorithms, which make the model components dependent on each other. The most important such algorithm is the Transmission Control Protocol (TCP), which carries over 90% of the total Internet traffic today. The TCP feedback algorithm is still not well understood, and although some important laws have been laid down [MSMO97, PFTK98], these results have not been generalized, nor have been applied to network engineering or dimensioning.

Making service guarantees work does not mean just proper network dimensioning. Especially not in case of wireless networks, where capacity is just one resource that needs proper control. Because of radio propagation, transmitting stations must cooperate in an efficient way so that the available air capacity is optimally shared among the demands, interference is minimized, and retransmissions due to collisions are minimized. Current methods in this field apply very strict central control algorithms to achieve these goals [MoPa92, GPRS, NLB99]. The centralized approach is not efficient for non-centralized ad-hoc networks. The major limitations of centralized algorithms are the same as in case of conventional dimensioning methods: they assume simple, predictive sources that are independent of each other.

To summarize the introduction, we argue that proper resource control in the Internet, either we consider wired or wireless networks, is faced with the same key challenges: to find more practical models based on better understanding of the interaction between traffic sources and network mechanisms.

2 Objectives

The objective of this thesis was to analyze the interaction of modeling components, and to develop practical performance management methods based on the new insights gained from the research.

The *first goal* of my research was to investigate the statistical properties of TCP connections competing with each other and sharing network resources with background traffic streams. The motivation behind this goal was that existing Call Admission Control algorithms and QoS schedulers have disregarded the impact of TCP protocol on the statistical properties of the managed traffic flows. It used to be common belief that the TCP mechanisms have only small-scale impact on the statistical properties of aggregate or individual traffic streams. My argument was, however, that this assumption had not been proven satisfactorily, and TCP might have important effects not just on the small, but also on large spatial and time scales.

Based on the new insights, my *second goal* was to develop better performance management methods, that would be more robust, deliver better QoS and would be more resource efficient. In this thesis, I classified two distinctly different performance management frameworks for wired and wireless TCP/IP networks. The specialties of the radio channel require special wireless control protocols (e.g., wireless Medium Access Control) suited for the wireless channel with different properties than wired scheduling algorithms. In addition, the statistical properties of traffic in wireless networks may be different than in wired networks due to host mobility. On the other hand, both wired and wireless networks share almost the same higher layer TCP/IP protocols and applications, thus most of the results from TCP/IP traffic modeling can be applied for both wired and wireless scenarios.

In summary, I set the following objectives in my dissertation:

- Analyze the dynamics of TCP connections competing with each other.
- Analyze the statistical properties of TCP adaptation and the connection between self-similarity and TCP control algorithms.
- Develop robust resource management and control algorithms for wired and wireless DiffServ networks based on realistic assumptions on the properties and behavior of the traffic.

3 Methodology

The objectives presented before set the main requirements for the methodology I used in this dissertation. To achieve the goals, I applied a combination of mathematical modeling, network simulations and network measurements.

The primary methodology was mathematical modeling to establish sound basis for the proposed performance management algorithms. For the evaluation of TCP behavior, I applied mathematical tools from *chaos theory, fractal theory, and control theory*. The research on DiffServ guarantees required probability bounds on packet loss and delay, while only minimal assumptions can be made on the statistical properties of traffic streams. This requirement motivated the use of *Large Deviation theory* and a class of *Chernoff bounds*.

Mathematical models are always "distilled" versions of real-life mechanisms that focus on the important and disregard the less important aspects of reality. Probably the most serious mistake a researcher can make is that he or she misses to take into account an important property present in real life when developing a mathematical model. In this thesis, I put special care to ensure that both the assumptions used in the models and the conclusions derived from the models are compared with measurements and simulations of realistic scenarios whenever possible.

To achieve this objective, I performed simulation studies to ensure that the findings are not just artifacts of a simplified mathematical model. The benefit of simulations was that it allowed me to perform a large number of simulation runs in a well-controlled environment where the parameters of the simulation can be arbitrarily adjusted. I used simulation techniques in three sections of my dissertation. I applied detailed *TCP protocol simulation* for the investigation of the TCP protocol. For the analysis of wireless DiffServ scenarios I used combined simulation of *802.11 DCF MAC* and *TCP protocols* with a simplified *radio channel model*. I used the same simulation platform, the NS [NS] simulator for the simulation studies.

To ensure that the analyzed scenarios are realistic, I performed measurements in a number of real networks. The real network measurements comprised of (i) *wide-area Internet connections* between Columbia University, Ericsson Hungary and dozens of servers in Europe, Australia and USA, (ii) *modem access lines* at Ericsson Hungary, and (iii) a special purpose *Wireless LAN testbed* built in the COMET laboratory (Columbia University, New York).

4 New Results

I. The Chaotic Nature of TCP Congestion Control [J4, C2, W3]

Previous work on TCP modeling is based on stochastic modeling techniques [MSMO97] [PFTK98] [Mor97]. I found that if I approach the problem using deterministic modeling techniques, we can explain several real-life phenomena that cannot be understood using stochastic models. My main contribution was that I demonstrated that the end-to-end congestion control used by the TCP protocol, while competing for networking resources, generates deterministic chaos.

I analyzed the following, most important chaotic phenomena in TCP/IP networks:

- I reconstructed the fractal attractor of a system consisting of competing persistent TCP flows.
- When the system is in the chaotic regime, I showed that the system exhibits extreme sensitivity to initial conditions.
- I demonstrated the existence of phase transitions between chaotic and non-chaotic states.
- I demonstrated that for certain parameters TCP dynamics produce self-similar traffic.

Thesis 1.1 Reconstruction and Analysis of the System Attractor of Competing TCPs [C2, W3], $Ch.2.2$[1]

I introduced a method to visualize the trajectory of a system consisting of two greedy TCP flows sharing a single, finite size (B packets) bottleneck buffer of constant service rate (C). I reconstructed the attractor of this system using the time shifted past values of the congestion window variables ($cwnd$) of the TCP sender hosts.

The result is a multidimensional vector that is projected to the 2D plane by averaging the values $\hat{X} = 1/n(x_t + x_{t-\delta t} + ...)$. The resulting graph of the 2-TCP configuration is given by:

$$x[i] = \frac{1}{n}\sum_{j=1}^{n} \text{cwnd}_x[i-j] \tag{1}$$

$$y[i] = \frac{1}{n}\sum_{j=1}^{n} \text{cwnd}_y[i-j] \tag{2}$$

where x and y denote the two TCPs. n controls the scale over which the congestion windows are averaged, the larger the value is, the more hidden dimensions can be reconstructed.

This new analysis method has the following properties and benefits:

- previous methods analyzed TCP dynamics always in the time-domain, this method enables the analysis in the phase space;

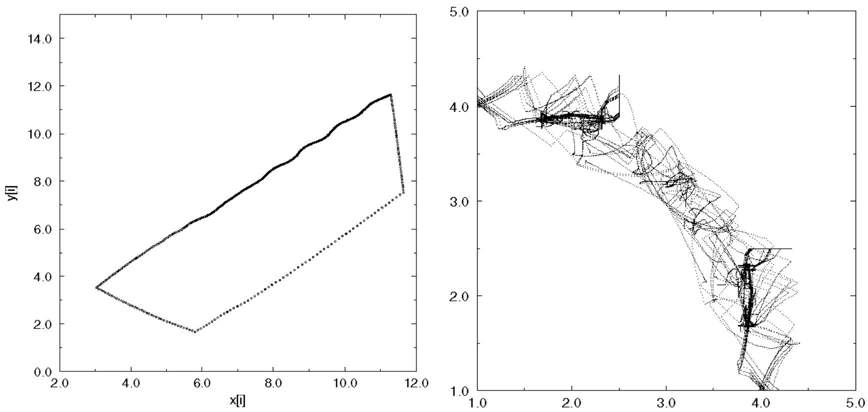
[1]References for conference papers start with letter ‘C’, journals with ‘J’, workshops with ‘W’, standardization and patent publications with ‘P’. References to the chapters in the thesis are marked with $italic$.

- the attractor of the system can be reconstructed by monitoring a simple parameter of the TCP state machine, the so-called congestion window;
- periodic systems can be differentiated from non-periodic systems because they have closed loop representation in the phase space;
- I demonstrated that although the system is completely deterministic, the resulting dynamics is non-periodic for certain parameters, in which case the reconstructed attractor had fractal Box-counting dimension $1 < D < 2$

To validate the method, I performed simulation and testbed measurements:

- In a simulation study, I investigated the dependence of the resulting attractor to different network configurations. (See Figure 1)
- I demonstrated that periodic and non-periodic behavior are present not just in simulation models but also in real networks. Four different configurations have been analyzed; these demonstrated stable periodic behavior, sensitive behavior when the system is on the edge of chaos, non-periodic chaotic behavior, and chaos with LRD properties.

Figure 1a shows the trajectories of periodic TCP flows, represented by closed loops. Figure 1b shows the trajectories of a different network of TCPs, which shows no periodicity over 4 hours of simulation.



(a) Periodic attractor. $C = 0.2$ Mbps, $d = 10$ ms, $B = 20$ packets, time shifts $n = 100$

(b) Strange attractor. $C = 0.1$ Mbps, $d = 10$ ms, $B = 4$ packets, time shifts $n = 300$

Figure 1: Attractors of two competing TCP sources.

Thesis 1.2 Analysis of the Sensitivity of TCP/IP Networks to Initial Conditions [J4, C2, W3], $Ch.2.4$

I introduced a new measure to determine the sensitivity of TCP/IP networks to initial conditions. I introduced a new analysis method to derive this measure using a series of special, directed network simulations. This new measure reveals that a network of TCP connections may be controlled by minute control actions, and this sensitivity can be evaluated numerically.

A summary of the directed simulation method to calculate this measure is the following:

- The same configuration is simulated many times, and a single perturbation happens in each simulation run by artificially increasing the congestion window of one of the TCPs with just one packet.
- The measure is calculated as the average maximum exponent of the trajectory:

$$\lambda = E\left[\max_i \lambda(t_0, i)\right] \tag{3}$$

- The local exponent at t_0 is:

$$\lambda(t_0, i) \approx \frac{1}{\Delta t} \ln \left|\frac{E(t_0 + \Delta t)}{\epsilon_i}\right| \tag{4}$$

  where ϵ_i is the size of the perturbation which happens at t_0.

- I defined the distance between the two systems at time t as the Euclidean distance in the congestion window (*cwnd*) space:

$$E(t) = \sqrt{\sum_{i=1}^{N} (w^{orig}(i,t) - w^{pert}(i,t))^2} \tag{5}$$

  where $w(i,t)$ is the congestion window of the ith TCP at time t.

This measure is analogue to the Lyapunov exponent used in dynamical systems. With this new method, I analyzed several network configurations using simulations, and reported the following new results:

- In certain configurations, external, small perturbations diminish after a while.
- There are cases, when the system exhibits extreme sensitivity to small perturbations, in which case, I measured a positive exponent.

Thesis 1.3 Chaotic TCPs can be Sources of Traffic Self-Similarity [J4, C2], $Ch.2.5$

I demonstrated using simulation that TCP competition itself can be the source of statistical self-similarity. This finding contradicted existing explanations that required the existence of heavy-tailed file sizes. I simulated a network configuration in the chaotic regime, and recorded the amount of sent bytes in non-overlapping periods $X(i)$.

The analysis revealed that the time series was statistically self-similar with the following properties:

- The m aggregated absolute values of the time series $\mu^{(m)} = \frac{1}{N/m}\sum_{k=1}^{N/m}\left|X^{(m)}(k) - \frac{1}{N}\sum_{i=1}^{N} X(i)\right|$ increased as $\log \mu^{(m)} \approx (H-1)\log m$ for large m, with estimated $H \approx 0.79$.
- The spectral density of the time series $I(\lambda) = \frac{1}{2\pi N}\left|\sum_{j=1}^{N} X_j e^{ij\lambda}\right|^2$. The spectrum behaves as $I(\lambda) \sim |\lambda|^{1-2H}$ at the origin, with $H \approx 0.81$.
- The rescaled adjusted range statistics (R/S) [TTW95] provided an estimation of $H = 0.813$.
- The wavelet analysis method [AbVe98] estimated $H = 0.787$, with 95% quantiles at $[0.754, 0.819]$.

II. Propagation of Self-Similarity in the Internet [J2, C3, W2]

In the previous thesis I discussed a new, chaotic modeling approach to TCP modeling. I found that TCP dynamics can cause not only seemingly random traffic fluctuations, but for certain parameters it can generate statistically self-similar time series. This finding provides a significantly different explanation to self-similarity found in the Internet, while it does not contradict with previous work. Previous research explains the emergence of self-similarity with stochastic reasons, for example, heavy tailed distributions in higher layers of the TCP/IP protocol stack [CrBe96] [CTB96] [PaFl95] [TWS97] [WTSW97].

In this thesis I discussed another role of TCP in the wide-scale emergence of self-similarity in the Internet. I showed that TCP, apart from generation, can also propagate self-similarity between distant areas in the Internet. This means that even if there are no reasons for self-similarity at a certain point of the network, for example, heavy-tailed file sizes or chaotic competition, it is still possible that traffic fluctuations become self-similar due to the propagation effect. I found that TCP propagates any kind of self-similarity, regardless of how it is generated. In addition, it was shown that TCP propagates other kinds of correlation structures as well, not just long-range dependence. I also analyzed the impact of self-similarity on end-to-end TCP dynamics, how the end-user perceived rate fluctuations depend on the end-to-end path properties, and what are the limitations of propagation.

Thesis 2.1 Measure of TCP Adaptivity [J2, C3, W2], $Ch.3.2$

I presented an analysis method and investigated the adaptation efficiency of the TCP congestion control algorithm to dynamic network conditions in the frequency domain. I introduced a new adaptation measure and proposed a method to measure this value in real-life networks or simulations. (See the configuration in Figure 2).

I introduced the *measure of adaptivity curve* $D(f)$ to describe the efficiency of the TCP congestion control algorithm adapting to changing network conditions on several frequencies denoted by f:

$$D(f) = S_{tcp}(f)/S_{background}(f) \tag{6}$$

where $S_{background}(f)$ is the spectral density of the background traffic rate process $A_{background}(f,t)$ and $S_{tcp}(f)$ is the spectral density of the adapting TCP rate process. $A_{background}(f,t) = a\sin(2\pi ft + \alpha) + m$ where α is a uniformly distributed random variable between $[0, 2\pi]$ at frequency f.

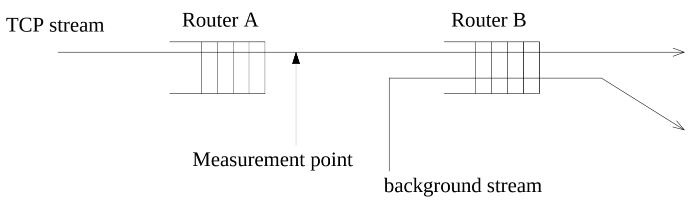


Figure 2: Simulation model for the test of TCP adaptivity.

Based on this analysis I reported the following new results:

- I performed a large number of simulations for a wide range of f to calculate $D(f)$, and I found that the shape of the adaptivity curve is the same for the most widely used TCP versions (Tahoe, Reno, NewReno, SACK, Reno with delayed ACK).

- I found that the shape of the curve has a characteristic timescale T_0, over which adaptation is perfect: $D(f) \to 1$ as $f \to 0$.

- Below T_0 the TCP congestion control is unable to adapt.

- I presented an analytic calculation that estimates this characteristic timescale:

$$T_0 = 1/f_0 \approx RTT * (B + Cd)/2 \qquad (7)$$

  where buffer size is denoted by B, service rate C and propagation delay is d, and the round trip time is $RTT = B/C + d$. This calculation was verified using simulations.

The adaptivity curve of TCP is shown in Figure 3 for several versions of TCP.

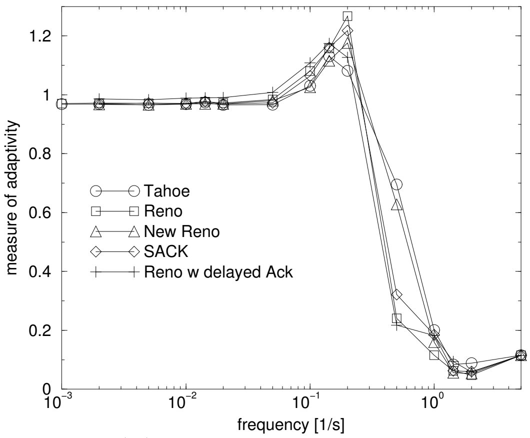


Figure 3: Measure of adaptivity $D(f)$ as a function of the frequency for several TCP variants.

Thesis 2.2 TCP approximates a Linear System and Propagates Self-Similarity[J2, C3, W2], $Ch.3.2$**,** $Ch.3.3$

I showed that a TCP flow passing through a bottleneck buffer can be approximated with a low-pass linear system in the sense that TCP takes over the correlation structure of the background traffic through a linear function approximated by the measure of adaptivity $D(f)$ in that configuration. The most important implication is that TCP propagates self-similarity inherited in a bottleneck buffer to other parts of the Internet.

Using simulational analyses I presented the following properties of TCP systems:

- I demonstrated by simulation that when the background process is a composition of a discrete number of narrow frequency processes, the TCP takes over the spectrum of the composition according to $D(f)$.

- I demonstrated the linearity property by simulations that covered a large range of relative frequencies.
- I demonstrated by simulation that the system adapts to the random White Noise process as a low-pass filter.
- I demonstrated by simulation that if TCP traverses a link where the traffic shows self-similarity, it adapts to it with a spectral response equal to the spectrum of the self-similar traffic. Self-similarity is "propagated" all along the TCP connection path. I verified this argument with spectral analysis of the TCP traffic time series measured before the congested buffer. The spectral density of the time series $I(\lambda) = \frac{1}{2\pi N}\left|\sum_{j=1}^{N} X_j e^{ij\lambda}\right|^2$. The spectrum behaves as $I(\lambda) \sim |\lambda|^{1-2H}$ at the origin, with $H \approx H_{background}$.

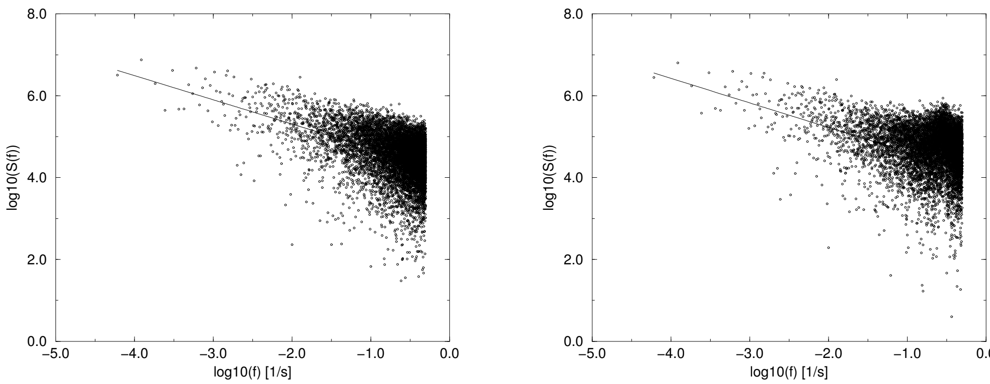


Figure 4: a) Power spectrum of background traffic $H = 0.8$. b) Power spectrum of TCP traffic adapting to the FGN, estimated $H = 0.8$.

Thesis 2.3 Adaptive Short-Rage Dependent Traffic Propagates Self-Similarity [J2, C3], $Ch.3.3$

I proved analytically that if short duration TCP connections are multiplexed with LRD traffic (see Figure 5), the covariance of the aggregate traffic $A(t)$ decays asymptotically as the background LRD process:

$$\gamma_A(\tau) \sim \tau^{-\beta_F} \quad \text{as} \quad \tau \to \infty \tag{8}$$

where the autocovariance of the background traffic decays asymptotically as $\gamma_F(\tau) \sim \tau^{-\beta_F}$ as $\tau \to \infty$, $0 \leq \beta_F < 1$.

Simulations and real-life measurements verified the results of the investigation:

- In a simulation study, I investigated the superposition of light-tailed TCP connections and self-similar background traffic flows passing through a common bottleneck buffer, and using statistical tests I showed that the light-tailed aggregate inherits self-similarity.

- The results were verified in the real Internet, where a large number of short TCP connections were created between two distant hosts in Europe and the USA.

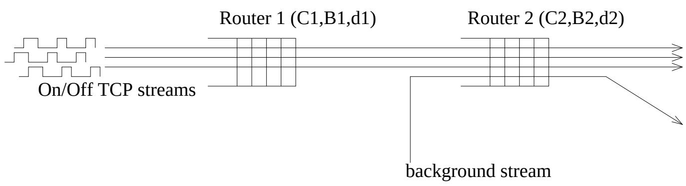


Figure 5: Simulation model of light-tailed TCP traffic multiplexed with self-similar background traffic in the bottleneck buffer.

Thesis 2.4 Spreading of Self-Similarity in the Multi-Hop Case [J2, C3], $Ch.3.4.1$

I proved analytically that if a TCP traverses several buffers on its path (see Figure 6), it is the largest Hurst exponent among the background LRD streams on the links that characterizes the TCP connection's correlation structure:

$$\gamma_A(\tau) = \tau^{-\min_i \beta_i} \quad \text{as} \quad \tau \to \infty \tag{9}$$

where he end-to-end TCP session congestion indicator process and the congestion indicator of router i are $A(t)$ and $F_i(t)$ respectively, the autocovariance of the TCP process is $\gamma_A(\tau)$ and the Hurst exponent of $F_i(t)$ is β_i.

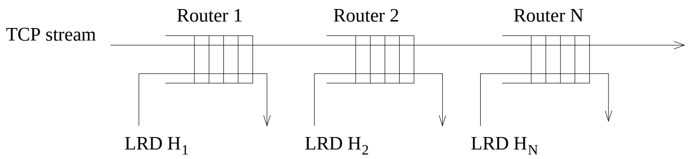


Figure 6: A TCP connection traversing multiple hops with independent background LRD (H_i) inputs.

I verified by numerical analysis that the above relation is also true for the rate processes and not just for the congestion indicator processes in case of statistically independent synthetic FGN background traffic processes and ideal TCP adaptation.

Thesis 2.5 Spreading of Self-Similarity among Adaptive Connections in Multiple Steps [J2, C3], $Ch.3.4.2$

I analyzed whether the self-similarity caused by adaptation can be passed on to adaptive traffic streams that have no direct contact with the source of self-similarity. The analysis investigated a simple network configuration, see Figure 7.

I presented analytic results for the following extreme-cases:

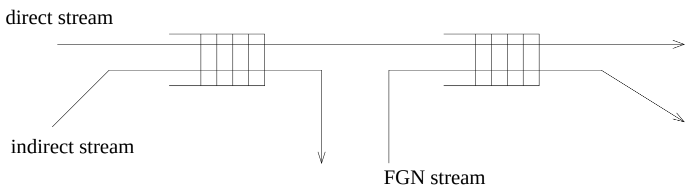


Figure 7: Network model for the investigation of self-similarity spreading. Both links have the same capacity C.

- I proved that spreading of self-similarity is "perfect" if the rate of the background LRD stream is always greater than $C/2$: $H_{dir} = H_{indir} = H_{FGN}$, where H_{dir}, H_{indir} and H_{FGN} are the Hurst exponents of the direct, indirect and the background streams respectively.
- If the rate of the background process is always smaller than $C/2$, then self-similarity disappears from both adaptive streams.

The assumptions for the analysis were:

- both adaptive streams adapt ideally: $D(f) = 1$ as $f \to 0$;
- buffers are shared in a max-min fair manner.

I investigated by simulation the non-trivial case, when the rate fluctuates around $C/2$, and demonstrated that self-similarity can still be passed on to the indirect stream.

III. Resource Management for Differentiated Services Networks [C1, C4, P3, W1]

I introduced a set of measurement based resource estimation methods for Differentiated Services (DiffServ) networks based on the effective bandwidth concept, first discussed in [GAN91] [Kel96] [GiKe97]. The methods are suitable for both traffic engineering and admission control purposes and are suitable to be implemented in routers, bandwidth brokers or in off-line traffic engineering tools.

The theoretical basis of my work is the effective bandwidth theory introduced by Frank Kelly. The definition of the effective bandwidth is the following:

Definition 1 *The* ***effective bandwidth*** *of a traffic flow aggregate is BW if the rate process of the aggregate traffic exceeds this value with probability less than ϵ. Denote the rate of the individual flows by stationary and independent random variables $X_k,\ k = 1 \ldots N$:*

$$\Pr\left(\sum_{k=1}^{N} X_k \geq BW\right) \leq \epsilon. \tag{10}$$

The objective of resource management is to maintain the above probability in the network by regulating the amount of admitted traffic, by allocating enough resources to accommodate the demand, or both. In either cases, it is important to precisely estimate the effective bandwidth BW.

The novelty of my work is that the resource estimation methods are better suited to the specialties of the DiffServ environment than prior work. The new mathematically derived bounds that are presented in this thesis can be grouped according to where they fit into a router architecture:

- For Assured Forwarding queues, I presented three bounds that have different complexity and performance. These bounds are more robust theoretically than previous methods and can be easily implemented.
- For delay sensitive, so called Expedited Forwarding queues, I presented two bounds, that differ in the numerical complexity and the method of how the sources have to be policed (class of leaky bucket policers).
- Finally, I presented a combined DiffServ router architecture, where the resource sharing between assured and delay sensitive queues was taken into account.

Thesis 3.1 A Tight Effective Bandwidth Bound for Assured Forwarding Classes Based on the Aggregate Load Measurement of a DiffServ Queue [C1, P3], $Ch.4.2.2$

Assured Forwarding queues are used by Internet applications that are throughput sensitive but less delay sensitive. I analyzed an Assured Forwarding DiffServ queue, where, for scalability reasons, only the aggregate average rate is available as a measurement:

- I presented a new improved effective bandwidth formula in closed form:

$$BW^A(s) = \frac{N}{s}\ln\left(\frac{M + \sum_{k=1}^{N}\frac{h_k}{e^{sh_k}-1}}{N}\right) - \frac{1}{s}\sum_{k=1}^{N}\ln\left(\frac{h_k}{e^{sh_k}-1}\right) - \frac{\ln(\epsilon)}{s} \tag{11}$$

  where ϵ is the maximum saturation probability, the peak rates of flows $k = 1 \dots N$ are h_k and the mean rate of the aggregate is M,

- I derived a closed form approximation for the optimal s value:

$$s_{opt} = \sqrt{\frac{8\gamma}{\widehat{H} - (2M - H)^2/N}} \qquad \text{where } H = \sum_{k=1}^{N} h_k \text{ and } \widehat{H} = \sum_{k=1}^{N} h_k^2 \tag{12}$$

- I proved analytically that my bound is more optimal than the previously proposed Hoeffding bound, but has the same statistical properties and is based on the same mathematical assumptions.

- I analyzed numerically on a realistic but random traffic mix that the gain of using the improved bound over the Hoeffding bound is significant when the traffic is biased towards either high or low mean-to-peak ratios. A real Internet measurement was presented which supports the assumption that such traffic classes are the typical.

Thesis 3.2 Improving the Effective Bandwidth Bound for Assured Forwarding Classes by Measuring the Aggregate Rate Variance [C1], $Ch.4.2.3$

I presented a more optimal resource estimation bound for an Assured Forwarding DiffServ queue, where the average rate and the variance of the aggregate traffic rate are both measured. Compared to the previous method, this enables even better utilization of the statistical multiplexing gain, while only small additional complexity is required in the routers.

- I derived a closed form effective bandwidth formula using the variance:

$$BW^V(s) = \frac{1}{s}\sum_{k=1}^{N}\ln\left[\frac{S + \sum_{j=1}^{N}\frac{h_j^2}{e^{sh_j}-sh_j-1}}{N} \cdot \frac{e^{sh_k} - sh_k - 1}{h_k^2}\right] + M + \frac{\gamma}{s} \tag{13}$$

  where the h_k are the peak rates of flows $k = 1 \dots N$, the mean rate of the aggregate is M, and the aggregate variance is S.

- I derived a closed form approximation for the optimal s:

$$s_{opt}^V = \sqrt{\frac{18\gamma}{9S + \widehat{H} - H^2/N}}. \tag{14}$$

- I showed by a numerical example that the derived bound can be significantly tighter than the Hoeffding bound and my previous bound BW_A.

- In addition, this new bound is theoretically more robust than bounds based on the Central Limit Theorem since it does not require large number of flows.

Thesis 3.3 An Improved Bound using Measurement Groups [C4, W1], $Ch.4.2.4$

I analyzed an Assured Forwarding queue where packets are statelessly classified to a small number of groups G, and measurements can be performed on a per-class basis. Since the number or groups is small and fixed, this architecture is still scalable and easy to implement, on the other hand it enables even more optimal resource management. In addition, there is a convenient possibility for the router vendor to trade efficiency with complexity.

- I derived a closed form effective bandwidth formula using per-group average measurements M_i, $i = 1..G$:

$$BW^G(s) = \frac{1}{s}\sum_{i=1}^{G} n_i \ln\left(\frac{M_i + \sum_{k\in A_i}\frac{h_k}{e^{sh_k}-1}}{n_i}\right) - \frac{1}{s}\sum_{k=1}^{N}\ln\left(\frac{h_k}{e^{sh_k}-1}\right) + \frac{\gamma}{s}. \quad (15)$$

  where $H_i = \sum_{k\in A_i} h_k$. Flows $k = 1 \dots N$ are grouped into G groups: $A_i,\ i = 1..G$. Let $n_i = |A_i|$ denote the number of flows in group i.

- I derived a closed form approximation for the optimal s analytically:

$$s_{opt}^{G} = \sqrt{\frac{8\gamma}{\widehat{H} - \sum_{i=1}^{G}\left(2M_i - H_i\right)^2/n_i}} \quad (16)$$

- The proposed bound is theoretically tighter than the Hoeffding or the H^A bound.

- I proposed a heuristic grouping strategy, where flows that have similar $V(k) = m_k + h_k/(e^{sh_k} - 1)$ are grouped together.

- Using this grouping strategy, I numerically analyzed a random flow mix, and show the amount of gain that can be utilized by increasing number of groups, hence increasing the implementation complexity.

- I proposed a set of grouping strategies that require no per-flow state in the schedulers, but helps to get the most gain from grouping. I presented an example based on a real Internet measurement.

Thesis 3.4 A Class of Probabilistic Delay Bounds for Expedited Forwarding Queues Described by the Effective Load [C1], $Ch.4.3.1$**,** $Ch.4.3.2$

In a DiffServ architecture, Expedited Forwarding queues serve delay sensitive traffic. The traffic sources are controlled using traffic policers. I analyzed the problem of guaranteeing delay in an Expedited Forwarding queue shared by random flows. The information for the estimation algorithm is limited to the admitted policer parameters and the aggregate queue measurements. In this thesis, I presented a generic bound for delay classes that can be fitted with a number of bounds to arrive at practical closed form estimations.

- I defined a new measure, the effective load of a traffic aggregate. $B(t)$ is the effective load of a traffic aggregate, if it satisfies (for $t \geq 0$)

$$\Pr\left(\sum X_k[t] \geq B(t)\right) \leq \epsilon \tag{17}$$

where the number of bits sent by flow k into the network during a time interval of length t is $X_k[t]$, $k = 1 \ldots N$, and the average rate of flow k is $m_k = \mathbb{E}X_k[t]/t$.

- I derived a probabilistic bound for delay sensitive traffic aggregates serviced by a First In First Out scheduler using the effective load. The delay in a queue of service rate C is probabilistically bounded by d_{max} if:

$$B(d_{max}) \leq Cd_{max} \tag{18}$$

- The bounds derived for Assured Classes can be reused to calculate B depending on what types of measurements are available. I presented one example, the Hoeffding bound, which takes the following form:

$$B^H(t) = Mt + \sqrt{\frac{\gamma}{2}\sum_{k=1}^{N}\min(h_k t, \sigma_k + \rho_k t)^2}. \tag{19}$$

$B^A(t)$, $B^V(t)$ and $B^G(t)$ are similarly derived from BW^A, BW^V and BW^G.

Thesis 3.5 A Tight Probabilistic Delay Bound for Expedited Forwarding Classes Described by the Probability Occupancy Curve [C1], $Ch.4.3.3$**,** $Ch.4.3.4$

I presented a more optimal resource estimation method for delay sensitive queues, which relies on a more complete analysis of the queue occupancy probabilities. This method, although more optimal, it is also more complex numerically.

- I defined the probabilistic queue occupancy curve. $\Delta O(t)$ is defined as a probabilistic upper bound on the queue length $Q(t)$, t seconds after the start of a busy period:

$$\Pr\left(Q(t) \geq \Delta O(t)\right) \leq \epsilon \tag{20}$$

where t is measured from the beginning of a busy period.

- I derived analytically a delay bound, which is tighter than the bound based on the effective load. The maximum delay in the queue is bounded by d_{max} with probability ϵ if:

$$\max_{t \geq 0} \Delta O(t) \leq Cd_{max}. \tag{21}$$

- Using the above theorem, I presented a closed form bound for delay sensitive traffic when flows are policed by leaky bucket policers with parameters (σ, ρ). Delay d_{max} is guaranteed in the queue, with probability ϵ, if the following relations hold:

$$M + \sqrt{\frac{\gamma}{2}\sum_{k=1}^{N}\rho_k^2} < C \quad \text{and} \quad \sqrt{\frac{\gamma}{2}\sum_{k=1}^{N}\sigma_k^2} < Cd_{max}. \tag{22}$$

- Using the above theorem, I presented another bound for delay sensitive traffic when flows are policed by more complex leaky bucket policers with parameters (h_k, σ, ρ). Delay d_{max} is guaranteed in the queue, with probability ϵ, if the following relations hold:

$$M + \sqrt{\frac{\gamma}{2}\sum_{k=1}^{N} \rho_k^2} \leq C \quad \text{and} \tag{23}$$

$$\Delta O^H(t_k) < C d_{max} \tag{24}$$

for all $k = 0 \ldots N$, where $t_k = \sigma_k/(h_k - \rho_k)$, and $t_0 = 0$, and where

$$\Delta O^H(t) = Mt - Ct + \sqrt{\frac{\gamma}{2}\sum_{k=1}^{N} \min{(h_k t, \sigma_k + \rho_k t)}^2}. \tag{25}$$

- A futher benefit of this last bound that the same algorithm can be used if flows are described by multiple leaky bucket descriptors.

Thesis 3.6 Supporting Multiple DiffServ Classes using Static Priority Scheduler, $Ch.4.4$

I analyzed a complex DiffServ router that has multiple queues in every interface for several service classes served with Strict Priority Queuing (SPQ). The DiffServ router architecture follows a typical router implementation: The router has L priority levels with one queue at each level, served in a fixed priority order. Let $\mathcal{X}_{a,b,c,\ldots}$ denote the set of flows in queues $a, b, c, \ldots$. The first R (high priority) queues provide different guaranteed delay d_k ($d_i \leq d_j, i \leq j$) with probability ϵ_k. The queues $R + 1 \ldots L$ provide assured service with saturation probabilities ϵ_k ($\epsilon_i \leq \epsilon_j, R < i \leq j$). See Figure 8.

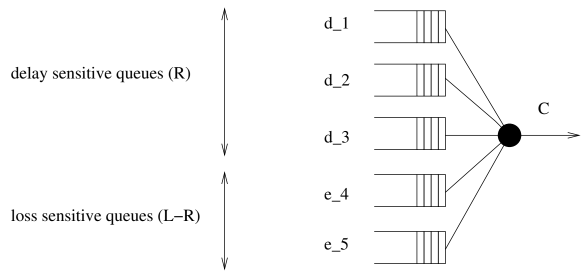


Figure 8: Guaranteeing multiple service classes with SPQ scheduling.

I derived analytically the following new results:

- I presented a bound for Assured Forwarding queues in the above architecture. Denote $BW^{\epsilon}[A]$ as the effective bandwidth of a flow set A with probability ϵ. The saturation guarantee ϵ_k is ensured in the assured forwarding queue k, if

$$BW^{\epsilon_k}[\mathcal{X}_{1\ldots k}] \leq C \tag{26}$$

where any previously derived form of the effective bandwidth BW can be used.

- I presented a bound for the Expedited Forwarding (delay sensitive) queues. The delay limit d_k, in queue k, is exceeded with probability less than $2\epsilon_k$ if, for $\forall t \geq 0$:

$$B^{\epsilon_k}[\mathcal{X}_{1\ldots k}](t) - Ct \leq Cd_k - B^{\epsilon_k}[\mathcal{X}_{1\ldots k-1}](d_k) \tag{27}$$

where $B^{\epsilon}[\mathcal{A}](t)$ is the effective load of flow set A and violation probability ϵ.

- I proved analytically that using my new bounds the statistical multiplexing gain is exploited not only within a queue, but among queues as well:

$$BW^{\epsilon}[\mathcal{X}_{1\ldots k}] \leq \sum_{j=1}^{k} BW^{\epsilon}[\mathcal{X}_j] \tag{28}$$

That is, the amount of resources required for a set of queues served by SPQ scheduling is less than the sum of the effective bandwidths of individual traffic aggregates in separate queues.

IV. Supporting Service Differentiation in Wireless Packet Networks [J1, C5, W4]

Wireless packet networks require different methods compared to wired TCP/IP networks because of the specialty of the radio environment. These specialties include relatively large bit error ratios due to interference and radio propagation effects, shared channel, scarcity of radio bandwidth, and host mobility. All of these have impact on traffic management. In case of wired networks, a transmission link usually has a well known service capacity C, which has to be managed to serve several traffic classes. In a wireless environment, the channel capacity available for a node is not constant, and the wireless Medium Access Control has to take into account the effect of shared radio channel, interference, collisions, overlapping cells, and it has to be aware of the packets waiting in the queues of other nodes as well.

Previous solutions for QoS provisioning over radio were based on inflexible central control, which is not well suited for picocellular, dynamic, or ad-hoc scenarios.

Because of the above arguments, my goal was to develop a complete traffic control “suite”, which incorporates methods for robust, flexible and distributed DiffServ packet scheduling and also resource estimation and traffic control algorithms. My results are valid for a broad class of shared channel wireless data technologies, but to be able to demonstrate the benefits of my solution in practice, I chose a popular wireless LAN technology, the IEEE 802.11b standard [IEEE802.11] as the base radio technology. I introduced a set of algorithms that form a fully distributed wireless differentiated services network based on:

- a distributed, differentiated services capable MAC;
- a distributed radio resource monitoring mechanism;
- service quality estimation; and
- distributed traffic and admission control.

Each of these components performs a well-defined task and can be implemented in a fully distributed manner, without the need of a central host.

Thesis 4.1 Delay Analysis of the IEEE 802.11 Distributed Coordination Function [J1, C5], $Ch.5.2.2$

I presented an analytic estimation of the average delay d of the packets sent by a host in a 802.11 wireless LAN occupied with background traffic. Assumption: flows are independent and the interarrival times are exponentially distributed.

$$d = Ud' + (1-U)m \tag{29}$$

where d' is given by:

$$d' = 2^u \cdot T_{slot} \cdot (L\lambda + 1)\left(\frac{1-(2p)^{v+1}}{1-2p} + 2^v \frac{p^{v+1}}{1-p}\right) + \frac{L}{1-p} - \frac{L}{2} + m \tag{30}$$

where U is the average channel utilization, the transmission time of the packets in the background is L. Denote the minimum and the maximum contention window of the hosts as W_{min} and W_{max} respectively and let $u = W_{min} - 1$, $v = W_{max} - W_{min}$.

I verified the result of the mathematical analysis in a differentiated services wireless testbed built at the Columbia University's COMET Laboratory. The testbed consisted of several mobile hosts equipped with 802.11 wireless LAN interfaces.

Thesis 4.2 Prediction of Available Resources using the Virtual MAC Algorithm [J1, C5, W4], $Ch.5.3$

I introduced the *Virtual MAC* (VMAC) algorithm, which continuously monitors the wireless channel and predicts the quality of service of traffic streams with high accuracy.

This new method utilizes a novel concept, which is a combination of channel monitoring and channel emulation algorithms. The VMAC is a real-time algorithm running in mobile hosts and emulates the mechanism of the DCF MAC algorithm in a completely passive way using so-called "virtual packets" streams.

The VMAC has the following benefits:

- The VMAC combines a theoretic source behavior (virtual traffic stream) with the real traffic pattern monitored on the channel, this way presents more precise estimation than purely theoretic calculations.
- The VMAC enables that precise performance predictions of the channel are possible by using virtual streams as predicted future traffic demands.

An example of the operation of the Virtual MAC is illustrated in Figure 9. In the core of the algorithm is an emulated duplicate of the 802.11 DCF MAC algorithm that takes as input a snapshot of the monitored channel state and an arbitrary stream of non-real (virtual) packets in real time. The algorithm emulates the DCF algorithm for the virtual packets and as the output is delivers loss and delay statistics.

The VMAC algorithm was verified using simulations and testbed measurements as well:

- The simulation study consisted of a large number of simulated mobile hosts running the VMAC algorithm in the presence of a random traffic mix of TCP and UDP streams.
- The VMAC algorithm was implemented and tested in the COMET testbed at the Columbia University.

Thesis 4.3 Distributed DiffServ Enabled Wireless Mac [J1, C5, W4], $Ch.5.2.3$**,** $Ch.5.2.4$

I proposed a modification of the Best Effort IEEE 802.11 DCF radio MAC algorithm [IEEE802.11], which extends the MAC with distributed DiffServ capability. The modification is based on the tuning of the *Contention Window* (CW) parameter of the DCF algorithm. Hosts sending packets in different DiffServ classes set different *CW* parameters.

The proposed distributed DiffServ MAC modification has the following benefits:

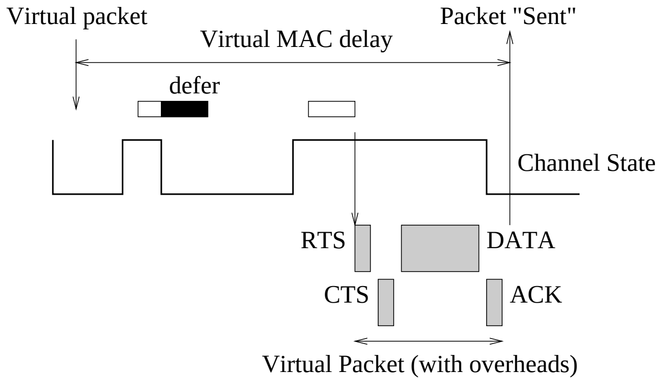


Figure 9: An example of the operation of the Virtual MAC algorithm. The channel state indicates an idle (state is high) or busy (low) channel. A virtual packet arrives during a busy period and the deferred timer is decremented during a short idle period, and virtual transmission happens during the next idle period, when the deferred timer expires.

- The new algorithm provides "soft" service differentiation that suits DiffServ architectures.
- The proposed algorithm is fully distributed, and does not require any central entity, and it can be used in ad-hoc networks as well.
- The new algorithm supports bursty traffic, not just constant rate traffic as the original PCF algorithm.
- The algorithm ensures service differentiation also when cell areas overlap.
- The new algorithm can be implemented in the firmware of existing wireless cards and the algorithm interoperates with existing Best Effort cards.

I evaluated the proposed modification using mathematical analysis and simulation:

- I built a complex simulation model to evaluate the distributed service architecture in a realistic scenario. My simulation analysis demonstrated that even in such complex scenario, the distributed algorithms, if used in tandem, can support globally stable service differentiation and absolute, probabilistic delay guarantees.
- The delay analysis of the DCF algorithm presented in the previous thesis is used to address the issue of how backoff values impact the average MAC delay for different levels of channel loads. The analysis shows that the proposed DiffServ MAC modification achieves service differentiation among traffic classes.

Thesis 4.4 Distributed DiffServ Control Architecture[J1, C5, W4], $Ch.5.4$**,** $Ch.5.5$**,** $Ch.5.6$

I developed a DiffServ control architecture for wireless LANs. This new architecture is fully distributed, every mobile host implements independent algorithms. The DiffServ control architecture includes the following components:

- DiffServ enabled Wireless MAC.
- VMAC to provide performance predictions.
- A *Virtual Source* (VS) algorithm, which builds on top of the VMAC and estimates QoS statistics as seen by the applications. The VS feeds the VMAC with a realistic stream of virtual packets.
- I introduced *probabilistic delay curves* that are obtained using the VS algorithm and describe the relation between session rate and achievable delay statistics, e.g., average delay and variance.
- I proposed an admission control algorithm, which runs in every mobile host and base station, and decides on the admission of real-time traffic flows. The admission control algorithm bases its decision on the results from the VMAC and VS algorithms.

I verified the precision of the virtual algorithms by simulations and also in an experimental IEEE 802.11 testbed under realistic network scenarios. The simulations consisted of several base stations and mobile hosts generating a traffic mix consisting of voice and TCP traffic streams.

5 Application of the Results

The objective of this thesis was to discuss, analyze, and improve several aspects of TCP/IP networks in the context of performance modeling and resource management in wired and wireless Differentiated Services networks.

The chaotic modeling technique presented in Chapter 2 allows us to understand TCP dynamics in a unified modeling framework by explaining previously separately modeled phenomena, such as phase effects, synchronization and apparent randomness. A possible future application of research is to make use of the sensitivity property of the chaotic system, and develop chaos control methods as buffer management to improve network performance using minute interactions.

Chapter 3 analyzed the adaptation property of TCP congestion control. Through a number of wide area Internet measurements I demonstrated that TCP propagates self-similarity encountered on its path to other parts of the network where self-similarity would not arise otherwise. The application of this result is in better resource management methods that take into consideration the propagation property when Internet service providers would like to dimension or manage their networks more optimally.

Chapter 4 introduced a set of resource estimation methods for wired Differentiated Services networks. I derived several analytic formulae for the estimation of required resources to provision loss and delay sensitive service classes. The specialties of DiffServ were taken into account, namely aggregate traffic handling, simple scheduling and traffic conditioning at the edges. The models behind the methods are based on the assumptions of the statistical properties of TCP/IP traffic flows analyzed in Chapters 2 and 3. The developed methods can be used for either admission control or network dimensioning. I put an effort to build on previous research results, and analyze their weaknesses and strengths from the perspective of practical application in real networks. I analyzed a simple DiffServ router implementation using SPQ schedulers, but extension to other types of class based scheduling methods is also possible, for example, Weighted Fair Queuing (WFQ) or Weighted Round Robin (WRR).

In Chapter 5, I presented a set of distributed algorithms to offer service differentiation in wireless packet networks. The methods are general to be used in a wide range of wireless technologies, however, to be able to demonstrate the feasibility of the framework, I applied them as an extension of the IEEE 802.11 wireless LAN standard. A possible future application is to integrate the DiffServ solution with Cellular IP, which provides a distributed solution for mobility management. Recently, there is a new proposed standard by the IEEE called 802.11e [MCMK02], which introduces a modification to the DCF mode called Enhanced DCF (EDCF). In EDCF, packets in lower priority must wait a longer waiting time before they can transmit on the channel. Our work predated and influenced the new proposed standard, which is very similar to our proposal.

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