Theses of the Ph.D dissertation
Network Management Algorithms for QoS Based Communication

Fancsali Alpár

Consultant: Prof. Levendovszky János

Budapest University of Technology and Economics
Department of Telecommunications
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1 Summary of the thesis

Packet-switched networking technology became the core philosophy of modern multiuser communication where a growing quantity of data has to be forwarded with acceptable quality. Therefore, the basic challenge lies in ensuring quality of service (QoS) data communication [14, 15, 16, 17]. The thesis proposes novel traffic management methods to meet the given QoS requirements. To guarantee quality communications two kinds of traffic control methods have been dealt with:

1. QoS routing: Path selection taking into account QoS parameters [27], where the task is to determine the path fulfilling QoS requirements with maximal probability (considering that only inaccurate information is obtained about the states of the network links);
2. Call/Connection Admission Control (CAC [19]): which controls the incoming traffic volume by admitting or rejecting the user configurations in order to maintain QoS communication.

The results provided the following benefits:

- More efficient routing results in higher available bandwidth in the network (i.e., the network is capable of transporting heavier traffic)[18].
- Higher network utilization can be achieved by a CAC algorithm which takes into account the stochastic behavior of the users as much as possible. This is an essential objective, because the more users communicate in the network the higher income the service provider has.

Even though the dissertation covers seemingly covers two different topics, they are driven by the same algorithmic treatment. Furthermore, they together can ensure QoS based communication: (i) on the one hand, CAC controls the traffic load; (ii) on the other hand, efficient routing implies that the emitted data streams arrives at the destination, subject to predefined end-to-end QoS parameters.

From algorithmic point of view, the two tasks are similar because the tail distribution of the aggregated traffic of the users has to be examined in the case of CAC, while, in the case of routing, the tail distribution of the aggregated link delays over the selected paths. In addition to these similarities, Chapter 4 shows that the corresponding algorithms can be implemented in a common hardware platform because both tasks can run on analogic computers.

2 Research objectives

The efficiency of the developed methods is supported by real-time adaptability to the possible changes both of the traffic and of the network. The more complex algorithms are applied, the more accurate traffic management can be achieved. The designer, though, must struck a delicate balance between the complexity of traffic management mechanisms and their operational time. This question has been taken into account throughout the research while the yielded results satisfied the requirements above.

Nowadays researchers often think of analogic computers (Cellular Neural Networks - CNN [78, 79, 80]) in connection with real-time signal processing. Since they have already been successfully applied to the field of image processing, the dissertation investigated the possibilities of their telecommunication applications, as well. A real breakthrough may be achieved by applying CNNs to modern telecommunication, because it makes possible complex traffic management algorithms operating in real-time.

3 Preliminaries of the subjects

QoS routing with incomplete information

After the introduction *Chapter 2* discusses the questions of QoS routing with inaccurate link-state information. Routing in IP networks is very often carried out by using the OSPF [25] (and, in the case of ATM, PNNI [21, 26]) protocol. Here costs assigned to links are manually set by observing the link-states in the working network. This method does not support the QoS based transfer because of the randomly fluctuating traffic load on links. Therefore, the major concern is the real-time selection of paths to fulfill the given QoS (e.g. end-to-end delay or minimum bandwidth) requirements. According to this demand, OSPF standard is extended in [23, 27] where link-states are periodically measured in the network (this is referred to as QOSPF). Among others, that is why link measures are not known exactly. Thus, R. Guérin [28] takes them into account as random variables characterized by their probability distribution functions. In this case routing proves to be NP-hard. Although [28] proposes some heuristic and approximative methods to solve the problem, they are hard to use because the equations always contains the hop-count. With my Consultant and some colleagues we tried to find more advantageous solutions presented in [2, 39]. Paper [39] reduces the problem to tail estimation using the Chernoff bound. The proposed algorithms seems to be very efficient on the basis of the simulation results, but the error of the approximation is not formulated. In the dissertation this problem is addressed by an abstract algebraic extension of the Bellman-Ford shortest path selection algorithm [34, 35]. It is demonstrated that this extended algorithm is still tractable and gives a very good approximation for the optimal solution of the original NP-hard task [1].

Call Admission Control on statistical multiplexed traffic flows

However efficient the applied routing is, the throughput of network is limited by link bandwidths. Therefore, besides routing, call admission control (CAC) is also necessary to achieve high network utilization and to get rid of congestion. Access networks connect to the backbone with only offering a given capacity. Then, the main task is to utilize this capacity as much as possible by taking into account the users' statistics. However, utilization needs to be maximized in such a way that the pre-defined QoS parameters (e.g. mean packet delay, packet loss probability) are preserved [20]. If the traffic generated by the users did not comply with these QoS requirements, then those users must be rejected, which task is carried out by CAC. It has been stressed by many papers [52, 53] that the greater is the diversity of the carried traffic, the more instrumental role the traffic management algorithms play in communication networking. At the same time, a compromise has to be made between algorithmic complexity and real-time operation. So far, only 'rule of thumb' type algorithms have been used, which severely reduced network utilization [44]. In papers [54, 55] CAC is regarded as a (neural based) set-separation problem in which high network utilization can be achieved. Furthermore, on/off model is applied as a traffic model, which crudely approximates the real sources, because their statistics are only characterized by a mean rate and peak rate. Of course, this model may be good enough if there is no more information about sources. The dissertation delves into other and more exact traffic models, as well. Chapter 3 shows that set-separation is exactly performed with relatively short pre-computational time and without neural architectures in the case of two traffic classes [4, 7]. An interpolation method extending this to three traffic classes is also presented on the basis of papers [3, 4, 7].

If the exact source parameters are unknown, CAC algorithm is designed on the basis of measures by using the results of non-parametric decision theory [61, 66]. Non-parametric methods are proposed by [44, 56, 62] where set-separation is completed by feed-forward neural nets. However, they approach the difficulties of the learning procedures of the neural nets in a different way. Therefore, the dissertation proposes an approach which leads a novel neural architecture: the "sphere-separator". Its learning algorithm is more robust and less sensitive for the initial weights.

4 Implementation with analog computers

The basic motivation of the dissertation were the application of CNNs. CNN is a neural architecture where processing units are implemented by simple analog circuits and are connected only to their neighbors (defined by a template). Therefore, a very large size CNN can be integrated in a single chip [78, 79, 80].

CNNs have received a considerable interest in real-time image processing and pattern classification [81]. They can out-perform sequential machines and algorithms (with their running time <20 μs). On the basis of these facts, the dissertation treats traffic management problems as how to implement them on CNN architectures. This approach raises the following questions:

- how to transform traffic management problems into quadratic optimization; or
- how to regard traffic management problems as image processing (nearest neighbor classification) task.

In both cases the corresponding traffic management algorithm can run on a CNN. The above-mentioned reasons is clearly indicated in the dissertation by reducing the path selection to quadratic optimization and mapping CAC to wave-propagation and image processing.

Routing by quadratic optimization

One of the possible heuristic methods for solving NP-hard problems is quadratic programming which has two important advantages:

- It has an advantage from algorithmic point of view, because the Hopfield recursion is a polynomial time algorithm. (This method has been also applied for the Traveling Salesman Problem. For instance in papers [82, 83, 84] where additive constraints in the goal function resulted in Hamilton circles. These additive constraints give heuristic nature to the solution.)
- Furthermore, it has another advantage from technological point of view, supposing that the solution can be implemented on fast integrated neural architectures. Such a neural architecture is the above-mentioned CNN, which provides a result within range of microseconds. To this, the connection structure of CNN cells needs to be reduced to the so-called template structure where only the neighboring cells are connected. This kind of problem formulation leads a new algorithmic endeavor and research area.

Section 4.1 in the dissertation clarifies that stability criteria of CNN are valid for Hopfield nets as well, which implies that optimization tasks on Hopfield nets can be implemented on CNNs, provided it is allowed by the connection structure. Section 4.2 based on [8, 11, 12, 13] proposes methods for solving QoS routing in a quadratic form with the help of Fantacci's results [85].

Applying Cellular Neural Networks for Call Admission Control

Section 4.3 treats non-parametric CAC as a set-separation problem regarded as an image processing task and a CNN is proposed to perform this set-separation [3, 9, 10]. This approach could be tested on a real CNN chip, because only the neighboring cells are connected. Since CNNs are two-dimensional, it seems that only two traffic class CAC can be carried out by using one CNN chip. Nevertheless, the interpolation method introduced in Chapter 3 can be applied for a three-dimensional extension of the CNN based CAC [3].

5 Research methods

The methods of the research is summarized in Figure 1 from formulating a problem to the performance analysis of the developed methods. In the course of the research, analytical methods have been developed to the corresponding problems. Performance analysis of the solutions has been carried out by the following three forms:

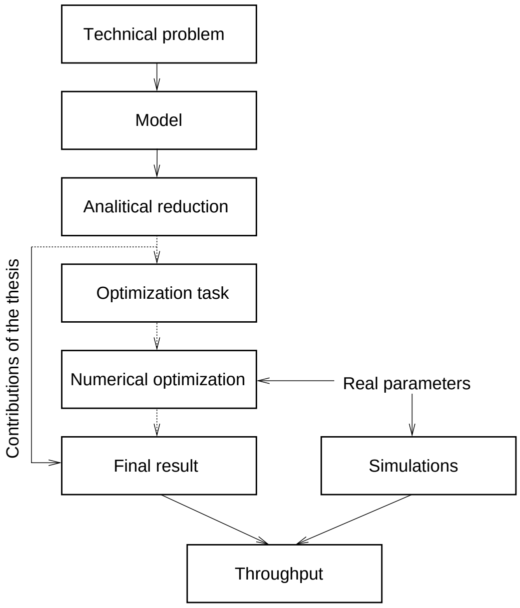

Figure 1: *Research process.*

1. *Analytical computations*: by using the apparatus of discrete mathematics (algorithm theory, combinatorics, graph theory), linear algebra and function analysis. This was possible only with some special constraints which did not impede the practical applications (e.g. in the case of QoS routing with incomplete information).
2. *Numerical optimization*: analytical computations often resulted in an optimization task which could be completed in a numerical fashion (e.g. in the case of the neuron based CAC and the template selection of CNNs).
3. *Simulations*: Numerical testing of the solutions was performed in lifelike environments. The data given by simulations were compared with the estimations obtained by the analytical derivations (if it was possible) and with the efficiency of other methods.

6 Results

According to the structure of the dissertation, the theses can be divided into two big groups: Thesis 1 and 2 deal with routing while Thesis 3 and 4 with CAC. Since Chapter 4 proposes solutions with analog computers in the field of both QoS routing and CAC, the corresponding theses are not summarized in a detached group for the sake of simplicity and understanding.

Thesis 1 ***Bellman-Ford algorithm has been extended and proven to be able to solve QoS routing with incomplete information.***

The following subtheses (1.1-1.3) discuss an extension of the Bellman-Ford shortest path selection algorithm which is capable of handling inaccurate link-state information over algebra $[A, \beta]$. In the applied model, the probability distributions of the additive costs are assigned to links instead of real values. These distributions are included in set A. The extension applies the operation of convolution denoted by β over A instead of the operation of addition. If there are two paths, the one of them is supposed to be better which meets the pre-defined QoS requirement with greater likelihood. To decide this, a tail-estimation based relation $\leq^*$ is introduced which orders the elements of set A:

$$C(R_1) \leq^* C(R_2) \Leftrightarrow \int_D^\infty C(R_1)(x)dx \leq \int_D^\infty C(R_2)(y)dy,$$

where R_1 and R_2 denote the edge set of the two paths and D refers to the QoS criterion (e.g. the given end-to-end delay bound). With this, QoS routing with incomplete information can be written into the following optimization task:

$$R_{\text{opt}} = \arg\min_R{}^* C(R)$$

the complexity of which proves to be NP-hard in general.

Subthesis 1.1 *Stability of the Bellman-Ford algorithm over* $[A, \beta]$ *has been proven and the conditions with which the optimal path is found have also been derived.*

It is proven that Bellman-Ford algorithm over $[A, \beta]$ is stable if β is associative and commutative, the sorting relation over $[A, \beta]$ $(\leq^*)$ is transitive, and non-negativity (i.e. $a \leq^* \beta(a, b) \forall a, b \in A$) is fulfilled; furthermore, it is optimal if monotonity (i.e. $\beta(a, c) \leq^* \beta(b, c) \forall a, b, c \in A$ when $a \leq^* b$) is also satisfied (according to Theorem 2 on page 14).
It is also demonstrated that the p.d.f-s over positive numbers (the delay is positive) meet these conditions except for monotonity. This implies that the extended Bellman-Ford algorithm can be applied as an approximative method (even though the monotonity is not necessarily fulfilled). When the criterion of monotonity is satisfied, the above mentioned NP-hard task becomes polynomially tractable.

Subthesis 1.2 *An upper bound is derived for the expected value and standard deviation of the error of the extended Bellman-Ford algorithm.*

It is demonstrated that the error caused by violating monotonity is very low in practice (in environments according to QOSPF). (See section 2.5.) This error is characterized by the expected value of the following difference: $P_E = \int_D^\infty C(R^*)(x)dx - \int_D^\infty C(R_{\text{opt}})(x)dx$ where R^* denotes the path given by the algorithm. Therefore, this P_E can be interpreted in a concrete graph representation with a concrete delay realization. In the case of a given graph representation, $\mathbf{E}_\delta\{P_E\}$ can be called "average-error" for which an upper bound is analytically expressed under practical circumstances (by Theorem 6 on page 27). Moreover, the standard deviation of P_E is also determined. Due to the nature of upper estimation and the very low resulting numerical values ($\mathbf{E}_\delta\{P_E\} < n0.01$), it can be stated that the given upper bound is of practical importance which proves the benefits of the extended Bellman-Ford algorithm.

Subthesis 1.3 *The extended Bellman-Ford algorithm has been adapted to handle link descriptors having a normal distribution.*

It has been proven that normal distributions also comply with the condition of non-negativity. Therefore, the extended Bellman-Ford algorithm can be applied to the case of normal distributions as well. (See Theorem 3 on page 21.) In this case, link descriptors are considered to have normal distributions with matching criterion $1 - \epsilon$. Thus, the complexity is significantly reduced, because one can get rid of tiresome calculations of convolutions.

Thesis 2 ***It has been demonstrated that routing can be performed by quadratic optimization in such a way that the result yields a valid path.***

Subtheses 2.1-2.2 (according to Section 4.2.2) propose quadratic solutions for routing. A path R can be represented by a matrix $\mathbf{P}$, each row of which corresponds to a node and each column of which relates to a hop in the path.[1] Set of path-matrices defining paths with length L are denoted by $\mathcal{P}^{(L)}$.

Subthesis 2.1 *The weight matrix has been derived in the Hopfield net which can solve routing with fixed hop-count in a recursive manner. It has been guaranteed that the result is a valid path, i.e. it is in set* $\mathcal{P}^{(L)}$.

The following Hopfield model can solve the task

$$y_{ij}(k+1) = \operatorname{usgn}\left\{ \alpha y_{ij}(k) - A\left(\sum_{\substack{l=1\\l\neq i}}^{N} y_{lj}(k) - \sum_{\substack{l=1\\l\neq j}}^{N} y_{il}(k) \right) - \right.$$
$$\left. - \left(\sum_{\substack{l=1\\j<N}}^{N} \kappa_{il} y_{l,j+1}(k) + \sum_{\substack{l=1\\j>1}}^{N} \kappa_{il} y_{l,j-1}(k) \right) + b_{ij} \right\} \quad \left(\text{where } \operatorname{usgn}(z) = \tfrac{\operatorname{sgn}(z)+1}{2}\right)$$

where the specific choice of constants A, α and b_{ij} is determined by Theorem 10 on page 83. This theorem also guarantees that the steady state $\mathbf{Y}^{st}$ indeed yields a valid path (with hop-count L) and minimizes the objective function:

$$\sum_{(u,v)\in R} \kappa_{uv} = \sum_{i=1}^{N} \sum_{j=1}^{N-1} \sum_{l=1}^{N} P_{ij} \kappa_{il} P_{l,j+1}$$

(where R corresponds to path $\mathbf{P} = \mathbf{Y}^{st}$ with hop-count L).

It has also been demonstrated (in Section 4.1.2) that the previous statement is true for CNNs as well.

Subthesis 2.2 *Quadratic routing is extended to select paths without any restriction for the hop-count.*

Quadratic solution for the polynomial Shortest Path Routing (SPR) is given by extending the previous sub-thesis to find the optimal hop-count as well. This results in a more faster path selection in large networks if implementation on analogic computers can be achieved. The extension is performed by the following recursion:

$$y_{ij}(k+1) = \operatorname{usgn}\left\{ \alpha y_{ij}(k) - A \sum_{\substack{l=1\\l\neq i}}^{N} y_{lj}(k) - \right.$$
$$\left. - \left(\sum_{\substack{l=1\\j<N}}^{N} \kappa_{il} y_{l,j+1}(k) + \sum_{\substack{l=1\\j>1}}^{N} \kappa_{il} y_{l,j-1}(k) \right) + b_{ij} \right\}.$$

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[1] For instance path $R = \{(s,v_1),(v_1,v_2),\ldots,(v_{L-1},f)\}$ corresponds to matrix $\mathbf{P}$ where $p_{s,1}=1, p_{v_1,2}=1,\ldots,p_{f,L+1}=1$ and the other elements are zero.

Due to Theorem 11 (on page 85), the obtained $\mathbf{P} = \mathbf{Y}^{st}$ minimizes the $\sum_{i=1}^{N} \sum_{j=1}^{N-1} \sum_{l=1}^{N} P_{ij} \kappa_{il} P_{l,j+1}$ SPR goal function when constants A, α, and b_{ij} meets the same conditions as in the case of the fixed hop routing.

Thesis 3 ***A novel neural based set-separation method has been carried out for non-parametric CAC.***

The following subtheses (3.1-3.2) propose a novel classification procedure for CAC regarded as a convex set-separation task. The traffic state space N has to be divided into two parts ($N^{(1)}$ and $N^{(-1)}$) in such a way that $N^{(1)}$ includes the states meeting QoS requirements (namely, the acceptable states), while $N^{(-1)}$ contains the rejected states. Performing exact CAC is of extensive computational complexity even if simple traffic models are used. Therefore, the optimal decision rule $g(\mathbf{n}) \in \{1, -1\}$ is approximated by using a training set ($\tau^{(K)} = \{(\mathbf{n}_k, d_k), k = 1, 2, \ldots, K\}$) which is obtained by measurements.

If the approximative classification function is denoted by $f(\mathbf{n}, \mathbf{w})$, the goal is to set the optimal values of weight vector $\mathbf{w}$ which minimize the $P(f(\mathbf{n}, \mathbf{w}) \neq g(\mathbf{n}))$ error probability. In section 3.3.3 a novel neural architecture is introduced to carry out convex set-separation which is required with CAC. Since the points keeping the same distance from two points (or two spheres) define a plain in the space, a separator can be constructed by using point-pairs or sphere-pairs. This is referred to as *sphere-separator* in the dissertation.

Subthesis 3.1 *It has been proven that the sphere-separator is capable of asymptotically minimizing the probability of the erroneous decisions when only some measurements are available about the traffic.*

Theorem 8 (see page 63 in the dissertation) states that if the

$$f(\mathbf{n}, \mathbf{w}) = \operatorname{sgn}\left(|\mathbf{n} - \mathbf{b}|^2 - \left|\mathbf{n} - \mathbf{w}^{(+i)}\right|^2 \right)\Big|_{i = \arg \min\limits_{j=1,..,M} \left|\mathbf{n} - \mathbf{w}^{(+j)}\right|}$$

(where $\mathbf{b} \in N^{(-1)}$ is a constant vector and $\mathbf{w} = \left(\mathbf{w}^{(+1)}, \ldots, \mathbf{w}^{(+M)}\right)$) architecture is applied for minimizing the

$$\tilde{E}(\mathbf{w}, \tau^{(K)}) = \frac{1}{2K} \sum_{\{\mathbf{n}_k | d_k = 1\}} (1 - f(\mathbf{n}_k)) + \frac{1}{2K} \sum_{\{\mathbf{n}_k | d_k = -1\}} (1 + f(\mathbf{n}_k))$$

empirical cost function, then the obtained result is asymptotically optimal. Since function $\tilde{E}(\mathbf{w}, \tau)$ is not continuous over $\mathbf{w}$, the hard nonlinearity can be changed to a sigmoid type function in $f(\mathbf{n}, \mathbf{w})$. In this case, the solution remains asymptotically optimal.

Subthesis 3.2 *A gradient method has been developed for training the sphere-separator.*

It has been demonstrated that the gradient method can be used for minimizing the $\tilde{E}(\mathbf{w}, \tau)$ cost function (see page 67). By analyzing the components of this cost function, it is clarified that the sphere-separator has significantly more advantages than the backpropagation type neural networks (see page 65).

Thesis 4 ***A CNN-based, adaptive CAC method has been developed for packet-switched networks.***

A CAC procedure has been introduced where CNN performs the set-separation. The $f(\mathbf{n})$ empirical decision rule based on training set $\tau^{(K)}$ is defined by the so-called propagation model which can be directly implemented on CNNs (see page 94). Eventually this propagation model is a fast implementation of the classification with nearest neighbor rule. Namely, nearest neighbor decision can be interpreted as associating a positive wave with each $\mathbf{n}_k$ point in the training set for which the decision is "accept", while a negative wave is associated with each $\mathbf{n}_k$ point for which the decision is "reject". Since the waves propagate at the same speed, when a specific wave "hits" first a particular $\mathbf{n} \in N$, this wave surely originates from the closest $\mathbf{n}_k$ reference point to $\mathbf{n}$ regarding the Euclidean distance. Section 4.3.2 in the dissertation demonstrates that this wave propagation model can be implemented on analog computers, (two-dimensional) CNNs in the case of two traffic classes.

An algorithm has also been given to determine the connection template with which CNN triggers the appropriate waves for the propagation model. The result is presented on the basis of articles [3, 10] on page 97 in the dissertation.

For the sake of the practical applications of the result, it has been demonstrated that every kind of 2D CAC can be performed by using one CNN chip with size $64x64$ or $256x256$. The arising approximation error proves to be low enough (see Section 4.3.6).

In general three traffic classes are used in Internet access networks (Internet access I, Internet access II, Voice over IP), which implies that the state space becomes 3D instead of 2D. The 2D CNN based CAC is extended to handle three traffic classes by applying various interpolation techniques (see Section 3.2.2 and 4.3.5).

7 Practical applications of the theses

QoS routing: The proposed algorithm for the QoS routing with incomplete information (Thesis 1) can run even in the present routers using OSPF protocol, supposing that the currently used Dijkstra's algorithm is replaced with the new extended algorithm detailed in Thesis 1. (Although the essence of this extension was discussed on the Bellman-Ford algorithm, of course it is valid for Dijkstra's algorithm as well.) Slight protocol modification is necessary for making the solution adjust to network fluctuations, which can be realized in QOSPF. Thesis 1, then, may yield an efficient routing even if the amount of signaling information is strictly limited. Since link descriptors keep changing, the distributed Bellman-Ford algorithm and one of its synchronization mechanisms (e.g Alpha synchronization [40]) needs to be used, which demands link descriptors only by the neighboring nodes.

Quadratic routing: The results of thesis 2 will be applicable in practice when it can be implemented on CNNs.

Call Admission Control: The results provide efficient applications for both VBR services in ATM networks and packet-switched IP access modules (e.g. in ADSL which is sometimes implemented over ATM). On the one hand, the main advantage of the solution proposed by Thesis 3 is the accuracy, on the other hand, CNN based solution of Thesis 4 has a great advantage in the rapid adaptivity.

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