Optimization of communication protocols of packet switched networks by neural algorithms

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1 Introduction

One of the biggest challenges of present day communication technologies lies in the constraints. Resources available to support high speed data transfers are limited which impose serious bottlenecks on communication systems, such as power- and band limited data transfers. On the other hand service providers must ensure Quality of Service (QoS) communication which requires a given level of transmission power (achieving low BER) and needs a given amount of radio spectrum (for providing high data rate). Furthermore the HW elements have limited battery powers which, in certain applications, may not be recharged (e.g. wireless sensor nodes) calling for energy aware communication. These challenges pose network planning and operation as a constrained optimization task e.g.: in the case of Wireless Sensor Networks we want to select the optimal route which requires minimal energy consumption from the nodes participating in packet transmission. Similar tasks can be defined for various network technologies such as Internet Protocol (IP), Wireless Sensor Network (WSN)[1], and Wireless Body Area Network (WBAN)[2, 3]. The main problems among the above mentioned areas are as follows:

- During the last few years multimedia communication (VoIP, Video Streaming) have become dominant as the main part of the internet traffic nevertheless these services require prescribed communication quality. This puts the emphasis on the importance of high speed packet classification on routers, because different packets belonging to different quality requirement needs to be treated differently. Thus actions referring to these services must be performed on real-time basis. In terms of IP, packet classification (PC) [4], which is among others the basis of QoS service [5], has become a key issue. Thus packet classification can become a bottleneck in modern communication systems. The specification of IPv6 (Internet Protocol version 6) provides an opportunity for prioritization of packets. In the IPv6 header alongside the title information a QoS type data field can also be found. Using these implementation, fire-wall and QoS applications become feasible. This task can be further elaborated to develop fast classifications based on the information included in the headers of packets. However, this poses deeper algorithmic challenges which falls within the scope of computational geometry (see [6]).

- Concerning Wireless Sensor Networks, optimization of energy consumption is of outstanding importance. It is widely accepted, that the probability of successful packet transfer under the condition of a given transmission energy and a given distance is determined by the Rayleigh fading model [7]. Since a direct one-hop packet transmission from a node being far away from the base station would consume huge amount of energies [8], we have to use a multi-hop communication model [9] in which there are relay nodes placed between the sending node and the base station. It is an interesting challenge to consider how those transmission energies within the Multi-Hop chain can be minimized which later result in given level of reliability (correct arrival of the packet to the base station with a given probability). Evidently, minimal energy means maximizing lifespan [10, 11] of the corresponding WSN, which can prove to be vital in some sensitive applications.

- The onset of broadband access networks with different QoS parameters presents a direct challenge concerning topology and capacity [12, 13] design. Typical characteristics of these systems that they are organized into a tree-like topology, where the inner nodes have further capacity constraints. Because of the shared-bus architecture the available capacity depends on the actual uploaded and downloaded traffic [14]. Consequently, the main objective is to present a design method for multi-node architectures, which is capable of handling capacity constraints and the effects of bidirectional traffic. With the help of this algorithm we are ready to establish the amount of nodes and link capacities needed in reality to be able to serve a given number of users by a given cell losing probability.

2 Methods

In the theses I applied the following research methodology:

- I set up the stochastic models
- I applied methods of optimization in order to improve the performance of the given communication system, like optimizing the objective function
- I used both numeric and analytic methods for optimization
- I examined the performance of the proposed solutions by simulations, as a result, I managed to set up a ranking of the certain communications protocols.

This methodology is illustrated by figure 1.

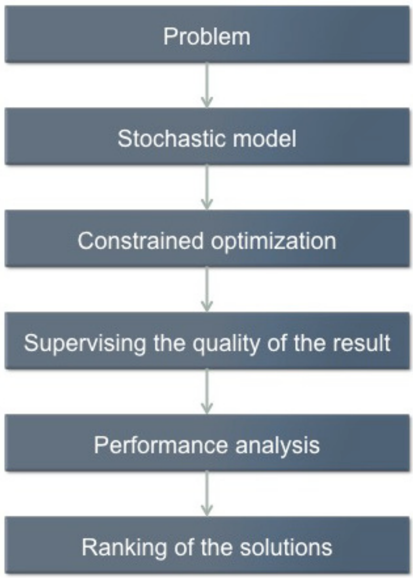

Figure 1: the methodology of the research

The disciplines used for developing the theses include the following elements

- probability theory
- stochastic processes
- combinatorial optimization
- randomized simulations

3 Technological Motivation

In the subsection below, I discuss the detailed technological motivation for all three topics of this thesis.
For the users' packets to reach their destination potentially the fastest way, and with the least errors, such algorithms have to be installed on the routers, which will process and relay those packets without any mistakes. These algorithms decide on the basis of the analysis of the headers of the packets, to which output port of the router the packet should be transmitted (address lookup) more to that, what kind of other processing is needed (for example: filtering the packets in case of utilising a firewall , or prioritised packet processing fulfilling QoS criteria)[5]

3.1 IPv6 and packet classification

Nowadays, usually the routers have a retransmission type function, where the direction of transmission is determined by the header of the incoming data-packet. However, in IPv6, a more complicated packet classification is required. The algorithmic challenge of this task is not only rooted in the great variety of the different packet classification tasks to be performed, but also in the speed at which these tasks are to be carried out. In recent years, the number of Internet users, and the bandwidth they use has dramatically increased [15]. The quality and the quantity of the sent and the received data needs new type of services from the routers. Thus, it is important in which order and priority the router manages data of a video conference, or an mp3 download, or an e-mail transmission. The order of the execution can differ from the order of the incoming requests; whereas the role of router is primarily to get the packets closer and closer to the addressee. For the routers to be able to decide about an action on a packet, or an incoming request, some extra information is needed. This could significantly decrease the transmission speed, because the routers have to process a larger amount of data. There are further difficulties, because according to the data, the 75 percent of size of the packets passing through the Internet are smaller, than an average TCP (Transmission Control Protocol)-packet (522 byte), and most of them are just 40-50 byte [16]. Considering, that the utilized bandwidth has increased to a gigabit scale, and that access time of the memory used by the router is imposing a time frame, it is clear that the algorithms working in the routers have to make a precise decision on the action within a very short interval of time. The need for a new solution can be illustrated by the following example: let's take the IP packets of the size of 40 bytes, the ports of the router to 10 Gbit/sec , and let the router have 10 ports. In this scenario, the worst case is that we have to make a decision about the classification of the packet under 3.2 nsec. The average access speed of the DRAM is also in this range, 3-5 nsec. This indicates, that only fast algorithms of packet classification can result in fast packet transmission.

3.2 Reliable packet transmission in wireless networks

In recent years, the application of sensor networks have penetrated in almost everywhere, hence, considering the limited energy resources of the sensors, the development of energy aware communication protocols have become mandatory [8]. This issue particularly came to the fore, in the case of situations, where re-charging of the sensor batteries is not possible. A good example of this is a body implanted sensor [17]. Here the priority is to utilize the given energy resource as long as possible. Considering, that the most energy consumption in the sensor is consumed by the radio transmitter, new communication protocols are mostly optimized for the transmission energy [18]. This assumption is particularly true for the so-called multi-hop communication, where nodes, in order to send their information to the base stations with relatively small transmission energy, are using other nodes in the network for relay. The likelihood of a successful packet transmission can be described with the help of a given fading-model (for example Rayleigh fading) [7], so during multihop-communication, packet loss can occur [9]. Therefore the task is to develop novel routing algorithms, which can guarantee that the probability of the packet loss is less than a prescribed value, and at the same time, the energy consumption of the nodes attending the packet transmission is minimal [10, 11]. Currently, the following protocols ensure the energy-consciousness:

- Energy Conserving Routing [19];
- LEACH [10];

- PAMAS [20].

These protocols, however, do not guarantee a prescribed reliability, therefore it is a challenge to design new protocols, which besides energy-consciousness, can guarantee the prescribed reliability.

3.3 Network-dimensioning in packet switched networks

In the case of packet switched networks, one has to guarantee a prescribed service quality. As a result network planning (dimensioning) becomes a constrained optimization task, where the objective is to design architectures with minimal hardware complexity with a given probability of cell loss. So the results of this thesis yield minimum complexity access architectures.

Thesisgroup 1

4 Packet classification in IP-networks

4.1 Formal model of packet classification - packet classification tables

The objective of packet classification is to perform actions (activities) on the packets based on their header fields. For example: in case of a firewall application, discarding a packet arriving from a forbidden address, or in terms of VoIP priority has to be ensured. This task can be formalized as follows:

- $q_1, ..., q_D$ denotes the binary strings in the headers of the packet;
- given a set of $f_1, ..., f_L$ logical functions defined on the given headers; together with an $A_1, ..., A_L$ action belonging to each functions;
- find as quickly as possible those logical functions $i_1, ..., i_l$, to which $f_{ij}(q_1, ..., q_D) = TRUE, j = 1, ..., l$
- selecting the one of the functions which take top priority $v \in i_1, ..., i_l$ and perform action A_v.

On the basis of the definition above the operation of the PC is demonstrated as follows:

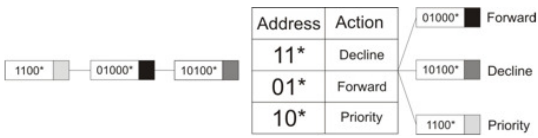

Figure 2: Operation of PC tables

In practice logical functions usually appear as masking operations, therefore their fulfillment means a “matching”. The longest match has the largest priority. A practical PC table is given as Table 4.1.

Rule	F1	F2
R_1	00*	00*
R_2	0*	01*
R_3	1*	0*
R_4	00*	0*
R_5	0*	1*
R_6	*	1*

Table 1: Structure of a PC table

According to the discussion above PC can also be interpreted as a geometrical task. (see [21, 22, 23]). Let Q_i denote the set belonging to action A_i, i.e. $Q_i = \{q_1, ..., q_D : f_i(q_1, ..., q_D) = TRUE\}$. Observing the packet header $q_1, ..., q_D$ this determines a D dimensional point $r = (q_1, ..., q_D)$, where each coordinate is given in a binary form. The objective is to identify the set Q_i which consists of r for which $r \in Q_i$. On the basis of this action A_i can be carried out.

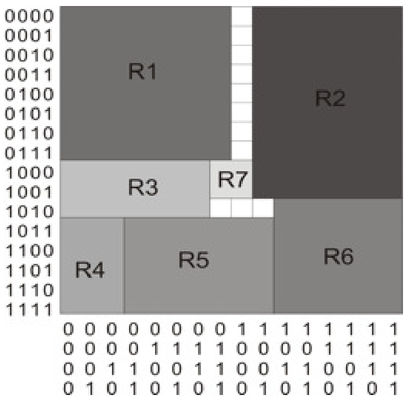

Figure 3: A PC képfeldolgozási módszerrel

Figure 3. shows the geometrical representation of one byte. One can see that the rule defines an area and the arriving PC corresponds to a point. The task is to locate the point in the plane. This problem has been studied by several authors (see [24, 25, 26]).

4.2 Packet classification as an image processing task - Packet classification using Cellular Neural Network (CNN)

As was mentioned earlier, packet classification can be conceived as a geometrical task. In this interpretation the header field of the incoming packet determines a point in the space and one has to identify the set to which it belongs to and the corresponding rule must be carried out. All this must be done with polynomial complexity. Consequently, if we map the rule set into a geometrical representation where each area unambiguously determines a rule, we only have to read out in which area the incoming address is included. This way the problem can also be interpreted as an image processing task: one has to "shade" the subset where the point determined by the current header of the packet belongs to. This interpretation is important because if there is an opportunity for real time image processing (eg. with a CNN) the processing time of packet classification can be considerably sped-up so the IPv6 based network communication can gain speed.

Thesis 1.1 *I have proven that packet classification can be solved with CNN-architecture with using the following templates*

The problem above can be solved by a CNN-architecture [27, 28, 29, 30], where the (black/white) state of each image points corresponds to a binary output. From the point corresponding to the header field of the incoming packet a wave is triggered which will "colour" the region where the point belongs to (so the outputs of all the neurons in the region become active in steady-state). As the transient time corresponding to the spread of waves is in the region of microseconds, the operation time of packet classification would move in this region which would enable packet classification at Mbit/sec speed in the routers. The intuitive picture of the solution is introduced in figure 4.

For CNN implementation, one must solve the following problems:

- each rule must be uniquely mapped into a 2D space (even if one has to examine more than two header-fields;
- placing the contours of the region in accordance with the rules, on the surface of the CNN;

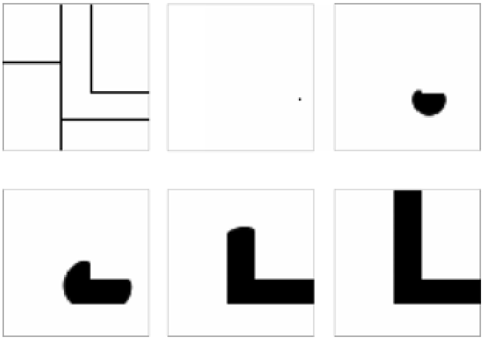

Figure 4: Wave propagation on a simple rule-set (τ =0,3,6,12,20)

- to set a packet header as a point on the raster;
- generating waves based on the given templates;
- identifying which region has been filled in.

In order to develop a CNN based PC algorithm let us start to denote the location of the cells with $C(i, j) = C(0, 0)$. The pixels are separated into two sets: every $u_{ij} : (i \wedge j = odd)$ pixel belongs to the area which contains the point corresponding to the incoming packet, while $y_{ij} : (i \vee j = even)$ pixel corresponds with the rules. The incoming IP address will uniquely determine a cell of the CNN, and the set of rules will define an area of cells. Our task is to determine the area which contains that specific cell which is associated with the incoming packet. This identification can be by the CNN architecture. If a wave is generated from the cell associated with the header of the incoming packet, then this wave will colour the cells belonging to the full region representing the corresponding rule. The nature of this wave propagation is is detailed in [31]. Since every area has a reference point $r_t \in u_{ij}(i \wedge j = odd)$, the "colour" of the reference point uniquely shows the active area.

The problem which occurs when implementing the CNN based PC is that we need the number of cells which is twice as much as the current IPv6 addresses. The largest presently available CNN chip is 256X256. As a result, we need to split up the address recognition task into smaller fields for instance into bytes. This requires the following steps:

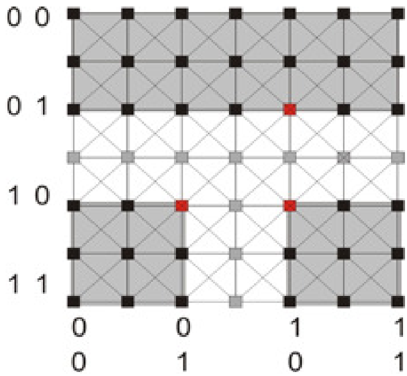

Figure 5: Location of reference points on the CNN grid

- The address of the incoming IP packet is split into bytes and each byte will uniquely determine a cell from which the waves are generated.
- The rules are also split up into subrules which will define areas on the corresponding CNN grid. If the rule is longer than one byte (for instance: 10101010111*) then there are some CNNs on which it defines a single cell, while on the other CNN it defines an area.

The rules can be mapped into geometric areas as follows:

For the nth byte a structure on the CNN is constructed by each R_k operating on the nth byte:

$y_{i,j}$ = 1, if $\exists$ such $p, q \in -1, 0, 1$ where $i + p$ and $j + q$ even and $IP_{i+p,j+q} \in R_k[n]$, and $IP_{i-p,j-q} \notin R_k[n]$, otherwise $y_{i,j} = -1$.

The $IP_{i,k}$ contains the binary values of the incoming IP packets identifying a part of the grid on a 32X32 CNN in the following way: $IP_{i,k}$ = [i(1) j(1) i(2) j(2) i(3) j(3) i(4) j(4)] 8 byte value where $i(x)$ means xth bit of i's binary value. There is a need for a CNN template which can carry out this mode of operation [32, 33, 34]. If the rules are considered as the input variables of the CNN ($y_{i,j}$), and the incoming packet is associated with the initial state of the corresponding cell (ui,j), and the pixels at the boundaries of CNN are set to be white (Boundary = -1), then with the following variables it will provide the solution to the problem:

$$A = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{pmatrix} \; B = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -8 & 0 \\ 0 & 0 & 0 \end{pmatrix} \; Z_0 = -2 \tag{1}$$

For the running condition of the CNN we set the change (activation) any reference points to 1. The final decision is made by a logical processor and all the 6 CNNs are connected to the input of this logical processor (see: graph 6) The logical processor requires results from all the 6 CNNs and on the basis of the rules at its disposal it decides which rule is to fulfil.

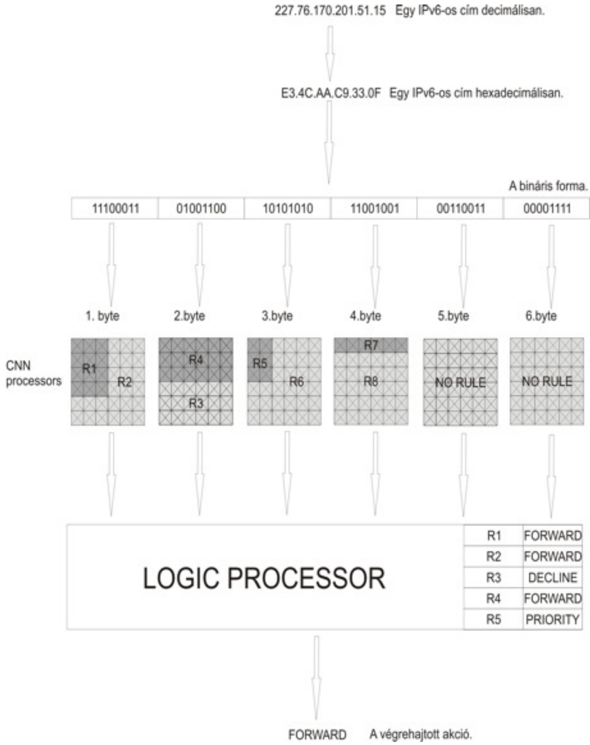

Figure 6: The logical setup of the architecture

4.3 Numerical results

The simulation environment has been constructed as follows: 80479 packets have been taken from the server Argus, Wilbreforce University, Ohio which amounts to a two-minute length data stream. The number of rules the router recognized was 1219. I have programmed each algorithms and I have run them on the same computer and topology. The following next graphs introduce the results of the above mentioned simulation so that to clearly demonstrate the differences.

One can see that the Radix algorithm is sensitive to rule numbers. At the same time if

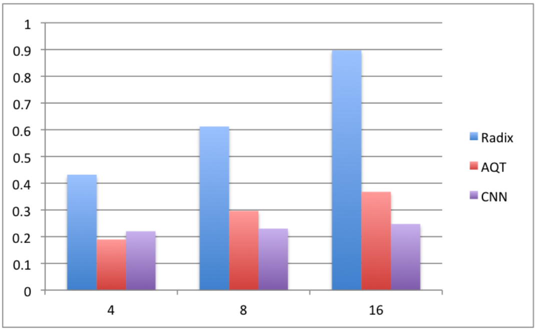

Figure 7: Performance of CNN PC compared with other PC algorithms on packets arriving from the same source but classified with different rule numbers.

AQT is implemented on DSP then due to the quick multiplication and parallelism it will become indifferent in respect to rule numbers. This procedure depending on the environment remains less sensitive to rule numbers. Furthermore, in case of proper length packets due to the first match the method will not make any difference.

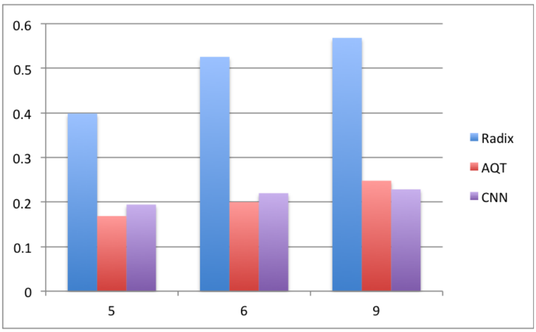

Figure 8: The effect of changing packet length under fixed rule number

It is clearly demonstrated above why the traditional Radix method is not capable for IPv6 networks. Because of the dependency of Radix on the length of packet stream it will slow down processing longer headers. In this case, the CNN provides the best performance.

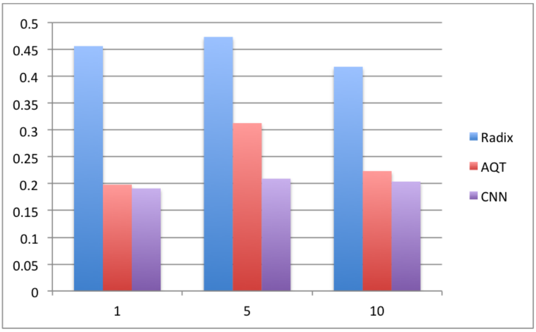

Figure 9: Classification time by changing the source numbers and fixing all the other parameters

Thesisgroup 2

5 Wireless Sensor Networks

Nowadays the main scope of research is the maximization of life span of sensor networks together with the optimization of energy. The common factor of these works is that optimal energy level generally is searched on a continuous scale [35, 36, 37, 38, 39, 40]. However, from the aspect of the physical feasibility the transmission energy of sensors can be chosen from a discrete set. According to this, the determination of the optimal transmission energy has to be conducted on discrete values used by the nodes. Consequently, it leads to a new type of combinatorial optimization task. In this second thesis I have worked out three novel methods which are close to each other. All these three methods are capable of identifying new routes by using low complexity operations which consume minimal energy from the discrete energy resources of the nodes. Although, these solutions can be regarded as sub-optimal but compared with the Leach protocol [10, 41] they guarantee energy saving route selection. The improvement can be explained as follows:

- On the one hand, it guarantees prescribed reliability (the packet is arriving to the base station under the condition of given level of reliability)
- On the other hand, besides fulfilling the reliability constraints, we transfer the packets to the base station by less energy consumption.

5.1 The Model

My objective is to find the optimal route with respect to minimizing the energy subject to the constraints that the packet reaches the base station with a given probability. The network is modelled by a two-dimensional graph where v denotes the edges which represent the radio links among the nodes. Each edge contains a weight referring to the probability of successful transmission successful packettransfer over the edge dictated by the Rayleigh

Fading model, given in (2).

$$P_{i_j,i_{j+1}} = \Psi(d_{i_j,i_{j+1}}, Gi_j, i_{j+1}) = e^{-\theta*\sigma^2*d^{\alpha}_{i_j,i_{j+1}}/Gi_j,i_{j+1}-G_0} \tag{2}$$

It can be seen that this probability depends on the transmission energy. If the packet is transmitted along a given route and supposing the independent packet losses, the probability of successful arrival to the base station is given as follows: A route denoted by R is described by a vector V and a vector E and a distance metric. Vector V in route R contains the participating v-s (edges) along the route, and vector E contains the energy belonging to the edges. The distance metric describes the distance between the edges.

$$R(V, E, d_{\in V}) \tag{3}$$

My objective is to find the optimal R_{opt}.

I have chosen an environment to my model where the probability of the packet transmission in case of wireless packet transmission in case of wireless packet transmission can be described with a function (Ψ) which is parameterized by (d) the distance and (g) the transmission energy.

$$P_{u,v} = \Psi(d_{u,v}, g) \tag{4}$$

The constraint to be met is that the probability of the arrival of the packet transmitted along the route should stay above the critical level (ϵ) defined either by us or the constructor of the network, so the assumption can be expressed by the following:

$$\prod_{u,v} \Psi(d_{u,v}, g) \geq 1 - \epsilon \tag{5}$$

or alternativle written

$$\sum_{(u,v)\in R} -\lg(\Psi(d_{u,v}, g)) \leq -\lg(1 - \epsilon) \tag{6}$$

Bearing in mind, that our present assumption is that the transmission energies can take discrete values $(G_1, G_2, ..., G_N)$, the objective function of the problem is to minimize transmission energy.

$$\min(g), g \in \{G_1, G_2, ..., G_N\} \tag{7}$$

Using this method, the objective function has been transformed to an additive function, which makes routing possible by the Bellman-Ford algorithm.

Instead of continuous energy level optimization we have to examine 8-10 discrete energy levels. With this assumption we can easily find an optimal route from the aspect of energy. The task can be solved with the following algorithm.

Step 1.

During the first phase I set all energies to be minimal and so I search the optimal route; I don't take into account the criterion referring to the whole probability of packet transmission (Formula 7). So the task is as follows:

$$g_0 \rightarrow R_0 : \min \sum_{(u,v)\in R} -\lg(\Psi(d_{u,v}, g)) \tag{8}$$

This can be solved in polynomial time by using either a Dijksra or a Bellman-Ford algorithm.

Step 2.

The second phase of the iteration step is to check whether the received values fulfil or not the above mentioned reception constraint and on the basis of these I can approach the solution.

$$\sum_{(u,v)\in R} -\lg(\Psi(d_{u,v}, g)) \leq -\lg(1-\epsilon) \tag{9}$$

If it fulfils, then

$$g_1 := g_0 - \Delta \tag{10}$$

If it doesn't, then

$$g_1 := g_0 + \Delta \tag{11}$$

This method raises the energy levels to that point till it meets the criterion set in the assumption. This way I can receive a cost efficient and quick solution.

Thesis 2.1 *Taking into account network topology I prepared a modified algorithm for further capacity improvement*

In case of an evenly distributed network it has very good results, but it doesn't take into account the fact that the nodes of the network might not be distributed evenly but they can be clustered as well. The other problem which is not taken into account that nodes close to the base station can easily become a bottleneck because they can quickly go flat losing their energy. That is the reason that we always raise the energy level of the most energy abundant node until it does not fulfil the assumption or its energy level does not differ from the basic level. Let's define n as an integer number which determines to what extent one can raise the energy level of the nodes. The basic energy level is raised once the energy level of the nodes cannot be raised further. Observe that in case of $n = 0$ the algorithm is similar to the earlier one.

The algorithm described as follows:

Algorithm 1 G - iteration algorithm

$GlobalG := 0$
loop
  $G_{1..N} := GlobalG$
  repeat
    if Required Probability satisfied **then**
      return G
    end if
    $G_x := G_x + 1$ where $G_x < GlobalG$
  until exists $G_{1..N} < GlobalG$
  $GlobalG := GlobalG + 1$
end loop

During the simulation the method is called as G.

Thesis 2.2 *I have developed the algorithm by excluding the nodes with minimal energy and this way I could reach a relatively high performance improvement.*

The second modification can be conceived as another approach to the same problem taking into account energy levels as well. The gist of the modification is that we exclude from the process of packet classification those nodes which energy level is under the average. These nodes transmit packets only if those packets are generated on them.

Algorithm 2 MinG - Low energy exclude

loop
  T :=average value of $A_{1..N}$
  $I = \emptyset$
  for all Nodes **do**
    if $A(Node) > T$ **then**
      $I+ = Node$
    end if
  end for
  RUN $G(I)$
end loop

With the application of this method we do not burden stronger ones but save weaker ones. During the simulation this method will be mentioned as MinG.

5.2 Performance analysis

The next figure shows how many packets can be transmitted in the networks till they reach the depletion criterion.

It can be clearly seen that our fix-G algorithms have multiple results. These results further underline that if parameter n too big to the fix-G algorithm the performance will definitely fall back.

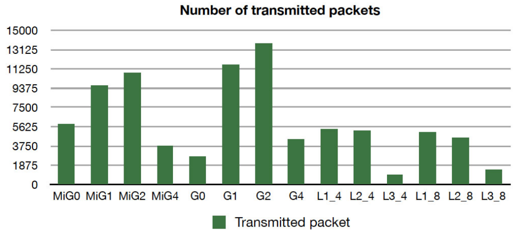

Figure 10: Number of transmitted packets (x1000) till the network goes flat

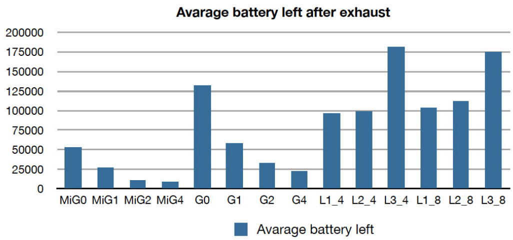

Figure 11: The remaining energy in the network after it went flat

This figure shows that MinG algorithms are really intended to share the energy load as uniformly as possible, because these algorithms use to the smallest amount of extra energy that is left in the network. Comparing with Figure 10 it can be clearly seen that from the aspect of the main goal (packet transmission) this method was not the most successful. I have to conclude that the performance of the network which has the least energy left at the end of the process is not necessarily the best one. Concerning the network with G2 algorithm, it can be stated that almost three times as much energy was left at the end than with MinG4 which has gone flat after transmitting three million packets, while the other could transmit more than thirteen million packets.

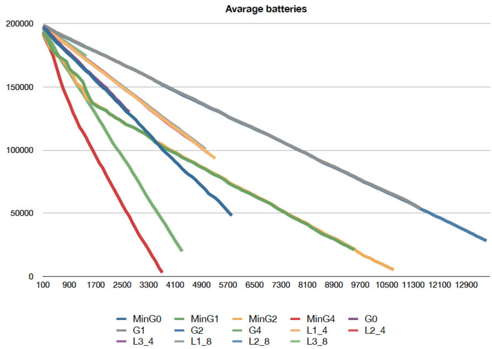

Figure 12: The average energy by networks

In Figure 12, it can be well observed that how nodes with more and with less energy survive. It is visible that MinG algorithms, as they have noticed that the energy of one of their nodes are diminishing do not let those nodes to take part in the communication. That is why the minimal energy has been decreased in smaller degree after a while. Further from that, it can also be stated that those networks where the max node energy is high enough do have additional resources.

5.3 Importance of the results

As a summary, one can tell, that the algorithms can achieve the following properties:

- preserving the energy of the nodes in the network
- synchronizing the energy levels between the nodes
- keep the desired transmission quality until the the network goes flat.

This for example decreases the costs of a facility-monitoring, but for example keeps the quality of the transmission in a client-monitoring system in a hospital, where it is critical.

Thesisgroup 3

6 Network dimensioning in packet switched networks

In this thesis I introduce new algorithms for dimensioning the Hierarchical Admission Module (HAM) which provides internet access to different users. These new algorithms ensure for each user a given quality service regarding fixed packet loss probability. Therefore, my objective is to design the optimal topology of HAM with minimal hardware complexity with respect to the number of units and link capacities. To be able to find the optimal architecture, we have to investigate the state space of topologies and link capacities so as to find the optimal architecture. The above mentioned process maps network dimensioning into an optimization problem to which hereafter I will refer to as NCAP (Node and Capacity Arrangement Problem). The planning can be performed with the help of two means: on the one hand, we estimate the tail distribution of the traffic applying the Large Deviations Theory and on the other hand, we use combinatorial optimization algorithms.

6.1 The model

In case of a typical internet access service providers categorize users into the following three traffic classes.

- Internet Access1;
- Internet Access2;
- Voice over ADSL.

For these traffic classes users can be seen as ON/OFF sources, with m_1, m_2, m_3 average and with h_1, h_2, h_3 peak respectively. The $\gamma_1, \gamma_2, \gamma_3$ QoS-parameter defines the degree of the acceptable Cell Loss Probability (CLP). According to the above mentioned statement the expected output of scaling is shown as follows:

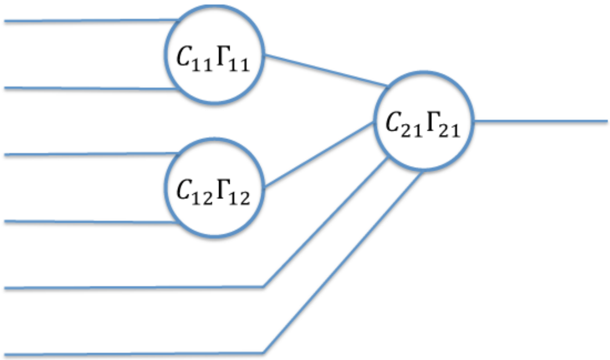

Figure 13: The output structure of scaling algorithm

On the basis of figure 13, HAM can be viewed as a set of nodes which are placed in a tree topology. Scaling algorithm defines the topology and also assigns QoS parameters and link capacities to each node. On the basis of this HAM can be formally described as follows:

$$HAM = \{V, E, \mathbf{C}, \mathbf{\Gamma}\}, \tag{12}$$

where V denotes the vertexes and E denotes the edges, while $\mathbf{C}$ and $\mathbf{\Gamma}$ denotes the capacities and the matrix of the QoS parameters in the following way:

$$C_{kj} = C_j(k) \tag{13}$$

the capacity of node j in the layer k.

$$\Gamma_{kj} = \gamma_j(k) \tag{14}$$

the expected QoS value of node j in the layer k.

It should be noted that when HAM compiled of a lot of nodes, cells can be lost any device so then stricter CLP requirements have to be enforced on each node. As a result of this, the decomposition of aggregated CLP values referring to the nodes is a real challenge indeed.

To describe HAM we are going to use the following notations:

- traffic classes: $i = 1, ..., M$;
- layers in the tree topology: $k = 1, ..., K$;
- nodes in layer k: $l = 1, ..., L_k$;
- admission vector of node j in layer k: $\mathbf{n}^j(k)$, where component $n_i^j(k)$ indicates the number of sources from class i
- the set of admissible vectors is termed as *Admission Set* (AS) containing traffic vectors which are associated with the corresponding nodes in the tree topology is defined as

$$\text{AS} = \left\{\mathbf{n}^l(k)\ \forall l = 1, ..., L_k\ \forall k = 1, ..., K\right\}; \tag{15}$$

- the input traffic state vector is given as

$$\mathbf{v}(1) = \left(\mathbf{n}^1(1), \mathbf{n}^2(1), ..., \mathbf{n}^{L_1}(1)\right) \tag{16}$$

Note that there is relationship between the input state vector and AS, namely every input state vector can be decomposed into an AS by using the following definition:

<u>Decomposition of the input state vector:</u>
The decomposition of the input state vector $\mathbf{v}(1) = \left(\mathbf{n}^1(1), \mathbf{n}^2(1), ..., \mathbf{n}^{L_1}(1)\right)$ *into an AS according to the flow of the graph is defined in the following way:*

$$n_i^l(k) = \sum_{j \in A_l} n_i^j(k-1), \tag{17}$$

where A_l denotes the set of nodes in layer $k-1$ which are connected to node l in layer k.

It is clear that the decomposition defined above can be regarded as a mapping $V \to$ AS, where the input is an input state vector $\mathbf{v}(1)$ and the output is an Admission Set denoted by AS$(\mathbf{v}(1))$.

The data-structure representing the HAM can be described as follows: the HAM as a graph $G\{V, E, \mathbf{C}, \mathbf{\Gamma}\}$ can be totally described with $\mathbf{C}$ and Γ matrices. Using these matrices both the topology and the corresponding capacity $\{C_l(k),\ l = 1, .., L_k,\ k = 1, ..., K\}$, and the QoS parameters $\{\gamma_l(k),\ l = 1, .., L_k,\ k = 1, ..., K\}$ can be restored.

The topology matrix can be described as follows:

$$G_{kl} = \begin{cases} 1 & \text{if there is a node at position } l \text{ in layer } k \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

The QoS arrangement of HAM in the case of a given topology $\mathbf{G}$ is denoted by a matrix Γ^G where element kl indicates the QoS parameter belonging to node l in layer k. If there is no node at position l in layer k then $\Gamma^G_{kl} = 0$, meaning that $G_{kl} = 0$ implies $\Gamma^G_{kl} = 0$. Furthermore, we assume that the possible QoS values form a discrete set $\gamma_1, ..., \gamma_V$. Therefore, the set $- = \{\Gamma_{min}, ..., \Gamma_{max}\}$ contains the possible QoS matrices. The matrix Γ^G_{min} is defined as $\Gamma_{kl} =$ Min, while matrix Γ^G_{max} is defined as $\Gamma_{kl} =$ Max, where Min and Max are previously determined values. In this way searching for a proper QoS scheme, the dimensioning algorithm will sweep through the interval $G_{kl} \in (\text{Min}, \text{Max})$ for each node ($l = 1, ..., L_k$ and $k = 1, ..., K$).

The capacity arrangement of HAM is expressed by matrix $\mathbf{C}$. One must note that if $G_{kl} = 0$ then $C_{kl} = 0$, which means that capacity can only be allocated to existing nodes in the topology. A possible capacity matrix belonging to a topology $\mathbf{G}$ is denoted by $\mathbf{C}^G$ (where $C_{ij}^G \in \{C_1, ..., C_R\}$). These matrices form a discrete space denoted by $\mathcal{C}^G = \left\{\mathbf{C}_{min}^G, \mathbf{C}_2^G, ..., \mathbf{C}_{max}^G\right\}$. Where $\mathbf{C}_{min}^G : C_{ij} = C_1 G_{ij} \, \forall i, j$ is the network topology containing minimum capacity nodes and $\mathbf{C}_{max}^G : C_{ij} = C_R G_{ij} \, \forall i, j$ is the same topology but containing maximum capacity nodes. Since there is a finite number of possible capacities the programmer can order the set $\mathcal{C}^G$ according to any arbitrary rules. (We adapted the ordering scheme which is based on the sum of the elements and on the rank of indices of the corresponding matrices.)

The dimensioning algorithm is engaged with optimizing the matrices describing HAM.

Given a set of discrete capacities $\mathcal{C} = \{C_1, ..., C_R\}$ $C_1 < C_2 < ... < C_R$*, an input load expressed by traffic configuration vector* $\mathbf{n} = (n_1, ..., n_M)$*, and a CLP level* γ *as the QoS parameter.*
Set $C := C_1$ *and* $r := 1$.
Calculate the logarithmic moment generating functions $\mu_i(s)$ $i = 1, ..., M$.

1. *Determine* $s_{opt} : \inf_s \sum_{i=1}^{M} n_i \mu_i(s) - sC$

2. *Check whether* $\sum_{i=1}^{M} n_i \mu_i(s_{opt}) < s_{opt} C - \gamma$ *holds.*

3. *If YES then return with* C *if NOT then set* $r := r + 1$ *and go back to* Step 1.

With this algorithm one finds the minimal capacity C_{min} which is sufficient enough to accommodate the load vector $\mathbf{n}$ at a γ level of QoS.

6.2 Multinode dimensioning algorithms

In the case of dimensioning the designer's task is to find a topology of HAM with the corresponding capacities which fulfill a given overall QoS parameters for a given load vector. Therefore, we seek a mapping from the input load vector $\mathbf{v}(1)$ and end-to-end QoS requirement to a $G_{opt}(V, E, \mathbf{C}, \mathbf{\Gamma})$. This optimization problem, referred to as NCAP, can be formally defined as

$$G_{opt}\left\{V, E, \mathbf{C}, \mathbf{\Gamma}\right\} = \Psi(\mathbf{v}(1), \gamma); \tag{19}$$

where

$$G_{opt}(V, E, \mathbf{C}, \mathbf{\Gamma}) : \, min_{G(V,E,\mathbf{C},\mathbf{\Gamma})} \sum_{k=1}^{K} L_k. \tag{20}$$

However, one must pay attention to the fact that there are many different Γ matrices which can fulfill an overall QoS requirement γ. Therefore, not only the capacity arrangement but also a QoS arrangement must be given, which identifies how the overall QoS parameter is ”distributed” among the nodes of a given topology.

To yield a solution, we take a recursive approach to the problem. Namely, we start with a minimal configuration $G\{V, E, \mathbf{C}, \Gamma\}$ (containing the smallest number of nodes) then we check whether the required QoS level is met or not. If not, we enlarge this configuration by adding nodes and check the QoS requirement until for the given input configuration $\mathbf{v}(1)$ the overall CLP is met. Since we start with the smallest capacity arrangement and continuously enlarge it this algorithm will find the optimal solution for a given input configuration.

Thesis 3.1 *To reach the optimal HAM I have developed a multi-node optimization algorithm*

Multi-node dimensioning algorithm

Given a traffic configuration at the input of all nodes in the first layer

$$\mathbf{v}(1) = \left(\mathbf{n}^1(1), \mathbf{n}^2(1), ..., \mathbf{n}^{L_1}(1)\right) \tag{21}$$

and a matrix of logical variables $\mathbf{T}$ the T_{kl} element of which indicates whether the local QoS criterion on node l in layer k is met or not.
An overall logical variable U indicating whether the overall QoS requirement is met or not.

1. *Set* $\mathbf{G}$=$\mathbf{G}_{min}$*;*

2. *Decompose* $\mathbf{v}(1)$ *into an admissible set* $AS(\mathbf{v}(1)) = \{\mathbf{n}^l(k),\, l = 1, ..., L_k,\, k = 1, ..., K\}$;

3. *Set* $\mathbf{C}^G := \mathbf{C}^G_{max}$;

4. *Set* $\mathbf{Q}^G := \mathbf{Q}^G_{max}$;

5. *Calculate* $s_{l\ opt}(k)$ *by solving*

$$s_{l\,opt}(k): \ \sum_{i=1}^{M} n_i^l(k) \frac{d\mu_i(s)}{ds} = C_l(k) \ \ \forall l = 1, ..., L_k \ k = 1, ..., K$$

6. *If*

$$T_{lk} = \begin{cases} \textit{TRUE} & \textit{if} \ \ \sum_{i=1}^{M} n_i^l(k)\mu_i(s_{l\,opt}(k)) < s_{l\,opt}(k)C_l(k) - \gamma_l(k) \\ \textit{FALSE} & \textit{if} \ \ \sum_{i=1}^{M} n_i^l(k)\mu_i(s_{l\,opt}(k)) > s_{l\,opt}(k)C_l(k) - \gamma_l(k) \end{cases} \tag{22}$$

7. *Calculate* $U := \bigcap_{k=1}^{K} \bigcap_{l=1}^{L_l} T_{kl}$.

8. *If* $U = $ *FALSE then enlarge the topology by setting* $\mathbf{G} := \mathbf{G}_2$ *and go back to* Step 3 *and repeat this loop until* $U = $ *TRUE*

9. *If* $U = $ *TRUE then topology is found but relax QoS requirements by choosing another* $\mathbf{Q}^G \in \mathcal{Q}^G$ *by setting* $\mathbf{Q}^G := \mathbf{Q}_2$ *and go back to* Step 5 *and repeat this loop until* $U = $ *FALSE or* $\sum_{k=1}^{K} \sum_{l=1}^{L_k} e^{-\gamma_l(k)} > e^{-\gamma}$ *then return to the previous value of* $\mathbf{Q^G}$

10. *If* $U = $ *TRUE then topology is found, but decrease capacity by choosing another* $\mathbf{C}^G \in \mathcal{C}^G$ *by setting* $\mathbf{C}^G := \mathbf{C}_2$ *and go back to* Step 4 *and repeat this loop until* $U = $ *FALSE then return to the previous value of* $\mathbf{C^G}$

11. *Return with matrices* $\mathbf{G}, \mathbf{C}^G, \mathbf{Q}^G$ *which completely determine* $G_{opt}\,\{V, E, \mathbf{C}, \mathbf{\Gamma}\}$

One can see that this algorithm returns the optimal AR indeed, as not only the number nodes are minimized (finding the smallest topology) but at the same token the corresponding capacity and QoS arrangements, as well. In this way we find the least stringent conditions in which the minimal topology network can serve the balanced traffic load vector with the given overall QoS.

6.3 Numerical results

The following tables introduce the optimal topologies for a given typical traffic load configuration (traffic load configuration can be expressed with the number of users in the given traffic class).

1. 100% Internet Access1 users (uplink+downlink): $\mathbf{n} = (3000, 3000, 0, 0, 0, 0)$;
2. 70% Internet Access1 users (uplink+downlink)+ 30% Voice over DSL users (uplink+downlink):$\mathbf{n} = (2100, 2100, 0, 0, 900, 900)$;
3. 50% Internet Access1 users (uplink+downlink) + 20% Internet Access2 users (uplink+downlink) + 30% Voice over DSL users (uplink+downlink): $\mathbf{n} = (1500, 1500, 600, 600, 900, 900)$
4. 70% Internet Access2 users (uplink+downlink)+ 30% Voice over DSL users (uplink+downlink): $\mathbf{n} = (0, 0, 2100, 2100, 900, 900)$

One must not forget that only 10 % of the users are actively engaged with transmitting or receiving cells.

Running the dimensioning algorithm, the optimal HAM is obtained as given in table 2.

One can see that for different output vectors only the capacity and QoS arrangements are different.

	number of subracks	QoS parameter((γ_1, γ_2))	capacity(C_1, C_2)
1.(100%)	1st layer 12 2nd layer 1	1st layer 7.895 2nd layer 9.215	5.23 Mbit/s 12.21 Mbit/s
2.(70-30)	1st layer 12 2nd layer 1	2nd layer 7.895 2nd layer 9.215	5.23 Mbit/s 12.21 Mbit/s
3.(50-20-30)	1st layer 12 2nd layer 1	1st layer 7.895 2nd layer 9.215	6.98 Mbits/s 19.2 Mbit/s
4.(70-30)	1st layer 12 2nd layer 1	1st layer 7.895 2nd layer 9.215	8.72 Mbit/s 22.69 Mbit/s

Table 2: Optimal topologies with balanced load algorithms found by traffic load configuration

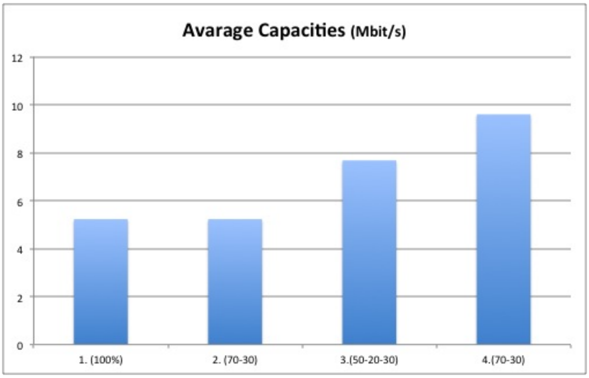

Figure 14: Average capacities for the different traffic mixes

Figure 14. indicates the average capacity need ($\frac{1}{\sum_{k=1}^{K} L_k} \sum_{k=1}^{K} \sum_{l=1}^{L_k} C_l(k)$) of the four different input scenarios. One can also see that the fourth one needs the largest average capacity.

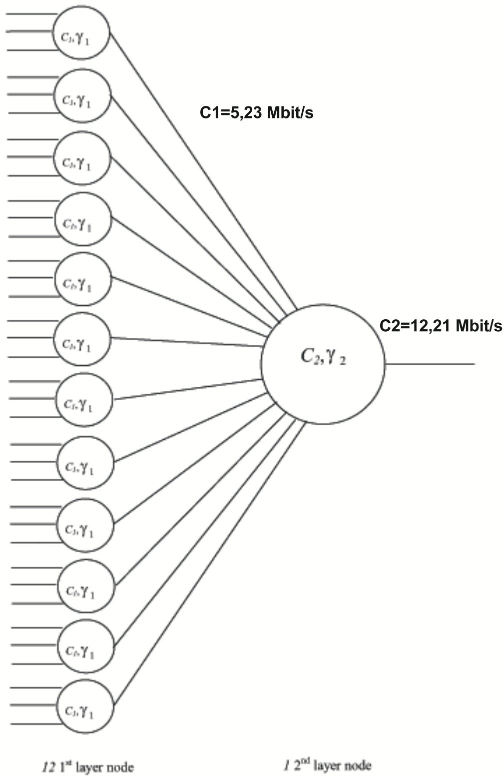

Figure 15: Optimal network topology obtained by algorithm for balanced load

7 Conclusions

In the dissertation I presented some results to overcome the bottlenecks of the current communication technologies. They results are summarized in Table 3 3.

	Packet classification	Wireless packet transmission	Network dimensioning
Packet transmission quality	Thesis 1.1	Thesis ??	Thesis ?? Thesis 3.1
Energy consumption		Thesis 2.1 Thesis 2.2	
Traffic optimization	Thesis 1.1		Thesis 3.1

Table 3: Discussed topics, bottleneck connected, signing the results and theses.

7.1 Packet classification with CNN based technology

With the help of the above proven method I have succeeded in improving the currently used IPv6 technology and therefore developing the quality of multimedia services mainly used via Internet.

Based on the thesis the new algorithm operates quite well, it successfully fulfils its packet classification task. I tested the algorithm with simulation and examined its capacity.

CNN based packet classification is a technological opening towards a completely novel system. Testing and introducing the algorithm has proved that the method is an operating and quick solution due to its graphical and paralell capabilities.

During the performance analysis, i have ranked the algorithms. The neural-based algorithm performed well, and using a proper hardware the method is operating. The implementation with a real routing table performed the classification task in 0,224 ms, while the AQT was 0,316ms and the Radix was 0,615ms. This way the CNN-based classification could reach 3x performance improvement.

With the results, new architecture can be used for packet classification, which can serve the new packet-transfer parameter needs.

7.2 Wireless routing

I have developed a new algorithm, which combines the routing with the energy-optimizing in that way it takes into account the real energy-levels of the nodes. The simulation proved that the algorithm is able to transfer the packets, and it is also capable to transfer the sending parameters to the nodes. The results showed us, this algorithm outperformed avarage 1,8 times the traditional Leach protocol. We can also see that in the 90% of the cases it perfom better than Leach, however when the nodes are located in clusters, the Leach can win.

Using the results, in a field of biology we can reach higher quality of life, cost-effectiveness and better organization in the industrial procedures; energy-effectiveness and more comfortable environment in home and business center monitoring.

7.3 Network dimensioning in packet switched networks

It is extremely important during designing of packet-switched networks, to minimize the number of hardware units, while maintain the required quality of service. This network-dimensioning task can be interpreted as a compulsive optimization task, where the cell-loss probability is given.

In the thesisgroup, I have showed iteration algorithms, which can solve the problem with each users trafficload configuration, as an initial condition, however the cell-loss probability criteria if fulfilled.

The users traffic could be served having links with minimal capacity, and eligible quality of service, where the link capacity was 12.21 MBit/sec.

7.4 Summary

The results above try to extend boundaries of performance of packet switched networks by the following methods:

- CNN based real time packet classification in routing technology
- implementing energy-effective routing protocol for energy-aware wireless sensor network
- designing minimal hardware-complexity access modules to serve a given amount of traffic

Thus, the dissertation could improve the performance of packet switched networks (the exact numbers can be found in chapter 7.1, 7.2 and 7.3).

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