Riga Technical University
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Experimental and Analytical Goodput Evaluation of Drive-thru Internet Systems

Summary of the doctoral thesis

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CONFIRMATION

I confirm that the work contained in the Dissertation submitted by me to Riga Technical University for the Doctor's Degree in Engineering is my own original work and has not previously been submitted by me for a degree at this or any other University.

Ipatovs Aleksandrs …………………………….(Signature)

Date: ………………………

The promotion work is written in English, contains introduction, 5 chapters, conclusions, references, 53 figures, 127 pages in total. A list of references consists of 90 publication titles.

Abstract

The main task of this diploma paper is an experimental and analytical estimation of Drive - thru Internet system based on 802.11g and 802.11n protocols.

Unlike the specially developed standard 802.11p, that allows transferring short official reports of urgent character only, protocols 802.11g and 802.11n allow large-scale data transfer at high speeds, and passing to free range of frequencies. The problem is - it is necessary to transfer large-scale data in short time intervals during movement of vehicle. The losses appear during transferring from zone to zone.

The important parameter to estimate connection quality for internet users is Goodput parameter. It shows real amount of useful information passed by user, without account of official data. Goodput parameter is the basic parameter to estimate Drive - thru Internet system in this diploma paper.

In this diploma paper on the base of experimental data several dependences for the analysis of Drive - thru Internet system have been defined and proven, such as Goodput exponential dependence on the amount of work stations, Goodput quadratic dependence on distance to base station, Goodput linear dependence on speed of vehicle.

A few analytical models were developed, which confirm the efficiency of Drive - thru Internet system based on 802.11g and 802.11n as compared to existent mobile data transfer systems. Truthfulness of developed analytical models and efficiency of protocol 802.11 is confirmed also by simulation construction in OPNET.

Taking into consideration this research, recommendations for construction, planning and development of Drive - thru Internet systems were established.

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General description

Theme relevance: Today more and more attention is given to questions, related to utilization of Wireless Networks in environment with movable objects. It is proved by articles published recently. This diploma paper considers experimental and analytical estimation of Goodput of Drive - thru Internet system based on 802.11g and 802.11n protocols.

The objective: In this connection the main task of this diploma paper is an experimental and analytical estimation of Drive - thru Internet system based on 802.11g and 802.11n protocols. The main parameter to estimate connection quality for internet users is Goodput parameter. It shows real amount of useful information passed by user, without account of official data. Goodput parameter is the basic parameter to estimate Drive - thru Internet system in this diploma paper.

Research method: On the base of wireless networks 802.11g and 802.11n, using wireless distribution system (WDS) technology, experimental Drive - thru Internet networks have been constructed. Then experimental researches for the estimation of possibility to construct Drive - thru Internet systems on the base of these wireless networks, as well as to estimate the efficiency of such networks, have been performed. Taking into consideration experimental data, the possibility to analyze and to construct analytical models of Drive - thru Internet systems appeared.

Results and scientific novelty: In this diploma paper on the base of experimental data several dependences for the analysis of Drive - thru Internet system have been defined and proven, such as Goodput exponential dependence on the amount of work stations, Goodput quadratic dependence on distance to base station, Goodput linear dependence on speed of vehicle.
In this diploma paper Goodput was analyzed, depending on speed of car. Possible and maximal speeds of Drive - thru Internet system based on 802.11g and 802.11n have been determined.

The relation between Goodput in Drive-thru Internet system based on 802.11g and 802.11n is established. The absence of Doppler shift on data transfer in Drive-thru Internet system, which is based on 802.11g, is identified experimentally and analytically, if speed of the drive-thru vehicle is less than 120km/h.

A few analytical models were developed, which confirm the efficiency of Drive - thru Internet system based on 802.11g and 802.11n as compared to existent mobile data transfer systems.

Truthfulness of developed analytical models and efficiency of protocol 802.11 is confirmed also by simulation construction in OPNET.

Research practical application possibilities:

Taking into consideration this research, recommendations for construction, planning and development of Drive - thru Internet systems were established.

Propositions:

1) The exponential dependence Goodput on number of workstations in 802.11 Drive-thru Internet systems is established experimentally and analytically.

2) The quadratic dependence Goodput on distance to the workstation in Drive-thru Internet system is established experimentally and analytically.

3) The author proved the dependence Gootput on speed of transfer of drive-thru vehicle in Drive-thru Internet system based on 802.11g and 802.11n. These patterns are identified experimentally.

4) The dependence between Goodput and ratio of signal/ noise for the drive-thru vehicle, which interacts with the workstation via 802.11g protocol, is found theoretically and experimentally.

5) The existence of maximal speed of the drive-thru vehicle is proved. This maximal speed allows data transfer in Drive-thru Internet systems, which are based on 802.11g and wireless distribution system (WDS), and it does not exceed 100km / h.

6) The absence of maximal speed of the drive-thru vehicle up to 100 km/ h is proved. This maximal speed allows data transfer in Drive-thru Internet systems, which are based on 802.11n and wireless distribution system (WDS).

7) The relation between Goodput in Drive-thru Internet system based on 802.11g and 802.11n is established.

8) As a result of modeling Drive-thru Internet system optimal distance between workstations was found, and this distance is equal to 280 m, with the speed of transfer of 100 km/h.

9) The absence of Doppler shift on data transfer in Drive-thru Internet system, which is based on 802.11g, is identified experimentally and analytically, if speed of the drive-thru vehicle is less than 120 km / h.

Validation and introduction of the research results: The main propositions have been presented, discussed and received appreciation at seven international conferences.

1) RTU 47. studentu zinātniskās un tehniskās konference, Rīga, RTU, 2006. g. (A. Ipatovs, „Sevlīdzīgas plūsmas vadības metožu pētīšana", 47. studentu zinātniskās un tehniskās konferences programma, p. 13, RTU, Rīga.

2) Electrical and Control Techologies 2006., Kaunas, Lietuva, 2006. g.

3) Electonics and Electrical Engineering 2006., Kaunas, Lietuva, 2006. g.

4) Electrical and Control Techologies 2008., Kaunas, Lietuva, 2008. g.

5) Electonics and Electrical Engineering, 2008., Kaunas, Lietuva, 2008. g.

6) Baltic Conference Advanced Topics in Telecommunication, Rostoka, Vācija, 2009. g.

7) Electonics and Electrical Engineering, 2011., Kaunas, Lietuva, 2011. g.

Publications: The research results have been published in seven publications having international quotations.

1) A.Ipatovs, E. Petersons. Performance Evaluation of WLAN depending on number of Workstations and Protocols // Proceedings of International Conference Electrical and Control Technologies, ISSN 9955-25054-2, 2006, 266.-270. lpp.

2) A.Ipatovs, E. Petersons. The Drive-thru Internet system installation for Mobile Users // Proceedings of International Conference Electrical and Control Technologies, ISSN 978-9955-25-484, 2008, 13.-17. lpp.

3) A.Ipatovs, E. Petersons. An Experimental Performance Evaluation of the Drive-thru Internet system for Mobile Users // Electronics and electronic engineering, ISSN 1392-1215, 2009, No. 5(93). 21.-24. lpp.

4) A.Ipatovs, E. Petersons. Реальная скорость передачи данных и соотношение сигнал/шум в беспроводной сети связи с подвижными объектами // AVT, ISSN 0132-4160, 2009, 56.-65. lpp.

5) A.Ipatovs, E. Petersons. Real speed of data transfer and the signal-to-noise ratio in a wireless net for connection with drive-thru vehicles // Allerton Press, Inc. distributed exclusively by Springer Science+Business Media LLC, ISSN 0146-4116, 2009, 40.- 46. lpp.

6) Jansons J., Ipatovs A., Pētersons E. Estimation of Doppler Shift for IEEE 802.11g Standart // Baltic Conference Advanced Topics in Telecommunication. - Rostoka, Vācija: Rostokas Universitātes izdevniecība 1111-09, 2009. - 73.-82. lpp.

7) Jansons J., Ipatovs A., Pētersons E. Model for Wireless Base Station Goodput Evaluation in Vehicular Communication Systems. // Electronics and Electrical Engineering. No. 5 (111), Kaunas, 2011, 19. - 22. lpp.

The results gained in the course of work have been used in the following projects:

1) RTU V1308:* Intelektuālo transporta sistēmu bezvadu datu pārraides tīklu analīze un modelēšana 1.10.2007 – 15.09.2008

2) LZP Nr. 04.1260:* Tīklu resursu iedalīšana servisa kvalitātes nodrošināšanai sevlīdzīgas darba slodzes vidē 2004. – 2008.g

3) VPP, Nr. V7408.2 „Jaunas elektronisko sakaru tehnoloģijas":* "Reālo stendu izveidošana datoru tīklu trafika mērīšanai un optimālai regulēšanai sakaros ar mobiliem objektiem"

4) VPP, V7552.2:* Bezvadu tīklu pārejas procesa imitācijas modeļa izpēte un realizācija. Pārejas procesamodelēšana. Modelēšanas rezultātu novērtēšana 01.01.2009 – 31.03.2009

5) VPP, V7552.2:* Bezvadu tīklu pārejas procesa imitācijas modeļa izpēte un realizācija 01.01.2009 – 31.12.2009

The thesis consists of an introduction, 5 chapters, conclusion exposed on 127 pages and containing 12 tables, 53 pictures. Also, the paper contains a list of literature used composed of 90 items and 1 appendix.

The relevance and urgency, as well as the direction and purpose of the current research is justified in the introduction.

In the second chapter the author presents static analysis of drive-thru internet systems.

In this chapter experimental data, obtained as a result of research of wireless networks in the static mode, when a client is in immobile state, are presented.

The exponential dependence Goodput on number of workstations in 802.11 Drive-thru Internet systems is established experimentally and analytically. The quadratic dependence Goodput on distance to the workstation in Drive-thru Internet system is established experimentally and analytically. Taking into consideration these data, the analytical model to calculate goodput depending on amount of wireless clients, has been obtained.

The third chapter analysis of drive-thru internet systems is presented. In this chapter detailed description of experimental networks based on 802.11g and 802.11n and WDS is presented. The experimental data, obtained as a result of this network research, are presented in this chapter too.
The author proved the dependence Gootput on speed of transfer of drive-thru vehicle in Drive-thru Internet system based on 802.11g and 802.11n. These patterns are identified experimentally. The dependence between Goodput and ratio of signal/ noise for the drive-thru vehicle, which interacts with the

workstation via 802.11g protocol, is found theoretically and experimentally. The relation between Goodput in Drive-thru Internet system based on 802.11g and 802.11n is established.

In the fourth chapter the Goodput Analytic Evaluation in Drive-thru Internet systems is presented. The model that is presented in this chapter helps to determine the number of drive-thru vehicles, depending on the distance to the base station and to determine real speed of data transfer for N drive-thru vehicles, which are located in the zone of Drive-thru Internet system the base station.

In the fifth chapter the author presents estimation of doppler spread for IEEE 802.11g standard. Doppler shift can cause significant problems if transfer technique is sensitive to carrier frequency offsets or if relative speed is too high. When an electromagnetic wave source and the receiver are moving towards each other, received signal frequency will not be the same as source signal frequency.

In this chapter author checks the influence of Doppler shift on drive - thru internet system theoretically and experimentally.

In the sixth chapter simulation of multi-base drive-thru internet system in opnet environment is presented. Data, obtained during drive-thru internet system simulation, have been estimated and compared to experimental data. The distance between base stations has been determined during drive-thru internet system simulation.

Analysis of results, discussion and plans for further research are demonstrated in the last chapter.

Appendix contains graphs of Goodput, which are not included in dissertation.

Exanded summary

Chapter 1 Introduction

In the last few years we have witnessed increasing number of cars connected to the Internet [42]. All indicators suggest that this trend will continue, and drive-thru vehicles will become soon first class citizens on the Internet. Drive-thru vehicle networking opens the door to vast new class of applications ranging from car monitoring and diagnosis to passenger assistance, communication and entertainment.

Due to rapid advances in wireless technology, the Internet becomes more mobile. Not only smart phones become more affordable and ubiquitous; also car manufacturers are looking into leveraging Internet connectivity in order to provide advanced applications on car maintenance - such as monitoring and diagnosis, on road assistance - such as providing route navigation, weather maps and automated toll payments, as well as on passenger entertainment, including various types of Internet-enriched applications. Although most of today's networks connected cars still rely on telematics systems with low-bandwidth connectivity (e.g., satellite link), which do not correspond to needs of emerging new applications. It is expected that such situation will change quickly. During this research several car manufacturers, such as General Motors, are offering Internet connectivity for handful models of cars via the third-generation (3G) network [44]; some other manufacturers also consider offering internet-enabled car applications or linking smart phone applications to cars [43]. The current trend suggests that ten millions of cars will go online in next years, and innovative car-based on Internet applications and services will emerge, which can have major impact on both manufacturers and passenger experiences.

To date the most popular data transfer network in mobile networks is 3G -third generation network. 3G networks provide two basic services – data transfer and voice transmission. In accordance with ITU regulations (International Telecommunications Union) 3G networks have to support following data transfer speeds:

- for subscribers with high mobility (to 120 km/h) — no more than 144 kBit/sec;
- for subscribers with low mobility (to 3 km/h) — 384 kBit/sec;
- for immobile objects — 2048 kBit/sec.

Time shows that users need to increase data transfer speed. 10 years ago the standard data transfer speeds was equal 1 Mbit/sec. I mean stationary mode of data transfer. At present the standard data transfer speed is equal to100 Mbit/sec and higher.

The main task of developers of data transfer mobile networks is to increase data transfer speed to the level of stationary systems. It is means that client has to be satisfied by mobile wireless network, in particular, subscribers will be allowed to look multichannel translations of high clearness and to manage technique for mobile device, to make cheap long-distance calls.

Many countries began to introduce new 4G – fourth generation network that will allow achieving data transfer speed to 1 Gbps/sec in stationary terms and achieving data transfer speed to 100 Mbit/sec in terms of data exchange with mobile devices. Unfortunately, development of this network has a few defects. The first defect is a lack of vehicles that are able to operate with 4G networks, their energy consumption is high. Important problem in 4G distribution is low activity of investors. The development of fourth-generation networks is delayed because 3G networks have high potential of intensive and extensive development.

Due to it the prospect of development of Drive - thru Internet systems, which are based on 802.11n, is positive. This technology allows achieving data transfer speed to 600 Mbit/sec that satisfies the necessities of users. Costs of this technology introduction in modern infrastructure are lower than costs of 4G networks introduction.

Commercial and research interest increases in utilization of wireless technologies like WiMax and WiFi to provide Internet connectivity to users in moving drive-thru vehicles. Such systems, termed Drive-thru Internet [46], operate by placing inter-connected roadside access points (APs) on city roads and trunk roads in order to enable vehicular users to obtain network connectivity by temporarily connecting to an AP as the drive-thru vehicle passes through the AP's coverage range. An important feature of Drive-thru Internet systems is the multi-access sharing of the AP's bandwidth among the drive-thru vehicles that are simultaneously under the coverage of the AP. By most AP resource sharing schemes or protocols, the amount of data that drive-thru vehicle can download from (or upload to) the AP depend on two main factors, i.e. (a) the period or sojourn time of the drive-thru vehicle within the AP's coverage range, and (b) dynamically changing number of other concurrent drive-thru vehicles competing for the AP's bandwidth resources during its sojourn. The drive-thru vehicle's sojourn time is determined by its speed and the length of the AP's coverage range. In turn, the drive-thru vehicle speed is impacted by the interactions among the drive-thru vehicles on the road. This leads to interesting and important interplays between vehicular traffic parameters, drive-thru Internet system settings and an individual drive-thru vehicle's communication/ data download performance within Drive-thru Internet system.

The object of research of this doctoral thesis is studying, modeling, construction and analysis of IEEE 802.11 Drive-thru Internet system for its further utilization in modern transport communications.

The main characteristic of this research is Goodput. Goodput is the application level throughput, i.e. the number of useful for the end client information (bits), delivered by network to certain destination, per unit of time. The amount of data considered excludes protocol overhead bits as well as retransmitted data packets. This is related to the amount of time from the first bit of the first packet is sent (or delivered) until the last bit of the last packet is delivered. If a file is transferred, the goodput that the user experiences corresponds to the file size in bits divided by the file transfer time. The goodput is always lower than the throughput (the gross bit speed that is transferred physically), which generally is lower than network access connection speed (the channel capacity or bandwidth).

This characteristic is most important for studying because it is crucial for the end user. To estimate it we can determine if the utilization of drive-thru Internet system in the Drive-thru Internet system is possible.

At the moment of creation of first experimental Drive-thru Internet system, the actual standard of IEEE 802.11 protocol was 802.11g standard. In future it will be planned to investigate other standards, but in this thesis 802.11g standard is considered as basic standard. That is why before issuing of final version of IEEE 802.11n standard (DRAFT 11.0), which was adopted on 11 September 2009, the research team was not aimed to include the results of research of the standard in this work.

At the moment of the adoption of standard a lot of devices already supported DRAFT 2.0, which has no fundamental differences from final version. Nevertheless, new off-the-shelf devices with full support of final standard began to appear on market only in mid-2010. As soon the possibility appeared, parallel studies of IEEE 802.11n standard began. In accordance with results of research some advantages of new IEEE 802.11n standard were identified, so it was decided to include results of research of this standard in final version of doctoral thesis.

During the process of Drive-thru Internet system`s development and during experiments some problems were determined, which have to be envisaged. Also it was necessary to think about ways how to solve mentioned problems. One problem related with choice of protocol is described.

The second problem is related with choice of equipment for research. It was necessary to select the device from large assortment of devices, which are available on market. Some of devices have already been presented above. All equipment should to interact strictly. The distance between data transfer stations and its interactions depended on choice of Inter-connected roadside access points (APs) and appropriate antennas.

During the process of transfer data over communications channel of drive-thru vehicle can be Doppler shift. Doppler shift can cause significant problems if the transfer technique is sensitive to carrier frequency offsets or if the relative speed is too high. When an electromagnetic wave source and a receiver move relatively one to another, received signal frequency will not be the same as source of signal frequency. When they move toward each other, the frequency of received signal is higher than source frequency. If they are moving to opposite directions, the frequency of received signal will be lower than source frequency. This occurrence is called the Doppler shift. The amount of the Doppler shift depends on relative motion between source and receiver and on the speed of wave propagation. In connection of above mentioned an important question appears, does the Doppler shift effect on the Goodput and if does - in which degree.

Some problems are related with movement of drive-thru vehicle from one Inter-connected roadside access points (APs) coverage area in area of another Inter-connected roadside access points (APs), but notably with handover decision. While the network discovery phase creates a set of potential destinations to which to conduct a handover, the handover decision phase uses this list to determine when and to which radio cell the handover occurs. Common criteria for such decisions include lower layer parameters, for example, Receive Signal Strength Indication (RSSI), packet loss and jitter, or delay, total load on given link. Either of parameters may be measured locally at the mobile proceeding with the handover, but also remotely at network level or at Access Point (AP) holding mobile's current position (and even at all APs in the set of potential handover destinations). Note that remote measurements impose an overhead on the system in terms of management messages signaling the outcome of the information acquisition to handover decision entity. Again, this decision entity can either be co-located with the mobile or placed in the (backbone) network.

The trunk with one line was investigated experimentally in this doctoral thesis. Only one drive-thru vehicle moved over this trunk. In real life the number of lines can vary from 2 to 10, or even more. Accordingly, the number of drive-thru vehicles may also change. The speed of data transfer depends on the density of distribution or number of drive-thru vehicles directly. The task was to find such relationship and to simulate this process.

One more that should be mentioned is IEEE 802.11p standard that was specially developed for Short Range Drive-thru vehicle Networks, but it use 5.85-5.925 GHz frequencies. These frequencies are paid and the equipment is not cheap. Of course 802.11g or 802.11n standards can be used for goodput analysis instead and results can be mapped on 802.11p. More of that 802.11g and 802.11n standard can be really used in V2R scenario. Such opinion is proved with experiments and modeling presented in this work.

Wireless communications in the public safety heavily depends on robustness, reliability and availability of the communication system. In past decades this was achieved at price of extremely high system costs, and was often based on specialized solutions that lacked interoperability. Faced by severe cost constraints the need to ensure interoperation of various agencies, and the desire to involve existing infrastructures where available, the public safety community is attracted increasingly by opportunity to utilize off-the-shelf technology in conjunction with both specialized and commercial communication systems. Wireless off-the-shelf devices that can be found on the market make 802.11g and 802.11n standards more preferable for developers and end users.

Chapter 2 Static Analysis of Drive-thru Internet systems

In the process of development of drive-thru Internet systems for drive-thru vehicles some problems appeared. And these problems must be solved by the developers of drive-thru Internet systems.

One problem is the determination of the number of drive-thru vehicles that affect the quality of the workstation. This problem is topical; because useful speed of data transfer is depend on number of customers located in the area of the workstation, and this useful speed of data transfer is called the «Goodput». This part describes determining the effect of the number of wireless customers on the network performance.

In this part experiments on real static drive-thru Internet system with 802.11g standard are made in order to perform evaluation depending on number of network customers. The metrical system for these experiments was program "Chariot" from "Netiq" company. It consists from "end points of the productivity" for all famous operating systems (Windows ME/NT/2000/XP, Linux or Solaris/x86 Sun) and from central console for measure management. Any of our end points can be connected into communication pairs in this work. Every pair has communication protocol (TCP, UDP, RTP, including variants for IPv6, and also SPX, IPX and APPC) without restrictions and user protocol. The "Chariot" program can simulate a lot of communication processes.

For analysis of drive-thru Internet system`s performance we have standard “Goodput” scenario that generates standard network traffic. Experiments are made either with bounded volume of information or in limited time interval. In our test the second method was used. We have no clear figures (average value of effective goodput, time of reaction and transferred data value), but we can see change of absolute values in time (graph results). Sharp rejections can be seen easily, so it is possible to repeat experiments more times. You can see influence of different factors on real goodput quickly. For example, if there are two protocols in one cell, such as 802.11.b. and 802.11.g, customer who has “g” standard can see that its goodput goes downward. The “Chariot” program makes this situation easer, because communicated pairs can start to send data with random set delay during one session.

There is “Chariot” program installed on the server. The customer`s version of “Chariot” program is set on other computers in our network.

Maximal goodput of network with one workstation was found the first. It was equal to 18.15 Mbps. But nominal goodput of D-Link access point is 54 Mbps. After it the number of workstations was increased one by one. You can get different average goodput values with different number of workstations.

Figure 1 shows some results of experiments. But there is only simple result for one, two and three workstations. To have sufficient accuracy we made more measurements and found average values. These results are presented in table 1. It should be mentioned, that customer`s Goodput in the table is the Goodput, which can be used by the end user.

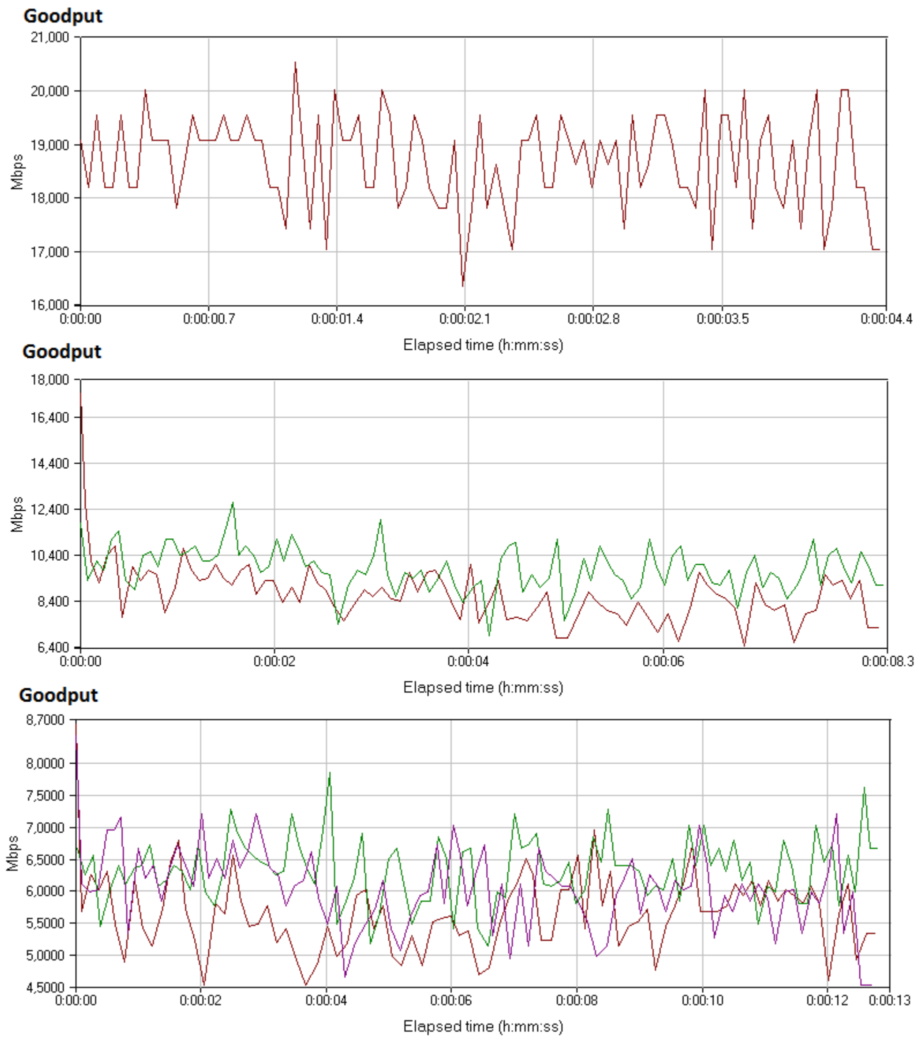

Figure 1. Graph Goodput analyses in the “Chariot” program (one, two and three workstations).

Number of workstations	Practical values	Model values
1	18.15	18.15
2	8.02	7.98
3	5.3	5.35
4	3.9	4
5	3.1	3.2
6	2.5	2.6

Table 1. Result of practical experiments and results from mathematical model

From these results we can conclude that decrease of goodput depends on number of workstations and decrease is not linear (see graph in figure 2).

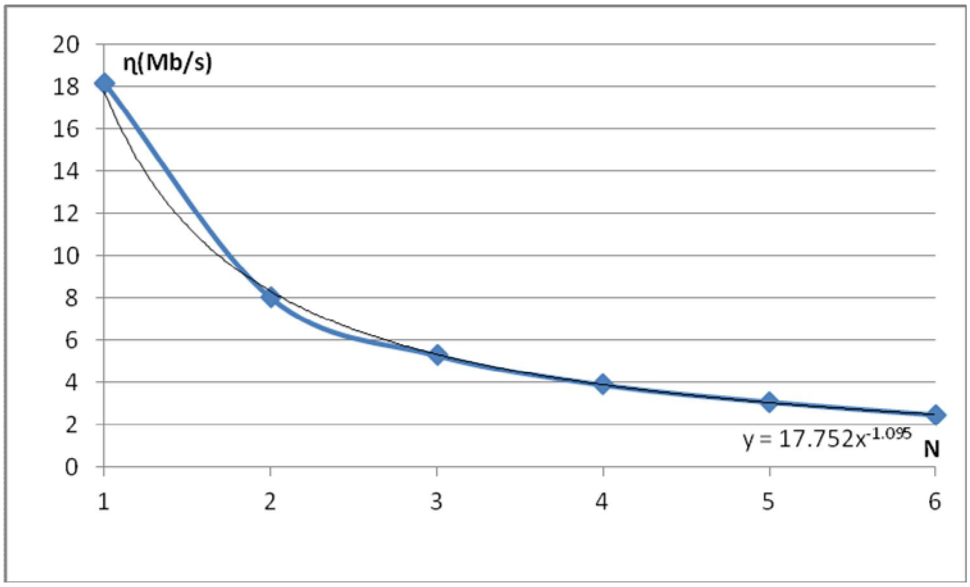

Figure 2. Decrease of experimental goodput (Mbps) in dependence on number of workstations and power trend line.

It is possible to find approximately real goodput for each stationary drive-thru Internet system depending on number of workstations by this graph. But there is one model that can help to find drive-thru Internet system goodput more precisely [32]. And we can state that Goodput Y related with number x of concurrent workstations is

$$Y = 17{,}752 \times x^{-1{,}095}.$$

It is clear that drive-thru Internet system goodput depends on distance to access point. Drive-thru Internet system goodput depends on which modulation is used.

There is one line in the graph of figure 3. The blue line shows experimental goodput evaluation depending on distance to Inter-connected roadside access points (APs) in stationary mode. More about this experiment can be found in [31].

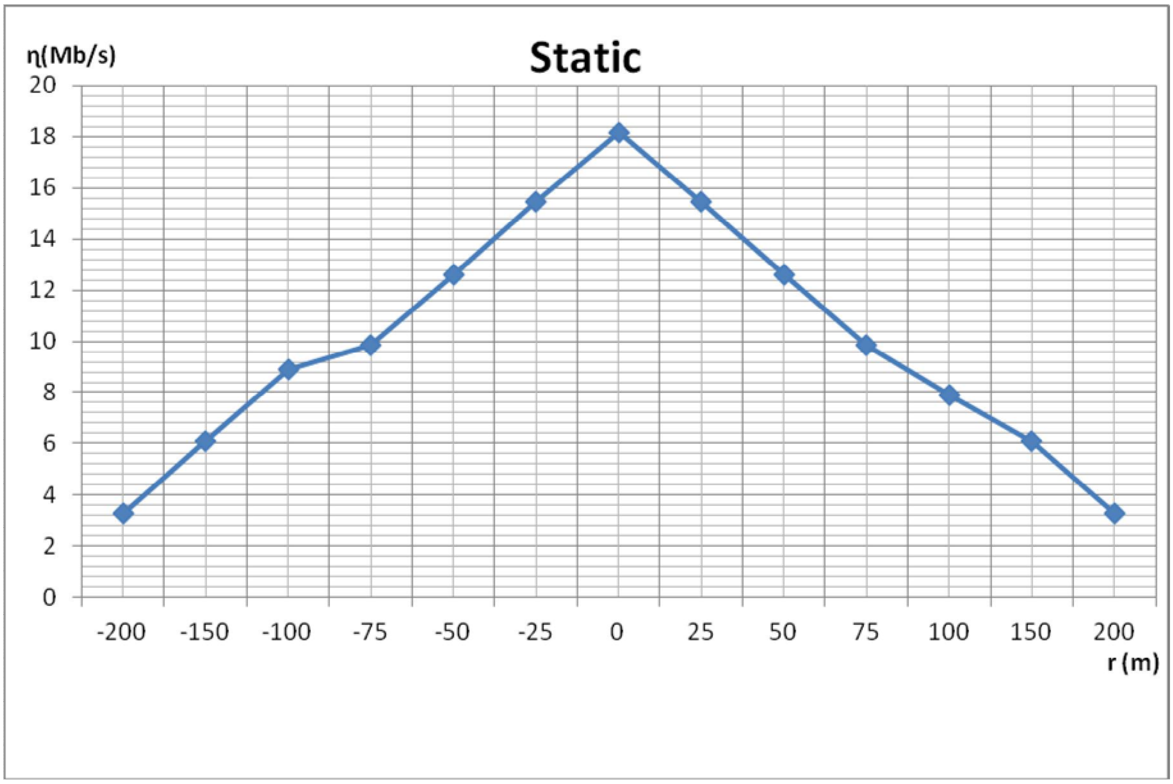

Figure 3. Comparative graphs of goodput (Mbps) in drive-thru Internet system (802.11g) depending on distance (m) to the access point

From this graph may be concluded how the goodput is variable in dependence on distance to access point. Combining two previous sections, it is simple to build common graphs (see graphs in figures 4).

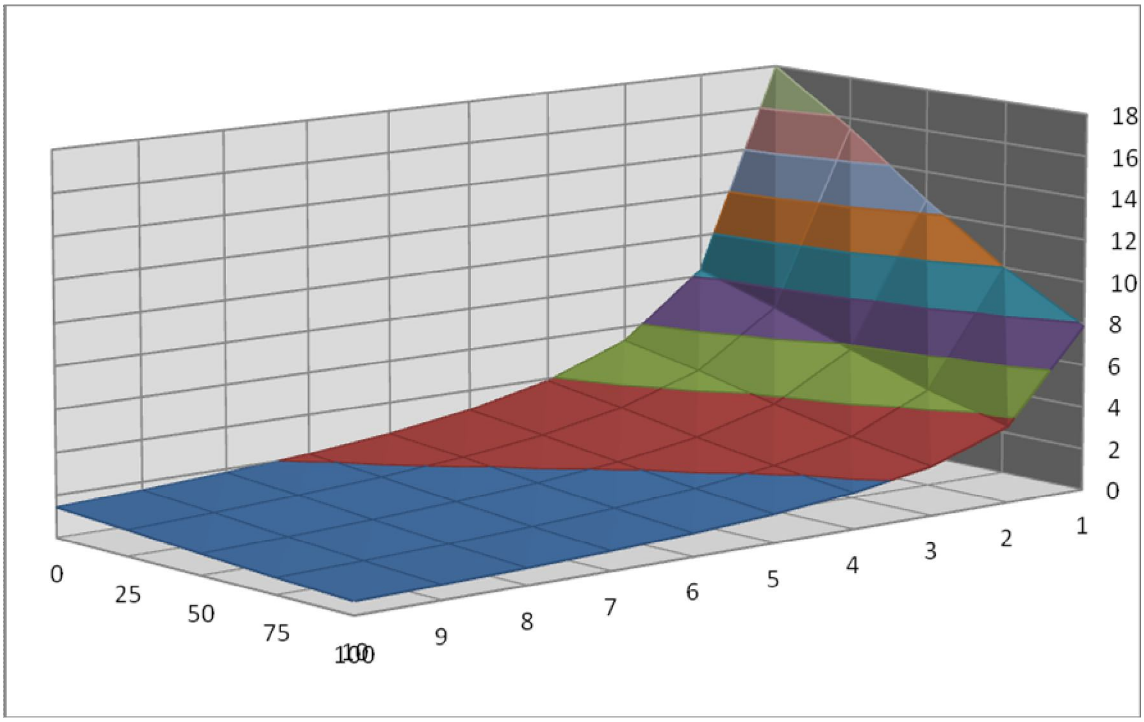

Figure 4. 3-dimension graph of goodput (Mbps) in dependence on number of workstations and distance (m) to the access point

There are three different goodput meanings. The first can be called overall, the second - conditional goodput and the third – individual goodput. In figure 6 conditional goodput on 100 m distance from the access point for two users is equal to16,04 Mbps, but average individual goodput is equal to 8,02 Mbps. Conditional goodput means AP goodput when it maintain certain number of customers. Conditional goodput is less then overall, because AP is involved in control process with some customer stations. Overall goodput can be found when only one customer is connected to the AP and there are no overheads in the drive-thru Internet system.

If developer plans to install new drive-thru Internet system, it is necessary to make prognosis depending on network structure and specification of devices. Mathematical model of the system gives substantial help in this situation. The problem of construction of adequate mathematical model consists in absence of objective rules of transition from the engineering and technical values of projecting system and mathematical symbols of this model, such as probability of transitions, intensity of service of model queries, etc. In this work we try to build mathematical model, using practical results of testing drive-thru Internet system with 802.11.g protocol. This model behaves to close queuing systems class.

The count of workstations in network are designated as *M*. Intensity of queries from one station to the access point are designated as λ . Therefore overall intensity of queries is

$$\Lambda = \lambda(M - i) , \quad (1)$$

where M is number of workstations in the network and i is number of queries in server.

By the stream of queries the stream of transactions (1500 byte stream packages) can be considered. Every query is maintained by the base station at first, and then it is maintained by the server. The goodput of the server during experiment was great, so it is possible to delete the server from model. That's why service of queries goes on the access point only. Service intensity of queries we will designate through μ . Intervals between the queries and during maintenance are casual and have own unknown laws of distributing. However, according to [1] and [2], in case of rational probability distributing of service time (either mode of service of queries with distributing of time or sharing of processors resources as it is in this case) during maintenance may be approached as exponential distributed. In that case average values of mentioned variables will be equal to $1/\lambda$ and $1/\mu$.

According with this model network performance will be expressed as:

$$\eta = (1 - p_0)\mu , \quad (2)$$

where p_0 - probability of system without requests for maintenance. Then goodput for one workstation of the network will be

$$\eta = (1 - p_0)\mu/M , \quad (3)$$

where M is number of workstations in the network and ($M \geq 2$).

After development and analysis of the model one can find

$$p_0 = \left[\sum_{k=0}^{M} \frac{M!}{(M-k)!} \left(\frac{\lambda}{\mu} \right)^k \right]^{-1} . \quad (4)$$

Let's put numerical values into variables of the model. First of all we will see intensity of maintenance, which is equal to maximal value of goodput. This value was exposed by "Chariot" program at maximal load of access point from one workstation.

Now we will expose dependence on point performance in dependence on amount of workstations

$$\eta_1 = f(M) = (1 - [\varepsilon]^{-1})\mu/M , \quad (5)$$

Now we will imagine case of heavy load of access point, when $\lambda \rightarrow \mu$, but $(\lambda / \mu) \rightarrow 1$.

Chapter 3 Analysis of Drive-thru Internet systems

The first problem was - to investigate experimentally the dependence on speed of data exchange between the drive-thru vehicle and the server of stationary computer network on the velocity of the drive-thru vehicle. As well real signal-to-noise ratio should be investigated at the moment of data transfer and functional dependence should be found out between the signal-to-noise ratio and real speed of data transfer. To solve this problem, the corresponding experimental basis was elaborated.

The part of road on highway was investigated as one of the most popular and perspective for future development of transport nodes. In order to reduce the factor of the influence of extraneous signals on experimental network, the takeoff zone Rumbula in Riga was chosen to develop the research polygon.

Three Linksys Inter-connected roadside access points (APs) (WRT54GL vl.1) were used for the experiment with 802.11g standard. The firmware Tomato 1.19 was installed on the Inter-connected roadside access points (APs).

ASUS RT-N16 Inter-connected roadside access points (APs) with TP-Link (2.4GHz, 8dBi Omni-Directional Antennas) were used for the experiment with 802.11n standard. Latest DD-WRT v24-14929 firmware was installed on the ASUS Inter-connected roadside access points (APs) in the experiments.

The power to the Inter-connected roadside access points (APs) was provided by UPS blocks APC 500. In real life we do not need UPS blocks APC 500, because Inter-connected roadside access points (APs) can be located along highway on poles with electrical wiring or on lampposts.

All three Inter-connected roadside access points (APs) were linked into one drive-thru Internet system using wireless distribution system (WDS) technology during experiments with 802.11g and 802.11n standards. In IEEE 802.11 terminology “Distribution System” is system that interconnects so-called Basic Service Sets (BSS). BSS is best compared to “cell”, driven by single Access Point. So “Distribution System” connects cells in order to construct premise wide network which allows users of mobile equipment to roam and stay connected to available network resources.

In plain terms, this technology allows the access points to establish wireless connection not only with wireless customers, but also between themselves, extending the zone of wireless net action. The main advantage to such net is that its access points are interconnected, comprising a drive-thru Internet system. In this case, there is no need to use landline nets for connection of access points. The net constructed using WDS technology allows the mobile stations to switch from one access point to another without losing connection with wireless net. Figure 5 shows the scheme of the Inter-connected roadside access points (APs) interconnection via WDS.

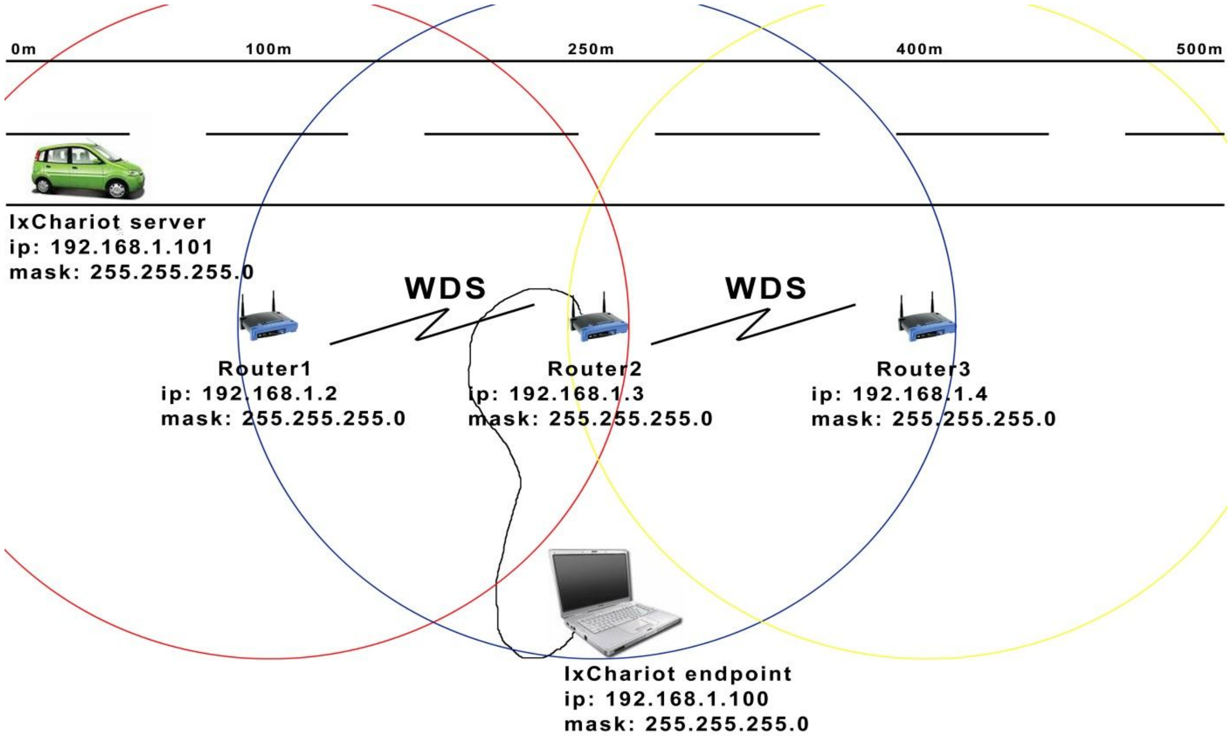

Figure 5. Connection scheme of Inter-connected roadside access points (APs) and zones of their activity.

The distance between Inter-connected roadside access points (APs) was equal to 150 meters. Middle Inter-connected roadside access points (APs) had direct cable connection with the notebook where "netiq" endpoint was installed. This endpoint is necessary for connection creation. The experiment was made on opened territory in terms of good weather. Three BACK-UPS CS 500 of APC company used to supply power to Inter-connected roadside access points (APs). Notebook with IxChariot server program was set in the car. It has external antenna for communication with Inter-connected roadside access points (APs).

The drive-thru vehicle moves in the zone of Inter-connected roadside access points (APs), which switched automatically. The notebook of the drive-thru vehicle used Chariot and Netstumbler programs. At concrete moment of time the drive-thru vehicle connected with only one Inter-connected roadside access point (AP) – one with larger signal-to-noise ratio.

These experiments were carried out in open territory. Direct current power supply sources for the Inter-connected roadside access points (APs) and the server were used.

Inter-connected roadside access points (APs) 2 (the central one) had direct cable connection with the server on which replying part of the Chariot program was installed; precisely for this reason data transfer speed was faster during the drive-thru vehicle connected to Inter-connected roadside access points (APs).

Short range drive-thru vehicle network goodput depends on mobile station speed. It can be found experimentally using mobile station and Chariot program. Experiments should be made at different speeds of drive-thru vehicle. Of course, there should be numerous access points, because the drive-thru vehicle will be in one access point zone for short time at high speed. Wireless Distribution System (WDS) can connect some Inter-connected roadside access points (APs) in one network without wires. Three Inter-connected roadside access points (APs) were used during the experiment [33].

The graph in figure 6 shows goodput dependence on different speeds of the drive-thru vehicle. As WDS was used, significant loss can be seen in left and right zones of the graph. Red point on graph shows static results in different points of the route.

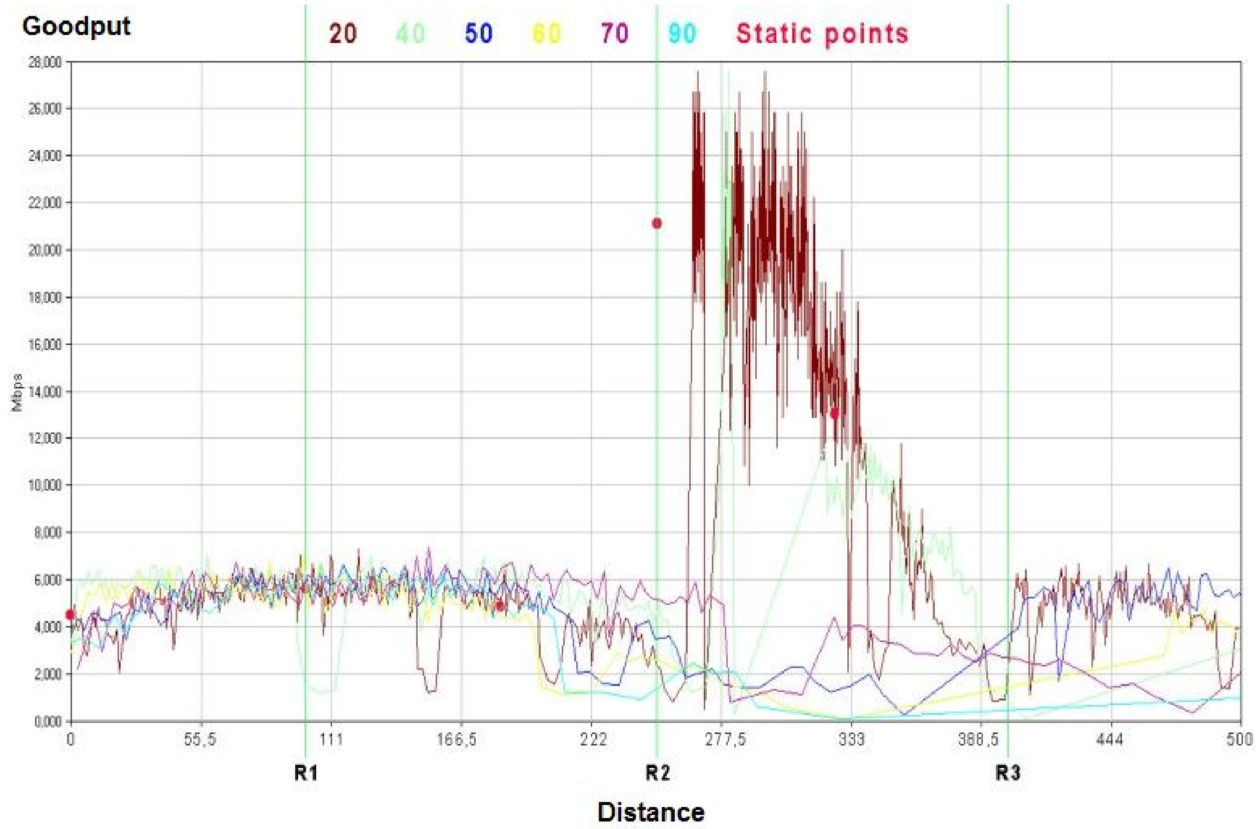

Figure 6. Analysis of Goodput (Mbps) at different speeds (km/h) in short range drive-thru vehicle network

With Netstumbler 0.4.0, the signal-to-noise ratio dependence on time (Figure 7) was found. Similarly to case mentioned above time axis is replaced by the distance axis.

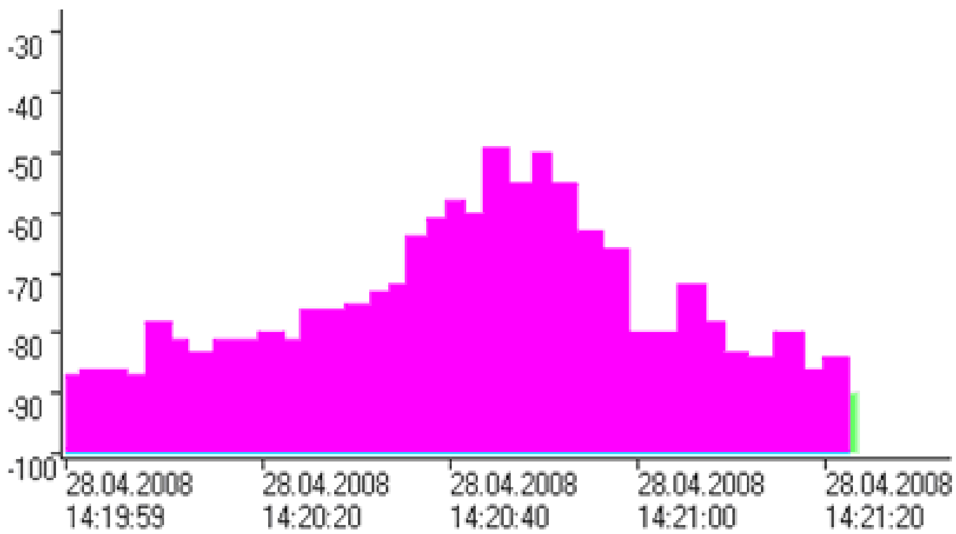

Figure 7. Dependence of signal-to-noise ratio on time of experiment (data recorded at speed of 20 km/h with relatively to central Inter-connected roadside access points (APs)).

To find out the maximal signal-to-noise ratios for entire net, two characteristics were combined.

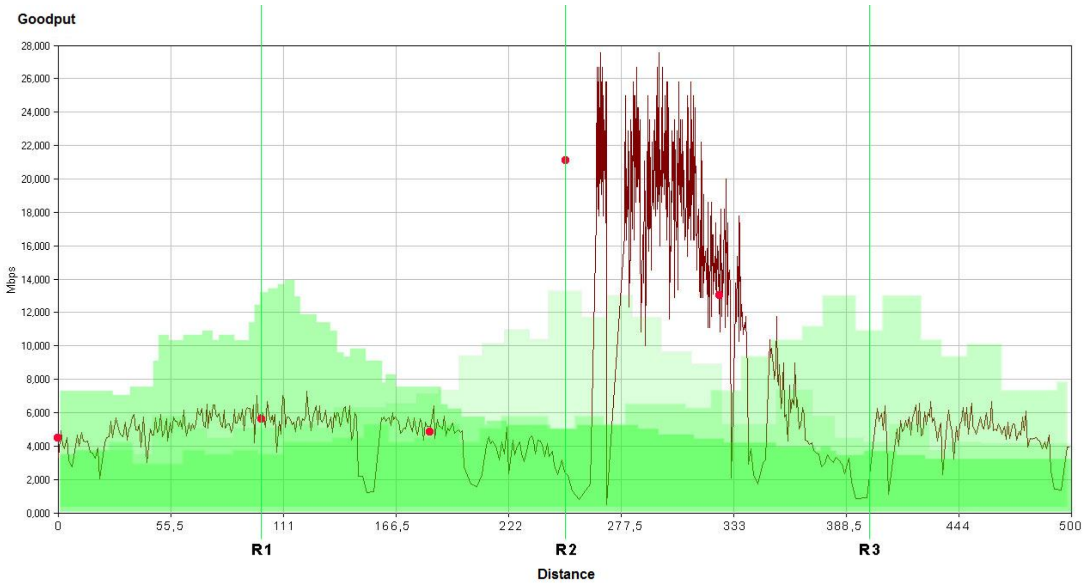

Figure 8. Speed of data transfer in wireless net and dependences on signal-to-noise ratios on location of drive-thru vehicle (at speed 20 km/h).

Figure 8 shows the superposition of signal-to-noise ratios of all the Inter-connected roadside access points (APs) in the graph of data transfer at speed 20 km/h. These relations were projected on distance scale. Figure 12 shows that in wireless net certain dependence exists between the data transfer speed and the signal-to-noise ratio. Let us construct the cross correlation function of these dependences and find mutual correlation coefficients.

The cross correlation function (CCF) of different signals describes the degree of similarity between the shape of two signals and their mutual arrangement relatively to each other in terms of independent variable. In our case, we need CCF of discrete signals. CCF is calculated according to the formula

$$B(n) := \frac{1}{K \cdot R} \cdot \sum_{j=0}^{\text{length}(X)-1-n} \left(X_j \cdot Y_{j+n} \right),$$

Where *K* is count number; *R* is normalization coefficient (to compare CCFs at different speeds); X is dependence of data transfer speed at moment of experiment beginning at velocity of 20 km/h. Y is dependence of the signal-to-noise ratio at moment of experiment beginning at velocity of 20 km/h.

The drive-thru vehicle covers the distance of 500 m at 20 km/h in 90 seconds. To find the CCF, let us assume time unit of 1 s. The CCF of these two dependences is shown in figure 9.

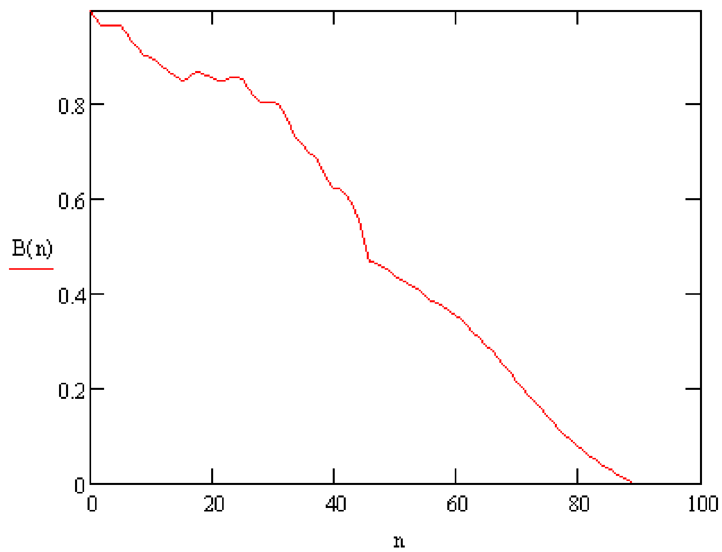

Figure 9. Cross correlation function of data transfer speed and signal-to-noise ratio at velocity of 20 km/h.

In the same way we find the CCFs at velocities of 40 and 90 km/h. The cross correlation functions at 20, 40, and 90 km/h are shown in figure 10.

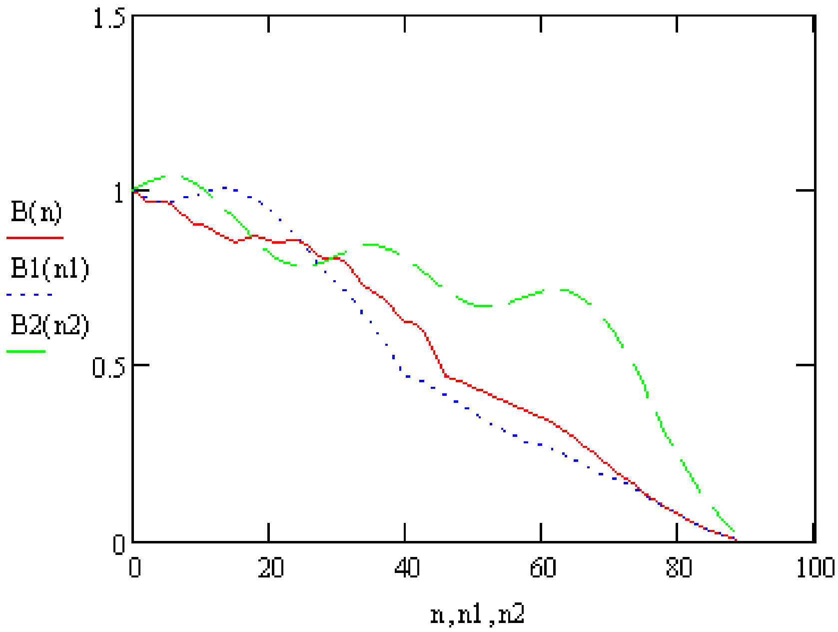

Figure 10. Comparison of cross correlation functions of data transfer speed and ratio signal-to-noise at velocities of 20 km/h—B(n); 40 km/h—B1(n1); and 90 km/h—B2(n2).

Was found the dependence between data transfer speed and signal-to-noise ratio, let us find the recalculation coefficients. These coefficients will show how dependences are interconnected.

The drive-thru vehicle at speed of 20 km/h was taken as an example. We divide measurements into three stages. Each stage is connected to concrete Inter-connected roadside access point (AP) and increases at first, followed by peak (maximal value) and then it decreases. Each stage takes about 10 s at speed of20 km/h.

Recalculation coefficients in accordance with following formula:

$$\alpha_{11} = \frac{\overline{S/N}}{\overline{\eta}},$$

where average signal-to-noise ratio is defined for 10 s; the average capacity is defined for 10 s.

Theoretical capacity of any information channel is defined by the Shannon formula. If signal occupies bandwidth F and ratio of signal power and that of the noise is P_S/P_N then maximal information in 1 s which can be transferred with arbitrarily small error probability is quantity

$$C = F \log_2(1 + P_S/P_N),$$

We must take into account that ratio S/N: P_S/P_N is given in times; therefore, data in dB should be recalculated into times: $x\text{dB} = 10\lg\frac{P_S}{P_N}$; from this $\frac{P_S}{P_N} = 10^{x/10}$. In table 3 we see that the Shannon formula with direct recalculation of signal-to-noise ratio for data transfer speed can not be used in nets with drive-thru vehicles. For possibility of recalculation we find approximate functions for data transfer speed (figure 11) . The graph 11 shows that goodput has quadratic dependence on the distance in Drive-thru Internet system.

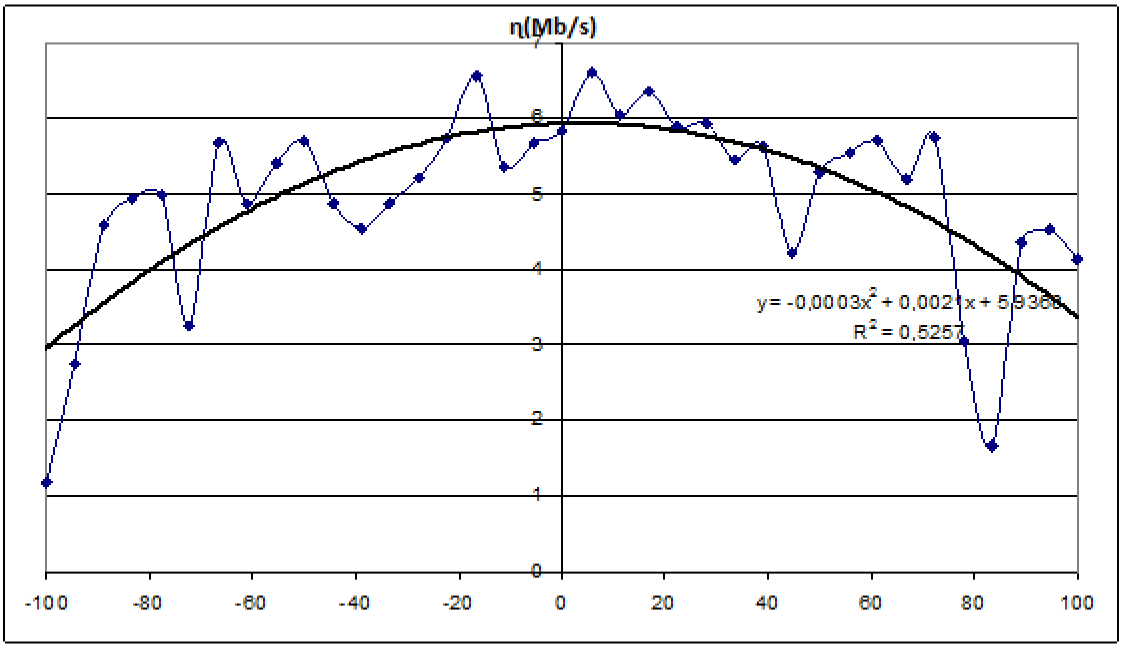

Figure 11. Dependence of data transfer speed Y in wireless net on the distance X to Inter-connected roadside access points (APs) and on approximate function (802.11g).

We found that the object switching from one base station to another causes gaps in data transfer speed. These gaps increase if object`s velocity increases. The results of the experiment allowed us to establish functional connection between the signal-to-noise ratio and the real data transfer speed from upper net level. It allows estimating data transfer speed if we have accessible means for measuring the signal-to-noise ratio.

Nowadays main wireless system standard is the 802.11n. This standard replaces the 802.11g standard. The 802.11n standard improves data transfer speed almost in four times in comparison with the 802.11g standard devices (maximal speed is 54 Mbit / s), using in 802.11n mode with other 802.11n devices. Theoretically the 802.11n standard can provide data transfer speed up to 600 Mbit/s, using data transfer via four antennas at the same time. Using one antenna, speed of data transfer will be up to 150 Mbit/sec.

We want once again to refer about usefulness of utilization of the 802.11n standard in Drive-thru Internet system, unless the utilization of specially designed 802.11p standard

- Equipment for the 802.11n standard is cheap and available.

• Frequencies of the 802.11n standard are free of charge.
• The 802.11p standard does not provide transfer of data large amount and it is developed for transfer of short messages.

All these advantages indicate on feasibility of utilization of the 802.11n standard in the Drive-thru Internet system.

The uniqueness of this research is development of real Drive-thru Internet system for experiments. All over the world several analytical models for mobile networks are developed, but they are based on theoretical data. The model presented in this doctoral thesis, takes into account experimental data.

The graph in figure 12 shows goodput dependence on different speeds of Drive-thru vehicle (20km/h and 100km/h) with 802.11n standard. As WDS was used significant loss can be seen in left and right zones of the graph.

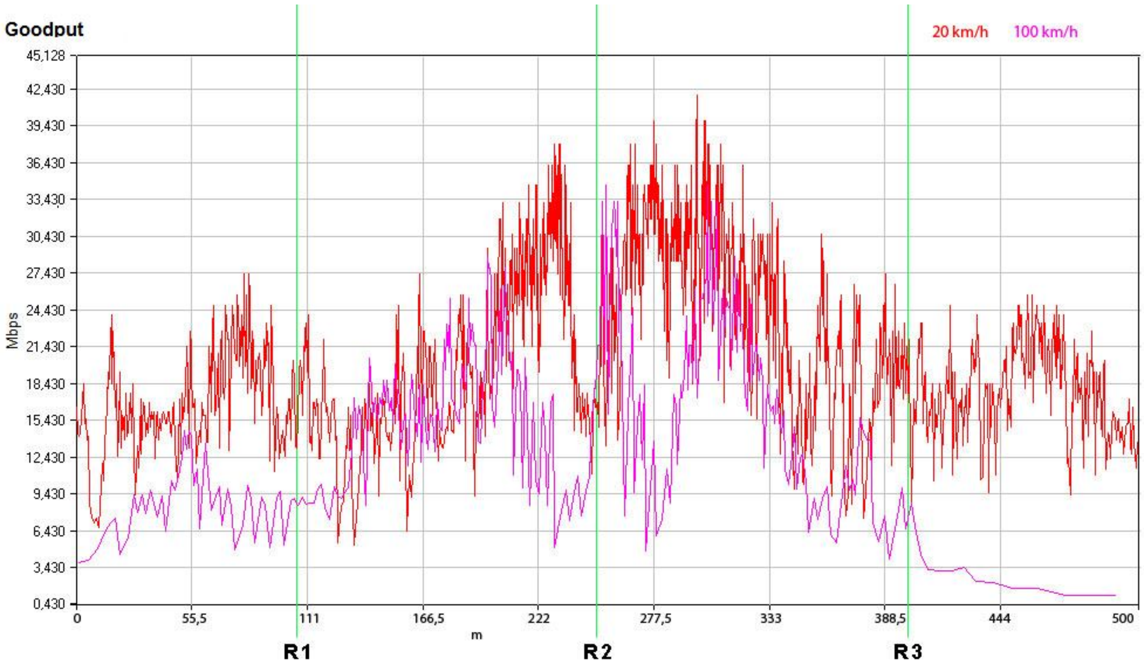

Figure 12. Analysis of Goodput (Mbps) at different speeds (20km/h and 100km/h) in short range drive-thru vehicle network with 802.11n standard

Analyzing these graphs, it can be concluded that by increasing speed of the drive-thru vehicle, goodput reduced slightly, but at the same time it remains stabile. The fading was not observed practically, and it once again proves superiority of the 802.11n standard in comparison with the 802.11g standard.

The graph in figure 13 shows goodput dependence on 802.11g and 802.11n at speed 20km/h.

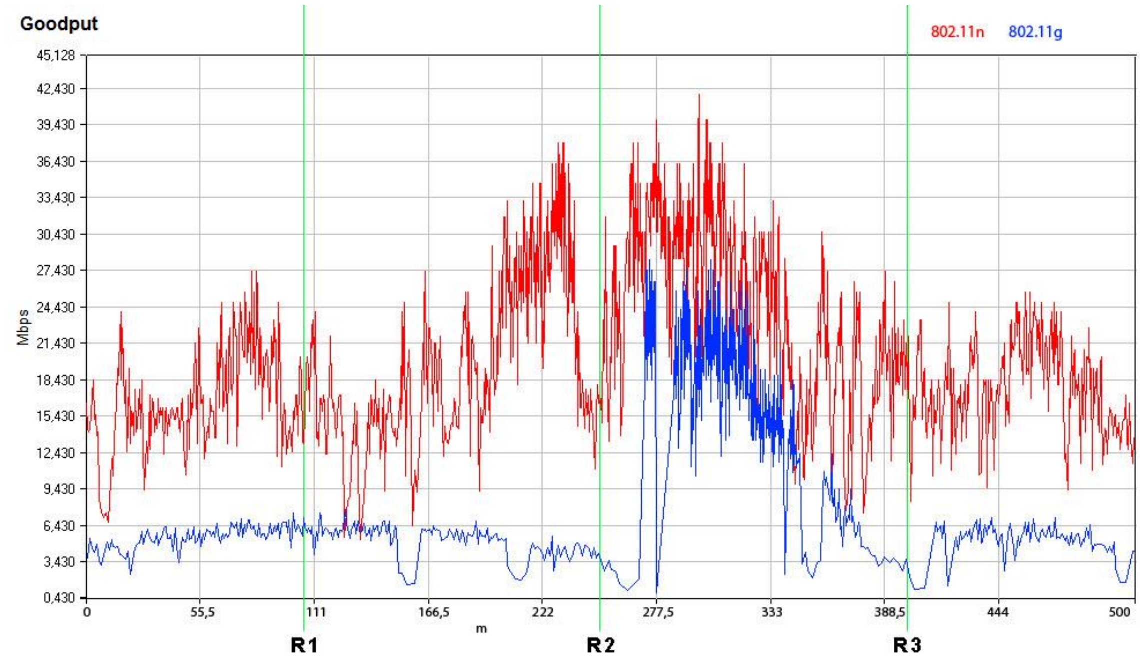

Figure13. Goodput dependence on 802.11g and 802.11n at speed 20km/h

Main advantage of the 802.11n standard is stability of data transfer in Drive-thru Internet system at high speed of drive-thru vehicles. The graph in figure 14 shows goodput dependence on 802.11g and 802.11n at speed 100 km/ h.

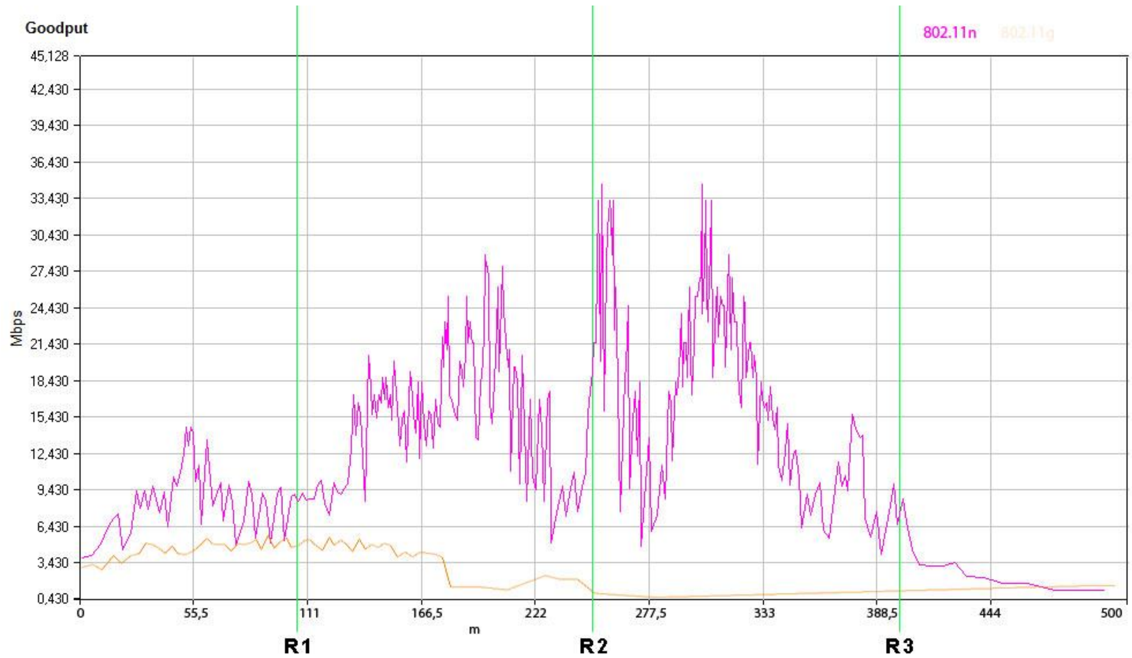

Figure 142. Goodput dependence on 802.11g and 802.11n at speed 100km/h

In some cases in the 802.11g standard transition between workstations can not be realized at speed over 90km/h. Using Inter-connected roadside access points (APs) with the 802.11n standard, transition between workstations is performed without fading. Average goodput on all stages was 9,838 Mbps.

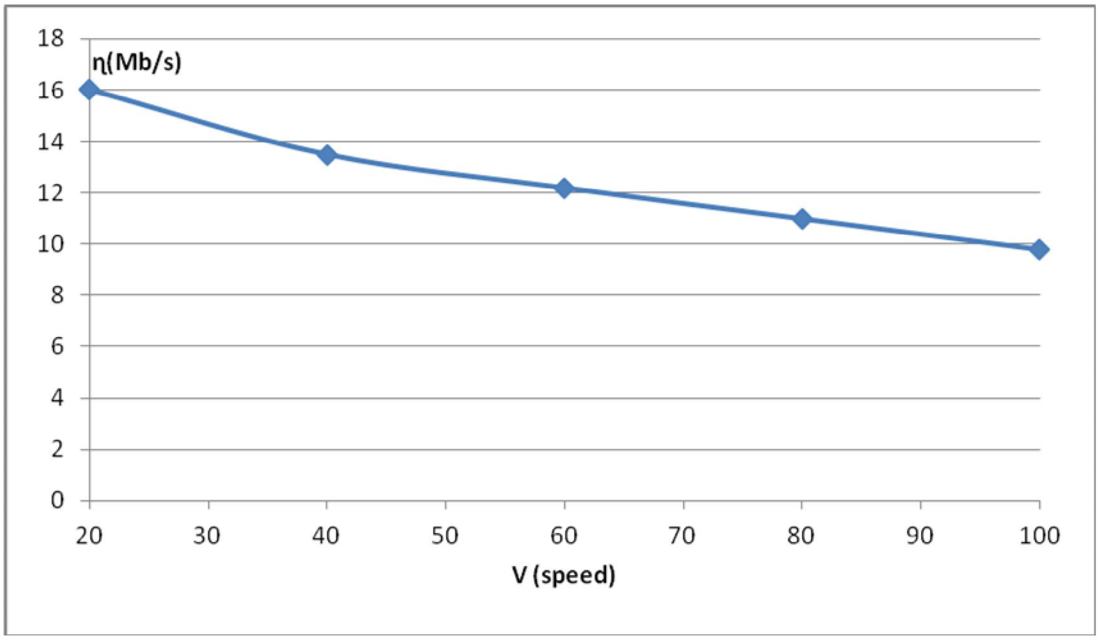

Figure 3. Average goodput dependence on 802.11n at different speeds.

Chapter 4 Goodput Analytic Evaluation in Drive-thru Internet systems

During process of Drive-thru Internet system development for drive-thru vehicles some problems appeared and these problems have to be solved by developers. One problem is to determinate the number of drive-thru vehicles, depending on the distance to the base station. This problem is topical, because useful speed of data transfer, which is called as the "Goodput" is depend on the number of customers located in the area of the base station. The determination of useful speed of data transfer in terms of traffic is another problem of Drive-thru Internet system development.

In this connection the first task of this chapter is to determine the number of drive-thru vehicles, depending on the distance to the base station and the second task is to determine real speed of data transfer for N drive-thru vehicles, which are located in the zone of Drive-thru Internet system the base station.

To solve and to check tasks the data from previous works are used. In work [2] experimental data are presented that estimated speed of data transfer between remote object and base station in Drive-thru Internet system the 802.11g standard.

Regular changes of data transfer speed for number M of remote objects were identified. All measurements and conclusions were done in terms of fixed location of objects in relation to the base station. For such terms it was possible to apply the model of the system of packages` mass maintenance of the base station.

Experimental results represented in work [3] were used to estimate real speed of data transfer between drive-thru vehicle and base station during operation in mode of files transfer via ftp protocol. During experiment real Goodput (the useful speed of data transfer) was measured. Assessment was performed using the Chariot program. Main feature is measurement of data transfer speed that depends on the distance between the drive-thru vehicle and the base station.

Approximation of accumulated experimental data allows conclude that intensity of packages` maintenance in the base station is not constant. This characteristic is variable and depends as quadratic polynomial function on the distance between corresponding points in Drive-thru Internet system.

Maximal useful data transfer speed varies in scope of 6 Mbit/sec, because data are collected from subsidiary base station, which in turn connects to main base station via WDS (Wireless Distribution System).

It should be noted that measurement of data transfer speed was performed only for one drive-thru vehicle without competition from other possible drive-thru vehicles. Based on data from work [1], it can be expected that real data transfer speed will depend on number of drive-thru vehicles that interact with the base station and on the distance to the base station, because the last determine the intensity of packets` maintenance by the base station.

To solve the first problem we use the model of drive-thru vehicles movement on highway from [4]. According to this work speed of drive-thru vehicles on highway characterized by density K of drive-thru vehicles` placement at one meter

$$\vartheta = \vartheta_0 \left(1 - \frac{k}{k_c}\right), \qquad (6)$$

where k_c – maximal allowed density of flow, but ϑ_0- speed of flow free movement (maximal allowed).

For example, if we consider that length of the stage is 300 meters and length of the drive-thru vehicle is approximately 3 meters, then k_c=300/3=100 units to 300 meters. If distance between drive-thru vehicles is equal to 17 meters, then k = 300 / (17 +3) = 15 units in selected area. Then, if free movement speed is $\vartheta_0 = 70$km/h, then average movement speed in the area of 300 meters will be $\vartheta = 70(1 - \frac{15}{100}) = 59{,}5$ km/h.

If we consider that road stage between lines x and x + Δx, divided by distance Δx, then change of drive-thru vehicles` number on this road stage in short time interval dt is described as variation of arriving and departing drive-thru vehicles on road stage Δx:

$$\Delta n = g dt - \left(g + \frac{dg}{dx}\Delta x\right) dt, \qquad (7)$$

where g – intensity of drive-thru vehicles` flow.

Here we can see complete analogy with the system of mass maintenance, which assesses the number of applications Δn, which are in queue for maintenance device (road stage), if assessment is conducted at average values, which do not take into consideration fluctuations – departments and arrivals of drive-thru vehicles.

To extend this model of stochastic component, let`s imagine the zone, where drive-thru vehicles and workstation interact, is divided into M segments. Each segment i intensity of requests` maintenance is μi (missed drive-thru vehicles on this road stage during one second). If length of road stage is S_i, and speed of drive-thru vehicle is ϑ_i, then intensity of drive-thru vehicles` maintenance in road stage is:

$$\mu_i = \frac{\vartheta_i}{S_i}.$$

According to (6) intensity of drive-thru vehicles` maintenance will depend not only on initial speed of drive-thru vehicles` entry in road stage, but also on density of drive-thru vehicles on this road stage.

Drive-thru vehicles pass all M stages consequentially, and number of all drive-thru vehicles in working zone of base station is equal N.

It is obvious that maximal number of drive-thru vehicles in zone length L is equal to k_c. If number of bands is equal to n, then N_{max} must be increased to n times.

Let`s assume that drive-thru vehicles` number N passed working area of the base station. Passed working area of the base station from zero state (without connection to the station) the drive-thru vehicle again became in zero state. Such system can be represented as closed cyclic network of mass maintenance systems, where number of maintenance devices is equal M, number of requests is equal N, with exponentially distributed time of maintenance. Requests maintenance intensity in the zone i is equal μ_i.

Then probability of requests distribution (of drive-thru vehicles) according to maintenance devices (road stages) will be equal:

$$P_{n_1,\dots,n_M} = \frac{1}{G(N)} \cdot \frac{\mu_1^{N-n_1}}{\mu_2^{n_2} \cdot \mu_3^{n_3} \dots \mu_M^{n_M}} \qquad (8)$$

Here G (N) is normalized constant that was obtained by summarizing and equating to one of probabilities or was calculated in accordance with the algorithm of Buzen [5].

Of course, that there are no limitations on number of drive-thru vehicles (requests) arriving at any stage i, except total number of drive-thru vehicles in working area of the base station is equal N.

Average number of requests (drive-thru vehicles) in stage i is equal:

$$E[n_i] = \sum_{K=1}^{N} (x_i)^K \cdot \frac{G(N-k)}{G(N)} \qquad (9)$$

Here x_i defined from system of equations:

$$\mu_i x_i = \sum_{i=1}^{M} \mu_i x_i p_{ij} \quad 1 \le j \le M \qquad (10)$$

In accordance with cycle of the model:

$$\mu_i x_i = \begin{cases} \mu_{i-1} x_{i-1} & i = 2,3,\dots,M \\ \mu_M x_M & i = 1 \end{cases} \qquad (11)$$

One x can be equal to one and then if $x_1 = 1$

$$x_2 = \frac{\mu_1}{\mu_2}, x_3 = \frac{\mu_1}{\mu_3}, \dots, x_{M-1} = \frac{\mu_1}{\mu_{M-1}}, x_M = \frac{\mu_1}{\mu_M}. \qquad (12)$$

Analogical Busen algorithm for first centre loading vary estimation are represented in table 4.

Example:

If area of the base station is 200 meters and it is divided into 5 zones with areas of 40 meters each. The third zone is nearest zone to the base station.

Let`s assume that number of drive-thru vehicles N pass working zone of the base station with zero speed. Further speed of drive-thru vehicles will increase exponentially.

$$\vartheta = \vartheta_0 (1 - e^{-\alpha r})$$, where

r –distance to the base station, and α = 0,01275. If r = 40 meters, then speed $\vartheta = 100(1 - e^{-0,01275 \cdot 40}) = 40$ km/h, and moving away from initial border of entry into base station by 100 meters, speed will be equal $\vartheta = 100(1 - e^{-1,275}) = 72,1$ km/h.

In our case we have 5 maintenance centers (figure 16). Requests maintenance time by each device is random. Time is distributed in accordance with potential rule at average value of $1/\mu_i$.

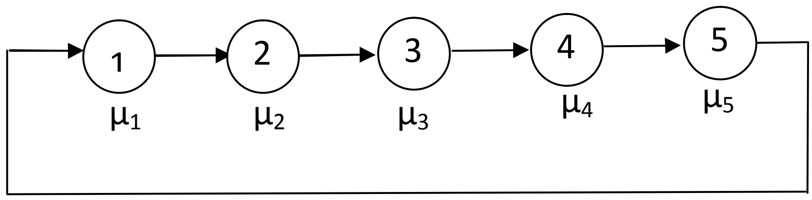

Figure16. Cycling system.

Drive-thru vehicles speeds in different areas, if maximal speed is 100 km/h, are represented in table 2:

i	1	2	3	4	5
m	40	80	120	160	200
ϑ_i	$100\left(1-e^{-0.01275\cdot 40}\right)=39.95$	$100\left(1-e^{-0.01275\cdot 80}\right)=63.941$	$100\left(1-e^{-0.01275\cdot 120}\right)=78.346$	$100\left(1-e^{-0.01275\cdot 160}\right)=86.997$	$100\left(1-e^{-0.01275\cdot 200}\right)=92.192$
μ_i	$\mu=\frac{\vartheta}{S}= =\frac{39950}{3600\cdot 40}=0.277$	$\frac{63941}{3600\cdot 40}=0.444$	$\frac{78346}{3600\cdot 40}=0.544$	$\frac{86997}{3600\cdot 40}=0.604$	$\frac{92192}{3600\cdot 40}=0.64$

Table 2. Drive-thru vehicles speeds in different areas, if maximal speed is 100 km/h

By determined values X_i Matrix of Buzen element is defined. Matrix of Buzen element is represented in row i and in column j according to formula:

$$g(i,j)=g(i,j-1)+g(i-1,j)Xj$$

In table 3 Algorithm of Buzen if N=10:

Nr.	$x_1=1$	$x_2=\frac{\mu_1}{\mu_2}=0.624$	$x_3=\frac{\mu_1}{\mu_3}=0.509$	$x_4=\frac{\mu_1}{\mu_4}=0.459$	$x_5=\frac{\mu_1}{\mu_5}=0.433$
0	1	1	1	1	1
…	…	…	…	…	…
9	1	2.63577002	5.29800606	9.61133638	16.52190141
10	1	2.64472049248	5.34140557702	9.75300897544	16.90699228597

Table 3. Algorithm of Buzen if N=10

G(N-1) = 16.52190141

G(N) = 16.90699228597

Probability that the stage i will be occupied is equal:

$$P(n_1\geq 1)=\frac{G(N-1)}{G(N)}$$

In table 4 Algorithm of Buzen if N=20:

Nr.	$x_1 = 1$	$x_2 = \frac{\mu_1}{\mu_2} = 0.624$	$x_3 = \frac{\mu_1}{\mu_3} = 0.509$	$x_4 = \frac{\mu_1}{\mu_4} = 0.459$	$x_5 = \frac{\mu_1}{\mu_5} = 0.433$
0	1	1	1	1	1
…	…	…	…	…	…
19	1	2.659441518005	5.415933464385	10.00962119746	17.644789333405
20	1	2.659491507235	5.416201640607	10.01061777024	17.650811551607

Table 4. Algorithm of Buzen if N=20

To calculate μ_i, by formula (12), values $x_2,...x_M$ are determined, and by formula (10) the average number of cars $E[n_i]$ is determined in every zone.

If we have distribution of transport vehicles on subzones of customer`s service zone of base station, we can develop a model for the estimation of actual speed of data exchange between objects and station.

For this purpose we will develop a network. The first node is transport vehicles, which generate packages for processing in base station.

Depending on transport vehicle remoteness from base station, speed of packages processing and processing intensity in base station will be different.

During transmission of files the accepted length of one package is equal $l_p = 1500$ bytes. Then, for a car remote from base station on distance r, we determine the productivity β_i of base station.

$$\beta(50) = \frac{5.5 \cdot 10^6}{1500 \cdot 8} = 458.333 \text{ packages in a second.} \quad (13)$$

We will consider separate subzones of base station. According to formula (10) we have a number of competitive vehicles, which have claim on the resource of base station.

For presented example of cars number E(n_i)in every subzone i for N=10 is equal:

$E(1) = 5.813$; $E(2) = 1.03$; $E(3) = 0.918$; $E(4) = 0.761$; $E(5) = 0.689$.

The number of cars E(n_i)in every subzone i for для N=20 is equal:

$E(1) = 15.698$; $E(2) = 1.654$; $E(3) = 1.035$; $E(4) = 0.848$; $E(5) = 0.763$.

The efficiency of base station β_i depending on the remoteness of vehicle from base station is presented in the table 5:

β_1	β_2	β_3	β_4	β_5
416.667	500	500	458.333	333.333

Table 5. The efficiency of base station β_i depending on the remoteness of vehicle from base station

Every vehicle in subzone i has to transfer packages to base station at intensity λ_i. Using the model M/M/1/Ni for every subzone i, we find probability of base station idle time:

$$P_0(i) = \left[\sum_{k=0}^{E(n_i)} \left(\frac{\lambda_i}{\beta_i} \right)^k \frac{E(n_i)!}{(E(n_i)-k)!} \right]^{-1} \qquad (14)$$

Here E(n_i)=Ni, In table 6 probability of base station idle time is presented for N=10:

$P_0(1)$	$P_0(2)$	$P_0(3)$	$P_0(4)$	$P_0(5)$
$5.632*10^{-3}$	0.667	0.667	0.647	0.571

Table 6. The efficiency of base station β_i depending on the remoteness of vehicle from base station

In table 7 probability of base station idle time is presented for N=20:

$P_0(1)$	$P_0(2)$	$P_0(3)$	$P_0(4)$	$P_0(5)$
$3.072*10^{-10}$	0.4	0.667	0.647	0.571

Table 7. Probability of base station idle time is presented for N=20

The efficiency of station that process area i will be equal:

$$\eta_i = (1 - P_0(i))\beta_i \qquad (15)$$

In table 8 the efficiency of station is presented for N=10:

η_1	η_2	η_3	η_4	η_5
414.32	166.5	166.5	161.792	143

Table 8. The efficiency of station is presented for N=10

In table 9 the efficiency of station is presented for N=20:

η_1	η_2	η_3	η_4	η_5
416.667	300	166.5	161.792	143

Table 9. The efficiency of station is presented for N=20

Total efficiency of base station for N=10:

$$\eta = \sum \eta_i = 1052 \frac{pakets}{S}$$

Total efficiency of base station for N=20:

$$\eta = \sum \eta_i = 1188 \frac{pakets}{S}$$

Thus, efficiency of base station is related to parameters of traffic and to characteristics of data transfer system Base station - vehicle.

Doppler shift can cause significant problems if transfer technique is sensitive to carrier frequency offsets or if relative speed is too high. When an electromagnetic wave source and the receiver are moving towards each other, received signal frequency will not be the same as source signal frequency. When they are moving toward each other the frequency of received signal is higher than source frequency. But when they are moving from each other the frequency of received signal is lower than source frequency. This occurrence is called the Doppler shift. The amount of the Doppler shift depends on relative motion between source and receiver and on speed of wave propagation. Maximal Doppler shift for frequency is calculated according to the formula:

$$f_d = \frac{v_r \cdot f_c}{c} \cos\alpha \qquad (16)$$

where f_c is source frequency, v_r is speed difference between objects, c is speed of light ($3x10^8$m/s), and $\alpha \in [0, \pi]$ is angle of velocity vector. Our purpose is to get maximal $f_{d,}$ which happen when $\alpha \to 0$. (16) can be changed to

$$f_d = \frac{v_r \cdot f_c}{3.6 \times 3 \times 10^8} \qquad (17)$$

Values of f_d for 2.4 GHz carrier and various speeds are listed in table 10. On speed range from 10km/h to 120 km/h the Doppler shift is equal from 20 Hz to 300 Hz.

V(km/h)	10	20	30	40	50	60	70	80	90	100	110	120
f_d(Hz)	22	44	66.7	88.9	111	133	155.6	177.8	200	222	244	266.7

Table 10. Doppler shift for various speeds

Relative Doppler shift (μ) is about 10^{-8} to 10^{-7}, which is small. The fact that all subcarrier frequencies changes identically destroys orthogonal system between subcarriers [36] and generate power leakage among the subcarriers, known as ICI. Theoretical influence of maximal Doppler shift on the 802.11g standard at speed of drive-thru vehicle from 10 to 120 km/h is low. In this case it is possible determine analytically speed (v_r) of the drive-thru vehicle when the Doppler shift can influence on the signal:

$$v_r = \frac{f_d \times 3.6 \times 3 \times 10^8}{f_c}$$

Analytical equation shows that Doppler shift negligible influence on wireless communication between drive-thru vehicle and infrastructure, using the IEEE 802.11g standard technology.

The goal of practical test was to investigate possibility of the 802.11g standard use in V2I practical environment from Doppler shift aspect. For assessing quality of signals we have measured error vector magnitude (EVM). EVM is a measurement of real, transmitted signal against perfect, theoretical signal. This measurement gives an overall view of quality of modulated signal, which in turn gives a sense of how well the receiver would be able to receive and interpret the signal. This information is closely related to the physics layer of the system and gives a complete picture of the channel distortion. EVM can be more useful to the microwave engineer because it contains information about both amplitude and phase errors of the signal [37].

For the experimental signal generation in the test bed vector signal generator R&S®SMBV100A was used. It was set on moving drive-thru vehicle. Signal analyzer R&S FSV-K91n for wireless signal estimation was used. Signal generator power supply was established by UPS APC 1000VA. But signal analyzer power supply was established by 2kW power generator with APC UPS.

The focus was to set the best link with highest signal transfer speed for OFDM 16-QAM (24Mbps) and for OFDM 64-QAM (54Mps) and optimal line of sight distance between receiving and transmitting sides (about 200 meters). For the experiment first channel (2.412 GHz) with signal output level +15 dBm was used. For the wireless measurements the sequence was performed at fixed link-layer data speed 24 Mbps and 54 Mbps in 802.11g-only mode and with no automatic data speed adaption. In order to get right moving speed for each measurement, the moving drive-thru vehicle with signal generator, was equipped with automatically controllable speed limiter.

Chapter 6 Simulation of multi-base Drive-thru Internet system in OPNET environment

OPNET modeler is network simulation software, which is leading in this industry. Using OPNET it is possible to develop and to explore communication networks, devices, protocols and applications by numerous methods and in large scale. OPNET modeller is used in prestigious technology organizations all over the world in order to accelerate research process and development of its technologies.

OPNET modeler uses modeling approach, which is oriented to objectives, and the graphical editor of actual networks and network`s components of structure mirror. OPNET software supports all network connection types and technologies that allow solving complex problems.

OPNET main features are the following:

- Hundreds of protocols and devices` models with source code (full list);
- Object-oriented modeling;
- Hierarchical modeling environment;
- Discrete events, hybrid, also after choice of analysis simulation;
- 32-bites and 64-bites fully parallel simulation kernels;
- In addition to system`s interface simulations with live systems;
- Open interface for integration of external objects files, libraries and other modellers;
- Integrated, graphical user interface.

OPNET modeler is based on several hierarchical editors, which are exactly parallel to real networks, equipment and protocols. OPNET includes numerous editors: the editor of the project, the editor of the node and the editor of the process. The editor of the project is graphic figure of network topology. Networks consist of nodes and sites of objects that can be configured with dialog box.

To develop network necessary nodes or connections can be easily transfer from palette editor of object, or possibility of implementation and fast placement of object can be used. Also built-in libraries of OPNET models can be used or you can develop your own necessary nodes and connections.

The editor of the project provides a geographical context, in accordance with physical characteristics reflects wired and wireless (mobile) network simulation. To use the protocol`s options in order to configure quickly and to activate specific opinions of the protocol.

The editor of the nodes captures architecture of network device or system, figures the flow of data between functional elements, called "modules". Each module can generate, send and receive the package from another module in node of its functions. Modules generally are applications, layer protocols, algorithms and physical resources, such as buffers, ports and buses. Modules are allocated to process models in order to achieve any necessary activities.

The editor of the process uses a powerful machine with last final state, which supports specific access to any level of details, protocols, resources, applications and algorithms. The state and transfers graphically show progress, responding to events.

Each state of process model is C / C + + software language code, which supports libraries with numerous functions, which are intended for planning of protocol. Using the processor editor, you can create a new process model, or you may apply to the library of OPNET model technology, and you can use selected model as a starting point. OPNET process modeling system supports fully graphic and parallel calculations.

OPNET includes such thing as the tool of integrated analysis. Using mentioned tool you can easily show results of the simulation. It is easily to create and to analyze time series, histograms, probability functions, parametric curves, confidence intervals, using the XML export of spreadsheets.

Animation of this model in real time or after the simulation, and graphical monitoring of statistical value during the simulation; reflection of 3D interface; data transfer from text files, XML, and most popular instruments, "CISCO", "HP", "NetScout", "BMC", "Sniffer", "InfoVista", "MRGT" and others.

Detailed protocols, models and network devices have extensive library, which includes multi-level applications, voice, HTTP, TCP, IP, OSPF, BGP, EIGRP, RIP, RSVP, Frame Relay, FDDI, Ethernet, ATM, 802.11 wireless LANs MPLS, PNNI, DOCSIS, UMTS, IP Multicast, Circuit Switch, MANET, Mobile IP and many other protocols. They are distributed with open code.

Standard library includes hundreds of models devices - specific and general - which include Inter-connected roadside access points (APs), switches, workstations and packet generators. The library also contains models of wireless technologies: mobile, mobile "Ad hoc" wireless local area networks and satellite networks, or any node of mobile network.

Each node can be controlled, installing it in dynamic or predetermined trajectory. Maps and other visual elements can be added to OPNET in order to complement context of graphic background. Libraries of modeller contain the model of server or workstation with single platform of hardware, but with different operating systems ("Windows", "Linux", "Solaris" and others).

OPNET provides:

- Adapted and efficient engine of simulation industry, which allows simulate quickly wired and drive-thru Internet systems;
- Advanced simulation platform, hybrid and analytical modeling and technology cooperation simulation;
- Intuitive intelligible graphical environment, actual network model, devices, protocols and applications;
- Simulation control with details in order to support necessary developed decisions;
- Built-in simulation support for all types of network technologies;
- Import of network topology automation;
- Detailed library model of standard protocol with fully open code of source C / C + + programming language.

One drive-thru vehicle simulation is designed in order to expand services, provided by ITS, in particular, to complement electronic payment system. This model was developed, which gives possibility to the driver after payment to use Internet on highway.

Wireless Internet devices, such as Inter-connected roadside access points (APs), which operate as a 'bridge', are located along highway. All devices are located in one network and switching between them is made, when user`s active device, which is connected to network, transfer over network.

In all simulation examples the same scheme of system connection was used. Mentioned scheme is represented in figure 17.

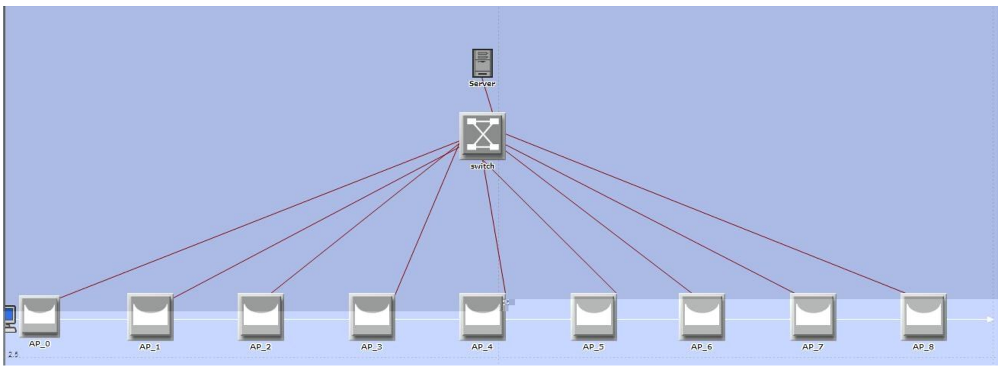

Figure 17. Connection scheme of WI-FI systems for ITS.

This scheme includes 12 objects, which are:

- 9 are Inter-connected roadside access points (APs), which operate as a „bridge", its codes are from AP_0 to AP_8;
- one drive-thru vehicle (objects are 3, it depends on simulation), its codes is CAR_0 (CAR_N,

where N – serial number);

- one switch with 16 ports – SWITCH;
- one servers – SERVER;

All Inter-connected roadside access points (APs) are connected to the switch, which serves as a divider and connector, and which in turn is connected to the server. For all connections optical fiber cable is used, that is why speed does not loss during connections. Customers turn to the server in order to get internet traffic. Depending on tasks the server may be only one, also servers may be more. Number of tasks and number of servers depends on size of the system and on costs of system. Along road additional devices are installed. The server maintains the mentioned devices.

When the drive-thru vehicle drives through payments points, it will receive sms on mobile phone or on smart card (preferably, if it is smart card of third generation with an LCD display) with unique identification number for connecting to network.

As each identification number is unique, this identification number will be saved in database of the system (if it is mobile phone), or ID tag to which identification number has been sent.

If wireless ID number was used, it depends on how the system is configured. In this case payment will be done as follows:

- to calculate Internet traffic, which was used by the user and to pay for it,
- or simply to pay for connection during day.

Payment may be done by bill on your mobile phone or by automatic money removal from user's account, as it is made by electronic payment system.

Supplemented infrastructure of the drive-thru Internet system also can be used for improvement of road traffic, for providing of information about accidents, about road repairs and about weather changes.

Operational information screens, cameras, speed fixing cameras and weather fixing sensors are located along highways. Depending on configuration of the system, information about weather, about traffic jams and about other emergent situations can be shown on operational information screens, or, if the user has paid for Internet, he will receive all necessary information on computer, on tag or on mobile phone as application. This infrastructure is managed by switchboard.

During each simulation different speeds of data traffic are used (bits per second). In order to achieve necessary speed the functions and formulas of OPNET software are used. It is shown in figure 18.

⊟ Packet Generation Arguments	(...)
Interarrival Time (seconds)	constant (0.00125)
Packet Size (bytes)	constant (1518)

Figure 18. Packets` generation function.

Packets generation of data transfer (Internet) is described, where:

- „Interarrival Time (seconds)"– is time interval of packets` transfer (in seconds);
- „Packet Size (bytes)"– is size of packets (in bytes).

During simulation used size of „Ethernet" packets is equal to 1518 bytes.

$V = 1/T \times 8P$ (6.1)

where, V – data transfer speed (bits/ second);
T – time interval (seconds);
P – size of packets (bytes);
1/T –number of packets during one second;
8P –transformation of bits into bytes (one byte is equal to 8 bits).

If to assume data, reflected in figure 18., then the formula 1.1. will be following:

$V = 1 / 0.00125 * (1518 * 8) = 800 * 12144 = 9\,715\,200$ bites/s,

as 1Kbite is equal to1024 bites, but 1Mbit is equal to 1024 Kbits, then result will be equal to ≈ 9.27 Mbit/s.

During simulation main problems, which should be solved, are the following:

- To obtain minimal possible interruption of operation in order to come to shift moment between base stations will be the least.
- Placement of Inter-connected roadside access points (APs).
- Selection of the drive-thru vehicle (customer) speed.

As the drive-thru vehicle speed on highways is rarely less than 100 kilometers per hour, in this part of work mentioned speed is used and it is considered as starting speed of simulation, as Internet and additional services, as well as rapid speed, are in order to get in time to necessary point. Test conducted for movement in distance of 2500 meters.

The first task of analysis is to define maximal data transfer speed for 100 kilometers per hour, when the shift moment between Inter-connected roadside access points (APs) is the least and data transfer speed is modern (enough to review web pages, e-mail, video in real-time mode, to listen to Internet radio and to get other Internet services).

Maximal speed of data goodput with two WiFi standards IEEE802.11g and IEEE802.11b with 54 Mbit/s and 11 Mbit/s, respectively, is tested.

In all graphs the X axis shows time, spent by the drive-thru vehicle on road in seconds, but the Y-axis shows data transfer speed in bits per second.

Considering the IEEE802.11g standard in all ranges of speeds, optimal data transfer speed with minimal shift moment between Inter-connected roadside access points (APs) was not found (Opnet 14.5 version does not contain the "n" and "y" standards). But switching to Wi-Fi IEEE802.11b standard, results were obtained with maximal possible data transfer speed, which is allowed by standard 6mbit/s and which can be seen in Figure 19. This figure shows the graph, where blue color shows data transfer speed in real time mode, when the drive-thru vehicle connected to network moves at speed of 100 km / hour, and road distance is equal to 2500. Average result is shown in red color and it is related to data transfer speed of 6mbit/s.

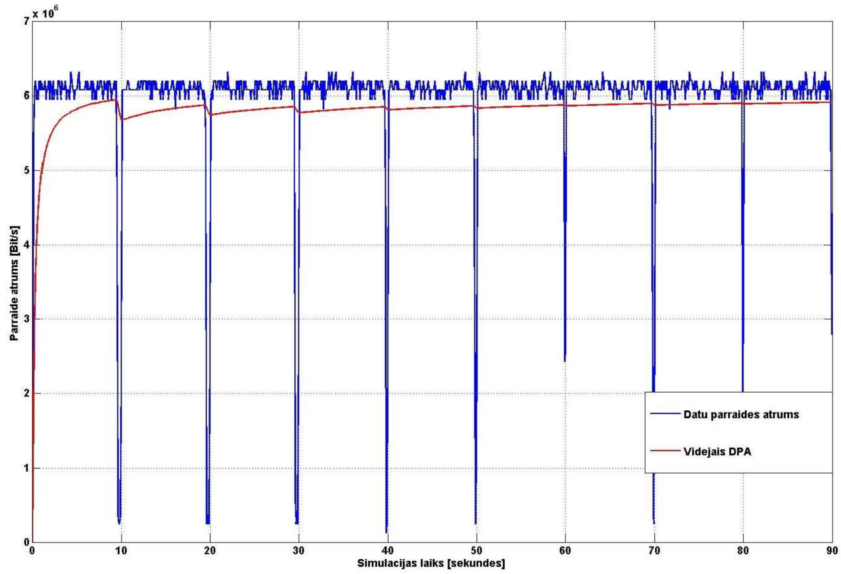

Figure19. Data transfer speed of 6 Mbit/s in 802.11b standard.

Other important problem is to define most effective ways of connection points (Inter-connected roadside access points (APs) placement in order to shift moment between them would be short, but the distance would be superior, and hardware costs would be low.

During numerous experiments, it was estimated that suitable distance between Inter-connected roadside access points (APs), when the drive-thru vehicle moves at speed of 100 km/h, is 280 meters (figure 20).

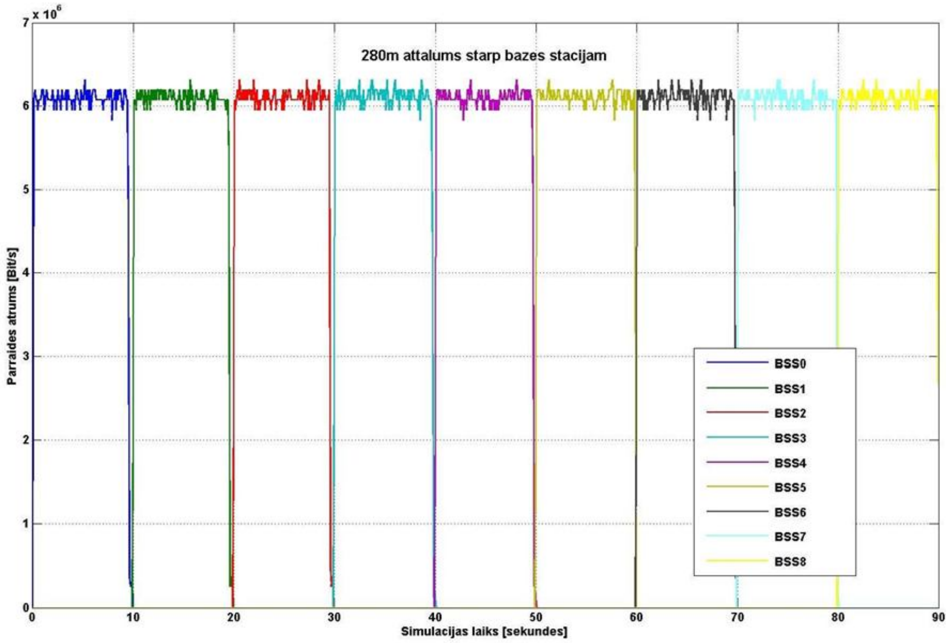

Figure 20. Distance between BSS is equal to 280 m.

If the distance is larger than 280 meters, then the shift interval between Inter-connected roadside access points (APs) will be greater, because the drive-thru vehicle will not get in time to next Inter-connected roadside access point (APs) signal, but it has already "gone" from current optimal signal.

If the distance is less than 280 meters, then efficiency of every next Inter-connected roadside access point (APs) will be lower. With this signal customer`s wireless system will operate shorter time than it could be. If Inter-connected roadside access points (APs) are located close to each other, then customer will operate any time with previous signal of Inter-connected roadside access points (APs), as it is adopted (can operate by maximal allowed data transfer speed) and it is not necessary to switch to next signal of data transfer device.

When the shift moment is performed, then working time of active device will be shorter than working time of previous Inter-connected roadside access point (APs).

Next simulation shows that selected speed was correct. Figure 21. shows numerous graphs with the same data transfer speed (6mbit/s for 802.11b standard). So you can see that customer`s speed, which is more than 100 km/h is not valid, because even average data transfer speed is equal approximately 3.5 Mbit/s, and transition moments require more time.

It is likely that data transfer will not performed. To estimate the graph we can say that moving at speed less than 100 km/h, internet will operate without any problems. But on highway, moving at speed less than 100 km/h, you will trouble traffic of other drivers. That is why in all simulations speed of 100 km/h was used.

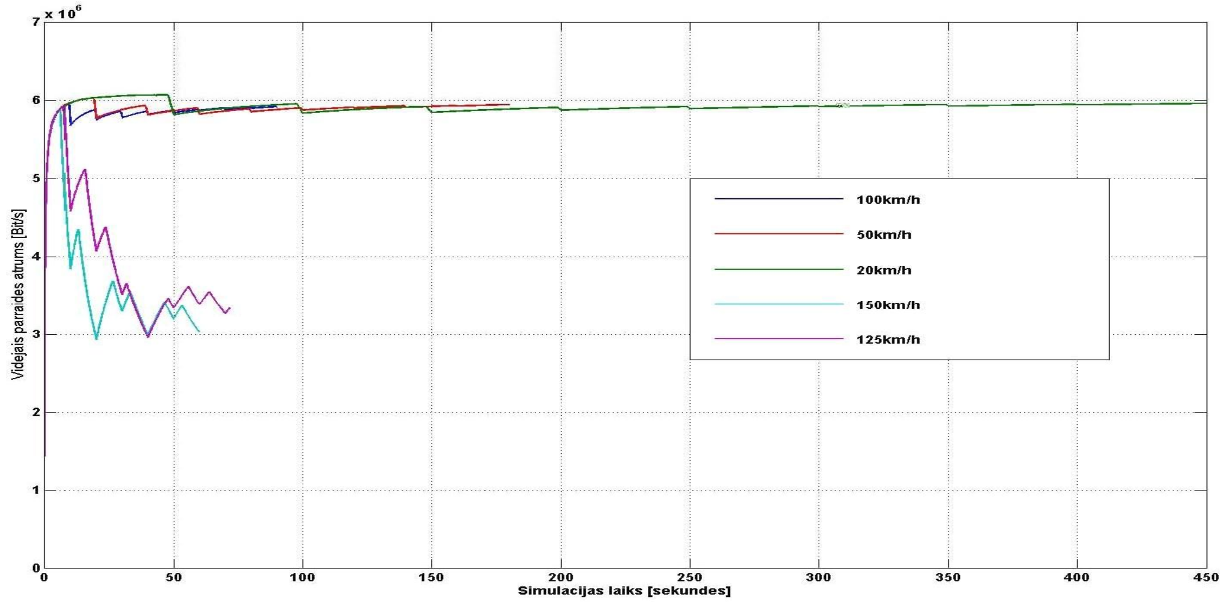

Figure 21. Average goodput (bits per second) at drive-thru vehicles different speeds.

During simulation two customers were used. The distance between them is 2.5 km, and they move face to face at speed of 100 km/h.

Figure 22. shows goodput of total infrastructure in time, when two customers, which are connected to network, move. The graph showsthat total data transfer speed is equal approximately to 12 Mbit/s, but in the middle - in drive-thru vehicles meeting point - it is lower. That is why before meeting and after meeting customers turn to their own base stations, but in the middle - in meeting point - data transfer is performed via only one Inter-connected roadside access point (APs). But as we know, maximal goodput is less than 12 Mbit/s (802.11b).

Results of this simulation correspond to conclusions, which are prescribed in second chappter, estimating the stacionary sitution in drive-thru Internet system of the 802.11g standard.

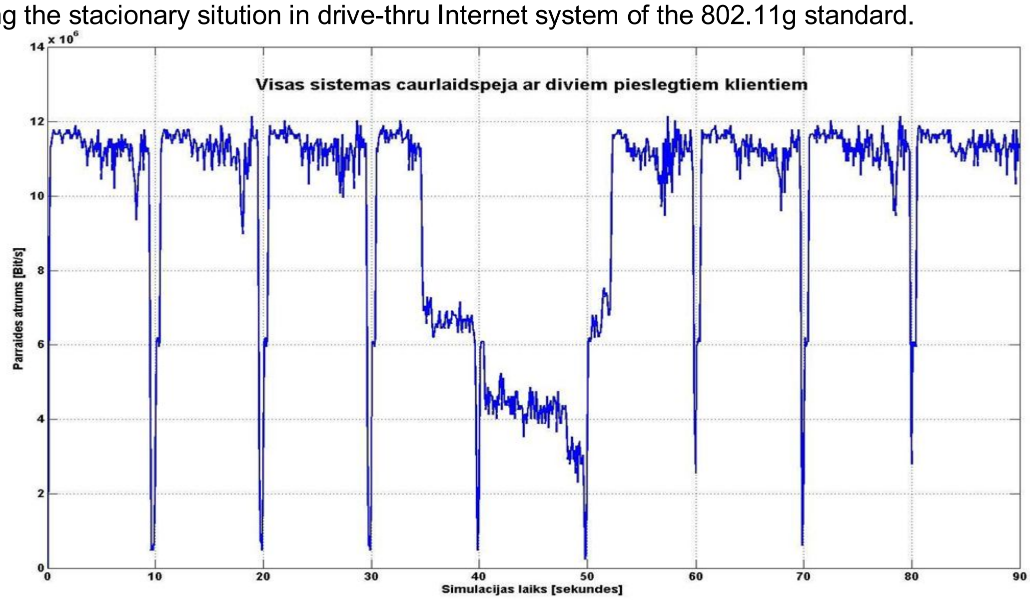

Figure 22. Data transfer goodput of all system.

During this simulation three customers connected to network were used. Two customers move toward one another, as it was already described in second simulation, and third customer begins to move in 40 seconds after beginning of simulation. Total goodput of system (in bits) can be seen in Figure 23.

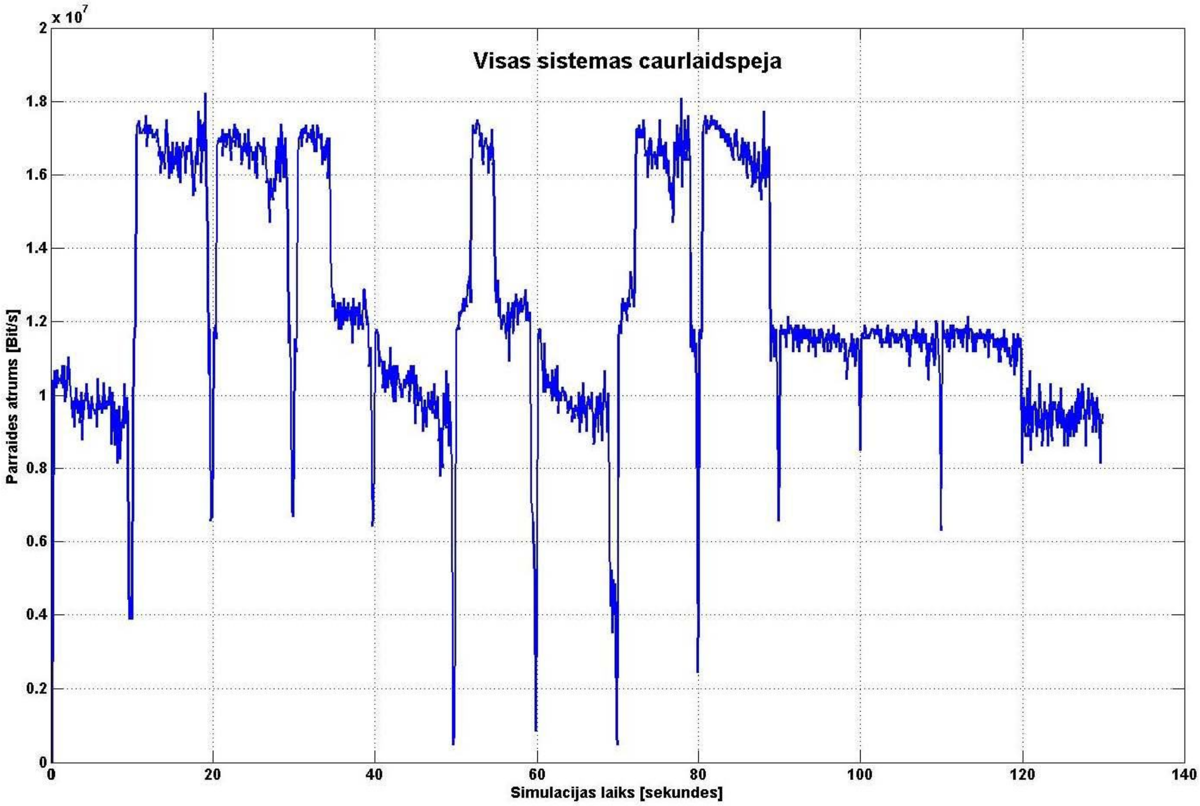

Figure 23. Data transfer goodput of all system with three customers.

The graph shows, when each customer turns to individual (own) base station (data transfer speed is equal ≈ 17 Mbit/s) and when - does not, then data transfer speed is equal≈ 12 Mbit / s (when two customers turn to one base station). After simulation 90 seconds total goodput of system speed is equal to ≈ 12 Mbit/s, because first customer has already left working area of system.

Chapter 7 Conclusions

Experimental and analytical estimation of Goodput of Drive-thru Internet system based on 802.11g and 802.11n protocols is presented in this diploma paper.

As a result of experimental part a number of dependences have been determined:

- Goodput exponential dependence on the amount of stations in wireless networks 802.11.
- Goodput quadratic dependence on distance to base station of in Drive - thru Internet systems.
- Goodput dependence on speed of vehicle in Drive - thru Internet system based on 802.11g and 802.11n.
- dependence between Goodput and rate signal/ noise for vehicle cooperating with base station in accordance with protocol 802.11g.

These dependences have been analyzed analytically. On the base of analysis two mathematical models have been developed. These models relate the characteristics of traffic flow and Data transfer system. To take into consideration the obtained data, the efficiency of base station is related to characteristics of traffic flow and to characteristics of Data transfer system. Also we can conclude that actual speed of data transfer will depend on the number of objects, cooperating with base station and distance to base station.

In this diploma paper the existence of vehicle maximal speed was proved, when data transfer in Drive - thru Internet systems based on 802.11g and WDS is possible, and it does not exceed 100 km/h.

Also the absence of vehicle maximal speed up to 100 km/h, when data transfer in Drive - thru Internet systems based on 802.11g and WDS is possible,

In this diploma paper rate between Goodput in Drive - thru Internet system based on 802.11g and 802.11n was determined. This rate indicates Goodput considerable tearing off, using standard 802.11n.

In this connection we can determine considerable advantage of standard 802.11n in comparison with standard 802.11g in development of Drive - thru Internet system.

As a result of Drive - thru Internet system construction the optimal distance between base stations was determined, and it is equal to 280 m, at speed 100 km/h. This fact has to be taken into account in the construction of Goodput of Drive - thru Internet systems.

The absence of Doppler shift on data transfer in Drive - thru Internet system based on 802.11g, if car speed does not exceed 120 km/h, was determined also.

In this diploma paper the necessity to continue researches of Drive - thru Internet system based on 802.11n was established, because the parameters of this structure are the best. This structure is able to satisfy potential clients due to its efficiency and relatively low price.

Future Work Results of the present work give significant scope for future work and especially in mobile wireless environment.

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