RIGA TECHNICAL UNIVERSITY
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DEVELOPMENT AND ANALYZING OF MODELS FOR PERFORMANCE EVALUATION OF VEHICULAR HETEROGENEOUS WIRELESS NETWORKS

Summary of the promotion work

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PROMOTION WORK
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The promotion work for a doctor's degree of enginnering sciencies (telecommunications) is to be defended publicly on 27 of january at 14:30 o'clock, 2015 at the faculty of Electronics and Telecommunications of Riga Technical University, 16/20 Azenes Str., in the lecture-room No. 215.

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CONFIRMATION

I confirm that I have developed this promotion work for a doctor's degree of engineering sciences which has been submitted for reviewing at the Riga Technical University. The promotion work is not submitted in any other university for a scientific degree.

Nikolajs Bogdanovs ……………………………. (Signature)

Date: ………………………

The promotion work is written in the English language. It contains Introduction, 5 Chapters, Conclusion, and Bibliography, 56 figures and illustrations, with the total number of 105 pages. The Bibliography has 87 titles.

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GENERAL DESCRIPTION OF THE WORK

Topicality of the subject matter

Vehicular networks are a novel class of wireless networks that have emerged thanks to advances in wireless technologies and the automotive industry. Vehicular networks are spontaneously formed among moving vehicles equipped with wireless interfaces that could be of homogeneous or heterogeneous technologies.

Vehicular network can be deployed by network operators and service providers or through integration between operators, providers, and a governmental authority. Recent advances in wireless technologies and the current advancing trends in ad hoc network scenarios allow a number of deployment structures for vehicular networks, on highway and city environments.

The construction of wireless networks for mobile objects involves a number of problems that developers must address. One problem is the determination of the number of mobile objects on the highway depending on their distance from the base station. This is a problem of current interest because the number of customers covered by the base station affects the effective data transfer rate (called "Goodput"). The determination of this effective data transfer rate related to road traffic is another problem of the construction of wireless networks for mobile objects. Here, the effective data transfer rate in a wireless transport network is defined according to [3] as the actual rate of data transfer from the user level of an onboard computer to the base station taking into account the time delays.

Objective of study – development and analysis of model symbiosis needed for the design of vehicular networks.

It is necessary to take into account the features of the traffic on the road in order to determine the number of vehicles in the active range of the base station. There are several models for traffic estimation [1] described in chapter 1. These models can be divided into two classes: macroscopic and microscopic. These models can be used for analysis of different situations on the road.

Two modes of traffic movement were considered in this paper. First mode was considered the open model with an unlimited number of transport ($N = \infty$). This mode describes the highway with the different number of bands and Erlang distribution of traffic flow. In the second mode the short span of road (200 m) was examined with Poisson distribution of traffic flow with a limited number of transports, this mode is a closed network model. This may correspond to a situation where vehicles are stopped at a traffic light and start to move with different speeds in the direction of the base station; for such mode a closed network model is appropriate. This mode is a closed network model. The main feature of the second mode is the fact of changes in speed under the Exponential Law.

The paper determines the number of moving objects, depending on the distance to the base station and identifies the parameters of data transmission systems. Thereupon, the actual speed of data transmission from moving objects in the active range of the wireless network base station is being determined wirelessly.

Experimental data were presented in the paper, evaluating the data transmission between the remote object and base station on the wireless network of 802.11n standard. The pattern of speed change of data transmission from the number of remote objects was determined. The experimental results, presented in the paper were used for the evaluation of actual speed of data transmission between the moving vehicle and base station, if operating in the mode of file transfer according to FTP protocol. The FTP protocol is designed for transferring large files. The actual Goodput in the program is measured during the experiment with the protocol FTP to determine the data transmission rate of large volumes.

The evaluation is carried out using the program IxChariot. The main feature is the fact of speed measurement of data transmission, depending on the remoteness of the mobile object from the base station and its speed of movement.

The second objective of the creation of analytical model is to assess not only the movable object – Access point, but also the distance from the Access point to the remote server. In two rank network customers connect with the AP via 802.11n protocol, then the AP connects via the Internet or via the mobile communications LTE with the remote server.

A proper model in this case can serve a closed network model of queuing system, consisting of two nodes.

The starting node stimulates the terminals of the mobile objects; on the direct connection with it is the AP model with the controller and the router, retrieving the AP to the connection to a remote server which stimulates the third node of network model.

In order to determine the model parameters, such as the intensity of processing in nodes and transition probability, it is necessary to evaluate the physical parameters of prototype. For the purpose of creation of such prototype the equipment of the company Cisco was used. Using Cisco equipment the wireless two rank transport networks was built.

This prototype represents 'test-bed' for the research of goodput dependence on the vehicle speed. Moreover, the measurement of useful data transmission rate covers not only the first rank of the system: "mobile object" – AP and further, the data transmission channels from AP to the remote server of the user.

Obviously, the goodput to a great extent will depend on the data transmission rate from the AP to the server, i. e., from the transmission data parameters. To carry out such research a router CISCO C819 M2M has been taken, which has two output channels. One channel provides the data transmission in GPRS mode. The second channel characterized by the high-speed data transmission, uses LTE – mode of the next generation of mobile communication.

The research has shown that the speed of data transmission can significantly differ from the data that were measured previously and cover the first rank of the system of mobile object – AP. It is explained by the presence of the second rank of the network to server.

Objective of the work: To develop a set of models providing vehicular network design, which is maximally consistent with the parameters of the traffic flow on the basis of the experimental studies of the elements of wireless network data transfer.

The aim and tasks of the work

To develop a set of models providing vehicular network design, which is maximally consistent with the parameters of the traffic flow on the basis of the experimental studies of the elements of wireless network data transfer.

The following **tasks** have been completed for the achievement of this objective:

1. Together with the colleagues the peer network for data transfer of the protocol IEEE 802.11n with three access points has been developed, set up and studied.
2. To study the maximum traffic capability of the wireless network at different speeds of vehicles. In order to identify the model parameters of the projected vehicular network.
3. To study the existing models of traffic flow on the road and to develop models themselves, which would be appropriate for determination of the number of clients in the area of vehicular network base stations.
4. To develop models of data transfer network, providing access for moving objects to base stations for different driving situations.

5. To develop, set up and study experimentally similar network for data transfer consisting of three base stations, concentrator and transmitter of mobile network, providing access of mobile customers to the remote server using GPRS and LTE channels.
6. To develop a model of similar network for data transfer, providing access for mobile objects to remote servers and to identify the parameters of the model based on experimental data.
7. To identify, set up and study the existing "advanced" simulation programs, which allow simulating the stochastic behavior of the vehicles on the road in the process of their interaction with the base stations of roadside wireless network.
8. To compare the vehicular network model results obtained using simulation models and in reality.
9. To develop recommendations for application of the proposed models in the process of construction of vehicular network for different situations.

The results and scientific novelty of the research

Analytical model for evaluation of the heterogeneous two rank network's Goodput for transferring protocol's data and GPRS/LTE channels using parameters of vehicle traffic flow.

Generated analytical models determine the parameters of vehicle wireless network.

The theses to be defended:

1. When comparing new empirical and analytical study results, a regularity was proven between mobile client flow and goodput in heterogeneous wireless network;
2. A regularity was obtained between mobile client density and the distance to the nearest access point of the two rank network using created closed queuing network model by expanding Gordon-Newel theorem's stationary probability distribution;
3. The proof that diffusion model, which can be used to determine mobile client density in non stationary mode of the one rank network, results show high Pearson's correlation linking with the results of stationary vehicle movement mode, where standard deviation is no more than 7 %;
4. Experimental and analytical proof that fourth generation mobile communication network in heterogeneous network's architecture with dynamic environment shows 11 times higher productivity than packet radio service mobile communication network.;

Approbation of the results of the research

The main results of the promotion work are presented at 8 international scientific conferences; these are reported in 19 publications in scientific journals.

Reports at the international scientific conferences:

1. RTU 52. studentu zinātniskā un tehniskā konference, Riga, Latvia, 2011. g.
2. The 15th International Conference of ELECTRONICS, Kaunas and Vilnius, Lithuania, 2011. g.
3. International Conference ELECTRONICS'2012, Palanga, Lithuania, 2012. g.
4. The 13th Biennial Baltic Electronics Conference (BEC2012), Tallinn, Estonia, 2012. g.
5. The 7th International Conference (ECT-2012), Kaunas, Lithuania, 2012. g.
6. The 8th International Conference on Electrical and Control Technologies, Kaunas, Lithuania, 2013. g.
7. The International Conference on Technological Advances in Electrical, Electronics and Computer Engineering (TAEECE2013), Konya, Turkey, 2013. g.
8. The 9th International Conference on Electrical and Control Technologies Kaunas, Lithuania, 2014. g.

The results of the promotion work were used for the realization of Latvian **scientific research projects**:

National research program: DEVELOPMENT OF INNOVATIVE MULTIFUNCTIONAL MATERIALS, SIGNAL PROCESSING AND INFORMATION TECHNOLOGIES FOR COMPETITIVE KNOWLEDGE INTENSIVE PRODUCTS (IMIS) Project No. 2 "Innovative signal processing technologies for development of intelligent and efficient electronic systems".

The research results of promotion work were shown 18 publications in scientific journals:

1. Pētersons E., **Bogdanovs N**. Performance Evaluation of Three Layer Vehicular Network // Electronics and Electrical Engineering.– 6. (2011) pp 25–28.
2. **Bogdanovs N**., Ipatovs A., Jansons J. Research of a 2-layer Closed Vehicular Network // Scientific Journal of RTU. 7. series., Telekomunikācijas un elektronika.– 11. vol. (2011), pp 34–40.
3. Jansons J., Pētersons E., **Bogdanovs N**. Vehicle-To-Infrastructure Communication Based on 802.11n Wireless Local Area Network Technology // 2nd Baltic Congress on Future Internet Communications (BCFIC 2012): IEEE Conference Proceedings: IEEE Xplore Digital Library, Lithuania, Vilnius, 25.–27. April, 2012.– pp 26–31.
4. Jansons J., Pētersons E., **Bogdanovs N**. IEEE802.11n Standard's Capability to Support Wireless Device in Vehicular Environment // Electrical and Control Technologies (ECT-2012): The 7th International Conference , Lithuania, Kaunas, 3.–4. May, 2012.– pp 44–47.
5. Ipatovs A., **Bogdanovs N**., Pētersons E. Evaluation of the Rate of the Data Transfer between Vehicles and Base Stations in Wireless Networks // Automatic Control and Computer Sciences.– Vol. 46, Iss. 2. (2012) pp 76–82.
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13. **Bogdanovs N**., Pētersons E., Šarkovskis S. Modelling of Vehicular Network for Short Range // Proceedings of the 12th International Conference „Reliability and Statistics in Transportation and Communication" (RelStat-12), Latvia, Riga, 17.–20. October, 2012.– pp 195–203.

14. Jansons J., Pētersons E., **Bogdanovs N**. Analyses and Evaluation of Wireless Local Area Network in Vehicular Mobility Scenarios. Electronics and Electrical Engineering, 2013, Vol. 19, No. 2, pp. 97.–100.
15. **Bogdanovs N**., Pētersons, E., Jansons, J. Two Layer Model for Performance Evolution of V2I Network. Electronics and Electrical Engineering, 2013, Vol. 19, No. 3, pp. 98–101.
16. Jansons J., Pētersons E., **Bogdanovs N**. WiFi for Vehicular Communication Systems. In: 27th International Conference on Advanced Information Networking and Applications Workshops: 27th IEEE AINA 2013, Spain, Barselona, 25–28 March, 2013. Fukuoka: 2013, pp. 425–430.
17. **Bogdanovs N.**, Pētersons E., Jansons J. Simulation to Evaluate Performance of Two Layer Vehicular Networks. In: The International Conference on Technological Advances in Electrical, Electronics and Computer Engineering (TAEECE2013), Turkey, Konya, 9–11 May, 2013. Konya: Mevlana University, 2013, pp. 548–553.
18. **Bogdanovs N**., Pētersons E. ROAD TRAFFIC NON-STATIONARY ANALYSIS OF THE VEHICULAR WIRELESS NETWORK GOODPUT EVALUATION. In: Electrical and Control Technologies, Lithuania, Kaunas, 8–9 May, 2014. Kaunas: 2014, pp. 46–49.
19. **Bogdanovs N**., Ancāns A., Martinsons K., Pētersons E., **Bogdanovs N**. Performance evaluation of integrated vehicular network // Автоматика и вычислительная техника.– 5. (2014) pp 39–49.

DETAILED DESCRIPTION OF THE WORK'S CHAPTERS

Chapter 1

At first, we consider the correlation between the speed υ and density K. In general, when the density K, the saturation rate is increased, drivers slow down the speed to ensure the safety of movement [2]. Therefore, there is a significant correlation between υ and K, the speed υ can be approximated as steadily decreasing function of density. Although, the form of this function is determined by the characteristics of the road, types of cars, flow consistency, weather conditions and etc., the simplest form is linear approximation [2], shown in Figure 1.1. This correlation between K and υ expressed by the equitation:

$$\upsilon = \upsilon_0 (1 - \frac{K}{K_c}), \tag{1.1}$$

Where υ - is a speed of free movement or maximum speed possible on the road, but K_c - is maximum density of the flow, while achieving it all the cars in the flow are stopped.

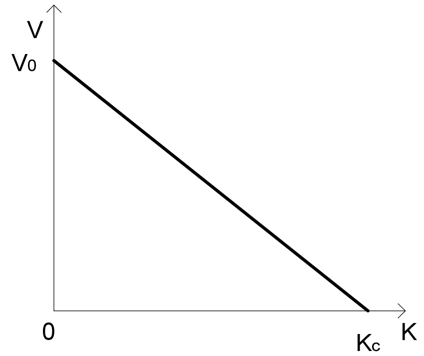

Figure 1.1. The approximate correlation between the speed and flow density

Statistical properties of traffic flow

Moving vehicles can be divided in general into two groups – free moving and following the leader. Free moving vehicles can move without obstacles on the side of the other cars, while the movement of cars, following for the leader is limited by the car, driving ahead.

The distribution of time intervals h_1 for free moving cars can be accepted exponential, shifted to the positive value equal τ to the minimum value of the interval between the vehicles, wherein they can be considered as free moving [1].

Consequently, the distribution density $f_1(h_1)$ of intervals between such vehicles is defined by the expression:

$$f_1(h_1) = \lambda_1 e^{-\lambda_1 (h_1 - \tau)}; h_1 \geq \tau, \tag{1.2}$$

where $\lambda_1 = 1/(\overline{h_1} - \tau)$, and $\overline{h_1}$ – mathematical expectation h_1, i. e. the average interval between free moving vehicles.

On the other hand, showed that the distribution of time intervals h_2, following for the leader of cars can be approximated by Erlang distribution k order (or gamma distribution) for value $\kappa > 1$.

$$f(h) = \varphi\lambda_1 e^{-\lambda_1(h-\tau)} + (1-\varphi)\frac{(k\lambda_2)^k h^{k-1} e^{-\lambda_2 kh}}{(k-1)!}, \tag{1.3}$$

where it's assume that the first term equals to zero, where $h < \tau$.

To determine the number of vehicles on a certain road section it is necessary to develop models themselves to appropriately determine the number of clients in the coverage area of base stations of vehicular network. The third chapter will be devoted to this issue.

Chapter 2

This chapter describes mobile wireless networks, which can be used in vehicle network. The standard 802.11p enables a wireless access to vehicular environment. 802.11p functions in the 5.9 GHz range; this technology permits access to navigational options, multimedia information and also telemetry. For design of a wireless network that would work by 802.11p standard, more expensive equipment is required than for other IEEE wireless network standards like 802.11n.

The significant improvement of 802.11n standards comparing to previous standards is the raw data rate of the wireless channel up to 600 Mbps – more than twenty-fold improvement over 27 Mbps of 802.11p maximum data speed [5].

WiFi standard 802.11n (which operates in the 2.4 GHz frequency band) supports up to 4 × 4 MIMO, which gives a theoretical channel bit rate of 600 Mbps. Table 2.1 present comparative speeds for wireless protocol:

Table 2.1.

Comparative speeds for IEEE 's 802.11 wireless protocol

Standard	Frequency band	Max. MIMO	Data Rate
IEEE 802.11a	5 GHz	None	54 Mbps
IEEE 802.11b	2.4 GHz	None	11 Mbps
IEEE 802.11g	2.4 GHz	None	54 Mbps
IEEE 802.11n	2.4 GHz	4 × 4	600 Mbps

The data stream is divided between the antennas to boost speed and to make the link more reliable. Using OFDM and MIMO lets LTE deliver data at a rate up to 100 Mbit/s downstream and 50 Mbit/s upstream under the best conditions. In 4G the theoretical upper data rate is 1 Gb/s. The provided connection to Internet will allow users to access all type of services including text, databases, and multimedia [6].

LTE technology and protocol 802.11n has the best performance for the organization of the transport network. Parameters of LTE technology and protocol 802.11n will be used for the development of the models of transport networks, and will be described in Chapter 3.

Our goal is to prove that WLAN technology is capable of enabling heterogeneous network access in the first place and to document the connection parameters we have observed with different measurement configurations using TCP as standard transport protocols.

Chapter 3

Considering that the distribution of queries is exponential with the parameter μi. According to this approach the speed of vehicle movement on the highway is characterized by density. Vehicle distribution per meter can be obtained using a Greenshield's model formula (1.1). Despite the fact that this model is not perfect, it is fairly accurate and relatively simple.

A number of passing through vehicles per second for each interval according to query intensity and processing is provided [9, 10]. If the interval length equals *Si*, and vehicle movement speed equals ϑ_i, then the intensity of vehicle service by road interval equals:

$$\mu_i = \frac{\vartheta_i}{S_i}. \quad (3.1)$$

According to the intensity of vehicle service will depend on the initial vehicle flow rate into the road interval as from the density of vehicle location on the road interval (see Figure 3.1).

$$\vartheta_i = \vartheta_o(1 - e^{-\alpha r}) \quad (3.2)$$

Where r – distance to base station (m), ϑ_0 - 100km/h.

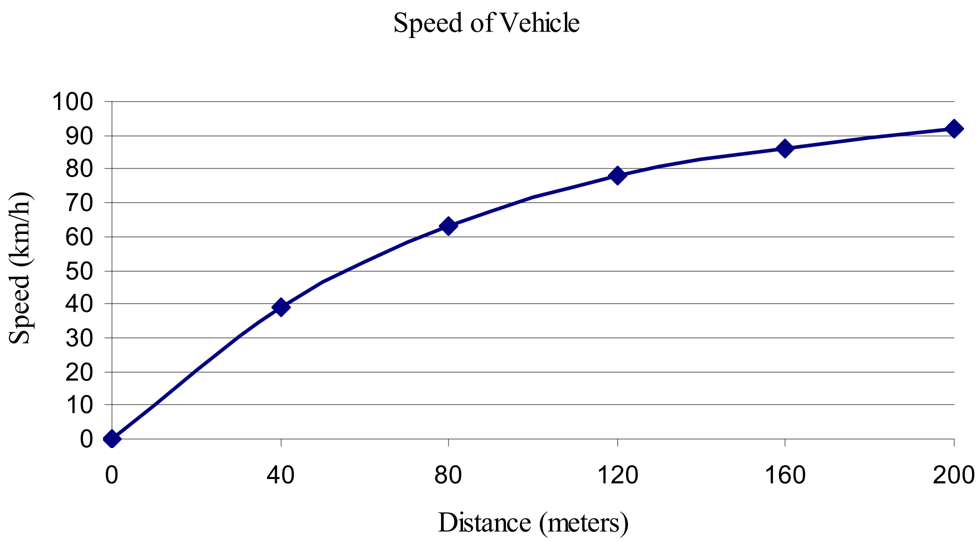

Figure 3.1. Exponential Equation

Buzen's Algorithm for Closed Queueing Network

A queueing network is a collection of service facilities organized in such way that customers must proceed from one facility to another in order to satisfy their service requirements.

Consider a closed queueing network with M service facilities and N circulating customers [12]. Write n_i for the number of clients present at the *i*-th facility at time *t*, so that

$$\sum_{i=1}^{M} n_i = N. \quad (3.3)$$

The service time for a customer at the *i*-th facility is given by an exponentially distributed random variable with parameter μi and that after completing the service at the *i*-th facility the customer will proceed to the *j*-th facility with probability. It follows from the Gordon-Newell theorem that the equilibrium distribution of this model is:

$$P(n_1, n_2, ..., n_M) = \frac{1}{G(N)} \prod_{i=1}^{M} (X_i)^{n_1} \quad (3.4)$$

Due to the periodic nature of this model $x_1 = 1$ and the next step is calculated as follows:

$$x_2 = \frac{\mu_1}{\mu_2}, x_3 = \frac{\mu_1}{\mu_3}, ..., x_M = \frac{\mu_1}{\mu_M} \quad (3.5)$$

Vehicle service intensity will depend from both initial velocity at entering the road segment and the density of vehicle placement on this segment.

Buzen's algorithm is among the methods for closed network analysis, as show in Table 3.1. Buzen's matrix, at the row *i* and column *j* can be calculated using the formula [16]:

$$g(i, j) = g(i, j-1) + g(i-1, j)xj \quad (3.6)$$

Table 3.1

Buzen's matrix

Nr.	$x_1 = 1$	$x_2 = 0.776$	$x_3 = 0.644$	$x_4 = 0.568$	$x_5 = 0.514$
0	1	1	1	1	1
…	…	…	…	…	…
9	1	4,111	10,630	22,535	42.284
10	1	4,190	11,038	23,835	45,569
…	…	…	…	…	...
19	1	4,443	12,377	28.432	57,991
20	1	4,447	12,414	28,562	58,370

Where *G*(*N*) – normalizing constant, resulted either from adding up and equating to one all probabilities, or by Buzen's method. Naturally, there are no limitations for the number of queries (vehicles) in the *i*-th interval.

Average number of queries (vehicles) in *i*-th interval:

$$E(n_i) = \sum_{K=1}^{M} (x_i)^K \cdot \frac{G(N-k)}{G(N)} \quad (3.7)$$

Table 3.2 shows average number of queries:

Table 3.2

Average number of vehicles

Number of Vehicles	Zone				
	1	2	3	4	5
N=10	6	1	1	1	1
N=20	15	2	1	1	1

Road traffic Nonstationary analysis for Vehicular Wireless Network Goodput Evaluation

Roadside Access Point may be used along roadside to provide moving user's multiple-access to heterogeneous network system. For this reason WiFi technology can be used.

The main questions in implementing Wireless technology are related to network goodput development. The Goodput depends not only on wireless channels and data transmission speed, but also on the number of Access Point clients (vehicles in AP coverage range).

The number of concurrent vehicles in the coverage area depends on the vehicle speed, vehicle's density on the road and also on the regime of road traffic.

There may be two regimes – stationary regime which may be proposed to us by the vehicle flow on the long main roads and the non-stationary regime. H. Kobayshi work has been taken as a basis for analyzing vehicle distribution non-stationary regime [18, 19].

For test purposes the same two-stage system in the stationary mode can be used. The bandwidth equation for a two-stage network:

$$X_1 = 1,\ X_2 = \frac{\mu_1}{\mu_2}, \tag{3.8}$$

$$G(N) = \frac{N_2^{N+1} - 1}{X_2 - 1} \tag{3.9}$$

The output flow is equal to input flow and from this rule of flow balance it is possible to write the equation. The number of vehicles is being calculated as follows:

$$n = \frac{N+1}{(1 - X_2^{N+1})} - \frac{1}{(1 - X_2)} \tag{3.10}$$

Let's compare the obtained results with the results of the diffusive approximation (Table 3.3):

Table 3.3

Comparative results

p	Diffusive approximation	Cyclic queuing model
0.75	8 vehicles	$7.485 \approx 8$ vehicles
0.95	6 vehicles	$5.51 \approx 6$ vehicles

The Table 3.3 shows that the diffusive approximation is correct.

Comparative Analyses Two Calculations

The average number of queries (vehicles) (3.10) in *i*-th interval for stationary regime as shown in Table 3.4.

Table 3.4.

Average number of queries for stationary regime

Vehicle (*N*)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Loading 0.95					
10	5.81	1.03	0.92	0.76	0.69
20	15.69	1.65	1.04	0.85	0.76
Loading 0.75					
10	4.36	0.77	0.69	0.57	0.52
20	11.77	1.24	0.78	0.64	0.57

Table 3.5 calculates the number of automobiles in every sub-zone AP according to *x y* from time as well as according to 2 values of loading 0.75 and 0.95.

Table 3.5.

Average number of queries for non-stationary regime

Vehicle (N)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Loading 0.95					
10	5.25	1.03	0.92	0.76	0.69
20	14.56	1.65	1.04	0.85	0.76
Loading 0.75					
10	3.94	1.03	0.917	0.761	0.689
20	10.91	1.24	0.78	0.64	0.57

The table 3.4 and table 3.5 show the time, when the distribution process of vehicles will become stationary. Based on this work, the distribution process will become stationary under exponential law.

Erlang Distribution for Vehicles

The given initial data allow obtaining the estimation of the average number of vehicles on the road. For this we assume that the ingoing stream of automobiles Erlang κ-1 order and $k = 5$. The service time of road vehicle flow with the bands is a random value of distribution on exponential law with the parameter q_z .

For the evaluation the number of vehicles which are in the coverage area of the road, use the $E_k / M / 1$ model. According to the number of customers in the service system, i. e., the average number of vehicles in the road segment [22]:

$$L = \frac{\rho}{1 - r_0^k} \tag{3.11}$$

Where ρ - the load ratio of the system.

In our case:

$$\rho = \frac{\lambda_2}{q_z} \tag{3.12}$$

So r_0 is a root of solution of characteristic equation which lies in the interval $\{0,1\}$.

$$q_z \cdot r^{k+1} - (k \cdot \lambda_2 + q_z)r + k\lambda_2 = 0 \tag{3.13}$$

In the considered situation $k = 5$. Note that r_0 is comparable with ρ , then the solution (3.13) for r_0 is sought iteratively.

In the table 3.6 the results of solution of equation for the different load factors are presented as well as the resulting indices of number of vehicles on the road section included in the service area of the base station.

Table 3.6.

The number of vehicles on the road section

ρ	0.25	0.5	0.6	0.75	0.8	0.9
r_0	0.56	0.76	0.84	0.88	0.9	0.92
$L = N$	0.265	0.67	1.031	1.588	1.954	2.64

Analysis of Cyclic Queueing Network Model

Vehicles pass all M intervals successively and the total number of vehicles in the base station's range of operation is N. Entering the base station's range of operation from the zero position (a lack of connection with the station) the vehicle finds itself in the zero position again.

Such a system can be described in a form of a closed cyclic mass service system network with *M* service devices, *N* queries and exponentially distributed service time [12, 14, 29]. Query service intensity in the *i*-th interval equals μ_i, as showed in Figure 3.2.

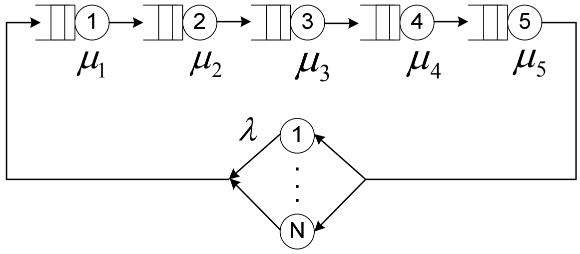

Figure 3.2. Closed cyclic system

Then the general form of the equilibrium distribution for $N \le \min_i m_i$.is known. If the number of stage is sufficiently large and if we assume that $\min_i m_i \ge 1$. As shown in Figure 3.3 in the first sub-zone of our segment 6 vehicles can be located. Consequently there won't be more than 6 vehicles per sub-zone, elsewhere too $m_i \le m_1 \le 6$. Following the obtained practical results, the base station performance at variable client count will be calculated. In our case the 200 meters long base station operational zone of is divided to 5 zones, 40 meters each, the third zone being the most adjacent to the base station.

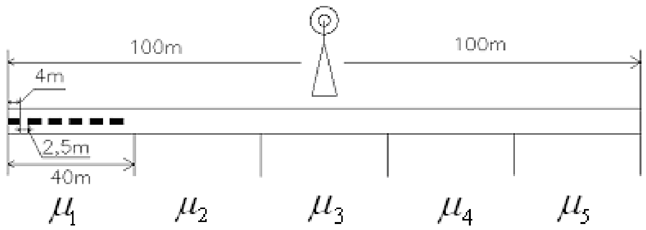

Figure 3.3. 200 meters long base station

It is assumed that *N* vehicles enter base station's operational zone. The Goodput rate of FTP depends on the vehicle speed and is decreasing proportionally with the vehicle speed. Using. Using the M/M/1//Ni , model for every sub-zone *i*, we find the probability of base stations idleness:

$$P_0(i) = \left[\sum_{k=0}^{E(n_i)} \left(\frac{\lambda_i}{\beta_i} \right)^k \frac{E(n_i)!}{(E(n_i) - k)!} \right]^{-1}. \quad (3.14)$$

Having the vehicle distribution by sub-zones of base stations client service zone it is possible to build a model for real data exchange rate evaluation between objects and base station. By first node we represent vehicles generating packets for processing in base station.

Depending on vehicles distance from base station the packet processing rate and packet processing rate in base station will be different. For file transfer the commonly accepted packed length $l_p = 1500$ bytes.

The Goodput rate of FTP depends on the vehicle speed and is decreasing proportionally with the vehicle speed. Depending from vehicles distance from base station, packet processing rate and packet processing rate in base station will be different.

Depending from the vehicles proximity to base station data processing rate and data processing intensity in base station will be different with exponential vehicles distributions, as show Figure 3.4.

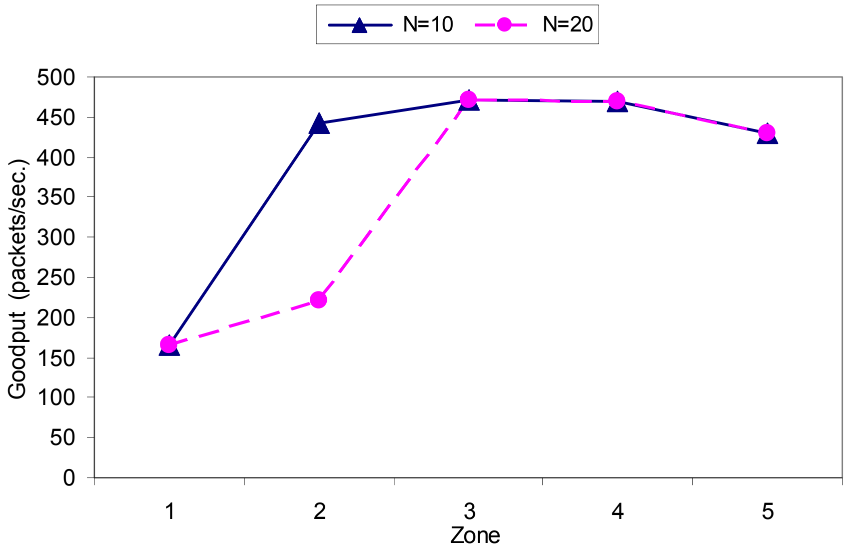

Figure 3.4. Goodput for moving with 10 and 20 vehicles

The Goodput of stations serving the area will be:

$$\eta_i = (1 - P_0(i))\beta_i . \tag{3.15}$$

Figure 3.5 shows the Goodput of the network at the Erlang distribution of the vehicles and probability.

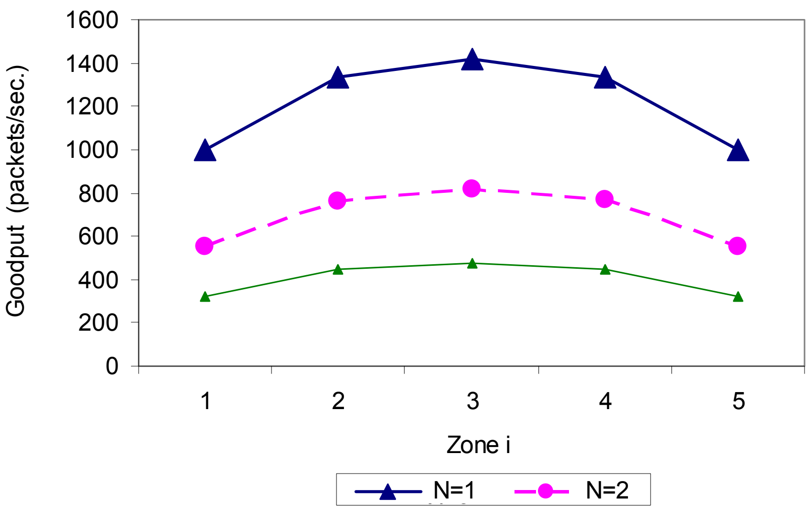

Figure 3.5. Goodput in wireless network with one router depending on distance for 802.11n

On the basis of this data it is possible to conclude that base stations goodput is bound with vehicular traffic parameters as well as with parameters of data transfer system. Also, in calculating goodput we took into account the possible amount of vehicles in sub-zone.

Performance Evaluation of Two-stage Vehicular Network

The physical implementation of connection for the transmission data from the vehicle to the user's server and back is the wireless network. At the first stage the data are transmitted from the mobile object to the nearest Access Point according to the protocol 802.11n [25].

However, the distance from the AP object should not exceed 200 meters. Further, from the AP the data are transmitted to the remote base station (server) by the channel according to the LTE. This option provides the data transmission at the distance up to the several kilometres [31]. Thus, the object of the research represents the two-stage system of the wireless networks. This system can be presented by the two-stage network model, as it is shown in Figure 3.6. The null node stimulates the data transmission from the movable object with the intensity of the data transmission ε_0.

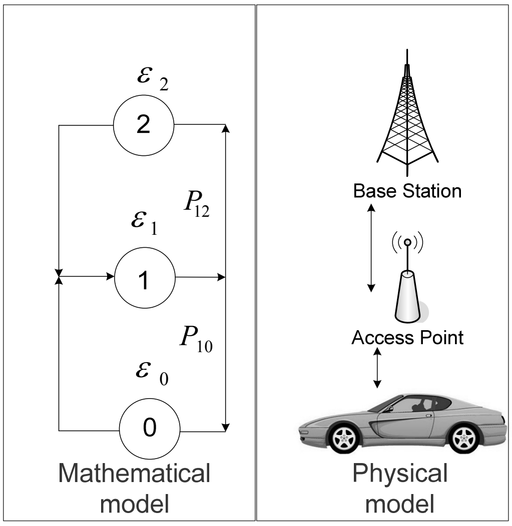

Figure 3.6. Two-stage vehicular network model

The second node stimulates the AP wireless network providing the data reception and transmission from the mobile objects of the null node. The intensity of the data processing is equal to ε_1:

$$\varepsilon_1 = \beta_i , \tag{3.16}$$

where β_i – transmission rating in the wireless network 802.11n depending on the distance to the base station as it is shown in the Figures 5.3.–5.5.

Depending on the vehicle's proximity to the base station, the data processing rate and data processing intensity in the base station will be different. For the file transfer with packet length of 1500 bytes, the base stations goodput β_i was estimated experimentally.

In its turn, AP is connected with the remote base station along the wireless network with the LTE. The intensity of the data transmission of the second node is to be taken to be equal to ε_2.

The route of the data transmission keeps the track from the null node to the first node and then to the second one, if the file transfer is considered from the vehicle to the BS. From the BS it is transmitted the ACK confirmations on the packet's transmission. In this case, the average time for the transmission will be different: more time is spent on the transmission of the data packets, which is denoted as $E(t_i)$.

The ACK transmission takes less time and denotes it as $E(t_0)$. Then the average time of the data processing in the ε_0 node will be:

$$E(t_1) = \frac{E(t_i) + E(t_0)}{2} \tag{3.17}$$

If on the top of each transmitted packet the ACK confirmations are received, the intensity of the processing in the ε_0 node will be:

$$\varepsilon_0 = \frac{1}{E(t_1)} \tag{3.18}$$

The model participates in the parameter *N*, determining the number of the data transmission initiators, which compete for the resource sharing of the 1 and 2 nodes. In our case this is the number of vehicles in the AP coverage area. Then the three-node and two-stage model of the goodput can be expressed by the (3.27) formula. In this formula the parameters α, *X*1 and *X*2 are determined by the value from (3.19).

The evaluation problem of the goodput provided by the model consists of the determination of the value *N* – the number of vehicles in the AP coverage area. Moreover, in the wireless network standard 802.11n the speed of data transmission depends on the remoteness of the vehicles from AP. The terminal count in each vehicular wireless network is usually high [26, 27, 29, 30]. The bandwidth equation for a two stage network being:

$$X_1 = \frac{\varepsilon_0}{\varepsilon_1 P_{10}};\ X_2 = aX_1;\ a = \frac{\varepsilon_1}{\varepsilon_2} P_{12}. \tag{3.19}$$

The intensity for the ε_2:

$$\varepsilon_2 = \frac{1}{t}, \tag{3.20}$$

$$t = \frac{l_p}{V_f} \tag{3.21}$$

Where V_f – the effective data transfer rate for the LTE. For the having the peak transfer rate V_n. The actual speed is determined in the following way:

$$V_f = \frac{V_n}{2} \tag{3.22}$$

The starting point for the calculation is the normalizing function *G*(*N*). It is chosen from the principle of the sum of probabilities being one. $p(n_0, n_1, n_2)$, where n_i in vector $\overline{n} = (n_1, n_2, n_3)$ is the inquiry count in $i-th$ node. The resulting equation for *G*(*N*) calculation looks like this:

$$G(N) = \sum_{\overline{n}} \prod_{i=1}^{3} (X_i)^n i, \tag{3.23}$$

$$\overline{n} \in \left\{ (n_1, n_2, n_3) / \sum_{i=1}^{3} n_i = N, n_i \geq 0 \forall_i \right\}. \tag{3.24}$$

Where N – number of vehicles.

The function of the studied two-stage vehicular network looks like this:

$$G(N) = \frac{1}{1-a} \sum_{j=0}^{N} X_1^j \left(1 - a^{j+1}\right) \tag{3.25}$$

The Goodput η of the two-stage network is defined as the count of the processed inquiries per time unit. The finished task is put out via the subsystem of input/output, and instantly a new task is loaded through it. The probability of the lack of inquiries in the *i*-th node will be:

$$p\left\{n_i = 0\right\} = \frac{G(N) - X_i G(N-1)}{G(N)} \tag{3.26}$$

The result is:

$$\eta = P_{10} \varepsilon_1 (1 - p\{n_i = 0\}) \tag{3.27}$$

From the equation (3.27) η for each segment can be calculated. The network performance influences the probability of transmission of the confirmation ACK, as ACK increases, the number of packages per unit of time increases too.

If the distribution of the vehicles is exponential the performance will be the following at the probabilities of $P_{10} = 0.999$ $P_{12} = 0.001$ (see Figure 3.7):

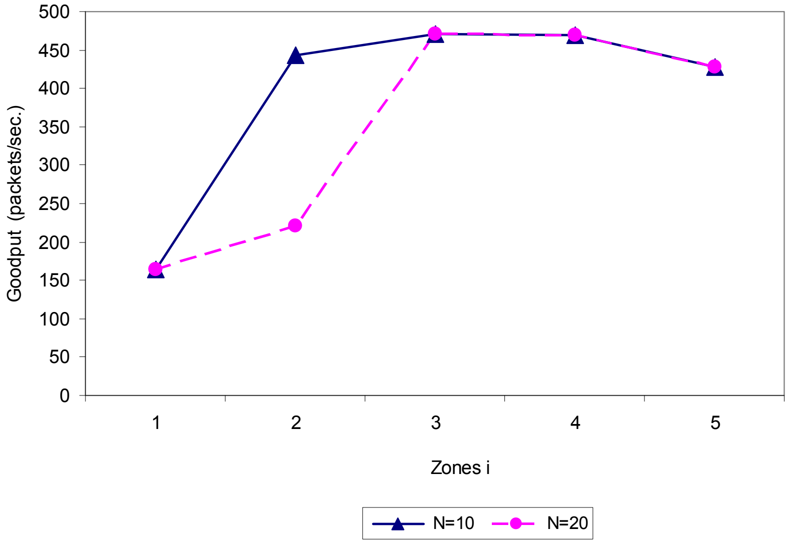

Figure 3.7. Goodput for a two-stage network model
with $P10 = 0.999$ $P12 = 0.001$ for 802.11n and LTE

Figure 3.8 show the goodput for the three-node closed network with the probabilities of P_{10} and P_{12} with the distribution of transport in Erlang:

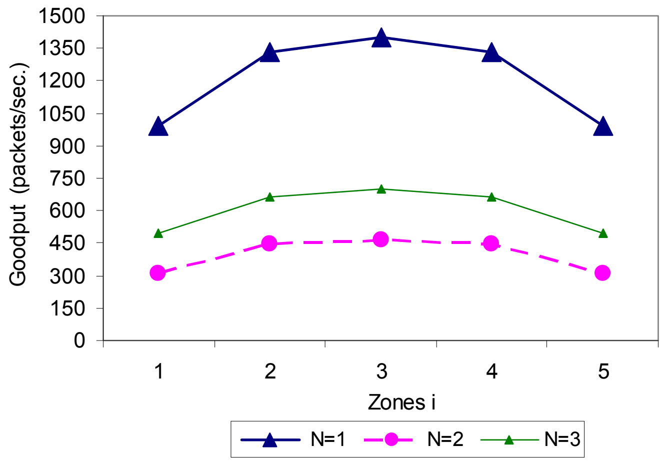

Figure 3.8. Goodput for a two-stage network model with $P_{10} = 0.999$ $P_{12} = 0.001$ for 802.11n and LTE at the Erlang distribution

Chapter 4

The results from previous studies were continued in the direction of the creation of the analytical model for performance assessment not only for the mobile unit – Access Point, but also further from the Access Point to the remote server.

The appropriate model in this case can be a closed network model of queuing systems, consisting of two stages. The initial node simulates terminals of the mobile units; it is directly connected to AP models with the controller and the router that connects AP to a remote server, which simulates the third node of the network model.

In order to determine the model parameters, such as the intensity of the processing in the nodes and probability of transitions, it is necessary to evaluate the physical parameters of the prototype. In order to create such a prototype, the Cisco equipment has been used. The Table 4.1 will resume the network setting for our experiments:

Table 4.1.

Network configuration

Name	**Parameters**
Protocol	IEEE 802.11n
Chanel frequency	20 MHz
Frequency	2,4 GHz
Transmitter power	17 mW
MIMO transmission settings	Auto
OFDM protective interval	0.8 μs

This prototype presents a “test-bed” for the study of the dependence of goodput on the speed of the vehicle. While the measurement of the effective data transfer rate covers not only the first range of the system “mobile unit – AP”, but also the data transfer channels from AP to a remote server of the user.

It is obvious that the goodput will be largely dependent on the data transfer rate from AP to the server, i. e. from the data transfer characteristics. For such studies the router CISCO C819 M2M with two output channels has been used. One channel provides data transfer in GPRS mode. The second channel, being characterized by a high data transfer rate, uses LTE mode – the mode of the next generation of mobile communications. Scheme “test-bed” is presented below (see Figure 4.1):

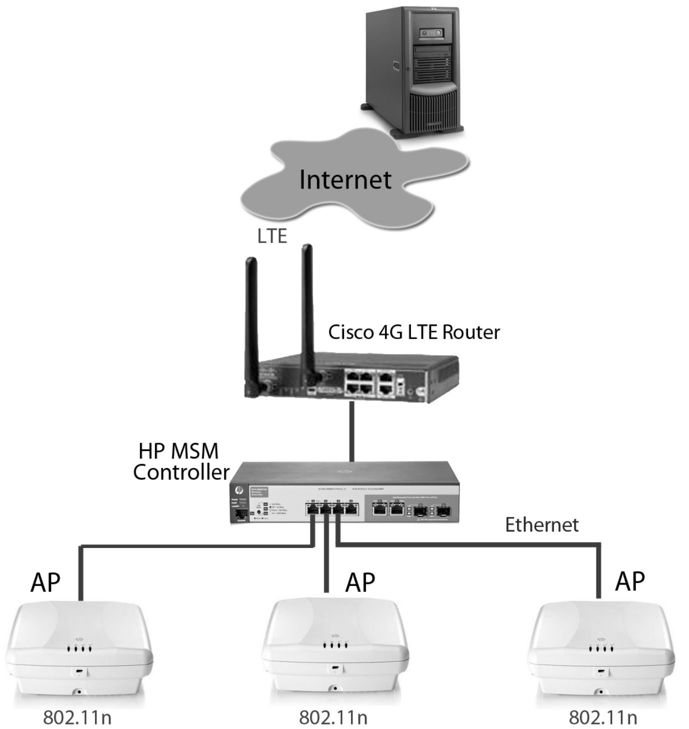

Figure 4.1. Two-stage network model

The first study showed that the data transfer rate may differ significantly from the data, which were obtained earlier and are covering the first range of the system "mobile unit – AP". This can be explained by the fact of the delay in the second range of the network to the server. As expected, goodput has a higher value at the transfer to the LTE channel.

In practice, it was determined that data transmission rate depends on the vehicle speed. At low speeds the Goodput of two-stage network is sufficiently high, while the increase in speed causes the significant reduction of Goodput. In this situation, many details depend on the method of data transmission rate adaptation method in a wireless network.

The main task in this experiment is to approximate data transmission speed in accordance with the distance to the base station, as well as the second task should be resolved, when the Internet speed should be fixed in accordance with the N moving objects, which are located in the coverage of the wireless network base station.

In order to carry out such study, the program IxChariot should be used. Over the FTP protocol the file is being sent via base stations from the computer to the remote server moving along the base station. FTP protocol is being used to transfer large amounts of data. During the experiment, the actual speed Goodput will be measured (the recommended data transmission speed) in the program over FTP protocol in order to determine the data transmission speed at the speed of the certain vehicle.

There are mathematical formulas to calculate the amount of packet transfer per second, as well as the possibility of obtaining the curves which will show the optimal speed for the moving object in order to receive more packages. The experiment was carried out with the use of access point in each direction at the distance of 100 meters from the controller in accordance with the principle, we use 3 access points and the client was moving with a speed of 20 km/h. It should be mentioned that these experiments have no authority controllers. Goodput – permeability and Elapsed time are denoting the experimental measurement time (see Figure 4.2).

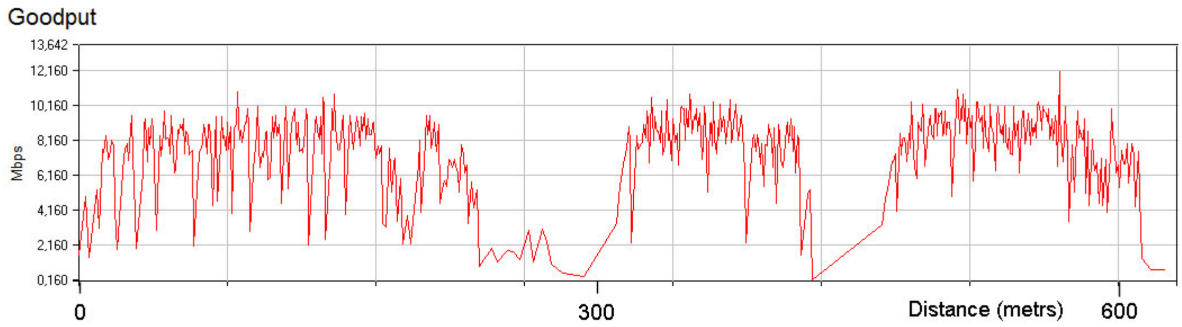

Figure 4.2. Two-stage goodput with 4G and 802.11n at speeds of 20 km/h

After studying of the Figure 4.2, it is seen that the secured speed is a bit lower than expected but this reflects the real internet speed to the server.

Chapter 5

A network simulator is a piece of software or hardware that predicts the behavior of a network, without an actual network being present. The most accurate data, regarding the performance can be obtained by measuring the network in the real environment. The evaluation of performance in the wireless networks in the real road environment is complex and requires a lot of resources, necessary equipment of the wireless local network, the number of vehicles and their drivers as well as the receivers of the wireless network. The network performance can be assessed, using different tools of modelling that have been developed in a virtual environment for modelling with pre-arranged scenarios. Despite the fact that the availability of simulation means is sufficient, they have a number of limitations which will be analyzed in this section.

In order to check the experimental and analytical results described in the previous sections, in this section the modelling tool Estinet 8.0 will be used, which provides an opportunity to model the simultaneous road traffic and the operation of the wireless networks.

Before modelling in the environment Estinet 8.0, the other modelling tools were carefully analyzed. All these tools are used in academic environment. Most of the open modelling tools require special knowledge and experience in order to have an opportunity to manage and control modelling.

In Figure 5.1 is shown the simulation performance diagram of the wireless network of protocol 802.11n with the mobile terminals at the speed of 20 to 90 km/h.

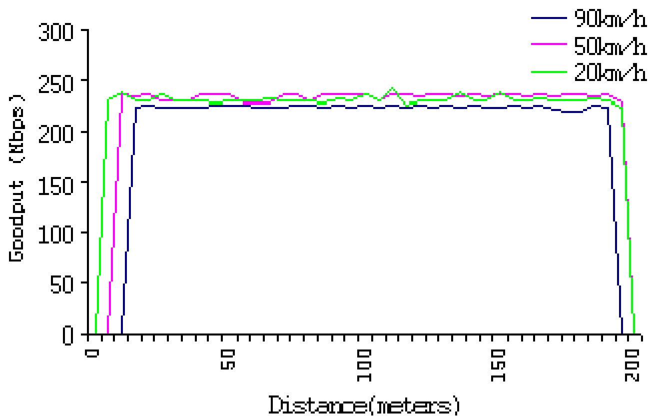

Figure 5.1. Simulation results with three AP for 802.11n

At the level of applications the bandwidth is less than the maximum data transmission rate. From the Figure 5.2 is seen that it looks impossible to model the influence of methods of the data rate adaptation over the wireless network by the means of modelling. In the simulation model the decrease of data transmission rate cannot be seen when remoting from AP as it was defined in the experimental measurement of the test-bed.

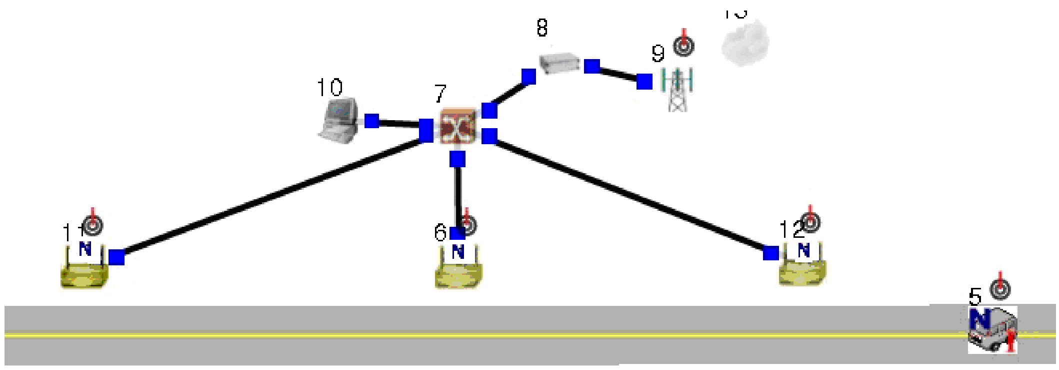

Figure 5.2. Two-stage network model

In the Figure 5.1 is shown the two-stage simulation model of the wireless network is shown with three AP and base station. In the model is used the different number of mobile customers (10 and 20 vehicles) is used which move along the AP at the speed of 20–90 km/h. With this model the following graph of network performance can be obtained [74, 76, 77].

From the simulation results it is possible to conclude that any changes of the speed of movement influence on the data transmission rate and on the overall performance of the wireless network. In the situations, when the customers of the network move from one AP to another, a rapid decrease of data transmission occurs. Besides, in the graph it is seen that at the various speeds (20–90 km/h) the movement of mobile customers a rapid decrease of the data transmission occurs. This is due to the fact that when moving to the new AP client authentication of the network occurs. From the practical measurements, which were reflected in the chapter, it can be seen that the Goodput reduction depends on the speed of mobile client, at low speed of mobile client movement the connection with AP is not interrupted.

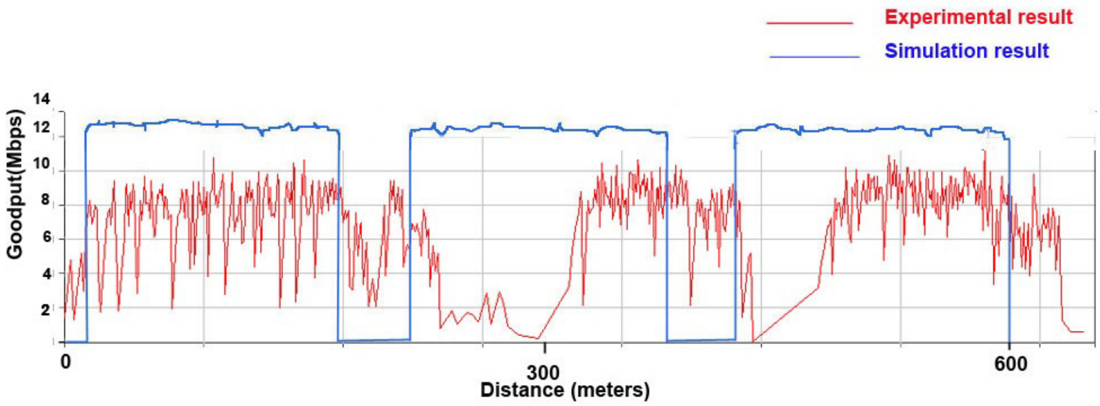

Figure 5.3. Goodput comparison with experimental and simulation results at 20 km/h

Comparing the obtained Goodput from the test bed with the modelling results, it can be seen that the measured average Goodput is below the 20–50 % of the simulation model of the wireless network and Goodput of modelling is constant at all speeds, in opposition to test bed. These differences can be explained by the fact that the chosen tool of modelling is not possible to set up the adaptation algorithm of connection speed of wireless network.

Measurements show that the switching torque of the Goodput on the average is 1 Mbit/per second and simulation, when switching from one AP to another, user connection to the server is not saved at all. Figure 5.6 shows the results of simulation and experimentation with the analytically obtained results under speed conditions of two vehicles.

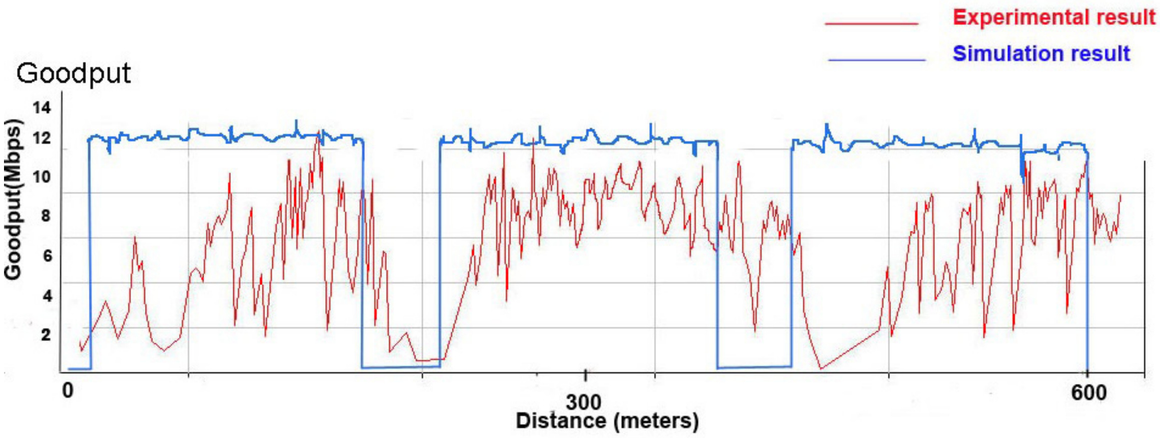

Figure 5.4. Goodput comparison with experimental and simulation results at 50 km/h

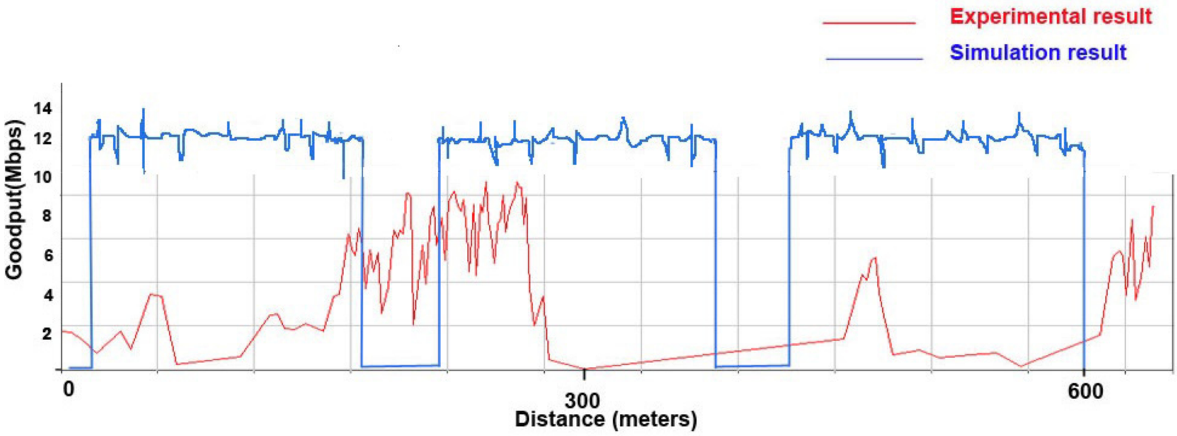

Figure 5.5. Goodput comparison with experimental and simulation results at 90 km/h

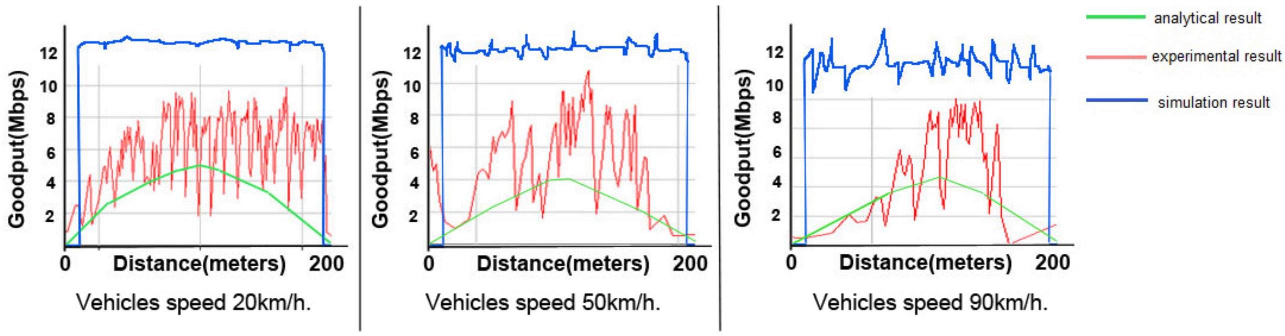

Figure 5.6. Goodput comparison with experimental, simulation and analytical results for vehicles speed 20-90 km/h

Figure 5.7. shows the comparison of experimental and analytical results. The results show that analytical results are 10 % less than practical.

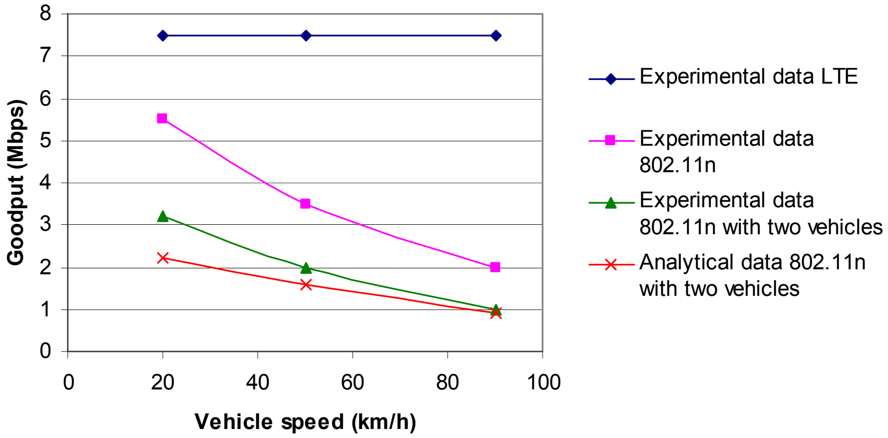

Figure 5.7. Goodput productivity dependence on the vehicle speed

Therefore, this analytical model to determine goodput, is fair. Network productivity dependence on the speed increase of customer (vehicle) motion. By comparing the results of the simulation and experimentation with the analytically obtained results, it is evident that the analytical two-rank model is right. Consequently, this model can be used to determine the performance of the vehicle two-stage network.

MAIN RESULTS OF THE PROMOTION WORK

In the result of experimental part the following dependences were determined:

- The dependence of performance of two rank networks on LTE and 802.11n protocol.
- The dependence of performance of two rank networks on GPRS and 802.11n protocol.
- The influence of speed of mobile client on the performance of two rank networks.
- The influence of number of mobile clients on the performance of two rank networks.

On the basis of analysis the mathematical models for the evaluation of performance of wireless two rank networks were developed. These models use the characteristics of the traffic flow and data transmission systems in the two rank wireless networks. In this work the experimental data are presented, that are related to the rate of information transmission in the wireless network with a remote server based on integrated interaction of mobile objects with the base station WiFi of the network protocol 802.11n and further promotion of data flow through the channels of the mobile network GPRS and LTE.

In this work the following models for the determination of network performance with the different number of vehicles were created:

- A cyclic closed model with the exponential distribution of transport.
- A cyclic unclosed model with Erlang distribution of transport.
- Two rank model of transport network with the exponential and Erlang distribution of transport.

In this promotion thesis the analytical models, results of experiment and the result of simulation in Estinet were analyzed. Results show that the analytical models are valid. From this it follows that these models can be used for the determination of network performance.

Based on obtained data it is possible to conclude that the performance of the base station is connected both to the traffic parameters and data transmission feature.

In this doctoral thesis the model for the determination of the actual speed of data transmission was developed, depending on the number N of the mobile objects, which are in the coverage area of the base station of the wireless network. Based on this paper, the actual rate of data transmission will depend on the number of objects interacting with the base station and their distance from it.

In this doctoral thesis the two rank structure of the transport network was developed that uses the protocol 802.11n and LTE. Because of its efficiency and relatively low price this structure is able to satisfy the potential mobile clients.

THE RECOMMENDATIONS ON THE USE OF ANALYTICAL AND SIMULATION MODELS OF VEHICULAR NETWORK

1. To analyze the productivity of peer-to-peer wireless network on highway with 1 client – vehicle, it is possible to use the results of experimental measurements of this paper. If traffic flow on highway consists of two or more vehicles, then for the capacity assessment of proposed data transmission network is recommended to use the model with the Erlang distribution and a cyclic model of the network.
2. To analyze the productivity of peer-to-peer wireless network on highway, where cars are lined up and start their motion from zero speed, it is necessary to use a cyclic network model.
3. From the experimental results it can be seen that the distribution of vehicles on the road after the beginning of movement there is a not established process. Therefore, for more accurate estimation of number of vehicles in the coverage area of base station is recommended to use the model with diffusive approximation.
4. However, from the paper it can be seen that the results of diffusive approximation is quite close to the results obtained on the cyclic model, describing the established – stationary process.
5. It follows that for the determination of number of vehicles in the coverage area of base station it is possible to use a simpler model that significantly, reducing the lengths of calculations.
6. For the performance assessment of two rank networks (client – AP – remote server of mobile client) of adequate model, in this case can serve two rank closed network model of queuing system, consisting of three nodes.
7. From the paper it can be seen that on the performance of network significantly influence the probability of the model: P_{10} and P_{12} i. e. probabilities, determining the confirmation box over TCP protocol. If these probabilities are distributed as: $P_{10} = 0{,}999$ and $P_{12} = 0{,}001$ at the upper level is used LTE channel, then it is possible to state that the influence of the third node of the network is minimal and for the calculation of performance it is possible to use peer-to-peer cyclic network model. If the probabilities are less, it is necessary to use two rank network models.

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