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Article

Distributed Edge Computing to Assist Ultra-Low-Latency VANET Applications

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Abstract: Vehicle ad hoc networks (VANETs) are a class of peer-to-peer wireless networks that are used to organize communication between cars (V2V), between cars and infrastructure (V2I), and between cars and other types of nodes (V2X). These networks are based on the dedicated short-range communication (DSRC) 802.11 standards and are mainly intended for organizing the exchange of various types of messages, mainly emergency ones, to prevent road accidents, alert when a road accident occurs, or control the priority of the roadway. Initially, it was assumed that cars would only interact with each other, but later, with the advent of the concept of the Internet of things (IoT), researchers began to analyze connectivity with other devices. This, in general, will allow the combination of various road users with other devices that can used in the creation of intelligent transport infrastructure in a single smart city management system. Infrastructure is necessary for the provision of services, monitoring, and management of the VANET. As infrastructure objects, stationary roadside units (RSUs) have been proposed. The aim of this paper is to analyze the use of mobile edge computing to decrease the load to the base station and latency between RSU clouds and to provide a real experiment using software-defined networking and mobile edge computing for RSUs.

Keywords: VANET; software-defined networking; mobile edge computing

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1. Introduction

Based on the preplanned road map announced by the International Telecommunication Union (ITU) and the Third Generation Partnership Project (3GPP), by 2020 it is expected that we will begin a new era of mobile communication systems with great and efficient capabilities with the announcement of the fifth generation of mobile communication systems (5G) [1]. By the end of this year, standards for building the 5G cellular system with the announced requirements will be ready, and the final step in the 5G road, which is the system implementation, will begin. With this great achievement, we will have a new era of telecommunication systems represented by the 5G system and its use cases. Each use case represents a challenge and requires certain design aspects to be realized [2]. Most of these use cases will be available and can be implemented with the realization of the 5G system, except for intelligent transportation systems like the vehicle ad hoc network (VANET).

The 3GPP identifies five main categories of 5G use cases, with potential services for each category [3]. These categories can be reduced and distributed over three major verticals of 5G services. These verticals are also defined by ITU-R as the three usage scenarios for 5G and beyond,

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which include and support a wide range of use cases, applications, and scenarios of 5G. The three main family groups of use cases include [4–5]

1- Enhanced Mobile Broadband (eMBB);
2- Massive Machine-Type Communications (mMTC); and
3- Ultra-Reliable and Low-Latency Communications (uRLLC) including Enhanced Vehicle-to-Everything applications (eV2x).

Vehicle-to-Everything applications are one of the main 5G use cases. For eV2X services, we expect

- Reliability = 1-10-5, packet of size 300 bytes, and user plane latency of 3–10 ms (for direct communication—communication range of few meters); and
- Reliability = 1-10-5, packet of size 300 bytes, and user plane latency of 3–10 ms (packet is relayed by the base station).

Nowadays, the telecommunications industry is showing significant progress in its development. In recent years, a large number of modern technologies that can cope with a wide range of tasks have been developed, tested, and implemented. Achievements in modern science toward the development of hardware, software, and interaction technologies allow us to design and implement a wide range of different telecommunication networks.

A clear example of technologies that have been rapidly developing in recent years is the Intelligent Transportation Systems (ITS). ITS are being introduced everywhere as they have huge potential for improving the safety and efficiency of road traffic, as well as the comfort of the population. ITS support multiple communication interfaces between network infrastructure devices: interaction between vehicles—Vehicle-2-Vehicle; interaction between vehicles and network infrastructure—Vehicle-2-Infrastructure; interaction between vehicles and cloud systems—Vehicle-2-Cloud; and interaction between vehicles and pedestrians (including cyclists)—Vehicle-2-Pedestrian. Such a set of interactions allows a complex and prompt response to changes in the network state and the location of all its participants, which ultimately increases the relevance of ITS for modern cities.

The development of modern transport systems is not only based on improving road safety, and scaling network and transport infrastructure, but also on creating a competent management complex. To the forefront comes such aspects of ITS function as the security of transmitted information, the current growth rate of the number of network users, the continuous growth of network traffic, and many other factors. To localize these tasks and a number of other well-known bottlenecks of ITS, it is necessary to develop an efficient architecture that will cope with the load generated by network elements, manage traffic flows correctly and in a timely manner, conduct uninterrupted statistical analysis, and meet the standards and requirements of modern communication networks.

ITS are at the center of the closest contact between the automotive industry and information technology industries. The use of ITS has developed a special environment in which management, operation, and maintenance can advance.

The obvious solution is to use the concept of software-defined networks (SDN) to manage intelligent transport systems [6–7]. The concept of software-defined networks is a relatively new technology that has already been widely used to manage modern networks. SDN technology is based on the principle of separation of the control level (control plane) and data transmission (data plane), which makes it possible to efficiently use network bandwidth for transmission of statistical information and control messages. Besides this, it manages the network architecture by its routing of a separate element—the SDN controller, which significantly simplifies both the network architecture and the hardware design. The ITS controller is a high-performance network element whose characteristics are directly dependent on the hardware used. An SDN controller can be deployed on server equipment from any manufacturer. Most software solutions are open source products, which makes it easy to study software-defined networks and their interaction with third-party networks.

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The system employs cloud units at the edge of the radio access network (RAN) based on the concept of Mobile Edge Computing (MEC). MEC is a new trend established by the cellular network operators to improve the whole network efficiency by offloading its operations to nearby clouds. The European Telecommunications Standards Institute (ETSI) is one of the main organizations concerned with MEC [8]. ETSI announced an Industry Specification Group (ISG) known as MEC to research and standardize the new technology. Simply put, MEC can be defined as the method of moving cloud computing capabilities to the edge of the mobile networks.

Moving from great, massive, and expensive data centers into small distributed cloud units based on a small hardware platform will open the way for achieving the required latency constraint for realization. Moving cloud units only one or two communication hops away from the end user is a key solution for 1 ms end-to-end latency. Moving cloud computing to the edge of the mobile network produces a lot of benefits that can be summarized in the following points [9]:

1- Reduces the round-trip latency of communicated data;
2- Provides an efficient way of offloading data delivered to the core network;
3- Provides high bandwidth; and
4- Introduces new services and applications by accessing the network context information.

Our SDN lab proposed an intelligent core network for tactile internet in [10] which can be employed side by side with the concept of multilevel edge computing to provide an appropriate structure for VANET systems [11].

The next step concerned with the edge computing units is related to simulating the remote environment of the edge cloud unit and its expected behavior by means of AI. This represents a critical part toward system realization and achieving the required latency.

2. Related works

Currently, research in the field of alternative methods of transport network management is gaining momentum.

A group of researchers from University of Toulouse reviewed the SDN hybrid architecture for ITS management [12]. The key idea of this architecture is the hybrid control level, which includes the base station controller of the mobile network and the controller of the roadside unit (RSU) modules, as well as the central controller to coordinate the actions of different controllers. The central controller creates a global view of the network infrastructure by sending information to the controller of each network with data in the cloud. It sends each controller global rules describing the general behavior of the network, while base station and RSU controllers define specific rules that must be set in each network device. Communication between SDN controllers is performed using a special interface, known as East–West; communication between SDN controllers and the cloud is performed through API interfaces.

The aim of the experiment was to demonstrate how a global view of the network, combined and enriched with information obtained from the cloud, allows us to more effectively manage network behavior by ultimately providing a service with increased performance.

Another research project on this subject comes from the work group from the University of Singapore (School of Electrical and Electronic Engineering Nanyang Technological University, Singapore) [13]. This approach also involves the use of existing mobile network architecture in addition to the implementation of management based on SDN technology. It should be noted that all VANET architecture is divided into segments (Control Region) which may contain a certain amount of RSUs and which operate a control member (Local Controller); this significantly reduces the delay in the case of transmission of information to the network management unit.

The central network controller is located in its core. The interaction between the central controller and local controllers takes place based on a mobile communication network. The authors called this architecture SDVN—Software-Defined Vehicular Network.

The key parameter chosen in this paper for the simulation and mathematical models is delay. For comparison, three network architectures were selected: a VANET based on the AODV routing protocol, SDVN with a central controller, and SDVN with controllers located within the segment.

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In [14], the authors proposed a context-aware packet-forwarding mechanism for ICN-based VANETs. The relative geographical position of vehicles, the density and relative distribution of vehicles, and the priority of content were considered during the packet forwarding.

In [15], the authors focused on a vehicle-to-vehicle communication system operating at a road intersection, where the communication links can be either line-of-sight (LOS) or non-line-of-sight (NLOS). The authors presented a semi-empirical analysis of the packet delivery ratio of dedicated short-range communication (DSRC) safety messages for both LOS and NLOS scenarios using a commercial transceiver.

The authors of [16] critically reviewed the existing methods of adaptive traffic signal control in a connected vehicle environment and compared the advantages and disadvantages of those methods.

The proposed architecture provides load balancing between distributed controllers and uses a local view of the network to make better decisions. Both the theoretical model and the simulation results confirm that the proposed SDVN architecture differs from the existing SDVN with a central controller in terms of latency. The proposed system has the same low latency as the existing VANET.

3. System structure

The IEEE 802.11 standard provides two modes of operation—infrastructure (BSS, ESS) and noninfrastructure (IBSS). The last one is a new class of networks, called ad hoc or target networks. Within the framework of ad hoc networks, networks are classified into mobile and fixed networks. Mobile ad hoc networks (MANETs) [17] include ad hoc networks for vehicles; a standard for these was developed as part of the IEEE 802.11p working group [18–19]. The interaction between vehicles and the public use network in the coming years may lead to the formation of a new, very-large-scale segment of the telecommunications market. Already, a modern car integrates a GPS/GLONASS receiver, various sensors, and an on-board computer. However, the task that is posed when creating a VANET is somehow different [20]. First of all, we need to create a network interface in the car that would support four groups of connections: car–car and car–infrastructure network. The technical requirements of the IEEE 802.11p standard are operation at speeds up to 200 km/h and at distances of up to 1 km. The physical layer and the MAC sublayer are based on the IEEE 802.11a standard. The frequency range for the USA includes the spectrum from 5.859 to 5.925 GHz; for Europe, the Electricity and Postal Services Commission (CEPT) recommends the use of two subbands 10 MHz wide each: 5.865–5.875 GHz and 5.885–5.895 GHz. The architecture of the studied VANET without the use of SDN is based on centralized remote management of RSUs via base station controllers, which, in turn, are connected to the main controller. Controllers transfer data to the cloud server. At the same time, the RSU service control packages are located in the same network as the traffic that comes from the On-Board Unit (OBU).

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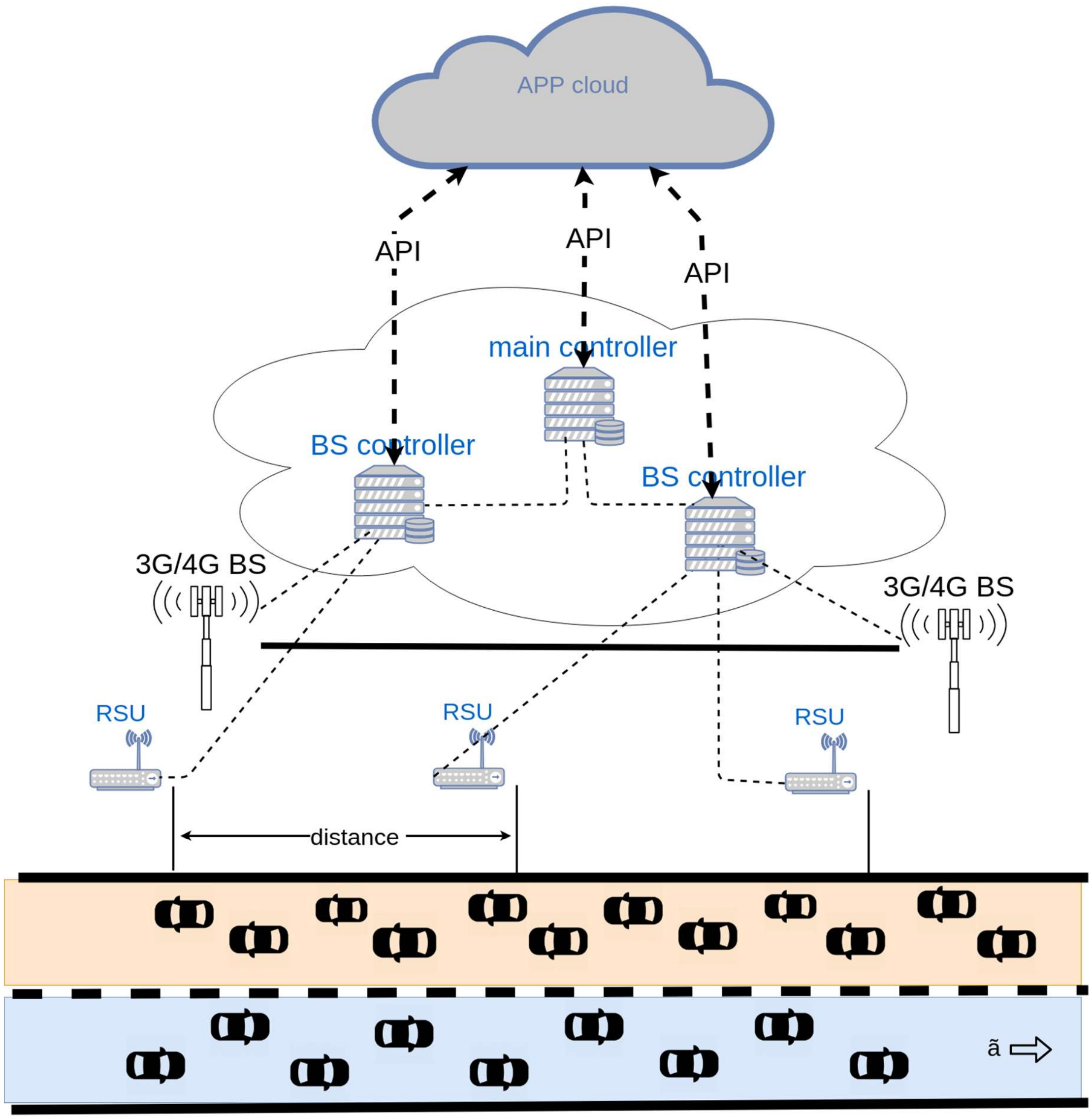

Figure 1. VANET architecture without SDN.

3. VANET Challenges

Traditional VANETs are characterized by maximum decentralization with no dedicated server in the network, and the entire infrastructure is distributed to communication centers. This feature brings the following disadvantages:

- low mobilization abilities;
- long system response time to external influences.

Today, VANETs support a large number of new services and protocols. Nevertheless, there are still a number of challenges that impede the full implementation of this technology in real life.

a) Problems ensuring noise immunity

In transport networks, VANETs receive a large amount of interferences of different types. The effect of interference can be maximized by choosing the optimal channel frequency or by adjusting the power of the receivers and transmitters of the devices in the network. However, in classical VANETs, this problem remains unresolved and has a significant impact on the network operation.

b) Problems ensuring the security of transmitted data

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The causes of problems related to the information security of VANET transport networks are

• a lack of means to protect nodes from intruders and hackers;

• the ability to listen to the channels and the substitution of messages due to the general availability of the transmission medium;

• the inability to apply a classical security system due to the peculiarities of the classical architecture of the VANETs;

• the need to use complex routing algorithms that take into account the likelihood of incorrect information from compromised nodes as a result of changes in the network topology;

• that any node in the signal source range that knows the transmission frequency and other physical parameters (modulation, coding algorithm) can potentially intercept and decode the signal. At the same time, neither the signal source nor the recipient will know about it;

• the inability to implement a security policy due to the peculiarities of the classical architecture of VANETs, such as the absence of a fixed topology and central nodes.

c) Problems in routing efficiency

In VANETs, the bandwidth problem is most acute with the simultaneous transmission of a large amount of video information. The situation is worsened by the inefficiency of the routing methods when the network becomes overwhelmed with broadcast requests or a bottleneck is formed. An example of inefficient routing is shown in figure 2 when all traffic transits through one node.

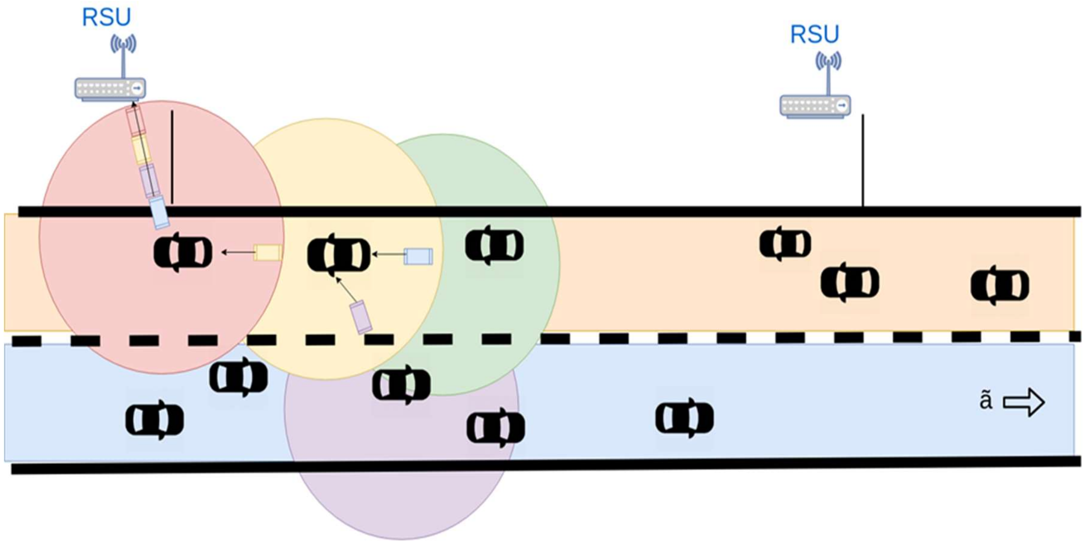

Figure 2. Inefficient routing in a VANET.

In this paper, we considered the possibilities of solving some problems that occur when using the local SDN controller by using the OpenFlow protocol, which can be used as a control over radio channels. OpenFlow SDN with minimal latency can safely solve the RSU control problem. The implementation of SDN MEC technology will partially solve the security problem. The concept of SDN implies the use of separate control channels and a traffic subscriber. Thus, in the case of DDoS attack from an OBU or an alleged OBU, the RSU control channel will not suffer. The SDN controller can then take any measures to solve the problem (temporarily disable the RSU or tune the RSU to other radio channels, for example).

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4. Traffic model

The approximate value of the waiting time in the packets queue in an RSU with linear packet generation is given by the G/G/1 queuing model:

$$\overline{W} \approx \frac{\rho \bar{t}}{2(1-\rho)} \frac{\left(\sigma_a{}^2+\sigma_b{}^2\right)}{t^{-2}} \frac{\left(t^{-2}+\sigma_b{}^2\right)}{a^{-2}+\sigma_b^2} . \quad (1)$$

In this case, $\sigma_b^2 = 0$; because the data rate on all channels between the cars is the same, the variance of service time equals 0.

The service time is determined by the packet length and data rate:

$$\bar{t} = \frac{L}{b} . \quad (2)$$

The ratio of the generated traffic to the data rate in the channel is

$$\rho = \frac{a}{b} . \quad (3)$$

The package delivery time is

$$T = \overline{W} + t. \quad (4)$$

The coefficient of variation of the generated traffic is

$$C_a^2 = \frac{\sigma_a^2}{a^2} . \quad (5)$$

In view of the above, the average waiting time can be estimated by the formula

$$\overline{W} \approx \frac{(\rho \bar{t})}{2*(1-\rho)} \left(\frac{\sigma_a^2}{t^{-2}}\right) \left(\frac{t^{-2}}{a^{-2}}\right) \approx \frac{\rho \bar{t}}{2*(1-\rho)} C_a^2, \quad (6)$$

giving the approximate average speed in the RSU and MEC.

5. Offloading algorithm based on edge computing

This structure is based on the use of a software-defined network (SDN) and on offloading the core network by unloading traffic to the border of the radio access network (RAN), namely, mobile edge computing (MEC) technology. The RSU offloads traffic to the edge of the RAN network, after which the traffic is directed to the SDN controller and the cloud server.

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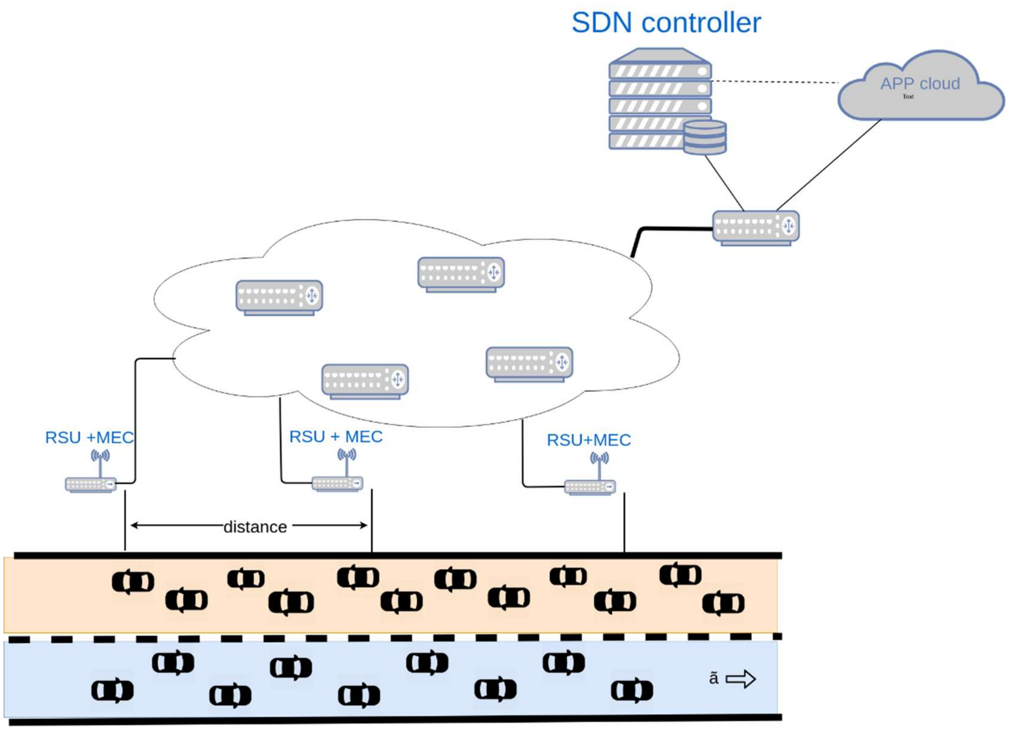

Figure 3. Offloading algorithm based on edge computing.

6. Experimental work and results

The analysis of the results of the full-scale experiment to identify key indicators for the VANET was based on a traffic dump recorded on the radio interface of one of the devices. The traffic was recorded using the utility built into the device. The experiment was performed in open space and the maximum removal of network elements from each other was 300 m. Based on the tests performed, the following set of WSMP protocol package parameters was chosen, which will be sufficient for statistical analysis:

802.11 radio information
Data rate: 6.0 Mb/s
Channel: 172
Signal strength (dBm):23dBm
TSF timestamp: 1508234676
[Duration: 172µs]
    [Preamble: 20µs]
IEEE 802.11 Data, Flags: ....
    Type/Subtype: Data (0x0020)
    Frame Control Field: 0x0800
        .... ..00 = Version: 0
        .... 10.. = Type: Data frame (2)
        0000 .... = Subtype: 0
        Flags: 0x00
            .... ..00 = DS status: Not leaving DS or network is operating in AD-HOC mode (To DS: 0 From DS: 0) (0x0)
            .... .0.. = More Fragments: This is the last fragment
            .... 0... = Retry: Frame is not being retransmitted
            ...0 .... = PWR MGT: STA will stay up
            ..0. .... = More Data: No data buffered

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```
            .0.. .... = Protected flag: Data is not protected
            0... .... = Order flag: Not strictly ordered
        .000 0000 0000 0000 = Duration: 0 microseconds
        Receiver address: Broadcast (ff:ff:ff:ff:ff:ff)
        Transmitter address: Arada_05:06:34 (00:26:ad:05:06:34)
        Destination address: Broadcast (ff:ff:ff:ff:ff:ff)
        Source address: Arada_05:06:34 (00:26:ad:05:06:34)
        BSS Id: 00:00:00_00:00:00 (00:00:00:00:00:00)
        .... .... .... 0000 = Fragment number: 0
        0000 0000 0000 .... = Sequence number: 0
Logical-Link Control
    DSAP: SNAP (0xaa)
        1010 101. = SAP: SNAP
        .... ...0 = IG Bit: Individual
    SSAP: SNAP (0xaa)
        1010 101. = SAP: SNAP
        .... ...0 = CR Bit: Command
Control field: U, func=UI (0x03)
        000. 00.. = Command: Unnumbered Information (0x00)
        .... ..11 = Frame type: Unnumbered frame (0x3)
    Organization Code: 00:00:00 (Officially Xerox, but
    Type: (WAVE) Short Message Protocol (WSM) (0x88dc)
Wave Short Message Protocol (IEEE P1609.3)
    Version: 2
    PSID: 0x00000020
    Channel: 172
    Data Rate: 6
    Transmit Power: 23
    WAVE element id: WSMP (128)
    WSM Length: 65
    Wave Short Message
```

The total packet size is 255 bytes. The data presented above were obtained from the test results of a segment of the transport self-organizing network and will be used in the future for modeling and calculating the RSU load. The key parameters of the functioning segment of the VANET model are presented in Table 1.

Table 1. Key operating parameters of the VANET segments.

Bandwidth	6 Mb/s
Packet generation frequency	1 Packet/s
Transmitter power	23 dBm
Packet size	255 byte

To determine the effectiveness of the VANET with control based on software-defined networking, a series of five experiments were conducted for each of the architectures shown on Figure 4. The duration of each experiment was 15 hours. During the experiment, 30 Raspberry pi devices were used to imitated vehicle OBUs, and the number of RSUs was 10 devices. The study scenario involved a serial connection of the OBU to the RSU at specified intervals, which was used to simulate the movement of vehicles. In situations where more than three OBUs were connected to

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one RSU, an additional delay of 5 ms was introduced. The results of the experiments are shown in Figure 4.

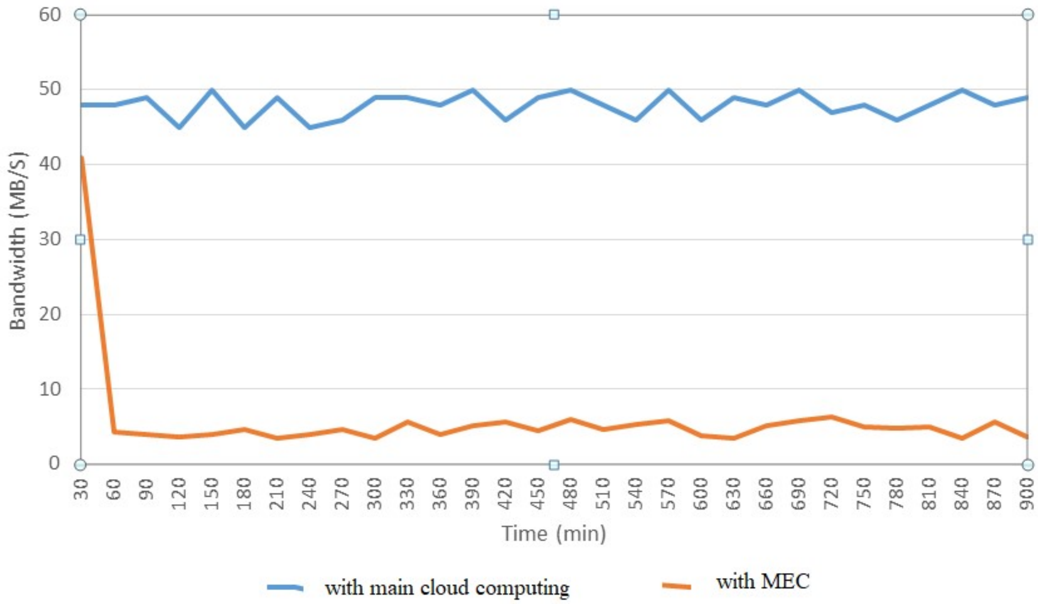

Figure 4. Bandwidth versus time for the VANET model.

According to the experimental results, the average packet loss amounted to 0.082%; it is possible to conclude that the controller coped with the requirement of reducing the network load, thus confirming the efficacy of the test approach.

1) The following proposed model was tested for the dependency of the packet delivery time on the distance between RSU stations.

A. Three cases were considered with a flow rate of 2000 cars per hour and respective speeds of 30 km/h, 50 km/h, and 60 km/h; the size of the packets was 30 bytes.

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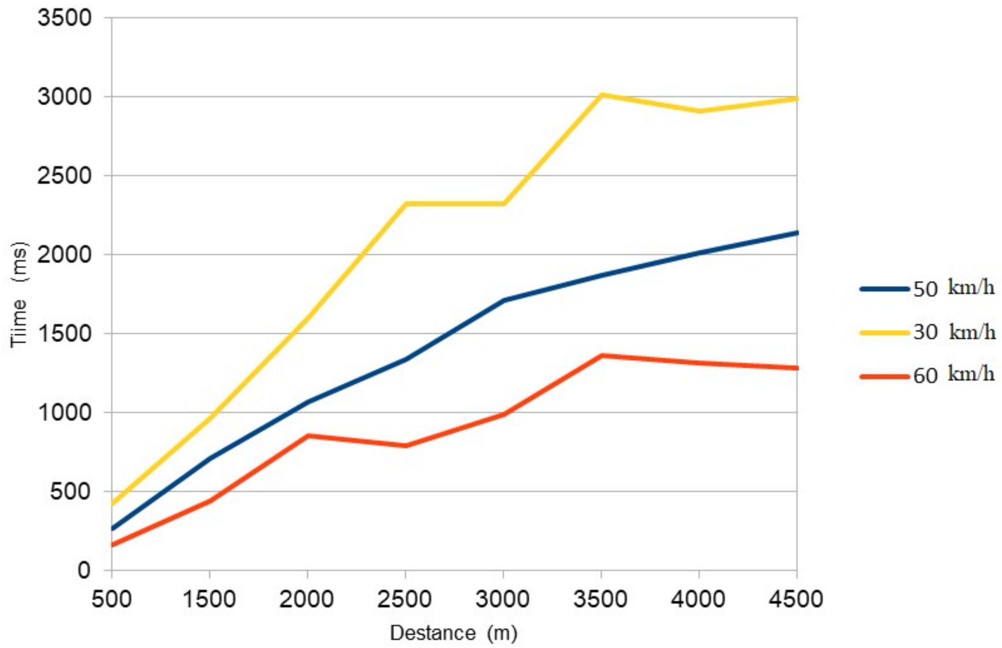

Figure 5. Bandwidth versus time for the VANET model in the case of 2000 cars per hour.

Based on the data obtained, the best packet delivery time is observed at a speed of 60 km/h. Moreover, with increasing distance between the RSUs, the packet delivery time increases.

B. Next, we consider a model with a flow rate of 3000 cars per hour.

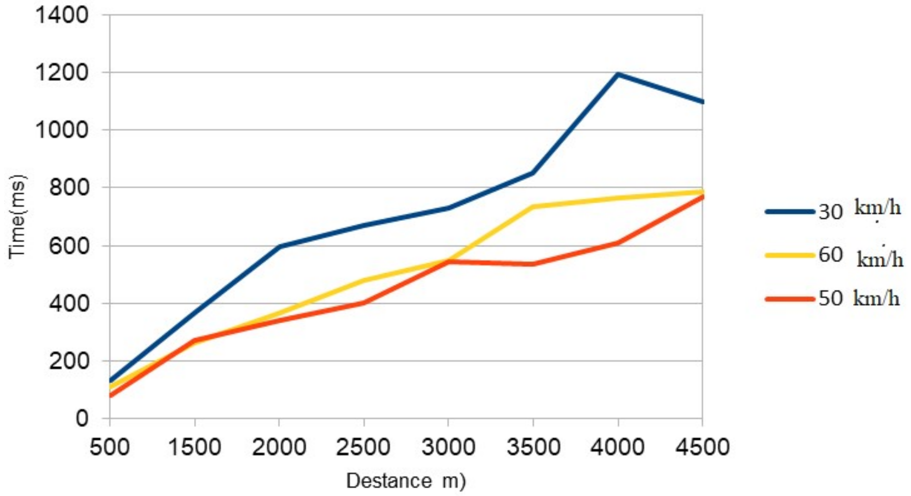

Figure 6. Bandwidth versus time for the VANET model with a flow rate of 3000 cars per hour.

The packet delivery time results for cars with speeds of 50 km/h and 60 km/h are almost the same; the longest package delivery time will be for cars moving at a speed of 30 km/h.

C. We also consider the case of a traffic intensity of 4000 cars per hour.

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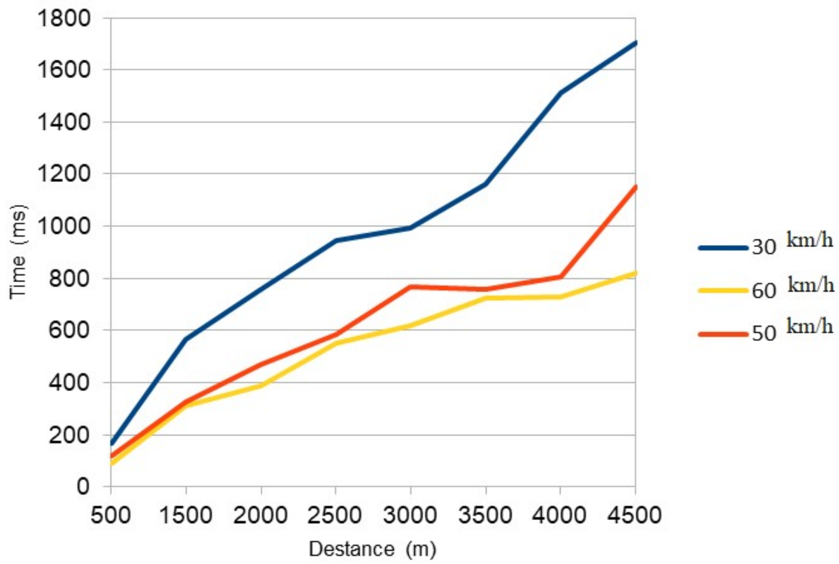

Figure 7. Bandwidth versus packet delivery time for the VANET model with traffic intensity of 4000 cars per hour.

The shortest packet delivery time was for cars moving at 60 km/h, and twice the delivery time was attained for packages for cars moving at 30 km/h.

7. System Realization

During the experiment, RSUs which could be included with the traffic lights on the road were realized. The use of these devices in the aggregate will give the possibility of unloading road traffic and allow emergency services to travel without traffic jams.

Figure 8. Developed model.

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Figure 9. Used devices.

The RSU, in turn, is implemented on the basis of a MikroTik RouterBOARD 435G motherboard and a MikroTik RouterBOARD R52n-M miniPCI network card. Table 2 shows the characteristics of the RouterBOARD 435G.

Table 2. Characteristics of the board RouterBOARD 435G.

	RouterBOARD 435G
CPU	AR7100 680 MHz network processor
Memory	256 MB onboard memory
Boot loader	RouterBOOT
Ethernet	Three 10/100/1000 Mbit/s Ethernet ports supporting Auto-MDI/X
MiniPCI slot	Five miniPCI Type IIIA/IIIB ports with 3.3V power signaling
Expansion	2 × USB 2.0 ports with 5V powering
Memory card slot	1 × microSD
Serial port	DB9 RS232C asynchronous serial port
LEDs	Power and User LED
Beeper	+
Powering	Power jack: 8-30VDC PoE: 8-30V passive (803.af not supported)
Fans	Up to 4 fans (connectors provided, no fans included)
Dimensions	105 × 155 × 32 mm, 165 g (note: miniPCI slots on the bottom of the device extend 21 mm deep, without miniPCI cards mounted)
Temperature	Operational: −20 °C to +65 °C (−4 °F to 149 °F)
Humidity	Operational: up to 70% relative humidity (non-condensing)
Operating System	RouterOS v5, Level5 license

Table 3 shows the characteristics of the RouterBOARD R52n-M.

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Table 3. Characteristics of the board Router BOARD R52n-M.

802.11b	RX Sensitivity	Composite TX Power
1Mbit	-95	20
entry 2	-91	21
802.11g		
6Mbit	-95	23
54Mbit	-81	19
802.11n 2.4GHz		
MCS0 20MHz	-95	21
MCS0 40MHz	-90	21
MCS0 20MHz	-78	17
MCS0 40MHz	-75	16
802.11a		
6Mbit	-95	21
54Mbit	-80	17
802.11n 5GHz		
MCS0 20MHz	-95	21
MCS0 40MHz	-92	19
MCS0 20MHz	-77	16
MCS0 40MHz	-74	13

Next, for our experimental needs, we selected the scale of the built pilot zone in Saint Petersburg (Russia) as follows:

1) The section of Bukharestskaya Street between its intersections with Salova Street and Prospekt Slavy;

2) The section of Salova Street between its intersections with Alexander Kovanko Street and Bukharestskaya Street; and

3) The section of Aleksandra Kovanko Street from the entrance of Bus depot No. 1 of the Saint-Petersburg State Unitary Enterprise "Passazhiravtotrans" to its intersection with Salova Street.

The type of the modulated pilot zones is shown on the map in Figure 10.

Figure 10. Map of pilot zones.

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8. Conclusions

Currently, the situation on the roads is becoming increasingly tense due to the increase in the number of cars, the scaling of the road transport network, population growth, and many other factors. To optimize and automate traffic, increase driver and pedestrian safety, and monitor traffic violations, we use intelligent transport systems, the load on which is constantly increasing. To solve problems with ITS, it is necessary to organize a competent management system. The current solution is to use the concept of software-defined networking for intelligent transport system management. SDN can reduce the workload, optimize the network infrastructure architecture to simplify scaling of the network, and improve the security of information transmission. During the work on this subject, we have considered the most promising approaches to the management of ITS, identified key indicators of the functioning of VANET segments, and experimentally proved the advantages of software-defined network management for ITS. A series of experiments were conducted with different densities and different speeds of traffic at different locations relative to RSUs. The results were analyzed and an appropriate RSU service model, QS G / D / 1, was composed. The results of this work allow us to consider the concept of SDN and MEC for ITS management and to continue research in this direction, given the trends in the development of modern communication networks.

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