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REVIEW OF METHODOLOGY AND DESIGN OF BROADBAND WIRELESS NETWORKS WITH LINEAR TOPOLOGY

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Creation of a modern infrastructure for multimedia data (voice, data, video) transmission along the long transport routes is one of the most important problems while designing and building up the new highways and exploiting the existing ones. The solution of this problem is especially relevant for countries with a vast territory, like the Russian Federation. Creation of such communication infrastructure allows to provide (i) the operating control over the technical parameters of a route by the means of high-speed data transfer from sensors and data units to the control center (ii) the security control over the route sections and strategically important objects using data from the video surveillance systems and (iii) the voice communication (IP-telephony) and transmission of multimedia information between the stationary and mobile objects on long highways as well as communication with the control center etc.

Key words : Broadband wireless communication networks; long transport systems; base stations; wireless communication protocols; analytical modeling and simulation; interference.

1. INTRODUCTION

This paper presents an analytical review of studies in the field of research and design of broadband wireless networks along the long highways, published in recent years. We describe the technology of creation of wireless networks of this class on the basis of IEEE 802.11n, s, IEEE 802.16 and UMTS (LTE) protocols. We investigate the methods and algorithms for the optimal location of the base stations along highways, which maximize the coverage area of the route under constraints on the total

cost and the delay time of data package transmission. An overview of the articles on the models of queueing theory, game theory and simulation is given, which are used for performance evaluation and optimization of the road communication networks. The final part of the article deals with the methods of interference and collision mitigation and solutions of the "hidden station" problem. These methods are aimed at improving the quality of performance of wireless networks along the extended transport routes.

In general, this survey is useful for experts in the field of communications for orientation in numerous studies on performance evaluation and design of broadband wireless networks, which have been published in recent years. The review indicates that the amount of work in this area has been continuously increasing which demonstrates not only the relevance but also the high practical need for such studies.

Creation of a modern infrastructure for multimedia data (voice, data, video) transmission along the long transport routes is one of the most important problems while designing and building up the new highways and exploiting the existing ones. The solution of this problem is especially relevant for countries with a vast territory, like the Russian Federation. Creation of such communication infrastructure allows to provide (i) the operating control over the technical parameters of a route by means of high-speed data transfer from sensors and data units to the control center, (ii) the security control over the route sections and strategically important objects using data from the video surveillance systems and (iii) the voice communication (IP-telephony) and transmission of multimedia information between the stationary and mobile objects on long highways as well as communication with the control center, etc.

Taking into account the high security requirements, using public networks (like Internet) in communication systems of this class is usually not allowed. Furthermore, the extended transport lines often pass through sparsely populated remote areas, where there is no access to the Internet or cellular networks [1, 2]. Creating the dedicated fiber-optic networks along the extended transport routes or extended relay links would require huge material expenses. The same applies to the use of satellite channels and communications networks. At the same time, the cost of broadband high-speed wireless communication implemented in hardware and software, working under IEEE 802.11-2012 [3] international standard, is much lower. This standard regulates the creation of high-speed communication channels and wireless networks that operate under the control of IEEE 802.11n and IEEE 802.11s protocols, on the basis of which one can effectively implement the wireless networks along the long transport routes. These networks can provide not only the backbone for high-speed transmission of multimedia information by deploying the base stations on high-rise buildings and towers along the

transport routes, but also an operation communication between the fixed and mobile users (cars, trains, road signs, weight control points and transport security control points, traffic light control points, etc.) as well.

Broadband wireless networks and communication channels have recently become two among the main directions of development of the telecommunications industry. This fact has been reflected in numerous monographs, articles in specialized journals: IEEE Wireless Communications Magazine, IEEE Communications; IEEE Wireless Network; IEEE Transactions on Vehicular Technology, and conference proceedings (IEEE GLOBECOM, IEEE INFOCOM, ICUMT, Net Ware, DCCN and many others), that cover studies on architecture, methods of evaluation and optimization of parameters of the protocols, mathematical models for performance and reliability evaluation of wireless networks and communication channels, and so on. For example, monographs of the Russian authors [1, 2] of the survey as well as separate articles in journals like Automation and remote control, Radio electronics, Telecommunications and transport, Problems of informatics, Electronica, Wireless technologies, etc., are devoted to research of broadband communication.

In the present paper we give an overview of scientific and technical papers, published in recent years on the theory and practice of building up the wireless networks along the long transport routes. These publications can be classified according to the following research trends: methods and algorithms for the optimal base station deployment; communication technologies used in the backbone of road networks for vehicular communication and communication between vehicles and the roadside units; methods of analytical modeling and simulation of broadband wireless networks along the long-distance transport routes; methods of interference and collision avoidance/mitigation and the design of antenna systems.

The next section gives an overview of work done in optimal deployment of base stations; in Section 3 technologies for building up the wireless multimedia data transmission networks along the extended transport routes is reviewed. Section 4 provides recent developments in methods of analytical modeling and simulation of broadband wireless networks along the long distance transport routes. Methods of interference and collision avoidance/mitigation and the design of antenna systems, recently developed in literature are given in some details in Section 5.

2. Optimal Deployment of Base Stations (Road Side Units) Along The Extended Transport Routes

The deployment and development of wireless networks along extended routes requires solving a number of complex organizational and technical tasks under tight restrictions on the use of frequency,

economic, and hardware resources. In this regard, it seems to be increasingly urgent to solve the problem of optimal allocation of base stations along the long transport routes, which is one of the most important problems in designing the broadband wireless networks of this class. Its solution is aimed both at the realization of high speed backbone network and at the maximum network coverage of the route to provide connectivity for mobile users, as well as to minimize interference and time delays when transmitting the multimedia data over the network.

Numerous papers are devoted to the solution of this problem [4-11]. Particularly, in [4] the problem of wireless network base stations deployment, maximizing the network coverage, is investigated under constraints on the total network cost. The initial data for solution of the problem are the potential locations for deployment of the base stations and beforehand-collected statistics of traffic from fixed and mobile users. The core problem of the deployment of base stations maximizing the coverage, is formulated in [5]. For the analytical description of the problem, it is modeled as a Maximum Coverage Problem with Time Threshold Problem (MCTTP) and a genetic algorithm is used to solve it.

Strategies for roadside placement of units (RSUs) based on the road traffic characteristics, aiming at improving connectivity in vehicular ad hoc networks, are presented in [12]. To divide the coverage area of each RSU, the authors propose an Expansion and Coloration Algorithm (ECA). The average connectivity model for all vehicles in the network is established based on the results obtained from ECA. The RSUs placement problem is formulated as a combinatorial optimization problem, of which the objective is to maximize the average connectivity probability by searching for an optimal combination of positions of the given RSUs. Taking part of an actual urban road network as an example, the RSUs placement problem is calculated and the optimal placement scheme is evaluated. Simulation results show that the optimal placement scheme obtained from the proposed strategy leads to the best connectivity compared to uniform placement and hot-spot placement.

The problem of roadside units placement in IEEE 802.11*p* / WAVE (wireless access in vehicular environment) networks is studied in [7]. An analytical model is presented that allows to analyze the delay of data transmission in communication networks along highways. The cases of bound and unbound base stations are investigated. It is shown that only those deployment strategies are efficient in which roadside units are connected to each other within the line-of sight range. Paper [15] designs a connectivity analysis scheme for the roadside-to-vehicle telematics network based on the real movement history of vehicle objects collected from taxi telematics system currently in operation, aiming at providing a useful guideline and information to build a telematics network. The implemented analyzer can locate the current and previous positions of all vehicles, decide whether

it can be connected to an RSU and calculate the duration of disconnected state, taking into account the transmission range, the number of RSUs, and RSU deployment. The RSU placement scheme can improve the network coverage exploiting the result of the analysis.

The results of simulation and measurement of the performance of a roadside unit placement scheme for the vehicular telematics network on the road network of Jeju city, South Korea, are presented in [9]. The calculated optimal topology of the backbone wireless network provides improvement of connectivity and reduction of the disconnection interval for the given number of roadside units, the transmission range, and the overlap ratio. A research problem of finding the optimal locations to place dissemination points (i.e. roadside infrastructure nodes for information dissemination) is considered in [17]. In this paper a novel approach is proposed for dissemination points placement in grid road networks without knowing trajectories. Based on the analysis of path number between two intersections, a probabilistic model is proposed to get the trajectories estimation of vehicles. The problem of the roadside unit placement in vehicular networks is studied in [18], where the authors focus on the highway-like scenario in which there may be multiple lanes with exits or intersections along the road. In the proposed model, each vehicle can access RSUs in two ways: 1) direct delivery, which occurs when the vehicle is in the transmission range of the RSUs, and 2) multi-hop relaying, which takes place when the vehicle is out of RSU transmission range. Both access patterns in this placement strategy are worked out and this placement problem is formulated via an integer linear programming model such that the aggregate throughput in the network can be maximized. The impact of wireless interference, vehicle population distribution, and vehicle speeds are also taken into account in the formulation. The performance of the proposed placement strategy is evaluated via NS-2 simulations to generate vehicle mobility patterns.

3. Technologies for Building Up The Wireless Multimedia Data Transmission Networks Along The Extended Transport Routes

When designing a wireless IEEE 802.11-2012 communication the following networking topologies can be implemented: a centralized scheme operating under IEEE 802.11g/n protocol, and a decentralized scheme of mesh structure (mesh-network) under control of IEEE 802.11*s* protocol. In the first case, the network consists of a combination of two types of communication channels - sections of the main (backbone) communication channels to deliver the content directly to the control center and the client channels for mobile and stationary network users. In the second case, the network has a mesh topology, wherein each access point not only provides access services to a user, but also functions as a router / transmitter for other access points of the same network.

Communication technologies used in the road networks for vehicular communication and communication between vehicles and the roadside units have received considerable attention in recent literature. Particularly the implementation of wireless mesh-networks is considered as a solution to manage the backhaul of communication along the roads [12-14]. Researchers are also heavily focusing on exploiting the IEEE802.11 protocol family [15-19] and building up communication systems combining different technologies, like WiMAX and WiFi [20-23].

Vehicular networks, where 802.11s wireless mesh networks are used as a costeffective and easily maintainable solution to manage the backhaul of vehicular communication, are considered in [12]. This paper proposes an efficient channel access mechanism based on IEEE 802.11s MCCA to provide proportionally fair channel access. A distributed scheme is proposed to calculate traffic load at every mesh point, and based on the traffic load, the MCCA is tuned to meet the required proportionality constraint. The efficiency of the proposed scheme is confirmed using theoretical analysis and simulation results.

In [13] a mesh-tree architecture for low latency and high-throughput data transfer to mobile vehicles along approach roads in and around a bus station is proposed. According to the authors' the chain topology, described in prior works, and proposed to be used, in particular, for communication set-up along railroads, resulted in high hop counts and poor end-to-end latency. Furthermore, a break in any of the links would disconnect the remainder of the chain from the network. Hence, they propose mesh-tree architecture in order to overcome these drawbacks of the conventional chain topology. The authors discuss the architecture, antenna selection, deployment and performance results of a 14-node system.

The paper [15] describes the methodology of design of wireless networks based on IEEE 802.11n along the long-distance routes, which allows the implementation of mobile and fixed communication, with a view to the terrain structure, the electromagnetic compatibility of radio electronic means and user traffic distribution while optimizing frequency and hardware resources. The results of design and three years of successful functioning are presented for the broadband wireless multimedia data transmission network along the ring highway of Kazan city, Russia (M7 Volga route).

The papers [16, 19] focus on vehicle to roadside communications in vehicular networks based on the IEEE 802.11 DCF MAC protocol. The authors propose a new mechanism called proxy-based vehicles to road side unit access (PVR) for V2R communications which is designed to exploit cooperative and opportunistic forwarding between any two distant RSUs and to emulate back-to-back transmissions within the coverage of an RSU. As a result, it can shorten the access delay by taking ad-

vantage of opportunistic forwarding and mitigate the interference problem during the short residence time within the coverage of an RSU.

In [17] the feasibility of vehicle-to-roadside communications is investigated when considering features and capabilities of the 802.11*p*/WAVE standard for vehicular environments, where the number of base stations is small due to their high cost. The authors expect that by complementing advertisement repetitions from RSUs with smart piggybacking of some RSU parameters in the beacons transmitted by all vehicles (On board Units (OBUs)), the RSU awareness can be improved and RSU-OBU connection lifetimes can be lengthened.

The purpose of [18] is to design techniques that make the best of sparse road-side unit placement by supporting the spreading of network initialization advertisements from RSUs, when considering the multichannel features of the recently published IEEE 802.11*p*/IEEE 1609.4 standards for wireless access in vehicular environment. The proposed techniques leverage time, space and channel diversity to improve efficiency and robustness of the network advertisement procedure in an urban scenario where obstructions to signal propagation due to buildings and traffic jam could hinder successful message spreading. Simulation under different RSU density, vehicular networking technology penetration rate, data rate, and packet size, aims at assessing effectiveness and efficiency of the proposed solutions.

Several weaknesses of standard fixed infrastructure-based networks as means of communication for mobile high-speed users are identified in [20]. The authors proposed a multilevel network architecture, which combines WiFi and WiMAX networks. Specifically, a distributed proxy system, algorithms, and a routing protocol supporting a feed-forward mechanism for efficient and reliable connection transfer between cells have been developed. A simulation model with the OPNET Modeler was created and evaluated.

In [21] a novel solution for vehicle-to-roadside communications using the standard IEEE 802.11b/g network devices is introduced. The proposed solution is composed of two layers. A wireless connection layer is responsible for network switching. The upper roaming layer is a proxy and tunneling module providing reliable connection for rapidly changing network environment. The system is designed to provide secure roaming capability on GSM, UMTS, HSDPA and WiFi networks. Proposed solution was experimentally verified and used as a part of projects involving a vehicle-to-Internet applications.

An adaptive networking platform using WiFi/WiMAX technologies for cognitive vehicle-to-roadside communications is presented in [22], which can be used to transfer safety messages and provide

internet access for mobile users inside vehicles. The proposed platform is based on a heterogeneous multihop cluster-based vehicular network, where a vehicular node can choose to play the role of a gateway or a client. The gateway nodes communicate directly with a roadside base station through a WiMAX link. The client nodes connect to the gateways through WiFi links. Traffic from client nodes are relayed by the gateways to a roadside base station. The vehicular nodes have capability to learn and adapt decision to achieve their objectives independently. A decision-making framework is proposed for this WiFi/WiMAX platform. This distributed decision-making framework, which enables the vehicular nodes with cognitive capability, is modeled and analyzed using game theory.

Authors of [23] provided a detailed architecture and demonstration system for a new combined WiMAX and Dedicated Short Range Communications (DSRC) network layer design for providing Internet access to vehicles. The overall design consists of subscriber station (SS) vehicles, cluster head relay station (RS) vehicles, WiMAX base stations (BSs), and Internet access gateways (IAGs). Here RSs serve as intermediate relays for serving virtual WiMAX connections to SS vehicles, relying on a WiMAX backend network for Internet connectivity. Simulation results show that the proposed system significantly improves the overall system efficiency as compared to the conventional WiMAX-only system, there by motivating a design of a complete WiMAX/DSRC Internet access architecture.

4. Methods of Analytical Modeling and Simulation of Broadband Wireless Networks Along The Long-Distance Transport Routes

Different methods of analytical (mathematical) modeling and simulation are used for performance analysis of communication systems along the roads, and for assessing the quality of the design solutions. For analytical description of optimization problems and when analyzing the mechanisms of coordinated access to a network as well as for infrastructure planning, linear programming methods and methods of game theory are commonly used [11, 22]. Methods of queueing theory and probability theory are used for assessing the delays, the optimal through put and other parameters characterizing the efficiency of communication systems [13, 24-28]. Finally, simulation methods are used for the near-real performance evaluation of communications systems operating in different environments [20, 29, 30].

In papers [24, 25] a model of multiphase stochastic system with cross-traffic from mobile users is considered for performance evaluation and design of broadband wireless networks along the long-distance transport routes. The input flow and the cross-traffic are assumed to be described by Poisson distribution. More complex models of multiphase queueing systems with Markovian Arrival Process (MAP) were elaborated in [26, 27]. Using the MAP model significantly complicates the mathematical apparatus of analysis and synthesis of wireless networks, but allows to adequately take into

consideration the correlated, transient nature of information processes in modern telecommunication networks.

Other approaches of implementing the models of queueing theory for analysis of performance characteristics of wireless vehicular networks are presented in [27, 28]. Particularly, authors of [28] have investigated handover and fresh call blocking probabilities for subscribers moving along a road in a traffic jam passing through consecutive cells of a wireless network. The theoretical motivation relates handover blocking probabilities to blocking probabilities in the M/D/C/C queue with time-varying arrival rates. The authors provide a numerically efficient recursion relation for these blocking probabilities.

Compared with the analytical models, simulation of wireless vehicular networks allows to take into account both the physical level peculiarities (like encoding, modulation, etc.) as well as the network characteristics (topology, type of network traffic). As opposed to expensive full scale experiments, simulation provides a significant reduction of time and cost when evaluating the design and solutions. In papers [29, 30] the popular distributed network simulators - NS3 and OPNET - were used by the authors for simulation and performance evaluation of the wireless vehicular networks; an example of implementation of another simulation method, using QualNet network simulator, is presented in [30].

5. Methods of Interference and Collision Avoidance/Mitigation and The Design of Antenna Systems when Building Up The Wireless Vehicular Networks

One of the key problems in the construction of wireless networks along the transport routes, is interference, which causes collisions, leading to packet loss and decreased throughput. The papers [12, 31-35] are devoted to the methods of interference and collision avoidance/mitigation, the design of efficient antenna systems. In [31] the authors present empirical results from a study examining the effects of antenna diversity and placement on vehicle-to-vehicle link performance in vehicular adhoc networks. The experiments use roof- and in-vehicle mounted omni-directional antennas and IEEE 802.11a radios operating in the 5 GHz band, which is of interest for planned inter-vehicular communication standards. Results show that: (i) radio reception performance is sensitive to antenna placement in the 5 Ghz band and (ii) a packet level selection diversity scheme using multiple antennas and radios, multi-radio packet selection (MRPS), improves performance not only in a fading channel but also in line-of-sight conditions. These findings have implications for vehicular MAC protocol design. Protocols may have to cope with an increased number of hidden nodes due to the directional antenna patterns. The authors conclude that car manufacturers can reduce these effects through careful antenna placement and diversity.

Electronically steerable parasitic array radiator (ESPAR) smart antenna in a highway scenario, where roadside access points are installed on a highway to provide intelligent transportation System (ITS) services, is investigated in [32]. The authors consider vehicle-to road side (V2R) communication for a vehicle that aims to send data to the access point (uplink). The simulation results indicate that ESPAR system can considerably improve the average capacity of the link.

Authors of [34] introduce a novel reliable and low-collision packet-forwarding scheme for vehicular adhoc networks, based on a probabilistic rebroadcasting. Their proposed scheme, called Collision-Aware REliable-FORwarding (CAREFOR), works in a distributed fashion where each vehicle receiving a packet rebroadcasts it, based on a predefined probability. This probability is manipulated by different physical factors derived from the vehicular environment, including density of the vehicles in the vicinity, distance between transmitting and receiving vehicles, and finally, transmission range of the next-hop. All these factors are combined into one probability that enables each vehicle to evaluate whether there is another vehicle that ought to be receiving this message and could be feasible if the message is rebroadcasted. The success of rebroadcast is determined based on allowing the message to travel the farthest possible distance with the least amount of packet rebroadcast collision. CAREFOR is different from other existing techniques as it accounts for the effect of the next-hop transmission in the rebroadcast decision. Simulation results show the effectiveness of the proposed approach in terms of limited number of rebroadcasts needed with low collision probability as compared to existing techniques. Two and three-hops message retransmissions are also considered.

Authors of another paper [35] present a new physical (PHY) and medium access control (MAC) cross-layer design frame collision correction (CC) architecture for correction of Dedicated Short Range Communications (DSRCs) safety messages. Conditions suitable for the use of this design are presented, which can be used for optimization. At its basic level, the CC at the PHY uses a new decision making block that uses information from the MAC layer for the channel estimator and equalizer. This requires a cache of previously received frames, and preannouncing frame repetitions from the MAC. The authors present the theoretical equations behind CC mechanism and describe the components required to implement the cross-layer CC using deployment and sequence diagrams. Simulation results show that, especially under high user load, reception reliability of the DSRC safety messages increases and PER decreases.

CONCLUSION

In this paper we presented an analytical review of studies in the field of research and design of broadband wireless networks along the long highways, published in recent years by researchers. The technology in the construction of wireless networks of this class on the basis of IEEE 802.11*n*, *s*, IEEE

802.16 and UMTS (LTE) protocols, is described. We overviewed the methods and algorithms for the optimal location of the base stations along highways, which maximize the coverage area of the route under constraints on the total cost and the delay time of data package transmission. An overview of related papers on the models of queuing theory, game theory and simulation was also given, which are used for performance evaluation and optimization of the road communication networks. The final part of the article described the methods of interference and collision mitigation and solutions of the "hidden station" problem. These methods are aimed at improving the quality of performance of wireless networks along the long-distance transport routes. This review is a useful tool for experts in the field of communications for orientation in numerous studies on performance evaluation and design of broadband wireless networks, which were published in recent years.

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