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Accessible, Customizable, High-Performance IEEE 802.11p Vehicular Communication Solution

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***Abstract*—Intelligent driving is a promising area for increased safety and comfort. Vehicular communication is an essential part of building such intelligent systems. To provide inter-operability of wide vehicle range, common standards are needed. One of recently established standards for vehicular networks is IEEE 802.11p. However, 802.11p hardware platform market is limited due to protocol immaturity. Existing solutions are complex, expensive and closed-source systems with limited applicability. In this paper we propose an open, accessible and customizable wireless system for vehicular communication supporting IEEE 802.11p protocol. The system consists of low-cost components and open source software suitable for experimental intelligent transportation system research and applications. Nevertheless, real world tests prove feasibility of the system.**

I. Introduction

Intelligent Transportation System (ITS) approach is promising to increase mobility effectiveness, safety and comfort while decreasing costs and environmental impact. To create smarter traffic flows, individual vehicles are augmented with wireless communication, providing group intelligence and cooperative decision making opportunities. Sensing and communication capabilities create a sixth sense allowing vehicles and drivers to see further, react faster and think smarter. One example of vehicular group intelligence: cooperative driving. It decreases commute time by creating smart vehicle platoons and using cooperative adaptive cruise control (CACC) [1].

To create cooperative algorithms, traffic participants must agree on common communication standards and protocols. One of recently established international standards for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication is IEEE 802.11p. The IEEE 802.11p Task Group was established to create standards for Wireless Access in Vehicular Environments (WAVE). The 802.11p protocol is a modification of 802.11a, with improvements towards extended communication range and higher transmission speeds in vehicular environment [2].

Due to WAVE standard immaturity, commercially available 802.11p solutions are limited (Section II). All solutions can be divided into two categories: commercial and open solutions. The former are designed for specific vehicle original equipment manufacturers (OEMs) and large companies. There are several known such solutions available. And, perhaps, part of the solutions are not published due to commercial secrets. Open and customizable solutions are required for technology research, experimental prototyping and evaluation studies. Such experimentation is very important as a 802.11p solution driver, especially in the starting phase, when the protocol has not reached critical user mass.

Authors of this paper propose an open, affordable and customizable 802.11p solution for vehicular application and protocol prototyping and experimental evaluation (Section III). Example application scenarios include cooperative driving, vehicle sensor data exchange, audio and video transmission, infotainment and vehicular internet.

To evaluate proposed solution, real-world communication tests have been performed (Section IV). Results show, that it provides reliable data transmission for distances up to 1.2km (Section V).

The main contribution of this paper:

- An open, customizable, accessible 802.11p solution for vehicular network research and application prototyping is proposed
- The solution is evaluated in real-world settings, providing lessons-learned from vehicular experiments in harsh environmental conditions (low temperature, high humidity)

II. Related work

Vehicular communication platforms are being slowly accepted and adapted by automotive industry. Existing commercial systems are specific examples, not mainstream representatives.

Toyota offers an on-board G-BOOK terminal - an automotive PDA featuring a communications module and a Secure Digital (SD) card, enabling customers to take advantage of the latest network services as easily as they would operate a car radio [3]. Blue&Me is an infotainment system for Fiat Group cars based on Microsoft Auto and developed in a partnership (started in 2004) between Magneti Marelli (part of Fiat Group) and Microsoft Corporation. The system is based on modular structure which allows installation and use of arbitrary services. Bluetooth wireless connection is used to interact with user devices [4].

Due to 802.11p protocol immaturity ready-to-use system availability is limited. Several such solutions are listed here:

- ARADA Systems' LocoMate-RSU [5]. A road-side unit and vehicular unit with industrial grade NEMA enclosure, allows outdoor deployment, with full software stack supporting the latest Digital Short-Range Communication (DSRC) WAVE specification. It supports Intelligent

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Transportation Systems (ITS) applications. This includes data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure.

- Cohda Wireless' MK2 WAVE-DSRC Radio is an advanced DSRC device to achieve constant and robust communications for V2V and V2I applications [6]. Ford, NXP and Cohda develop platform called C2X (for "car-to-x"). It uses 802.11p to let equipped cars see one another around blind corners, through other vehicles, or even chat with traffic signals up to a mile away [7]. According to NXP, production should start in 2014.
- Kapsch TrafficCom is an international traffic telematic solution provider, maintaing two facilities responsible for development and engineering of 5.9 GHz DSRC WAVE products and applications, such as WAVE Transceiver TRX-9450 [8].
- Unex DCMA-86P2 is an industrial-grade, high power wireless mini-PCI module designed specifically to support V2V and V2I applications using 5.9GHz DSRC protocol [9]. It is not a complete solution, rather a cost-effective component usable to create customized systems. This wireless module is used in the proposed solution.

Perhaps, more industrial solutions are unpublished due to commercial secrets.

802.11p has gained notable academic attention in recent years. Multiple research groups have evaluated it:

- COMeSafety2 (successor of COMeSafety) is launching a European network for those who develop and use cooperative system architectures. [10]
- InscTec is testing 802.11p solution similar to proposed one [11]. However, the results have not been published and made available to research community.
- The FOT-Net project aims to bring together stakeholders of vehicular communication research and field tests [12]
- The objective of Grand Cooperative Driving Challenge (GCDC, organized by TNO) was to bring together international teams to create cooperative driving system composed of different hardware and software solutions, interconnected using 802.11p communication standard [13]. The same TNO company, Netherlands, is creating intelligent wireless alert system using IEEE 802.11p [14]
- In SAFESPOT project, a local high speed ad-hoc network based on the IEEE 802.11p protocol was implemented [15]
- California PATH program also contributes to DSRC protocol development and evaluation using simulations [16]
- CVIS project performs IEEE 802.11p tests using software defined radio [17]

Open and customizable solutions are required for technology research, experimental prototyping and evaluation studies. Such experimentation is very important as a 802.11p solution driver, especially in the starting phase, when the protocol has not reached critical user mass. Authors argue, that open and customizable 802.11p solution market is very limited and therefore propose one in this paper.

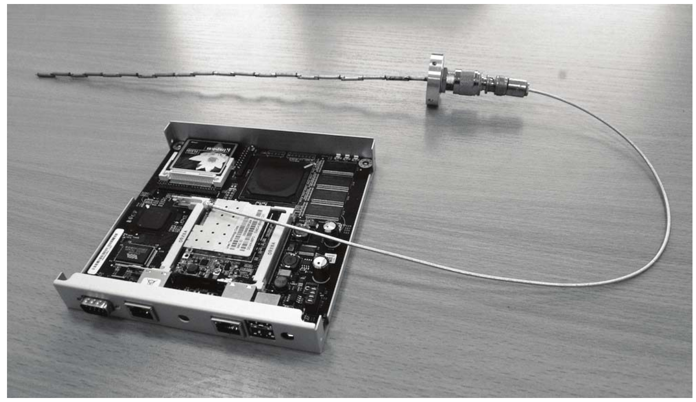

Fig. 1. One of the Alix.2D2 routers with IEEE 802.11p wireless adapters and 10dBd omnidirectional vertical collinear antenna, connected using 6GHz low-loss cable

III. Proposed approach

We propose a communication system supporting IEEE 802.11p protocol for vehicular network experimentation. Its main characteristics are:

1) *Accessibility* - all the building blocks of the system are commercially available components with reasonable price
2) *Openness* - users are able to access and assess every part of the system, hardware modules are well documented and open source software is used
3) *Customizability* - every hardware component is interchangeable, every software module can be modified, adjusted and recompiled

The central part of the system is a wireless router acting as a bridge between Car-Area-Network (CAN) and wireless DSRC network using IEEE 802.11p protocol (Figure 1). Hardware and software setup is described in the following subsections. The router was initially used for participation in GCDC 2011 Challenge. However, specific networking protocol stack was used in the challenge. The proposed solution uses conventional IP, UDP and TCP stack in the default setup, with modifications accessible upon desire.

A. Hardware setup

To provide a low-cost 802.11p communication solution between participating vehicles, a router is used as a bridge between wired car-area-network (CAN) and 802.11p wireless network (Figure 2). It consists of PC Engines ALIX.2D2 router with x86 architecture CPU, 256MB RAM, 8GB FLASH and Unex DCMA-86P2 miniPCI 802.11p wireless adapter [9], [18]. Powered by 12V DC, the energy consumption is below 10W (below 5W with radio turned off). External antenna - omnidirectional vertical collinear antenna with 20 half wave elements with approximate gain 10 dBd is used. Antenna is connected using 0.5m long 6GHz low-loss cable to be able to adjust antenna placement independent from the router. Multiple antennas and cables were tested and we concluded, that when appropriate cable is used, antenna gain is secondary.

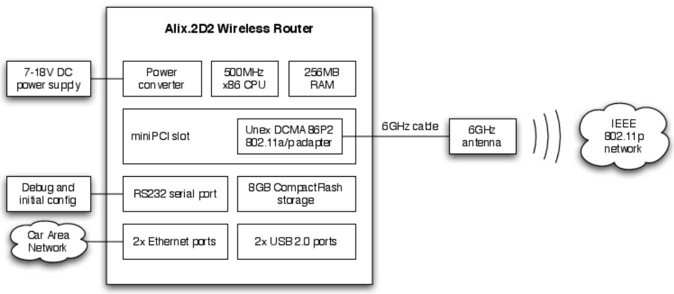

Fig. 2. Hardware components of the wireless IEEE 802.11p router

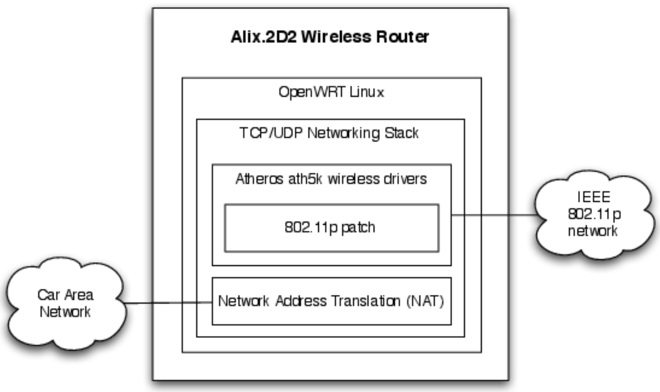

Fig. 3. Software modules of the wireless IEEE 802.11p router

Wired CAN is connected to the router through ethernet ports. When wireless technologies (Bluetooth, 802.11b/g/n WiFi) are used in the CAN, they must be bridged by using appropriate adapters in the router, connected either to USB ports or miniPCI slots. RS232 serial port is used for initial configuration and system debugging.

B. Software setup

OpenWRT Linux operating system is used on the router [19] (Figure 3). It provides ready-to-use implementations of conventional TCP/IP and UDP stacks for communication between vehicles and roadside. Network Address Translation (NAT) is also available for separation of internal CAN. In the physical and MAC layer, Atheros at5k driver is used [20]. A patch written by Eric Koenders is applied to support IEEE 802.11p protocol for the wireless adapter which runs in 802.11a mode by default.

Linux is selected as a reliable, configurable and accessible open source system width multitude of networking tools and can be adopted for custom needs. It fits the established design rules: accessibility, openness and customizability.

IV. Real-world test setup

To assess usability of proposed solution, wireless connection was evaluated in two real-world tests, measuring:

1) performance and reliability dependance on distance
2) stability over time

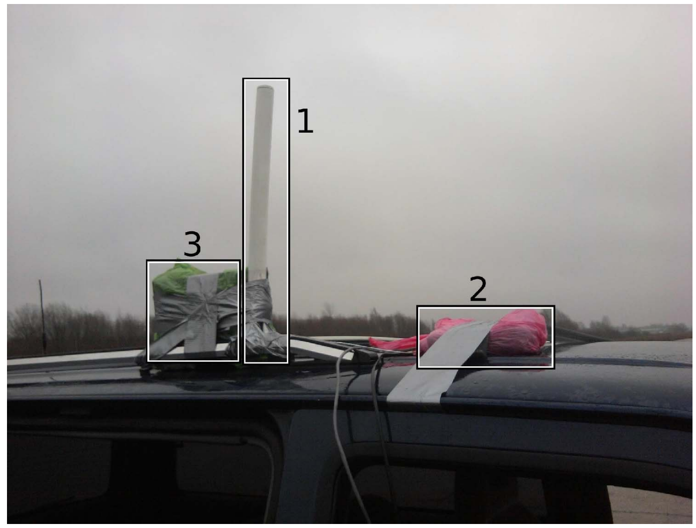

Fig. 4. Evaluated vehicular communication system mounted on the roof of a car: (1) antenna, (2) router, (3) antenna holder

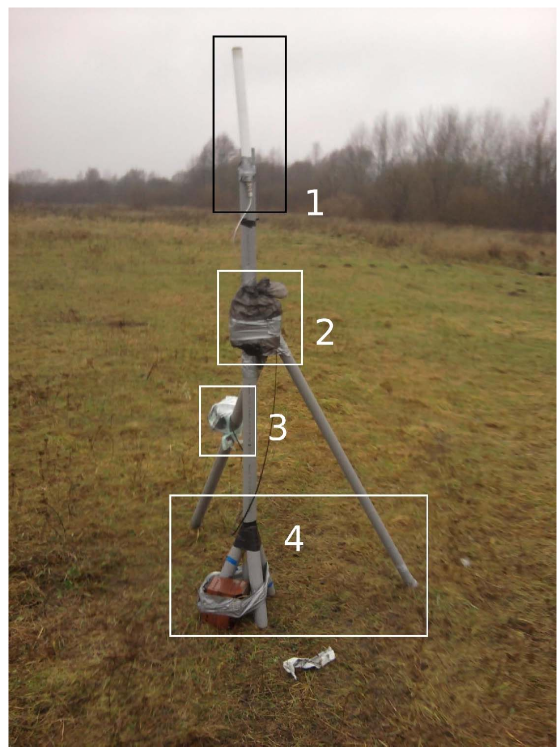

Fig. 5. Emulated road side unit with 802.11p router and antenna: (1) antenna, (2) router, (3) accumulator, (4) stand holder with weight for balance

The antenna was positioned on the roof of a Volkswagen Sharan passenger car (Figure 4) passing by a static base station on the roadside, 1.5 meters above the ground, representing roadside unit (RSU) (Figure 5). Direct visibility was ensured between both ends.

In both tests bandwidth, jitter and received signal strength indicator (RSSI) was measured. In the first test vehicle was moving up to 2.4km away from the RSU in straight line, and returning along the same trajectory. In the second test, vehicle

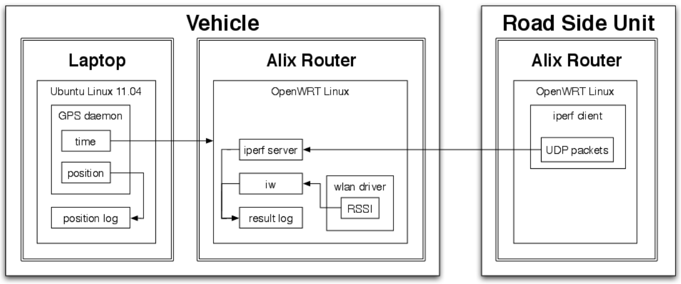

Fig. 6. Test tools used on vehicle and RSU routers, and on the laptop

was driving on an elliptic trajectory and RSU was positioned in the center of it. Ellipse radiuses: 1200m and 20m.

Tests were carried out on a rainy day at $-6°C$ (21° F) temperature. The environment was relatively harsh. Therefore heaters were used to ensure stable thermic operational conditions.

First test was repeated twice: the vehicle was moving at speed 50km/h (31mph) and 90km/h (56mph) accordingly. The second tests was performed once, the vehicle was driving 4 laps with a speed up to 50km/h (31mph).

Linux tools were used for connection evaluation (Figure 6):

- `iperf` to generate UDP packets at maximum speed, measure bandwidth and jitter
- `iw` to measure received signal strength (RSSI)

Communication statistics were logged on the vehicles router. Vehicle position was recorded using GPS on a laptop located in the vehicle. It was connected to the router over ethernet cable. The same GPS was used to synchronize time on the laptop and router right before the tests. Resulting statistics were linked to geographical positions and post-processed offline, using custom scripts and MathWorks Matlab.

V. Test results

Collected results show, that connection parameters vary significantly over time (See Figure 7). Therefore, to visualize general characteristics more markably, moving average filter (5 sample window) was applied for all the figures listed in this section. Although it may seem, that such approximation looses information, it actually reveals interesting features of the communication, such as modulation changes initiated by the wireless driver, depending on recent RSSI (Figure 8).

First test bandwidth graphs at speeds 50km/h and 90km/h are shown in Figures 8 and 9 respectively. Jitter graphs: Figure 12 and Figure 13. RSSI graphs: Figure 10 and Figure 11.

Conclusions of the first test:

- There is no strict communication range boundary. Link quality deteriorates smoothly. 1200m is an approximated range of stable communication (marked with a vertical line in the graphs). Yet partial communication is possible in larger distances, even up to 2.4km. In fact, the size of the aerodrome was insufficient to find a distance, where the communication is completely interrupted.

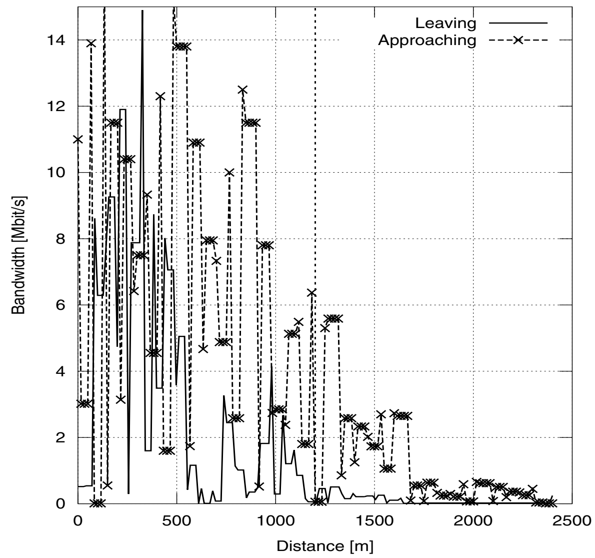

Fig. 7. Test 1: Bandwidth dependance on distance, raw data, high variance suppressing visual perception

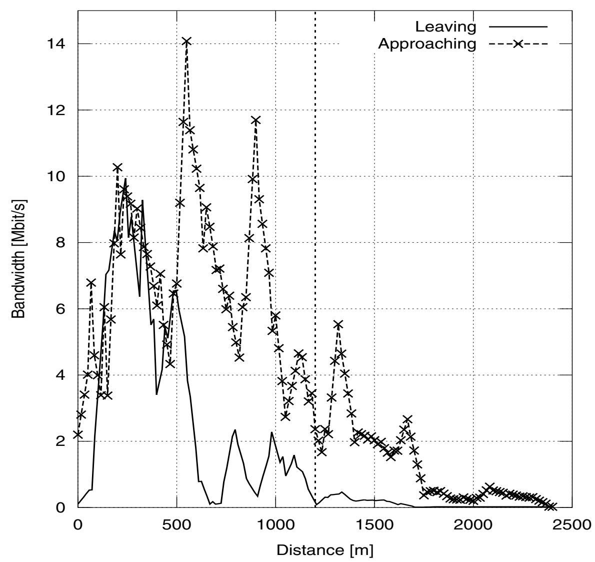

Fig. 8. Test 1: Bandwidth dependance on distance, 50km/h, filtered data

- Data transmission bandwidth of more than 2Mbit/s can be reached in the entire session in communication range, having separate regions with bandwidth more than 8Mbit/s. Such data channel is usable for audio and voice transmission for several vehicles simultaneously. Video transmission is possible for at least two vehicles (1Mbit/s for each channel) and for several vehicles in shorter distances. Example applications include video chat between team or family members traveling in multiple neighboring vehicles on the road
- When moving at higher speeds, communication bandwidth is lower and jitter is higher. As the distance between routers changes more rapidly, wireless adapters are not able to adapt parameters (sensitivity, modulation and

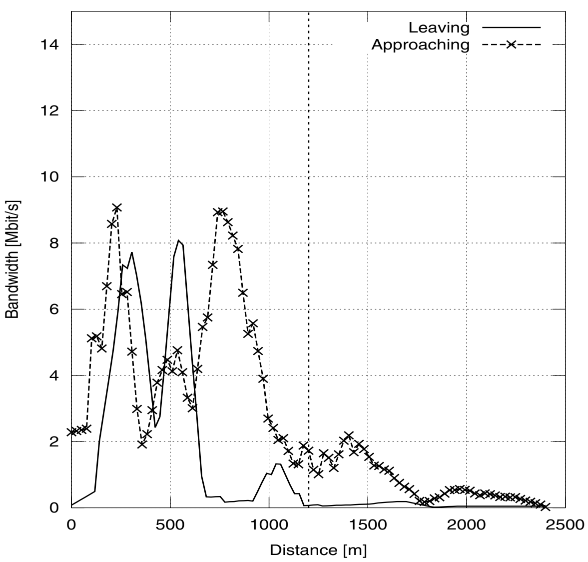

Fig. 9. Test 1: Bandwidth dependance on distance, 90km/h

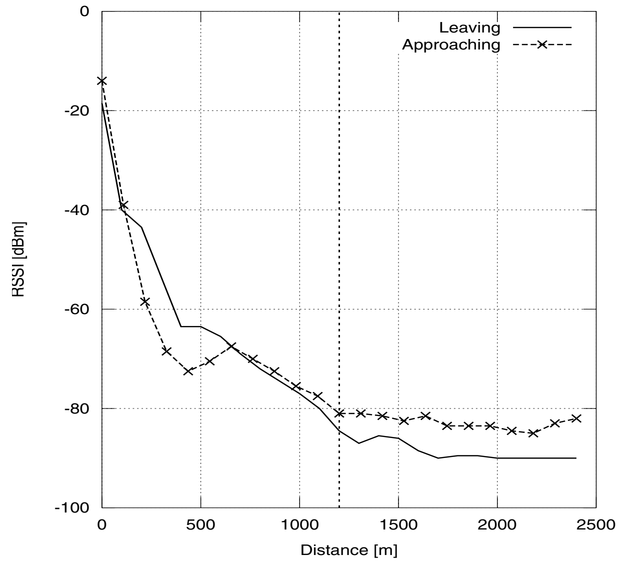

Fig. 11. Test 1: RSSI dependance on distance, 90km/h

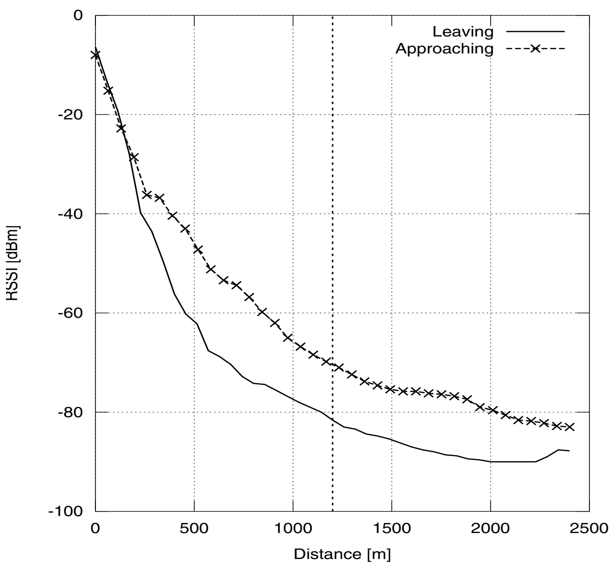

Fig. 10. Test 1: RSSI dependance on distance, 50km/h

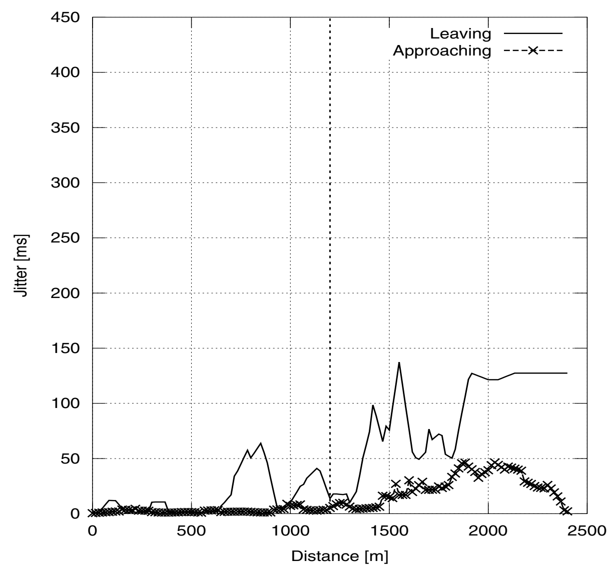

Fig. 12. Test 1: Jitter dependance on distance, 50km/h

transmission speed) accordingly.

- Link stability is notably lower when the vehicle is leaving the base station, comparing to same distances in when approaching it. RSSI difference is especially remarkable in Figure 10. Authors hypothesize, that it is a result of antenna placement and vehicle shape - radio waves are reflected on the vehicles surface differently on the front and back sides of the vehicle.

In the second test, the same parameters were recorded while driving 4 laps around the RSU on an elliptic trajectory with radiuses 1200m and 20m. Bandwidth graph is shown in Figure 14. Conclusions:

- Bandwidth dependence on communication distance is relatively stable. The same pattern repeats in all 4 test laps.
- There is a surprising bandwidth drop in short distances. Most probable explanation: transmit rate and sensitivity adaption based on RSSI - when the vehicle is approaching, RSSI increases, sensitivity is decreased and it leads to lost packets short after the vehicle leaves the RSU.

VI. Conclusion

In this paper an accessible, customizable solution for vehicular communication supporting IEEE 802.11p standard has been proposed. Real-world evaluation results show, that the proposed platform provides reliable data transmission (more than -85dBm) up to 1.2km, with channel bandwidth more than 2Mbit/s. Further link is unstable, yet partial communication is available up to 2.4km with the particular antenna. The distance and bandwidth should be sufficient for most of ITS

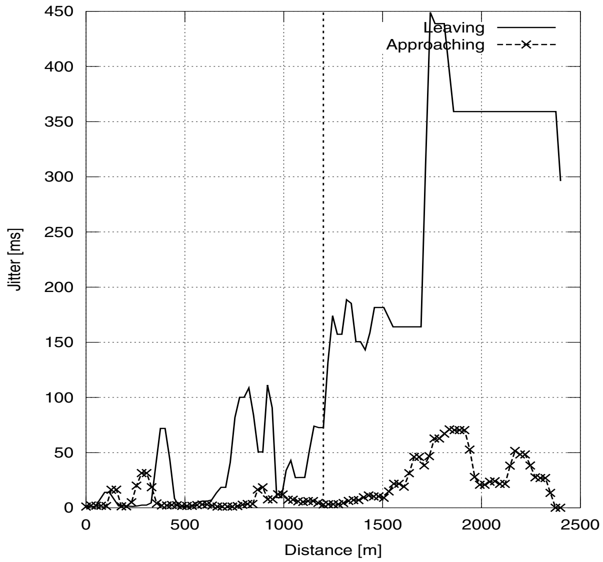

Fig. 13. Test 1: Jitter dependance on distance, 90km/h

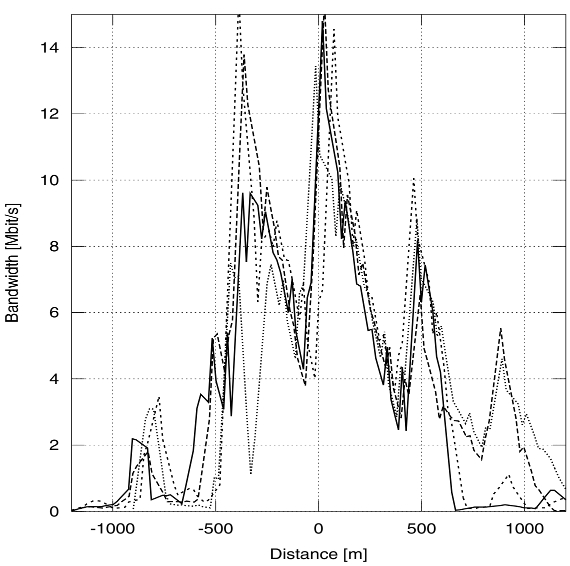

Fig. 14. Test 2: Bandwidth stability on an elliptic trajectory, 4 laps

applications, including cooperative driving, traffic warnings and audio/video streaming between neighboring vehicles and road side infrastructure. Connection bandwidth dependence on vehicle driving direction (approaching or leaving RSU) proves antenna placement problem importance. More appropriate antenna options can be investigated, however, it is not the main focus of this paper. Experience with link instability in low temperature conditions suggests, that communication platform enclosure design is a serious issue, especially for road side units.

Remarkable bandwidth deviation points to possible optimizations to the used 802.11p wireless adapter driver - 802.11a is not designed for mobile communication participants and the patch for 802.11p support does not impose any improvements.

While more complex communication tests would represent real situations more accurately, authors presume, that point-to-point connection assessment proves usability of proposed communication solution. Evaluation consisting of multiple vehicles and RSUs would assess not only platform performance, but also IEEE 802.11p protocol scalability.

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