An Ad-Hoc Opportunistic Dissemination Protocol for Smartphone-based Participatory Traffic Monitoring

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***Abstract*—This study introduces an ad-hoc opportunistic data dissemination protocol, called VADISS, that facilitates participatory traffic monitoring applications with smartphones. As a ubiquitous alternative to existing vehicular networking methods, VADISS uses the default WiFi interfaces universally adopted by today's mobile devices. The routing is enabled with intermittent service advertisements and discoveries, and the data exchange is provided via built-in IEEE 802.11 beacon frames. VADISS orients neither association nor connection between devices, is not based on any road-side unit, and thus is readily available for vehicular end-use applications. Together with a smartphone-based online road monitoring application, VADISS has been tested in a real-traffic setup to assess the data dissemination performance. With the increasing coverage, quite promising efficiency has been reached, especially for routing of critical traffic information.**

***Keywords*—VANETs, ad hoc networks, opportunistic networks, data dissemination, participatory traffic monitoring**

I. Introduction

In this paper, a collaborative way of intelligent traffic monitoring is offered with considerably larger coverage and less financial effort compared to the systems based on permanent infrastructures or dedicated on-board wireless adapters. Accordingly, an ad-hoc opportunistic data dissemination protocol is introduced to enable participatory monitoring through smart mobile devices carried by traffic participants. Our protocol sets up open, free, and direct communication in vehicular environments with the ubiquitously present WiFi-compliant devices. It facilitates vehicular networking for any interested device without requiring special adaptations of the operating platforms, without violating the IEEE 802.11 standard, and without relying on any fixed road-side unit (RSU) installations.

Intelligent traffic systems are still demanding in terms of broad public reach. First and foremost, such systems have significantly high deployment costs [1]. An efficient routing runs on RSUs, or specialized adapters, or both [2]. Another issue is the standardization concerns for the physical & medium access control layer (PHY/MAC) protocols . As the commonly accepted PHY/MAC standard, IEEE 802.11p is still open for enhancements together with IEEE 1609 protocol family. Above IEEE 802.11p, IEEE 1609 includes WAVE as a higher-level amendment [3]. Often tested with simulation models, both IEEE 802.11p and IEEE 1609/WAVE are offered with many modifications [4]. Real deployments might likely need specific hardware/software, hence seem to remain unsuited for end-use unless a stable set of standards becomes widespread.

Proposed as an upper-layer operation above IEEE 802.11, our protocol has a routing approach similar to IEEE 802.11p. As Figure 1 delineates, instead of IEEE 802.11 independent basic service set (IBSS), IEEE 802.11p links exert a wildcard basic service set (WAVE BSS) to disable management frames related to association and authentication request/response [3]. Thus, links allow an ad-hoc mode to directly transmit and receive data frames via authentication-free access points (APs). By contrast, our protocol ignores WiFi association, authentication, and connection establishment, and allows data exchange via the Service Set Identifier (SSID) of WiFi beacon frames. Routed data is embedded in the SSID field and announced immediately to others sharing the same communication range. Regardless of smart mobile platform types, the routing therefore operates on top of the universal IEEE 802.11 standard. This highly-available opportunistic "link" can only be provided with at least one AP and one client serving in WiFi Hotspot and WiFi Infrastructure modes, respectively. To enable sending and receiving multiple data, the protocol employs a continuous switch between mutually-exclusive hotspot and client services.

Named VADISS (Vehicular Ad-Hoc Dissemination via SSID), our protocol provides decentralized data sharing for many traffic monitoring applications such as, but are not limited to, road pavement monitoring, traffic density estimation, pollution detection. To this end, the effectiveness of VADISS is investigated through an online participatory road monitoring application. In a real-life deployment, several road anomalies are detected and the collected data is shared in a network setup.

VADISS can be applied also for other PHY/MAC protocols as a specific use-case of Opportunistic Beacon Networks [5]. It is a straightforward dissemination method compared to the protocols based on peer-to-peer, mesh, and ad-hoc connections which require either manual configurations or root privileges on today's mobile operating systems [6]. It can operate directly

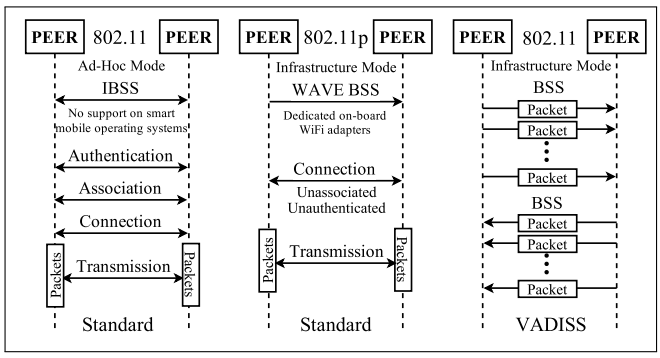

Fig. 1. IEEE 802.11, IEEE 802.11p, and our protocol VADISS

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on any platform, thus in networks of heterogeneous devices. Similar protocols have been recently studied on smart mobile platforms for data sharing [7]–[9] and data dissemination [10], [11] applications, which mostly require special adaptations of the standards. Relevant to our approach, the study in [12] proposes a smartphone-based vehicular communication model via WiFi interface. Nevertheless, the model necessitates internet access to reach collected traffic information through back-end servers. To the best of our knowledge, our study represents the first experimental study of utilizing wireless network identifiers as opportunistic information carriers for distributed vehicular networking applications.

II. VADISS: The Vehicular Ad-Hoc Opportunistic Data Dissemination Protocol

Our protocol is based on a low-throughput but connection-free message switching with an alternating use of WiFi Infrastructure (client) and WiFi Hotspot modes. In client mode, smart mobile devices used by traffic participants (hereafter, referred to as devices) can scan available WiFi APs in traffic environments. In hotspot mode, devices can serve as WiFi APs with a specific SSID announcement. With today's technology, client and hotspot modes cannot simultaneously operate on a single WiFi adapter. To make data exchange possible between devices, Algorithm 1 is run based on the automaton given in Table I. One switches to hotspot mode (State H) to announce a message, if any, as its current SSID. Serving in client mode (State C), others scan to receive encoded SSIDs within the communication range. As long as there is at least one present message, the automaton cycles between States C and H, thus devices periodically announce and can receive messages. If no message is available, State C is repeated. Based on received messages or application concerns, SSID can be encoded and t_C and t_H can be adjusted at each switch cycle. For instance, once a critical message is received, t_H can be increased to announce the message with a longer duration, or switches between States C and H can be made relatively infrequent with shorter t_C. In our previous study [5], the protocol is comprehensively analyzed with various parameters including t_C and t_H.

Algorithm 1: VADISS Data Exchange Process

```
require t_H > t_BI and t_C > t_SI ensure Initial State: C;
repeat
    if ∃ message ∈ messageList then
        SSID ← encodePacket(messageList);
        switchTo(H);
        repeat every t_BI
            announce(SSID);
        until t_H expires;
        switchTo(C);
    end
    repeat every t_SI
        messageList ← scan();
    until t_C expires;
until end of runtime;
```

TABLE I. WiFi Switch Cycle Automaton

State	Transition	Operation	Duration	Note
C	$C \rightarrow C$	scan()	t_C	Repeats every t_{SI}
	$C \rightarrow H$	switchTo()	t_{XH}	Duration is WiFi chip-specific
H	$H \rightarrow H$	announce()	t_H	Repeats every t_{BI}
	$H \rightarrow C$	switchTo()	t_{XC}	Duration is WiFi chip-specific
t_{SI} is the WiFi scan interval, t_{BI} is the WiFi beacon interval				

In spite of short inter-contact times in traffic environments, VADISS provides highly-scalable data dissemination, thanks to the high frequency in t_{SI} and t_{BI} provided by smart mobile platforms. Moreover, it exploits the wireless broadcast advantage since multiple SSID announcements can be received with a single scan operation. Nevertheless, it has low-throughput due to limited packet size and half-duplex operation. A packet can be at most 32 bytes—that is the maximum size allowed for the SSID field, and therefore is bound to contain limited data. Besides, it also introduces potential delays during message sharing since *scan* and *announce* operations are mutually exclusive. Consecutive switches between States C and H enable reception intermittently while blocking transmission, or vice versa, which may drop routing efficiency. Devices serving in same WiFi mode cannot exchange data if their state switches are synchronized. To overcome this problem, a randomized short duration is added to t_C and t_H in each cycle.

III. A Smartphone-based Participatory Road Traffic Monitoring Application

Road anomalies such as potholes cause many traffic incidents ranging from congestions to accidents. Drivers tend to avoid such anomalies prudently or are unfortunately exposed to take whatever they may come across. In order to increase traffic-flow safety, participatory monitoring of road anomalies and unusual driver behavior requires a well-functioning networking between participants. To this end, VADISS is investigated together with a smartphone-based online road anomaly and driver behavior detection application.

A. Information Dissemination Scenarios

Figure 2 illustrates two general traffic information dissemination scenarios that engage smart devices of drivers forming an ad-hoc opportunistic vehicular network through VADISS:

- S_1, alongside a two-way road.
- S_2, at an "at-grade" intersection of two or more roads.

Detecting all road anomalies in a single drive is unrealistic, hence the scenarios are based on increasing awareness about the road conditions and incidents by collaboration. Devices individually perform road monitoring and meanwhile opportunistically exchange road anomaly and driver behavior data.

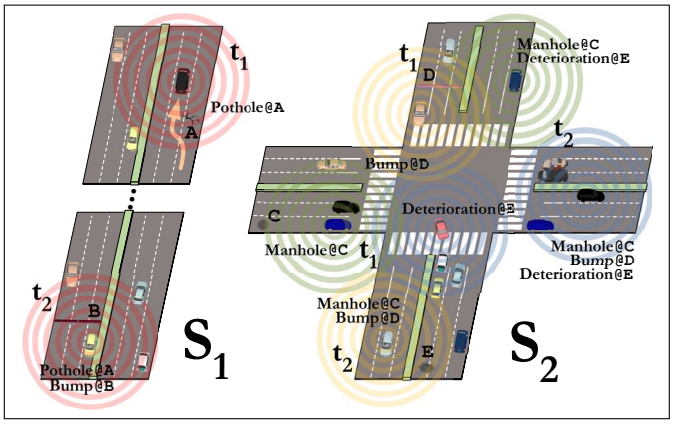


Fig. 2. Smartphone-based Participatory Traffic Monitoring Scenarios

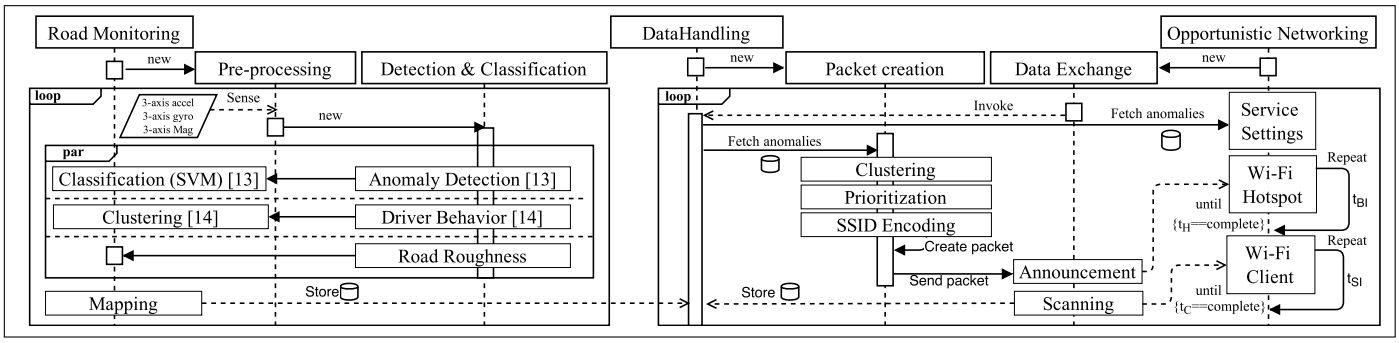


Fig. 3. Sequence diagram of our Cyber-Physical Road Monitoring System

As shared data size increases in the network, the resulting information on traffic conditions gets actual and highly accurate.

B. System Architecture

Our application model together with VADISS represents a mobile cyber-physical system since devices cooperatively handle monitoring and data sharing over a network. Devices sense inertial changes with accelerometer, magnetometer, and gyroscope and locate the incidents with GPS sensors. For routing, devices intermittently utilize WiFi client and hotspot modes. Figure 3 shows the sequence diagram of the system running road monitoring, data handling, and networking processes concurrently on a single device. The system employs two continuous processes: The first deals with road monitoring whereas the latter deals with data handling and networking.

Devices with the aforementioned specifications are used to detect and classify a set of road anomalies, driver behaviors, traffic streams in real-time. Initially, sensed data from the gyroscope, accelerometer, and magnetometer goes through a number of preprocessing steps including high-pass filtering, envelope calculation, demodulation, windowing, and wavelet transform. For online road anomaly detection and classification, the algorithm in our previous study is run as a separate smartphone process [13]. In parallel, driver behavior results are clustered to perceive the reasons of unusual driver behavior. The clustering distinguishes accidental and periodic turns and swerves as well as to detect current traffic flow. During our experiments, it is noticed that drivers tend to avoid the impact of an anomaly by swerving around it. Our smartphone-based algorithm introduced in [14] is utilized to detect this driver behavior. The algorithm detects all significant changes in direction of the vehicle and classifies them into several turn and swerve types. The aim of the algorithm is to increase the accuracy of detections by clustering the detected anomalies and swerves received by others in the network.

Another aspect of road monitoring is the road roughness determination. Studies show a strong correlation between vertical vehicle vibration and suspension frequency [15]. Thus, a current road roughness index can be estimated with the fourth level of decomposition on the vertical axis of the accelerometer. With participation, the index calculation is improved.

C. Data Dissemination with VADISS

In this subsection, several definitions refer to the notations provided in Table II for the sake of brevity.

1) Packet Creation: In order to deal with the limited packet size, the following steps are held in each networking cycle:

i. Clustering: $a_k \in A$ which are detected in a radius less than 10m are merged into one anomaly data.
ii. Prioritization: All P_i are determined based on application concerns. A is prioritized as $A^\star$.
iii. Packet Encoding: A packet, namely an encoded SSID is created based on two urgency sets, U_1 and U_2.

A packet is structured as a 32b case-sensitive ASCII string—the maximum length allowed for the SSID field. Hence, only a limited number of data in $A^\star$ is selected for the payload. The packet is encoded based on either Type I or Type II, as shown in Figure 4. Type I is selected if there are anomalies in $A^\star$ satisfying U_1. Otherwise, Type II is selected to embed the anomalies in $A^\star$ satisfying U_2. Type I contains at most 12 $(a^\star, \delta)$ pairs whereas Type II contains at most 4 $(a^\star, \ell)$ pairs.

Several ASCII mapping tables are used to compactly report the operational flags and anomaly data set. For numerical data, a decimal to ASCII conversion is applied. For conversion, 94 printable ASCII characters can be used, thus δ values less than 95 is indicated in 1 ASCII digit. Similarly, ℓ is encoded with 6 ASCII bytes, with special methods to encode latitude and longitude values shortly. A special mapping for f_1 is used to indicate the urgency type, or to inform an incomplete payload if there are not enough anomalies in $A^\star$. With the mapping in Table III, f_2 is used to announce the direction, routing-related data, and current sensing properties. f_3 and f_4 are used for road roughness results. Based on the used ASCII mappings, received packets are decoded and stored locally.

2) Data Exchange: At each switch cycle, a ready packet is announced in State H, after which the traffic is scanned in State C. Once new data are detected or received, A is reprioritized. Just before the packet creation, the operational flags,

TABLE II. LIST OF NOTATIONS

Symbol	Definition
A	Mapped road anomaly and driver behavior data set
$A^\star$	Prioritized A with regard to a set of P_i
P_i	A priority level for an anomaly type, where $i \leq n$
n	Total number of anomaly types
a_k	A single anomaly data, where $a_k \in A$ and $k \in \mathbb{N}$
$a_k^\star$	A single anomaly data, where $a_k^\star \in A^\star$ and $k \in \mathbb{N}$
U_1	$\{a_k^\star \mid a_k^\star$ happened in the last travelled kilometer$\}$, where $U_1 \subseteq A^\star$
U_2	$\{a_k^\star \mid a_k^\star$ happened within a defined radius away$\}$, where $U_2 \subseteq A^\star$
ℓ	A 6 ASCII bytes GPS position representation.
ℓ_H	Start position of the current hotspot service
δ	Relative distance with regard to ℓ_H.

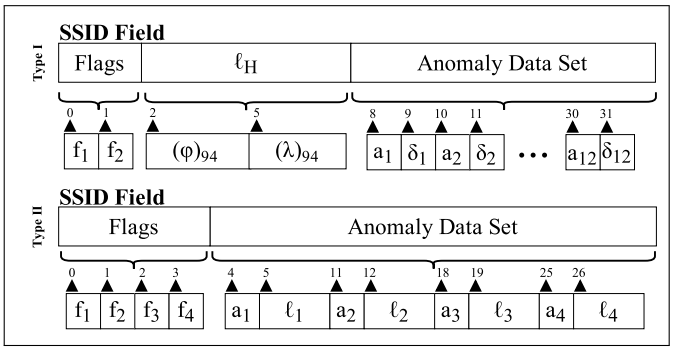


Fig. 4. Packet Encoding Types. Type I allocates 2 bytes for two operational flags, 6 bytes for the GPS (ℓ_H), and the rest for the anomaly data set. Type II allocates 4 bytes for four the flags, and the rest for the anomaly data set.

TABLE III. MAPPING INFORMATION

Direction	N	NE	E	SE	S	SW	W	NW
Cycle (sec)	15	30	60	90				
FS	Game	Fastest						

the encoded anomaly data set, and other related numerical data are updated based on the start time of State H and ℓ_H.

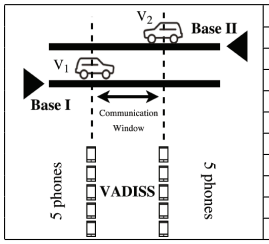
IV. PERFORMANCE ANALYSIS

VADISS is implemented on our *Android*-based mobile opportunistic networking platform, which is named *Cocoon* (Community-Oriented Context-aware Opportunistic Networks) and is introduced in [5]. The data dissemination performance is tested with 10 *Samsung S4 Mini* phones, denoted as $D_1 \cdots D_{10}$. The phones are placed 5 by 5 in 2 cars, V_1 and V_2. Table IV gives our experimental setup. In opposite directions, V_1 and V_2 shuttle between two base stations for 9 times, each time with a different velocity (v) and t_C=t_H. V_1 and V_2 wait at their bases for a time, then start travelling at the same time, and meet in the halfway. In the beginning of each shuttle, all D_i create a unique network packet, denoted as $p_1^c \cdots p_5^c \in V_1$ and $p_1^c \cdots p_5^c \in V_2$, at random times. The average data dissemination rate solely in the opposite direction (s_O) is calculated with the general formula given in Equation 1. Belonging to either V_1 or V_2, a p_i^r denotes a received packet, respectively. The average dissemination rate in both directions (s_B) is calculated with Equation 2. Since $D_1 \cdots D_5 \in V_1$ and $D_1 \cdots D_5 \in V_2$, $n = 5$ in our example.

$$s_O = \left(\frac{\Sigma_{i=1}^{n} p_i^r \in V_2}{\Sigma_{i=1}^{n} p_i^c \in V_1} + \frac{\Sigma_{i=1}^{n} p_i^r \in V_1}{\Sigma_{i=1}^{n} p_i^c \in V_2} \right) \Big/ \left(p^c \in V_1 + p^c \in V_2 \right) \quad (1)$$

$$s_B = \left(\frac{\Sigma_{i=1}^{n} p_i^r \in V_1 + \Sigma_{i=1}^{n} p_i^r \in V_2}{\Sigma_{i=1}^{n} p_i^c \in V_1 + \Sigma_{i=1}^{n} p_i^c \in V_2 - 1} \right) \Big/ \left(p^c \in V_1 + p^c \in V_2 \right) \quad (2)$$

TABLE IV. FIELD TEST PARAMETERS

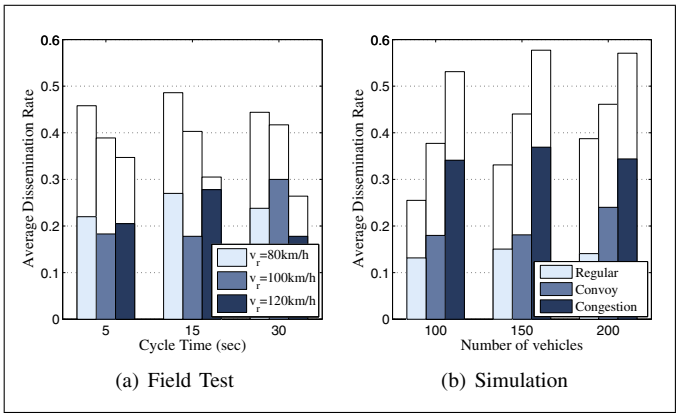


Scenario: 600m-long two-lane expressway
Shuttle 1: v =40km/h, $t_C = t_H$ =5s
Shuttle 2: v =50km/h, $t_C = t_H$ =5s
Shuttle 3: v =60km/h, $t_C = t_H$ =5s
Shuttle 4: v =40km/h, $t_C = t_H$ =15s
Shuttle 5: v =50km/h, $t_C = t_H$ =15s
Shuttle 6: v =60km/h, $t_C = t_H$ =15s
Shuttle 7: v =40km/h, $t_C = t_H$ =30s
Shuttle 8: v =50km/h, $t_C = t_H$ =30s
Shuttle 9: v =60km/h, $t_C = t_H$ =30s
Other parameters: t_{BI} =100ms, t_{SI} =100ms

Figure 5(a) illustrates the data dissemination results with regard to different t_C=t_H and relative speed (v_r=2×v). The blue bars show s_O results whereas the white bars depict s_B results stacked on top of s_O results. The overall results show that t_C=t_H and v_r have a slight influence on the data exchange performance. The average rate varies between 20% and 30% for the dissemination in opposite directions. The overall rate increases up to 48% with every-which-way dissemination.

In order to test the robustness of VADISS in broader vehicular environments, scaled-up tests are taken with a realistic simulation in MATLAB. Table V expresses the deployments based on the scenarios S_1 and S_2 described in Section III-A. For S_1 and S_2, a unique packet is created per km travelled in each device. Thus, the average number of packets created per vehicle in S_1 is ≈10, and in S_2 is ≈20. Figure 5(b) depicts the data dissemination results with regard to different number of vehicles and under different traffic stream scenarios. The blue bars show dissemination rates obtained for S_1 whereas the white bars that of for S_2. In S_1, during regular traffic flow, the average data dissemination rate is 12% regardless of vehicle density. As the vehicles move coherently (convoy), the performance slightly increases. In congested traffic, this rate increases up to 35% in average. In S_2, the performance drastically increases since the vehicles have more inter-contact times. In average, the dissemination rate is 32%, 42%, and 54% for regular, convoy, and congestion, respectively.

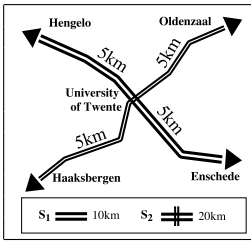
The networking tests represent the average packet switching performance. Nevertheless, packets can be composed of several anomaly data set. To this end, VADISS results are evaluated with the online participatory monitoring performance results as well. First, the road anomaly detection algorithm presented in Section III is tested on the Dutch and Albanian roads. Putting our algorithm into a context of comparison, an



(a) Field Test (b) Simulation

Fig. 5. Opportunistic Networking Results

TABLE V. SIMULATION PARAMETERS



Real Map-based Movement with paths
Number of vehicles (devices): 100,150,200
Vehicle speed: [40. . .90]km/h, comm.range=90m
S_1-Regular Average Wait Time: 10s
S_1-Convoy Average Wait Time: 20s
S_1-Congested Average Wait Time: 30s
S_2-Regular Average Wait Time: 30s
S_2-Convoy Average Wait Time: 60s
S_2-Congested Average Wait Time: 90s
$t_C = t_H$ =15s, 30s, t_{BI} =100ms, t_{SI} =100ms, t_{XH} =4.2±[0. . .1.7]s, t_{XC} =2.8±[0. . .1.3]s

TABLE VI. ROAD ANOMALY CLASSIFICATION RESULTS

				Detection	Classification			Mapping	Evaluation			
	KM	S/R	#Win	Anom	Sev.	Mild	Span	mapped	Sev.	TD	FD	MA
Trip 1	22.8	47Hz	609	165	119	26	20	113	73	64	15	4
Trip 2	22.8	96Hz	764	207	93	72	42	123	61	52	12	3
Trip 3	16.3	47Hz	1067	222	120	51	512	152	82	74	10	8
Trip 4	33	47Hz	2240	412	255	98	59	296	173	no video		
Trip 5	5.46	47Hz	794	192	99	93	0	134	76	74	6	

Sev.= Severe, TD= True Detections, FD= False Detections, MA= Missed Anomalies, #Win= Number of windows

TABLE VII. ROAD ANOMALY DISSEMINATION RESULTS

	Mapping Anomaly		Packet	Estimated Dissemination Rate					
	per km	per veh.	per dev.	S1-reg	S1-cvy	S1-cng	S2-reg	S2-cvy	S2-cng
Trip 1	3.20	32	3	0.15	0.24	0.41	0.36	0.47	0.61
Trip 2	2.67	27	3	0.17	0.28	0.49	0.43	0.57	0.73
Trip 3	5.03	51	5	0.15	0.25	0.43	0.38	0.50	0.64
Trip 4	5.24	53	5	0.15	0.24	0.41	0.37	0.48	0.62
Trip 5	13.92	140	12	0.13	0.22	0.37	0.33	0.44	0.56

S1=Scenario 1, S2=Scenario 2, reg = regular traffic, cvy =convoy traffic, cng=congested traffic

objective audiovisual method is used to evaluate our results. Table VI shows the number of anomalies detected, classified, and evaluated for each trip. Anomalies are classified into 3 types: severe, mild, and span. Overall, a consistent accuracy of $\approx 90\%$ is obtained regardless of vehicle and road types.

Based on the online road anomaly detection test results, Table VII gives the average number of severe anomalies detected in each trip and their estimated dissemination rate in our simulation scenarios. Results evidently demonstrate that having less number of anomalies provides high dissemination rate. Trips 1 and 2 result in better performance compared to Trips 3-5 as the packets can announce an anomaly longer as long as it is overwritten with new anomalies. For regular traffic stream scenarios, the maximum dissemination rate reached is 17% whereas for other scenarios it is 73%. Oppositely, having high number of anomalies has a negative effect on the dissemination performance, especially for the scenarios that devices have short inter-contact durations. In Trip 5, for instance, S_1-regular can provide a dissemination rate only up to 13%. Nevertheless, S_1-congestion shows 37% of dissemination rate. This amount increases up to 56% for the scenarios in which the vehicles move more coherently.

V. CONCLUSION & FUTURE WORK

In this study, a smartphone-based ad hoc data dissemination protocol has been proposed, intended for vehicular networks, in particular for participatory traffic monitoring applications. Named VADISS, the protocol has been offered as a higher level operation above IEEE 802.11 standard. VADISS provides platform-independent data exchange between smart devices carried by traffic participants. Through VADISS, such devices directly form opportunistic networks without requiring dedicated adaptations of WiFi connectivity. As a straightforward approach, devices switch data via SSID fields of IEEE 802.11 beacon frames. VADISS has been introduced together with a smart-phone based online participatory road monitoring applicaton. A set of real-traffic experiments has been held to investigate the data exchange efficiency. The results have indicated the fast and high dissemination performance of VADISS in several scenarios. In average, 38% of dissemination rate of critical traffic monitoring data has been reached. While the wireless broadcast advantage of VADISS is exploited, $\approx 63\%$ of dissemination rate has been reached in denser scenarios.

Our future work is threefold. First, we will broaden our real-life experimental deployments with VADISS for various opportunistic vehicular use cases. Second, we will investigate more adaptive schemes to make VADISS more congruent to the offered application scenarios. Third, we will perform face-to-face comparisons between existing device-to-device vehicular data dissemination protocols and VADISS.

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