The Effects of Vehicle-to-Infrastructure Communication Reliability on Performance of Signalized Intersection Traffic Control

Ilya Finkelberg, Tibor Petrov, Ayelet Gal-Tzur, Nina Zarkhin, Peter Počta, Tatiana Kováčiková, Ľuboš Buzna, Milan Dado, *Senior Member, IEEE*, and Tomer Toledo

***Abstract*— Vehicle-to-infrastructure communications can inform an intersection controller about the location and speed of connected vehicles. Recently, the design of adaptive intersection control algorithms that utilize this information received substantial research attention. These studies typically assume perfect communications. This study explores the possible effects of a temporal decrease in the reliability of the communication channel, on the intersection throughput. Road traffic and DSRC-VANET communications are modelled by integrating traffic and communication simulation tools (Vissim and OMNeT++, respectively). Simulations of scenarios with challenging, but realistic communication distortions conditions show significantly larger average delays to vehicles compared to scenarios with perfect communication conditions. These additional delays are largely independent of whether all or only some of the intersection approaches are affected by the communication distortions. Furthermore, delays do not increase uniformly on all signal groups. They may even decrease for some, which causes unfair allocation of green times. The control may be corrected for the lost communications using the information received in previous time intervals and simple assumptions about the vehicle movements. This correction decreases delays in all scenarios both for isolated and connected intersections. It performs similarly to the case with perfect communications when the communication distortions are distributed uniformly among all intersection approaches. Overall, the results demonstrate that the impact of the communication distortions should be considered in the design of the adaptive intersection control algorithms.**

***Index Terms*— Communication distortions, reconstruction of incomplete communication, signalized intersection control, vehicle delays, vehicle-to-infrastructure connectivity.**

I. Introduction

TRAFFIC congestion in urban areas is increasing, which leads to longer delays, increased emissions and decreased traffic safety. The introduction of connected vehicle (CV) technology may help improve traffic performance through driving assistance, collision avoidance and traffic management applications [1]. CV telematics is a rich source of real-time information about the state of the traffic system, which may be used to enhance the efficiency of traffic management and control, most notably intersection signal control.

In recent years, various traffic signal control algorithms utilizing CV data were developed. Ref. [2] provided an up-to-date summary of 26 different studies together with an overview of their use of simulation modules and simulation scenarios. Ref. [3] proposed a distributed coordinated signal control methodology, where the signal control parameters were optimized to reduce vehicle delay and increase throughput. Ref. [4] developed a two-level optimization model where the sequence of signal stages and their durations were optimized based on incoming CV data. Another recent work [5] proposed a heuristic approach to determine optimal platoon discharge order at a signalized intersection to minimize vehicle delay. Additional studies [6], [7] focus on minimizing fuel and energy consumption by optimizing both signal timing and recommended speed profiles for the VCs. The calculations rely on the fusion of vehicle acceleration, speed and location data and relevant signal controller parameters communicated via V2X network.

A common assumption in these studies is that the communication, both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I), is perfectly reliable, i.e., without any loss or delay. This assumption is rarely realistic. Communication performance is affected by a variety of factors, such as the separation distance, vehicle speed, number of vehicles within

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Ilya Finkelberg, Ayelet Gal-Tzur, Nina Zarkhin, and Tomer Toledo are with the Transportation Research Institute, Technion—Israel Institute of Technology, Haifa 32000, Israel (e-mail: ilya.f@technion.ac.il; galtzur@technion.ac.il; ninaz@technion.ac.il; toledo@technion.ac.il).

Tibor Petrov is with the Department of International Research Projects—ERAdiate+, University of Žilina, SK-010 26 Žilina, Slovakia (e-mail: tibor.petrov@uniza.sk).

Peter Počta and Milan Dado are with the Department of Multimedia and Information-Communication Technologies, University of Žilina, SK-010 26 Žilina, Slovakia (e-mail: peter.pocta@feit.uniza.sk; milan.dado@feit.uniza.sk).

Tatiana Kováčiková is with the Department of International Research Projects—ERAdiate+ and the Department of Information Networks, University of Žilina, SK-010 26 Žilina, Slovakia (e-mail: tatiana.kovacikova@uniza.sk).

Ľuboš Buzna is with the Department of Mathematical Methods and Operations Research and the Department of International Research Projects—ERAdiate+, University of Žilina, SK-010 26 Žilina, Slovakia (e-mail: lubos.buzna@fri.uniza.sk).

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the communication range, physical obstacles (e.g., buildings, trees), presence of interference sources and weather conditions [8].

Currently, two communication technologies dominate in the context of connected vehicles: Dedicated Short-Range Communication-based Vehicular Ad hoc Network (DSRC-VANET) technologies that use Wi-Fi-like IEEE 802.11p communication standard and Cellular Vehicle-to-Everything (C-V2X) technologies that are built on mobile cellular networks, such as LTE or 5G. Several studies evaluated their performance. Ref. [9] showed that LTE-based C-V2X can achieve similar block error ratio with lower Signal-to-Noise Ratio (SNR) compared to DSRC-VANET systems on a larger coverage area. Similar results were presented in [10] for message exchange within a platoon of trucks on a highway. The authors concluded that LTE C-V2X outperforms DSRC-VANET in terms of communication reliability while DSRC-VANET has the advantage in communication latency. It is worth noting that LTE C-V2X was first standardized in 2017 and is still not market ready [11]. DSRC-VANET is more mature and already popular. It is therefore used in this research.

Regardless of the technology used, the communication reliability of CVs is far from ideal. Ref. [12] showed that when considering a realistic signal propagation model and a moderate distance of 300 meters between transmitter and receiver, the application-level reliability of the DSRC-based communication is not more than 55% for delay sensitive safety applications. Similarly, [13] concluded that the placement of the Onboard Unit (OBU) antenna inside a vehicle or on its roof and terrain topology play a major role in communication reliability. Even with the OBU antenna installed on the vehicle's roof, the message delivery ratio ranges from 71 to 88% in an urban environment. Furthermore, the authors found that even on a straight road, altitude variations between the CVs can significantly reduce the reliability of V2V communication.

Real-world applications of connected vehicles are still rare. Therefore, their evaluations, especially for high traffic volumes, are mostly carried out using simulation models. Ref. [14] calibrated communication simulation models with empirical data obtained from a CV testbed operated by the Federal Highway Administration. Refs. [12], [15]–[17] used a hybrid model that combines a traffic micro-simulation model and a communication network simulator. These studies focused on the performance of the communications network and did not consider the effects of imperfect data transmission on traffic flow. Few studies considered the bi-directional dependency between the two systems. Ref. [18] presented a communication-fault tolerant control algorithm for a platoon of autonomous CVs, primarily focusing on safety aspects. Ref. [19] addresses the security aspect of communication, falsified data attacks, and their impact on traffic control performance. Ref. [20] presents a protection scheme to minimize the impacts of cyber-attacks on the communication.

In summary, the literature shows that traffic control and traffic flow conditions both affect and are affected by the CV communication network reliability. However, the dependence between the two systems is often ignored in their performance evaluations, which commonly assume perfect communications. To the best of the authors knowledge, none of the few studies that considered this dependency addresses the need to explore the impact of communication faults on traffic flow quality and possible measures to overcome its negative consequences.

The paper makes the following contributions to the state of the art: i) An integrated simulation framework that enables study of the impact of communication distortions on the performance of signalized intersections is developed. The model combines a microscopic traffic simulation model (VISSIM) and a communication network simulator (OMNET++); ii) The integrated model is used to compare traffic control performance is scenarios with perfect communication conditions and with challenging but realistic communication conditions. The results show that communications distortions may significantly increase average delays to vehicles. iii) A mechanism to correct for communication distortions within the traffic control logic is presented. It is shown to be able to reduce the effects of the communication distortions. In the context of this paper, communication distortions refer to short-term disruptions to message delivery caused by a challenging communication environment, i.e. decreased reliability of the communication channel. Long-term unavailability of the communication system caused by hardware failures is not considered.

The rest of this paper is organized as follows: the next section presents the integrated traffic and communications modelling framework and the main assumptions made in setting it up. Section III introduces the intersection signal control algorithm and a mechanism, which the algorithm incorporates, to consider the possibility of communication distortions. Section IV describes the case studies and design of simulation experiments. Section V presents the results of simulation experiments and their analysis. Finally, discussion and conclusion are presented in Section VI.

II. Integrated Traffic and Communications Model

A. Overall Simulation Framework

As noted above, simulation modeling is currently the only viable approach to evaluate the performance of traffic systems that include CVs and to consider the communications system. Fig. 1 shows the flowchart of the integrated traffic and communications simulation framework. It supports modeling of the real-time bi-directional data exchange between the two models. After initialization of the simulation process, at the beginning of every time step, the traffic simulation model receives a list of communication messages from CVs (e.g., their identification numbers, locations, intended maneuver at the intersection) that were received by the roadside unit (RSU) in the previous time interval. Within the traffic simulation step, control actions (e.g., traffic light indications) are determined using this information and the vehicles in the model are advanced based on traffic conditions and the prevailing control states. At the end of the traffic simulation time step, a list of communication requests from CVs is

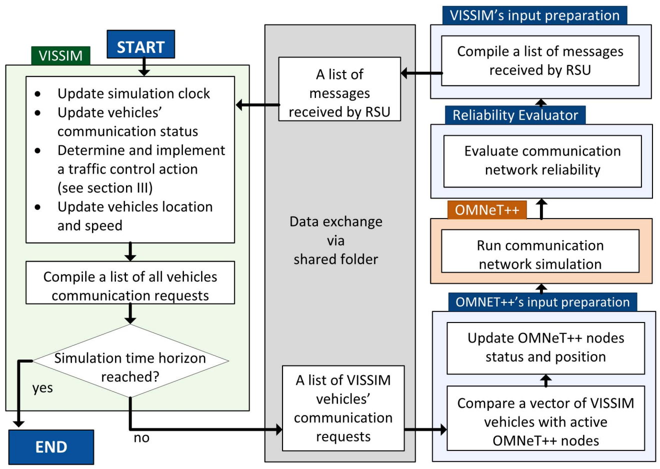

Fig. 1. Flowchart of the integrated traffic and communications simulation framework. Green and orange rectangles represent traffic and communication simulators, respectively. Blue rectangles represent auxiliary data processing and grey rectangles represent the data exchange platform.

generated. These requests are sent to the communications network simulation model. The model simulates the message exchange between the CVs and RSU within the same time step. It generates a list of communication messages that were successfully delivered to the RSU. The simulation clock is advanced and the received communications list is used by the traffic simulation model in the next time step. This loop continues until the simulation end time.

The implementation of the framework in this research used the VISSIM traffic simulation model. The traffic control algorithm described in Section III was implemented as an external computer program and integrated into VISSIM with VISCOM module (VISSIM Component Object Model). The Objective Modular Network Testbed in C++ (OMNeT++) was used to model the communication network. Communication protocols in OMNeT++ were simulated with the INET framework [21]. The exchange of information between the traffic and communication simulators was based on shared files.

B. Communication Network Modeling

The communication network model consists of three components: vehicles equipped with a communication module, communication channel and the RSU interconnected with the Intersection Controller (IC) as shown in Fig. 2. The following features are assumed for the communication network:

- Both the RSU and the vehicles use standardized IEEE 802.11p wireless interfaces operating in the 5.9 GHz frequency band as specified in ETSI EN 302 663 [22].
- The communication messages are transmitted using the IEEE 802.11p-based DSRC-VANET technology.
- All the vehicles and the RSU are mutually compatible and use standardized interfaces, communication protocols and messages.
- All network devices in the model use idealized omnidirectional antennas, which do not amplify the transmitter output or introduce any loss to the system.

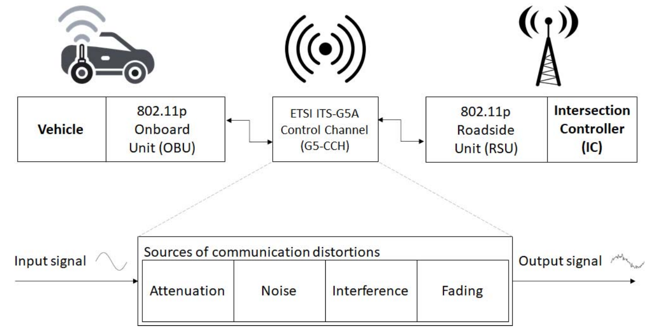

Fig. 2. Main components of the DSRC-VANET communication network and sources of communication distortions.

- Default DSRC-VANET data rate and underlying error protection mechanisms (e.g., modulation, channel coding) are used [22].
- All the vehicles are in a line-of-sight to an RSU antenna.
- The RSU and IC are connected via a wired link, which is assumed to be lossless, reliable and causing a negligible communication delay compared to the wireless links.

Each vehicle in the OMNeT++ simulations is represented by a compound module using IEEE 802.11 Physical (PHY) and Medium Access (MAC) layers. Each vehicle runs a User Datagram Protocol (UDP) application and uses standardized Cooperative Awareness Messages (CAMs) to transmit their telemetric data to the IC via RSU. Each vehicle sends the RSU one CAM per second to update the IC about its current state. To avoid MAC layer collisions, a start time of the first message transmission is selected randomly at the time when the vehicle enters the simulation. Subsequent messages are regularly transmitted with a separation of one second. This CAM generation frequency reflects the requirements determined by preliminary simulation experiments and complies with CAM generation frequencies specified in ETSI EN 302 637-2 [23]. Similarly, preliminary simulation experiments confirmed that it is sufficient if CAM transmissions occur in the close vicinity of the intersection, hence, the communication messages are sent directly from the vehicles directly to the RSU. Routing of messages via intermediate CVs is not considered. The wireless communication channel is an ETSI EN 302 663 [22] compliant Control Channel (CCH). The CCH is reserved for CAM broadcasts and safety-related V2X applications according to ETSI TS 102 724 [24].

Fig. 2 also shows the sources of communication distortions considered in the model, which may induce CAM message loss over the DSRC-VANET network. Besides natural attenuation, the quality of the communication can be affected by noise, interference and fading [25]. Noise is any unwanted fluctuation in a signal, which obstructs and masks the desired signal [8]. Interference signal sources may include frequency reuse, signals in adjacent channels with components outside their allocated frequency range or colliding transmissions coming from transmitters using the same channel/frequency band [25]. Fading is a variable attenuation of the signal that may result from obstacle shadowing, atmospheric disturbances, or multiple propagation paths of the signal.

In the model, the level of overall noise signals (both natural and man-made) in the communication channel is represented by background noise power level, which is kept constant in all simulation experiments. Signal attenuation experienced during its propagation over the communication environment is modelled by the Two-Ray Interference path loss model [26]. The level of signal distortion introduced by fading and interference is quantified by a Signal-to-Noise Ratio (SNR) penalty [27], which describes the change to SNR of the transmitted signals at the RSU compared to a baseline situation in which only background noise and signal attenuation are considered. The combined effect of fading and interference is modelled by varying the sensitivity of the receivers located at the RSU.

III. Traffic Signal Control Scheme

The focus of this research is on evaluation of possible impacts of communications distortions on traffic signal control performance. Therefore, it is advantageous to use a transparent control scheme with a clear set of rules that are easy to diagnose. The archetypical control used can also be easily adapted to include realistic constraints and additional modules for improved performance and fault redundancy. The heuristic traffic control logic used in this research is an extension of the algorithm proposed by [28]. It selects control stages and determines their durations in real-time using a weighted score functions that measure the current vehicle demand associated with each stage. The weights used in the score are higher for vehicles that are closer to the intersection aiming to prioritize them and increase overall throughput. Similar stage prioritizations were proposed, for example, in [29] and [30].

The basic principles and definitions of the traffic control logic are consistent with common practice. Vehicle movements at the intersection are organized in a set G of Signal Groups (SG). A subset of non-conflicting SGs that can receive green light at the same time constitutes a stage. For a more flexible control, a set of feasible stages S is defined. A SG can belong to one or more stages. The association of SGs $g \in G$ to a stage $s \in S$ is modeled by an incidence matrix B with entries $b(g, s)$, which take value 1, if SG g belongs to stage s and 0 otherwise. Both SGs and stages are pre-defined in the design process.

During signal operations, after each second, the control can either extend green to the current active stage or end it and switch to another one. This decision is based on the following conditions:

- The green period length of stage s is bounded by minimum (l_s^{min}) and maximum (l_s^{max}) values. A stage switch may not occur before the minimum duration is reached and is mandatory when the maximum duration is reached.
- The green time for the active stage is extended by one second, if the discharge flow is sufficiently high. Specifically, the green time is extended if the current headway h_g at the stop line (gap time) is smaller than a predefined threshold h^{max} for at least one of the lanes associated with the stage. Otherwise, the current stage is terminated and a stage switch is initiated.
- For safety reasons, an all-red inter-green period with a predefined duration is activated before a stage transition.
- A control cycle is used to limit the maximum possible delay to vehicles. All SGs with non-zero demand must receive green light and each stage can only be activated once within a cycle.

When stage is terminated, the selection of the next stage to switch to is based on a weighted demand score derived from the information received from CVs. It is assumed that all vehicles are connected and that they constantly transmit their telemetric data to the IC. This data includes their unique ID, location coordinates, speed, current lane and intended movement in the intersection. The IC identifies the current set C of vehicles that intend to cross the intersection. It assigns each CV $c \in C$, to the relevant SG. This assignment is captured by a matrix A with entries $a(c, g)$, which take value 1 if vehicle c is assigned to SG g and 0 otherwise. The IC than calculates the current distances d_{ct} of the CVs from the stop line and assigns them weights based on these distances:

$$w_{ct} = max\{0, 1 - \frac{d_{ct}}{d_{max}}\}. \tag{1}$$

where, w_{ct} is the weight of the vehicle c at time t. The parameter d_{max} is the maximum detection distance from the intersection.

The weighted scores w_{gt} are calculated as the sum of scores of the associated vehicles:

$$w_{gt} = \sum_{c \in C} w_{ct} a(c, g). \tag{2}$$

Finally, stage scores w_{st} are calculated as the sum of scores of the SGs that are active in the stage:

$$w_{st} = \sum_{g \in G} w_{gt} b(g, s). \tag{3}$$

When a stage is terminated, the algorithm will initiate a transition to the stage with the currently highest weighted score, denoted as w_s^{max}, on a condition that this stage includes at least one SG that has not yet been served in the current cycle. Thus, in most cases the green light is granted to the stage with the largest number of vehicles close to the stop line, which increases green time utilization and yields higher throughputs.

A control adaptation mechanism that updates the maximum green times for the next cycle is also implemented. This approach is a core principle in classic adaptive traffic control algorithms, e.g., SCATS [31] and aims to better accommodate current demands. The total maximum green time extensions over all stages is limited by a constant e to restrict the cycle length. When a stage is selected, the value w_s^{max} is stored in the memory. At the end of the cycle, the stored values are used to determine a proportion of the available green time extension allocated to each stage:

$$w_s^e = \frac{w_s^{max}}{\sum_{s \in S} w_s^{max}}. \tag{4}$$

The maximum length of stage green times used in the next cycle, are given by:

$$l_s^{max} = l_s^{min} + w_s^e e. \tag{5}$$

As shown in the literature review, most of the research on CV-based traffic control assumes full and perfect information is available. Therefore, mechanisms to handle communication distortions are missing. The first step towards overcoming this problem is to identify communication distortions. In each time interval, the RSU receives messages from CVs, which include their unique ID numbers. C_t is the list of these vehicles. The weighted scores for these vehicles are calculated based on their reported locations as described above. C_{t-1} is the list of the vehicles that communicated in the previous interval. Vehicles in C_{t-1} but not in C_t are suspected to have failed to communicate. The locations of these vehicles are extrapolated from their previous received reports. To simplify the extrapolation, it is assumed that they travel at a constant speed and do not change lanes, so that their position is constrained by that of their leader. Under these assumptions, the estimated current distance and speed of a CV are given by:

$$d_{ct} = max\{d_{c,t-1} - v_{c,t-1}, d_{c-1,t} + x_{min}\}, \quad (6)$$

$$v_{ct} = v_{c,t-1}. \quad (7)$$

where, v_{ct} and $v_{c,t-1}$ are the speeds of the vehicle in the current and previous time steps. $d_{c-1,t}$ is the position of the vehicle in front of vehicle c on the same lane. x_{min} is the minimum assumed distance between consecutive vehicles on the same lane.

Vehicles that are estimated to still be on the approach to the intersection ($d_{ct} >= 0$) are added the set C_t. $d_{ct} < 0$ implies that the vehicle crossed the intersection. If the light for its movement is currently green, the vehicle is not considered further. If the light is currently red, it is added the set C_t, and assumed to be at the stop line ($d_{ct} = 0$).

IV. Case Studies

The impact of communication distortions on the performance of the signal control is evaluated with two case studies. First, a single isolated intersection is used for thorough analysis. Then, the application is extended to a system of adjacent intersections.

The isolated intersection case study considers a generic four-legged intersection, as shown in Fig. 3. The traffic movements on each approach to the intersection are organized in two SGs: one for through and right turn (TR) traffic and the other for the left turn (L) traffic. These SGs are assigned to a total of eight possible stages, shown in Fig. 3.

The traffic demand volumes used in the simulations are presented in Table I. The demand is unbalanced with lower volumes on the North-South direction, and especially the North approach. These values reflect a degree of saturation of 0.77.

The values used for the traffic control parameters discussed in Section III are presented in Table II.

Parameter values used in the communications model and their sources are shown in Table III. Message length was set to 300 bytes to accommodate the payload data fields (position, driving lane and movement, distance to the intersection), the message header and authentication overhead. In general,

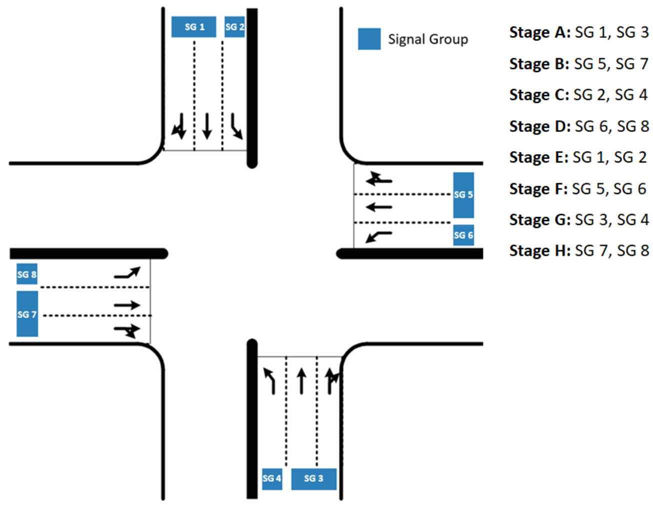

Fig. 3. Layout of the case study intersection with marked signal groups and the composition of signal stage.

TABLE I
Vehicle Flows at the Intersection

Approach	Signal Group	Volume [veh/hr]	Volume/ Capacity of critical signal groups
North	SG 1	213	
	SG 2	137	
South	SG 3	640	0.77
	SG 4	160	0.74
East	SG 5	648	
	SG 6	252	0.78
West	SG 7	748	0.78
	SG 8	102	

TABLE II
Traffic Control Parameter Values

Parameter	Description	Value
l_s^{min}	Minimum green time	6 s
I	Interstage duration	10 s
e	Total Available green extension	56s
h^{max}	Gap time	3 s
d_{max}	Maximum detection range	300 m

a single antenna may allow line-of-sight communication for all the intersection legs. Therefore, an RSU with an independent antenna, located above the stop line, for each of the four intersection legs was assumed.

The simulation experiments focus on three factors that affect the performance of the communications and traffic systems:

1. Communication environment - Three types of environments are considered: (i) A baseline condition assumes perfect communications with no failures. The traffic control algorithm works with the actual locations of all vehicles. This condition is used as a benchmark to the traffic impacts of imperfect communications. (ii) A homogenous

TABLE III
COMMUNICATION MODEL PARAMETER VALUES

Simulation model parameter	Value
Message generation frequency	1 s [23]
Message length	300 Bytes
Carrier frequency	5.9 GHz [22]
Communication channel bandwidth	10 MHz
DSRC-VANET maximum data rate	6 Mbps [22]
Permittivity of asphalt at microwave frequencies	4.75 [32]
RSU antenna height above the road surface	5.897 m
Vehicle antenna height above the road surface	1.895 m [26]
Transmitter power	20 dBm [33]
Background noise level	-86 dBm

communications environment condition assumes similar communication characteristics on all approaches to the intersection. This does not necessarily imply an equal information loss on every approach, as the dynamic spatio-temporal state of the CVs impacts communication reliability. (iii) A heterogeneous communication environment condition considers uneven communications characteristics. A higher level of channel degrading factors is assumed on the West approach to the intersection. This condition was designed to examine the impact of asymmetry in the quality of information about traffic flows on the performance of the traffic control.

2. The level of SNR penalty captures the combined effect of fading and interference in a challenging communication environment. Ref. [34] showed that the power offset of the received signal in the 5.9 GHz frequency band introduced by the fading, i.e., the SNR penalty, can be as high as 30 dB. In the simulation experiments this value is used as a worst-case with penalty levels of 0, 20, 25 and 30 dB. It is worth noting here that the combination of the highest value of the SNR penalty, i.e., 30 dB, and the background noise level represents a situation, where too many devices are broadcasting in the same bandwidth and very little or no effective information can be extracted from the corresponding communication. In the homogeneous communication environment, the same SNR penalty is applied to all the intersection approaches. In the heterogeneous communication environment, these SNR penalty values are applied only to the West approach. The other approaches face 0 dB SNR penalties. Thus, the homogeneous and heterogeneous communication environments are identical only when the SNR penalty is 0 dB.
3. Correction of communication distortions - Two variants of the control algorithm are considered: One that does not correct communication distortions, and the other that does, using the estimation approach described in Equations (6)-(7).

The combination of the values of these three factors defines a total of 15 conditions. For each condition, 10 independent simulation replications were run. Each run includes a 10 minute warm-up period used to populate the intersection with vehicles and a 30 minutes evaluation period.

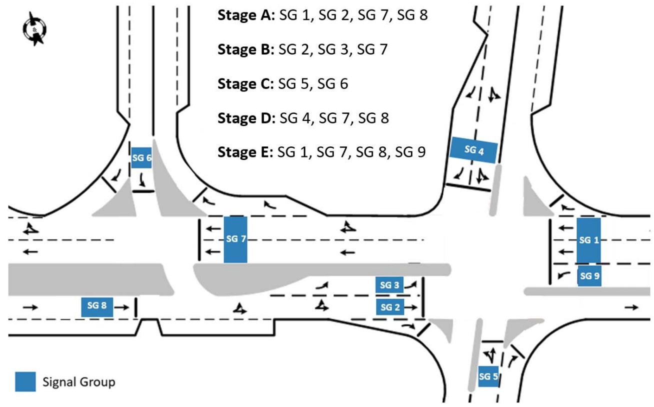

Fig. 4. Layout of the adjacent intersections showing SGs and signal stages.

The second case study extends the work to evaluate the effects of imperfect communications on the coordination between the two adjacent real-world intersections in Haifa Israel that are shown in Fig. 4. The intersections are 110 meters apart and are managed by a single controller. Coordination is achieved by appropriate sequence of the signal stages. SGs 6 and 8 are most vulnerable to possible lack of coordination, as a queue spillback from the buffer between two intersections (SG 2) might block their movement. Flows through this system operates at V/C of 0.9. Three communication scenarios were evaluated within this case study: A baseline condition with perfect communication and two conditions affected by 25 dB homogenous SNR penalties with and without correction for the communication distortions.

V. RESULTS

The performance of communication networks can be quantified by the message loss ratio (MLR), which is given by:

$$MLR = 1 - \frac{N^{rec}}{N^{snt}}, \tag{8}$$

where N^{snt} and N^{rec} are the numbers of sent and received messages, respectively.

Table IV shows the average MLR values for the various scenarios in the single intersection case and their standard deviations among simulation runs. Note that homogenous and heterogenous scenarios with same SNR penalties are not directly comparable, as in the latter, the more challenging communication conditions were applied only to the West approach. MLR values are shown for the whole intersection, as well as for the West approach and the other approaches separately. The results show substantial loss of messages in all cases. The loss is around 20%, with 0 dB SNR penalties and reaches almost 80% with 30 dB SNR penalties. These MLR results are consistent with the ranges reported by [12], [13]. The SNR penalties for different approaches are modeled independently, since it was assumed that each approach has a separate RSU antenna and interface. Thus, the MLR for the West approach is similar in the homogenous and the heterogenous scenarios, and the

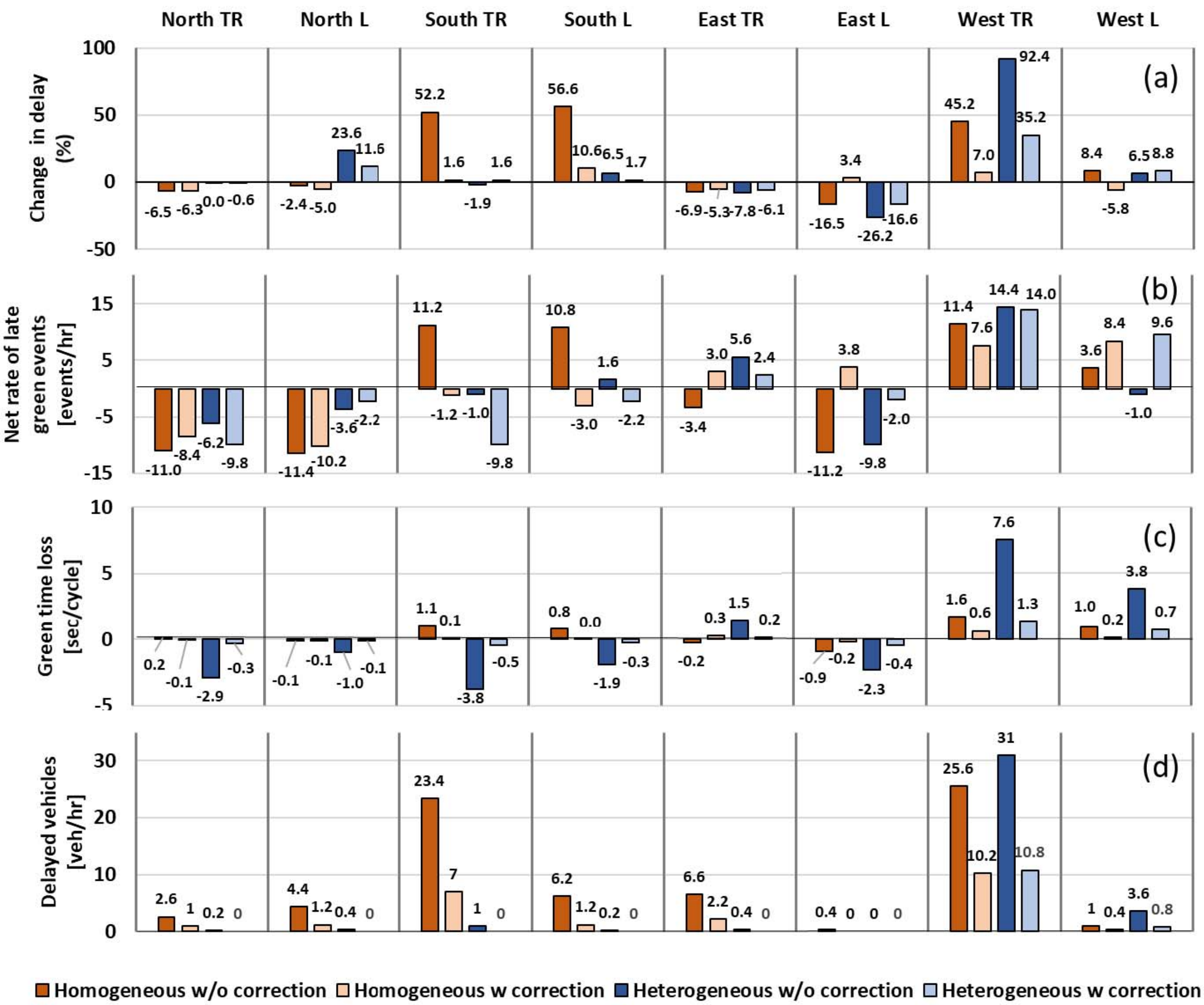

Fig. 5. (a) Change in delay; (b) Frequency of Late green time provision events minus frequency of Early green time provision; (c) Green time loss; (d) Number of delayed vehicles. (a)–(d) refer to scenarios with 30 dB SNR penalties compared to perfect communication scenarios.

values for the other approaches in the heterogenous scenarios are similar to those of the 0 dB homogenous scenario. Finally, it is noted that the MLR for the scenarios with communication distortion corrections are consistently lower than those for the scenarios without correction. These differences are statistically significant at all SNR penalty levels and are larger for the 30 dB condition. They may be attributed to the changed vehicular flow dynamics.

The communication distortions translate into degradation of the traffic system performance. Table V shows the average vehicle delays and their standard deviations in the various conditions. When the communication distortion correction is not applied, as the SNR penalty increases, initially only marginal and statistically insignificant increases in the vehicle delays over the baseline condition are observed. Only with the highest, but still realistic, 30 dB SNR penalty, the increase in delays is large (22.0% and 20.7%, for the homogenous and heterogenous conditions, respectively) and statistically significant. This suggests the existence of a critical MLR value beyond which traffic performance is strongly affected. With all SNR penalty levels, the delays are similar for the homogeneous and heterogeneous disruption conditions.

These results also demonstrate the value of implementing a correction mechanism for communication distortions, such as the one presented in the previous section. When these corrections are applied, the additional delays are reduced substantially. In the homogeneous disruption conditions, the delays are similar to those in the baseline scenario in all SNR penalty scenarios including the 30 dB SNR penalty, for which the delay is only 1.0% higher than the Baseline. In the heterogenous disruption conditions the delay reduction is smaller, especially for the high SNR penalties. With 30 dB SNR penalty, the delays are 7.5% larger than in the baseline.

To better understand how the communication distortions affect the signal control algorithm and its performance, further analysis of the worst-case scenarios with 30 dB SNR penalties was conducted. It was already shown in Table V that the overall delays increase in these scenarios. The effects on the various SGs are presented in Fig. 5. Fig. 5a shows the percentage change in average delays to the various SGs compared to the baseline condition, under four conditions: with heterogenous or homogenous communication conditions, and with and without applying correction for communication distortions. The results demonstrate that the change in delay is not uniform. Without the correction for the distortions, in the homogenous communication condition, the increase in delays is largest for the SGs from the South and West, while those from the East and North experience reduced delays. In the heterogenous communications condition, the West movements, which suffer the largest communication losses experience large delay increases, which are much larger than those experienced in the other approaches. Thus, the communication losses not only increase the overall delays, but they also change the distribution of the delays among the various SGs. Thus, the fairness of the green time allocation is negatively affected. In both environments, the correction mechanism reduces both the overall excess delays and the inequality in their distribution among the SGs. Most notably, in the heterogeneous condition, the additional delay to the West SG 7 reduces from 92.4% to 35.2%.

Message losses may affect the control algorithm due to three fundamental phenomena:

- The selected next stage at switching points when the current stage is terminated is the one with the highest score (see Eq. 3). Communication distortions may cause the stage with the highest demand not to be selected due to underestimation of its score. Thus, provision of green time to SGs within this stage is postponed and the delays to the relevant vehicles increase.
- The calculations of proportional scores w_s^e (see Eq. 4) may also be affected. When these are underestimated, shorter maximum green durations would be set in the next cycle. Thus, shorter green times may be available to high demand stages. When the proportional scores are overestimated, longer maximum green times will be allowed for stages that would not utilize them.
- Loss of communication with approaching vehicles may also result in a termination of the current stage when a demand for it is still sufficiently high to extend it.

Fig. 5b shows the rate of occurrence of situations where the next stage selected by the control algorithm is not the one that would have been selected under the perfect communication condition. As a result, some SGs receive green time later in the cycle than they should have, while others receive it earlier. The figure presents the net rate of such occurrences (late green times less early ones) for each SG. A correlation $R^2 = 0.68$ between these rates and SG delays shows their negative impact. As expected, the West SGs tend to receive late green more frequently in the heterogenous communications condition. However, there is no clear pattern on which SGs receive early or late green times in the homogenous communication conditions. In both cases, the communication distortions correction reduces these events by about 40% and improves the equality of their distribution among the SGs.

The effect of errors in the allocation of maximum green times to stages on the actual green times, is evaluated through calculation of the resulting green time loss to each SG. A stage loses green time, compared to the perfect communication condition, when all the following conditions are met: the maximum green time allocated to it is shorter than it should have been, the maximum green time is reached, and there is an additional demand that would merit an extension of this stage. In contrast, a stage gains green time when the actual green time for the stage exceeds the maximum green time that should have been allocated to it. Fig. 5c presents the green time losses and gains for the various SGs. As expected, in most cases, green time loss is associated with increased delay ($R^2 = 0.65$). Losses in the homogeneous communication conditions are small. In the heterogeneous communication conditions, the West SGs that suffer higher communication distortions lose substantial green times, while most other SGs gain green times. In both conditions, the introduction of the communication distortions correction substantially reduces the losses and gains: by 75% for the homogenous conditions and 83% for the heterogeneous conditions.

Finally, Fig. 5d shows the numbers of vehicles that are delayed an additional cycle because their stage is not extended when it should have been because of communication distortions. This type of event is strongly correlated with the delays in the various SGs ($R^2 = 0.82$). As with the other effects of message losses, the West approach is negatively affected in the heterogeneous communication conditions, while there is no clear pattern in the homogeneous communication conditions. The correction of communication distortions reduces the number of vehicles that are delayed a full cycle due to communication losses by 67% and 68% for the homogeneous and heterogeneous conditions, respectively. These delayed vehicles are also more evenly distributed among the stage groups.

TABLE IV
MLR VALUES AND THEIR STANDARD DEVIATIONS IN THE VARIOUS CONDITIONS

Condition	SNR penalty	MLR (%) and their standard deviations					
		Without correction			With correction		
		All	West	Others	All	West	Others
Homogenous	0	20.3 (0.25)	23.4 (0.68)	19.4 (0.32)	18.2 (0.29)	20.8 (0.90)	17.2 (0.37)
	20	36.9 (0.42)	42.3 (0.76)	35.4 (0.72)	34.9 (0.49)	39.6 (1.52)	33.0 (0.49)
	25	47.6 (0.46)	55.3 (1.31)	45.3 (0.58)	46.3 (0.57)	53.4 (1.20)	43.4 (0.70)
	30	64.7 (2.03)	74.7 (2.53)	61.4 (2.77)	60.8 (1.67)	71.3 (2.31)	56.6 (1.42)
Heterogenous	20	25.7 (0.44)	42.3 (1.40)	19.7 (0.32)	23.6 (0.42)	39.8 (1.01)	17.3 (0.33)
	25	29.9 (1.12)	54.6 (0.97)	19.8 (0.49)	27.6 (0.95)	53.5 (1.71)	17.1 (0.33)
	30	40.7 (2.35)	77.4 (2.81)	20.4 (0.31)	35.0 (2.46)	73.2 (2.69)	17.2 (0.38)

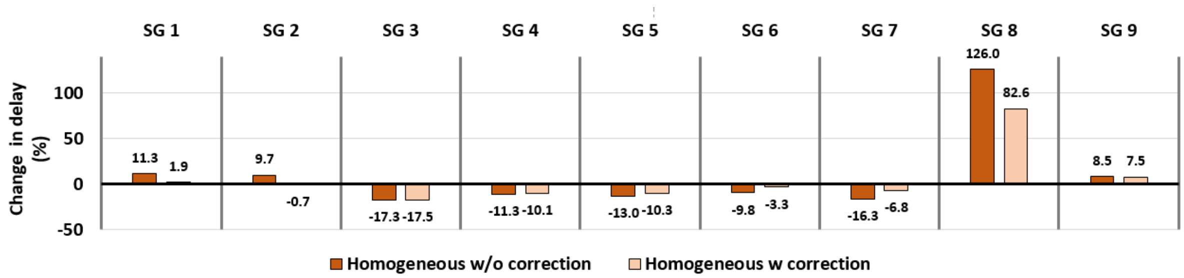

Fig. 6. Change in delay in the networked intersections case study with 25 dB SNR penalty compared to perfect communication scenario.

TABLE V

AVERAGE VEHICLE DELAYS AND THEIR STANDARD DEVIATIONS IN THE VARIOUS CONDITIONS

Condition	SNR penalty	Vehicle delays (sec.) and their standard deviations	
		Without correction	With correction
Baseline		40.6 (1.87)	
Homogenous	0	41.3 (2.86)	40.5 (2.58)
	20	40.0 (2.22)	40.5 (1.62)
	25	41.5 (2.69)	40.7 (1.75)
	30	49.5 (4.35)*	40.9 (1.70)
Heterogenous	20	41.5 (2.34)	40.7 (2.43)
	25	42.2 (3.01)	41.9 (2.64)
	30	49.0 (5.13)*	43.6 (2.76)*

* p-value < 0.05 for difference from baseline

TABLE VI

AVERAGE VEHICLE DELAYS AND THEIR STANDARD DEVIATIONS IN VARIOUS TRAFFIC DEMAND SCENARIOS

V/C Ratio	Vehicle delays (sec.) and their standard deviations		
	Baseline	Heterogeneous SNR penalty 30 dB w/o correction	Heterogeneous SNR penalty 30 dB with correction
0.77	40.6 (1.87)	49.0 (5.13)	43.6 (2.76)
0.90	42.1 (2.01)	65.5 (10.36)	47.7 (2.74)
0.98	49.9 (3.63)	117.1 (14.85)	75.4 (15.50)

TABLE VII

AVERAGE VEHICLE DELAYS AND THEIR STANDARD DEVIATIONS IN THE NETWORKED INTERSECTIONS

Vehicle delays (sec.) and their standard deviations		
Baseline	SNR penalty Without correction	SNR penalty with correction
41.7 (10.2)	55.4 (10.4)	50.3 (9.5)

As noted above, the traffic scenario reflects a V/C ratio of 0.77. Table VI shows the average vehicle delays and standard deviations for three V/C levels. In all cases, the delays increase non-linearly with the V/C ratio, as expected. The impact of communication distortions, represented by the gap between the second and rightmost columns also increases non-linearly increases as V/C approaches a unit. In the perfect communications baseline, delays increased by 23% from the lowest V/C to highest one. But, with high SNR penalty the equivalent delay increase is 73%. The reduction in additional delays to vehicles due to application of the correction mechanism is similar: 64% and 63% in the lowest and highest V/C ratio conditions, respectively. However, These are more meaningful when flow approaches capacity, where they represent a reduction of 41.7 seconds compared to only 4.9 seconds in the lowest V/C ratio condition.

The delay results for the case of adjacent intersections, which are presented in Table VII are similar in their trends. Communications distortions increase the average delay by 33% compared to the baseline. The introduction of the correction algorithm eliminates 38% of the additional delays. Still, vehicle delays in this case are still 21% higher than in the baseline.

The detailed effects on the various SGs are presented in Fig. 6. SG 8 includes the main movement that cross the two intersections and is most vulnerable to the effects of communication distortions. It experiences a large increase in delays due to suboptimal selection of stages, shorter maximum green duration and premature termination of its green extension. The other SGs, including SG6, did not experience similar changes and in some cases even benefitted from the communication distortions. Thus, the increased delays are also unfairly allocated among the various road users. The figure shows that the correction mechanism decreases both the overall additional delays and the fairness of their allocation, as the reduction in delays is especially large for SG 8.

VI. CONCLUSION

This paper investigated the effect of communication distortions in CV environments on the performance of a signalized intersection control. Communication distortions have been previously ignored in the literature. A model system that integrated a traffic flow model with a communication model was developed and applied to two intersection control case studies. The case studies show that, using the standard DSRC-VANET communication network, a large fraction of messages may be lost. However, the control algorithm is relatively robust to these loses, even if their fraction is high. Still, when the lost messages fraction exceeds a critical level, about 75% in the case study, vehicle delays increase dramatically. The negative impact of communication failures is also amplified when the flows through the intersection approach its capacity. The trend of increased delay due to message loss is largely independent of whether all the approaches to the intersection experience similar communication distortions. The effects do not cancel out when all approaches experience similar message losses. Furthermore, the increases in delays are not evenly split among the various movements in the intersection. Hence, the fairness of allocation of green times and the resulting delays are reduced.

The control algorithm was enhanced to incorporate a mechanism to correct for message failures, which is based on previously received messages from the vehicles and simple assumptions about their movements. This correction mechanism was able to significantly reduce vehicle delays, especially in the case of homogenous communication distortions. Analysis of the additional delays to vehicles shows that they are highly correlated to all the various incorrect actions that are taken due to communication distortions. These include wrong selection of a next stage, errors in determination of maximum green times and premature termination of green times. The impact of the ability to correct for communication distortions larger when the intersection operated under more saturated conditions. Application of this mechanism can also be used to reduce the reliability or V2I communication volumes requirements within the communication system technical design.

These conclusions provide a basis for several directions of future research. A higher applicability of the results can be achieved by improving the understanding of the minimum required information (i.e., the frequency of the sent CAM messages and the acceptable MLR) that guarantees sufficient performance of the intersection control. Research is also needed to identify methods to improve the communication reliability of C-V2X networks such as LTE or 5G.

Improved and more robust algorithms to correct the control for communication distortions, for example by applying more sophisticated interpolations of vehicles' position, such as the one described in Ref. [35], could be developed and evaluated. Given the results concerning the increased impact of communication failures as the volume approaches capacity, integrating shockwave behavior into the correction algorithm for better representation of vehicles' queueing and discharging movements may help improve the quality of control decisions.

The results may also be extended to networks of coordinated traffic signals. The negative effects of communication distortions on traffic flow within signalized networks may be magnified for two reasons: First, signal coordination reduces the flexibility to adapt control settings in real time compared to isolated intersections. Second, intersections that are relatively close may also experience spillbacks, as seen in the presented case study. The control in these settings should therefore exploit the availability of additional information from communication devices throughout the sub-network for data completion. The impact on other methods for signal control, such as those based on control theory, artificial intelligence or game theory could be investigated and appropriate correction mechanisms be designed.

The current research addressed networks with only CVs. Further research should consider varying CV penetration levels, integrating messages from CV with detection techniques for vehicles without OBU, and their impacts on traffic delays. Furthermore, communication failures may occur not only from natural distortions, which were considered in this paper, but also from cyberattacks and other intentional sources. These require not only enhancements to the control algorithm itself, but also design of methods to identify attacks and malicious entities.

Finally, it is noted that the case studies presented in this study were based on DSRC technologies as an example. The underlying reasons causing communication distortions and resulting in additional traffic delays would also exist with C-V2X technologies. Nevertheless, there are differences in communication frequency bands and sources of interference. C-V2X deploys licensed or dedicated frequency band, which often implies less sources and lower levels of the interference compared to DSRC. However, it should also be noted that the baseline performance of C-V2X under ideal communication conditions is inferior to that of DSRC in the context of V2I [36], which would negatively affect its realistic performance.

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Ilya Finkelberg received the M.Sc. degree from the Technion—Israel Institute of Technology in 2012. He has been a Researcher and a Traffic Engineer with the Transportation Research Institute since 2008. He specializes in traffic management and urban mobility applied research. He is a member of the Development Team of AVIVIM–traffic management system of Tel Aviv and Haifa municipalities.

Tibor Petrov received the PhD. degree in telecommunications from the University of Žilina in 2018. He is currently a Researcher in intelligent transport systems with the Department of International Research Projects–ERAdiate+, University of Žilina. His research activities include vehicular and cellular communication networks, vehicular network applications, and computer modeling of cooperative intelligent transportation systems.

Ayelet Gal-Tzur received the B.Sc. and M.Sc. degrees in industrial and management engineering and the D.Sc. degree in traffic management from Technion, Israel. She is leading the Traffic Mobility Research Team at the Transportation Research Institute, Technion, and she is also a Senior Lecturer at the Ruppin Academic Center. Her research focuses on sustainable mobility and urban traffic management with particular interest in ICT-based information sources, decision support methodologies, and big data analytics in transportation.

Nina Zarkhin received the B.S. and M.A. degrees in applied mathematics from the Faculty of Computer Science, Technical University of Kazan, Russia. She has been a member of the Urban Mobility Research Team at the Transportation Research Institute, Technion, since 2007. She took part in various traffic mobility research projects, including CONDUITS project in collaboration with several European municipalities. Her focus is on the software development aspect of traffic mobility applications and methodologies.

Peter Počta received the M.S. and Ph.D. degrees from the Faculty of Electrical Engineering, University of Žilina, Slovakia, in 2004 and 2007, respectively. He is currently a Full Professor with the Department of Multimedia and Information-Communication Technologies, University of Žilina, and is involved with international standardization through the ETSI TC STQ as well as ITU-T SG12. His research interests include speech, audio, video, and audiovisual quality assessment; speech intelligibility; multimedia communication; and QoE management.

Tatiana Kováčiková has been the Head of ERAdiate+ at the University of Žilina, Slovakia, since July 2019. From October 2017 to June 2019, she was the ERA Chair Holder for Intelligent Transport Systems (ITS) at the University of Žilina. In 2016, she was nominated as the National Delegate for H2020 PC on Smart, Green and Integrated Transport. She has been active in ICT&ITS standardization for more than 15 years, currently she represents Slovakia in CEN TC 278 on ITS. From June 2013 to October 2015, she held the position of the Head of Science Operations at the COST Association in Brussels. In 2013, she was appointed as a Full Professor in applied informatics. Her research interests include ICT and intelligent transport systems (ITS), in particular network architectures, services, and applications.

Ľuboš Buzna received the Ph.D. degree from the University of Žilina in 2003. In the past, he worked as a Post-Doctoral Researcher at several institutions, including the University of Barcelona, ETH Zürich, and TU Dresden. He is currently a Professor of applied informatics with the University of Žilina. His research is focused on the development of the optimization algorithms applied to transportation and other complex systems.

Milan Dado (Senior Member, IEEE) is currently a Full Professor with the Department of Multimedia and ICT, University of Žilina. He has been actively involved in European research and education programs (TEMPUS, COST, LEONARDO, Socrates, 5th, 6th, and 7th Framework Program, H2020, European University association projects) and has managed national projects related to information and communication technologies, intelligent transportation systems, regional innovation strategies, and e-learning. Main milestones for his international activities were stays abroad, e.g., two-month stay at the York University, Canada, Northern Telecom, and Bell Canada in 1993; and six-month stay at the KTH Royal Institute of Technology, Stockholm, in 1990, and the Vienna University of Technology from 1981 to 1982. He has visited many other foreign institutions during last 30 years.

Tomer Toledo received the B.Sc. and M.Sc. degrees in civil engineering from Technion and the Ph.D. degree in transportation systems from MIT. He is currently a Professor with the Faculty of Civil and Environmental Engineering and the Transportation Research Institute, Technion—Israel Institute of Technology. His research focuses on driver behavior, traffic modeling and simulation, intelligent transportation systems, and transportation network analysis.