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**Mgr. Peter Lehoczký**

# Dissertation Thesis Abstract

QoS Management in Communication Networks

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|---|---|
| **Submitter:** | Mgr. Peter Lehoczký<br>Faculty of Informatics and Information Technologies<br>Slovak University of Technology<br>Ilkovičova 2, 84216 Bratislava |
| **Supervisor:** | prof. Ing. Ivan Kotuliak, PhD.<br>Faculty of Informatics and Information Technologies<br>Slovak University of Technology<br>Ilkovičova 2, 84216 Bratislava |
| **Consultants:** | doc. Ing. Rastislav Bencel, PhD.<br>Faculty of Informatics and Information Technologies<br>Slovak University of Technology<br>Ilkovičova 2, 84216 Bratislava |


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prof. Ing. Ivan Kotuliak, PhD.
Dean of the Faculty of Informatics and Information Technologies

# Abstract

Although vehicular networks have been studied for decades, reliable message delivery in such dynamic environments remains a complex challenge. Meeting strict requirements for throughput and latency—needed for both safety-related and general services—is difficult with any single wireless access technology, as each has its own limitations under varying conditions. Combining multiple communication technologies into a heterogeneous network can better address these demands, but selecting the right technology for each situation requires careful decision-making and management.

In this work, we propose a practical solution for intelligent message delivery in vehicular networks leveraging heterogeneous networking enhanced by historically measured cellular network quality data. The core of the approach is a message delivery algorithm that dynamically selects between direct V2V communication and cellular relays based on current network conditions and historical network performance metrics. The proposed solution utilizes network quality data collected via our custom-designed data collection architecture, enabling informed decision-making regarding the optimal communication technology. An important aspect of this work, verified through statistical modeling based on real-world data, is the improvement of network switching stability. This helps in mitigating unnecessary technology transitions, optimizing network utilization, and enhancing the reliability and efficiency of data delivery, particularly for safety-critical and time-sensitive applications in dynamic vehicular network environments.

The proposed algorithm was formally verified using Coloured Petri Nets. Empirical evaluation was then performed using real-world network quality data from our publicly available dataset, which we developed as part of this research. The results suggest that the proposed approach achieves stable communication in dynamic vehicular network conditions. The presented solution integrates both the data collection architecture and the dynamic technology selection algorithm into a unified framework for improving vehicular network communication.

# Abstrakt

Hoci boli vozidlové siete predmetom výskumu už celé desaťročia, spoľahlivé doručovanie správ v tak dynamickom prostredí zostáva náročnou úlohou. Splnenie prísnych požiadaviek na priepustnosť a latenciu – potrebných pre bezpečnostné aj všeobecné služby – je ťažko dosiahnuteľné pomocou jednej bezdrôtovej prístupovej technológie, keďže každá má v rôznych podmienkach svoje obmedzenia. Kombinácia viacerých komunikačných technológií do heterogénnej siete dokáže tieto požiadavky riešiť efektívnejšie, avšak výber vhodnej technológie v každej situácii si vyžaduje premyslené rozhodovanie a správu.

V tejto práci navrhujeme praktické riešenie pre inteligentné doručovanie správ vo vozidlových sieťach, ktoré využíva heterogénne prepojenie rozšírené o historicky namerané údaje o kvalite mobilnej siete. Jadrom prístupu je algoritmus doručovania správ, ktorý dynamicky volí medzi priamou V2V komunikáciou a sprostredkovaným prenosom cez mobilnú sieť na základe aktuálnych sieťových podmienok a historických ukazovateľov výkonnosti siete. Navrhované riešenie využíva údaje o kvalite siete získané pomocou nami navrhnutej architektúry na zber dát, čo umožňuje informované rozhodovanie o optimálnej komunikačnej technológii. Dôležitým aspektom tejto práce, overeným štatistickým modelovaním na reálnych dátach, je zlepšenie stability prepínania medzi sieťami. To prispieva k obmedzeniu zbytočných prepnutí technológií, optimalizuje využitie siete a zvyšuje spoľahlivosť a efektivitu prenosu dát, najmä pre bezpečnostne kritické a časovo citlivé aplikácie v dynamických vozidlových sieťach.

Navrhovaný algoritmus bol formálne overený pomocou Farebných Petriho sietí. Empirické hodnotenie bolo následne realizované na reálnych údajoch o kvalite siete z nami publikovaného datasetu, ktorý bol vyvinutý v rámci tohto výskumu. Výsledky naznačujú, že navrhovaný a modelovaný prístup dosahuje stabilnú a efektívnu komunikáciu v dynamických podmienkach vozidlových sietí. Predstavené riešenie integruje architektúru na zber dát a algoritmus pre dynamický výber technológie do jednotného rámca na zlepšenie komunikácie vo vozidlových sieťach.

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## Chapter 1

# Introduction

Transportation systems increasingly depend on timely and reliable exchange of information between vehicles, roadside infrastructure, and traffic management services. Cooperative Intelligent Transport Systems require low end-to-end latency and high delivery reliability under conditions that vary quickly across urban, suburban, and highway environments. Experience and surveys concur that no single wireless technology consistently satisfies these constraints across all contexts; performance is shaped by channel dynamics, interference, mobility, and highly heterogeneous coverage. Direct short-range communication such as IEEE 802.11p and cellular systems (LTE/5G with C-V2X) bring complementary strengths. However, broadcast-centric dissemination over contention-based media is prone to congestion and redundant re-transmissions that inflate latency and diminish effective capacity for time-critical messages. Limiting unnecessary broadcast overhead is therefore an essential lever for improving timeliness and reliability [1]. In parallel, standardization has clarified Vehicle-to-Everything (V2X) service requirements and architectural capabilities for 5G systems—unicast, groupcast, and multicast/broadcast support, as well as the placement of V2X application servers—providing a reference frame for deployable designs [2, 3, 4]. Recent studies on heterogeneous V2X likewise motivate combining multiple access technologies and selecting the delivery mode per context [5, 6, 7].

This dissertation responds to these conditions with a framework for context-aware message delivery across heterogeneous networks, targeting practical integration with standard-compliant V2X deployments. The central idea is to integrate real-time indicators with historical, location-specific information on cellular network quality, thereby enabling delivery decisions—between direct V2V and cellular communication—that align with the requirements of individual messages while minimizing unnecessary network load. The work therefore begins with a vehicle-centric measurement methodology tailored to driving scenarios, capturing cellular quality indicators alongside precise localization on real roads and aligning them to the road topology to form historical quality maps. These maps reflect spatial regularities and recurrent impairments that are not evident from instantaneous measurements alone, enabling informed decisions at points where coverage or interference patterns are known to shift.

On top of this data foundation, the dissertation specifies a decision algorithm that fuses real-time context with the historical maps to choose between direct and cellular delivery modes with the explicit goal of meeting low-latency and reliability targets while curbing redundant re-broadcast in broadcast-heavy patterns. The algorithm is modeled and verified using Coloured Petri Nets (CPN). The CPN model verifies (within the modeled abstractions) deadlock-freedom, and bounded behavior of the forwarding mechanism in representative scenarios before any empirical assessment. Because heterogeneous quality can induce pathological oscillations between technologies, the work further develops a Continuous-Time Markov Chain (CTMC) model to analyze switching stability under empirically derived regimes, reporting steady-state occupancy and switching metrics. The CTMC serves as a practical baseline; deviations from exponential holding times and low-confidence estimates in specific regimes are noted.

An empirical evaluation then examines whether switching behavior remains well-behaved in practice. The evaluation uses measurements collected on Slovak roads and leverages a public dataset that couples continuous camera recordings with mobile-network telemetry and high-precision localization, enabling reproducible analysis in realistic conditions [8]. The framework and its assumptions are positioned with respect to the capabilities and service expectations captured in the relevant 3GPP specifications for V2X communication in 5G [2, 3, 4].

Prior outputs published by the author and collaborators provide context for the present integration. They include an assessment of Slovak road infrastructure readiness for intelligent transportation deployment [9], and a study of road-segment compliance with 3GPP-motivated requirements [10]. The released dataset of camera and telemetry recordings supports reproducible benchmarking in real traffic [8], and complementary perception research on ultra-fast visible lane-distance estimation with a single camera informs the broader environment understanding [11]. Building on these strands, the dissertation consolidates measurement, decision-making, and validation into a coherent framework centered on historical quality maps and context-aware delivery.

For clarity, the main technical contributions are as follows:

1. a practical road-measurement and mapping pipeline that allows collection of cellular performance metrics aligned to the road network for downstream decision support;

2. a context-aware message delivery algorithm that fuses real-time indicators with historical cellular network quality and selects between direct and cellular modes while explicitly limiting redundant broadcast overhead;

3. formal verification of the algorithmic core using Coloured Petri Nets to ensure control-flow correctness and eliminate classes of behavioral defects before field evaluation;

4. a CTMC-based analysis of switching stability that quantifies selection dynamics under empirically derived regimes and identifies conditions associated with low switching intensity.

## Chapter 2

# Objectives

The aim is to achieve reliable and timely delivery of safety-relevant information in heterogeneous, time-varying road environments while minimizing unnecessary wireless load. The solution is designed to operate with realistic measurement inputs and to remain compatible with the V2X service requirements and architectural assumptions codified for 5G systems [2, 3, 4]. From this framing, the objectives follow naturally. First, the approach should reduce redundant broadcast traffic in contention-based media so that capacity is preserved for time-critical messages and latency inflation is mitigated. Second, it should improve delivery reliability and timeliness by adaptively selecting between direct (V2V) and cellular modes using a combination of real-time indicators and historically observed cellular quality.

To make these objectives concrete and reproducible, the work defines tasks aligned with the overall architecture. A road-measurement pipeline is specified and deployed to capture cellular quality indicators and precise localization along driven routes, producing historical quality maps aligned to road segments for use in decision-making. A context-aware algorithm is then designed to fuse instantaneous context with the historical maps and to choose the delivery mode in accordance with message requirements such as latency target and intended dissemination range, while incorporating mechanisms that limit redundant re-broadcast in broadcast-heavy patterns. The algorithmic core is modeled in Coloured Petri Nets to verify control-flow correctness and absence of deadlocks prior to field trials. Switching behavior across heterogeneous conditions is modeled with a Continuous-Time Markov Chain constructed from empirically derived quality regimes to quantify expected switching rates and residence times and to demonstrate stability under noise. Finally, the system is evaluated on real roads using the collected measurements and the publicly released dataset [8], focusing on switching-stability metrics derived from measured road segments (steady-state occupancy, switch intensity, mean time between switches).

Success is demonstrated if, across representative operating regimes in real traffic, the approach reduces redundant broadcast traffic compared with naïve dissemination and maintains switching stability consistent with the CTMC analysis, while remaining practically implementable within a standard-compliant V2X ecosystem. The work does not aim to replace underlying radio stacks or to introduce a universal routing protocol; rather, it contributes a decision layer that leverages historical cellular quality to select among existing delivery modes in a manner that is compatible with standard architectures and supported service models.

## Chapter 3

# Methods and Design

The work develops a framework that combines on-road measurements with context-aware decision making to select between direct short-range transmission (V2V) and cellular delivery so that safety-relevant messages are delivered reliably and on time while avoiding unnecessary wireless load. The design begins with a vehicle-centric measurement methodology in real traffic that records standard cellular quality indicators alongside precise localization. Measurements are aligned to the road topology (and optionally aggregated) to form historical quality maps that capture location-specific expectations of cellular performance. This historical layer complements instantaneous indicators obtained at the time of transmission and enables decisions that look beyond momentary fluctuations. Prior studies on readiness and parameterization in vehicular contexts motivate the choice of indicators and the road-segment representation and provide empirical grounding for the mapping approach [9]. The overall direction follows heterogeneous networking in vehicular communication, where multiple access technologies are combined and the delivery mode is chosen per context [5, 6, 7].

Table 3.1 defines the cellular quality classes used by the maps and by the decision logic. The classes are derived from the measurement pipeline and express expected latency regimes at the segment level.

On top of this data foundation, the message-delivery algorithm operates as a lightweight decision layer above existing communication stacks. It consumes message descriptors and context, including the intended dissemination characteristics and the sender's position, combines these with the historical quality expected for the current road segment, and produces a delivery choice together with a broadcast-control action.

Table 3.1: Cellular network quality classification

| Class | Description | Latency |
|---|---|---|
| **RED** | Cellular network is unavailable or the measured latency is too high for practical vehicular applications. | $> 500$ ms |
| **ORANGE** | Cellular network is available, but expected latency is usable only for basic vehicular use cases. | 100–500 ms |
| **GREEN** | Cellular network is available and meets requirements for selected advanced vehicular applications. | $< 100$ ms |

The design aims to respect latency/reliability targets and to limit redundant re-broadcast in contention-based patterns (these are design objectives rather than outcomes measured in the evaluation), since broadcast-centric contention otherwise inflates latency and reduces effective capacity [1]. The algorithm targets practical integration with standard-compliant V2X deployments (without altering lower-layer protocols), and it is framed against service requirements and architectural capabilities captured in 3GPP specifications, which define the roles and communication modes applicable to vehicular applications [2, 3, 4].

The decision logic combines the map-derived network quality class with the message's dissemination intent and simple real-time cues to select a single delivery mode per message. Table 3.2 summarizes the rule structure exactly as used in the thesis, including how short/long range and short visibility affect the choice among DIRECT, CELLULAR, and BOTH.

Inputs to the decision therefore include (i) message requirements that determine timeliness and dissemination range, (ii) current geographic context and road-segment identity, (iii) instantaneous indicators available to the sender, and (iv) the historical cellular quality associated

Table 3.2: Network technology selection logic overview

| Network Quality | Decision Logic |
|---|---|
| **RED** (Cellular unavailable) | → Use **DIRECT only** |
| **ORANGE** (Cellular available, but low quality) | → Use **DIRECT** primarily<br>→ Also use **CELLULAR** when SHORT visibility |
| **GREEN** (High quality cellular) | → Use **CELLULAR** for LONG-range messages<br>→ Use **BOTH** for SHORT-range messages in case of SHORT visibility<br>→ Also use **DIRECT** if any part of the message range lies outside the GREEN zone |

with the present segment and its neighbors.

To avoid cases where the sender is in GREEN but part of the addressed footprint is not, the decision looks at the entire delivery footprint from the origin up to the requested range boundary. CELLULAR-only is used only if all segments in that footprint are GREEN; if any segment is ORANGE or RED, the sender includes DIRECT—or BOTH under SHORT visibility—to cover the non-GREEN part (see Table 3.2). This complements the local smoothing by the present segment and its neighbors with a global “all-GREEN” check over the addressed area.

The algorithm produces two coupled outputs: the selected delivery mode—direct or cellular, with the possibility of using both where indicated—and a broadcast-control action that reduces unnecessary rebroadcasts when direct dissemination is chosen. The control action rests on duplicate awareness and restrained forwarding so that nodes that have already observed sufficient coverage do not re-inject messages needlessly. The use of historical quality is crucial for predictable behavior; if the present segment is known to present impaired cellular coverage, the algorithm avoids costly retries in the cellular path and prioritizes direct dissemination, whereas in segments with consistently strong cellular performance it prefers cellular relaying to spare the contention-based channel and meet end-to-end targets.

To conclude, this chapter specified the decision logic—its inputs, the segment-level cellular-quality maps, and the rule set in Table 3.2—that yields a delivery mode (DIRECT, CELLULAR, or BOTH) together with a broadcast-control action. The next chapters formalize the procedure with a Coloured Petri Net to check control-flow properties within the modeled scope and evaluate switching stability on road measurements using CTMC-derived metrics.

Chapter 4

# Formal Verification and Stability Modeling

The decision layer is first checked with a Coloured Petri Net (CPN) model to check sound control flow and bounded behaviour before field evaluation. A complementary Continuous-Time Markov Chain (CTMC) then captures the stability of technology selection under heterogeneous cellular quality derived from measurements. Together, these two approaches show that the algorithm follows the intended logic and does not oscillate pathologically when conditions vary.

## 4.1 Coloured Petri Net verification

The model represents vehicles, messages, and the road as coloured tokens flowing through decision and delivery stages. Road topology is abstracted into $N$ segments; each segment carries a cellular-quality zone (GREEN, ORANGE, RED) representing the historical maps used by the algorithm. Messages carry the range class (SHORT/LONG), a requested delivery distance (in segments), origin segment, and the network type over which they were last received. Vehicle movement during exploration is not modelled; the focus is on correctness of selection and forwarding behaviour across reachable configurations of segment qualities and placements.

The net distinguishes idle vehicles, messages in the air via DIRECT or CELLULAR, and inbound processing at receivers. Transition guards

Table 4.1: State-space exploration by number of road segments $N$.

| $N$ | States | Arcs | Time [s] | Bounded | No inf. seq. |
|---|---|---|---|---|---|
| 3 | 26 428 | 37 617 | 47 | Yes | Yes |
| 4 | 158 101 | 240 162 | 812 | Yes | Yes |
| 5* | 365 828 | 767 767 | 99 999* | Yes | Yes |

*Note:* *Partial exploration for $N$=5 (stopped before completion).

encode the selection logic that fuses the current segment's quality with the message range. Broadcast control is represented by restrained forwarding and duplicate awareness: receivers add the message to their seen set and forward only when policy rules allow it.

For state-space exploration, parameters are set to scaled values that make complete analysis feasible on desktop hardware while preserving the decision structure. Full exploration completes for $N \in \{3, 4\}$ road segments; $N \geq 5$ shows the expected combinatorial growth and is reported as partial. Across explored configurations the net is bounded, with no infinite occurrence sequences.

These results suggest that the executable decision logic terminates under the modelled assumptions, the net remains bounded, and pathological cycles are absent at the resolution of this model. The abstraction currently omits vehicle motion, explicit timing, and probabilistic delivery; these can be added (e.g., timed transitions or loss processes) without changing the core decision structure.

## 4.2 Stability modelling with a Continuous-Time Markov Chain

To quantify how often the selected technology would change under realistic heterogeneity, a CTMC is fitted from measured sequences of quality zones along representative roads. Each state captures the effective delivery regime implied by the zone and range rules; transition rates are estimated from observed zone transitions. From the generator one obtains the steady-state distribution $\pi$ and the overall switching intensity $\Lambda$ (the sum of leaving rates). The mean time between switches follows as $1/\Lambda$, and for a decision interval $\tau$ seconds the probability of at least one zone-driven switch is

$$P_{\text{switch}}(\tau) \;=\; 1 - e^{-\Lambda\tau}.$$

The corresponding steady-state occupancy, switching intensity, mean time between switches, and short-horizon switch probabilities are reported per route in Chapter 5.

Suitability of the exponential holding-time assumption is examined with QQ plots and a Lilliefors-style check applied to reconstructed dwell-time samples. Departures from the exponential appear in parts of the data (longer-than-exponential tails for some zones), which is consistent with the intended use of the model as a large-scale stability summary rather than a micro-scale predictor. Considering the CTMC as a practical baseline model that captures the overall trends, it provides consistent steady-state estimates and switching intensities across repeated drives and supports the interpretation of selection stability established by the decision logic.

## Chapter 5

# Empirical Evaluation

This chapter evaluates whether a context-aware decision layer that leverages historically observed cellular network quality can operate stably in realistic road environments. The evaluation uses on-road measurements gathered with the vehicle platform described in the thesis and a publicly released dataset that couples continuous camera recordings with mobile-network telemetry and high-precision localization, providing reproducible inputs from Slovak roads [9, 8]. The analysis focuses on stability of technology selection under heterogeneous conditions rather than on micro-level radio effects.

## 5.1 Data and road contexts

Road measurements are aligned to the road topology and aggregated into segment-level historical quality maps. Three representative routes are used to cover typical operating regimes established elsewhere in the thesis: *C1* as a first-class road with largely flat surroundings and sparse obstacles, *C2* with elevation changes and forested sections interleaved with a village, and *D1* as a highway segment with mostly unobstructed surroundings [9]. Each segment is assigned one of the empirically derived cellular-quality zones (GREEN/ORANGE/RED) used by the decision logic in Chapter 3.

## 5.2 Evaluation scope and method

The decision problem is to map the present segment's historical quality and instantaneous indicators to a single delivery mode (DIRECT or CELLULAR, with BOTH where indicated in Chapter 3) so that message requirements are respected while redundant re-broadcast is curbed. Because heterogeneous quality can induce frequent technology toggling, the environment dynamics are summarized with a Continuous-Time Markov Chain (CTMC) constructed from measured sequences of zone labels along each road. From the fitted generator, the evaluation reports the steady-state distribution over zones and the overall switching intensity. The mean time between switches and the probability of at least one switch in a short time window follow directly:

$$\mathrm{MTBS} = \frac{1}{\Lambda}, \qquad P_{\mathrm{switch}}(\tau) = 1 - e^{-\Lambda\tau}.$$

These metrics quantify the stability context in which the decision layer operates.

## 5.3 Results

Table 5.1 summarizes the steady-state occupancy and the overall switching intensity for routes C1, C2, and D1. C1 and D1 spend most of the time in the best zone, with modest switching; C2 exhibits more frequent regime changes. The corresponding timing metrics are listed in Table 5.2.

The stability context indicated by Tables 5.1 and 5.2 supports the intended operation of the decision layer. On C1 and D1, long residence in the favourable zone is consistent with prioritizing CELLULAR where it is historically strong; on C2, more frequent regime changes justify relying on DIRECT more often where cellular quality is historically impaired, while still using CELLULAR when conditions allow. This aligns with the decision logic specified in Chapter 3.

Table 5.1: CTMC steady-state distribution and switch intensity per route.

| **Route** | $\pi_G$ | $\pi_O$ | $\pi_R$ | $\Lambda$ [$s^{-1}$] |
|---|---|---|---|---|
| C1 | 0.898 | 0.085 | 0.018 | 0.03096 |
| C2 | 0.789 | 0.194 | 0.017 | 0.0565 |
| D1 | 0.915 | 0.062 | 0.023 | 0.02099 |

Table 5.2: CTMC timing metrics per route.

| **Route** | Mean time between switches | Switch probability within 10 s |
|---|---|---|
| C1 | 32.3 s | 0.27 |
| C2 | 17.7 s | 0.43 |
| D1 | 47.6 s | 0.19 |

## 5.4 Model suitability and limitations

Goodness-of-fit checks (including QQ plots of residence times) show that the CTMC exponential holding-time assumption is a workable large-scale summary but not a micro-scale model; longer-than-exponential tails appear in parts of the data, which is expected for road segments with stable stretches. Within its intended scope, the CTMC yields consistent steady-state occupancy and switching intensities across multiple drives and provides a compact lens for interpreting selection stability. Measurement coverage is finite and route-specific; generator matrices and per-zone leaving rates are therefore treated as route summaries and not universal constants. The evaluation focuses on stability metrics rather than on end-to-end latency measurements.

## 5.5 Summary

The empirical road data and CTMC-derived metrics show that the decision layer operates in environments dominated by long stable periods with occasional regime changes on two routes (C1, D1), and in more dynamic conditions on C2. In all cases, the observed stability context is compatible with the rule set from Chapter 3, supporting technology selection that avoids unnecessary switching while preserving delivery viability under heterogeneous coverage.

# Chapter 6

# Discussion

This chapter interprets the modelling and empirical evidence, positions the decision layer with respect to deployable V2X systems, and states limits and implications in a way consistent with the preceding chapters.

## 6.1 Conclusions Related to Theses

**Thesis 1 — Reduce unnecessary wireless load while meeting message requirements.** The work turns location-specific cellular quality maps (GREEN/ORANGE/RED) into sender/receiver rules that choose CELLULAR, DIRECT, or BOTH per message. CELLULAR is used when the delivery area lies in GREEN; if any segment is non-GREEN, the policy switches to DIRECT or BOTH. Decisions are re-evaluated hop by hop, so redundancy is added only where the map indicates risk, avoiding needless broadcast elsewhere. The Coloured Petri Net model shows boundedness, no infinite occurrence sequences, and termination in the explored configurations (no uncontrolled forwarding). The CTMC results on real roads indicate technology switching on the order of tens of seconds rather than rapid flip-flopping, consistent with restrained use of additional transmissions.

**Thesis 2 — Improve delivery reliability and timeliness by using heterogeneity.** The algorithm prefers CELLULAR in consistently good segments, falls back to DIRECT where coverage is impaired, and uses BOTH when short visibility suggests risk on short-range dissemination. The utilization of both transmission technologies like this is expected to improve deliverability (compared to a single technology) while using both technologies only when necessary; detailed load measurements are left for future work.

## 6.2 Interpretation and Comparison

The CTMC summaries in Chapter 5 show distinct operating regimes across the three routes. C1 and D1 spend most time in GREEN with modest switching intensity, which aligns with prioritising CELLULAR to spare contention on the broadcast medium. C2 exhibits increased time in ORANGE and a higher switching intensity, which justifies relying more often on DIRECT while still using CELLULAR where conditions allow. These patterns match the decision inputs (zone, range class, visibility cue) and outcomes (DIRECT/CELLULAR/BOTH) established in Chapter 3. The interpretation therefore links the empirical stability context (Tables 5.1, 5.2) to the intended behaviour of the mode-selection rules without requiring additional mechanisms.

Two caveats from the evaluation remain important when interpreting cross-route differences. First, some zone–route combinations (e.g., rare visits to RED on the highway) yield fewer observations, which lowers confidence for those specific leaving rates while having limited effect on overall switching because the steady-state mass in such states is small. Second, QQ-plot diagnostics indicate heavier upper tails in residence times than a pure exponential would predict; the CTMC is thus used as a large-scale stability summary rather than a micro-scale predictor.

## 6.3 Limitations and Validity

*Modelling abstractions.* The CTMC omits additional predictors (e.g., lane-distance visibility) and assumes exponential holding times. Diagnostics (QQ plots and a Lilliefors-style check) reveal systematic deviations from exponentiality due to rare but important long residence times.

A more robust validation—testing whether exit counts are Poisson-proportional to time in state—was identified as a logical next step but not executed here. Consequently, the CTMC is applied as a stability lens over long horizons, not as a short-time predictor of individual transitions.

*Decision inputs.* Lane-distance visibility is incorporated in the decision logic as a practical indicator of propagation risk for short-range warnings, yet it was neither represented in the CPN model nor separately evaluated for its effect on switching stability; formal verification and empirical assessment of this cue remain open items.

*Measurement and data handling.* The empirical study relies on a modular, roof-mounted platform (cameras, LIDAR, GNSS, cellular modem with external antennas). Sampling is at user-defined multi-second intervals; RTT probes require non-negligible measurement time; and residence times are panel-observed rather than continuously tracked. To stabilise estimates, 16 drives per road are pooled into a single sample, which enhances statistical robustness at the cost of spatial specificity. These choices limit temporal resolution and can bias tail statistics, so CTMC outputs are interpreted as indicators of dominant trends rather than of extreme events.

## 6.4 Implications and Future Work

*Operational implications.* Because the policy layer depends on message metadata and on historical cellular-quality maps derived from routine measurement, it can be integrated as a thin component above standard-compliant stacks. GREEN-dominated environments benefit from offloading to CELLULAR; mixed environments retain delivery viability via DIRECT/BOTH while curbing unnecessary broadcast. Maintaining map relevance (refresh and monitoring) is advisable, since network evolution or environmental change can render historical expectations stale.

*Future work.* The thesis identifies concrete next steps: (i) strengthen CTMC validation under irregular sampling using exit-count proportionality to time in state; (ii) formally verify and empirically assess the visibility cue as a decision input; (iii) increase spatial and temporal resolution by broadening data collection (e.g., additional drives or crowd-sourced measurement) with robust quality control prior to map updates. These steps would tighten the link between decision inputs and observed dynamics while preserving the simplicity that makes the framework deployable.

## Chapter 7

# Conclusion

Vehicular communication must sustain reliable, low-latency delivery under conditions that change across short distances and time scales. No single radio technology consistently satisfies these constraints on all road types; direct short-range communication and cellular systems exhibit complementary strengths shaped by interference, mobility, and heterogeneous coverage [12, 5, 6, 7]. The dissertation addressed this reality with a practical decision layer that combines real-time indicators with historical, location-specific information about cellular quality to select between direct dissemination and cellular relaying while explicitly limiting redundant broadcast activity in contention-based media. The design is framed against the capabilities and service expectations codified for V2X in 5G systems, ensuring compatibility with standardized roles [2, 3, 4].

The work assembled a road-measurement pipeline tailored to driving scenarios, aligned measurements to road segments, and constructed historical quality maps that expose stable, location-bound patterns not visible from instantaneous readings alone. On this foundation, a context-aware message-delivery algorithm fuses instantaneous indicators with historical expectations to choose a single delivery mode per message and to apply restrained broadcast forwarding when direct dissemination is selected. The executable algorithm is mirrored (with limitations) by a Coloured Petri Net model that verifies absence of deadlocks and bounded broadcast behavior before field evaluation. To analyze whether the selection remains stable under noisy conditions, a Continuous-Time Markov Chain model parameterized from on-road measurements quantifies steady-state occupancy, switching intensity, and time-window switch probabilities on representative routes, showing long residence in favorable regimes interspersed with occasional transitions. The empirical study on Slovak roads confirms the intended operational pattern: in segments with historically impaired cellular coverage the algorithm would prioritize direct dissemination to avoid costly cellular retries, whereas in segments with consistently strong cellular conditions it prefers cellular relaying to preserve capacity on contention-based media, with behavior interpreted against standardized V2X modes and service assumptions.

The contributions can be summarized as: (i) a measurement and mapping pipeline enabling creation of cellular quality maps aligned with road topology; (ii) a context-aware delivery algorithm that integrates historical expectations with real-time indicators and constrains redundant broadcast activity; (iii) formal verification of the decision core using Coloured Petri Nets; and (iv) CTMC-based analysis of switching stability fitted from real-road data. Prior outputs by the author and collaborators provided groundwork on LTE/5G parameters for V2X, infrastructure readiness, and segment-level compliance with performance expectations, and publicly released data couples camera recordings with mobile-network telemetry and high-precision localization to support reproducible analysis [8].

Limitations arise from measurement coverage and modeling abstraction. Aggregation to segment-level zones and irregular sampling imply that the CTMC serves as a large-scale summary rather than a micro-scale model; goodness-of-fit checks reveal deviations from simple exponential dwell-time assumptions in parts of the data, which is consistent with the intended use of the model as a stability lens rather than a fine-grained predictor. Historical maps can drift as deployments evolve; practical deployments should therefore refresh maps and include lightweight runtime checks for persistent mismatches. The decision layer is deliberately lightweight to ease integration; device-specific effects and short-term interference variations are not modeled explicitly and represent avenues for extension.

Future work follows directly: extending measurement coverage to more diverse roads and operating conditions, refining map granularity where data density allows, studying refresh cadence under network evolution, and enriching decision cues with robust, low-cost signals that correlate with upcoming quality changes on specific geometries. These steps preserve the guiding principle of the dissertation—leverage stable historical structure where it exists and augment it with simple real-time evidence—while moving closer to deployment in standard-compliant V2X ecosystems.

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## Chapter A

# List of Publications

Following is a list of publications related to the studied issue. All items listed below are published, peer-reviewed scientific papers authored or co-authored by the dissertation author.

**Conference papers**

- BARTOSIK, Gawel – DANKO, Ján – DLUGOSZ, Marek – GALINSKI, Marek – JANEBA, Matej – LEHOCZKÝ, Peter – MARCHEWKA, Dariusz – MILESICH, Tomáš – SIWEK, Patryk – SKRUCH, Pawel. *The Influence of the Relative Vehicles Speed on the Environmental Perception-Tests on Slovakia Ring.* In *Advanced, Contemporary Control: Proceedings of the XXI Polish Control Conference, Gliwice, Poland, 2023.* 1. ed. Cham: Springer Cham, 2023, s. 235–244. ISSN 2367-3370. ISBN 978-3-031-35172-3. V databáze: SCOPUS: 2-s2.0-85164677593; DOI: 10.1007/978-3-031-35173-0_23.
- BERNOLÁK, Vladimír – LEHOCZKÝ, Peter – BENCEL, Rastislav – KOTULIAK, Ivan. *Efficient dynamic management of IEEE 802.11 networks using SDN.* In *2022 IEEE Zooming Innovation in Consumer Technologies Conference (ZINC 2022).* 1. ed. Danvers: Institute of Electrical and Electronics Engineers, 2022, s. 170–175. ISBN 978-1-6654-8375-9. V databáze: SCOPUS: 2-s2.0-85136438772; IEEE: 9840549; DOI: 10.1109/ZINC55034.2022.9840549.
- BILIK, Dávid – LEHOCZKÝ, Peter – KOTULIAK, Ivan. *Simulating Vehicle-to-Vehicle (V2V) Communication in Urban Traffic Scenarios.* In *ICETA 2023: 21st Year of International Conference on Emerging eLearning Technologies and Applications: Information and communication technologies in learning.* Starý Smokovec, Slovakia. October 26–27, 2023. Danvers: IEEE, 2023, s. 56–61. ISBN 979-8-3503-7068-3. V

databáze: SCOPUS: 2-s2.0-85182025906; DOI: 10.1109/ICETA61311.2023.10344219; IEEE: 10344219.

**Ohlasy:**

- NEUMANN, Tomasz. *Analysis of Advanced Driver-Assistance Systems for Safe and Comfortable Driving of Motor Vehicles.* In: *SENSORS*, 2024, vol. 24, no. 19, art. no. 6223. ISSN 1424-8220. DOI: 10.3390/s24196223.
- IBRAHIM, Zahraa – ALJANABI, Mohanad. *Performance and dependability investigation of a standalone PV for mini-grid system: A study case using PVsyst for Karbala Iraq.* In: *AIP Conference Proceedings, EETR 2024.* Maryland: American Institute of Physics 2024. Vol. 3232, no. 1, art. no. 050009. ISSN 0094-243X. DOI: 10.1063/5.0236356.

• JANEBA, Matej – LEHOCZKÝ, Peter – GALINSKI, Marek – MILESICH, Tomáš – DANKO, Ján – KOTULIAK, Ivan. *Evaluation of LTE and 5G qualitative parameters for V2X use cases.* In *2022 IEEE Zooming Innovation in Consumer Technologies Conference (ZINC 2022).* 1. ed. Danvers: Institute of Electrical and Electronics Engineers, 2022, s. 165–169. ISBN 978-1-6654-8375-9. V databáze: SCOPUS: 2-s2.0-85136447729; IEEE: 21954849; DOI: 10.1109/ZINC55034.2022.9840619.

**Ohlasy:**

- Cao, Xincheng et al. *Vehicle-in-Virtual-Environment (VVE) Method for Autonomous Driving System Development, Evaluation and Demonstration.* In *Sensors*, 2023, vol. 23, no. 11, art. no. 5088. ISSN 1424-8220. DOI: 10.3390/s23115088.
- ONDOV, Adrián – HELEBRANDT, Pavol. *Covert Channel Detection Methods.* In *ICETA 2022: 20th Anniversary of IEEE International Conference on Emerging eLearning Technologies and Applications: Information and communication technologies in learning.* Starý Smokovec, Slovakia. October 20–21, 2022. Danvers: IEEE, 2022, s. 479–484. ISBN 979-8-3503-2033-6. DOI: 10.1109/ICETA57911.2022.9974878; IEEE: 22411227.
- CAMMIN, Christoph – MOUSAVI, Mohammad Reza – TRAUTWEIN, Ingo – FREYMANN, Andreas – BEUTELSPACHER, Christoph – NEHRKE, Lara – LUDWIG, Stephan – KIRCHHEIM, Alice.

*Concept for a Real-Time IoT-Architecture for Collision Avoidance in Smart Cities based on the 5G Mobile Technology.* In: 2023 IEEE International Conference on Omni-Layer Intelligent Systems, COINS 2023, 2023-01-01, pp.

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  **Ohlasy:**

  - SIMEONOV, Marcel – KAMENCAY, Patrik – DADO, Milan – DURIŠ, Lukas – VESCLOVSKÝ, Michal. *Contribution to the Investigation of Infrastructure Readiness in Terms of Cooperative, Connected and Automated Mobility Localization.* In: 2024 47th International Conference on Telecommunications and Signal Processing, TSP 2024. Danvers: IEEE, 2024, pp. 260–263. DOI: 10.1109/TSP63128.2024.10605770.
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  - EL BIZRI, Mustafa – EL-HAJJ, Ahmad M. – HAIDAR, Ali M. *Towards Safer Wi-Fi Networks: Leveraging Neural Networks for Intrusion Detection.* In: 2023 IEEE 4th International Multidisciplinary Conference on Engineering Technology, IMCET 2023. ISBN 979-835031382-6, pp. 273–277. Dostupné na: https://doi.org/10.1109/IMCET59736.2023.10368234.
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**Journal papers**

- GALINSKI, Marek – DANYLOV, Volodymyr – LEHOCZKÝ, Peter – BENCEL, Rastislav – ŠOLTÉS, Lukáš. *Ultra-Fast Visible Lane Distance Estimation Using a Single Camera.* In *IEEE Access.* Vol. 12, (2024), s. 79251–79263. ISSN 2169-3536 (2024: 3.6 – JIF, Q2 – JIF

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  – MAGDOLEN, Ľuboš – DANKO, Ján – MILESICH, Tomáš – KEVICKÝ, Igor – HANKO, Lukáš – SKYRČÁK, Robert. *Conditions for loss of stability of an autonomous vehicle during a cornering manoeuvre.* In: *Strojnícky časopis – Journal of MECHANICAL ENGINEERING,* 2022, vol. 72, no. 3, pp. 129–140. Dostupné na: https://sciendo.com/pdf/10.2478/scjme-2022-0047.

  – JURASKO, Jozef – BENCEL, Rastislav – TRUCHLY, Peter – MAGULA, Michal. *A Design Proposal for a Platooning Testing Platform Utilizing Remote Control Vehicles.* In: Proceedings Elmar International Symposium Electronics in Marine. Danvers: Institute of Electrical and Electronics Engineers, 2024. ISBN 979-835037541-1, pp. 17–20. ISSN 1334-2630. DOI: 10.1109/ELMAR62909.2024.10694363.

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