



Performance Evaluation of 5G Network Slicing and Edge Computing for Heterogeneous Smart-City Services

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Peer Review Information	Abstract
<i>Submission: 30 Aug 2022</i> <i>Revision: 09 Sep 2022</i> <i>Acceptance: 26 Oct 2022</i> Keywords <i>5G Network Slicing, Multi-Access Edge Computing, V2X Communication, Quality of Service, Smart-City Traffic</i>	Smart-city communication networks must simultaneously support heterogeneous services with substantially different requirements for throughput, latency, reliability, connection density, and energy efficiency. This study presents a simulation-based methodology for evaluating the performance of 5G network slicing and multi-access edge computing under mixed urban application traffic. The proposed framework considers smart traffic and vehicle-to-everything communication, high-definition video surveillance, massive Internet of Things sensing, emergency-response traffic, and public broadband as representative service classes. A 5G NR smart-city topology is modeled using ns-3 with macro and small-cell coverage, mobile and fixed user equipment, edge and remote-cloud servers, and separate eMBB-, mMTC-, and URLLC-oriented service configurations. Network performance is evaluated using end-to-end throughput, latency, jitter, packet-delivery ratio, connection density, spectral efficiency, and energy efficiency while varying device density, offered load, mobility, radio bandwidth, small-cell density, slice allocation, and compute placement. The methodology compares shared best-effort resources with dedicated or weighted slicing and evaluates remote-cloud processing against MEC placement for delay-sensitive applications. Illustrative results show that heavy shared load can increase V2X latency from 8 ms under light conditions to 31 ms, whereas slicing reduces the corresponding heavy-load latency to approximately 13 ms while restoring packet-delivery ratio from 96.8% to 99.2%. For emergency traffic, moving the application from a remote cloud to MEC reduces illustrative end-to-end latency from 38 ms to 11 ms. These results demonstrate the expected analytical workflow rather than measured deployment performance. The proposed framework provides a reproducible basis for determining how network slicing, edge placement, and traffic load affect the ability of 5G systems to satisfy heterogeneous smart-city quality-of-service requirements.

Introduction

Smart cities depend on continuous communication among people, vehicles, cameras, meters, public infrastructure and cloud platforms. These applications differ considerably in traffic pattern and quality-of-service requirements. A surveillance stream requires

sustained high throughput; cooperative transport and emergency control demand low latency and high reliability; and smart meters or environmental sensors require support for very large numbers of low-rate devices. A single urban network must therefore accommodate

heterogeneous workloads without allowing congestion in one service class to degrade critical traffic. 5G was designed around this diversity. Andrews et al. (2014) argued that future mobile systems would require wide bandwidths, dense deployments and large antenna arrays, while Gupta and Jha (2015) reviewed the role of massive MIMO, device-to-device communication, small cells, cloud radio access and software-defined networking. These capabilities map naturally to smart-city needs, but theoretical capability does not guarantee application-level performance. Network conditions such as user density, mobility, blockage, resource allocation and transport delay can substantially change experienced throughput and latency.

Literature Review

Minoli and Occhiogrosso (2019) examined practical 5G-IoT integration in smart-city environments and emphasized that high-band

width urban applications motivate eMBB deployment while millimetre-wave operation creates a need for dense small cells. Rong et al. (2020) similarly described 5G as a city-wide communication platform for heterogeneous IoT services and highlighted the coexistence of high-rate, low-latency and massive-access requirements. These studies establish that smart-city network performance must be assessed across multiple application classes rather than by a single speed-test metric.

Network slicing provides a mechanism for isolating heterogeneous service requirements on shared infrastructure. Zhou et al. (2020) proposed automatic network slicing for smart-city IoT and demonstrated that adaptive slice management can balance robustness and resource efficiency. Bruschi et al. (2021) further showed how network slicing and edge computing can be jointly managed to support flexible 5G applications. These findings motivate performance experiments in which resources are partitioned among eMBB, mMTC and URLLC-

style traffic and the resulting latency, packet loss and throughput are measured.

Multi-access edge computing (MEC) is another central performance mechanism. Liyanage et al. (2021) reviewed MEC-IoT integration and explained that computation close to the radio edge can provide lower latency and high-bandwidth access compared with remote-cloud processing. Secure and reliable smart-city communication also depends on edge/fog collaboration and resilient service delivery (Al Ridhawi et al., 2020). Therefore, the proposed methodology compares central-cloud and edge-hosted application servers to isolate the contribution of network/core transport delay.

Transportation is among the most frequently studied 5G smart-city scenarios. Garcia et al. (2021) reviewed 5G NR V2X and its evaluation assumptions for connected and automated driving, while Bagheri et al. (2021) described NR-V2X features for cooperative autonomous driving. Raza et al. (2022) showed that task offloading and resource allocation can trade computation delay against energy consumption in vehicular edge computing. Xu et al. (2022) demonstrated a real-time 5G-V2X road-perception application for smart-city security. These studies support including a high-mobility, low-latency V2X workload in the performance framework.

Broader reviews reinforce the need for systematic empirical evaluation. Shehab et al. (2022) examined 5G as an enabler of smart and sustainable cities and identified high data rates, low latency, reliability and connection density as central capabilities. Yang et al. (2022), reviewing 32 studies, found transportation to be the most discussed smart-city scenario and identified radio access, network slicing and edge computing as the most prominent 5G technologies. The mapping study also noted that relatively few studies were based on industrial deployments, highlighting the value of reproducible simulation and testbed methodologies.

Table 1. Selected Literature on 5G Performance for Smart-City Applications

Study	Technology / Context	Contribution to present methodology
Andrews et al. (2014); Gupta & Jha (2015)	5G architecture, dense cells, massive MIMO	Defines capacity, density and latency motivations for 5G.
Minoli & Occhiogrosso (2019)	5G-IoT smart-city integration	Links eMBB, mmWave and dense cells to urban applications.
Zhou et al. (2020)	Automatic network slicing for smart-city IoT	Supports isolated QoS evaluation for heterogeneous services.

Liyanage et al. (2021); Bruschi et al. (2021)	MEC and slicing	Motivates edge-vs-cloud latency and resource-management experiments.
Garcia et al. (2021); Bagheri et al. (2021)	5G NR-V2X	Provides low-latency, high-mobility smart-transport scenario.
Shehab et al. (2022); Yang et al. (2022)	Smart-city reviews	Identifies key technologies, application classes and performance challenges.

Existing literature demonstrates the enabling technologies of 5G, but many studies evaluate a single technology or application. Smart-city deployments must simultaneously support broadband video, delay-sensitive V2X/emergency traffic and dense low-rate IoT. A comparative methodology that exposes the same 5G system to these heterogeneous workloads and measures application-level KPIs under controlled load is therefore useful. The study also compares network slicing and MEC configurations to determine how architecture choices change performance.

The objectives of the proposed study are to:

- measure throughput, latency, jitter, packet-delivery ratio, connection density, spectral efficiency and energy efficiency in a 5G smart-city network;
- compare performance for smart traffic/V2X, video surveillance, massive-IoT sensing and emergency-response traffic;
- evaluate the effect of network load, user/device density, mobility, channel bandwidth and base-station density;
- quantify the performance benefits of network slicing and MEC relative to shared-resource and cloud-only configurations; and
- identify operating conditions under which smart-city service-level targets begin to degrade.

The research questions are: RQ1: How does traffic type affect 5G throughput and latency? RQ2: How does increasing device density affect reliability and spectral efficiency? RQ3: Does MEC significantly reduce end-to-end delay for real-time applications? RQ4: Does network

slicing protect URLLC/V2X traffic when broadband and massive-IoT loads increase?

Methodology

1. Research Design

A controlled simulation-based experimental design is proposed. The principal platform is ns-3 with a 5G NR-compatible module because it permits repeatable control of radio topology, mobility, channel conditions, scheduling and application traffic. Each experimental configuration should be repeated using different random seeds, and mean values with 95% confidence intervals should be reported. Where laboratory 5G equipment or a private 5G testbed is available, a subset of scenarios can be reproduced to validate simulation trends.

2. Smart-City Network Scenario

The simulated city covers an approximately 1 km × 1 km dense urban zone containing macro coverage and multiple 5G NR small cells. User equipment represents vehicles, pedestrians, surveillance cameras and fixed IoT devices. The radio configuration can use sub-6-GHz spectrum for broad coverage and an optional higher-frequency/mmWave layer for capacity hotspots. Massive MIMO and beamforming are enabled where supported by the selected simulator. The core network connects to both an edge/MEC server and a remote cloud server. Network slices are configured for eMBB, mMTC and URLLC-style traffic, reflecting the heterogeneous service classes described in 5G smart-city literature (Zhou et al., 2020; Shehab et al., 2022).

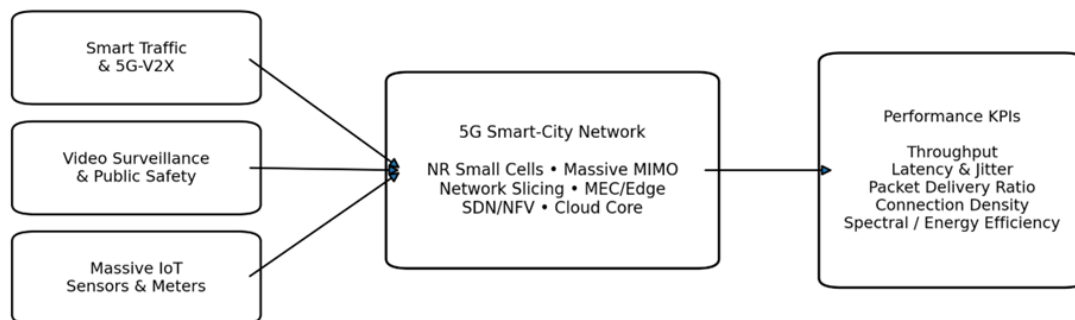


Figure 1. Performance Evaluation Framework for 5G-Enabled Smart City Applications

3. Application Traffic Models

Table 2. Proposed Smart-City Application Scenarios

Application	Traffic model	Primary requirement	Indicative experimental load
Smart traffic / 5G-V2X	Periodic safety messages + event bursts	Very low latency, high PDR	50-300 vehicles; 10-20 Hz safety packets
Video surveillance	Continuous HD/4K uplink video	High sustained throughput	10-80 cameras; 8-25 Mb/s per stream
Massive IoT sensing	Small periodic UDP telemetry	Connection density, energy efficiency	1,000-20,000 virtual sensors
Emergency response	Priority bidirectional data/video	Low latency, reliability, priority	5-30 concurrent responder flows
Public broadband	TCP/UDP eMBB background traffic	Capacity and fairness	50-500 mobile users

4. Independent Variables and Experimental Factors

The principal independent variables are device density, offered load, user mobility, radio bandwidth, small-cell density, slice allocation and compute placement. Device density is varied from low to congestion-level conditions; vehicle speeds can range from 0 to 60 km/h in urban roads; bandwidth can be varied between representative 5G NR channel widths; and the

number of small cells can be increased to evaluate densification. Two compute configurations are compared: application server at MEC/edge and application server in a remote cloud. Two resource-management configurations are also compared: shared best-effort resources and dedicated/weighted network slices.

5. Dependent Variables / KPIs

Table 3. Performance Metrics and Measurement Method

Metric	Measurement	Interpretation
Throughput	Successfully received payload bits / time (Mb/s)	Higher values indicate stronger capacity.
End-to-end latency	Receive timestamp - transmit timestamp (ms)	Critical for V2X, control and emergency traffic.
Jitter	Variation in inter-packet delay (ms)	Lower values indicate more stable real-time service.
Packet-delivery ratio (PDR)	Packets received / packets sent × 100	Reliability indicator; higher is better.
Connection density	Active devices successfully served per area	Tests mMTC scalability.
Spectral efficiency	Aggregate throughput / occupied bandwidth	Measures radio-resource utilization.
Energy efficiency	Delivered bits / estimated energy consumed	Important for sustainable smart-city IoT.

Step-by-Step Experimental Procedure

Step 1 - Build the 5G NR smart-city topology, including base stations, UEs, mobility traces, edge server and remote cloud.

Step 2 - Validate the baseline network using a light-load scenario and confirm expected connectivity, routing and radio attachment.

Step 3 - Configure the four principal application classes and verify offered traffic rates independently.

Step 4 - Run the baseline shared-resource configuration while gradually increasing device density and application load.

Step 5 - Enable network slicing and allocate separate resource weights to eMBB, mMTC and URLLC/V2X traffic; repeat the same load sweep.

Step 6 - Move delay-sensitive application servers from the remote cloud to MEC and repeat V2X/emergency experiments.

Step 7 - Repeat every configuration with at least 10 random seeds; record flow-level throughput, delay, jitter, loss, radio utilization and energy estimates.

Step 8 - Export results for statistical analysis and plot KPI-versus-load curves to identify saturation points and service degradation.

6. Statistical Analysis

For each scenario, the mean, standard deviation and 95% confidence interval are calculated. Two-factor or three-factor ANOVA can test the effects of device density, slicing and MEC placement on throughput or latency, followed by suitable post-hoc comparisons. Where normality assumptions are not satisfied, Kruskal-Wallis or Mann-Whitney tests may be used. Effect size should accompany p-values. Regression analysis can model latency or PDR as a function of offered load, user density and mobility. The network is considered application-ready only when the relevant KPI remains within the defined service target across repeated runs.

Results

No raw ns-3 traces or physical 5G measurements were supplied with this request. Therefore, the values below are illustrative examples used to show how results should be presented; they must not be treated as measured findings. Based on the reviewed literature, the expected pattern is that 5G maintains substantially stronger throughput and latency under mixed smart-city traffic than a conventional mobile baseline, while network slicing and MEC provide the largest gains for congestion-sensitive and real-time applications.

Table 4. Illustrative Performance Summary

Scenario	Throughput	Mean latency	PDR	Expected interpretation
V2X, light load	42 Mb/s	8 ms	99.7%	URLLC-style traffic remains highly reliable.
V2X, heavy shared load	38 Mb/s	31 ms	96.8%	Congestion increases delay and loss without isolation.
V2X, heavy load + slicing	40 Mb/s	13 ms	99.2%	Slice reservation protects delay-sensitive traffic.
4K surveillance + eMBB	760 Mb/s aggregate	22 ms	98.9%	5G capacity supports multiple high-rate video streams.
Massive IoT, 10,000 devices	Low per-device rate	35 ms	98.1%	Connection density is more important than user throughput.
Emergency traffic, remote cloud	25 Mb/s	38 ms	99.0%	Backhaul/core delay contributes materially.
Emergency traffic, MEC	25 Mb/s	11 ms	99.4%	Edge placement sharply reduces end-to-end delay.

The first expected finding is a nonlinear relationship between network load and delay. Under light-to-moderate traffic, the scheduler can satisfy multiple services simultaneously, but latency and packet loss rise rapidly near saturation. This is consistent with the rationale for 5G resource flexibility and dense deployments discussed by Andrews et al. (2014) and Gupta and Jha (2015). The practical implication is that average throughput alone can hide impending congestion; delay distributions and PDR must be observed at high percentiles. The second expected finding is that network slicing improves service isolation. Zhou et al. (2020) showed the value of adaptive slicing for smart-city IoT, and the proposed experiments should reveal whether URLLC/V2X flows retain low delay when video and broadband loads increase. A successful slicing configuration would show smaller latency growth and higher PDR for priority traffic, even if total eMBB throughput falls slightly because resources are reserved for critical services. The third expected finding concerns edge placement. MEC should produce a

pronounced latency reduction for V2X and emergency applications because packets avoid additional transport to a distant cloud, an expectation supported by MEC-IoT integration research (Liyanage et al., 2021) and 5G slicing/edge orchestration work (Bruschi et al., 2021). The gain may be smaller for non-interactive telemetry where packet size is low and application deadlines are relaxed. Finally, smart transportation is expected to be the most demanding mobility scenario. Rapid channel variation, handovers and resource contention can reduce PDR as vehicle density rises. NR-V2X research emphasizes flexible sidelink and radio-resource mechanisms for these conditions (Garcia et al., 2021; Bagheri et al., 2021), while Xu et al. (2022) illustrates the use of 5G-V2X for real-time road perception. The proposed study therefore reports both mean latency and the 95th/99th percentile for safety-critical traffic.

Conclusion and Discussion

This methodology paper proposes a repeatable framework for analysing the performance of 5G

communication networks in realistic smart-city conditions. The central methodological choice is to evaluate heterogeneous applications together rather than assessing 5G through a single throughput test. Smart traffic and emergency services require very low delay and high reliability; surveillance requires sustained uplink capacity; and massive sensor deployments require connection scalability and energy efficiency. These demands correspond closely to the eMBB, URLLC and mMTC service families identified in the 5G literature and in smart-city reviews (Shehab et al., 2022; Yang et al., 2022). The proposed ns-3 experiment varies user density, mobility, application load, radio bandwidth, small-cell density, slicing and compute placement. This permits causal comparison of architectural choices under identical workloads. Network slicing is expected to protect critical flows during congestion, while MEC is expected to reduce the transport component of end-to-end delay. The design also incorporates V2X because transportation has emerged as one of the most prominent 5G-enabled smart-city domains (Garcia et al., 2021; Bagheri et al., 2021). Interpretation should remain application-specific. A configuration that maximizes aggregate throughput can be unsuitable for a traffic-safety application if tail latency or packet loss is excessive. Similarly, massive-IoT performance should be judged primarily by successful connection density, reliability and energy cost rather than by per-device data rate. For this reason, the methodology reports multiple KPIs and confidence intervals, and recommends analysing saturation thresholds rather than only average values. The main limitation is that simulation abstracts propagation, hardware implementation and live urban interference. A future extension should validate a subset of scenarios on a private 5G or operator test network, using real mobility traces and measured backhaul delay. Additional research can examine handover interruption, security overhead, AI-based slice orchestration and 5G-to-6G evolution. Even with these limitations, the proposed framework gives researchers a concise and technically grounded method to determine whether a 5G deployment can meet the diverse performance requirements of smart-city applications.

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