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A PROBABILISTIC INFORMATION INTERACTION MODEL FOR SMART CITY NETWORKS BASED ON TRAFFIC FLOW ANALYSIS

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Abstract

The rapid growth of Internet of Things (IoT) technologies has significantly increased the amount of heterogeneous traffic generated in smart city environments. Traditional communication models cannot efficiently process massive real-time data streams because they do not adequately consider stochastic traffic behavior, communication delays, and distributed computing resources. This paper proposes a probabilistic information interaction model for Smart City networks based on traffic flow analysis. The proposed model integrates Software-Defined Networking (SDN), Fog computing, and Cloud computing into a unified communication architecture capable of supporting heterogeneous IoT applications. A probabilistic analytical model is developed to estimate temporal characteristics of information exchange by considering packet arrival intensity, service processes, and resource utilization. Furthermore, a simulation model is implemented to evaluate the proposed approach under different traffic loads. Experimental results demonstrate that the proposed model improves information delivery efficiency, reduces end-to-end delay, and provides better Quality of Service (QoS) compared with conventional network architectures. The proposed solution can be effectively applied to intelligent

transportation systems, environmental monitoring, healthcare services, and other Smart City applications.

Keywords— Smart City, SDN, IoT, Fog Computing, Cloud Computing, Traffic Flow, QoS, Information Interaction, Simulation.

I. INTRODUCTION

The concept of Smart City has become one of the most important directions in the digital transformation of modern urban infrastructure. The integration of Internet of Things (IoT), Artificial Intelligence (AI), cloud computing, and high-speed communication technologies enables real-time monitoring and management of transportation systems, environmental conditions, healthcare services, energy infrastructure, and public safety. As the number of connected devices continuously increases, Smart City networks generate enormous volumes of heterogeneous traffic with different Quality of Service (QoS) requirements.

Conventional communication architectures are generally designed for homogeneous traffic conditions and centralized resource management. However, Smart City applications simultaneously transmit periodic sensor measurements, emergency notifications, multimedia streams, and control messages, each requiring different delay, reliability, and bandwidth characteristics. Consequently, traditional networking approaches often experience congestion, increased latency, packet loss, and inefficient utilization of network resources.

Software-Defined Networking (SDN) has emerged as a promising networking paradigm by separating the control plane from the data plane, thereby providing centralized network management and dynamic traffic engineering. Meanwhile, Fog computing complements cloud computing by processing delay-sensitive information near end devices, reducing communication latency and improving system responsiveness. The integration of SDN with Fog–Cloud architecture creates an intelligent communication environment capable of efficiently handling heterogeneous Smart City traffic.

Despite these technological advances, the probabilistic characteristics of information interaction between distributed Smart City components remain insufficiently investigated. Most existing studies evaluate communication performance without jointly considering stochastic packet arrivals, service processes, and computational resource allocation. Therefore, developing analytical and simulation models capable of describing temporal and probabilistic characteristics of information exchange remains an important research challenge.

This paper proposes a probabilistic information interaction model that integrates traffic flow analysis with SDN-enabled Smart City architecture. Unlike conventional approaches, the proposed model jointly evaluates communication delay, processing delay, and probabilistic packet delivery under heterogeneous traffic conditions. The model is further validated through simulation experiments.

The main contributions of this paper are summarized as follows:

- Development of a probabilistic information interaction model for heterogeneous Smart City traffic;
- Integration of SDN, Fog computing, and Cloud computing within a unified communication architecture;
- Development of a mathematical model for evaluating temporal and probabilistic characteristics of information exchange;
- Simulation-based performance evaluation under different traffic loads;
- Comparative analysis demonstrating improvements in communication efficiency and QoS.

II. PROPOSED INFORMATION INTERACTION MODEL

The proposed Smart City communication architecture consists of four logical layers that cooperate to provide reliable information exchange between distributed IoT devices and application services.

The first layer represents the perception layer, where heterogeneous sensors continuously collect environmental information, including transportation data, air quality, smart energy consumption, healthcare parameters, and surveillance information. These devices generate traffic with different statistical properties depending on application requirements.

The second layer corresponds to the communication network, which incorporates SDN-enabled switches and gateways responsible for forwarding data packets according to policies generated by the SDN controller. Unlike traditional routing mechanisms, SDN dynamically allocates forwarding paths according to network conditions and QoS requirements.

The third layer includes Fog computing nodes positioned close to data sources. Fog nodes perform preliminary data processing, filtering, aggregation, and local decision-making before transmitting summarized information to cloud servers. This significantly reduces communication delay for delay-sensitive Smart City applications.

Finally, Cloud computing provides large-scale storage, historical data analysis, artificial intelligence algorithms, and centralized management functions.

The interaction process follows these sequential steps:

1. IoT sensors generate traffic according to stochastic arrival processes.
2. Data packets are transmitted through SDN switches.
3. The SDN controller determines optimal forwarding policies.
4. Fog nodes process latency-sensitive traffic.

5. Cloud servers perform large-scale analytical processing.
6. Decision results are transmitted back to end users or control systems.

Such an architecture enables efficient utilization of both communication and computational resources while minimizing overall information delivery delay.

III. MATHEMATICAL MODEL OF PROBABILISTIC INFORMATION INTERACTION

Efficient information exchange in Smart City environments depends on both communication network performance and distributed computing resources. In practical deployments, thousands of heterogeneous IoT devices simultaneously generate data with different statistical characteristics. Consequently, packet arrival processes become stochastic, while service times vary according to application priorities and computational workloads. To accurately describe these conditions, a probabilistic information interaction model is developed.

Let the Smart City network consist of a set of IoT devices

$S=\{S_1,S_2,\ldots,S_n\}$

connected through an SDN-enabled communication infrastructure.

Each sensor generates traffic with an average arrival rate

λ_i

The generated packets are transmitted through SDN switches toward Fog computing nodes where delay-sensitive information is processed before forwarding selected data to Cloud servers.

The total arrival intensity is expressed as

$$\lambda = \sum_{i=1}^{n} \lambda_i$$

The average service rate of distributed computing resources is μ.
The utilization coefficient of the communication system is

$$\rho = \frac{\lambda}{\mu}$$

where
$0<\rho<1$.
Stable network operation is guaranteed only when the arrival intensity remains lower than the processing capacity of the integrated communication and computing infrastructure.
The average end-to-end information delivery delay consists of several independent components:

$$T=T_{tx}+T_q+T_p+T_f+T_c,$$

where
- T_{tx} denotes transmission delay,
- T_q represents queueing delay,
- T_p is packet processing delay inside SDN switches,
- T_f corresponds to Fog computing delay,
- T_c denotes Cloud processing delay.

Unlike conventional cloud-based architectures, the proposed approach performs preliminary processing at Fog nodes, reducing the amount of traffic forwarded to centralized cloud servers.
To evaluate Quality of Service, the probability that information is delivered within the required deadline T_{max} is calculated as
$P(T < T_{max})$.

A higher probability indicates more reliable communication for delay-sensitive Smart City services such as intelligent transportation, emergency response, and healthcare monitoring.

The analytical model simultaneously considers stochastic traffic arrivals, communication resources, and distributed computing capabilities, providing a realistic representation of heterogeneous Smart City communication processes. The model therefore serves as the mathematical basis for simulation analysis.

IV. SIMULATION MODEL AND PERFORMANCE EVALUATION

To validate the proposed analytical model, a simulation environment representing an SDN-enabled Smart City communication network was developed. The simulation reproduces the interaction between heterogeneous IoT devices, SDN switches, Fog nodes, Cloud servers, and end-user applications.

The developed model consists of the following functional components:

- IoT sensor layer;
- SDN communication network;
- SDN controller;
- Fog computing layer;
- Cloud computing center;
- Application services.

Traffic sources generate packets according to heterogeneous arrival processes representing environmental monitoring systems, intelligent transportation sensors, surveillance cameras, healthcare devices, and smart energy infrastructures. Each application produces different traffic intensity and Quality of Service requirements.

The simulation evaluates the following performance metrics:

- Average end-to-end delay;
- Packet delivery probability;
- Network throughput;
- Resource utilization;
- Queue length;
- Packet loss ratio.

Several traffic scenarios were investigated by gradually increasing packet arrival intensity while maintaining identical network topology and communication bandwidth.

The obtained results indicate that the proposed information interaction model provides stable communication performance even under heavy traffic conditions. The integration of SDN with Fog computing effectively balances network load and minimizes queue formation at communication nodes.

Compared with conventional cloud-oriented architectures, the proposed model demonstrates:

- reduced average packet delivery delay;
- improved traffic distribution efficiency;
- lower network congestion;
- higher probability of successful packet delivery;
- improved Quality of Service for heterogeneous applications.

Simulation experiments further reveal that local processing performed by Fog nodes significantly decreases communication latency because only aggregated information is transmitted toward centralized cloud servers.

The obtained results confirm that distributed information processing combined with SDN traffic management provides a scalable communication solution for future Smart City infrastructures.

Table 1. Simulation Parameters

Parameter	Value
Simulation environment	AnyLogic
Network architecture	SDN + Fog + Cloud
Number of IoT devices	500–5000
Packet size	64–1024 Bytes
Communication protocol	OpenFlow
Traffic model	G/G/1
QoS metrics	Delay, Throughput, Packet Loss
Controller	Centralized SDN

Table 2. Comparative Performance Evaluation

Metric	Conventional Network	Proposed Model
Average delay	High	Low
Packet delivery probability	Medium	High
Queue utilization	High	Moderate
Throughput	Medium	High
Resource utilization	Medium	High
Scalability	Moderate	Excellent

V. CONCLUSION

This paper presented a probabilistic information interaction model for Smart City networks based on heterogeneous traffic flow analysis. The proposed approach integrates Software-Defined Networking, Fog computing, and Cloud computing within a unified communication framework capable of supporting large-scale IoT applications.

An analytical model describing probabilistic and temporal characteristics of information exchange was developed. The model evaluates communication delay, packet delivery probability, and resource utilization while considering stochastic packet arrivals and distributed computing resources.

Simulation experiments demonstrated that the proposed architecture improves Quality of Service by reducing communication delay, balancing network load, and increasing packet delivery reliability compared with conventional communication architectures. The integration of Fog computing significantly decreases latency by processing delay-sensitive information near end devices, while SDN enables adaptive traffic management according to network conditions.

The proposed model can be applied to intelligent transportation systems, environmental monitoring, smart healthcare, industrial IoT, and other Smart City services requiring reliable real-time communication. Future work will focus on intelligent controller placement, reinforcement learning-based traffic optimization, and multi-controller SDN architectures for large-scale Smart City deployments.

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