On the Impact of Road Traffic Control on Mobile Communications

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ICC 2022 - IEEE International Conference on Communications | 978-1-5386-8347-7/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICC45855.2022.9838310

Abstract—**Road traffic control systems can change vehicles' speeds, density, and distribution in spatial and temporal dimensions, which may have significant impacts on the performance of pre-established cellular networks and Vehicular Ad-hoc Networks (VANETs). Identifying these impacts is crucial for satisfying service requirements, especially for the future of connected autonomous vehicles. Despite the extensive research that studied the impact of mobility on communication, the impact of traffic control on communication has not been addressed. Therefore, in this paper, we attempt to understand how traffic control strategies can affect communication network performance. We focus on vehicle navigation techniques because of their global network impacts that can significantly affect the load and handover rate on base stations. In this paper, we compare the Dynamic Shortest Path Routing (DSPR) to the state-of-the-art vehicle routing techniques, namely, the K-Shortest Path Routing (K-SPR) and Travel Time System Optimum Navigation (TTSON). We build a real network with calibrated traffic and use a microscopic traffic simulator as a testbed to measure the load and handover rates on base stations. Moreover, we developed and validated an analytical model to compute the packet drop probability based on the base station normalized load in the Fifth Generation New Radio (5G-NR) cellular networks. The developed model is integrated into the testbed to evaluate the reliability of the three traffic control systems. The analysis shows that road traffic load-balancing achieved by both TTSON and K-SPR improves communication performance in the simulated network.**

Index Terms—**Cellular networks, Road traffic, CAV, 5G-NR, Simulation, Performance.**

I. INTRODUCTION

In the future, Connected Autonomous Vehicles (CAVs) will represent an integral portion of road traffic that will rely on communication technologies to achieve efficient and safe driving. CAV applications are expected to require high and strict communication performance in terms of throughput, latency, and reliability as described in [1]. These Key Performance Indicators (KPIs) depend on several parameters including the load on the base station, in the case of cellular service, or Roadside Unite (RSU) when utilizing Vehicular Ad-hoc Networks (VANETs). This load depends on the spatial distribution of the network users. A second key parameter that has significant impacts on communication performance is vehicle mobility which includes speed and location. The speed affects the network performance in different ways. First, higher speeds degrade the quality of the communication channel because of the Doppler effect, where the received frequency depends on the difference between the sender's speed and the receiver's speed. This frequency shift factor can be calculated as the speed difference Δv between sender and receiver divided by the speed of light c, i.e., $\Delta f = \frac{\Delta v}{c} f_0$. At higher speeds and higher frequency bands (such that in the 5G-NR), this frequency shift is noticeable and could significantly impact the channel quality, hence the communication KPIs. Secondly, user speed also has another important impact on the handover in cellular networks. As mentioned in [2], the impact of handover hysteresis values on communication latency and packet loss ratio cannot be ignored in some cases. This effect becomes more noticeable in 5G-NR because of the shorter coverage range and the dense deployment of the Next-generation Base stations (gNBs), which will result in higher handover rates that will increase with the user speed. The other component of mobility is the location, which also affects the communication quality as it determines the distance between the vehicle and base stations. Therefore, the vehicle location determines the signal strength it receives from the serving base station and how much interference a vehicle receives from other base stations.

Road traffic is controlled and managed by traffic control systems such as navigation systems [3], perimeter control and gating [4], traffic signal timing [5] and ramp metering [6]. A common feature of all traffic control systems is that they alter the vehicles' mobility on the road network, where they can change the speed vehicles are travelling on, and their spatial and temporal distributions. Therefore, deploying such traffic control technologies and the changes they produce in the vehicle speeds and distribution may have significant impacts on the performance of the pre-established communication networks.

Communication performance is not only important for users who may be using high-traffic applications such as video streaming, but also crucial for CAV, especially for levels 4 and 5 of the Levels of Automation (LoA). In these higher LoA, most of the applications running the vehicles are completely automated and depend heavily on inter-vehicle communication [1]. For instance, as mentioned in Rel. 16 of the 5G-NR [1], the sensor and state map sharing application requires a throughput of 25 Mbps at 90% reliability, which is a high throughput application, but it is tolerant to packet drops. Another application also mentioned in [1] is automated cooperative driving which requires exchanging 1200 bytes every 25 ms (= 384 Kbps) with a 99.99% reliability level. In such an environment, if the communication network does not satisfy the requirements of the CAV applications, this may result in accidents and fatalities, in addition to the low mobility performance on roads.

In cellular networks such as LTE, 5G, and 6G, communication KPIs are sensitive to the load on the base stations because each base station has a limited capacity depending on its equipment and configuration. Therefore, in future smart cities, before deploying new road traffic control strategies, it is imperative to understand how these will affect the performance of the communication network, and whether the existing network will be able to satisfy the requirements of the Vehicle-to-Everything (V2X) applications. This is a key to enabling service providers and telecommunication operators to plan and update their networks to meet the minimum requirements for CAV while providing the best service to users.

Therefore, this paper's objective is to study the impact of different road traffic control strategies on the performance of the cellular network. In this paper, we focus on the base station load and handover rates in cellular networks. More specifically, we compare the cell load and handover rate under three road traffic control techniques: the shortest path routing (DSPR), the Random K-Shortest Path Routing (K-SPR), and the Travel Time Optimum-Navigation (TTSON). The DSPR is the base case used by many navigation systems. The K-SPR is a promising technique because of its ability to mitigate the DSPR problems by utilizing load-balancing. The TTSON is the state-of-the-art that was published in [7]. The contributions of this paper are the following:

- We quantify the load and handover rate on the base stations under three different traffic control strategies on a real network. To do so, we implement two traffic control strategies (K-SPR and TTSON) within a microscopic traffic simulator; INTEGRATION software [8]. The simulator already has the DSPR developed.
- To study the impact of these loads on communication KPIs, we develop an analytical model to compute the Packet Drop Ratio (PDR) for the down-link in 5G-NR based on the normalized loads on the gNB. This model is validated against simulation data that is generated using the LENA 5G-NR implementation [9] within the NS3 simulator [10].
- The developed model is integrated within the traffic simulator and coupled with the traffic control system to compute the PDR under the three traffic control techniques.

To the best of the authors' knowledge, none of the previous related work addresses this issue. So, the work presented in this paper is a pioneering study to understand the mutual interdependence between road traffic control and communication performance, which is imperative for the future of CAV and network operators.

The remainder of this paper is organized as follows. Section II provides a brief overview of traffic control systems and designing cellular networks. Section III shows how the different road traffic control systems affect the load and handover rate on base stations in a real network. Finally, the developed analytical model and relationship between the network reliability and traffic control are presented in Section IV before the conclusions.

II. BACKGROUND AND RELATED WORK

This paper addresses a multi-disciplinary topic that covers communication in cellular networks and road traffic control. So, this section gives a brief background on traffic control systems and the cellular network design. It also discusses the relationship and mutual impact between traffic control and communication performance. Then, an overview of the related work is presented

A. Traffic Control

Smart cities employ information and communication technologies and use advanced computation methodologies to build efficient traffic control systems. By better managing the road network resources, traffic control systems can run the transportation system more efficiently to minimize road congestion, travel times, emissions, and more importantly, to reduce accidents and associated fatalities. This integration builds what is known as Intelligent Transportation Systems (ITS) [11], which are expected to be the core of transportation in future.

Many traffic control systems run under the umbrella of ITS. For instance, congestion detection and routing systems try to detect congestion and route vehicles away from congested roads, such as [12]. Most of the congestion detection systems utilize Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) communication to collect data on road conditions and send decisions or recommendations back to vehicles or drivers. Another example of traffic management and control applications is the eco-routing systems which aim to reduce greenhouse gases and fuel consumption by routing vehicles through environment-friendly routes, such as in [3], [13]. Eco-routing attracted the research community's attention because of its potential to solve not only road congestion problems but also to mitigate environmental and global warming problems. Perimeter traffic control and gating techniques represent another category of traffic control applications aimed at lessening congestion, especially in urban areas [4]. Most of the gating techniques limit access to a protected area by controlling the number of vehicles entering that area. This control can be achieved through traffic signal timing or blocking specific roads. There are other traffic control techniques including eco-driving which is a modern and efficient way of driving that emphasizes fuel efficiency and speed when approaching traffic lights, and ramp metering where signals manage traffic entering a freeway by optimizing the use of available gaps for vehicles to merge.

B. Cellular Network Design

When designing and planning cellular networks, a set of site locations and respective configuration of base stations is defined to meet the coverage and capacity requirements [14]. The design takes into consideration many parameters such as propagation characteristics of the area, traffic and demographic information, the type of radio frequency equipment, and types of base stations to be deployed (i.e., sectorized, omni devices) [14]. It is also important to account for frequency reuse to minimize interference.

Given these considerations, changing or updating cellular networks is complicated. So, most cellular network sites are set up once and then updated over long intervals. Consequently, when deploying a new road traffic control strategy, many things could go wrong. For example, the available capacity of the cellular base stations might not be able to satisfy performance requirements for the different services because the resulting vehicle loads may be significantly different from those were considered when designing the network.

A principal factor in designing cellular sites, is the maximum load on the site in terms of active users and packet load. As detailed in [15], the number of active users on a base station can be calculated as:

$$active\_users = \frac{pop \times adopt\_ratio \times market\_share}{OBF} \quad (1)$$

where pop is the maximum expected population in the area covered by the base station, $adopt\_ratio$ is the portion of the population which is expected to have mobile devices, $market\_share$ is the market share for the operator, and OBF is the overbooking factor which reflects the proportion of users expected to use the network at any single point in time.

As shown in Equation (1), the population density is the most important factor in determining the site capacity. Since this factor can be significantly affected by road traffic control, it is imperative for the cellular network operator to update their networks to be able to provide the required services under the new traffic control systems being deployed. For instance, if the traffic signal timing plans changed, vehicle queues at intersections would significantly change, consequently, the capacity of the covering sites may need to be upgraded.

C. Related Work: Mobility and Communication

Although numerous efforts attempted to study the impact of mobility on communication, none studied the impact of traffic control systems on communication. Most of the previous work focuses on evaluating the impact of vehicle mobility on communication performance. For instance, the author in [2] studied the impact of different handover parameters on the communication KPIs such as end-to-end delay and packet loss ratio around cell borders using a synthetic Manhattan grid network with synthetic traffic. The authors in [16], [17] evaluated the impact mobility on various metrics such as packet loss ratio, throughput, and delay in the MAC layer of the DSRC. In [18], the authors focus on safety-critical broadcast on the CCH in a VANET environment in highway scenarios.

Unlike previous work, this paper studies the impact of road traffic control and the changes it produces in vehicle distribution and vehicle routing on communication network performance. This study is the first work that links road traffic control and the spatio-temporal distribution of vehicles to communication KPIs.

III. THE IMPACT OF ROAD TRAFFIC CONTROL ON CELL LOAD AND HANDOVER RATES

This section presents the methodology we used to evaluate and compare the load and handover rate on the base stations under different traffic control techniques using a real-world network.

A. Simulation Network

To make this comparison a real-world road network is developed for Doha city in Qatar. Road parameters, such as road speeds, number of lanes, and traffic lights, are generated using data from multiple sources. The Doha city shapefile is used to generate the network nodes and links. OpenStreetMap data were used to extract intersection traffic control information including the traffic control methods (signs or traffic signals). The number of phases for each traffic signal and traffic signal timing data was obtained based on field observation and was augmented with real-time traffic signal optimization. Google Maps and ArcGIS were utilized for validating road attributes, including the number of lanes, one-way streets, and speed limits for each road segment. The resulting simulation network has 169 nodes, 301 road segments, and 11 traffic signals. The network is shown in Fig. 1. To accurately capture the real mobility, we use a microscopic traffic simulator, the INTEGRATION software [8] which is a discrete-time continuous-space traffic simulator. The road traffic in the network is calibrated based on car counts data collected from OpenStreetMap. The road traffic in the network is generated for 15 minutes and the simulation continues until the network is completely cleared. We run this network under the three navigation techniques using the travel time as a cost function.

B. DSPR, K-SPR, and TTSON

All three vehicle navigation techniques attempt to minimize travel time. DSPR is based on Dijkstra's shortest path algorithm where each vehicle is assigned the shortest travel time path when it starts its trip. DSPR continuously updates link travel times for the road network graph, allowing new vehicles to take different routes. Instead of using the shortest path, when a vehicle requests a route, K-SPR computes the k best paths and randomly selects one and sends it the vehicle. K-SPR, therefore, attempts to avoid congestion on the shortest path by utilizing alternative routes. Similar to K-SPR, TTSON also archives load-balancing and avoids congestion on the best routes by simultaneously utilizing alternative routes. But, rather than using a random route from the top k routes, TTSON uses an optimization model to compute the optimum load-balancing across the road network graph based on the utilization of each road segment, its travel time, and the current traffic demand entering the network. A detailed description of the TTSON optimization model can be found in [7].

C. Communication Setting

Regarding the communication setting, we assume that there are five base stations located in the area as shown in Fig. 1. We compute the load on each base station every second.

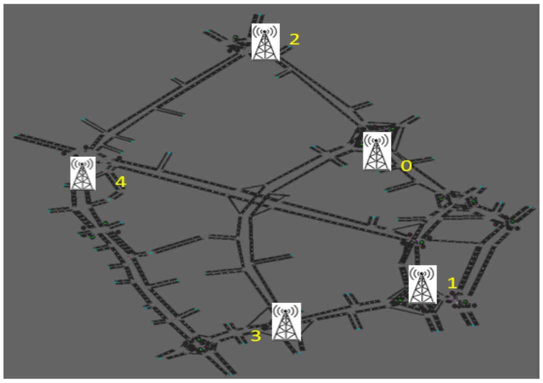

Fig. 1: The Network Model.

Assuming each vehicle is associated with the closest base station, every second the position of each vehicle is computed based on its speed, then, the closest base station is identified. Subsequently, the vehicle load on each base station can be calculated. As vehicles move, a vehicle may need to handover from the current base station to another one. These handovers are also tracked and the total number of handovers on each base station is recorded.

D. Cell Load

Fig. 2 compares the load under the three different traffic control systems for the five base stations. From Fig. 2, we see the cell load on all base stations using K-SPR and TTSON is lower than that in the case of DSPR most of the time. The reason is two-fold. Firstly, the TTSON and the K-SPR can assign vehicles going to the same destination different alternative routes at the same time compared to using the best route in the case of DSPR. This way, TTSON and the KSRP can load-balance the vehicular traffic across different routes, resulting in a more even distribution of vehicles on the road network which is reflected in the number of vehicles associated with each base station. Secondly, this distribution reduces congestion and leads to higher speeds and shorter trip times. Consequently, vehicles leave the network faster which reduces the total number of vehicles in the network as illustrated by the total curves in Fig. 2, resulting in reduced load on base stations.

Fig. 2 also shows that the load on base stations in the case of TTSON is lower than that when using the K-SPR, thanks to the optimized routing and load-balancing in the TTSON that produces a better distribution over the road network.

E. Handover Rate

Handover rate is an important factor that affects communication performance and service availability. A higher handover rate means more service disruption and higher packet drop rates. Fig. 3 shows the number of handovers during the simulation on each base station as well as the network total under the three traffic control techniques. In the simulation, there are 6574 vehicles. The average number of handovers per vehicle is 2.1, 2.6, and 2.7 for TTSON, K-SPR, and DSPR, respectively. These results demonstrate that TTSON reduces the total number of handovers by 22% compared to the DSPR. This is attributed to the fact that in DSPR, the shortest distance route may not be used (notice that we use the travel time as a cost function) and the shortest travel time route may be longer in distance, which means the vehicle may pass by more base stations. On the other hand, in the case of TTSON and K-SPR, a vehicle may be assigned non-optimal (from the travel time perspective) which might be shorter in distance. The results also show that the handover rate for K-SPR is close to DSPR, which can be reasoned to the selection of random routes (of the k top shortest routes). Meaning, some random routes may be longer in distance.

IV. CELL LOAD AND RELIABILITY IN 5G-NR DOWN-LINK

In this section, we study the impact of different road traffic control strategies on the reliability of down-link in 5G-NR cellular networks. First, we develop an analytical model for the down-link PDR versus base station load using queuing theory and validated this model against simulation data. Then, we use this model to study the impact of traffic control on down-link reliability.

A. Down-link Model for PDR

In this model, the base station is assumed to have a total bit rate capacity $C\ bps$ and there are N_u users associated with it. Each associated user establishes a connection to download a traffic stream from a UDP server in the network core with an average packet rate$\lambda\ bps$. For each connection, the packet inter-arrival delay is extracted from an exponential distribution with mean $1/R\ seconds$ and the packet size is $S\ bytes$. Users are randomly positioned in the coverage area of the base station as shown in Fig. 4. Given this setting, the base station has a total packet processing rate $C/(8 \cdot S)\ pps$. For each user download connection, the base station creates a queue of size k as shown in Fig. 4. Since all the users share the gNB resources, and they have independent and identically distributed (iid) packet inter-arrival intervals, they share the capacity equally, i.e., the packet processing capacity for each user is $r = C/(8 \cdot S \cdot N_u)$. In this scenario, each connection can be modelled using an M/M/1/K queue with processing rate r and packet arrival rate λ. And any packet that arrived at the queue can be dropped with average packet drop probability P_d as shown in Fig. 4, which can be computed as:

$$P_d = \rho^k \cdot \frac{1-\rho}{1-\rho^{k+1}}, \tag{2}$$

where $\rho = \lambda/r = 8 \cdot \lambda \cdot N_u \cdot S/C$ is the traffic intensity.

To validate this model, we use the NS3 simulator [10] and the LENA implementation for the 5G-NR [9] to run this scenario at different numbers of users N_u and different average user packet rate λ. In the simulation scenarios, the base station uses a frequency band of width $W = 100\ MHz$ at a center frequency of 28 GHz, which is in the millimetre wave band, i.e., FR2 in 5G-NR. Numerology μ number 4 is used. Given these parameters, the base station has $N_{PRB} = 34$ resource blocks which can be calculated as

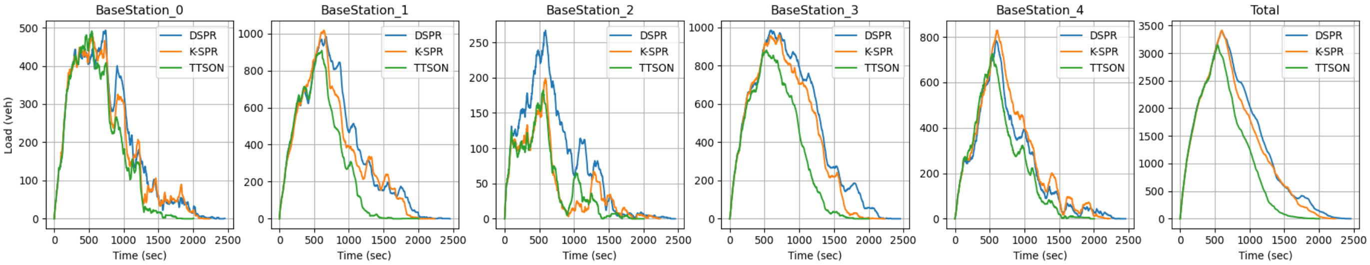

Fig. 2: The load on base stations.

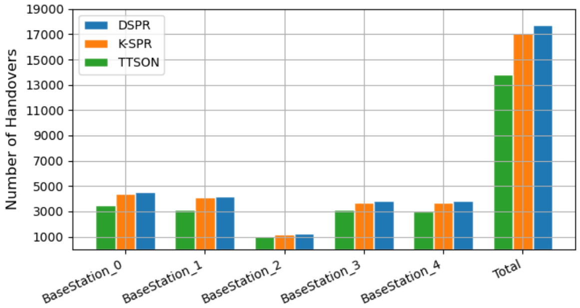

Fig. 3: The total number of handover on base stations and the total.

$$N_{PRB} = \frac{W}{12 \cdot 15KHz \cdot 2^{\mu}}, \tag{3}$$

where W should be in KHz. The total capacity C in $Mbps$ can be computed by Eq. 4, as detailed in [19].

$$C = Q_m \cdot f \cdot R_{\max} \cdot \frac{N_{PRB} \cdot 12}{T_s^{\mu}} \cdot (1 - OH). \tag{4}$$

where the modulation order $Q_m = 2$, the scaling factor $f = 1$, $R_{\max} = 948/1024$, the average OFDM symbol duration $T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}} = 4.4642\ microseconds$, and the overhead $OH = 0.18$. These values result in 138 $Mbps$ total capacity. According to the LENA implementation [9], the first and the last OFDM symbols in each slot are reserved for DL control and Up-link control, respectively. This means that 12 of the 14 symbols in each slot (i.e., 0.857 of the total capacity) are allocated for the data, which means that $C \approx 118\ Mbps$. The application UDP packet size is 1252 $bytes$, therefore, the total packet size $S = 1280\ bytes$, including the UDP and IP headers.

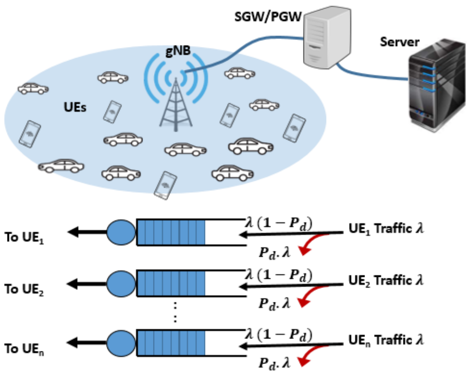

Fig. 4: The down-link queuing model at the base station.

Fig. 5 shows that regardless of the number of users the model can accurately compute the packet delivery ratio based on the normalized load on the base station which is the load on the base station divided by the base station capacity i.e., normalized load = $N_u \cdot R \cdot S \cdot 8/C$.

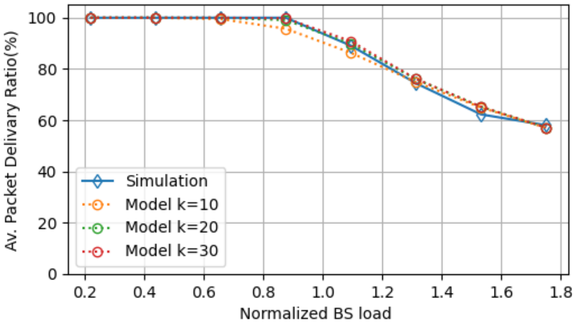

Fig. 5: Communication reliability vs normalized base station traffic load for different values of k.

B. The Impact of Road Traffic Control on Communication Reliability

In this subsection, we use the developed model to capture the impact of the different road traffic control strategies on down-link reliability. In our analysis, we assume that the base stations are designed to serve 2000 users with an average rate of 500 $pps/user$. In reality, the load on the base station comes from two types of users: stationary users (such as pedestrians or users in buildings) and moving users (such as vehicles or vehicle passengers). We assume that 60% of the capacity is used by stationary users, i.e., each base station has on average around 1200 stationary users connected. Therefore, the actual total load on each base station equals 1200 + the vehicular load that was computed in the previous section.

Fig. 6 shows the average packet drop probability on the five base stations for the three traffic control strategies based on the given assumptions. It shows that the drop probability in the case of TTSON is significantly lower than that in both DSRP and K-SPR cases. When Fig. 2 and Fig. 6 are combined, we see that even a slight change in the load caused by changing the traffic control can result in significant impacts on communication network reliability, which is reasoned to the exponential relationship between the load and the packet drop probability.

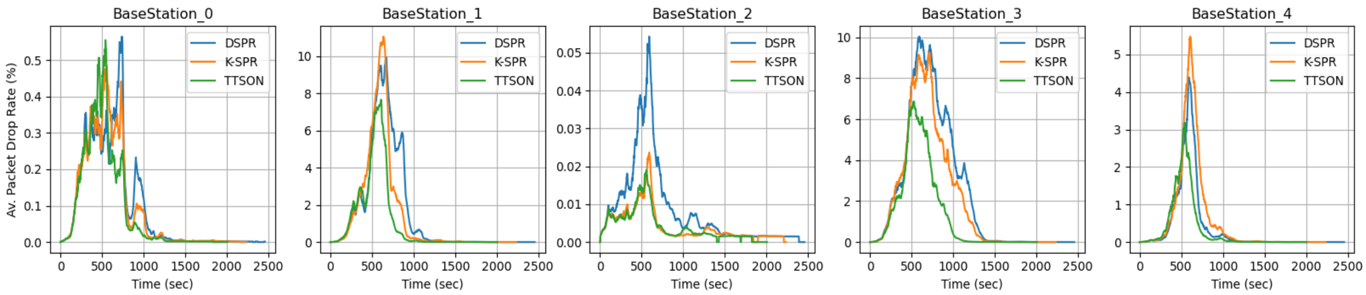

Fig. 6: The packet drop ratio on base stations.

V. CONCLUSION AND FUTURE WORK

This paper presents a novel study that helps understand the impact of traffic control on communication performance. This analysis is important for cellular network operators, especially when considering the future of CAV. The analysis shows that changing the road traffic control system can have significant impacts on cellular network performance. The study reveals that using advanced traffic control techniques that utilize traffic load-balancing can improve communication performance. The analysis also demonstrates that even slight changes in cell loads due to traffic control can have a significant impact on communication reliability because of the exponential relationship between the load the packet drop probability. Therefore, it is important for network operators to account for the traffic control systems and the produced impact on the cell load, especially in the future of the CAV and the need for high communication performance.

This study opens new doors to topics and questions in this area. For instance, it's important to understand how various mobility parameters, are affected by traffic control and how they can affect communication, especially congestion and low speeds at cell edges where channel quality is poor. Another question that is crucial for CAV is can we route vehicles in such a way that satisfies the communication requirements for the different CAV applications? As well, how can this communication-aware navigation affect different performance KPIs? Another important point is investigating these impacts in the case of events that have large gatherings where communication resources are scarce compared to the number of users.

ACKNOWLEDGMENT

This research is supported by a grant from the Natural Sciences and Engineering Research Council of Canada (NSERC) under grant number: STPGP521432-2018.

The authors would like to acknowledge Prof. Hesham Rakha for granting us access to the INTEGRATION software [8].

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