V2XArcSim: Evaluation of Efficient and Scalable 5G-based V2X Infrastructure Architectures

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***Abstract*—With the emergence of autonomous vehicles and intelligent transportation systems, vehicular communications will play a significant role in innovating, optimizing and realizing the next generation transportation systems. However, with the rise in these intelligent transport systems, it will be necessary to have flexible, efficient, scalable, and cost-effective vehicular infrastructure in place to support these transportation systems. This work studies the existing 5G NR architectures and radio capabilities, and alternative evolved 5G architectures which can be expanded to V2X communications. A novel V2X architecture with unique characteristics and advanced capabilities is proposed. A Python-based simulator is designed, which models vehicular mobility and signaling and data traffic. All the candidate V2X architectures are studied and evaluated using the simulator. These candidate architectures are evaluated using a variety of relevant metrics including the backhaul bandwidth utilization, IP packet latency, Physical Resource Block (PRB) Utilization efficiency, end-to-end packet transmission ratio. The simulation results clearly demonstrate that the proposed novel V2X architecture provides superior performance compared to other candidate architectures and provides additional benefits of flexibility, scalability, ease of deployment on a massive scale, power efficiency, and low cost.**

***Index Terms*—5G, 6G, Architecture, Autonomous Vehicles, KPI, Low Latency, NR V2x, Performance Analysis, URLLC, V2X Communications, NR V2X Simulator**

I. Introduction

The need for vehicular communications and automated traffic intersections has been rising as the overall traffic on roads increases. Vehicular communications is an excellent mechanism to ensure safety, enhance transport experience, and enhance fuel efficiency. The valuation of autonomous car market was $76.13 billion in 2020 and is projected to increase to $2,161.79 billion dollars by 2030 [1]. Hence, it is of utmost importance to focus on the safety and cooperative awareness of these vehicles to prevent any accidents and to ensure a smooth and fuel-efficient traffic flow. Researchers worldwide believe this level of safety can be achieved when vehicles can communicate directly and via the network [10].

The 5G NR radio interface supports usage scenarios such as enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC), and massive Internet of Things (mIoT) [16]. Compared to LTE, 5G NR's unique advantage is the ability to support URLLC. The 5G NR radio interface is significantly more complex, flexible, and capable compared to the LTE radio interface.

The authors in [11] propose a multi-level architecture which incorporates multiple wireless access technologies, multiple cellular technologies, and security. However, the 3GPP defined 5G architectures for end to end (E2E) V2X communications are not considered in their study. The authors in [17] propose a V2X architecture where vehicles collect their own state, transmit the individual state information to a virtualized Roadside Unit (RSU), and finally the RSU transmits this information back to other vehicles. The authors also perform a comprehensive study on the existing V2X simulators. The authors consider a virtual RSU architecture in their study, but to understand which architecture is best suited for NR V2X communications, there is a need to study standard existing architectures and their relative performance.

The authors in [14] propose a fog-computing based distributed architecture with three levels of processing power, at the vehicle, the edge, and the core. This distributed architecture supports both Vehicle to Network (V2N) and direct Vehicle to Vehicle (V2V) communications. The work does not perform an end-to-end performance analysis of the proposed architecture and does not provide a baseline architecture for a comparative analysis. The authors in [13] perform a comparative analysis between LTE based V2X and DSRC based V2X communications based on metrics like Packet Error Rate (PER) and Packet Delivery Ratio (PDR), but do not consider NR-V2X communications and the associated architectures in their study. The authors in [12] propose a V2X architecture where the vehicles share sensory data among each other to enable autonomous driving. The authors in [6] design a simulator to enable vehicle platooning. The authors in [9] develop a simulator to evaluate C-V2X scenarios and evaluate them based on packet delay and packet loss ratio. The above designed simulators lack the capabilities of evaluating these studied scenarios for multiple architectures.

The authors perform studies on several V2X architectures and simulators. To further research in this area, this work studies various standard architectures, proposes a flexible and cost effective 5G based NR- V2X architecture and propose a python-based simulator to study various architectures and their comparative performance in a simulated environment.

Three key contributions of the work are as follows.

- This work performs a comprehensive study of the various

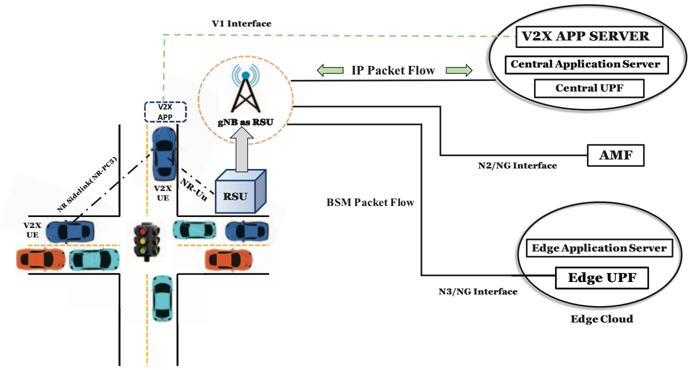

Fig. 1. 5G V2X Architecture with gNB as the RSU

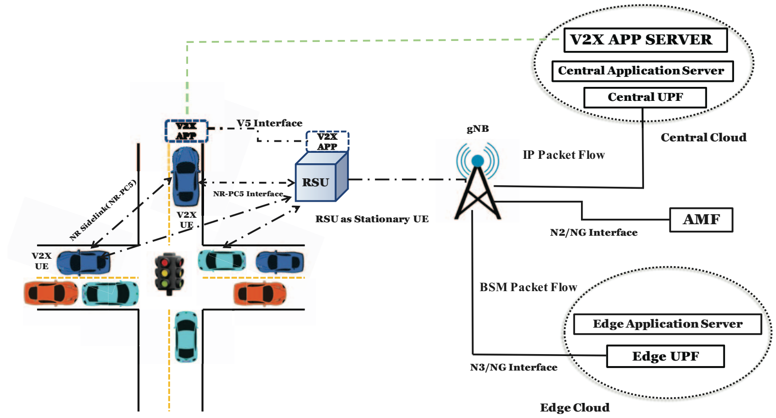

Fig. 2. 5G V2X Architecture with UE as the RSU

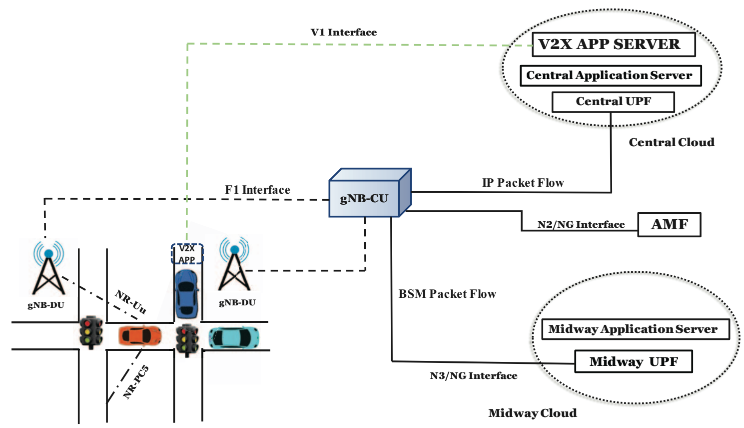

Fig. 3. Disaggregated gNB architecture for V2X

5G NR-V2X architectures defined in the 3GPP such as the gNB as the RSU architecture, the stationary UE as the RSU architecture, the disaggregated gNB architecture and the Integrated Access and Backhaul (IAB) architecture.

- This work proposes a novel Hybrid RSU architecture which aims to be more flexible, spectrally efficient, power efficient, and cost effective when compared to the other candidate architectures.
- A Python-based simulator, V2XArcSim is designed to simulate real world traffic intersections with vehicles. Both BSM and IP traffic originate from every vehicle in the simulated environment and are tracked until they reach the application server. The simulator evaluates all the candidate architectures using four KPIs such as the backhaul bandwidth utilization, the IP packet latency, the PRB utilization and the packet transmission ratio.

The rest of the paper is organized as follows. Section 2 studies the various conventional and alternative 3GPP 5G NR-V2X architectures and proposes a novel hybrid RSU architecture. Section 3 discusses the simulator design for evaluating the performance of these architectures. Section 4 discusses the performance evaluation results, and Section 5 provides concluding remarks and future work.

II. Candidate Architectures

A. *Standard Architectures*

gNB as the Roadside Unit. This architecture option consists of vehicles with the OBUs and the UEs, the gNB as the RSU, the 5G Core, and the V2X Application Server. Fig. 1 describes the overall architecture of a gNB- RSU. The vehicle UEs communicate with each other using the sidelink interface (i.e., PC5 interface), and the vehicle UEs communicate with the 5G gNB through the Uu interface [3]. The vehicles typically generate two types of information, Basic Safety Messages and IP user traffic. The gNB transmits these packets to the UPF in the 5G Core, and these packets are then transmitted to the Application server in the central cloud. The UPF entity may be situated in (i) the edge cloud, (ii) the central cloud, or (iii) both the edge and central clouds. The gNB functioning as an RSU contains all its functionalities defined in [5]. It is thus responsible for scheduling resources for transmission of the uplink data from the vehicle to the Application Server.

The approach of using the gNB as the RSU can be enhanced by introducing an instance of VAS/ECS connected to the intersection gNB for local intersection management. The intersection VAS/ECS can be connected to the centralized VAS through a new interface. However, the UE-VAS interface can be used as the VAS-VAS interface.

Stationary UE as the Roadside Unit. This architecture is similar to the first conventional architecture. However, as shown in Fig. 2, the RSU in this architecture is a stationary UE [4]. Thus, it will not have all the resources and functionalities of a gNB. The UE-RSU thus communicates with the vehicles through the sidelink interface and transmits the BSM and IP traffic to the gNB. Additionally, the UE-RSU supports both modes of resource allocation through the sidelink, either with the gNB allocating resources dynamically or the RSU using resources from a pool of pre-configured resources. Fig. 2 describes an example architecture with a stationary UE as the RSU.

Disaggregated gNB Architecture. Deployment of Disaggre-

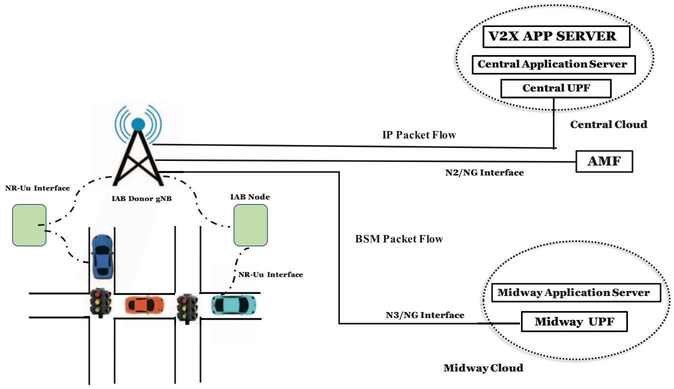

Fig. 4. IAB Architecture for 5G NR V2X

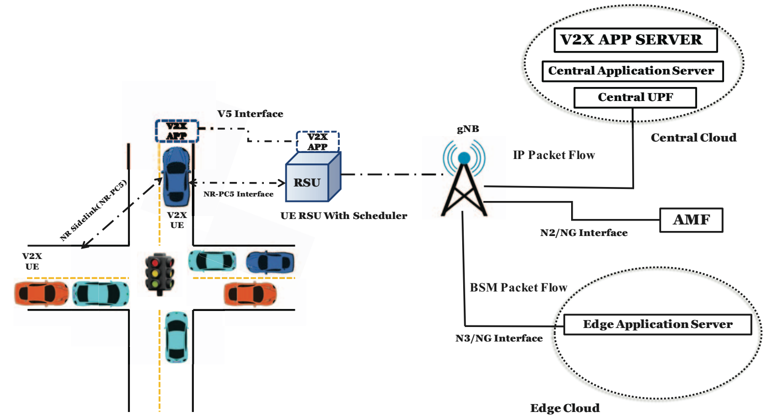

Fig. 5. Hybrid RSU Architecture for 5G NR Vehicular Communications

gated RAN in a distributed manner is mentioned in [15]. The gNB-DU serves the intersections, and the gNB-CU can be deployed at a centralized location for scalability as shown in Fig. 3.

One advantage of this deployment option is uninterrupted services for the vehicle, as the IP address and the connection are preserved across multiple gNB-DUs served by one gNB-CU. and one UPF. As shown in Fig. 3, the gNB-DUs are deployed at the intersections and a gNB-CU is deployed at a centralized location. The vehicle UE communicates with the gNB DU through the Uu interface, and the gNB-DU-gNB-CU communications is enabled through the F1 interface. The F1 interface is usually implemented using a wireline connection. Since the traffic flows through the gNB-CU at a centralized location away from the gNB-DU, the BSM and IP traffic traverse from the gNB-CU to a midway cloud in an example implementation. Such a midway cloud resides between the edge cloud and the central cloud. The midway cloud is intended to be placed close to the gNB-CU, inside which the midway UPF and midway application server are located.

Integrated Access and Backhaul Architecture. Fig. 4 describes an example deployment of the Integrated access and Backhaul (IAB) architecture for V2X communications. The IAB architecture is similar to the disaggregated gNB architecture, with a few differences. The IAB architecture deploys IAB nodes which communicate with the vehicle UEs through the Uu interface and relay the information to a donor IAB node through a wireless backhaul channel [15]. Only the IAB donor needs to be directly connected to the 5GC; IAB-nodes do not directly connect to the 5GC. This architecture option also provides additional flexibility by further disaggregating the donor gNB into the DU and CU splits.

B. Proposed Architecture

Hybrid RSU Architecture. This work proposes a novel architecture that can be implemented and deployed to significantly improve flexibility, increase efficiency, and reduce costs for the V2X communications infrastructure. The proposed architecture is designed to facilitate widespread deployments of the V2X communications infrastructure cost-effectively, as shown in Fig. 5.

Only mobile devices or Base Stations can be placed at the RSU per 3GPP specifications, significantly limiting deployment flexibility and increasing deployment complexity and costs. The proposed new architectural entity will reduce the cost of V2X deployments and enhance the communication service experience of users.

The proposed architecture combines selected characteristics of a mobile device, Base Station (BS), and optionally core network to create a new medium-complexity entity to enhance spectral efficiency, reduce latency, and decrease costs. The HDN obtains sidelink resources from its serving BS and schedules radio resources by acting as a BS to significantly increase the efficiency of radio resource utilization.

The proposed architecture is similar to the UE-RSU architecture with a few innovations as shown in Fig. 5. The Hybrid RSU would function as a distributed scheduling anchor/reference UE for allocating radio resources to vehicle UEs by performing the gNB scheduling function. This architecture would decrease the latency of the network traffic flow. The UE is transformed into a Hybrid Device, and it performs the scheduling function of a base station for the vehicles.

The hybrid device architecture obtains the radio resources from its serving BS using one or more of several approaches. In one approach, the hybrid device obtains its resources to be used in its target service area dynamically from its serving BS. In another approach, the hybrid device obtains its resources semi-statically through signaling, such as RRC signaling. Alternatively, the hybrid device is preconfigured or pre-provisioned with radio resources.

III. V2XArcSim Design and Analysis

The Python-based simulator designed and developed integrates seven key aspects for enabling vehicular communication simulations, as shown in Fig. 6. They are configuration and initialization, traffic generation, vehicular traffic modelling, resource scheduling, network and vehicular traffic tracking, and quantifying performance metrics. To begin the study,

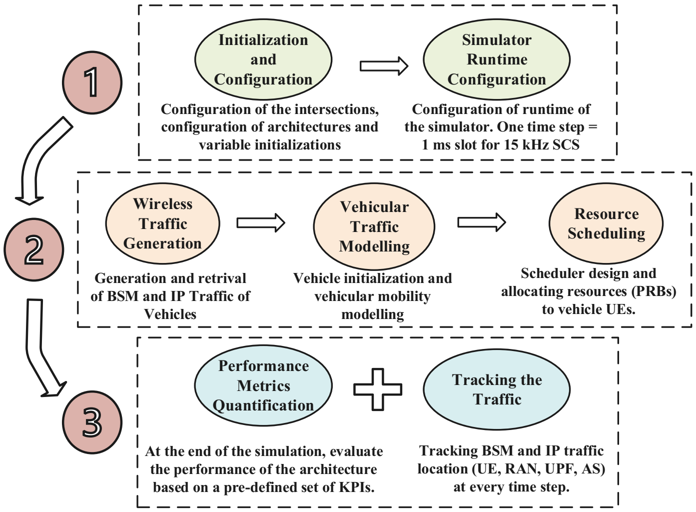

Fig. 6. Key Aspects in Simulator Design

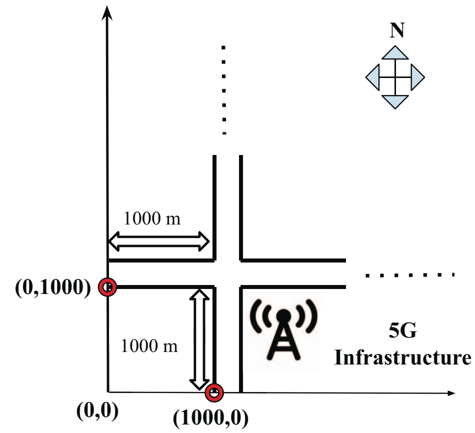

Fig. 7. Single Intersection Model

an environment of 16 intersections is created. Then vehicles are introduced into these 16 intersections. From a network perspective, vehicular and network traffic is generated, tracked and the performance of various 5G architectures based on Key Performance Indicators (KPIs) like the backhaul bandwidth utilization, number of Physical Resource Blocks (PRB) utilized during the simulation, the IP packet delay and the end-to-end delivery of IP packets are analyzed. The RSU-gNB architecture and the RSU-UE architecture are modelled using the 3GPP TS 23.285 [2] and the Annex B of TS. 23.287 [3] and used as baseline architectures for further modelling and analysis.

A. Environment.

The simulator is designed to replicate mobility, vehicular traffic and network traffic close to a real-world scenario. To evaluate the performance of various 5G architectures in such a scenario, an environment of 16 intersections is considered. The environment is modeled on a co-ordinate plane, with each road in the intersection being 1000 meters long. A 5G infrastructure element is placed at each intersection Fig. 7 describes an intersection modelled on the co-ordinate plane, and the environment in the simulator extends to 16 intersections.

B. Vehicle Modelling.

Vehicular mobility and traffic model development is another key aspect considered in designing the simulator. First, a vehicle is spawned randomly at one of the 16 entry points of the environment. The vehicle's speed is 35 mph or 15.6464 m/s, and it remains constant throughout the simulation. Once the vehicle spawns in the simulation, it moves toward the nearest intersection, which would be 1000 m away from the spawn point.

Vehicle specific information like the X and Y co-ordinates, the velocity of the vehicle, the spawn point of the vehicle and the number of intersections it crossed are updated each time interval, which is considered 1 ms in the simulation. Once the vehicle reaches its first intersection, the vehicle then turns in one of three directions randomly, except for the direction which it previously traversed.

When the vehicle spawns at one of the 16 intersection points, the vehicle would spawn at the extreme ends of the intersections: the four north (N1-N4), east (E1-E4), west (W1-W4) or south (S1-S4) points. The initial co-ordinates of the vehicle are assigned based on the spawn point. Once the vehicles are spawned and assigned their co-ordinates, based on the direction of traversal, we update the co-ordinates of the vehicles.

C. Cell Functions.

Two primary functions are defined for a network element (e.g., a gNB, Hybrid RSU, a gNB DU, or an IAB-node), serving a specific intersection. The network element will need to consider the traffic of all the vehicles in the intersection. To achieve this, the network element queues all the vehicles with traffic in the serving range. Then, it transmits the network traffic of one vehicle to the core network, and once all the available packets are transmitted, the vehicle is placed at the bottom of the queue. The vehicle will again be able to transmit, after all the vehicles in the serving range are able to transmit all their data. In summary, round-robin scheduling is used.

The second primary function of the cell is resource scheduling. This resource scheduling involves both BSM resource scheduling and IP traffic resource scheduling. The cell will schedule resources to the vehicle, which is at the top of the queue, and the vehicle information is obtained from the above function. The network element would first allocate resources for establishing the connection and determining the appropriate amount of resources through Access Stratum (AS) signaling messages. Once the connection is established and the gNB determines the appropriate amount of resources to allocate for a specific vehicle based on the amount of traffic it needs to transmit, the network element would allocate resources appropriately. Additionally, we consider the maximum amount of PRBs available at each network element for one TTI to be 52 [5]. Resources are allocated to the vehicles to transmit BSM, and if there are PRBs available after BSM message transmission, IP messages are transmitted. Each vehicle transmits basic safety information to the network element every 10 ms or every 10 TTIs. In case the vehicle is not able to transmit all the intended traffic in one TTI, it will be able to transmit its data in subsequent TTIs until all of its data is transmitted. Once a vehicle transmits all its data, it goes to the bottom of the queue.

D. BSM and IP message Generation and Tracking.

Basic Safety Messages (BSM) carry vehicle related critical information like the location of the vehicle, the velocity, acceleration, and vehicle size among others. The overall flow of the BSM message is from the vehicle to the roadside unit (RSU) infrastructure. To enable reliable vehicular communications, we allocate dedicated resources to the RSU for transmission and reception of BSM messages. The simulator is designed to consume 5 PRBs to transmit one BSM message.

IP messages carry the internet traffic from the vehicles. The overall IP packet flow starts at the vehicle, then it passes through the network element at the intersection, the gNB, and the UPF of the 5G core and finally reaches the application server. The simulator is designed to consume anywhere between 1 and 12 PRBs to model variations that reflect the size of the generated IP packet and the radio channel conditions. Fig. 8 describes the overall packet traffic modelling.

Before the simulation begins, two 2-dimensional data structures are created which store the BSM and IP packet arrival times for each vehicle. Hypothetically, all vehicles spawn at random at the edge of the environment, and it is assumed that the vehicles start generating BSM and IP data from the time of spawn (i.e., at TTI=0). It is additionally assumed by default that every vehicle generates one BSM message every 100 ms or 100 TTI. In case of IP packet generation, the simulator generates 5 to 20 IP packets randomly in a uniform distribution. The next instant that the vehicle generates IP packets again is determined randomly in an exponential distribution.

E. Bring it all together.

Once the preparation is complete, the simulator starts to run. A few functions in the simulator are called at every instant and others are called periodically, based on their usage.

At the first instant, the simulator spawns all the vehicles into the environment. The position of the vehicle in the environment updates at the first time instant and every 1000 TTI or 1 second thereafter, as the vehicle moves 15.6 meters per second. The simulator keeps track of the unique vehicle IDs, their co-ordinate data and their serving network element at every instant. Once the vehicle tracking is completed, the scheduling job of every network element serving its set of vehicles begins. The network element checks if there is a BSM message that the vehicle is trying to transmit. In case the vehicles are waiting to transmit a BSM packet, the network element schedules resources appropriately. Additionally, the simulator keeps track of the location and state of the BSM packet.

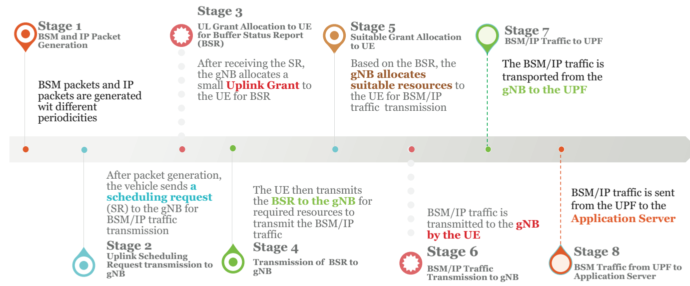

Fig. 8. Packet Traffic Modelling of BSM and IP Messages

After scheduling and tracking the BSM packet, the network element checks if there are IP packets from vehicles that are waiting to be transmitted. If there are IP packets in queue, the IP scheduler is activated and transmits the packets from the UE to the application server. Again, the simulator keeps track of the location of every IP packet. The simulator design and analysis follows a similar thought process to the works in [8] and [7].

IV. Results and Discussion

Backhaul Bandwidth Utilization. The backhaul bandwidth utilization depicts the amount of traffic flowing from the RAN to the UPF. The simulation assumes that 16 RAN units are connected to one UPF in the 5G Core. Fig. 9 shows the backhaul bandwidth utilization at each intersection throughout the simulation. The figure provides us insights on the maximum amount of backhaul bandwidth utilized by each architecture, with the hybrid architecture utilizing the maximum amount of bandwidth and the IAB architecture utilizing the minimum amount. Faster scheduling at the Hybrid RSU enables more traffic to be transferred. Thus, this metric gives us an insight of how much dedicated bandwidth every architecture requires to transmit information from the gNB to the UPF at the 5G core.

Another insight that can be drawn from Fig.9 is that the intersections 16 through 32 are the intersections at the edge of the simulated environment and are commuted by vehicles in the simulations less frequently when compared to the intersections towards the center of the intersection environment. The the backhaul bandwidth utilization at the edges of the simulation environment is low when compared to the utilization toward the center.

IP Packet Latency. This KPI tracks the amount of time it would take for an IP packet (that is generated at the vehicle) to reach the application server after traversing through the RAN and the 5G core. Fig.10 describes the IP latency of various 5G

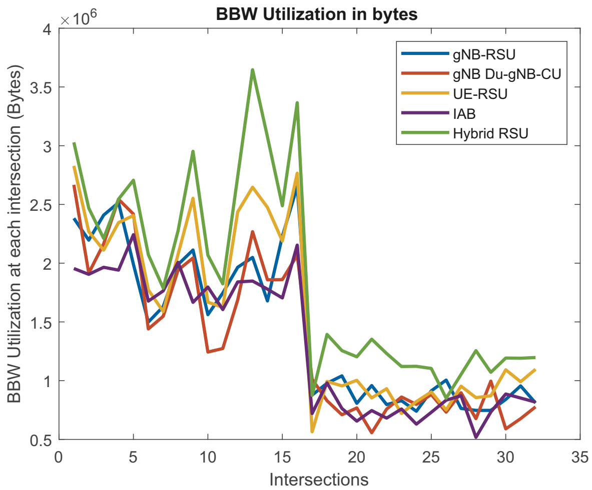

Fig. 9. Backhaul Bandwidth Utilization

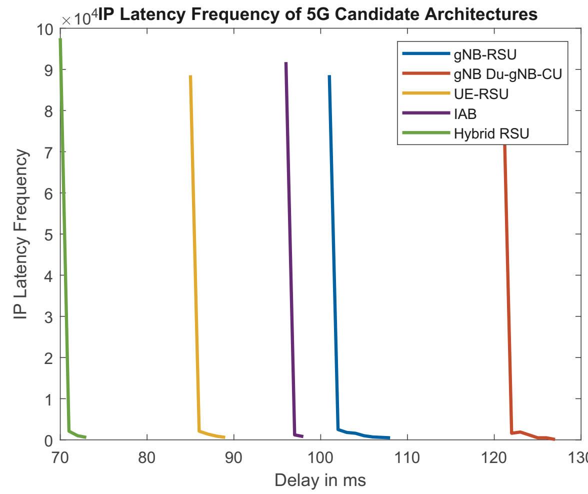

Fig. 10. Histogram of the IP Packet Latency for 5G candidate Architectures

candidate architectures. The disaggregated gNB architecture has the highest IP packet delay among the architectures. The IAB architecture and the aggregated gNB architectures have an IP packet delay greater than 100 ms. This observed trend is caused due to a number of factors such as increased latency due to increased number of network infrastructure elements and their associated transmission, scheduling and processing delays. Another factor for the increased latency in the IAB architecture is due to the wireless backhaul link between the IAB node and the donor gNB. The proposed architecture reduces the overall latency due to the decisions made by the HDN UE compared to other architectures where decisions are relatively centralized and processing and transport delays occur.

One major insight that can be drawn from Fig.10 is that a majority of the IP packets experience a delay close to their theoretical approximate, with a minority of IP packets experiencing a little longer delay, even with constraints like limited radio resources and randomness in IP packet generation times and their size. The second insight is that hybrid architecture has significantly lower latency when compared to the other architectures. When the IP Packet latency is considered, the hybrid-RSU architecture has the best performance among all the 5G candidate architectures, with a latency of around 70 ms.

PRB Utilization. The amount of resource blocks consumed by all the vehicles at each of the 16 intersections to transmit BSM and IP traffic. The maximum number of PRBs available at each network element at each intersection for one time interval is 52 PRBs. The number of PRBs consumed at each intersection for each TTI are observed and added up at the end of the simulation. For 100 vehicles, the PRB utilization is similar for all candidate architectures. One insight that can be drawn from this KPI in Table 1 is, since the median and mean PRB utilization are close in value to each other, the distribution of PRB utilization is symmetric. Thus, the PRBs are sufficient to support the amount of traffic load modeled in the simulator. Future work can carry out a detailed sensitivity analysis to further evaluate PRB variations. Finally, when we consider the PRB utilization statistics in table 1, all the candidate architectures perform equally well.

TABLE I
PRB Utilization Statistics for Various Candidate Architectures

Architectures	98 %	90%	50%	Mean
gNB as RSU	52.0	52.0	35.0	30.847
gNB DU- CU as RSU	52.0	52.0	35.0	30.501
UE-RSU	52.0	52.0	35.0	30.625
IAB	52.0	52.0	35.0	30.574
Hybrid RSU	52.0	52.0	35.0	30.501

End to End Packet Transmission. This KPI allows us to understand what percentage of the generated packets actually reaches the application server. The end-to-end transmission success rate of IP packets can be determined by the ratio of the number of packets that reached the application server to the number of packets generated. Note that only relative values matter; when the simulator stops, there would be many IP packets still waiting to be scheduled or in transit to the AS. Table 2 describes the packet transmission ratio of all the candidate architectures. The hybrid RSU architecture has the best performance with a 0.54 packet transmission ratio. Considering this KPI, the hybrid RSU architecture deployment would be the best deployment option.

V. Conclusion

The work studies various 3GPP 5G NR based architectures for their applicability to V2X communications infrastructure. These architectures include the gNB as the RSU, a stationary UE as the RSU, the IAB architecture, and the disaggregated

TABLE II
PACKET TRANSMISSION RATIO OF VARIOUS CANDIDATE ARCHITECTURES

Architectures	Transmission Ratio
gNB as RSU	0.367
gNB DU- CU as RSU	0.384
UE-RSU	0.417
IAB	0.32
Hybrid RSU	0.54

gNB architecture. A novel Hybrid RSU architecture is proposed and evaluated to improve flexibility, increase spectral efficiency, and reduce costs for the V2X communications infrastructure. The paper introduces a Python-based simulator to simulate various aspects of vehicular communication. The simulator begins with vehicular and vehicular network traffic generation to generate vehicles and their respective BSM and IP traffic. The simulator then performs vehicular traffic modelling to define a 16-intersection environment and model the movement of vehicles in this environment. The simulator also performs resource scheduling, network and vehicular traffic tracking, and quantifying performance metrics such as the backhaul bandwidth utilization, IP packet latency, PRB utilization, and end to end packet transmission. An extensive simulation-based analysis has been carried out, and all candidate architectures are evaluated using a variety of relevant performance metrics. The simulation results clearly demonstrate that the proposed architecture outperforms the other candidate architectures in terms of utilizing the backhaul bandwidth more efficiently, having low IP packet latency, and having the most packet transmission ratio. Additionally, the proposed V2X architecture yields additional benefits of flexibility, scalability, ease of deployment on a massive scale, power efficiency, and low cost. As a part of future work, the proposed simulator could be enhanced by designing the vehicular mobility aspect in terms of addition of adaptable traffic lights, variable speeds of vehicles and increased simulation times. Additional KPIs to consider are the handovers between the 5G infrastructure units and the normalized cost to deploy these infrastructure units at traffic intersections. Another direction of future work would be the optimization of the unicast, broadcast, and groupcast strategies for smart intersections.

VI. ACKNOWLEDGEMENTS

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