Vehicular Intelligence: Towards Vehicular Network Digital-Twin

Duaa Zuhair Al-Hamid and Adnan Al-Anbuky
Electrical and Electronic Engineering
Auckland University of Technology
Auckland, New Zealand
Email: {Duaa.alhamid, Adnan.anbuky}@aut.ac.nz

***Abstract*— Vehicular network (VN) is considered as one of the enabling technologies that requires stable connectivity among the vehicles. The significant dynamics in vehicular structure on the road necessitate the rapid information flow in managing crucial events. Dynamically, each network has a given lifetime from the initial formulation of a networked group to the final diminishment of the group. Throughout this lifecycle, a group of vehicles form a network and open the door for further vehicles to join, or existing vehicles to leave. Vehicles departing the group may rupture the data network and cause fragmentation or isolation of part of the network structure that raises the need for smart self-healing. The response to these events may cause latency in handling the flow of data, and hence efficient operation with minimal latency is required. Such network demands a flexible and autonomous self-structure approach with real time computational capabilities. Realizing this vision requires a network that supports low latency for interaction among the members as with the edge, fog and/or cloud. It is anticipated that driving towards the novel concept of vehicular network digital twin will offer the platform with backup intelligence and support for designing the scenarios that can have better interaction with road dynamic events with minimal latency. The objective of the paper is modelling the latency associated with the dynamics of the vehicular grouping approach to investigate the performance of a given dynamic group running on the road. This is aligned with road model boundary and limitations. Herein, the applicability of the grouping approach is tested based on the road capacity supported by the road boundary and number of lanes. Testing using Contiki-Cooja simulator has been implemented focusing on the latency and packet loss performance measures for the self-healing and self-formation phases.**

Keywords*— *Vehicular network, Wireless sensor network, Virtualization, Network digital twin

I. INTRODUCTION

As with the rapid growth of vehicular technical capability, the high mobility, and heterogeneous structure of the vehicular network (VN) makes it challenging to maintain communication among the vehicles, and to structure an intelligence-enabled network with the ever-increasing traffic data demands. The concept of connected vehicles and self-structured network has gained substantial momentum to bring a new level of an adaptive network approach. The applicable network structure along with the onboard sensing and computing technologies can enhance the intelligent transportation systems (ITS) promoting autonomous vehicles on the road. Therefore, the future intelligence of the VN would allow the network to be self-adaptive to the road and traffic conditions as well as user requirements. From the topological structure point of view, network connectivity and decision-making impose significant challenges in managing the nodes resource constraints and enhancing network performance. Therefore, some advanced techniques such as intelligent clustering for VN, cloud computing, and virtualization are proposed to offer network intelligentization and overcome those challenges [1].

The clustering approach that is considered as one of the intelligent VN elements has been studied by researchers suggesting various methods to improve cluster stability [2]. Although existing clustering schemes reflect enhancement in cluster structure and stability, the classical existing approaches have not satisfied the distinctive requirements such as a flexible, manageable, and scalable network under the dynamic changes. As vehicular clustering tends to be influenced by the road structure and the frequent topological changes, the network lifecycle plays an important role in network management. Thus, the network performance mainly its response and recovery time can significantly be affected under the road dynamics.

The VN intelligent self-organized structure can be employed to enable the rapid response capability supporting the low-latency massive data exchange. This has been looked at from the dynamic grouping through self-x phases (i.e., self-formation, self- leaving, self-healing, and self-joining) based on functional ability of each node within wireless sensor network (WSN) [3], [4]. These are three core functions represented by 'Leaf Sensor Node', 'Router Node', and 'IoT Gateway Node' that can be modelled and tested on a virtual platform before the physical implementation [5]. A self-configured network formation that could similarly behave as the physical network entails the support of the digital twin [6]. This could then facilitate dynamic planning for orchestrating the vehicular network as demanded by road events. As twinning technology has evolved with the advent of the Internet of Things (IoT), the interaction between the virtual vehicular network and the vehicular network on the road can lead to the Internet of Vehicles (IoV) paradigm. This is emerged as the new architecture of VN, providing reliable connectivity, and presenting various services through extensive sensing, storage, computation, intelligence, and learning capabilities [7].

In this paper, the end-to-end delay performance measure is considered as one of the important metrics to be used for evaluating the network under the various dynamic phases. This should be aligned with the road analysis reflecting the group life cycle through the life, sustainability, and death. This in effect requires identification of the ideal size of a given group on the road as it goes through the phases of grouping. The scheme could be placed on the virtual machine to be tested and analysed in offering the best performance for a physical network. It could also be used as edge computational resources for managing the group dynamics in reaction to the various road generated events. The data for self-adaptive networks can be managed through the communication messages exchanged among the vehicles, and the gateway be it a ground infrastructure or a mobile node such as UAV [8]. Various enabling technologies such as virtualization, and software-defined network (SDN) can greatly benefit the proposed self-x scheme. This is through the future supervised prediction when a group formation, and group maintenance can be modelled virtually. In addition, the road model can enhance the virtual grouping model before the actual network implementation on the road.

The remainder of this paper is structured as follows: Section II provides the proposed system architecture for vehicular group communication and functional components. Section III presents road traffic and network latency modelling. Section IV describes the network scenario and results. Finally, the conclusion of the research work is presented in section V.

II. VEHICULAR GROUPING ARCHITECTURE

A. *The System Architecture*

The Figure 1 below depicts the suggested system architecture for the vehicular grouping approach, where the physical vehicular network is connected over the Internet via a gateway node, that could be represented by infrastructure or a mobile node, to the cloud paving the way for establishing the digital twin. The overall structure of a cyber physical system can be reflected by the organisation of a VN operating system supported by the IoT virtual cloud environment. Each tier/layer of the system architecture can offer to assist in overcoming the overall system challenges and to make the system more robust and scalable. For instance, the cloud interaction with the vehicular physical network on the road could be utilized for exploring future improvement in the operation with various software scenarios through the virtualization, data history and learning methods. Hence, based on the data analysis, the cloud service platforms could support, monitor, plan and interact with the physical network environment.

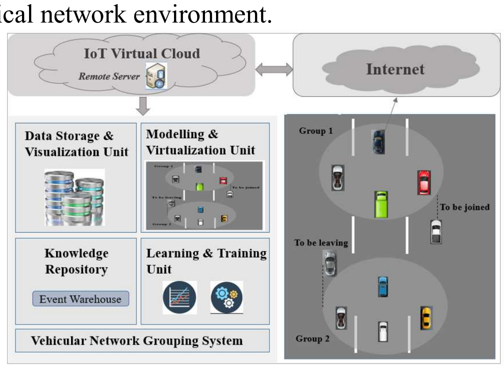


Fig. 1. The system architecture of vehicular grouping approach [5]

The functionality of vehicular network nodes that is supported by the WSN three core functions can be modelled and tested on a virtual platform before its actual physical implementation. The virtual platform is used to test the dynamic re-orchestration of the network organization allowing for the network reformulation where the related virtual functions are deployed onto virtual motes. For example, a node functional role at the virtual platform can be switched through software reformulation in which any of the core functions is implemented. Hence, the network operation and performance requirements can be met and any major modifications that may take place can be prevented beforehand as the structure and history of the dynamic events of the physical VN can be retained in the cloud.

Figure 2 depicts some of the activities associated with each function that can benefit the network operation requirements. A node that is capable of accessing the cloud holds a gateway function that can be elected as the group head and be responsible for the connected nodes such as router nodes or leaf nodes. The gateway function main activities include being the sink for the data gathered from the vehicular group and providing the connectivity to the internet. Other activities can be based on communication, buffering, local computation, and management. The router function has the capability to route the received data to the sink or other routers if the network is multi-hop, and act as a cluster head for the group. The core activities associated with the leaf function include the sensing, data acquisition, and the local edge capability. The edge activity here is related to data management such as buffering (data samples are sensed by the leaf node and buffered), and local computation.

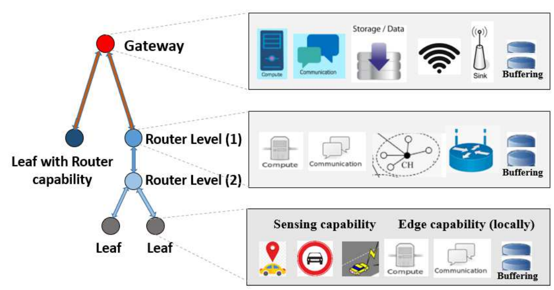


Fig. 2. The node function activities

B. *Vehicular Group Scheme: Self-X Phases*

The dynamic events within the road represented by vehicles leaving or joining the network while changing lanes during the driving require adaptive, and real time network management. The network data management is one of the aspects that needs to be taking into consideration, mainly when it comes to self-adaptive networks considering the communication among the vehicles, and the gateway (be it a ground infrastructure or a mobile node). Emphasis has been laid on the vehicular network topology structure to be based on the road nature wherein the vehicles are distributed over number of lanes and along the length of the road. Herein, the data flow in tree network setup is seen as an authentic approach that could be aligned with the road structure.

From the modelling point of view, the proposed vehicular grouping algorithm considering the phases of Self-X is designed to be tested at the virtual level before the actual implementation. Based on the WSN functions, each phase is conditionally initiated and maintained to offer the full virtual organization of a flexible vehicular sensor network. This in effect is an on-going mechanism as some of the processes can be initiated at any time. The grouping phases are generally assumed to be in the process of group formation, the process of new members, in the process of departing, and in the process of recovery. The dynamic nature of this structural approach necessitates real-time and flexible mechanisms supported by the functional role of the node. Herein, the configuration process of the node function can be tested in the virtualization platform to serve any scenario. This can offer a testing ground for any grouping dynamic phase and allow any necessary adjustment needed to improve the network performance. The key parameters for structuring the grouping phases are related to RSSI (Radio Signal Strength Intensity), node capacity, and vehicular speed. Furthermore, the look-ahead approach using route information is considered as part of sustaining the mobile structure of the vehicular group. Additional parameters can be utilized in some of the phases as part of the dynamic phase requirements.

III. Road traffic and communication Network latency modelling

A. Analysis of Road Traffic Model

The traffic flow on a highway or urban road is characterized by the number of vehicles distributed on each side of the road over one or more lanes. The highway scenario indicates the continuous flow and sparse layout of vehicles and offer good potential for the formulation of isolated groups, taking into consideration the stretch of the road. The size of a vehicular group can be modelled based on various road parameters such as defined end to end distance of the group, number of lanes, and the minimum distance defined between two vehicles within the same lane. The later could be simply the 2- second traffic compliance rules. Further complexity may also be expressed analytically and embed within the model. In such a case, the capacity and density of any group within the lane can be defined to analyse the group size on the defined stretch of the road. Also, the factors of the communication type, number of hops, and type of measurements are considered as the network parameters for defining the group size limits.

The lane capacity C_L on a highway road can be calculated based on a given mobile group stretch (boundary) over the road BR, and the 2-second distance (safety distance), D_{safety}, as it can be obtained based on a given lane speed Ls. C_L is expressed as in the following equation (1):

$$C_L = \frac{BR}{D_{safety(Ls)}} \quad where: Ls_{min} \le Ls \le Ls_{max} \quad (1)$$
$$BR_{min} \le BR \le BR_{max}$$

In which C_L is the capacity per lane (the maximum number of vehicles that the lane could accommodate within a given BR), the $D_{safety\,(Ls)}$ is obtained as per the lane speed (Ls). Herein, based on the obtained capacity per lane, the distribution of vehicles would vary depending on the total number of vehicles travelling along the lane. In a road with number of lanes, the high-speed lane could have the least number of vehicles due to its limited capacity while the lower speed (the left lane in our case) could have a greater number of vehicles.

As the number of lanes N_L is one of the road parameters that can have an impact on the possible distribution of number of vehicles N_v on the road, the ultimate road capacity CR_{N_L} can be calculated as:

$$CR_{N_L} = N_L * \sum_{m=1}^{N_L} \frac{BR}{D_{safety_{[Lsm]}}} \quad (2)$$

In which $D_{safety\,(Lsm)}$ is dependent on the speed of each lane within the road. For example, most of the highways in New Zealand specify the speed limit to be 100 Km/h. Here 90 and 110 km/h may be considered as Ls_{min} and Ls_{max} respectively. This allows ± 10 speed tolerance for the highway road. Let us consider (for the analysis purposes) $Ls = 100$ Km/h, then $D_{safety\,(Ls)}$ will be $56\,m$, CR_{N_L} can be obtained depending on the set of number of lanes and road boundary. The ultimate road capacity is 284 vehicles when the road boundary is 4Km and number of lanes is 4.

Given that we have defined the road capacity over a given stretch, we need to explore how would the population of a given group be structured as a network. Here we are looking at the parameter that encourages a given network topology. From the network communication and structure point of view, the number of hop(s) N_{Hop} is calculated as:

$$N_{Hop} = \frac{BR}{(TR_{Max} \times K)} \quad (3)$$

The ideal N_{Hop} is dependent on BR and the transmission range of the communication protocol used for vehicle-to-vehicle communication. Herein, the maximum effective transmission range TR_{Max} is multiplied by the confident range factor K, where $0.1 \le K \le 1$. The factor is defined based on $RSSI_{th}$ constraint wherein the received RSSI can be higher than a $RSSI_{th}$ constraint. For example, IEEE 802.11p transmission range is up to 1 Km, BR=1, K= 0.5, then N_{Hop}=2 hops. The size of each hop in terms of number of vehicles $N_{Hope\,(size)}$ can be calculated based on the road capacity and the obtained number of hops as:

$$N_{Hope\,(size)} = \frac{CR_{NL}}{N_{Hop}} \quad (4)$$

It is worth mentioning here that if tree topology is used, each hop could have more than one router at the same level that get connected to number of nodes. Each router capacity within a given level is subjected to the network performance evaluation. This relates to node joining selection criteria and load balance among hops of the same level.

B. Latency Model for Vehicular Grouping Phases

Each phase of the vehicular grouping approach consists of the stages of initialization and data dissemination, event trigger such as a node leaving the network, and event final response such as a node replacement. These stages are expressed through a series of communication messages exchanged among the related nodes, and any computation during the process. Herein, these stages could influence the latency associated with each phase of the grouping approach mainly the self-formation and self-healing phases. The self-formation tree-based approach experiences a growth in the data/packet length as the information is passed from the lower level to the top level represented by the gateway node. The delay occurred in each level is explained by Fig.3(a) and (b). Herein, the delay occurred in a single-hop, $D_{R\text{-}Hop}$, when the data is transmitted from the source to the destination is assumed to be calculated based on the propagation delay within a hop D_{Prop} and the transmission delay D_{TR}. Equations (5), (6), and (7) calculate D_{Prop}, D_{TR}, and $D_{R\text{-}Hop}$ respectively.

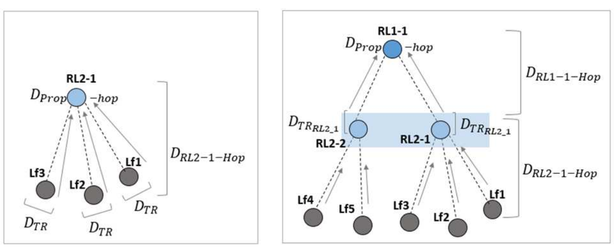
$$D_{Prop} = T_{received} - T_{transmission} \quad (5)$$

Where D_{Prop} is the difference between time stamps of the message reception $T_{received}$ of the destination and transmission $T_{transmission}$ of the source node.

$$D_{TR} = \frac{P_{length}}{R_{data}} + S_{rate} \quad (6)$$

Where P_{length} is the length of a packet/message transmitted by a node, R_{data} is the data rate. Both of P_{length} and R_{data} of a router or gateway node could vary depending on the number of connections. S_{rate} is the communication message transmission rate.

$$D_{R-Hop} = D_{Prop} + D_{TR} \quad (7)$$



(a) delay occurred in level 2 level1

(b) delay occurred from level 2 to

Fig. 3. The vehicular tree structure packet format and delay

The delay occurred when the source node transmitted packet travels through multiple hops to reach to the destination node can be expressed as:

$$D_{L2-L1} = D_{Prop} + D_{TR(source)} + D_{TR(mid\ router)} \quad (8)$$

where $D_{L2\text{-}L1}$ is the delay from level 1 to level 2. Following the given structure in Fig.3(b), D_{Prop} is the difference between the received time of the destination (RL1-1) and the transmission time of the source (Lf1). $D_{TR(source)}$ is the transmission delay of Lf1 and $D_{TR(mid\ router)}$ is the transmission delay of RL2-1, both are calculated as defined in (6). The delay varies in each hop as each router located in each hop has different payload.

An event could take place in the vehicular group causing latency that needs to be analysed. For example, the self-healing phase is one of the crucial processes that can take place in any level of the network. The event trigger stage is defined when a router node at any level of the network or a gateway node departs the network. Therefore, the event response stage is defined when a replacement node is elected. Fig.4 illustrates the nodes involved in the process when RL1-1 departs from its location. The latency of the event trigger D_{ET} represented by the departed router R_D data dissemination can be calculated as:

$$D_{ET} = D_{Prop(D-S)} + D_{TR(R_D)} \quad (9)$$

where $D_{Prop(D-S)}$ is the difference between the time of the destination (last affected node to receive the data from R_D) and the time of R_D. $D_{TR(R_D)}$ is the transmission delay entailed by R_D. The node election stage involves computation time causing processing delay $D_{Process}$. The latency entailed by each eligible node $D_{Eligible\_N}$ can be expressed as:

$$D_{Eligible\_N} = D_{Prop(D-S)} + D_{TR(EN)} + D_{Process} \quad (10)$$

Herein, for example, RL2-2 is the new elected node that sends a notification of its new role to the affected nodes as well as its leaf nodes and to establish the new connection to RL2-1 and the gateway. The latency for this stage can be expressed as:

$$D_{Elected\_N} = D_{Prop(D-S)} + D_{TR(EN)} \quad (11)$$

Then, the leaf nodes of the elected node, RL2-1, and gateway node send acknowledgment to the elected node causing $D_{Prop(Ack)}$. Each node sending the (ack) can experience transmission delay D_{TR}. The processing on a gateway node such as updating its capacity cause $D_{Process}$. Also, the new elected node will update its ID to be the RL1-1 and its capacity causing $D_{Process}$. The latency of the post-election can be expressed as:

$$D_{Post\_Election} = D_{Prop(Ack)} + \sum_{i=1}^{n}(D_{TR_i} + D_{Process_i}) \quad (12)$$

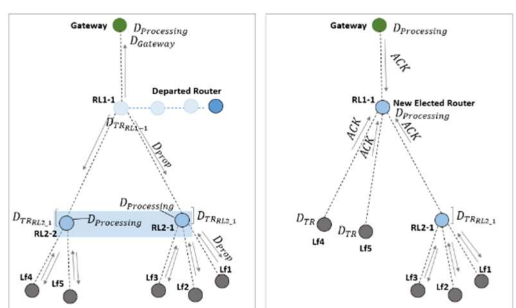


Fig. 4. The self-healing phase delay

IV. Network Scenario and Results

The behaviour of the network-based grouping approach has been modelled using the Contiki-Cooja network simulator as a virtualization tool. The main parameters have been set to design the various scenarios related to, for example, network self-formation with emphasis on multi-hop to be aligned with the suggested road traffic model. Also, a router node may leave the network, self-leaving, due to lane change or the node being faulty. Herein, the self-healing process scenario will take place for the node replacement. These processes are executed based on vehicular-related parameters, sequence of communication messages, and the event response computation element (such as fitness model). The following Table I depicts the Cooja simulation parameters taking into consideration the network and road parameters.

TABLE I. SIMULATION PARAMETERS

Simulation Parameters	Value
Simulation time	5 minutes
Total number of vehicles	30
Number of lanes	4 highway lanes (same direction)
Number of hops	4-hops
Speed varying	80-110 Km/h

The following Cooja figure 5 shows the network structure of a tree-based with four hops network. It also shows the possibility of departure of a router node ID 4 from the network.

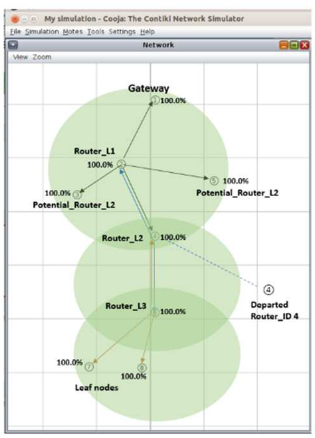


Fig. 5. Vehicular grouping network scenario based cooja

In this section, the results of Cooja scenarios are discussed based on the phase (such as self-formation) transactional latency following the suggested generic latency model. The router and/or gateway node capacity performance is related to the suggested road traffic model, mainly the lane ultimate capacity.

- *Router and/or Gateway Node Capacity Performance*

The router and/or gateway functional node that is operational under any phase of the vehicular grouping approach is set to have number of connections (capacity). This factor can be evaluated based on the packet/message received as to be aligned with the ultimate capacity per lane. As per suggested in the road traffic model that the ultimate capacity per lane is 17 when the speed lane is 100km/h, the set of number of vehicles (5, 10, 15, and 20) is considered. Herein, the router or/and gateway node capacity can be affected by the network structure be it a single or multi-hop network, the road capacity depending on number of lanes. In the cooja scenario, the communication message rate of (10, 20, and 30) message/second is considered. It can be seen from the figure below that the 10 message/second as a communication rate causes the functional node to receive 98%-80% messages for the vehicles of 5 to 20 vehicles respectively.

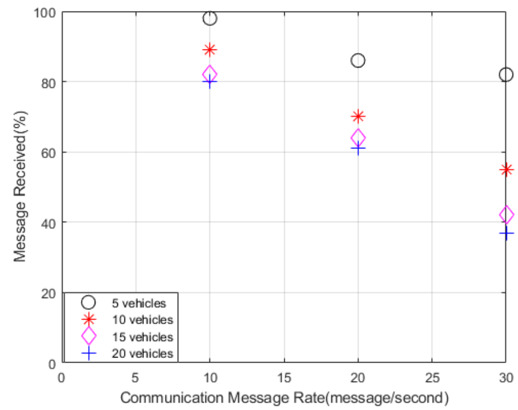


Fig. 6. The functional node capacity performance

- *Single- and Multi-Hop Network Self-Formation*

This phase has the stages of initialization and data dissemination represented by the ad-hoc approach before establishing the network self-structure. The event trigger stage is when the nodes exchange their data and decide to elect a cluster head. The event response stage is when the fitness values are exchanged to make a decision for group head election as well as the rest of the topology. Each stage entails latency when it is executed and thus the self-formation phase is evaluated based on the transactional latency. The router node load, in terms of number of connections, within the formulated network is tested based on the latency in transmitting the data through a router to a gateway as it is shown in the figure below. The set of number of vehicles (5, 10, 15, and 20) is chosen as number of connections to the router. This also offers an indication about the given load of a router and the latency occurred when it comes to the parallel hop.

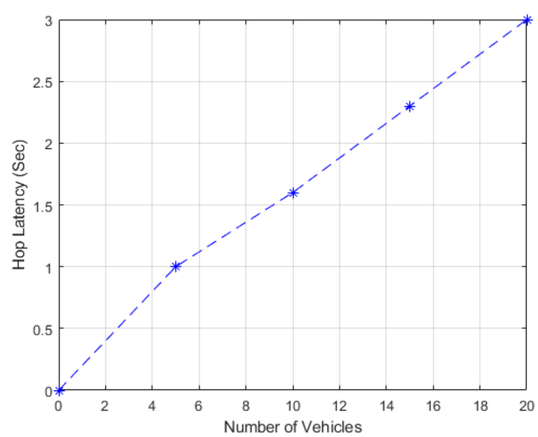


Fig. 7. The router node load latency

The factor of multi-hop network is considered to test its impact on the overall network latency with different number of vehicles. Herein, to be aligned with the suggested road traffic model, a single to four hops are designed to be tested with each set of vehicles. The set of number of total vehicles on the road (10, 20, and 30) is chosen for the test as 10 vehicles to be used for a single hop where one router is connected to it. The 10 vehicles are chosen for the 2-hop, 3-hop, and 4-hop where each router in each hop is connected to some nodes. The scenario has been evaluated based on the transactional latency of the full process occurred by the number of transactions, computation, and the latency of the network structure based on number of hops as suggested in the analytical latency model.

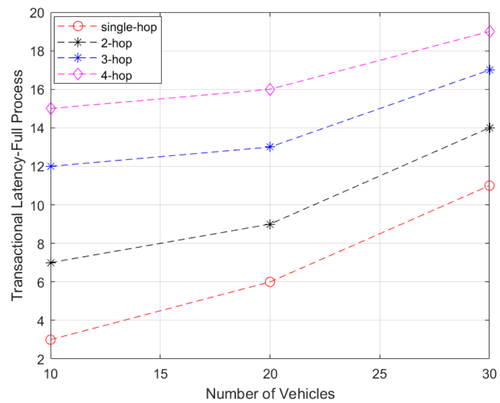


Fig. 8. The multi-hop self-formation: transactional latency

- *Self-Healing Phase Performance*

The self-healing phase has mainly an impact on the network performance when a router or gateway node departs from the network. The phase is initiated to replace the departed node with low latency to offer the recovery that is needed in the network. The transactional latency of the full process follows the suggested generic latency model. The figure below depicts the transactional latency of the full process based on the set of number of eligible vehicles (5, 10, and 15) to participate in the election process. As it is shown that the network with 5 nodes entails different transactional latency as compared with the 10 vehicles when its router departs.

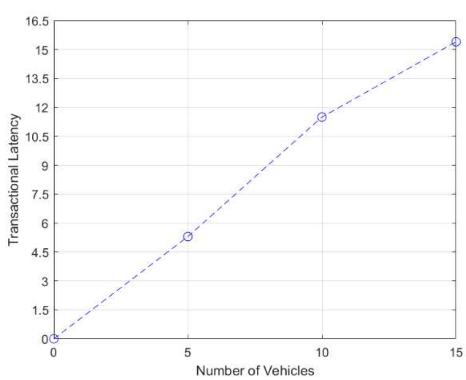


Fig. 9. The transactional latency of the self-healing phases

V. Conclusion

The paper has provided an analysis of the vehicular grouping approach based on the Self-X phases (i.e. self-formation, self-leaving, self-healing, and self-joining). The approach has emphasis on the flexibility of the nodes to assume one or more function as has been implemented or planned for the re-orchestration process. The features of each node that can fit the requirements of each grouping phase have been highlighted. The proposed approach has been modelled using Contiki-Cooja simulation tool and analysed based on transactional latency. Both analytical latency generic model and the road traffic model have been considered to support the vehicular grouping approach analysis. The approach, mainly the self-healing and self-formation, has been tested based on enabled router and/or enabled gateway node capacity and the number of hops considering the road stretch and its ultimate capacity. Herein, the data received by a router node with a different set of number of vehicles reflects the possible size of a vehicular group. The other performance measure used is the latency that is supported by the proposed analytical model. For future work, the model will be validated using the physical network with the use of mobile edge offering network intelligence.

References

[1] Kaur, R., Ramachandran, R.K., Doss, R., & Pan, L., "The importance of selecting clustering parameters in VANETs: A survey". *Computer Science Review,* 2021. **40**: pp. 100392.

[2] Rashid, S.A., Audah, L., Hamdi, M.M., & Alani, S., "Prediction Based Efficient Multi-hop Clustering Approach with Adaptive Relay Node Selection for VANET". *Journal of Communications*, 2020. **15**(4).

[3] Al-Hamid, D.Z. and A. Al-Anbuky, "Vehicular grouping and network formation: virtualization of network self-healing". in *International Conference on Internet of Vehicles*. pp. 106-121. 2018. Springer.

[4] Al-Hamid, D.Z. and A. Al-Anbuky, "Vehicular Grouping Protocol: Towards Cyber Physical Network Intelligence". in *IEEE International Conferences on Internet of Things (iThings)*. 2021. IEEE.

[5] Al-Hamid, D.Z. and A. Al-Anbuky, "Vehicular Network Dynamic Grouping Scheme". in *IEEE International Conference on Autonomic Computing and Self-Organizing Systems Companion (ACSOS-C)*. 2021. IEEE.

[6] Madni, A.M., Madni, C.C., & Lucero, S.D., "Leveraging Digital Twin Technology in Model-Based Systems Engineering". *Systems*, 2019. **7**(1): pp. 7.

[7] Zhuang, W., Ye, Q., Lyu, F., Cheng, N., & Ren, J., "SDN/NFV-empowered future IoV with enhanced communication, computing, and caching". *Proceedings of the IEEE,* 2019. **108**(2): pp. 274-291.

[8] Karegar, P.A. and A. Al-Anbuky, "Travel Path Planning for UAV as a Data Collector for a Sparse WSN". in *2021 17th International Conference on Distributed Computing in Sensor Systems (DCOSS)*. 2021. IEEE.